INVESTIGATIONS INTO CONTINUOUS EXTRUSION

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ABSTRACT

Continuous extrusion is an important recent development in the production of long lengths of rod and wire. In the process the normally round or rectangular feedstock is forced by friction towards the die by the feed channel, where three distinct regions, the primary, transitional and tertiary zones must develop before extrusion can commence. Stresses and strains in the deforming material along the feed channel, together with the characteristic dimensions of these regions must be known before continuous extrusion machines and tooling can be designed with confidence and product properties predicted.

A finite element computer program with quadrilateral two dimensional elements was used to calculate the various parameters in this non-steady state problem, when the development and spread of the transitional region in the billet must be predicted. The program is based on the assumption of rigid-plastic material behaviour and penalty function flow formulation was chosen. This is presented in the thesis in detail, together with other possible formulations and the advantages of the selected method are outlined.

For the experiments an existing rig was redesigned and rebuilt to suit the particular task. Two subsequent operations were carried out: first the billet was laterally compressed to provide an initial grip on the material when the primary zone developed, followed by axial compression leading to the development of the transitional and tertiary zones, which are of main interest in the present work. The various parameters were recorded by an IBM microcomputer and Labmaster analogue to digital convertor.

Experimental results were compared with theoretical findings obtained under the same conditions as in the experiments and suitability of the developed computer code assessed. Further, various parameters influencing the continuous extrusion processes Context, Linex and Conform were numerically assessed and conclusions drawn. The thesis concludes with suggestions for extending the theoretical model to predict the temperature distribution developed during the deformation process, together with possible implementation of a three dimensional model of the processes under consideration.

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CONTENTS

		Page
INVESTIGATIONS INTO CONTINUOUS EXTRUSION		1
ABSTRACT		2
ACKNOWLEDGEMENTS		3
CONTENTS		4
NOTATION		8
CHAPTER 1	CONTINUOUS EXTRUSION - GENERAL CONSIDERATIONS	10
1.1.	INTRODUCTION	11
1.2.	CONTINUOUS EXTRUSION PROCESS	11
1.2.1.	CONTINUOUS HYDROSTATIC EXTRUSION	
1.2.1.1.	Continuous Hydrostatic Extrusion with Stationary Chamber	11
1.2.1.2.	Continuous Hydrostatic Extrusion with Moving Chamber	14
1.2.2.	CONTINUOUS CONVENTIONAL EXTRUSION	14
1.2.2.1.	Conform	14
1.2.2.2.	Linex	15
1.2.2.3.	Extrolling	18
1.2.2.4.	Context	18
1.3	AIM OF THE PRESENT WORK	22
CHAPTER 2	FINITE ELEMENT METHOD - GENERAL THEORY	23
2.1.	INTRODUCTION	23
2.2.	CONCEPT OF THE FINITE ELEMENT METHOD	23
2.2.1.	DISPLACEMENT FUNCTION	25
2.2.2.	STRAINS	26
2.2.3.	STRESSES	27
2.2.4.	GENERAL FORMULATION	27
2.2.5.	ELASTIC FORMULATION	28
2.2.6.	INFINITESIMAL ELASTIC-PLASTIC FORMULATION	29

2.2.7	INCREMENTAL STRESS-STRAIN RELATIONSHIP (PLASTICITY)	30
2.2.8.	ELASTIC-PLASTIC ELEMENT STIFFNESS MATRIX	31
2.2.9.	ELASTIC-PLASTIC METHOD OF SOLUTION	33
2.2.9.1.	Incremental Tangential Method	33
2.2.9.2.	Initial Stress Method	35
2.2.9.3.	Initial Strain Method	37
2.2.10.	ELEMENTS USED IN THE FEM COMPUTER PROGRAMS	38
2.2.10.1.	Triangular Membrane Element	39
2.2.10.2	Two Dimensional Isoparametric Elements	42
2.2.10.3.	Three Dimensional Isoparametric Elements	45
CHAPTER 3	FLOW FORMULATION	47
3.1.	INTRODUCTION	47
3.2.1.	VISCOPLASTIC BEHAVIOUR	47
3.2.2.	THE PENALTY FUNCTION APPROACH	49
3.3.	GENERAL FORMULATION	51
3.3.1.	FORMAL STATEMENT OF THE PROBLEM	51
3.3.2.	MATRIX PROBLEM. DISCRETISATION	53
3.3.3.	ELEMENT MATRICES	57
3.3.4.	LOCKING EFFECTS IN THE PENALTY FUNCTION FORMULATION	61
3.3.5.	SOLUTION PROCEDURE	62
3.3.5.1.	Sequence of Operation	63
CHAPTER 4	EXPERIMENTAL INVESTIGATION	64
4.1	INTRODUCTION	64
4.2	EXPERIMENTAL EQUIPMENT	64
4.2.1.	TESTING MACHINE	64
4.2.2.	THE TEST RIG	66
4.3.	INSTRUMENTATION	77
4.3.1.	RECORDING OF THE DATA	77
4.3.2.	LOAD CELLS AND DISPLACEMENT TRANSDUCER	77
4.4.	SPECIMENS	82
4.5.	EXPERIMENTAL PROCEDURE	83

CHAPTER 5	EXPERIMENTAL RESULTS AND COMPARISON WITH THE THEORETICAL PREDICTIONS. PRELIMINARY DISCUSSION	85
5.1.	INTRODUCTION	85
5.2.	STRESS-STRAIN CURVE	85
5.3.	EXPERIMENTAL AND THEORETICAL MODEL	86
5.4.	EXPERIMENTAL DATA AND COMPARISON WITH THE THEORETICAL PREDICTIONS	91
CHAPTER 6	RESULTS AND DISCUSSION	123
6.1.	INTRODUCTION	123
6.2.	CASES CONSIDERED AND COMPUTATIONAL CONDITIONS	123
6.3.	DISCUSSION	128
6.3.1.	COMPARISON OF THE THREE PROCESSES	129
6.3.2.	DESIGNING OF CONTEXT	139
CHAPTER 7	CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK	204
7.2.	CONCLUSIONS	204
7.2.	SUGGESTIONS FOR FURTHER WORK	205
REFERENCES		207
APPENDICES:		213
APPENDIX 1	NUMERICAL INTEGRATION	214
APPENDIX 2	THEORY OF PLASTICITY IN BRIEF	216
	MATRIX FORMULATION	222

APPENDIX 3	COMPUTER PROGRAM	226
A3.1	INTRODUCTION	226
A3.2.	GENERAL DESCRIPTION OF THE PROGRAM	226
A3.3.	PROGRAM TERMINOLOGY	228
A3.4.	COMPUTER CODE "FEFF2D"	231
APPENDIX 4	LABMASTER DATA COLLECTION	258
	IBM-PC	258
	MOTHER BOARD	258
	DAUGHTER BOARD	259
	PROGRAMMING	260
APPENDIX 5	EXPERIMENTAL DATA	271

NOTATION

Scalar Quantities

A	- cross-sectional area
C_{ijkl}	- tensor of elastic constants
E	- elastic (Young's) modulus
E^t	- elasto-plastic tangent modulus
F	- plastic potential
H'	- hardening function
J_1, J_2, J_3	- first,second and third stress invariant respectively
J'_1, J'_2, J'_3	- first, second and third deviatoric stress invariant respectively
k	- shear yield stress
R	- extrusion ratio
S	- area
t	- plate thickness
u, v, w	- components of the vector of the unknowns, i.e. either displacement vector or velocity vector
V	- volume
W_p	- total plastic work
x, y, z	- cartesian coordinates
α	- penalty coefficient
δ_{ij}	- Kronecker delta
γ_{ij}	- shear strain components
$\dot{\bar{\varepsilon}}$	- equivalent (effective) strain rate
$\dot{\varepsilon}_v$	- volumetric strain rate
ε_{ij}	- normal strain components
$\dot{\varepsilon}_{ij}$	- strain rate components
$(d\varepsilon_{ij})^E$	- elastic strain increments
$(d\varepsilon_{ij})^P$	- plastic strain increments
$\bar{\varepsilon}$	- equivalent (effective) strain
κ	- hardening parameter
μ	- coefficient of friction
$d\lambda$	- plastic multiplier
ν	- Poisson's ratio
σ_{ij}	- stress components
σ'_{ij}	- deviatoric stress components
σ_y	- yield stress

$\bar{\sigma}$	- equivalent (effective) stress
$\sigma_1,\sigma_2,\sigma_3$	- principal stresses
τ_{ij}	- tangential stress components
Φ, $\bar{\Phi}$	- functionals
ξ, η	- natural coordinates

Matrices and Vectors

$\{a\}$	- flow vector
$[B]$	- displacement-strain matrix
$[D]$	- stress-strain matrix
$[D^E]$	- elasticity matrix
$[D^{EP}]$	- elastic-plastic matrix
$[D^P]$	- plasticity matrix
$\{f\}$	- load vector
$[J]$	- Jacobian matrix
$[k]^E$	- element stiffness matrix
$[K]$	- global stiffness matrix
$[L]$	- differential operator matrix
$[N]$	- shape function matrix
$\{P\}$	- vector of virtual loads
$[U]$	- velocities vector
$\{\delta\}$	- vector of nodal displacements

Convention used

$\{\}, \sim$	- column vector
$[], -$	- row vector, or rectangular or square matrix
$[]^e, _^e, \{\}^e, \sim^e$	- refers to an element quantity
$[]^t, _^t, \{\}^t, \sim^t$	- transposed vector or matrix
$[]^{-1}, _^{-1}, \{\}^{-1}, \sim^{-1}$	- inverse of vector or matrix
$[^E], _^E, \{^E\}, \sim^E$	- refers to an elastic state
$[^P], _^P, \{^P\}, \sim^P$	- refers to a plastic state

Other Variables

Any other variables are local to the text where they occur and are defined there.

CHAPTER 1

CONTINUOUS EXTRUSION - GENERAL CONSIDERATIONS

1.1. INTRODUCTION

The last two decades have seen considerable progress both in the development of new industrial processes and techniques, and in the theoretical treatment and methods of assessment of metalforming operations. All of these developments have resulted in a growing understanding of the existing processes, and have improved our ability to predict the behaviour of materials. Nowadays, a number of forming techniques are no longer laboratory curiosities but begin to find their places in production.

Modern metal-forming technology can be defined adequately as a combination of better understanding of metal behaviour and the deformation mechanics of a given operation in order to improve existing processes and to develop new ones. It is therefore a mixture of theory, experimentation and prediction of the behaviour of material in new circumstances that can be created by changes in factors such as lubrication, material property, workpiece shape, die shape, processing velocity, initial die and workpiece temperatures, ambient temperature and so on.

In the field of metal-forming, extrusion is a relatively young process. In extrusion a billet of material is forced to flow, under high pressure, through a die shaped to give the required cross-section to the product. It was first introduced early in the nineteenth century for the production of lead pipes. Since then, the application of the process to other materials progressed rather slowly and for some time it was almost exclusively a hot working process. The process was first used on steel around 1930, but the cold extrusion of steel started only during the Second World War in Germany.

Extrusion is capable of handling large reduction ratios in a single die and producing many special sections in a rapid and economical manner with high dimensional accuracy. This process is widely used in the production of rods and tubes of various sizes and cross-sections. Most of the products are extruded from standard size billets and as such, the process is intermittent.

For many industrial applications a semi-continuous or continuous process would be more attractive because of its low running cost and the continuity of its product, which in turn would reduce waste of metal. As a result the idea of continuous extrusion was developed, in which great lengths of feedstock in some standard size are fed continuously into a machine which reduces the input stock by extrusion into the desired shape.

1.2. CONTINUOUS EXTRUSION PROCESSES

The continuous extrusion processes developed so far are mainly for the extrusion of wire using small diameter feedstock. The processes can be divided into two categories namely:

(i) Continuous hydrostatic (or viscous drag actuated) extrusion

(ii) Continuous conventional (or friction actuated) extrusion.

1.2.1. CONTINUOUS HYDROSTATIC EXTRUSION

In the viscous drag actuated system the feedstock is pushed against the die by the motion of various media which envelop the feedstock. There are two versions of such systems, both hydrostatic in operation:

a) Viscous drag with stationary chamber

b) Viscous drag with moving chamber

1.2.1.1. Continuous Hydrostatic Extrusion With Stationary Chamber

A scheme of this process [25] is given in Fig.1.1. The process depends essentially on the drag of a very viscous fluid (such as bees wax) urging a long length of feedstock into the back end of the pressurised container which is separately supplied with hydrostatic extrusion fluid. Extrusion pressure p_1 is maintained continuously in the extrusion compartment by two rams, working alternately.

In order to prevent plastic flow of the billet at the separating wall between the feed compartment and the extrusion compartment, the difference between the pressure of the extrusion fluid p_1 and that of the viscous fluid p_2 must be less than the yield stress of the billet material. The same principle applies for the pressure difference at the entry to the first compartment and a series of steps is therefore needed until the pressure is reduced to the ambient pressure p_a. For this reason a number of compartments are used with a pressure

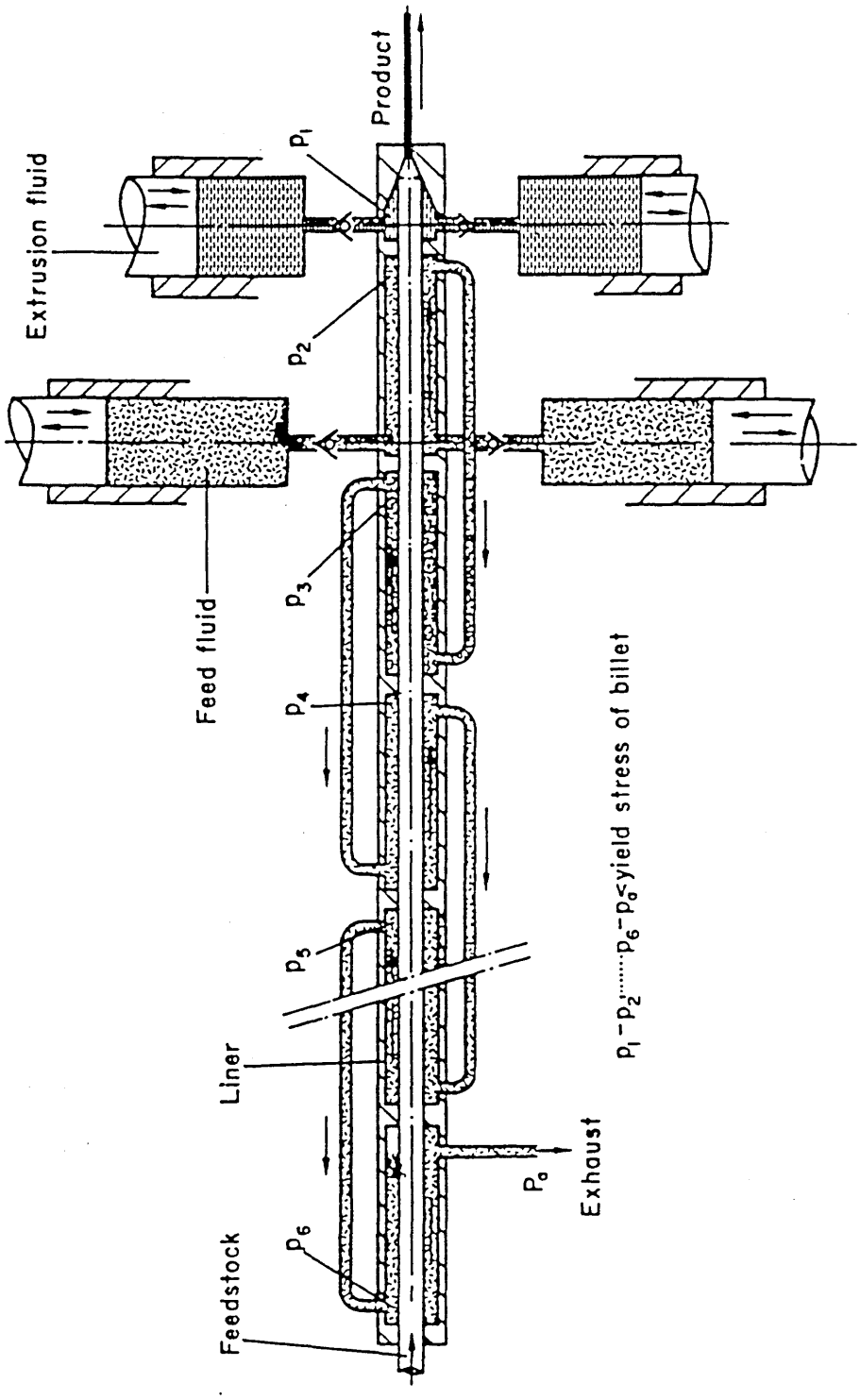
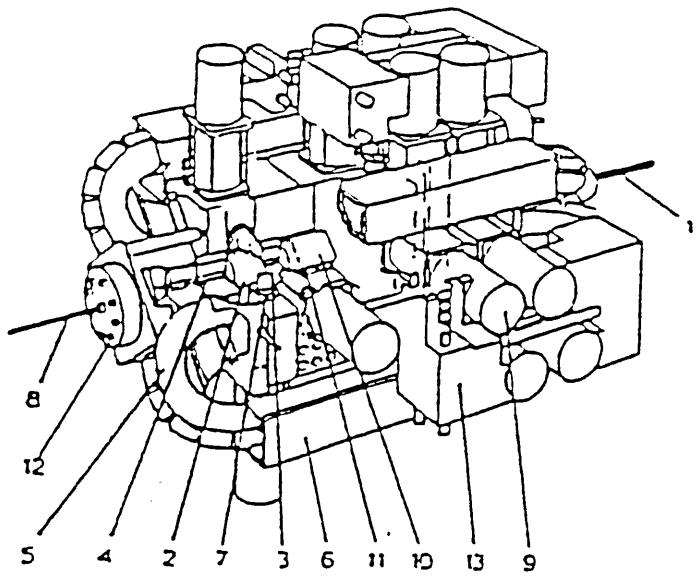


Fig.1.1 Continuous hydrostatic extrusion



1. Wire rod
2. Chamber segments
3. Extrusion die
4. Die stem
5. Track loop
6. Straight track
7. Pinion gear
8. Extruded wire
9. Hydraulic motor and gear reducer
10. Fluid pressure pad
11. Cooling water passage
12. Load cell
13. Hydraulic fluid manifold

Fig.1.2. Gear Extruder

difference between the neighbouring compartments less than the yield stress of the billet material. Referring to Fig.1.1 the condition to be obeyed may be expressed as:

$$p_1\text{-}p_2,\ p_2\text{-}p_3,\ \ldots\ldots,\ p_6\text{-}p_a < \sigma_y$$

where:

σ_y - is the yield stress of billet material.

1.2.1.2. Continuous Hydrostatic Extrusion With Moving Chamber

In Fig.1.2 is shown a gear driven continuous hydrostatic extrusion machine [24]. This machine operated successfully on a laboratory scale and a number of them were built on a production scale.

The device is a container built up of four tracks continuously moving in the axial direction, each comprising a large number of hard segments. These segments have a rack on their outer surface meshing with the gears which drive them around the system. The feedstock picks up a special liquid polymer (low molecular weight polyethylene) just before entry to the moving container. This acts as the viscous medium. The moving segments are coupled to the feedstock by the viscous medium which moves through the machine towards a fixed die. As the segments pass over the die, the rod is extruded through it. The segments are then transported back to the front end of the extruder for re-use. The last version of this machine is a real competitor to conventional wire drawing.

1.2.2. CONTINUOUS CONVENTIONAL EXTRUSION

This is a more attractive idea since the problems associated with the sealing of high pressure fluid in continuous hydrostatic extrusion would be absent. So far four types of friction actuated machines have been developed:

a) Conform
b) Linex
c) Extrolling
d) Context

1.2.2.1. Conform

In Fig.1.3 is shown the basic concept of Conform [27]. The container having a rectangular cross-section is made up of two parts, one of them incorporating a rectangular

groove and the other one being just a plane rectangular slab. When they are fitted together, they form a rectangular section block with a square-section hole. A square die is fixed into the plain slab in such a way that it protrudes into and effectively blocks off one end of the square hole in the composite container. With this arrangement, the slab portion of the container may be held stationary while the other portion may slide along, and over, the stationary die. Thus three sides of the container may move relative to the remaining fourth side.

In such a model a billet of round cross-section, partially contacts all four sides of the container after initial lateral indentation. If the container is now moved as described, the frictional force between its three sides and the billet will provide a force tending to move the billet against the die. Obviously the frictional force between the fourth side and the billet will tend to oppose billet movement. Therefore, a residual force equal to that arising from friction between the billet and two sides will remain and is available for extruding the billet through the die.

In practice the container is comprised of a three-sided groove in the perimeter of a rotating wheel, with a stationary shoe making up the fourth side of the container, as shown in Fig.1.4. The groove serves to grip the round feedstock and, along with the shoe, confines the material during upsetting. This upsetting is an essential feature of all continuous extrusion processes since sufficient frictional drag can only be achieved by the high interfacial pressure introduced between the feedstock and its container due to this upsetting. When the wheel rotates the pressure at the die face increases until it is sufficient for extrusion to take place. At that instant the upset length stabilises and the process runs continuously in a steady state fashion without interruption.

Conform is mainly used for the extrusion of wire. The late inventor D.Green claimed that this is also an excellent device for continuous powder compaction and extrusion.

1.2.2.2. Linex

An alternative form of continuous conventional extrusion can be performed in a linear fashion, rather than circular as in Conform . It is called Linex [87] and is shown in Fig.1.5. The machine uses two endless recirculating loops of gripping blocks which grip and advance the feedstock along a linear path towards the extrusion die. The gripping surfaces, which make up the two sides of the chamber, are hardened steel blocks assembled on two chains which are pulled by drive sprockets past the die. The other two sides of the chamber are fixed and are composed of the legs of a unique fork-shaped die element. Round stock is formed into rectangular shape at a pre-form stage. The opposing

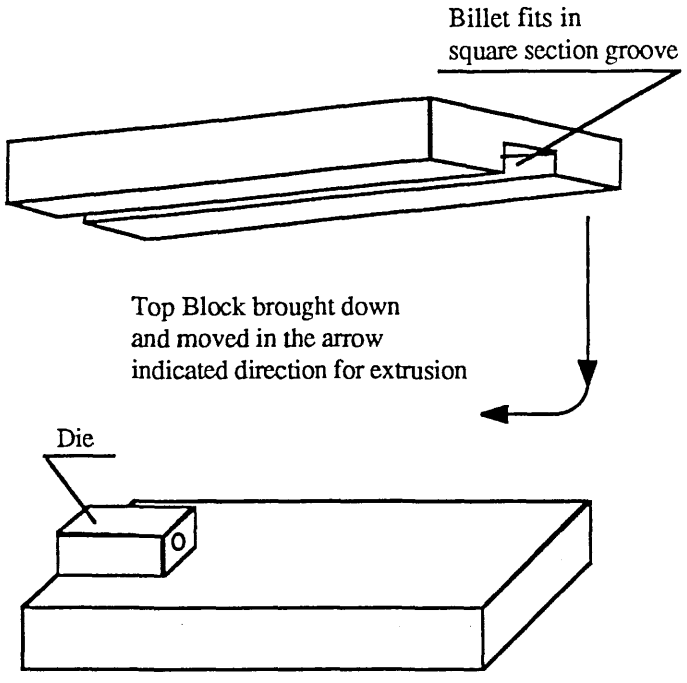


Fig.1.3 Container concept

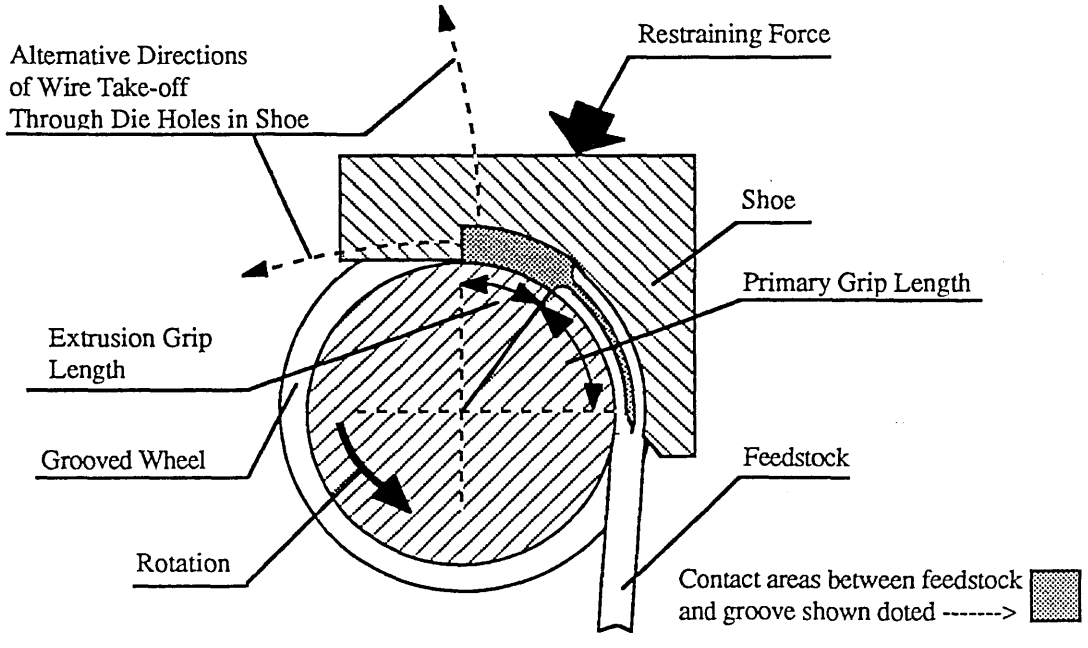


Fig.1.4 Conform Process

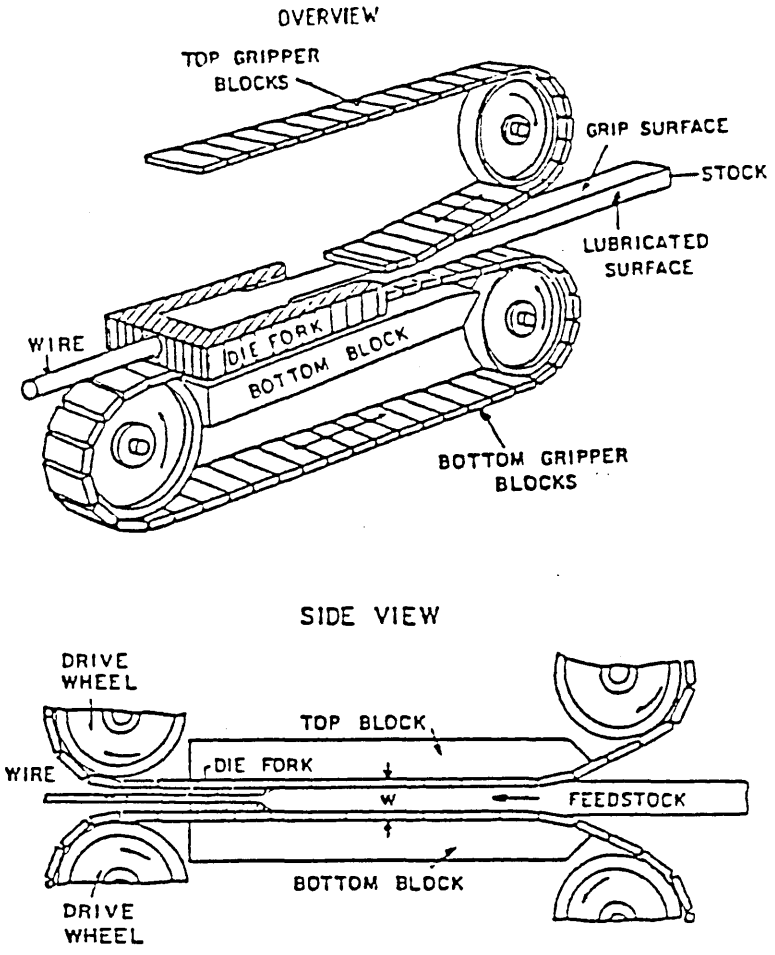


Fig.1.5 Linex Process

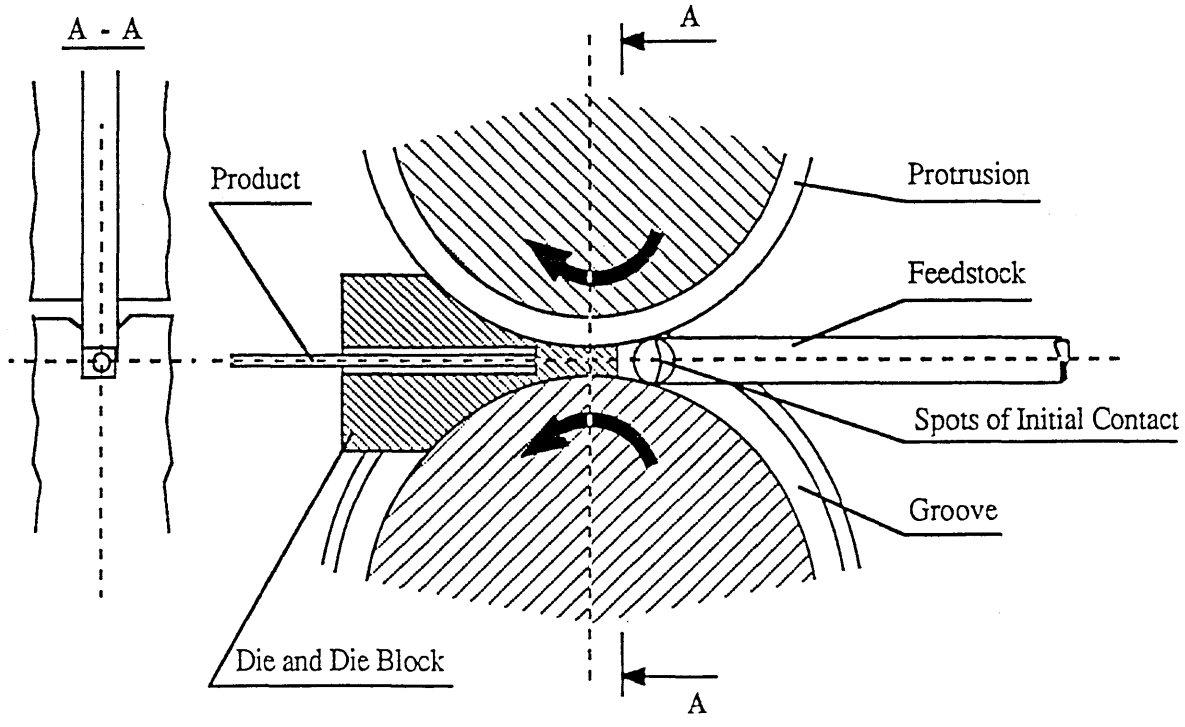


Fig.1.6 Extrolling Process

ungripped surfaces of the feedstock are lubricated before the stock is upset against the constraining walls of the chamber. A variety of lubricants can be used but solid lubricants are preferable since they are easy to handle on a continuous basis and tend to remain where applied. As the feedstock is advanced against the die, the pressure builds up at the die face and the feedstock upsets into the chamber walls. As in Conform, the upset length continues to grow until the pressure at the die face reaches the extrusion pressure. The grip length then stabilises and the process continues in a steady state manner.

Linex is developed mainly for the extrusion of wire. Compared with Conform, Linex operates at lower temperatures due to the effect of lubrication, which reduces unwanted friction on the non-gripping surfaces and hence temperature rise there. Lower output temperatures mean that the product will not self-anneal, but will exhibit an increase in hardness approximately equivalent to that obtained by wire drawing at the same reduction.

1.2.2.3. Extrolling

Combining extrusion and rolling Avitzur [6] invented a new continuous conventional extrusion process called Extrolling. This variety of continuous conventional extrusion is a combination of extrusion and rolling and is presented in Fig.1.6. Extrolling combines the continuity of the rolling operation with the high reduction ratios possible in extrusion. The process is basically the same as Conform, except that the stationary shoe is replaced by a roll as shown. The two rolls provide the forward moving chamber. The feedstock is fed into the groove and the rolls squeeze the rod and enhance the friction drag, advancing the feedstock towards the die. As in Conform, for extrusion to occur continuously, a minimum length of contact must be maintained between the workpiece and the chamber.

The process was mainly intended for the production of wire, although a wide strip can also be extruded into wide product or a number of products depending on the shape of the die outlet. Extrolling has never been developed for commercial use and it seems to be not a practical idea.

1.2.2.4. Context

The most recent idea for continuous extrusion, Context, is proposed by B. Lengyel [50]. The basic principle of this process is shown schematically in Fig.1.8.

The moving container stack consists of a number of parts, but alternative arrangements are possible, such as those shown in Fig.1.9, to accommodate various

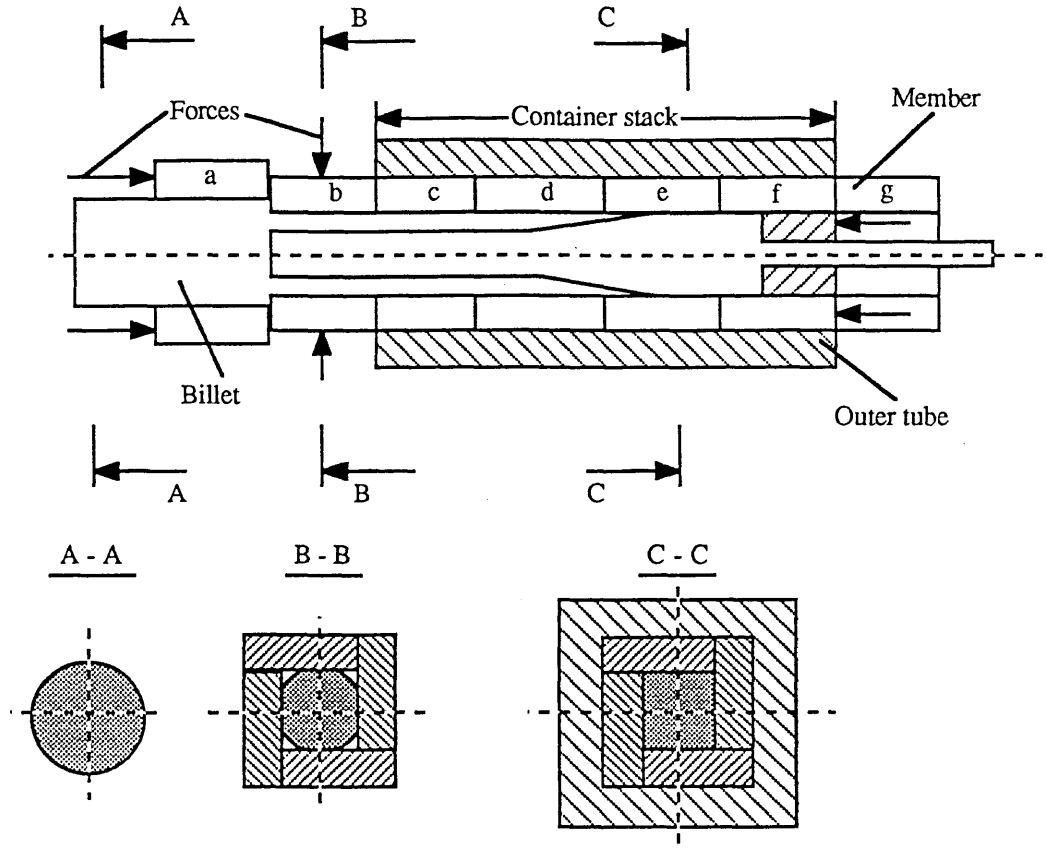


Fig.1.8 The Scheme of Context

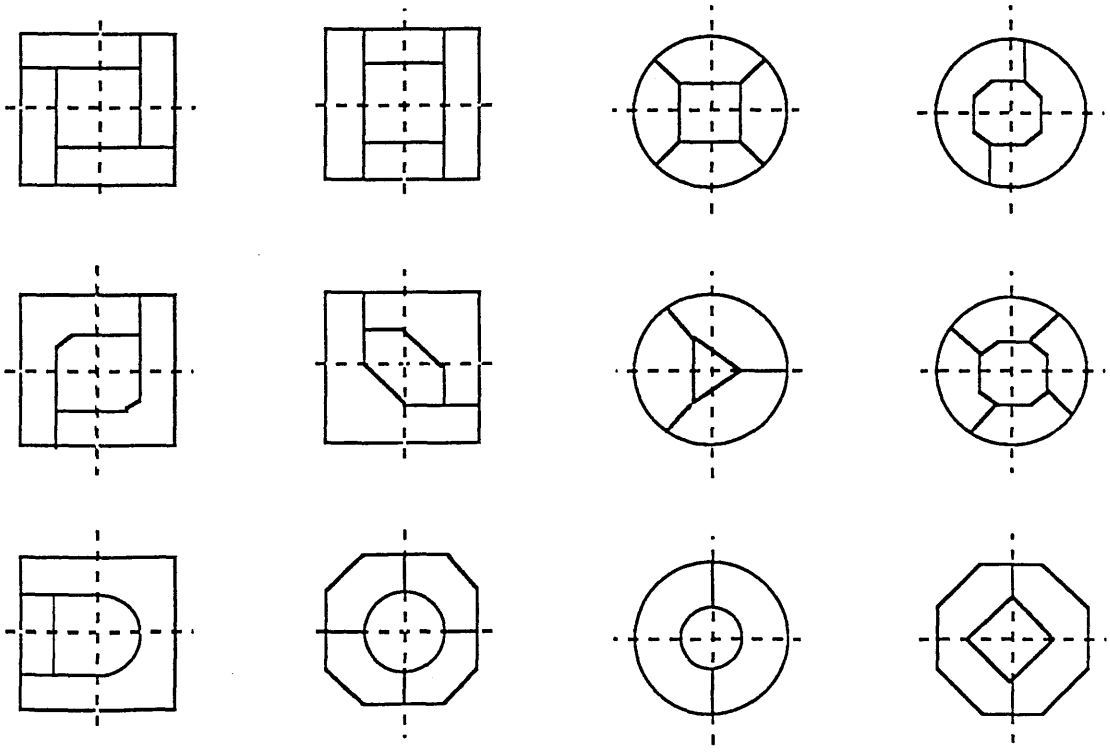


Fig.1.9 Alternatives in the Chamber Section

shapes of feed stock.These billet shapes would be useful when extruding products of different geometry. The versatility of the process is extended by the fact that it is able to accommodate not only feedstock of various sections, but also of varying size. This is so because each member can be moved towards the axis and away from it and can also slide on both its adjacent parts to create a fully enclosed channel of suitable size.

With the outer tube empty, a long billet of round or other cross-section (section A-A) is moved into position, coaxial with the tube. The four parts of the first member of the container are placed into position and forced towards the axis, plastically deforming the billet material. This is shown in section B-B. This member together with the billet is then forced towards the die and the four parts of the second member are placed into position behind the first one and forced towards the axis deforming the billet. The process is repeated with the subsequent members until the front end face of the billet reaches the die with one member of the container supporting the die in position **'f'**. The container is then forced towards the die exerting pressure on the billet end. Provided the frictional force between the billet and the container is sufficiently large, the billet material near the die suffers further plastic deformation and fills the cross-section completely as shown in section **C-C**. The area of the interface, thus the frictional drag, and the interfacial pressure between the billet and the container is thus increased. This process continues until the pressure between the die and the billet material becomes so large as to extrude the latter through the die orifice. As the foremost member clears the outer tube, position **'g'**, it is returned to position **'a'** and the process continues. As the back end of the billet reaches the entry section, a second billet is placed behind the first one and the process continues for as long as desired without interruption or change of speed.

Three different zones can be identified on a billet in Context, Fig.1.8. They are classified in terms of the amount of plastic deformation applied to the billet material. In the primary zone (Fig.1.8, section B-B) the only plastic deformation is due to the initial lateral compression of the billet by the container members. In the tertiary zone (Fig.1.8, section C-C) the billet fills up the channel completely. The secondary zone is a transitional region between the other two zones. In this region the billet is not completely upset into the chamber and it can suffer further plastic deformation.

Due to its rather recent introduction, Context has not yet been extensively investigated. Early feasibility studies relating to Context had been conducted by C.K. Teo [84] and P.S. Chua [11]. K. Noori [60] carried out a design study relating to a machine for Context. A. Kondylides [43] studied, both experimentally and theoretically, the effect of the relevant parameters on the development of forces and stresses in the square feed channel in the transitional and tertiary zones. He determined the normal and shear stress distributions along the container-billet interface and the axial pressure distribution along the

billet both experimentally and theoretically, using the equilibrium method. In his investigation billets of round cross-section were compressed in a square chamber.

A more detailed investigation relating to the primary zone was carried out by A. N. Sani [78], who studied the lateral indentation of long round billets. He assumed plane strain conditions in the analysis using the finite element method, the upper bound approach and slip line fields. He found a good correlation between the results obtained by the finite element method and those obtained experimentally.

A. Shaari [79] conducted theoretical and experimental investigations into the lateral indentation of long billets of square cross-section between cylindrical dies. As Sani, he also investigated only the first stage of continuous extrusion, the lateral indentation in the primary zone using the slip line field method and found that the theoretical results agreed well with those found by other people for similar processes, but they differed considerably from those obtained in his own experiments.

H.T. Man [54] determined the distribution of the axial pressure along the initially square billet, the normal and shear stress distributions along the container/billet interface and the total frictional force for various conditions in the transitional and tertiary regions. As in the work of A. Shaari, billets of rectangular cross-section and cylindrical tools were used. Reasonable agreement was found between the experimental results and those obtained by the equilibrium method.

It should be noted that in Context all four sides of the container are providing a frictional force, which drags the billet towards the die face, while in the three previously mentioned continuous extrusion processes only part of the container sides provide forward driving frictional force. For example in Linex only two of the container sides provide the useful frictional force, while the other two are opposing the billets' forward move. This is the reason why in Linex only rectangular cross-section billets can be used. If the container was square shaped the forces on the two driving and two opposing sides will cancel each other. In Conform, there are three sides providing useful frictional force and the fourth is providing negative frictional force. Also, as the three active sides are usually made as a groove in a rotating wheel, there is a significant work to bend the billet and this is the reason why only small diameter feedstock can be used with this particular process. In Extrolling the chamber is incorporated in two rotating wheels, so in this case all sides of the container are providing useful frictional force. On the other hand, for continuous extrusion to take place, there a minimum gripping length is required. In order to achieve big extrusion ratios bigger initial gripping length is required, which in turn increases the diameter of the wheels. This is the reason why Extrolling is intended for wire production and uses small diameter feedstock.

1.3. AIM OF THE PRESENT WORK

The main objective of this project is to determine strains, stresses and forces inside a rectangular feed channel in the transitional and tertiary zones for flat rectangular billets laterally indented in the primary zone, for the various continuous extrusion processes, to compare the obtainable extrusion ratios for different processes under similar conditions and to propose the optimum.

For the theoretical investigation the finite element method (FEM) is used to make predictions concerning the stress and strain distributions along the rectangular feed channel: the development of the transitional and tertiary zones and the variation of the axial pressure and frictional shear stress in these zones.

In order to make comparison and critically assess the results obtained by the finite element method, experiments were conducted using a rig designed to simulate conditions in the feed channel of Context and results were compared with theoretical predictions. After concluding both theoretical and experimental investigations, relationships between the obtainable extrusion pressure and process parameters were established.

CHAPTER 2

FINITE ELEMENT METHOD - GENERAL THEORY

2.1 INTRODUCTION

The Finite Element Method (FEM) seeks to satisfy the necessary boundary and equilibrium conditions in an approximate way. The continuum is separated by imaginary lines or surfaces into a number of so called 'finite elements'. The elements are assumed to be interconnected at a discrete number of nodal points situated on their boundaries. The displacements of these nodal points are the basic unknown parameters of the problem. A set of functions is chosen to define uniquely the state of displacement within each finite element in terms of nodal displacements. The displacement fields must be chosen in such a way as to satisfy the compatibility condition within each element and between the neighbour elements. An unsuitably chosen displacement field can cause gaps or overlaps within the elements or at interelement boundaries.

In the FEM the equilibrium equations and boundary conditions are satisfied only approximately. The approximation improves as more elements are used, and in the limit of an infinitely fine mesh, the stresses calculated by the FEM would be equal to the exact values within the continuum.

The characteristics of a 'finite element' are derived and represented in mathematical form. The virtual work principle is applied to a single element and no assumption of linearity or non-linearity of the material is made. The derived equation is in a general form and applicable to any situation. In what follows, the special case for elastic continua is presented and some basic definitions are given.

2.2. CONCEPT OF THE FINITE ELEMENT METHOD

The finite element method [12,14,18,22,26,34,56,62,81,89], whose engineering application started in the 1960's in structural analysis, is spreading to a variety of fields in

engineering and science. Taking advantage of the rapid development of digital computers with large capacity as well as fast computation, the method is used more often than other analytical and numerical approaches. In the area of solid mechanics, the method is recognised as the most powerful numerical tool because of its capabilities to treat complex boundaries and anisotropic materials. It becomes possible to obtain the local state of stress and strain, and other detailed information such as pressure distributions and local workpiece deformations for work-hardening materials [41,45,48,49].

The concept of the finite element method is one of discretization. The finite element model is constructed in the following manner. A number of points is identified in the domain of the function, and the values of the function and its derivatives, when appropriate, at these points are specified. These points are called nodal points. The domain of the function is represented approximately by a finite collection of sub-domains called finite elements. The domain is an assemblage of elements connected together appropriately on their boundaries. The function is approximated locally within each element by continuous functions which are uniquely described in terms of the nodal point values associated with the particular element. The path to the solution of a finite element problem consists of five specific steps:

(a) define the problem
(b) select the proper element
(c) derive the element equation
(d) assemble the element equations into the global system of equations
(e) solve the global system of equations.

The basis of finite element metal flow simulation using the variational approach is to formulate a proper functional, depending upon the specific constitutive relations. Or another way is to formulate a proper weak form from the equilibrium equations using the Galerkin method. The solution of the original boundary value problem is obtained by the solution of the dual variational problem, where the first order variation of functional vanishes. Choosing the approximate interpolation function for the field variable in the elements, the functional is expressed locally within each element in terms of the nodal point values. The local element equations are then assembled into the overall problem. Thus, the functional is approximated by a function of global nodal point values. The condition for this functional to be stationary results in the stiffness equations. For metal-forming problems the stiffness equations are non-linear [8,65] and solved by the Newton-Raphson iterative method.

For rigid-plastic materials, obeying the Mises yield criterion and its associated flow rule, the incompressibility constraint can be removed by introducing either the Lagrangian multiplier or the penalty function into the functional. If the body contains a rigid region, the

stresses in the region cannot be determined. This difficulty is handled by considering an offset of the effective strain-rate which is several orders of magnitude smaller than the average strain-rate in the deforming zone. The deviatoric stresses are assumed to vary linearly from zero to the flow stress if the effective strain-rate is smaller than the offset value. This stress and strain-rate relation in the "nearly rigid" region modifies the functional accordingly.

For rigid-viscoplastic material, the constitutive equations derived from the viscoplastic theory are similar to those of rigid-plastic materials except that the flow stress is a function of strain and strain-rate.

For rigid-thermoviscoplastic material, where the flow stress is a function of strain, strain-rate and temperature, the parameters determining the thermo-mechanical state are represented by velocity and temperature. The analysis of the velocity field is treated by the same constitutive equations as used for the rigid-viscoplastic materials, and the analysis of the temperature field is obtained by solving the heat balance equation at the corresponding state of deformation. The coupling procedure between the two fields is done by the idea - "The Coupled Analysis of Rigid-Thermoviscoplasticity" - developed in 1979 [74,75]

An actual application of the finite element technique to metal-forming problems started in the early 70's with several simple examples such as axisymmetric upsetting of a cylinder, and plane-strain side-pressing [45,49]. Also it was applied to stretching sheet metal [41]. Recently, some computer programs [68] were developed to provide detailed analysis for both the deformation mechanics and the heat transfer based on rigid-thermoviscoplasticity for plane strain and axisymmetric problems with arbitrary die shapes. In order to cope with the demand to provide practical information to industry, much effort is being made to develop the finite element technique for three dimensional analysis of metalforming, including sheet metalforming and exploring new areas in metalforming.

2.2.1. DISPLACEMENT FUNCTION

A typical finite element **'e'**, in a two dimensional case, defined by nodes **i**, **j** and **k** with straight line boundaries is shown in Fig.2.1.

The displacements at any point within the element can be interpolated in terms of nodal point displacements by column vector **f(x,y)**:

$$\{f\} = [N]\{\delta\}^e = \left[N_i, N_j, N_k, \ldots\right] \begin{Bmatrix} \delta_i \\ \delta_j \\ \delta_k \\ \cdot \\ \cdot \\ \cdot \end{Bmatrix} \qquad (2.\ 1)$$

in which the components of [N] are in general functions of position and $\{\delta\}^e$ represents nodal point displacements for a particular element. The function [N] is called the shape function.

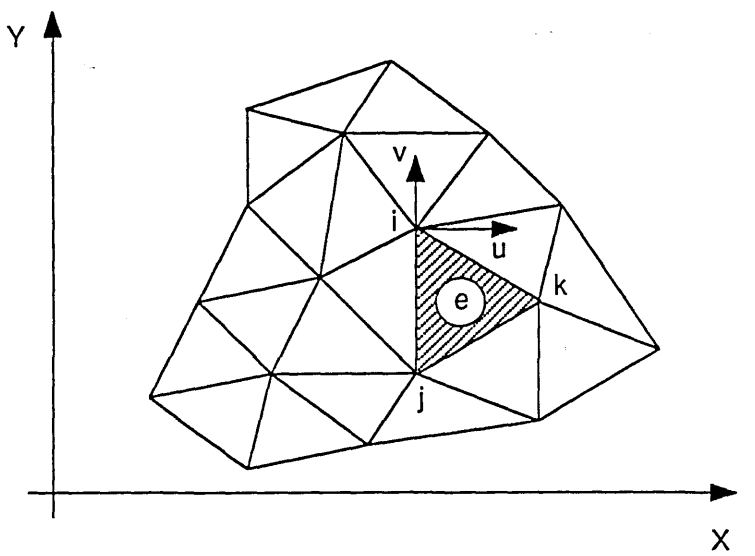


Fig. 2.1

2.2.2. STRAINS

The strain-displacement relationship within an element can always be written in matrix notation as:

$$\{\varepsilon\} = [B]\{\delta\}^e \qquad (2.2)$$

The matrix [B] is commonly known as the strain-displacement matrix. With displacements known at all points within the element the strains at any point can be calculated.

2.2.3. STRESSES

In general the material within the boundaries may be subjected to initial strains due to e.g. temperature changes, shrinkage and so on. If initial strains are denoted by $\{\varepsilon_0\}$, then stresses within the elements will be caused by the difference between the total and initial strains. In addition it can also be assumed that, at the outset of analysis, the material is stressed by some known initial stress $\{\sigma_0\}$.

Assuming general elastic behaviour, the relationship between stresses and strains will be linear of the form:

$$\{\sigma\} = [D^E](\{\varepsilon\} - \{\varepsilon_0\}) + \{\sigma_0\} \qquad (2.3)$$

where:

$[D^E]$ - is the elasticity matrix.

2.2.4. GENERAL FORMULATION

Equivalent nodal forces for an element are denoted by $\{F\}^e$. The distributed loads $\{P\}$ are defined as those acting on a unit volume of material within the element. To derive a mathematical formulation for the finite element 'e' the method of virtual work is used.

The procedure is to impose an arbitrary (virtual) nodal displacement and to equate the external and internal work done by the various forces and stresses during the displacement. The virtual displacement at the nodes is denoted by $d\{\delta\}^e$. This results, by Eqns. (2.1) and (2.2), in displacement and strain within the element:

$$d\{f\} = [N]d\{\delta\}^e \qquad \text{and} \qquad d\{\varepsilon\} = [B]d\{\delta\}^e \qquad (2.4)$$

The work done by the nodal forces is equal to the sum of the products of the individual force components and corresponding displacements, i.e. in the matrix notation:

$$(d\{\delta\}^e)^t\{F\}^e \qquad (2.5)$$

The internal work done by the stresses and distributed forces per unit volume is:

$$d\{\varepsilon\}^t d\{\sigma\} - d\{f\}^t \{P\} \qquad (2.6)$$

or

$$\{d\{\delta\}^e)^t([B]^t\{\sigma\} - [N]^t\{P\}) \qquad (2.7)$$

The external work is equated to the total internal work obtained by integrating over the volume of the element:

$$(d\{\delta\}^e)^t \{F\}^e = (d\{\delta\}^e)^t \left(\int [B]^t \{\sigma\}\, dV - \int [N]^t \{P\}\, dV\right) \qquad (2.8)$$

As this relation is valid for any value of virtual displacement, equality of the multipliers must exist and so:

$$\{F\}^e = \int [B]^t \{\sigma\}\, dV - \int [N]^t \{P\}\, dV \qquad (2.9)$$

By a proper modification of the nodal point loads the effect of distributed loads can be taken into account and Eqn.(2.9) reduces to:

$$\{F\}^e = \int_{\text{Element volume}} [B]^t \{\sigma\}\, dV \qquad (2.10)$$

Eqn.(2.10) is written for a single element and a similar relationship is obtained for the entire continuum by writing Eqn. (2.10) for different elements and assembling the equations together. So:

$$\{F\} = \int_{\text{Entire Continuum}} [B]^t \{\sigma\}\, dV \qquad (2.11)$$

where {F} denotes the nodal forces at all nodal points of the continuum.

Eqn. (2.11) is in general applicable to a linear or non-linear continuum.

2.2.5. ELASTIC FORMULATION

In elastic cases the relationship between stresses and strains are linear and Eqn. (2.9) can be presented in more interpretive form. Substituting Eqns. (2.2) & (2.3) into Eqn. (2.9), the following equation can be obtained:

$$\{F\}^e = \left(\int [B]^t [D^E]\, dV\right)\{\delta\}^e - \int [B]^t [D^E]\{\varepsilon_0\}\, dV + \ldots$$

$$\ldots + \int [B]^t \{\sigma_0\}\, dV - \int [N]^t \{P\}\, dV \qquad (2.12)$$

The term $[k]^e = \int [B]^t [D^E] dV$ is called the elastic element stiffness matrix.
Nodal forces due to distributed loads are:

$$\{F\}_p^e = - \int [N]^t \{P\}\, dV$$

and those due to initial strains are:

$$\{F\}_{\varepsilon_0}^e = - \int [B]^t [D^E]\{\varepsilon_0\}\, dV$$

Due to the initial stresses present at the outset of the analysis, their contributions to nodal forces are:

$$\{F\}_{\sigma_0}^e = + \int [B]^t \{\sigma_0\}\, dV$$

In a special case where the initial stresses $\{\sigma_0\}$ and the initial strains $\{\varepsilon_0\}$ are zero and the distributed loads are taken into account by appropriate modification of $\{F\}^e$, Eqn. (2.12) reduces to:

$$\{F\}^e = \left(\int [B]^t [D^E]\, dV\right)\{\delta\}^e \qquad (2.13)$$

2.2.6. INFINITESIMAL ELASTIC-PLASTIC FORMULATION

As the plastic formulation is a path dependent phenomenon, the equilibrium equations are given in an incremental form. For small increments of load Eqn.(2.10) can be written as:

$$\{F\}^e + d\{F\}^e = \int ([B] + d[B])^t (\{\sigma\} + d\{\sigma\})\, dV$$

or

$$\{F\}^e + d\{F\}^e = \int [B]^t \{\sigma\}\, dV + \int [B]^t d\{\sigma\}\, dV + \ldots$$

$$\ldots + \int d[B]^t \{\sigma\}\, dV + \int d[B]^t d\{\sigma\}\, dV \qquad (2.14)$$

The last term of the equation above can be ignored as negligibly small in comparison with the other three terms. For infinitesimal strains the change in the matrix $[B]^t$ can also be ignored. Thus Eqn. (2.14) reduces to:

$$\{F\}^e + d\{F\}^e = \int [B]^t \{\sigma\}\, dV + \int [B]^t d\{\sigma\}\, dV \qquad (2.15)$$

Subtracting Eqn.(2.10) from Eqn.(2.15) yields:

$$\{F\}^e = \int [B]^t d\{\sigma\}\, dV \qquad (2.16)$$

It can be shown that a relationship similar to Eqn. (2.13) can be obtained for elastic-plastic continuum but in an incremental form. For this the value of $d\{\sigma\}$ has to be expressed in terms of corresponding strain increments. An incremental relationship between stresses and strains will be given in the following section. Eqn. (2.16) is written for a single element and a similar equation can be obtained for the entire continuum by writing Eqn. (2.16) for each element and assembling eventually all the equations together. In such a manner the following equation is obtained:

$$d\{F\} = \int [B]^t d\{\sigma\}\, dV \qquad (2.17)$$

In the above equation $d\{F\}$ denotes the increment of loads at all the nodal points of the structure and the integral has to be taken over the entire continuum.

2.2.7. INCREMENTAL STRESS-STRAIN RELATIONSHIP (PLASTICITY)

An incremental stress-strain relationship analogous to Hook's law but valid beyond the proportional limit can be obtained as:

$$d\{\sigma\} = \left([D^E] - [D^E]\left\{\frac{\partial \bar{\sigma}}{\partial \sigma}\right\}[W]\right) d\{\varepsilon\} = \ldots$$

$$\ldots = \left([D^E] - [D^P]\right) d\{\varepsilon\} = [D^{EP}]\, d\{\varepsilon\} \qquad (2.18)$$

where:

$[D^E]$ – matrix of elastic constants

$[D^P]$ – plastic stress – strain matrix and $[D^P] = [D^E]\left\{\frac{\partial \bar{\sigma}}{\partial \sigma}\right\}[W]$

$[D^{EP}]$ – elastic– plastic stress – strain matrix and $[D^{EP}] = [D^E] - [D^P]$

$$[W] = \frac{\left\{\frac{\partial \bar{\sigma}}{\partial \sigma}\right\}^t [D^E]}{H' + \left\{\frac{\partial \bar{\sigma}}{\partial \sigma}\right\}^t [D^E]\left\{\frac{\partial \bar{\sigma}}{\partial \sigma}\right\}}$$

Also

$$d\bar{\varepsilon}^P = [W]d\{\varepsilon\} \qquad (2.19)^*$$

$[D^P] = [D^E]\{\partial \bar{\sigma} / \partial \sigma\}[W]$ – is called plastic stress-strain matrix. $[D^{EP}] = [D^E] - [D^P]$ is called the elastic-plastic stress-strain matrix and examination of the matrices involved has shown that $[D^{EP}]$ is a symmetric one. Eqns. (2.18) & (2.19) are both valid for elastic-perfectly plastic materials, as nothing in the derivation becomes indefinite if $H'=0$. Matrix $[D^{EP}]$ is a 6 x 6 matrix and can be expressed as Eqn. (2.20), in a simple and closed form ready for implementation in computer programs [53].

2.2.8. ELASTIC-PLASTIC ELEMENT STIFFNESS MATRIX

Substituting Eqns. (2.18) & (2.4) into Eqn. (2.16) the following can be obtained:

$$d\{F\}^e = \left(\int_V [B]^t [D^{EP}][B]dV\right)d\{\delta\} \qquad (2.21)$$

Eqn. (2.21) is similar to Eqn. (2.13) except for the use of $[D^{EP}]$ instead of $[D^E]$.

The matrix $[k^{EP}] = \int[B]^t[D^{EP}][B]dV$ is called elastic-plastic element stiffness matrix, the value of $[D^{EP}]$ is calculated from Eqn. (2.20).
Writing Eqn.(2.21) for every single element and assembling them together the following equation applicable for the entire continuum can be obtained:

$$d\{F\} = \left(\int_V [B]^t [D^{EP}][B]dV\right)d\{\delta\} = [K^{EP}]d\{\delta\} \qquad (2.22)$$

**For definition of $[D^E]$, H', σ, $d\varepsilon$ see Appendix 2.*

$$
\left[D^{EP}\right] = \frac{E}{1+\nu}
\begin{bmatrix}
\frac{1-\nu}{1-2\nu} - \frac{\sigma_x'^2}{s} & & & & & \text{SYMMETRIC} \\
\frac{\nu}{1-2\nu} - \frac{\sigma_x'\sigma_y'}{s} & \frac{1-\nu}{1-2\nu} - \frac{\sigma_y'^2}{s} & & & & \\
\frac{\nu}{1-2\nu} - \frac{\sigma_x'\sigma_z'}{s} & \frac{\nu}{1-2\nu} - \frac{\sigma_y'\sigma_z'}{s} & \frac{1-\nu}{1-2\nu} - \frac{\sigma_z'^2}{s} & & & \\
-\frac{\sigma_x'\tau_{xy}}{s} & -\frac{\sigma_y'\tau_{xy}}{s} & -\frac{\sigma_z'\tau_{xy}}{s} & \frac{1}{2} - \frac{\tau_{xy}^2}{s} & & \\
-\frac{\sigma_x'\tau_{yz}}{s} & -\frac{\sigma_y'\tau_{yz}}{s} & -\frac{\sigma_z'\tau_{yz}}{s} & -\frac{\tau_{xy}\tau_{yz}}{s} & \frac{1}{2} - \frac{\tau_{yz}^2}{s} & \\
-\frac{\sigma_x'\tau_{zx}}{s} & -\frac{\sigma_y'\tau_{zx}}{s} & -\frac{\sigma_z'\tau_{zx}}{s} & -\frac{\tau_{xy}\tau_{zx}}{s} & -\frac{\tau_{yz}\tau_{zx}}{s} & \frac{1}{2} - \frac{\tau_{zx}^2}{s}
\end{bmatrix}
\tag{2.20}
$$

where: $s = \frac{2}{3}\bar{\sigma}^2\left(1 + \frac{H'}{3G}\right)$

2.2.9. ELASTIC-PLASTIC METHOD OF SOLUTION

The final solution to an elastic-plastic problem is obtained by solving Eqn. (2.17). The equation is in incremental form and is valid only for infinitesimal strains. The complete solution to an elastic-plastic problem has to be carried out by a step by step method.

Depending on how the value of $\mathbf{d}\{\sigma\}$ is substituted in Eqn. (2.17), different approaches to the solution can be obtained.

2.2.9.1. Incremental Tangential Method

By applying load in increments and following the plastic deformation as it develops, one may properly account for the path-dependent nature of plasticity. In section **2.2.8.** it was shown that the equilibrium equation of the system can be written in the form $\mathbf{d}\{F\} = [K^{EP}]\mathbf{d}\{\delta\}$, where $[K^{EP}]$ depends on the current state of stresses within the elements.

In each load increment the value of $[K^{EP}]$ can be assumed constant and is obtained according to the state of stress within the elements prior to load increments. By knowing the value of $[K^{EP}]$ and the load increments, the nodal point displacements can be determined.

A typical step of solution is described below for a single degree of freedom problem (see Fig. 2.2).

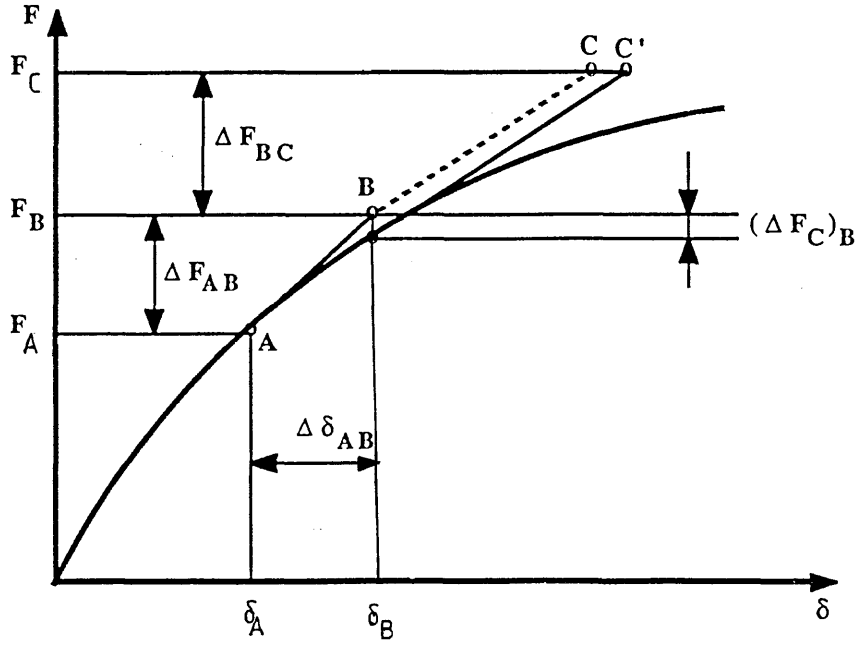


Fig.2.2.

If under load $\mathbf{F_A}$, the correct displacement δ_A and the structure tangent stiffness matrix $[\mathbf{K^{EP}}]_A$ are known, the displacements produced by the next load increment are computed as:

$$[\mathbf{K^{EP}}]_A \Delta\delta_{AB} = \Delta\mathbf{F}_{AB} = \mathbf{F}_B - \mathbf{F}_A$$

$$\delta_B = \delta_A + \Delta\delta_{AB} \qquad (2.23)$$

Stresses, strains and the tangent stiffness matrix must now be updated. Displacements of each element are extracted from $\Delta\delta_{AB}$. Using the updated values the appropriate $[\mathbf{D^{EP}}]_B$ for each sampling point (for the centroid in the case of triangular elements) is found. The elastic-plastic tangent stiffness matrix of an element is evaluated in the usual way:

$$[k^{EP}] = \int_{\text{Element volume}} [B]^t [D^{EP}] [B] dV$$

Upon reaching $\mathbf{F_B}$ in Fig. 2.2, the computed displacement δ_B is smaller than the actual amount of displacement, hence the resulting stresses will be smaller than the amount required to resist the applied load $\mathbf{F_B}$. If a 'corrective load' $\Delta\mathbf{F_C}$ were added to $\Delta\mathbf{F}$, the computed δ_B would be larger and closer to the correct value. Load $\Delta\mathbf{F_C}$ plays the role of an unbalanced force which is the difference between applied loads and resistance produced by distorted elements. This resistance is evaluated from the term $\{\sigma_o\}$ of Eqn.(2.12) with $\{\sigma_o\}$ now regarded as the total accumulated stress $\{\sigma\}$ in the element. Therefore, in general:

$$\Delta F_C = F - \sum \int_V [B]^t \{\sigma\} dV$$

where the summation extends over all elements of the structure. Force $\{\mathbf{F}\}$ and stress $\{\sigma\}$ are those at the end of a step. Correction force $\Delta\mathbf{F_C}$ is applied in the subsequent step. For example, equations for the step from point **B** in Fig. 2.2 are:

$$[K^{EP}]_B \Delta\delta_{BC} = \Delta F_{BC} + (\Delta F_C)_B \qquad (2.24)$$

In this way the point C' will be obtained instead of point C which is closer to the

real solution. If the correction load is not considered, the final answer drifts from the actual curve as the load increment increases. The drift can be minimised by making the load increments as small as possible.

2.2.9.2. Initial Stress Method

As correction load (ΔF_C) serves to return drifting values to the proper path, it is not essential that the tangent stiffness matrix be used within a step of load (ΔF) (see Fig.2.3)

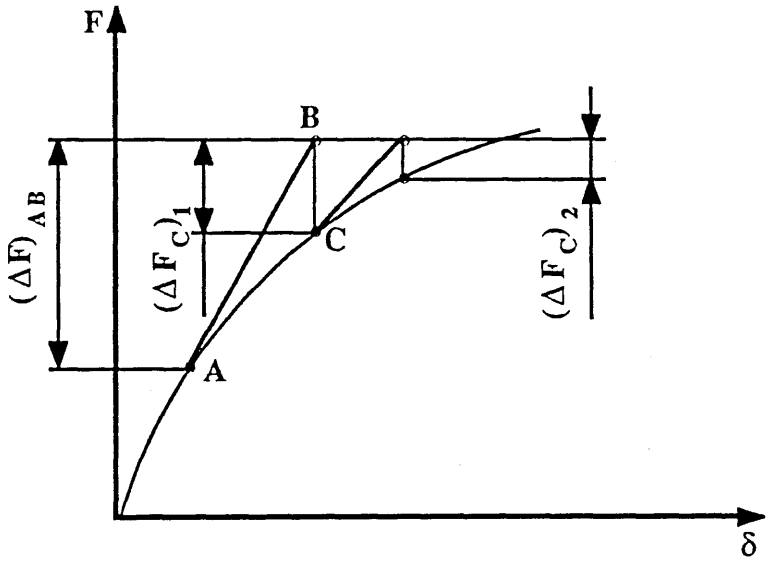


Fig.2.3.

Indeed, the original elastic structure stiffness matrix may be used in all loading steps. This approach of solution is called initial stress method. Iteration within each step is mandatory, as computed points, such as B in Fig. 2.3 are far from the correct path. The 'initial stress' method converges rapidly only when non-linearity is mild thus making a tangent modulus method preferable when large areas have yielded. The sequence and the formulation for the initial stress method is given below.

Eqn. (2.18) can be rewritten as:

$$d\{\sigma\} = [D^{EP}]d\{\varepsilon\} = ([D^{E}] - [D^{P}])d\{\varepsilon\}$$

The term $[D^E]d\{\varepsilon\}$ is denoted by $d\{\sigma^E\}$ and $[D^P]d\{\varepsilon\}$ by $d\{\sigma^P\}$ so:

$$d\{\sigma\} = d\{\sigma^E\} - d\{\sigma^P\} \qquad (2.25)$$

The value of $d\{\sigma\}$ is substituted in Eqn. (2.17) and using Eqn. (2.4) we get:

$$d\{F\} = \int_V [B]^t \left(d\{\sigma^E\} - d\{\sigma^P\} \right) dV$$

$$d\{F\} = \left(\int_V [B]^t [D^E] [B] \, dV \right) d\{\delta\} - \int_V [B]^t \, d\{\sigma^P\} dV$$

so

$$d\{F\} = [K^E] \{\delta\} - \int_V [B]^t \, d\{\sigma^P\} dV \qquad (2.26)$$

The term $\int_V [B]^t d\{\sigma^P\} dV$ is denoted by $\{\Delta p\}$, i.e.:

$$\{\Delta p\} = \int_V [B]^t d\{\sigma^P\} dV \qquad (2.27)$$

Eqn. (2.26) can be rewritten as:

$$d\{F\} = [K^E] d\{\delta\} - \{\Delta p\}$$

or

$$[K^E]^{-1} (d\{F\} + \{\Delta p\}) = d\{\delta\} \qquad (2.28)$$

To solve Eqn. (2.28) an iterative method is required. The following sequence is applied:

1. Assume $\{\Delta p\}_1 = 0$ and from Eqn.(2.28) calculate $d\{\delta\}_0$

   $$d\{\delta\}_0 = [K^E]^{-1} d\{F\}$$

2. Using Eqn. (2.4) calculate $d\{\varepsilon\}_0$

3. Calculate $d\{\sigma^E\}_0 = [D^E] d\{\varepsilon\}_0$ and $d\{\sigma^P\}_0 = [D^P]_1 d\{\varepsilon\}_0$ and so:

   $$d\{\sigma\}_0 = d\{\sigma^E\}_0 - d\{\sigma^P\}_0$$

   The total stress is $\{\sigma\}_2 = \{\sigma\}_1 + d\{\sigma\}_0$

4. Knowing the $d\{\sigma^P\}_0$ calculate$\{\Delta p\}_2$ from Eqn. (2.27)

5. From Eqn. (2.28), using the new value of $\{\Delta p\}_2$ calculate the new value for $d\{\delta\}$

6. Steps 2 to 5 are repeated until the required accuracy is obtained.

2.2.9.3. Initial Strain Method

The initial strain method is very similar to the initial stress method. The difference between the initial stress and initial strain approaches is illustrated diagrammatically in Fig.2.4. The stress-strain level reached by the first solution is shown as point **1**. In the initial stress process the stresses are brought down to the correct level by introducing an initial stress $\mathbf{d}(\sigma)_0$ while with the initial strain process the strains are adjusted by a correction $\mathbf{d}\{\varepsilon\}_0$.

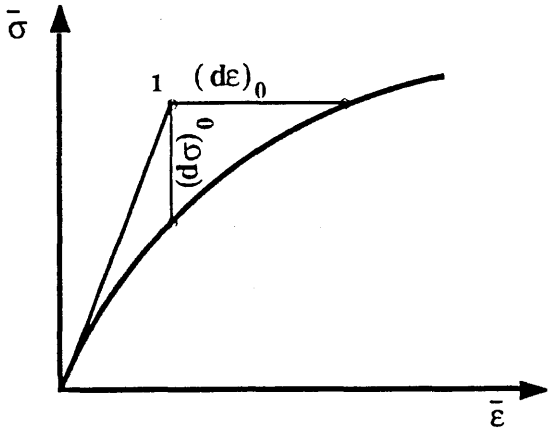


Fig.2.4.

The formulation and sequence of the procedure which can be implemented in the computer program is given below. The value of $\mathbf{d}\bar{\varepsilon}^{p}$ is found to be equal to:

$$\mathbf{d}\,\bar{\varepsilon}^{p} = \frac{1}{H'}\left\{\frac{\partial\bar{\sigma}}{\partial\sigma}\right\}^{t}\mathbf{d}\{\sigma\}$$

Substituting into the equation above $\mathbf{d}\{\varepsilon^{p}\} = \left\{\frac{\partial\bar{\sigma}}{\partial\sigma}\right\}\mathbf{d}\,\bar{\varepsilon}^{p}$ we get:

$$\mathbf{d}\{\varepsilon^{p}\} = \frac{1}{H'}\left\{\frac{\partial\bar{\sigma}}{\partial\sigma}\right\}\left\{\frac{\partial\bar{\sigma}}{\partial\sigma}\right\}^{t}\mathbf{d}\{\sigma\} \qquad (2.29)$$

Using Eqn. (2.29) the following equation can be written (see also Fig. 2.4):

$$\mathbf{d}\{\sigma\} = [D^{E}]\mathbf{d}\{\varepsilon^{E}\} = [D^{E}](\mathbf{d}\{\varepsilon\} - \mathbf{d}\{\varepsilon^{p}\}) \qquad (2.30)$$

Substituting Eqn. (2.30) into Eqn. (2.17) we get:

$$d\{F\} = [K^E]d\{\delta\} - \int_V [B]^t [D^E]\, d\{\varepsilon^P\}\, dV \qquad (2.31)$$

$$\{dp\} = \int_V [B]^t [D^E]\, d\{\varepsilon^P\}\, dV \qquad (2.32)$$

$$d\{F\} = [K^E]d\{\delta\} - \{dp\}$$

or:

$$[K^E]^{-1}(d\{F\} + \{dp\}) = d\{\delta\} \qquad (2.33)$$

As the value of $\{dp\}$ and $d\{\delta\}$ are unknown, to solve Eqn (2.33) an iterative method is needed and the following sequence can be employed:

1. Assume the stress increments $d\{\sigma\}$
2. Calculated $\{\varepsilon^P\}$ from Eqn. (2.29)
3. Compute $\{dp\}$ from Eqn. (2.32)
4. Compute $d\{\delta\}$ from Eqn. (2.33)
5. Calculate total strain increment $d\{\varepsilon\}$ from Eqn.(2.4)
6. Calculate stress increment using Eqn. (2.18)

$$d\{\sigma\} = [D^{EP}]d\{\varepsilon\}$$

7. Repeat steps 2 to 6 until required accuracy is obtained.

2.2.10. ELEMENTS USED IN THE FEM COMPUTER PROGRAMS

It was shown in Sections 2.2.1. and 2.2.8. that the element stiffness matrix is defined in terms of the displacements at the nodes of the element. Considering one element in isolation, the stiffness matrix could be set up by applying unit displacements in turn to the freedoms at each node. In order to obtain a useful stiffness matrix, simplifying approximations have to be made. Usually these approximations take the form of a simple interpolation polynomial. The coefficients of this polynomial are defined by nodal freedoms. This implies that the more nodal freedoms, the higher the order of the interpolation polynomial which can be used for the element. This assumed displacement field will not be unique for the element and the best form is usually found by practical comparisons. However, the assumed displacement field must satisfy at least two conditions:

a) It must be able to represent any rigid body movements that the element can undergo.

b) It must be able to give a constant strain throughout the element.

The satisfaction of these two conditions implies that, as the element shrinks in size as a mesh is made finer, in the limit it will behave as an infinitesimal element of material behaves. In practice quite large elements can be used, the actual size depending upon the rate of change of strain throughout the structure.

In the following a brief description of some commonly used elements will be given. The establishment of the shape functions, element stiffness matrix and the calculation of the stresses and strains will be outlined in the following sections.

2.2.10.1. Triangular Membrane Element

Historically one of the first elements to be developed was the triangular membrane, with a node at each vertex (see Fig.2.5). There are two degrees of freedom at each node, the horizontal and vertical displacements. Since there are three horizontal displacements, the corresponding polynomial can contain up to three terms, i.e.:

$$u = a_0 + a_1x + a_2y \tag{2.34.a}$$

Similarly

$$v = b_0 + b_1x + b_2y \tag{2.34.b}$$

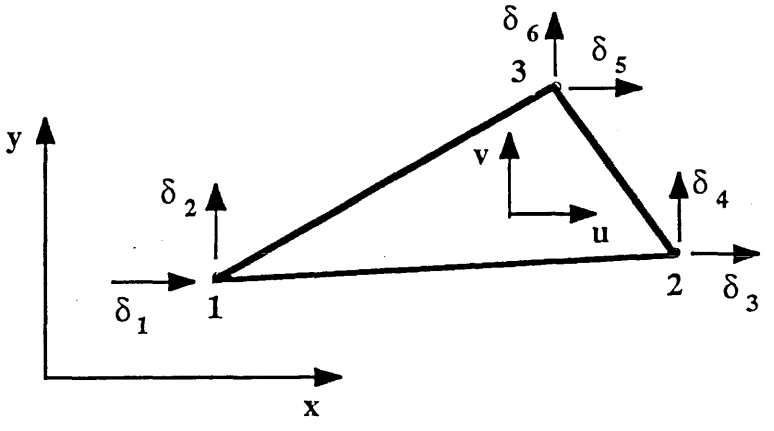


Fig.2.5.

Writing these in matrix form

$$\{f\} = [N]\{\alpha\} \tag{2.35}$$

where:

$$[N] = \begin{bmatrix} 1 & 0 & x & 0 & y & 0 \\ 0 & 1 & 0 & x & 0 & y \end{bmatrix}$$

$$\{\alpha\} = \{\alpha_0\ \beta_0\ \alpha_1\ \beta_1\ \alpha_2\ \beta_2\}^t$$

The constants a_0 to b_2 can now be found in terms of the nodal point displacements δ_1 to δ_6 since:

At node 1 $x = x_1$, $y = y_1$, $u = \delta_1$, $v = \delta_2$, therefore:

$$\begin{aligned} \delta_1 &= a_0 + a_1 x_1 + a_2 y_1 \\ \delta_2 &= b_0 + b_1 x_2 + b_2 y_2 \qquad \text{etc.} \end{aligned} \tag{2.36}$$

These can be combined into a single matrix equation:

$$\{\delta\} = [C]\{\alpha\} \tag{2.37}$$

where:

$$[C] = \begin{bmatrix} 1 & 0 & x_1 & 0 & y_1 & 0 \\ 0 & 1 & 0 & x_1 & 0 & y_1 \\ 1 & 0 & x_2 & 0 & y_2 & 0 \\ 0 & 1 & 0 & x_2 & 0 & y_2 \\ 1 & 0 & x_3 & 0 & y_3 & 0 \\ 0 & 1 & 0 & x_3 & 0 & y_3 \end{bmatrix}$$

which can be inverted to give

$$\{\alpha\} = [C]^{-1}\{\delta\} = [T]\{\delta\} \tag{2.38}$$

Although {C} is 6 x 6 matrix, it should be noted that the form of it is such that only 3 x 3 matrix need to be inverted. This inversion becomes less and less accurate as the size of the edge of the triangle is reduced with respect to the other two. Hence it is more sensible to choose a mesh which gives elements as near equilateral as possible.

The displacements at any point within the element can now be expressed in terms of the nodal displacements. Using Eqns. (2.35) & (2.38) we get:

$$\{f\} = [N]\{\alpha\} = [N][C]^{-1}\{\delta\} = [N][T]\{\delta\} \qquad (2.39)$$

The matrix [N], named the interpolation matrix, is a function of **x** and **y** . [T] is a transformation matrix between the global nodal coordinates and coordinates in which the element is originally defined.

After the displacements have been defined within the element, differentiating them the corresponding strains can be found. Considering again the element in Fig.2.5, there are three strain components, two direct and one shear, i.e.:

$$\varepsilon_{xx} = \frac{\partial u}{\partial x}$$

$$\varepsilon_{yy} = \frac{\partial u}{\partial y}$$

$$\varepsilon_{xy} = \frac{\partial u}{\partial y} + \frac{\partial u}{\partial x}$$

These three can be written in matrix form as:

$$\{\varepsilon\} = [d]\{f\} \qquad (2.40)$$

where:

[d] - is a matrix of differential operators which acts upon the displacement vector {f} and

$$[d] = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}$$

Now the strains can be defined in terms of the nodal displacements as:

$$\{\varepsilon\} = [d]\{f\} = [d][N][T]\{\delta\} = [B][T]\{\delta\} \qquad (2.41)$$

Matrix [d] acts only upon [N] since [T] and {δ} are not functions of **x** and **y**. The matrix [B] (= [d][N]) relates the element strains at any point within he element to the

nodal displacements. In other words the matrix is constant over the element, implying that the strains are constant over the element. This result follows from the initial assumption of a linear variation of displacements.

Now using the stress-strain relationship (see also Eqn.(2.3)) $\{\sigma\} = [D]\{\varepsilon\}$ the stresses can be expressed in terms of the nodal displacements and substituting for $\{\varepsilon\}$ the right hand side of Eqn. (2.41) we get:

$$\{\sigma\} = [D][B][T]\{\delta\} \qquad (2.42)$$

Using the principle of virtual displacement eventually the element stiffness matrix can expressed as:

$$[k]^e = [T]^t[B]^t[D][B][T]tA \qquad (2.43)$$

where

A - is the area of the triangle

t - is the plate thickness.

The procedure illustrated above can be applied in general to establish the stiffness matrix for any element. The basic steps are:

i. Assume an interpolation matrix [N] relating the displacements {f}, anywhere within the element, to the nodal displacements $\{\delta\}$, i.e. $\{f\} = [N][T]\{\delta\}$

ii. Set up the strain-displacement relationship, where the displacements are differentiated to give the strains $\{\varepsilon\} = [d]\{f\}$

iii. Substitute for the displacements at any point in terms of the nodal displacements. Explicitly differentiate the interpolation matrix to obtain the [B] matrix
$[B] = [d][N]$

iv. Establish the [D] matrix.

v. Substitute and integrate to obtain the element stiffness matrix

$$[k] = [T]^t \left(\int_V [B]^t [D] [B] \, dV \right) [T]$$

This integration is usually performed numerically using Gaussian Quadrature which is described in *Appendix 1*.

2.2.10.2. Two Dimensional Isoparametric Elements

For an isoparametric element the same shape function that is used to define the displacement field is also used to define the geometry of the element. This allows the

element to be distorted into almost any geometrical shape, especially the edges need no longer be straight, Fig. 2.6.

For the quadrilateral the actual geometry is mapped on to a 2 x 2 basis square, Fig. 2.7. The element is then defined on this basis square.

Here the same interpolation matrix is used to define both he displacement field and the geometry. It is set up on the 2 x 2 basis square in the (ξ_1,ξ_2) coordinate space. There are various ways in which the interpolation function can be defined. It is possible to follow the same approach as outlined in the previous section, i.e. define the four terms polynomial as there are four horizontal displacements and therefore here are four

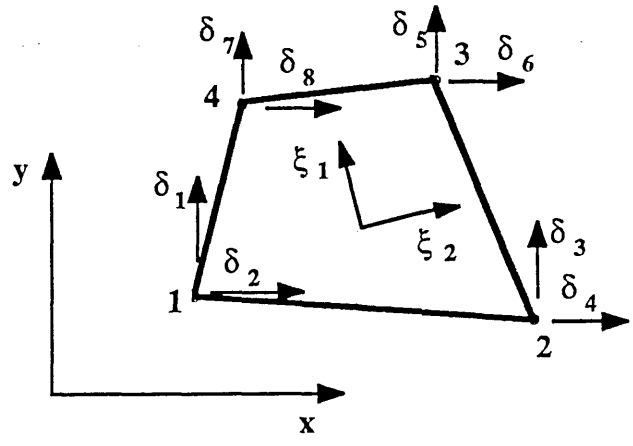
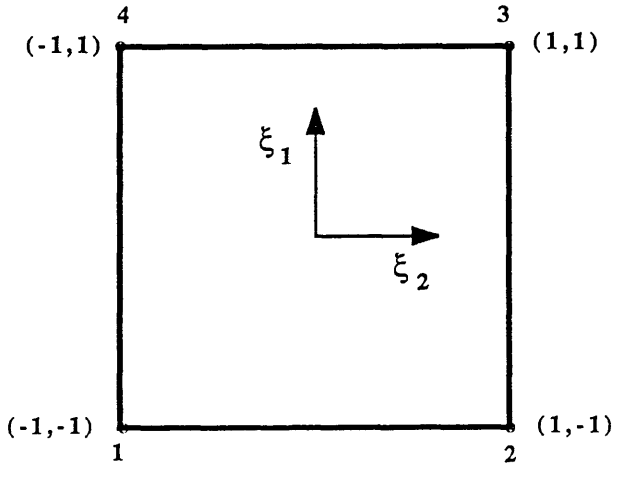


Fig.2.6. Real Element Geometry



$$-1 \le \xi_1 \le +1$$

$$-1 \le \xi_2 \le +1$$

Fig.2.7. (2 x 2) Basis Square

degrees of freedom. Further the same procedure as described previously is employed to obtain the element stiffness matrix. Another possibility is to use a method not involving the matrix inversion.

The interpolation matrix can be set up systematically by defining functions which are zero along lines ξ_1 and constant along ξ_2. These are then combined to give functions which are unity at one node and zero at the others. In this case there is a string of nodes along the lines ξ_1 = **-1,0,+1** and ξ_2 = **-1,0,+1** and functions which are zero along these lines are defined by:

$$\alpha_1 = (1+\xi_1) \qquad \beta_1 = (1+\xi_2)$$

$$\alpha_2 = \xi_1 \qquad \beta_2 = \xi_2 \qquad (2.44)$$

$$\alpha_3 = (1-\xi_1) \qquad \beta_3 = (1-\xi_2)$$

These are then combined to give the required interpolation functions:

$$n_1 = \frac{1}{4}\alpha_2\alpha_3\beta_2\beta_3$$

$$n_2 = \frac{1}{4}\alpha_1\alpha_2\beta_2\beta_3 \qquad \text{etc....} \qquad (2.45)$$

These functions are now used to define the interpolation matrix for the displacements:

$$\{f\} = [N]\{\delta\} \qquad (2.46)$$

where:

$$[N] = \begin{bmatrix} n_1 & 0 & n_2 & 0 & \dots & n_4 & 0 \\ 0 & n_1 & 0 & n_2 & \dots & 0 & n_4 \end{bmatrix} \qquad (2.47)$$

Obtaining in the usual manner the [B] matrix, by differentiating the interpolation matrix, i.e.:

$$[B] = [d][N] \qquad (2.48)$$

then the element stiffness matrix is:

$$[k]^e = \int_V [B]^t [D] [B] dV \qquad (2.49)$$

The integration is carried out again numerically using the Gaussian Quadrature.

2.2.10.3. Three Dimensional Isoparametric Elements

Full three dimensional elements are typified by the hexagonal brick type element, Fig.2.8.

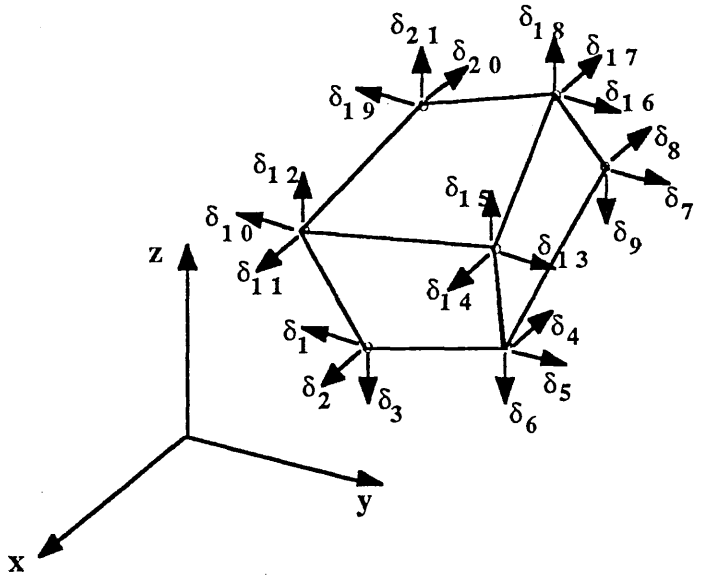


Fig.2.8. Element in Actual Coordinates

This element is established on (2 x 2 x 2) basis cube in ($\xi_1\xi_2\xi_3$) coordinates.

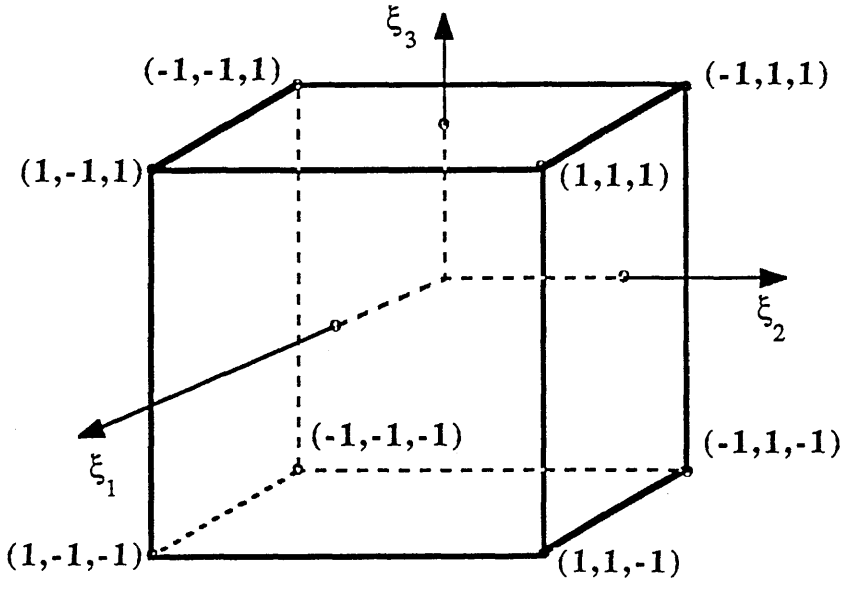


Fig.2.9. (2 x 2 x 2) Basis Cube

The interpolation matrix [N] is then established in exactly the same way as for membrane elements in Section 2.2.10.1 except that it now involves the three coordinates ($\xi_1\xi_2\xi_3$). The Jacobian, allowing the element to be distorted, is now a (3 x 3) matrix

involving the various combinations of derivatives of (xyz) with ($\xi_1\xi_2\xi_3$).

The strain-displacement matrix is of the form:

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \qquad (2.50)$$

The stiffness matrix coefficients can then be set up in the usual manner.

CHAPTER 3

FLOW FORMULATION

3.1. INTRODUCTION

This chapter is a brief review of the various concepts and techniques to be used throughout this work. The various properties of stress and strain/strain rate constitutive relations and yield conditions as applied to rigid-plastic bodies are discussed in order to make the penalty function flow formulation, further discussed, more clear. Also, variational techniques and finite element method are summarised.

3.2.1 VISCOPLASTIC BEHAVIOUR

Some attempts to describe the behaviour of the materials including time effects assume that the main mechanical properties of the material can be described with a visco-plastic constitutive equation. Since the elastic part of the material is neglected the simplest possible model which may be thought of is a Bingham type constitutive equation of the form [69], [91]:

$$\dot{\varepsilon}_{ij} = \gamma < \Phi(F) > \frac{\partial Q}{\partial \sigma_{ij}} \qquad (3.1)$$

where **F** is the description of a yield surface and **Q** is the definition of a plastic potential.

The symbol <...> means that:

$$<\Phi(F)> \equiv 0 \quad \text{if} \quad F<0 \quad \text{and} \quad <\Phi(F)> \equiv \Phi(F) \quad \text{if} \quad F \geq 0 \qquad (3.2)$$

The most common description of the viscoplastic flow of metals follows the assumption that both yield surface and plastic potential surface are identical, and that these depend only on the second stress invariant, i.e.:

$$F = Q = \sqrt{3}\sqrt{J_2'} - \sigma_y \qquad (3.3)$$

where:

$$J'_2 = \frac{1}{2}\sigma'_{ij}\sigma'_{ij}$$ - second invariant of the deviatoric stress

σ_y - the uniaxial yield stress

If the plastic strain-rate second invariant is defined as:

$$I_2 = \sqrt{\frac{1}{2}\dot{\varepsilon}^p_{ij}\dot{\varepsilon}^p_{ij}} \qquad (3.4)$$

the general constitutive equation can be written as:

$$\dot{\varepsilon}_{ij} = \gamma < \Phi\left(\sqrt{3}\sqrt{J'_2} - \sigma_y\right) > \frac{\sqrt{3}}{2\sqrt{J'_2}}\sigma'_{ij} \qquad (3.5)$$

or

$$\dot{\varepsilon}_{ij} = \frac{1}{2\mu}\sigma'_{ij} \qquad (3.6)$$

where the viscosity $1/2\mu$ is identified by:

$$\frac{1}{2\mu} = \gamma < \Phi\left(\sqrt{3}\sqrt{J'_2} - \sigma_y\right) > \frac{\sqrt{3}}{2\sqrt{J'_2}} \qquad (3.7)$$

and is a function of the stress level.

The similarity between Eqn.(3.6) and the relation between stress and strain for an isotropic elastic material (see *Appendix 2*) is evident. In order to write an equivalent expression in terms of the strain rate, from Eqns. (3.3), (3.4) & (3.5) can be seen that:

$$J'_2 = 2\mu^2\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij} = 4\mu^2 I_2^2 \qquad (3.8)$$

Substituting in Eqn.(3.7) it can be obtained:

$$\frac{1}{2\mu} = \gamma < \Phi\left(\sqrt{3}\,2\mu I_2 - \sigma_y\right) > \frac{\sqrt{3}}{4\mu I_2} \qquad (3.9)$$

Hence:

$$I_2 = \gamma < \Phi\left(\sqrt{3}\,2\mu I_2 - \sigma_y\right) > \frac{\sqrt{3}}{2I_2} \qquad (3.10)$$

from which μ can be determined for any strain rate function.

For an exponential type law, Eqn.(3.5) takes the form:

$$\dot{\varepsilon}_{ij} = \gamma < \Phi\left(\sqrt{3}\sqrt{J_2'} - \sigma_y\right)^n > \frac{\sqrt{3}}{2\sqrt{J_2'}}\sigma'_{ij} \qquad (3.11)$$

Now μ can be evaluated explicitly from Eqn.(3.10) as:

$$\mu = \frac{\sigma_y + \left(\frac{2I_2}{\gamma\sqrt{3}}\right)^{\frac{1}{n}}}{2\sqrt{3}I_2} \qquad (3.12)$$

Ideally plastic material with a fixed yield point is simply obtained by taking $\gamma = \infty$ and this gives:

$$\mu = \frac{\sigma_y}{2\sqrt{3}I_2} \qquad (3.13)$$

Substituting the last equation in Eqn.(3.6) the stress-strain rate relationship can be obtained as:

$$\sigma'_{ij} = \frac{\sigma_y}{\sqrt{3}I_2}\dot{\varepsilon}_{ij} \qquad (3.14)$$

It is evident that this equation is the same as Eqn.(A2.16), which represents the associated flow rule for a material obeying the von Mises yield criterion.

3.2.2. THE PENALTY FUNCTION APPROACH

Penalty functions are traditionally used to modify variational principles in the finite element analysis to enforce constraint. The problem of flow of a rigid-plastic material can be regarded as a constrained minimisation of a functional.

This approach is based on the application of a penalty to the square of error, in this case the square of the compressibility value. Thus, when the functional is minimised, the compressibility will be forced to be close to zero. Therefore, the penalty approach in solid mechanics amounts to approximating an incompressible media by a slightly compressible one.

This approach was originally established by Zienkiewicz [90] and subsequently used by Zienkiewicz and Godbole [92] for problems of creeping flow in which they include some extrusion problems as well as problems involving large surface deformations.

ZIenkiewicz and Godbole [93] have stated that the use of a penalty is identical to the use of a Poisson's ratio close to 0.5 in elasticity problems. Because of its simplicity of implementation, this approach has become widely popular and its application is continuously increasing.

Sharman [80] applied it to the problem of hot extrusion; Cornfield and Johnson [17] tackled the problem of hot rolling and studied the effect of various temperature distributions. Turner [86] and Alexander and Turner [3] solve the problem of hot die-less drawing; they reported some success on the prediction of the deformed shape, but some osculations in the stresses were also found and this was attributed to the use of simplex elements. Price and Alexander [72], [73] presented solutions for various problems of isothermal forming; they use serpendity quadratic elements and devised a method for calculating the mean stress, being able to calculate then the stress distribution.

Jain [38] and Zienkiewicz [95] extended further the application to various problems of extrusion, presenting some comparisons with results obtained using the Lagrange multiplier approach.

Zienkiewicz et al [97] and Zienkiewicz and Onate [96] used the penalty function together with an analysis of the energy dissipation to solve the problem of coupled thermal flow in extrusion and hot rolling. They also extended the flow approach to sheet metal forming.

The penalty function approach is the simplest to implement since, at its most basic form, it only involves a simple modification of existing elastic codes. Recent investigations have given mathematical formality to the approach and to its particular form of numerical integration. The method is also being used in other areas. Worth noting is the work by Hughes et al [35], where a comprehensive account of the theory behind the method is presented together with computational technics referred to the fluid mechanics context.

The penalty function approach was selected for the investigation reported in this work and a more detailed discussion of the formulation is presented further in the next section.

3.3. GENERAL FORMULATION

In the preceding sections, some of the existing formulations for plasticity problems have been reviewed. Both elastic-plastic and rigid-plastic formulations have advantages and drawbacks, hence, the choice of any specific formulation is by no means a straightforward one, let alone a logical one.

In this context, any choice has to be regarded as an arbitrary one, and only its later success in tackling specific problems will justify, or otherwise, the wisdom of the selection.

From an engineering point of view, simplicity of formulation is generally felt to be an asset, although this has to be weighted against the number of the assumptions made. Nevertheless, this simplicity is a relative one since any numerical method will, in general, involve more complexity than any non-numerical approach. Therefore, the choice is in degree of complexity rather than between a simple approach or a complex one.

Of the existing approaches the rigid-plastic one affords the inclusion of most of the parameters involved in metal forming, and at the same time renders a formulation that is relatively simple to handle on the computer. Therefore, rigid-plastic approach, namely, penalty function formulation, is chosen as the one to be used in this work.

3.3.1. FORMAL STATEMENT OF THE PROBLEM

Consider a body, V, whose surface, S, consists of S_u and S_T. The body is composed of a rigid-plastic material which obeys the Von Mises yield criterion and its associated flow rule, under the boundary conditions, such that the entire body is deforming plastically. Body forces are assumed to be absent in the region V. Than according to the extremum principle [46] the functional (3.15) takes an absolute minimum value for the actual solution with respect to a kinematically admissible velocity field:

$$\Phi = \int_V \underset{\sim}{\sigma}'_{ij}\, \underset{\sim}{\dot{\varepsilon}}_{ij} dV - \int_{S_T} \underset{\sim}{F}_i\, \underset{\sim}{u}_i \, dS \qquad (3.15)$$

This functional can be re-written as [49]:

$$\Phi = \int_V \bar{\sigma}\, \dot{\bar{\varepsilon}}\, dV - \int_{S_T} \underset{\sim}{F}^T\, \underset{\sim}{u}_i \, dS \qquad (3.16)$$

where:

$\dot{\bar{\varepsilon}}$ – the effective strain rate

$\bar{\sigma}$ - the equivalent stress

F^T - the traction vector specified at boundary S_T

It is obvious that the functional Φ does not include the effect of incompressibility constraint, therefore, it is necessary to introduce it. This can be done in various ways. Here the discussion will be limited to the penalty function approach.

In this approach, which stems originally from the optimisation literature [90], the constraint is introduced by imposing a penalty on the integral of the square error, in this case the value of compressibility.

Therefore, functional (3.16) can be rewritten as:

$$\int_V \bar{\sigma}\,\dot{\bar{\varepsilon}}\, dV - \int_{S_T} \underset{\sim}{F}^T \underset{\sim}{U}\, dS + 2\alpha \int_V \dot{\varepsilon}_v^2\, dV \qquad (3.17)$$

or

$$\bar{\Phi} = \Phi + 2\alpha \int_V \dot{\varepsilon}_v^2\, dV \qquad (3.18)$$

where $\alpha > 0$ is the penalty number and requires the stationality for the constrained solution. The solution obtained from functional (3.18) will satisfy the constraint only approximately. The larger the value of α the better the constraint will be achieved.

It is worth noticing that the formulation does not introduce any additional unknown parameters.

Examination of functionals (3.15) and (3.18) shows that the penalty approach is equivalent to elimination of the variable σ_m in the Lagrange Multiplier formulation [89] by writing the constitutive relation:

$$\sigma_m = \alpha\, \dot{\varepsilon}_v^2 \qquad (3.19)$$

where:

σ_m - hydrostatic or mean stress

Application of the stationery conditions leads straight to discretisation. This, together with the problems arising from overconstraint, will be discussed below.

3.3.2. MATRIX PROBLEM. DISCRETISATION.

The domain **V** is discretised into **M** non-overlapping elements connected at **N** nodal points. If $\bar{\Phi}^{(m)}$ is the value of the functional $\bar{\Phi}$ evaluated over the $\mathbf{m^{th}}$ element, then:

$$\bar{\Phi} = \sum_{m=1}^{M} \bar{\Phi}^{(m)} \qquad (3.20)$$

The approximation of the functional $\bar{\Phi}$ by a functional ψ is performed on the elemental level by replacing $\underset{\sim}{U}^{(m)}$ with a kinematically complete distribution given by:

$$\underset{\sim}{U}^{(m)} = \sum_{i=1}^{M} N_i^u u_i = \underline{N}^u \underset{\sim}{u}^{(m)} \qquad (3.21)$$

where:

$\underline{N}$ - interpolation function

$\underset{\sim}{u}$ - vector of nodal point velocities.

Similarly, if the pressure is one of the variables involved, then:

$$P = \underline{N}^P \underline{p}^{(m)} \qquad (3.22)$$

Let **u**, **v** and **w** describe the three Cartesian components of the velocity vector $\underset{\sim}{U}$.

The strain vector rate $\dot{\underset{\sim}{\varepsilon}}^{(m)}$ is related to the velocities by:

$$\dot{\underset{\sim}{\varepsilon}}^{(m)} = \underline{L}\ \underset{\sim}{U}^{(m)} \qquad (3.23)$$

where:

$$\dot{\underset{\sim}{\varepsilon}}^{(m)^t} = \left[\dot{\varepsilon}_x , \dot{\varepsilon}_y , \dot{\varepsilon}_z , \dot{\gamma}_{xy} , \dot{\gamma}_{yz} , \dot{\gamma}_{zx} ,\right] \qquad (3.24)$$

The operator $\underline{L}$ is defined as:

$$\underline{L} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 \\ 0 & \frac{\partial}{\partial y} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \end{bmatrix} \qquad (3.25)$$

The incompressibility constraint takes the form:

$$\dot{\varepsilon}_v^{(m)} = \dot{\varepsilon}_x^{(m)} + \dot{\varepsilon}_y^{(m)} + \dot{\varepsilon}_z^{(m)} = \underline{M}^t \underset{\sim}{\dot{\varepsilon}} = 0 \qquad (3.\ 26)$$

where:

$$\underline{M}^t = [1,\ 1,\ 1,\ 0,\ 0,\ 0]$$

The effective strain rate and effective stress are defined respectively as*:

$$\bar{\dot{\varepsilon}} = \left(\frac{2}{3} \underset{\sim}{\dot{\varepsilon}}^t \underline{D}_0 \underset{\sim}{\dot{\varepsilon}} \right)^{\frac{1}{2}} \qquad (3.\ 27)$$

and

$$\bar{\sigma} = \left(\frac{3}{2} \underset{\sim}{\sigma'}^t \underline{D}_0 \underset{\sim}{\sigma'} \right)^{\frac{1}{2}} \qquad (3.\ 28)$$

where

$\underset{\sim}{\sigma'}$ - deviatoric stress vector.

The deviatoric stress vector σ' is related to the strain rate vector ε according to the Levy-Mises equations by:

$$\underset{\sim}{\sigma'} = \frac{2}{3} \frac{\bar{\sigma}}{\bar{\dot{\varepsilon}}} \underline{D}_0 \underset{\sim}{\dot{\varepsilon}} \qquad (3.\ 29)$$

in which $\underline{D}_0$ is a diagonal matrix defined as:

$$\underline{D}_0 = \begin{bmatrix} 1 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & \frac{1}{2} & & \\ & & & & \frac{1}{2} & \\ & & & & & \frac{1}{2} \end{bmatrix} \qquad (3.\ 30)$$

**In this and the following sections all quantities are at the elemental level, but for convenience the superscript (m) is dropped unless otherwise specified.*

Noting relations (3.21) to (3.29) the functional and (3.18) can now be rewritten as:

$$\int_{V^{(m)}} \bar{\sigma}\left(\frac{2}{3}\,\underset{\sim}{u}^t\,\underline{B}^t\,\underline{D}_0\,\underline{B}\,\underset{\sim}{u}\right)^{\frac{1}{2}} dV - \int_{S_T^{(m)}} \left(\underline{N}^u\,\underset{\sim}{u}\right)^t \underset{\sim}{F}\, dS + \int_{V^{(m)}} \left(\underline{M}^t\,\underline{B}\,\underset{\sim}{u}\right)^t \underline{N}^p\,\underset{\sim}{p}\, dV \quad (3.31)$$

and:

$$\int_{V^{(m)}} \bar{\sigma}\left(\frac{2}{3}\,\underset{\sim}{u}^t\,\underline{B}^t\,\underline{D}_0\,\underline{B}\,\underset{\sim}{u}\right)^{\frac{1}{2}} dV - \int_{S_T^{(m)}} \left(\underline{N}^u\,\underset{\sim}{u}\right)^t \underset{\sim}{F}\, dS + \int_{V^{(m)}} \left(\underline{M}^t\,\underline{B}\,\underset{\sim}{u}\right)^t 2\alpha\left(\underline{M}^t\,\underline{B}\,\underset{\sim}{u}\right) dV \quad (3.32)$$

where:

$$\underline{B} = \underline{L}\,\underline{N}^u \quad (3.33)$$

Applying the stationary condition to functional (3.31), when the yield stress is independent of the strain rate, leads to:

$$\frac{\partial \psi^{(m)}}{\partial \underset{\sim}{u}^{(m)}} = \int_{V^{(m)}} \underline{B}^t\,\underline{D}\,\underline{B}\,\underset{\sim}{u}\, dV + \int_{V^{(m)}} \left(\underline{M}^t\,\underline{B}\right)^t \underline{N}^p\,\underset{\sim}{p}\, dV - \int_{S_T^{(m)}} \underline{N}^{u^t}\,\underset{\sim}{F}\, dS = 0 \quad (3.34)$$

and:

$$\frac{\partial \psi^{(m)}}{\partial \underset{\sim}{p}^{(m)}} = \int_{V^{(m)}} \underline{N}^{p^t}\,\underline{M}^t\,\underline{B}\,\underset{\sim}{u}\, dV = 0 \quad (3.35)$$

where:

$$\underline{D} = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}}\,\underline{D}_0 \quad (3.36)$$

This results in a simple set of equations which can be written as:

$$\begin{bmatrix} \underline{K}^u & \underline{K}^p \\ \underline{K}^{p^t} & 0 \end{bmatrix} \begin{pmatrix} \underset{\sim}{u} \\ \underset{\sim}{p} \end{pmatrix} + \begin{pmatrix} \underset{\sim}{f}^u \\ 0 \end{pmatrix} = 0 \quad (3.37)$$

or:

$$\underline{\underline{K}}\ \underline{a} + \underline{f} = 0 \qquad (3.38)$$

where:

$$\left.\begin{aligned} \underline{\underline{K}}^{u}_{ij} &= \int_V \underline{\underline{B}}^{t}_{i}\ \underline{\underline{D}}\ \underline{\underline{B}}_{j}\ dV \\ \underline{\underline{K}}^{p}_{ij} &= \int_V (\ \underline{\underline{M}}^{t}\ \underline{\underline{B}}_{i}\ )^{t}\ \underline{N}^{p}_{j}\ dV \\ \underline{f}^{u}_{i} &= -\int_S \underline{N}^{u^t}_{i}\ \underline{F}\ dS \end{aligned}\right\} \qquad (3.39)$$

where **i** and **j** are element 'local' node numbers.

Analogously, the stationary condition applied to the functional (3.32) leads to:

$$\frac{\partial \psi^{(m)}}{\partial \underline{u}^{(m)}} = \int_{V^{(m)}} \underline{\underline{B}}^{t}\ \underline{\underline{D}}\ \underline{\underline{B}}\ \underline{u}\ dV + \int_{V^{(m)}} \underline{\underline{B}}^{t}\ \underline{\underline{M}}\,\alpha\,\underline{\underline{M}}^{t}\ \underline{\underline{B}}\ \underline{u}\ dV - \int_{S_T^{(m)}} \underline{N}^{u^t}\ \underline{F}\ dS = 0 \qquad (3.40)$$

Again this results in a simple set of equations of the form:

$$\underline{\underline{K}}\ \underline{u} + \underline{f} \equiv (\ \underline{\underline{K}}^{u} + \underline{\underline{K}}^{\alpha}\ )\ \underline{u} + \underline{f} = 0 \qquad (3.41)$$

where:

$$\left.\begin{aligned} \underline{\underline{K}}^{u}_{ij} &= \int_V \underline{\underline{B}}^{t}_{i}\ \underline{\underline{D}}\ \underline{\underline{B}}_{j}\ dV \\ \underline{\underline{K}}^{\alpha}_{ij} &= \int_V \underline{\underline{B}}^{t}_{i}\ \underline{\underline{M}}\,\alpha\,\underline{\underline{M}}^{t}\ \underline{\underline{B}}_{j}\ dV \\ \underline{f}^{u}_{i} &= -\int_S \underline{N}^{u^t}_{i}\ \underline{F}\ dS \end{aligned}\right\} \qquad (3.42)$$

This process is formally identical to that of solving an elastic problem with a Poisson's ratio $\nu \rightarrow 0.5$.

A comparison with equations (3.39) stresses the advantages of the penalty function: the only variables involved are the velocities and use of the constitutive equation (3.19) renders the pressure variable which is then used to find the complete stress distribution. In coding terms this leads to considerable simplification.

3.3.3. ELEMENT MATRICES

Examination of equations (3.39) and (3.42) shows that elements with C^o continuity are required for the velocity field but discontinuous functions can be used to describe the pressure field in the velocity formulation. Indeed, practitioners [89] have found that, generally, a lower order of interpolation of the pressure field compared with that of the velocity field is desirable to avoid over-constraints.

The element used for the present investigation is the 4-node, bi-linear, isoparametric quadrilateral element. This element has proved to be the simplest effective one for use in both the mixed and the penalty function formulations [49], [55].

For convenience of calculations it is usual practice to transform the actual coordinate system into a natural coordinate system, see Fig. 3.1.*

Thus, the following relationship may be written:

$$\left.\begin{aligned} x(\xi, \eta) &= \sum_{i=1}^{4} N_i x_i \\ y(\xi, \eta) &= \sum_{i=1}^{4} N_i y_i \end{aligned}\right\} \qquad (3.43)$$

where the shape functions, N_i, are expressed as [89]:

$$N_i = \frac{1}{4}(1 + \xi\xi_i)(1 + \eta\eta_i) \qquad (3.44)$$

and (x_i, y_i) and (ξ_i, η_i) are the coordinates of the nodal points in actual and natural coordinates respectively.

The (ξ, η) system shown in Fig.4.1. is defined such that ξ and η vary from **-1** to **+1** within each element.

The velocity components **u** and **v** in the horizontal (**x**) direction and vertical (**y**) direction respectively are assumed to be:

**In this section all the derivations shall be made for the plane strain case. Axisymmetric matrices can be found by adding the appropriate terms.*

$$\left.\begin{aligned} u(\xi,\eta) &= \sum_{i=1}^{4} N_i u_i \\ v(\xi,\eta) &= \sum_{i=1}^{4} N_i v_i \end{aligned}\right\} \qquad (3.45)$$

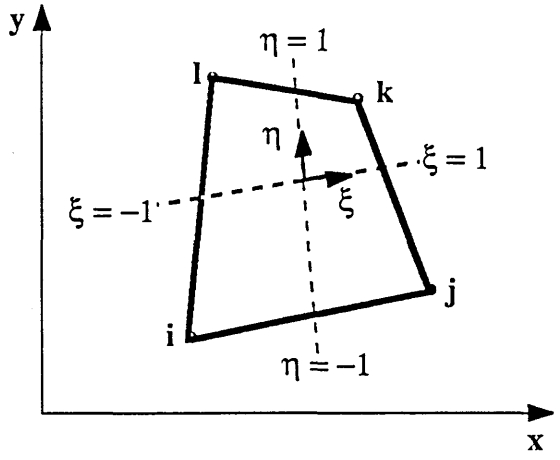


Fig.3.1 Isoparametric Bilinear Element

If the velocity vector is noted as $\underset{\sim}{U}^t = \{u,v\}$ and the nodal point velocity vector as $\underset{\sim}{u}^t = \{u_1,v_1,u_2,v_2,u_3,v_3,u_4,v_4\}$, then according to equation (3.21) the interpolation matrix $\underline{\underline{N}}^u$ is given by:

$$\underline{\underline{N}}^u = \left\{ \underline{\underline{N}}_1, \underline{\underline{N}}_2, \underline{\underline{N}}_3, \underline{\underline{N}}_4 \right\} \qquad (3.46)$$

where:

$$\underline{\underline{N}}_i = \begin{bmatrix} \underline{\underline{N}}_i & 0 \\ 0 & \underline{\underline{N}}_i \end{bmatrix} \qquad (3.47)$$

Similarly, the operator matrix $\underline{\underline{L}}$ can be defined as:

$$\underline{\underline{L}} = \left\{ \underline{\underline{L}}_1, \underline{\underline{L}}_2, \underline{\underline{L}}_3, \underline{\underline{L}}_4 \right\} \qquad (3.48)$$

where:

$$\underline{\underline{L}}_i = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \qquad (3.49)$$

Therefore, matrix $\underline{B}$ in equation (3.34) can be expressed as:

$$\underline{B} = \left\{ \underline{B}_1, \underline{B}_2, \underline{B}_3, \underline{B}_4 \right\} \tag{3.50}$$

where:

$$\underline{B}_i = \begin{bmatrix} \frac{\partial N_i}{\partial x} & 0 \\ 0 & \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} \end{bmatrix} \tag{3.51}$$

To evaluate such matrices, two transformations are necessary. In the first place as N_i is defined in terms of local coordinates it is necessary to devise some means of expressing the global derivatives of equation (3.50) in terms of local coordinates.

Secondly, the element volume over which the integrations are to be carried out needs to be expressed in terms of the local coordinates. Noting that:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial \xi} \\ \frac{\partial N_i}{\partial \eta} \end{Bmatrix} = \begin{bmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial y}{\partial \xi} \\ \frac{\partial x}{\partial \eta} & \frac{\partial y}{\partial \eta} \end{bmatrix} \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} = [J] \begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} \tag{3.52}$$

the derivatives in equation (3.50) can be rewritten as:

$$\begin{Bmatrix} \frac{\partial N_i}{\partial x} \\ \frac{\partial N_i}{\partial y} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \frac{\partial N_i}{\partial \xi} \\ \frac{\partial N_i}{\partial \eta} \end{Bmatrix} \tag{3.53}$$

where:

[J] - the Jacobian matrix (which can be easily evaluated numerically).

Similarly:

$$\left.\begin{aligned} dV &= |J|\, d\xi\, d\eta t \\ dS &= |J|\, d\xi d\eta \end{aligned}\right\} \tag{3.54}$$

The stress/strain-rate relationship, matrix $\underline{D}^0$ in equation (3.36), is given by:

$$\underline{D}^{0} = \begin{bmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & \frac{1}{2} \end{bmatrix} \qquad (3.55)$$

noting that:

$$\underset{\sim}{\sigma}'^{t} = \{\sigma'_x, \sigma'_y, \tau'_{xy}\} \qquad (3.56)$$

and:

$$\dot{\underset{\sim}{\varepsilon}}^{t} = \{\dot{\varepsilon}_x, \dot{\varepsilon}_x, \dot{\gamma}_{xy}\} \qquad (3.57)$$

The matrix $\underline{M}$ is expressed as:

$$\underline{M}^{t} = [1, 1, 1, 0] \qquad (3.58)$$

For the element considered the pressure field is taken as constant within the element, hence:

$$P = \underline{N}^{p}\ \underset{\sim}{p}^{(m)} = \sigma_m \qquad (3.60)$$

Assuming that the inverse of [J] can be found, the evaluation of the element properties is reduced to finding integrals of the following form:

$$\int_{-1}^{1}\int_{-1}^{1} |J|\, f(\xi, \eta)\, x(\xi, \eta)\, y(\xi, \eta)\, d\xi\ d\eta \qquad (3.61)$$

This is usually done using Gaussian quadrature, thus equation (3.61) is transformed to:

$$\sum_{i=1}^{n}\sum_{j=1}^{n} W_i W_j f(\xi_i, \eta_j) \qquad (3.62)$$

where:

W_i and W_j - weight coefficients

$f(\xi_i,\eta_j)$ - the value of the function to be integrated at the n^{th} point of integration.

3.3.4. LOCKING EFFECTS IN THE PENALTY FUNCTION FORMULATION

The penalty function formulation leads to a system of equations of the form:

$$\underline{\underline{K}}\,\underline{u} + \underline{f} \equiv (\underline{\underline{K}}^{u} + \underline{\underline{K}}^{\alpha})\,\underline{u} + \underline{f} = 0 \qquad (3.63)$$

In this system the matrices $\underline{\underline{K}}^{u}$ and $\underline{\underline{K}}^{\alpha}$ are finite, and a solution is sought when the penalty number $\alpha \rightarrow \infty$. It is apparent that if $\underline{\underline{K}}^{\alpha}$ is non-singular, then $\underline{u} \rightarrow 0$ as $\alpha \rightarrow \infty$.

This illustrates a problem of over-constraint which causes the mesh to lock, resulting in worthless results. This problem of over-constraint of elements in the isochoric regime has been extensively discussed by Hughes et all [36], Fried [23], Malkus and Hughes [53] and Nagtegaal et al [58].

To alleviate this condition, $\underline{\underline{K}}^{\alpha}$ must be made singular so that:

$$\underline{\underline{K}}^{\alpha} = 0 \qquad \text{but} \qquad \underline{u} \neq 0 \qquad (3.64)$$

The singularity (or its' absence) is a function of the number of independent relations used at each integrating point. Zienkiewicz [89] states the condition for the presence of singularity in the following words: "If the number of such relations introduced at all the integrating points is less than that of the degrees of freedom available, then the singularity must exist" .

It is interesting to note that the wording of this statement is in the context of the existence of the singularity, for, as Zienkiewicz readily admits, the non-singularity is more difficult to prove.

It turns out that virtually all the commonly used conforming elements result in non-singular $\underline{\underline{K}}^{\alpha}$ when 'exact' numerical integration is performed. It is then possible to show [94] that singularity of $\underline{\underline{K}}^{\alpha}$ is introduced for bi-linear quadrilaterals with a single point of integration.

Malkus and Hughes [53] have used an heuristic theory to predict the behaviour of elements and integration schemes. Briefly, the theory suggests that the most effective elements in applications of the type considered here are the so-called 'Lagrange' isoparametric elements with appropriate selective-integration scheme. Triangular elements and 'serendipity' quadrilateral elements are predicted to exhibit inferior behaviour, which has been confirmed numerically [58].

Thus, for the bi-linear quadrilateral element used in this work, one point integration is used to evaluate $\underline{K}^{\alpha}$. The 2 x 2 integration is retained on $\underline{K}^{u}$ so as to ensure non-singularity of $\underline{K}$ in equation (3.63).

When this element is used in axisymmetric analysis, the property of 'incompressibility in the mean', introduced by the under integration, is lost. Nevertheless, the element is still convergent [35]. Bicanic and Hinton [10] have reported that reduced integration introduces extra zero energy modes. These extra modes can combine into either mechanisms, leading to singular stiffness matrices, or into near mechanisms which are spurious low energy modes which mask the solution. These zero energy modes on the elemental level combine into the well known 'hour-glassing' or 'keystonning' mode for the 4-noded element into the so-called 'Escher' mode for the 2-noded element. In meshes formed from 8-noded elements these near mechanisms do not exist. They also found that elimination of the overall matrix singularity does not suppress the influence of the modes completely. If the modes are exited they can completely destroy the solution.

3.3.5. SOLUTION PROCEDURE

It is obvious that the system of equations (3.37) and (3.41) are non-linear and that an iterative mode of solution is needed.

In general, the most simple and direct solution procedure is a direct iteration which starts from the form:

$$\underline{\underline{K}}\,\underline{u} + \underline{f} = 0 \qquad (3.65)$$

in which:

$$\underline{\underline{K}} = \underline{\underline{K}}(\dot{\underline{\varepsilon}}) \qquad (3.66)$$

If initially a value of $\dot{\underline{\varepsilon}} = \dot{\underline{\varepsilon}}^{0}$ is assumed, an improved approximation is obtained as:

$$\underline{u}^{1} = -\left(\underline{\underline{K}}^{0}\right)^{-1} \underline{f} \qquad (3.67)$$

where:

$$\underline{\underline{K}}^{0} = \underline{\underline{K}}\left(\dot{\underline{\varepsilon}}^{0}\right)$$

Repetition of this process can be written as:

$$\underline{u}^{n} = -\left(\underline{\underline{K}}^{n-1}\right)^{-1} \underline{f} \qquad (3.68)$$

and the process is terminated when the error is sufficiently small.

This system of solution has been applied successfully to metalforming problems [2], [72] and gives very rapid convergence, provided the forcing function is specified as velocities.

3.3.5.1. Sequence of Operation

The start is from prescribed initial strain rate distribution, namely, a uniform distribution. The system of equations is then solved and the velocities thereof computed are used to evaluate a new strain-rate distribution which modifies the system of equations accordingly.

Iterations of the type described in equation (3.68) are then performed. For the analysis of non-steady state processes, the problem is analysed in a step-by-step manner treating it quasilinearly during each step of incremental deformation. A proper increment size is chosen to justify this approximation.

The convergence is measured by the quantity $\|\Delta \mathbf{u}\| / \|\mathbf{u}\|$, where the Euclidian vector norm is defined by:

$$\|\underset{\sim}{\mathbf{u}}\| = \sqrt{\sum_{i=1}^{N} \left\{ (u_x)_i^2 + (u_y)_i^2 \right\}} \qquad (3.69)$$

The solution with a reasonable accuracy is accepted as the final velocity distribution. At this stage the new geometry of the deformed material is determined by adding the nodal point velocities incrementally to the current coordinates of the nodal points.

In the steady state processes, since the velocity solution for the current geometry is also the solution for the subsequent steps, the process of incremental addition of the velocity distribution for the determination of the new geometry is not required.

Computer code based on the formulation developed in this chapter is presented and described in *Appendix 3*.

CHAPTER 4

EXPERIMENTAL INVESTIGATION

4.1. INTRODUCTION

The experimental work was aimed at determining the various factors which influence the development of the forces and stresses in the final stages of continuous extrusion. It included design changes to an existing test rig in order to simulate a particular extrusion process, Context in this case.

The chamber mechanism is assumed to compress the billet in one plane only. The third dimension of the billet, its thickness, remained unchanged during axial compression once the initial indentation was completed.

The equipment and experimental procedure used in the course of this study are discussed in the following sections.

4.2. EXPERIMENTAL EQUIPMENT

4.2.1. TESTING MACHINE

A DENISON testing machine, model T42 B4, shown in Fig.4.1, was used to provide the load. The machine is of vertical type, and is fully self-contained. The load to the specimen, maximum 500 kN, is applied hydraulically by means of a knife-edged weighing lever system. The multi-capacity dial is arranged so that only the figures appropriate to the range in use are visible.

The machine is a single unit, comprising a frame with massive cast-iron base plate and four steel columns carrying two steel top beams. The latter are spaced by the cylinders, supporting the weighing levers and thus carrying load action and reaction. The weighing frame consists of the transverse beam and table, and weighing wedge box with connecting

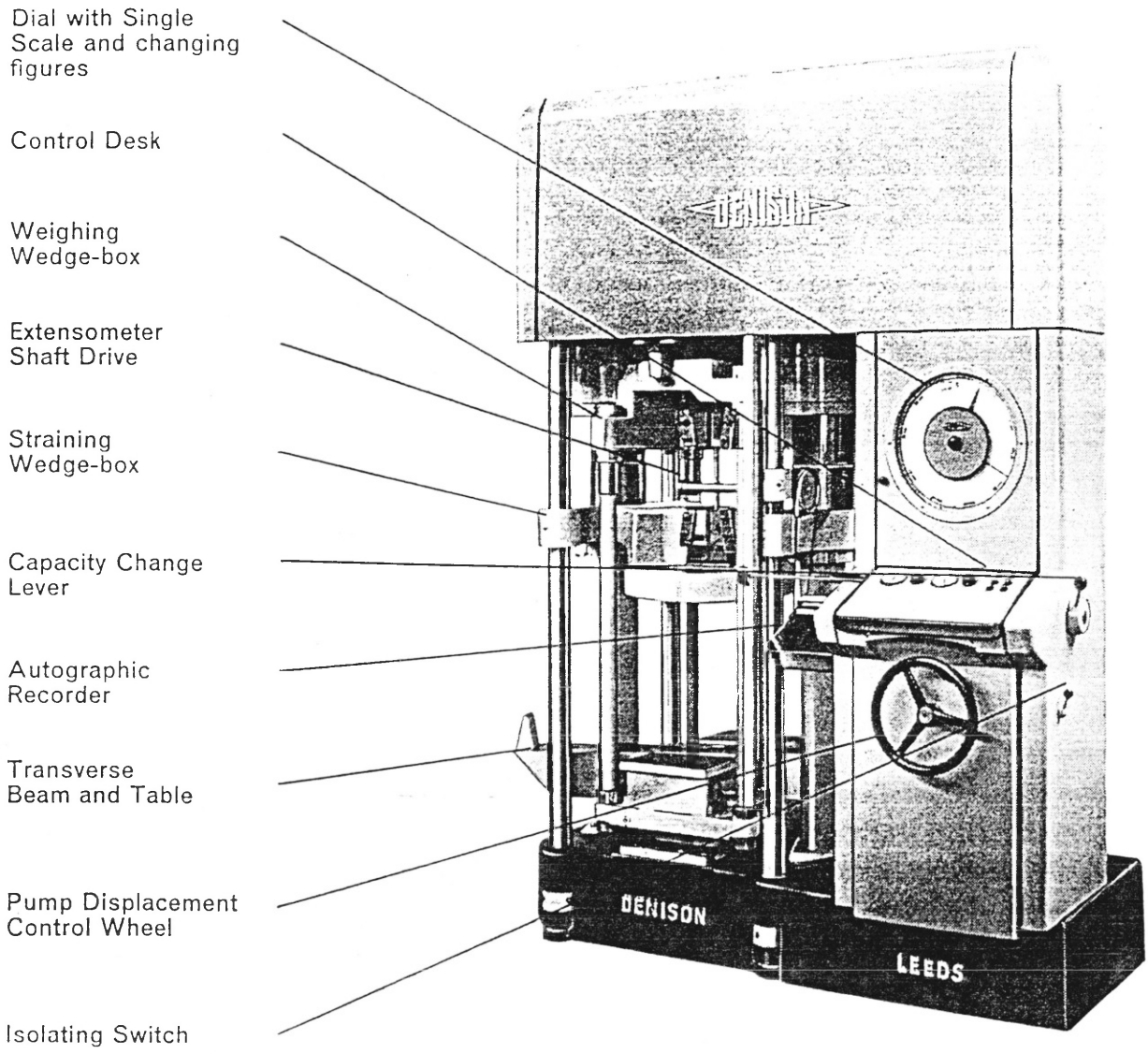


Fig.4.1. Principal Features of the Denison Testing Machine

rods and main shackle. In plan, the transverse beam is arranged diagonally so that long spans can be tested. It will support loads up to the full capacity of the machine. Lateral movement is prevented by means of a diaphragm unit.

4.2.2. THE TEST RIG

The experimental set-up is shown in Fig.4.2. The experimental rig (Fig.4.3) was initially designed and subsequently modified to simulate Context. It retains the principle of the process as far as billet deformation and stresses are concerned. In Context the chamber segments clamp the billet and advance it towards a stationary die. In the rig, (Fig.4.4) the billet is clamped in a stationary chamber and a pressure pad, simulating the die, advances into the chamber.

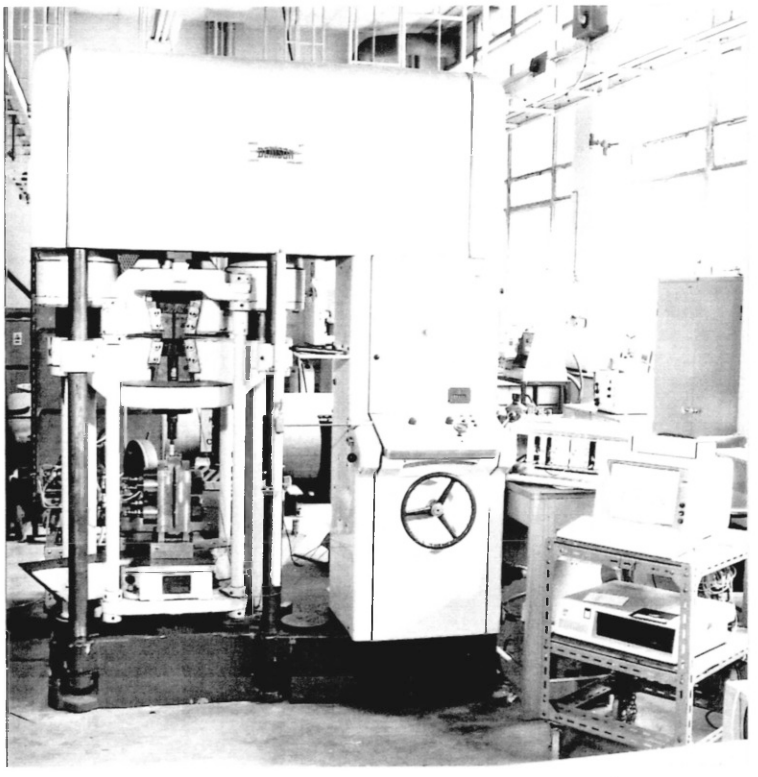
The liner was made up of seven pieces from 817M40 (EN24T) steel with the inside faces, which make up the chamber, fine ground. They are shown in Fig.4.5 and Fig.4.6. The container consists of two identical parts made of 835M30 (EN30B) steel shown in Fig.4.7.

Initial lateral compression was applied to the specimen by tightening four hydraulic Pilgrim nuts (Fig.4.4, 4.8 and 4.9), with a maximum working pressure of 173.5 MN/m^2 (25,000 psi) over a piston area of 2280 mm^2 (3.534 in^2), equivalent to a maximum force of 400 kN (40 tons).

The punch, shown in Fig.4.10, is made from 817M40 (EN24T) steel, heat treated to 53 RC hardness and designed against buckling.The top of the punch is fitted into two mild steel supporting plates, shown in Fig.4.11, bolted to the top cross head of the Denison testing machine.

The top and bottom load cells, (Fig.4.12.a. and Fig.4.12.b respectively), were made from 817M40 (EN24T) steel and heat treated to 35 RC hardness. The bottom load cell supported the bottom pressure pad(s). Their positions are shown in Fig.4.3.

The pressure pads, which transmitted the load to the specimen (Fig.4.13), were ground to a sliding fit in the chamber. The top pad is made of 817M40 (EN24T) steel, while the bottom pads are of mild steel, since the load on them is expected to be lower. The relief on the top pad is aimed at minimising the effect of the extrusion of flash on the load. The bottom pressure pads are either used individually or in combination depending on specimen length.



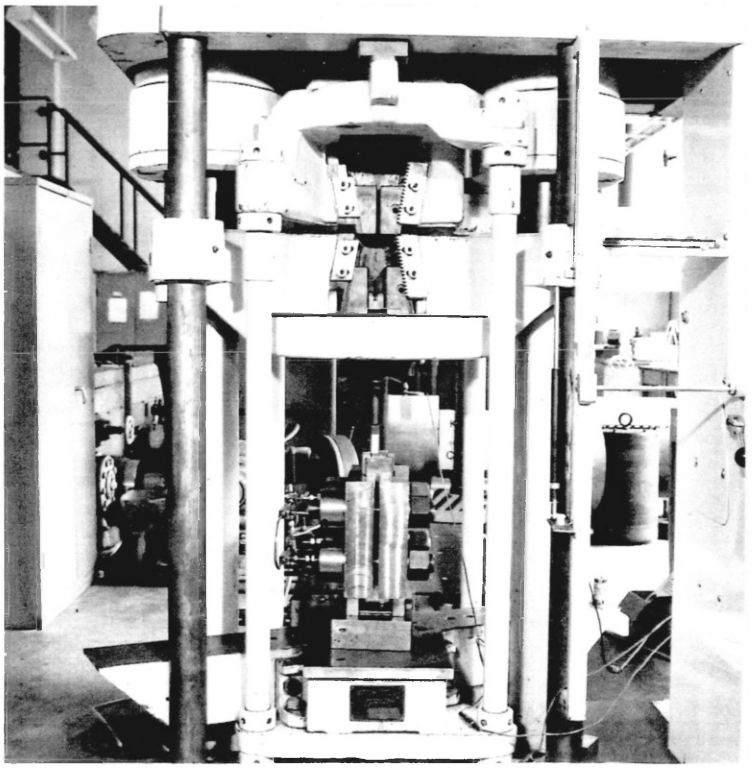


Fig.4.2. Experimental Set-up

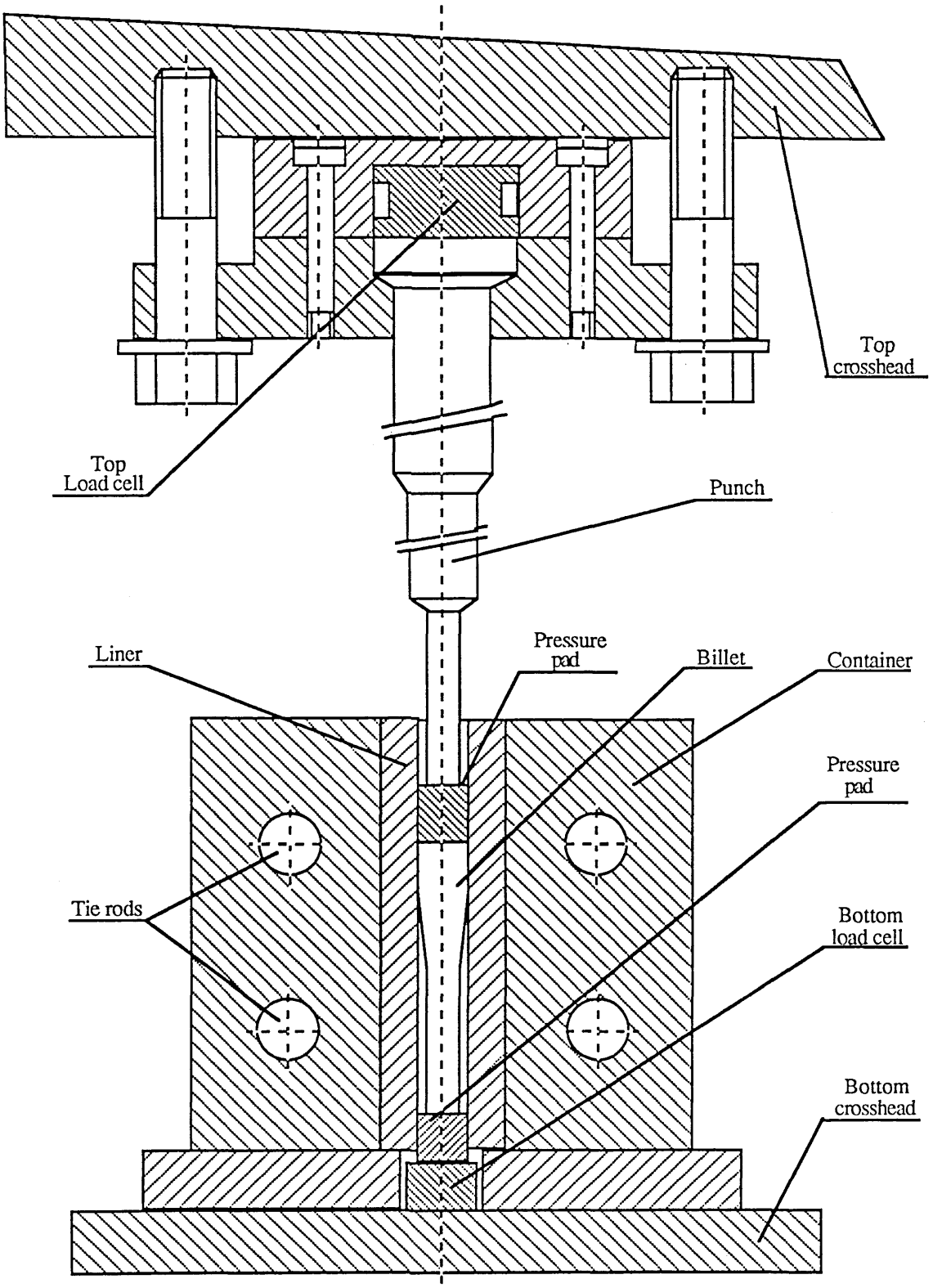


Fig.4.3. Assembly Drawing of the Experimental Rig

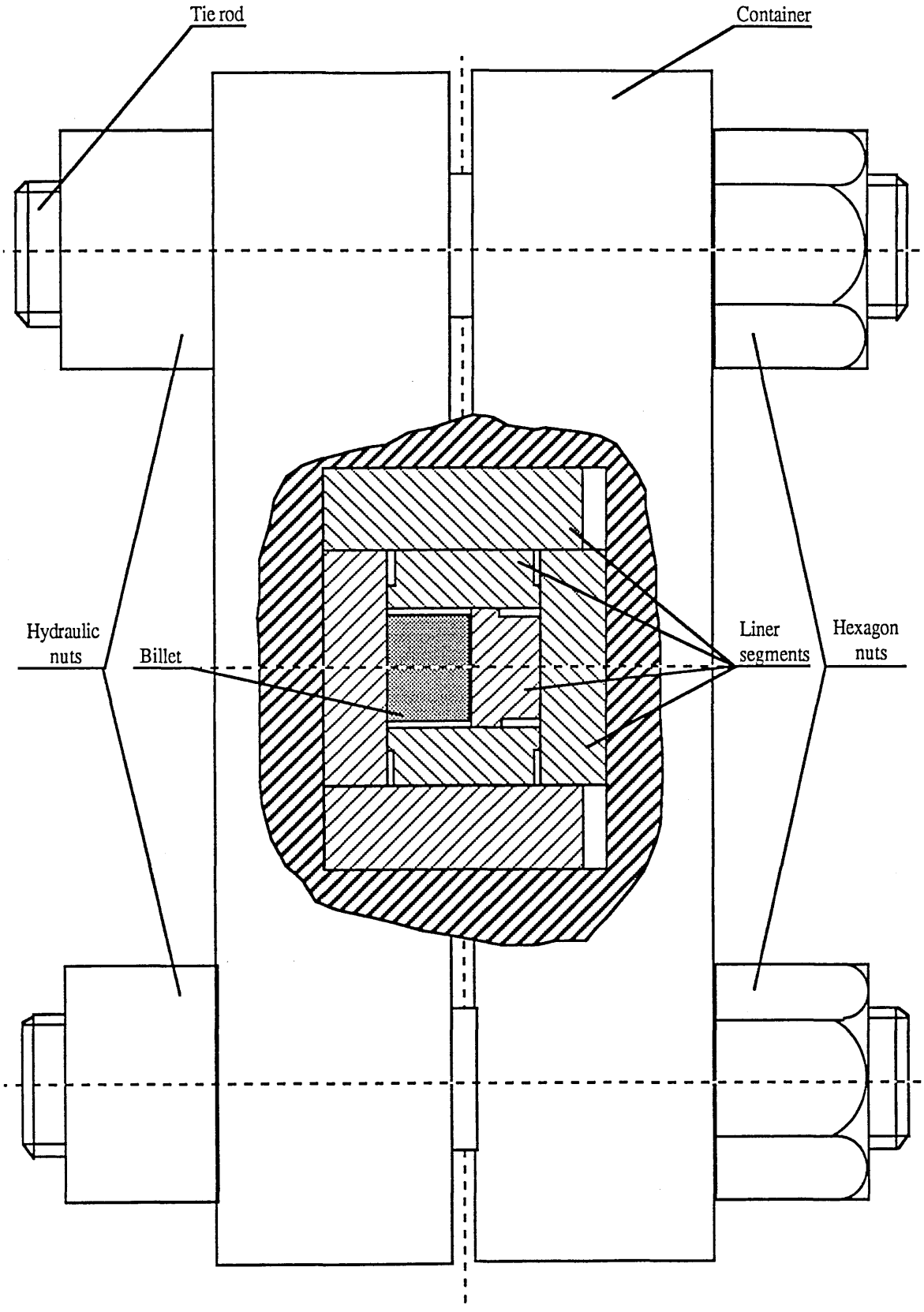
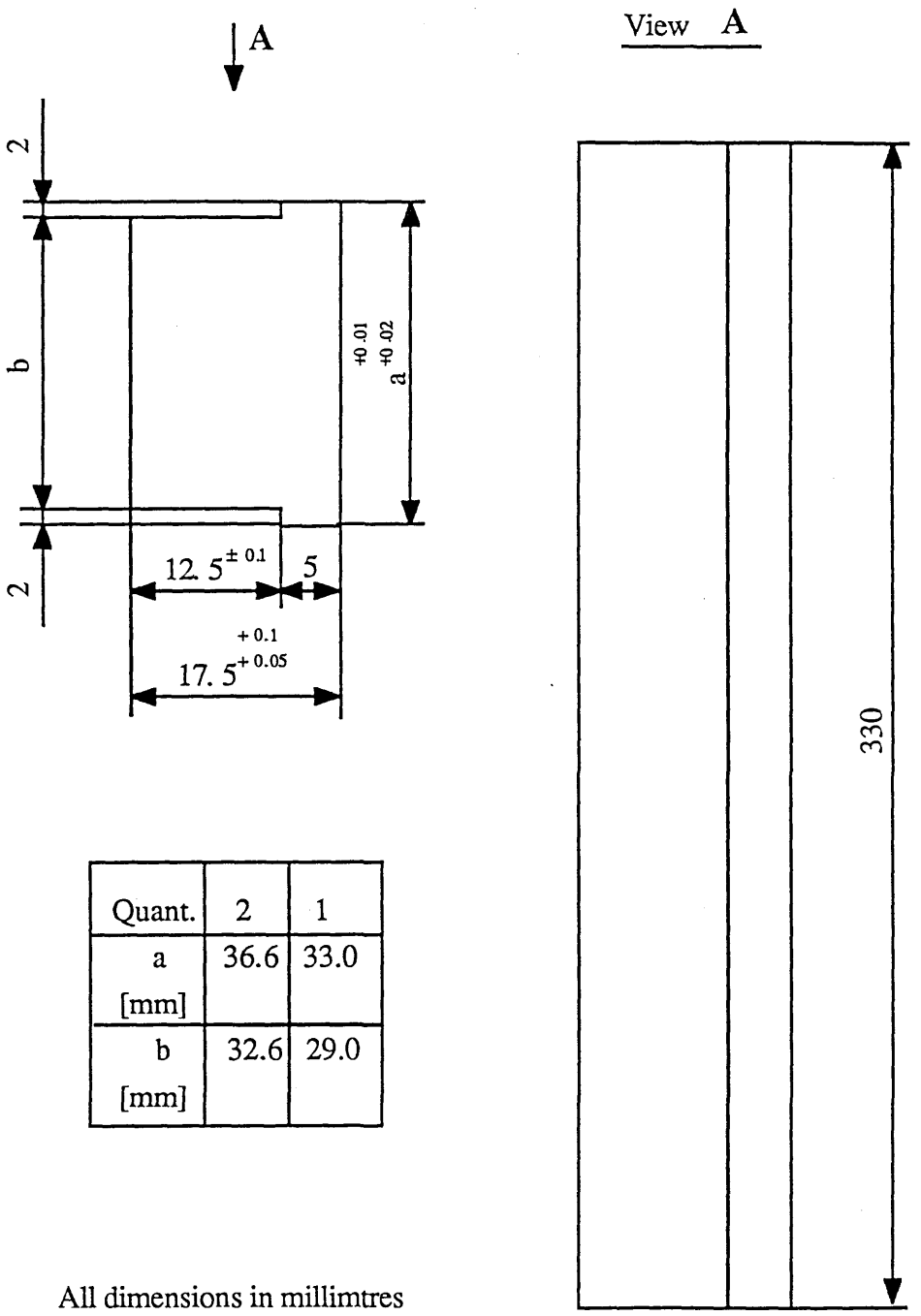


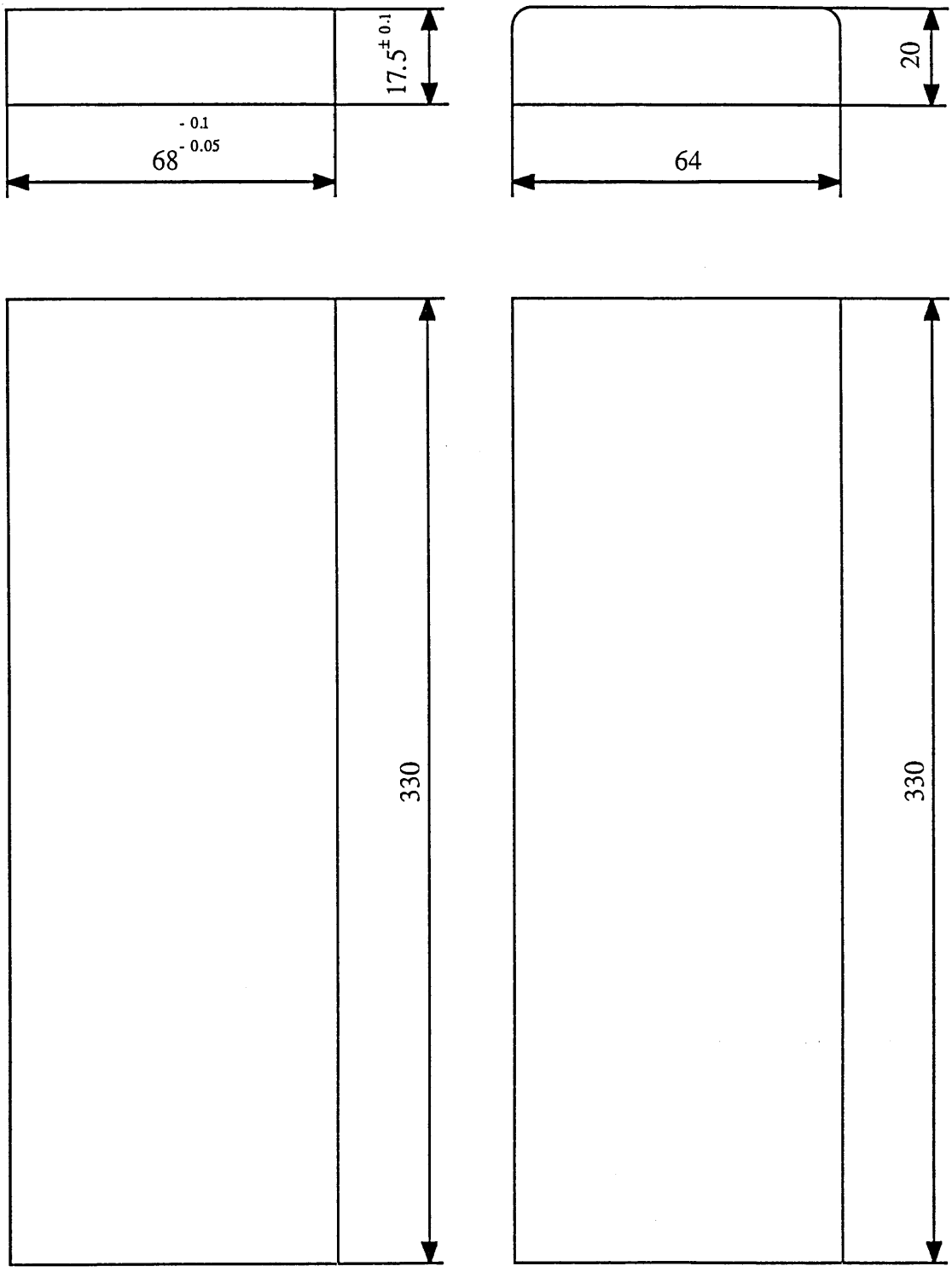
Fig.4.4. Container Design



Quant.	2	1
a [mm]	36.6	33.0
b [mm]	32.6	29.0

All dimensions in millimtres

Fig.4.5. Liner Side Restrain Plates



All dimensions in millimetres.

Fig.4.6. Liners Top Restrain Plates (a) and Side Supporting Plates (b)

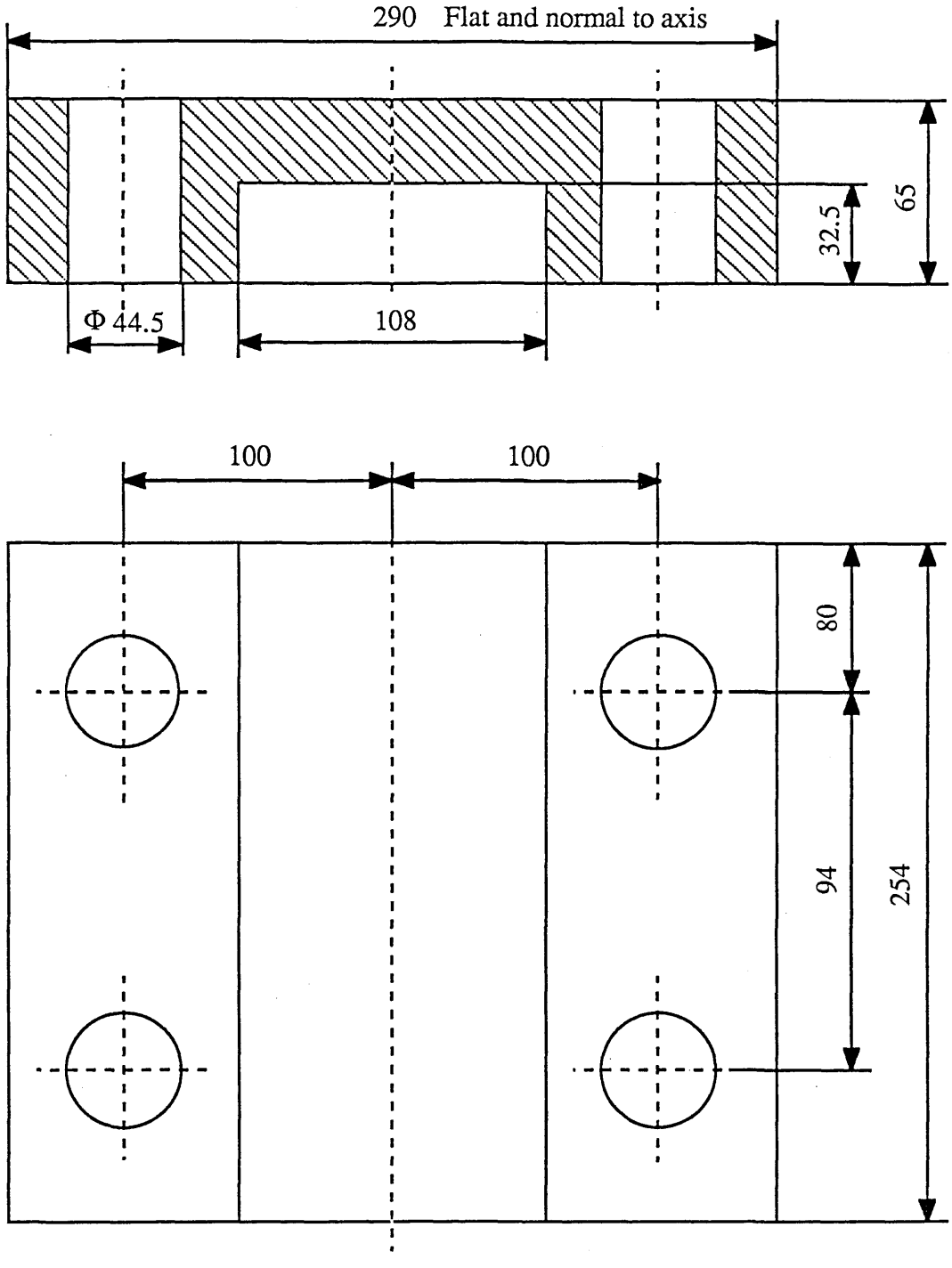


Fig.4.7. Container Design

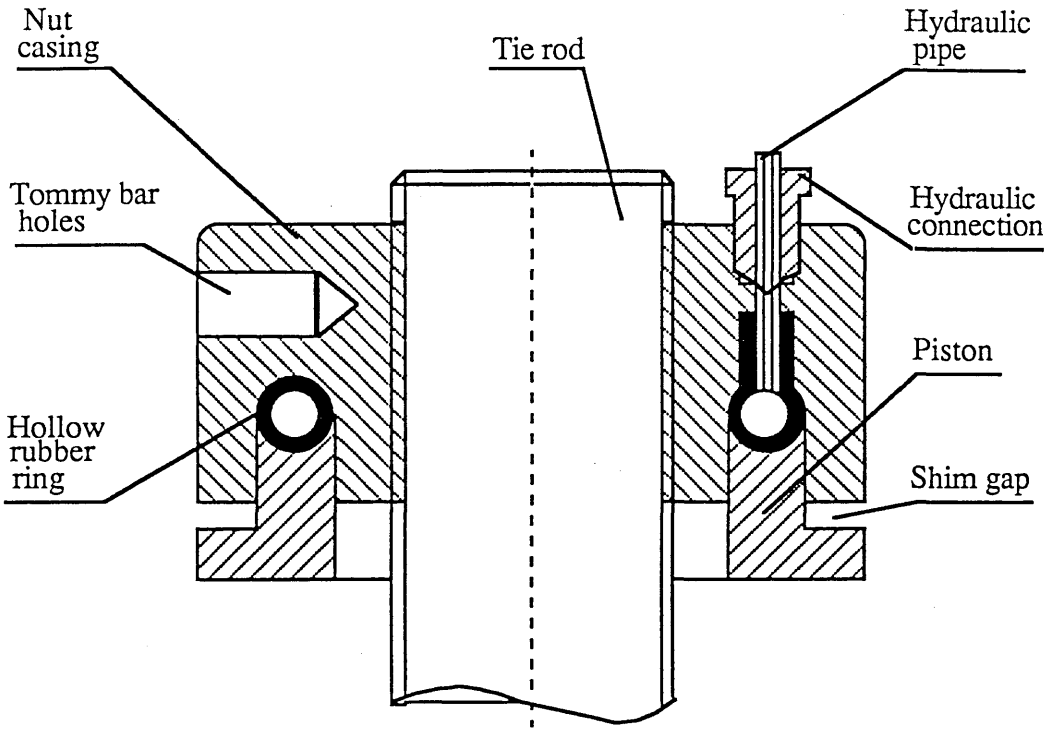


Fig.4.8. The Hydraulic Pilgrim Nut

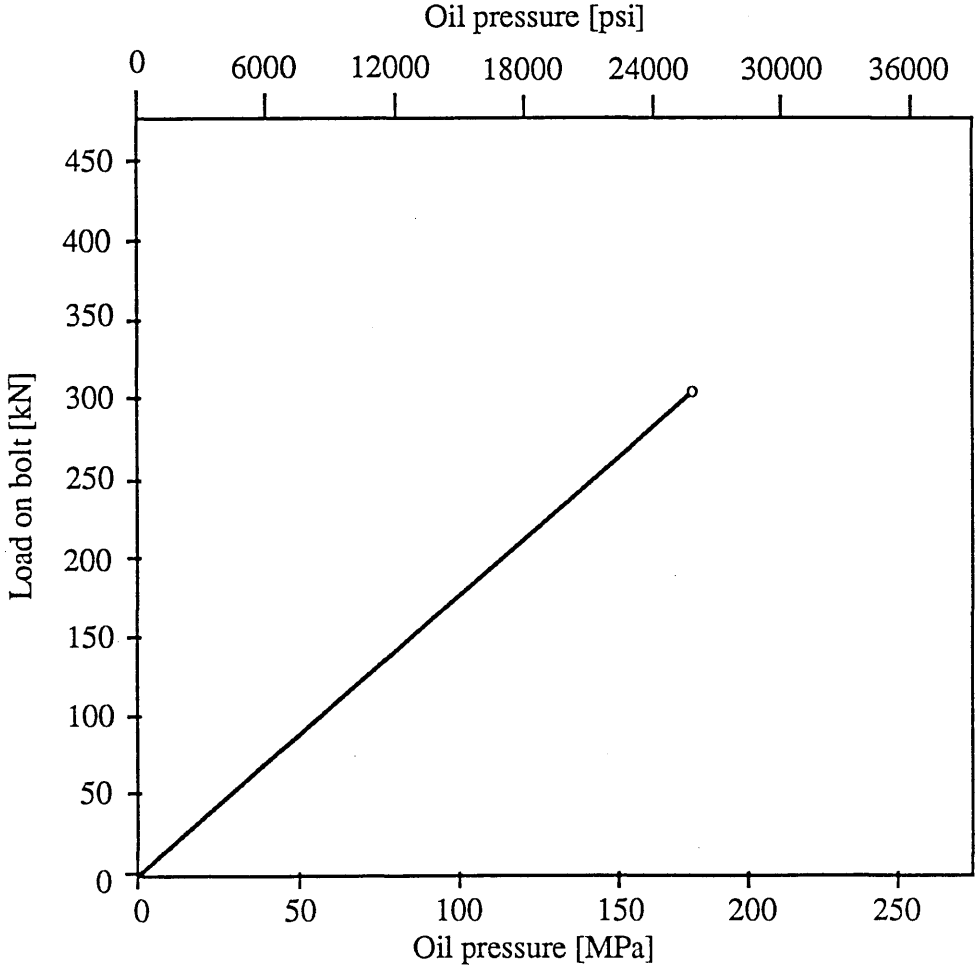


Fig.4.9. Operating Line of the Hydraulic Nut

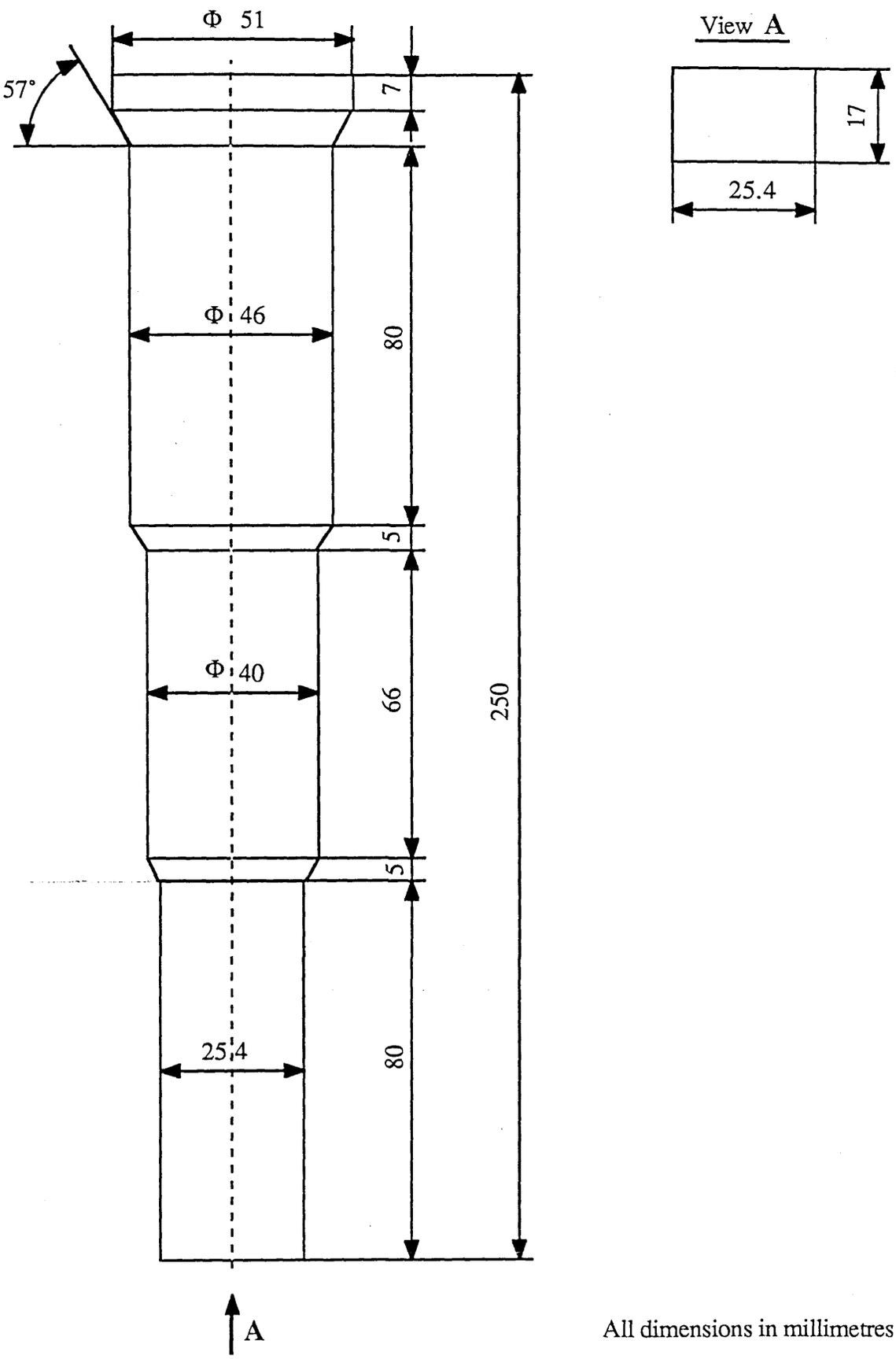
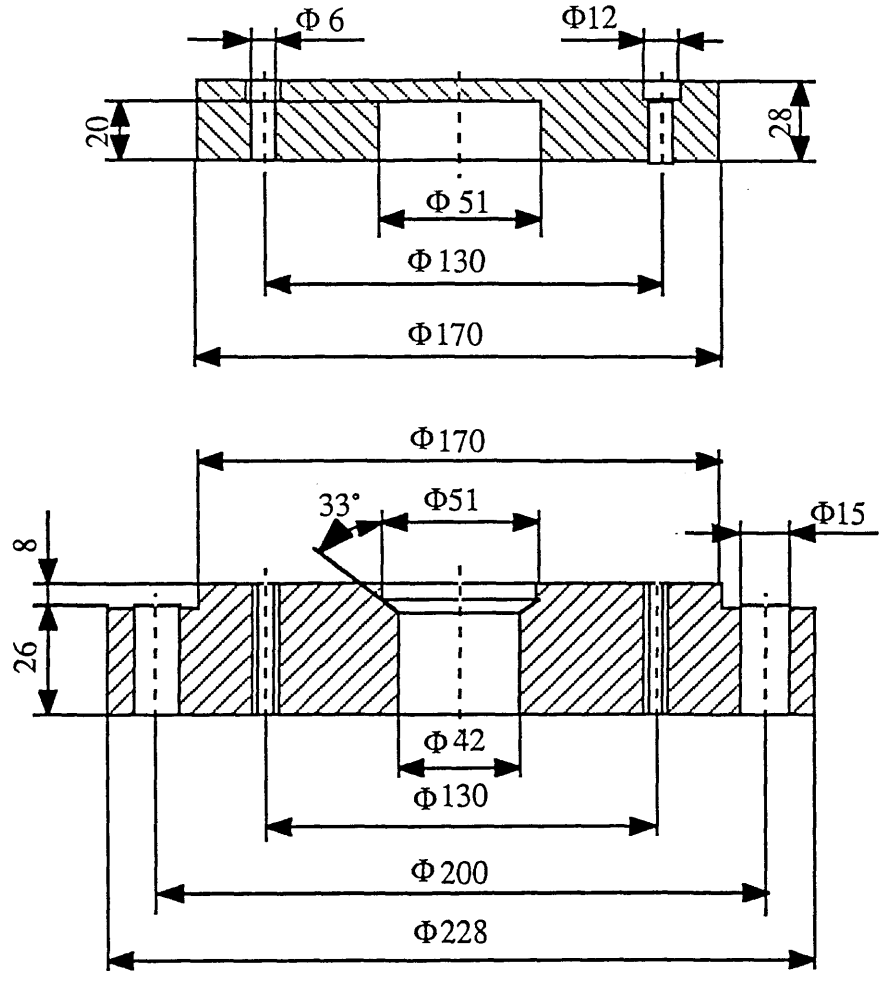
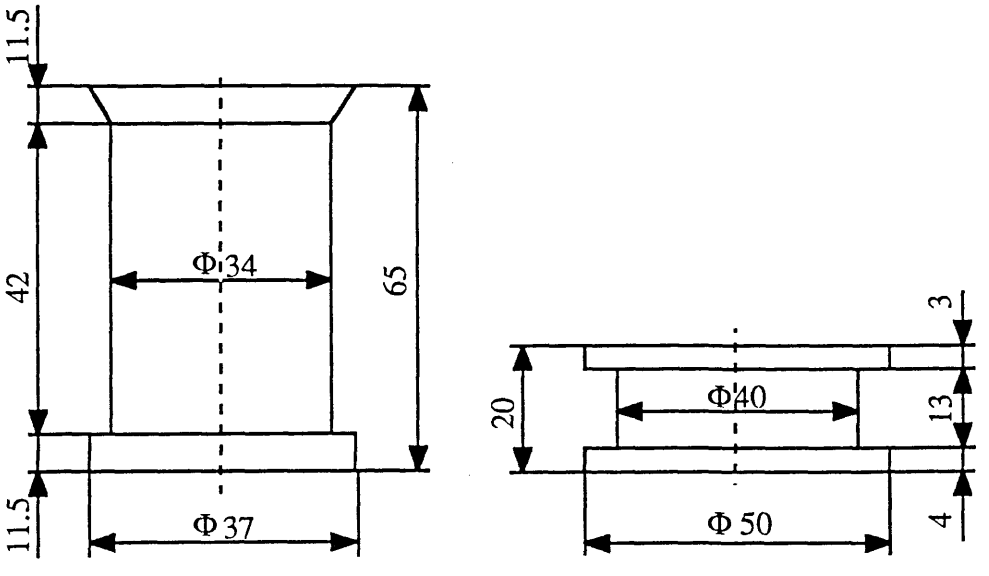


Fig.4.10. The Punch



All dimensions in millimetres

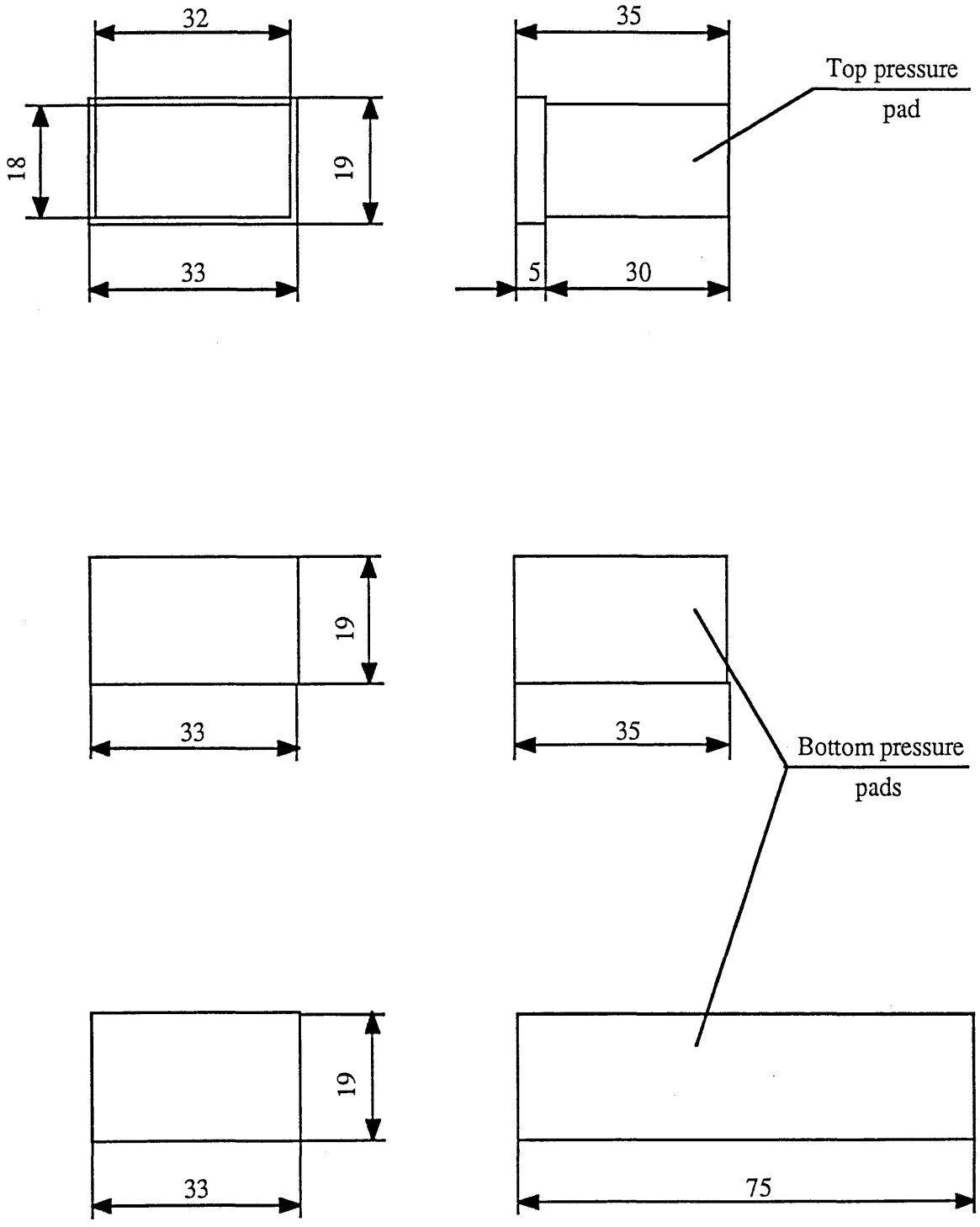
Fig.4.11. The Supporting Plates



a) b)

All dimensions in millimetres

Fig.4.12. The Load Cells



All dimensions in millimetres

Fig.4.13. The pressure pads

4.3. INSTRUMENTATION

4.3.1. RECORDING OF THE DATA

The experimental data were recorded using an IBM personal computer with a PC-Mate Labmaster, consisting of a mother board which plugs into the IBM bus and a daughter board which can reside outside the computer and is connected to the mother board via a ribbon cable. The Labmaster enables real time, high speed analogue to digital (A/D) and digital to analogue (D/A) conversions. The standard board can be set with jumpers for 16 single ended or 8 true differential inputs. The input range on the standard board is jumper selectable between 0 to 10 V or -10 to +10 V. Once the daughter board has performed the (A/D) conversion, the data are latched providing the capacity to start the next conversion while writing the prior conversion to the computer memory. The standard board has a maximum conversion rate of 30 kHz.

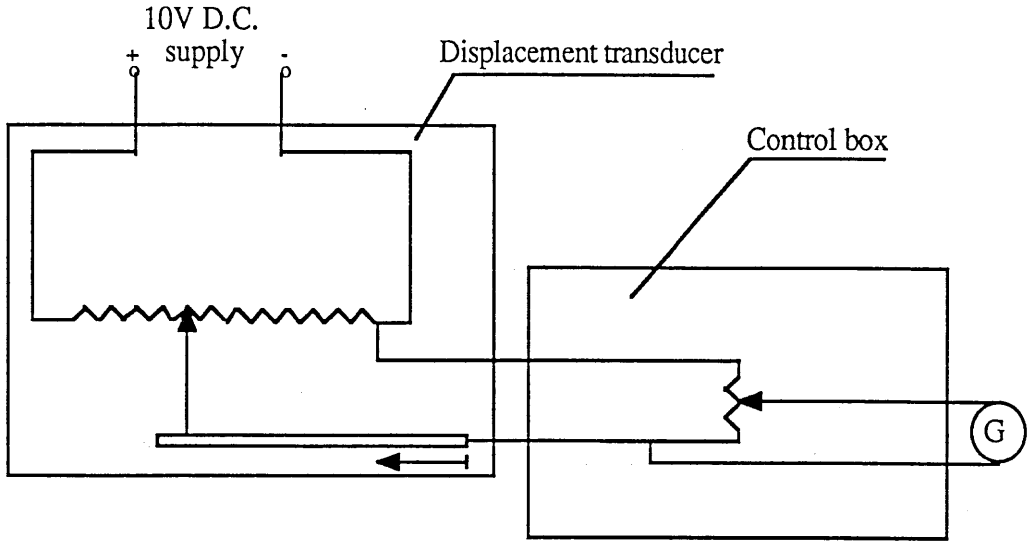
A computer program was written to record loads on the top and bottom load cells together with punch displacement during the experiments. The Labmaster board was set with jumpers to give a differential voltage input and an input range of -10 ÷ +10 V. The jumper selections, operation amplifier circuits and details of the program used are given in *Appendix 4*.

4.3.2. LOAD CELLS AND DISPLACEMENT TRANSDUCER

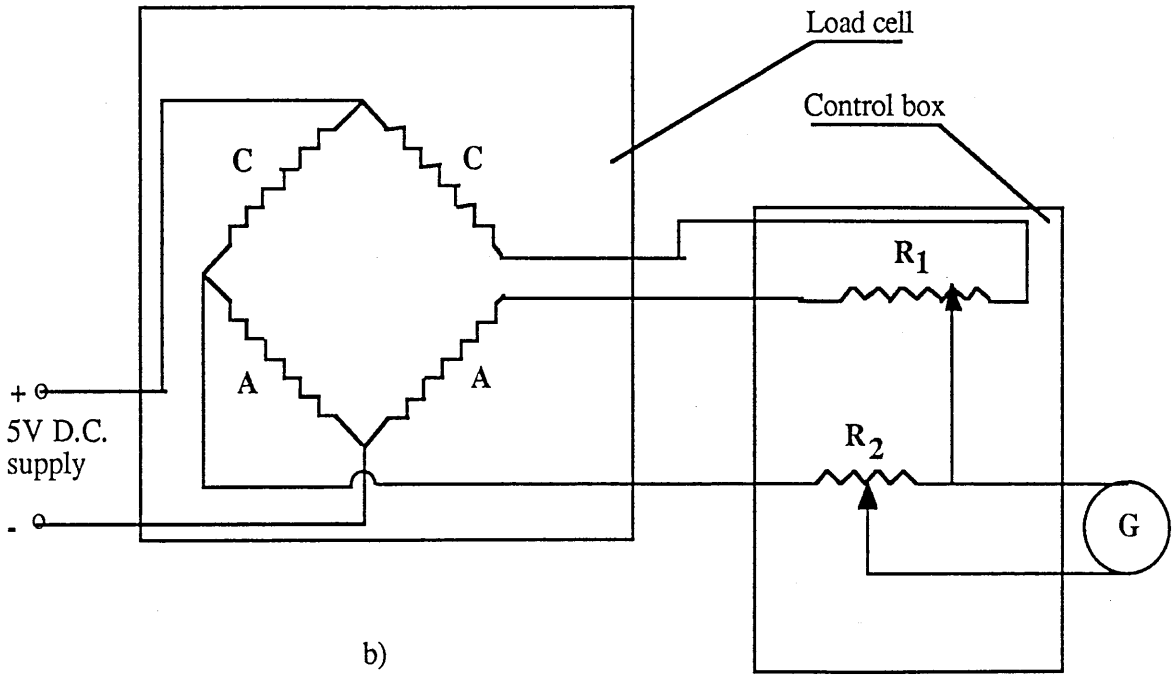
Each load cell had four strain gauges two axial and two circumferential marked 'A' and 'C' in Fig.4.14.b. to form a complete Wheatstone bridge. The strain gauges were EA-06-125AD-120 type with a resistance 120.0 ± 15% Ω. Both load cells were calibrated separately against a standard 300 tonf proof ring before the experiments commenced.

To record punch displacement a HLP/90/SA1/150/6K linear transducer was used with a working range of 150 mm (~ 6') from its nominal electrical zero point, (Fig.4.14.a). One end of it was attached to the top cross-head of the testing machine while the other, via adjustable plate, to the bottom cross-head. The displacement transducer was calibrated over its full working range using a travelling microscope.

The control box comprising the D.C. supply unit and the amplifiers together with the IBM-PC and PC-Mate Labmaster are shown in Fig.4.15. The calibration curves for the two load cells and the displacement transducer are shown in Fig.4.16 to Fig.4.18.



a)



b)

Fig.4.14. Displacement transducer and load cells wirings

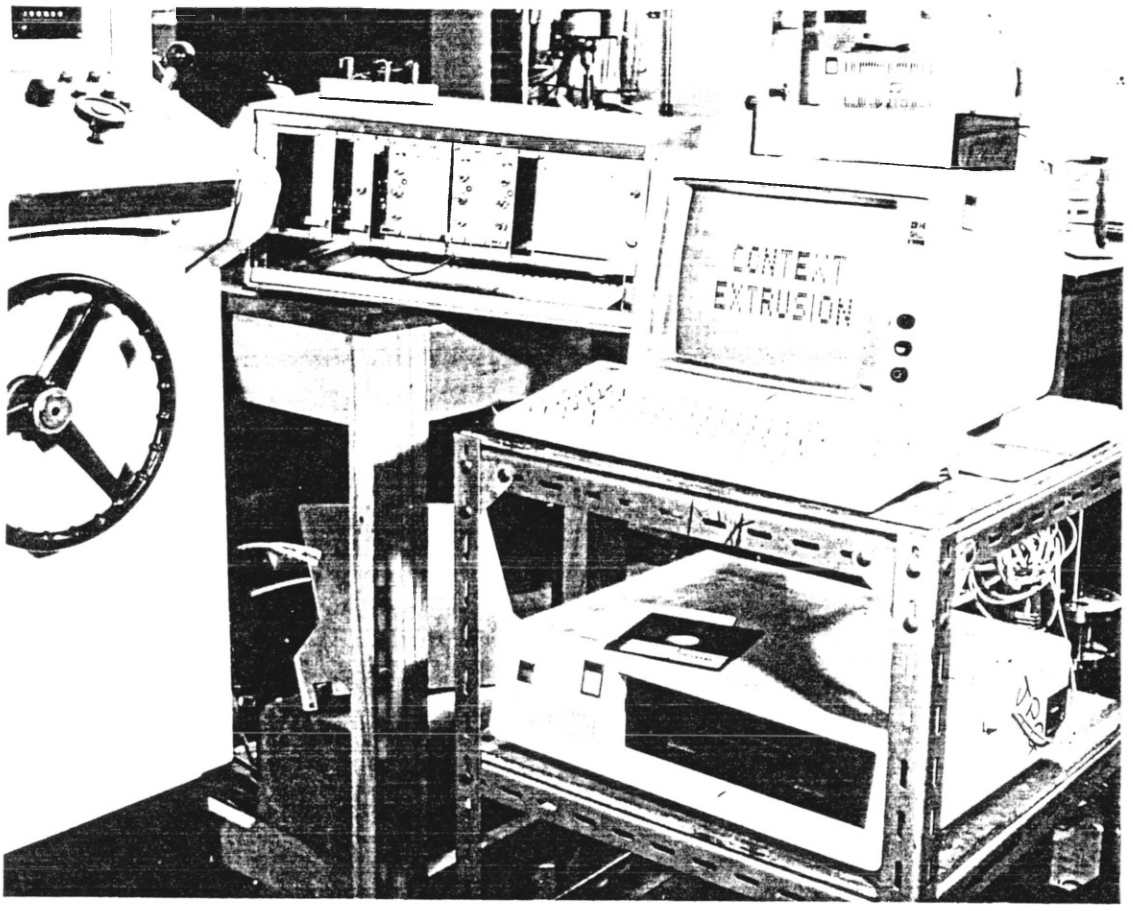


Fig.4.15. The control box containing the D.C. supply unit and the amplifiers for the load cells and the displacement transducer together with the IBM-PC and the PC-Mate Labmaster

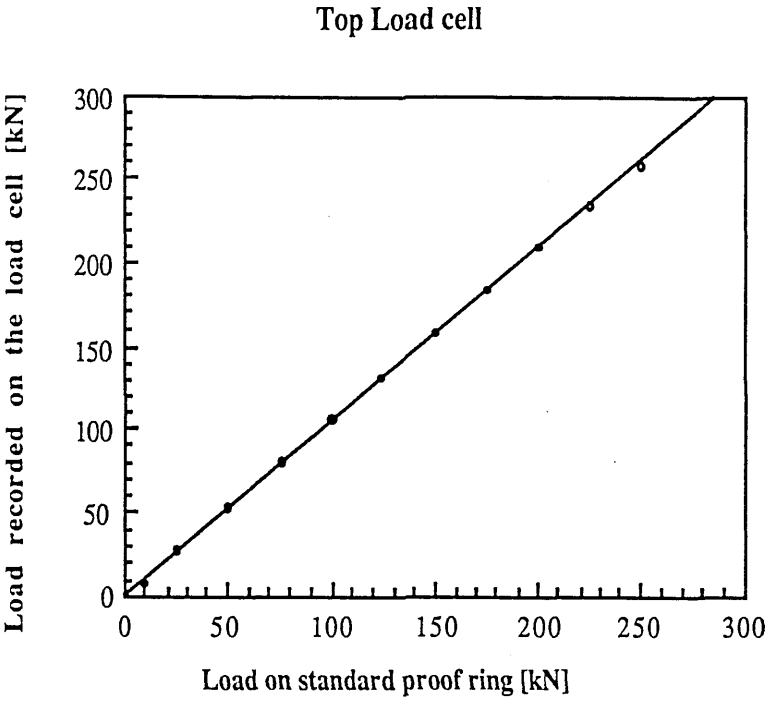


Fig.4.16. Calibration curve for the top load cell

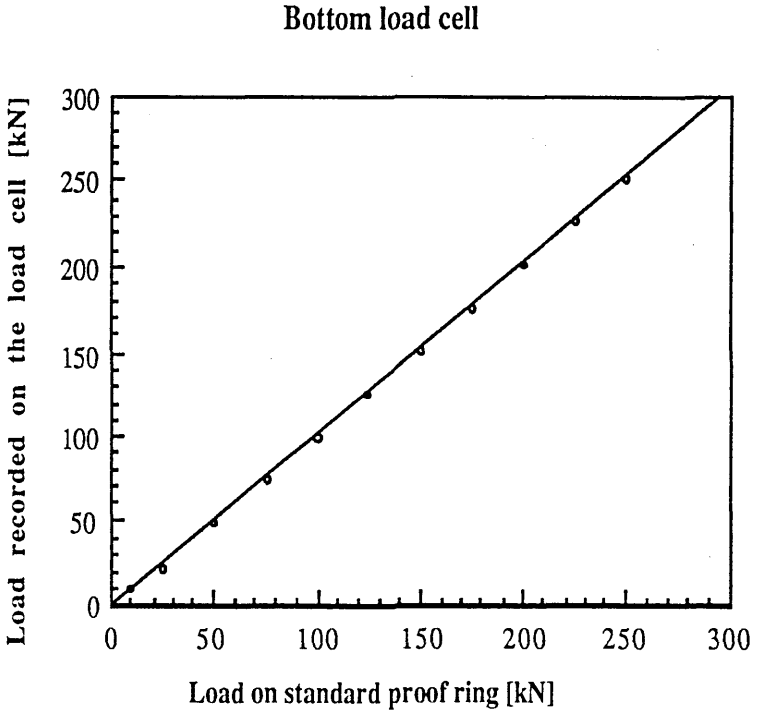


Fig.4.17. Calibration curve for the bottom load cell

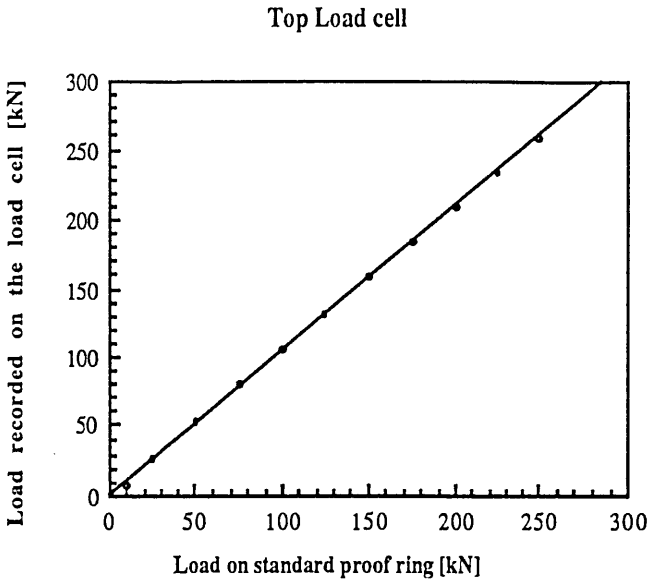


Fig.4.16. Calibration curve for the top load cell

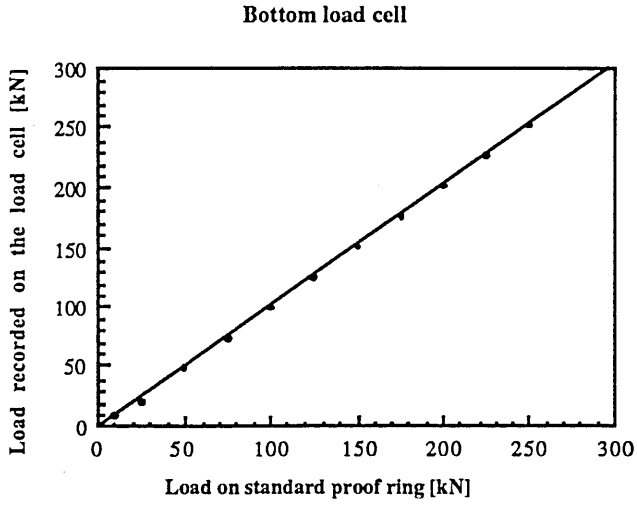


Fig.4.17. Calibration curve for the bottom load cell

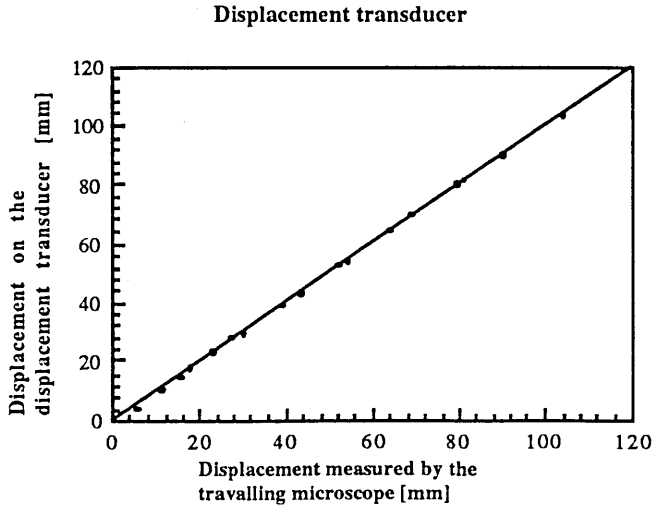


Fig.4.18. Calibration curve for the displacement transducer

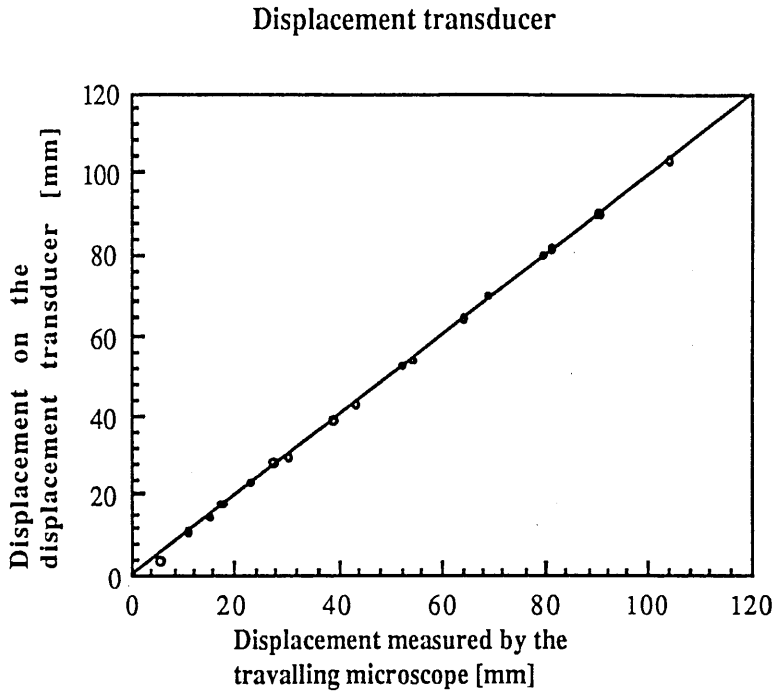


Fig.4.18. Calibration curve for the displacement transducer

4.4 SPECIMENS

Rectangular cross-section lead specimens were used during the experiments. Lead was used as experimental material mainly because it best simulates material behaviour used in the theory, partly because it ensured that stresses on the experimental rig were within acceptable limits. One size of thickness, two sizes of width and four different lengths of the specimens were used.

Cast bars of commercially pure lead were first rolled to the desired thickness, subsequently machined to the required specimen size. The dimensions of the specimens are shown in Table 4.1. and their shape in Fig.4.19.

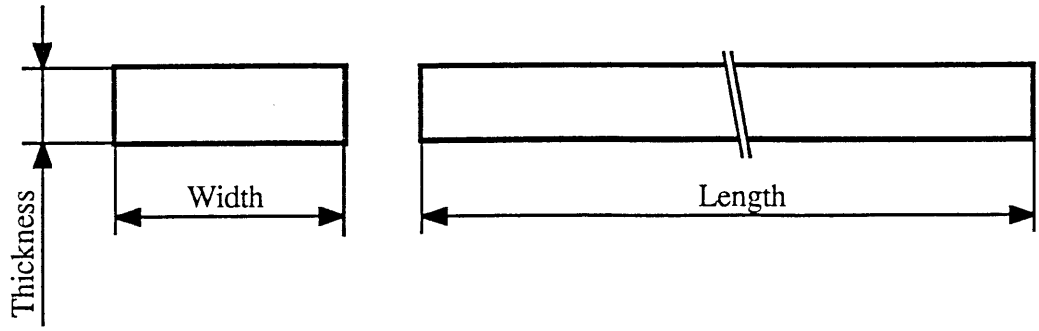


Fig.4.19. Specimen

Table 4.1.

Thickness [mm]	Width [mm]	Length [mm]	Quantity
20	28	150	3
20	28	165	3
20	30	165	3
20	28	180	3
20	30	180	3
20	28	200	2
20	30	200	2

4.5. EXPERIMENTAL PROCEDURE

Before each experiment, the chamber walls, the pressure pads and billet surfaces were thoroughly cleaned with methyl alcohol. A thin film of molybdenum disulphide in grease was then applied to the billet surfaces in order to ensure consistent frictional conditions.

Then the segments of the container and liner were assembled and the bottom pressure pad(s) lowered into the chamber, Fig.4.3. The billet and the top pressure pad were then introduced, misalignments corrected and the assembly was then ready for starting the test.

The pilgrim nuts were then pressurised, the studs tensioned and the billet subjected to initial indentation. In order to ensure sufficient frictional force acting on the billets' surface, the thickness of the billet was 20 mm, while the corresponding chamber dimension 19 mm. This gave 5% reduction in thickness during the initial indentation of the billets.

The punch was then forced down to compress the specimen axially. During the experiment the pressure in the Pilgrim nuts was maintained at a constant value of 138 MPa (20,000 psi) with a hand pump. After the required force was reached the punch was withdrawn, the pressure on the hydraulic nuts released and the recorded data saved on a

disk.The container was then opened, the billet extracted, measured and marked.

By measuring the loads simultaneously at both ends of the specimens of various lengths, the axial stress on the 'die' (represented by the top pressure pad) and at various cross-sections along the length of the billet in continuous extrusion can be established and the findings compared with theoretical predictions. The coefficient of friction between the billet and the chamber walls was determined earlier by Kondylides [43] who used the same material and conditions, and the method suggested by Male and Cockcroft [52].

CHAPTER 5

EXPERIMENTAL RESULTS AND COMPARISON WITH THE THEORETICAL PREDICTIONS. PRELIMINARY DISCUSSION

5.1. INTRODUCTION

In this chapter the experimental results are presented together with the numerical (theoretical) findings obtained by means of the finite element computer code discussed in *Chapter 3*. Experimental conditions were fully taken into account when simulated on the computer and every possible effort was made to simulate as closely as possible the real conditions. The large number of experimental current loads are compared with loads predicted by theory, to confirm the applicability of the theoretical model to the continuous extrusion process Context. It is assumed that, if a reasonable agreement between the theory and the experiments is obtained for this case, then the developed computer code will be applicable to other cases of continuous extrusion, like Linex and Conform.

5.2. STRESS-STRAIN CURVE

Stress-strain curve of the experimental material, commercially pure lead, is presented in Fig. 5.1.

In the computations rigid-ideally plastic material was adopted, i.e a constant yield stress was assumed. This is reasonable for lead, as this material recrystallises at ambient temperature.

The mean yield stress of the material, σ_y^{mean}, was obtained for each strain between the value of the initial strain, ε_i, achieved during the initial indentation and common for all specimens and final strain, ε_f, different for the two groups of specimens with two different initial widths, 28 mm and 30 mm. The respective strains and mean yield stresses are:

Initial width = 28 mm

$$\varepsilon_i = 0.05 \qquad \varepsilon_f = 0.10 \qquad \rightarrow \qquad \sigma_y^{mean} = 20.42 \text{ MPa}$$

Initial width = 30 mm

$$\varepsilon_i = 0.05 \qquad \varepsilon_f = 0.15 \qquad \rightarrow \qquad \sigma_y^{mean} = 21.11 \text{ MPa}$$

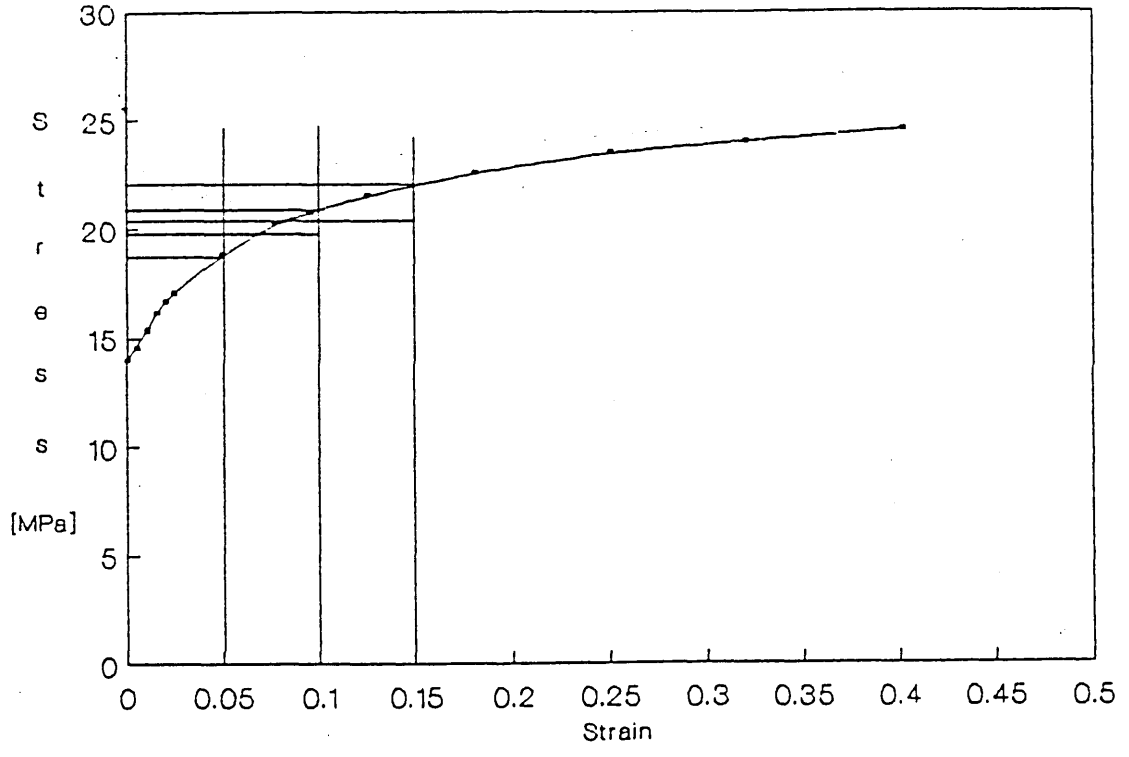
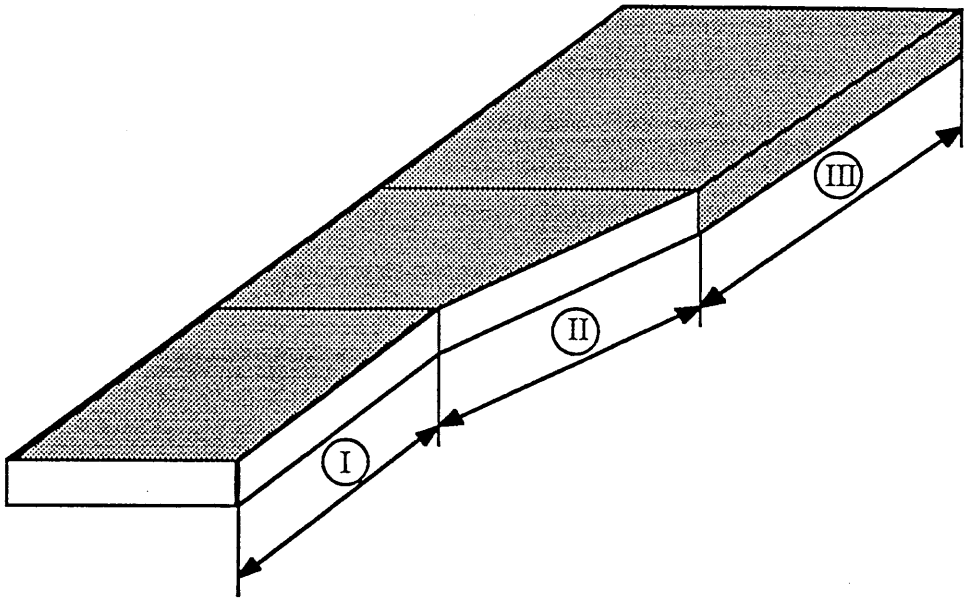


Fig.5.1 Stress-strain curve for commercially pure lead

As the difference between the two obtained values of the mean yield stress is less than 4% for both widths the same mean yield stress was assumed , $\sigma_y^{mean} = 20.756$ MPa.

5.3. EXPERIMENTAL AND THEORETICAL MODEL

As it was described in *Chapter 1*, in all methods of continuous extrusion three zones are developed in the chamber, namely primary zone, transitional zone and tertiary zone. In Fig.2.5. is shown sketch of the tree zones.



(I) - Primary zone - initial lateral indentation

(II) - Transitional zone - axial upsetting of the billet and filling of the chamber starts

(III) - Tertiary zone - the chamber is fully filled and the pressure builds up on the die face for extrusion

The shaded areas show the contact interface between billet and feed channel.

Fig.5.2. The three zones of the deformed billet in continuous extrusion processes.

On all shaded areas a frictional force is acting. On the flat top and bottom surfaces the frictional force is positive, i.e. the direction in which the force is acting coincides with the direction of the movement of the billet, and it is dragging the billet towards the die face.

The difference between the three considered continuous extrusion processes lies in the direction in which the frictional force acts on the sides of the billet in the tertiary zone. In Context it is positive and contributes towards building of the pressure on the die face. In Linex the frictional force is negative and thus reduces the main drag on the billet. In Conform it is positive on one side and negative on the other, so it can be assumed that the frictional forces there cancel each other and there is no influence on the main drag of the billet towards the die face.

The initial conditions imposed are those achieved after lateral indentation and are shown in Fig.5.3.

In the experiments first a lateral indentation load was applied in the **z** direction, (Fig.5.3) to produce thickness $\mathbf{Th_{ind}}$ together with the normal stress σ_z on the **x-y** planes

on the front and back faces of the specimen, Fig.5.3. Subsequently end load Ld^{top} was applied on the top end which simulates the extrusion load, to give rise to the frictional shear stress τ_{xy}. As the load was increased the specimen plastically deformed increasing in width W^{top} so that the tertiary zone developed with frictional shear stress τ_{fr} on both edges of the specimen.

Pressure on the front and back faces of the specimen, σ_z, is first due to the initial lateral indentation imposed on the billet. Because of this normal pressure a frictional shear stress, τ_{xy}, develops as the axial load is applied and provides the frictional drag for the specimen:

$$\tau_{xy} = \mu\sigma_z \tag{5.1}$$

where:

μ is the coefficient of friction.

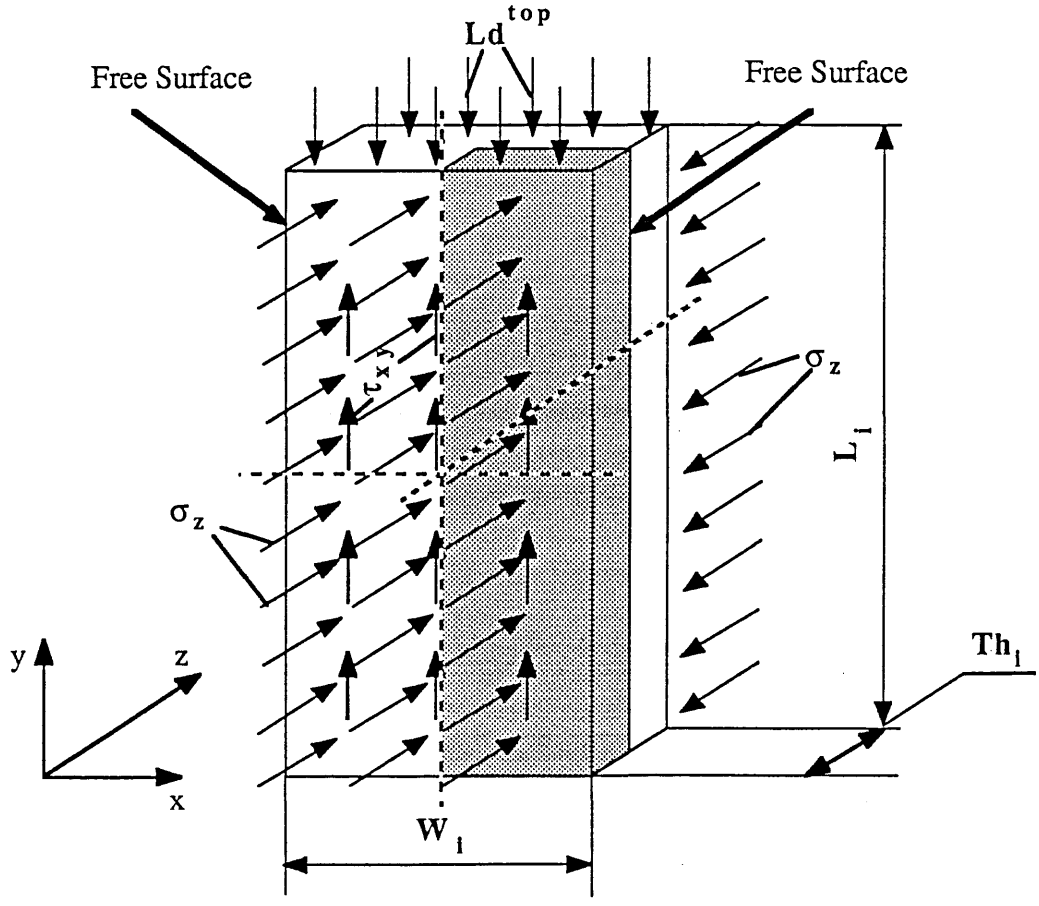


Fig.5.3. Initial conditions

From ring tests (Male and Cockroft [52]) a value of 0.12 for the coefficient of friction μ was found for commercial purity lead by A. Kondylides [43]. This value was used in this work assumed constant throughout the deformation process.

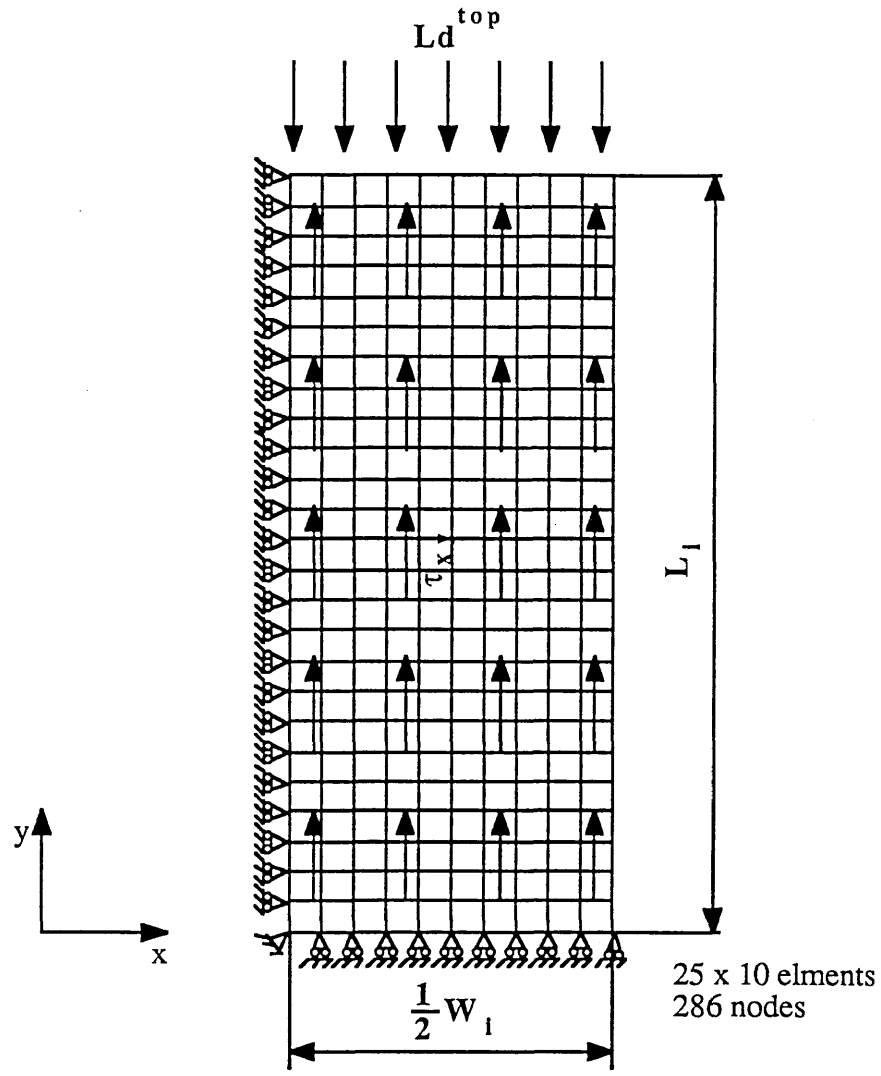
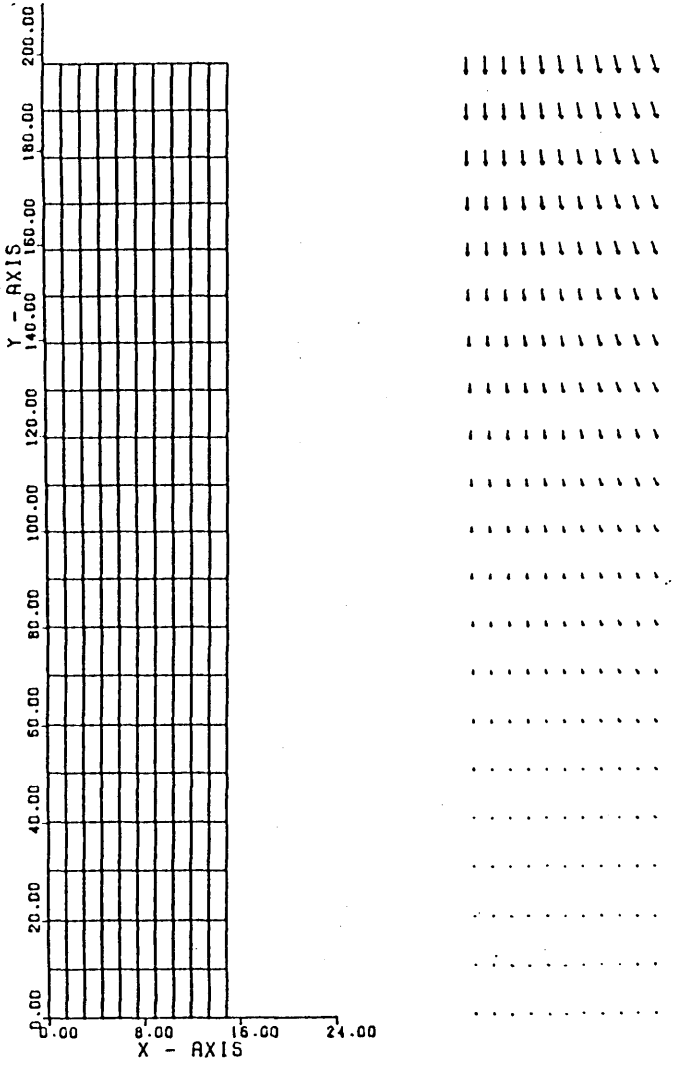


Fig.5.4. Finite element model: boundary and initial conditions.

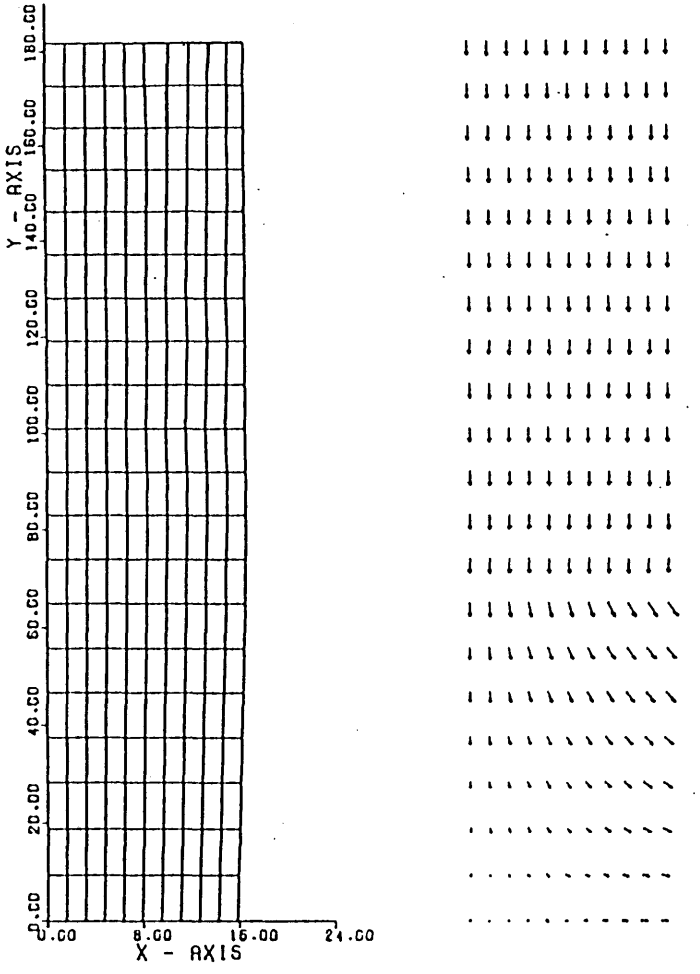
The finite element model of the experiment and the boundary conditions are shown in Fig.5.4. Due to symmetry only one quarter of the specimen was considered. The considered part of the billet is shown shaded in Fig.5.3.

The position of the nodes on the initially free vertical surface of the specimen was monitored constantly during the calculations. Once a node has reached the container wall, the boundary conditions for this particular node were updated, the node was restrained from moving the in **x**-direction and allowed to move vertically only, i.e. in the **y**-direction.

Examples of the deformed mesh and associated velocity field are shown in Fig.5.5. Fig.5.5.a. shows the specimen just after the load $\mathbf{Ld}^{\mathbf{top}}$ has been applied and Fig.5.5.b. shows the specimen after the tertiary zone has been developed.



a. Deformed mesh and velocity field at 1% reduction in height.



b. Deformed mesh and velocity field at 9% reduction in height.

Fig.5.5. Samples of the deformed mesh and associated velocity field.

5.4. EXPERIMENTAL DATA AND COMPARISON WITH THE THEORETICAL PREDICTIONS

Experimental data obtained together with the plots of load at the top pressure pad, load at the bottom pressure pad and punch displacement versus time are presented in *Appendix 5*. Here some of the obtained data relevant to the discussion that follows are given in ascending order of the specimen width and length. The specimens were numbered consecutively at the time of experiments.

The experimental data and theoretical predictions are shown in Table 5.1 to Table 5.7. Theoretical curves and experimental points of load at the top of the specimen, load at the bottom of the specimen, change in length of the specimen, change of the the width of the specimen at the bottom and change of the length of the tertiary zone (L3) versus strain [%] as well as photos of the deformed specimens are shown in Fig. 5.7 to Fig. 5.59.

The normal and frictional shear stresses increased with increasing the end load until $\mathbf{Ld}^{top}$ exceeded the frictional resistance and the specimen slipped onto the bottom load cell to record $\mathbf{Ld}^{bot}$.

As Fig.5.9, Fig.5.17, Fig.5.25, Fig.5.33, Fig.5.41. Fig.5.48 and Fig.5.55 illustrate, the axial load $\mathbf{Ld}^{top}$ increased first in the linear manner. The increase became steep once the tertiary zone began to develop (Fig.5.13, Fig.5.21, Fig.5.29, Fig.5.37, Fig.5.45, Fig.5.52 and Fig.5.59) adding to the friction surface and simultaneously, the normal and frictional stresses increased due to the rising level of the hydrostatic component of stress.

The load on the bottom load cell increases steeply (Fig.5.10, Fig.5.18, Fig.5.26, Fig.5.34, Fig.5.42, Fig.5.49 and Fig.5.56) once the tertiary zone extends on the full specimen length, Fig.5.13, Fig.5.21, Fig.5.29, Fig.5.37, Fig.5.45, Fig.5.52 and Fig.5.59.

The rapid rise of load with the development of the transitional and tertiary zones means that a short additional length of billet results in a considerable increase in load, which in turn means higher obtainable extrusion ratios.

The correlation between the experimental data and theoretical predictions is reasonable. The differences can be explained by experimental scatter and by the following factors:

- The billet material was assumed to be rigid and perfectly plastic in the theoretical analysis. This does not match completely with the experimental results, because a small amount of workhardening was present over the range of strains used;

- The principal planes were assumed to coincide with the faces of the billet. This in practice, would certainly not occur since the frictional forces exerted on the billet would cause the principal planes to rotate;

- Some flash formation between the pressure pads and the liner segments and also between the liner segments themselves, due to slight relative movements of the liner segments during the indentation and the following axial compression created an additional drag force, which in turn caused the axial force to increase;

- The coefficient of friction, μ, was assumed to be constant. In practice, however, it could vary;

- The friction between the top pressure pad and the liner segments, due to the tight fit, was not taken into account in the theoretical model. Moreover, this friction was not constant throughout the experiments, due to wear as experiments progressed. As a direct result of this friction the load on the top pressure pad was higher than it should have been, which is evident from the first two specimens (Fig.5.56). For the same specimens (Fig.5.56) the load on the bottom pressure pad is higher than the loads theoretically predicted. The reason for this is that initially there was an unavoidable gap between the liner and the bottom cross head of the testing machine. Due to the above mentioned friction between the top pressure pad and the segments, the liner assembly moved downwards until the bottom cross head of the testing machine was reached, dragging with it the billet and in this way exerting pressure on the bottom pressure pad, which would not have been present if the gap did not exist;

- During some of the experiments, due to the slight relative movement of the liner members, the top pressure pad slightly damaged one of the liner segments and for this reason obtained values of the load were higher than the theoretical ones and than the mean experimental values (see Fig.5.17-Experimental-13 & Fig.5.25). For the next experiment, the damage was rectified resulting in lower loads (Fig.5.17-Experimental-14-2).

The largest disagreement between the experimental results and the theoretical predictions are in the length of the tertiary region, because it was difficult to align the billet accurately so that mean values on the two sides were taken.

With these reservations the difference between the theoretical and experimental results are acceptable and it can be concluded that the developed computer code based on FEM flow formulation described in *Chapter 3* can predict with reasonable accuracy the required parameters of the continuous extrusion processes.

The meaning of symbols used in Table 5.1 to Table 5.7 are illustrated in Fig.5.6 and is given in the the following:

L_i → initial length of the billet
W_i → initial width of the billet
Th_i → initial thickness of the billet
L_{ind} → length of the billet after lateral indentation
Th_{ind} → thickness of the billet after lateral indentation
L_f → final length of the billet
Th_f → final thickness of the billet
W_f^{top} → final width of the billet at the top
W_f^{bot} → final width of the billet at the bottom
Ld_{max}^{top} → maximum load at the top pressure pad
Ld_{max}^{bot} → maximum load at the bottom pressure pad
L_3 → length of the tertiary zone at ε_{max}
ε_{max} → maximum achieved reduction in height

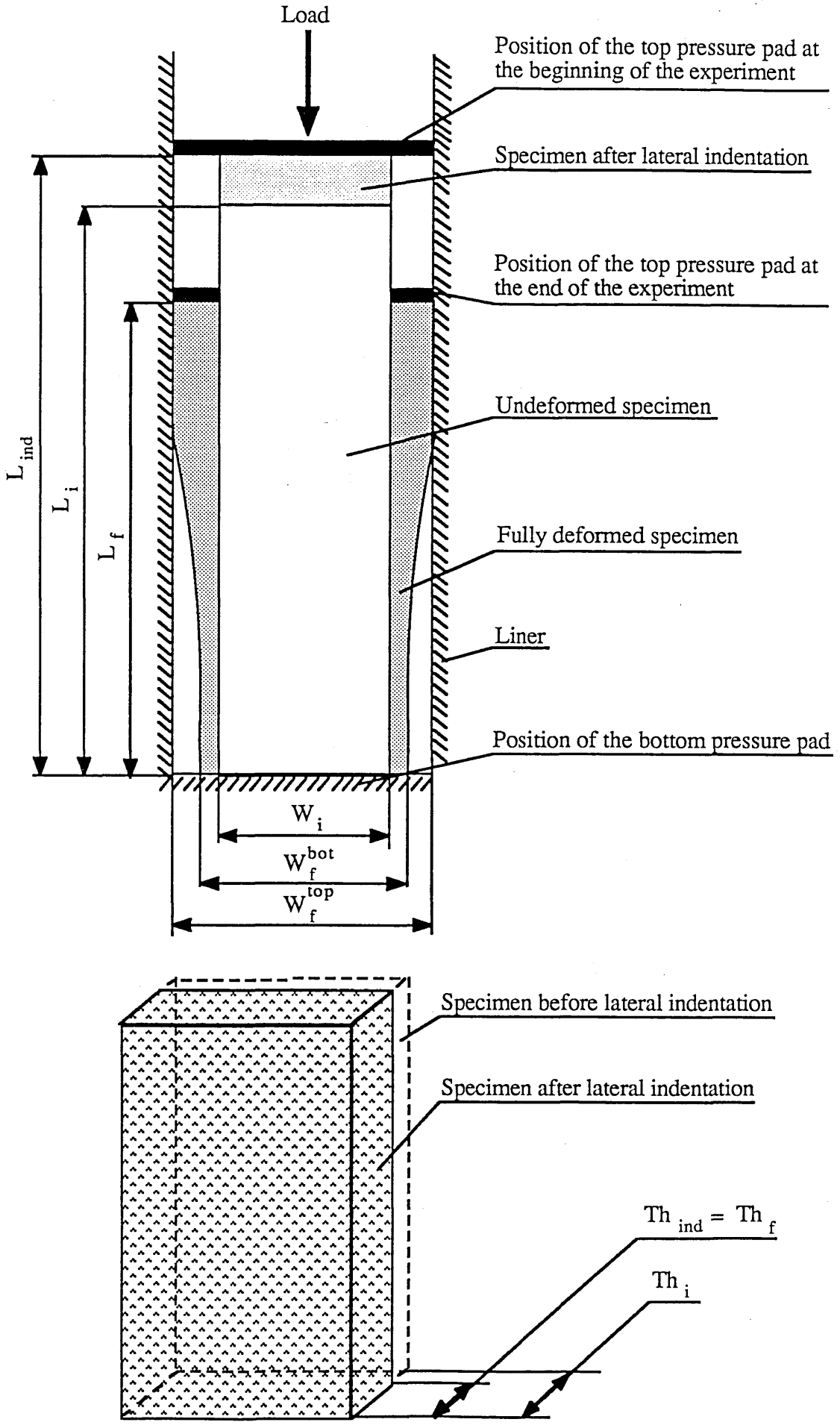

Load
Position of the top pressure pad at the beginning of the experiment
Specimen after lateral indentation
Position of the top pressure pad at the end of the experiment
Undeformed specimen
Fully deformed specimen
Liner
Position of the bottom pressure pad
L_{ind}
L_i
L_f
W_i
W_f^{bot}
W_f^{top}
Specimen before lateral indentation
Specimen after lateral indentation
$Th_{ind} = Th_f$
Th_i

Fig.5.6.

Table.5.1

150 mm x 28 mm Specimen													Experimental data
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
18	150.00	28.26	19.92	157.5	18.90	138.53	18.90	33.08	33.08	100.793	20.775	133.3	12.44
19	150.00	28.15	19.87	157.5	18.90	140.19	18.90	33.06	31.05	57.353	20.775	52.4	11.37
													Theoretical data
L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]			
157.5	28.00	19.00	132.125	19.00	33.00	33.00	243.2000	161.4224	132.125	16.11			

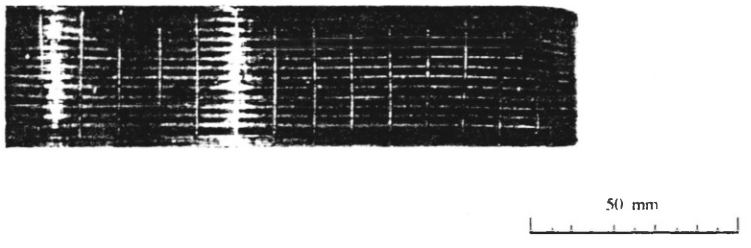


Fig.5.7. Deformed Specimen No.18

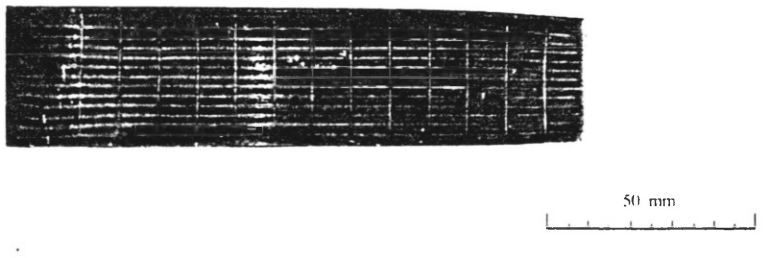


Fig.5.8. Deformed Specimen No.19

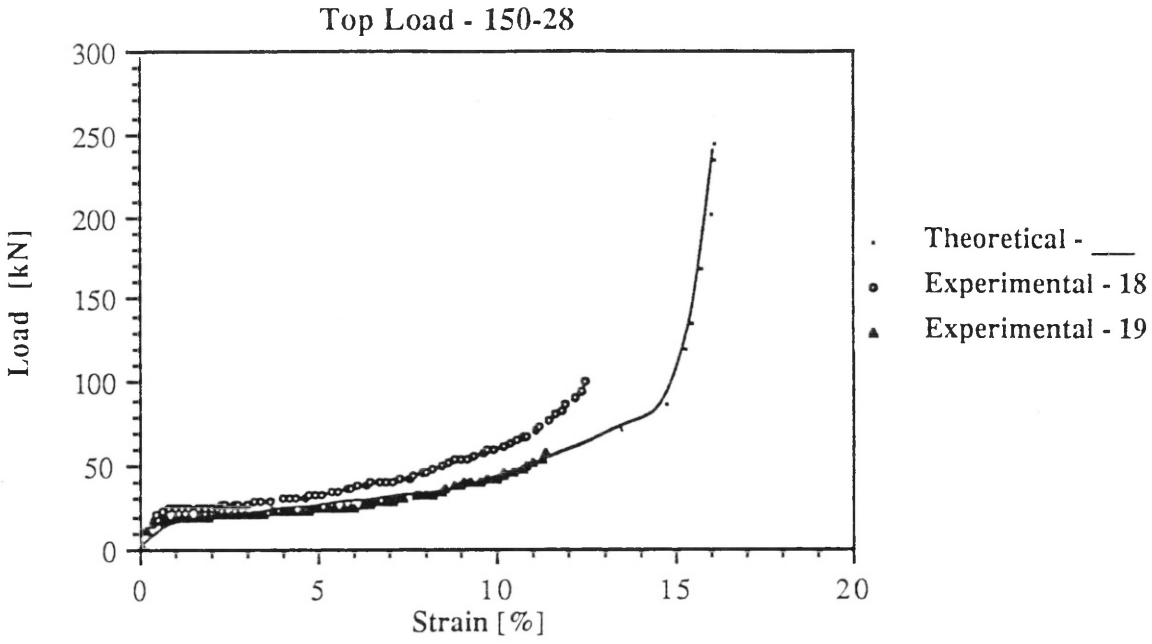


Fig.5.9.

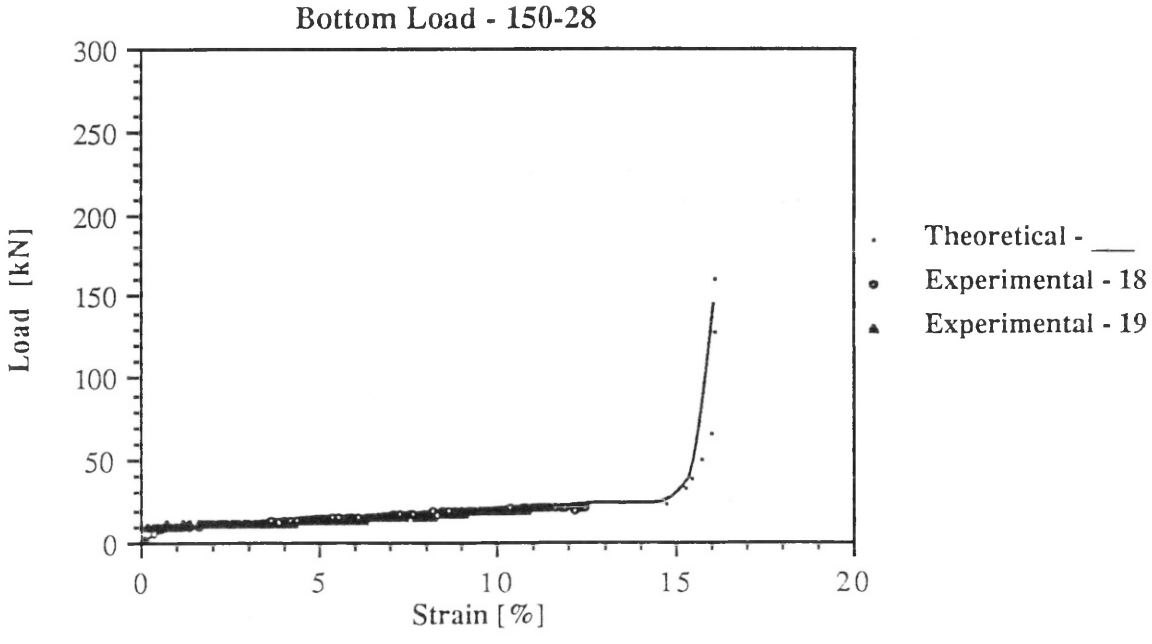


Fig.5.10.

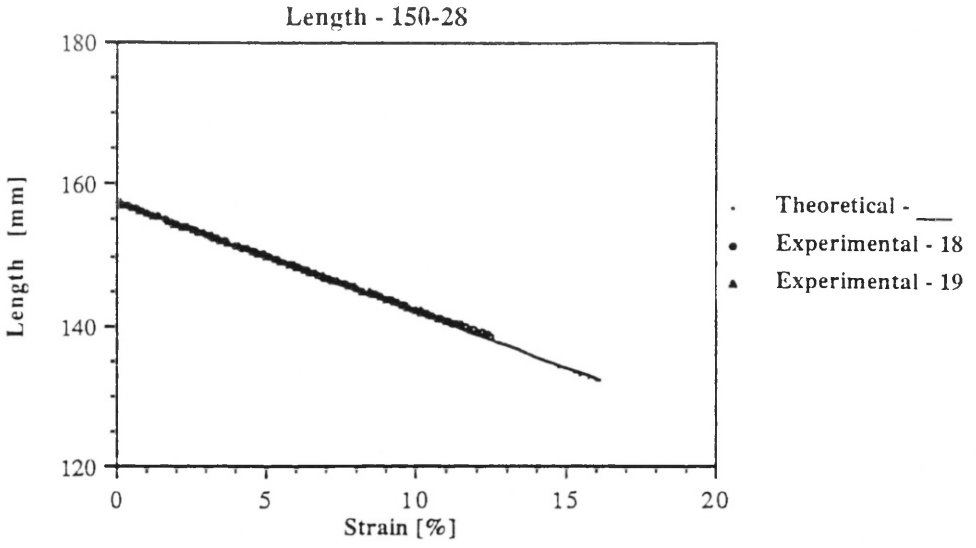


Fig.5.11.

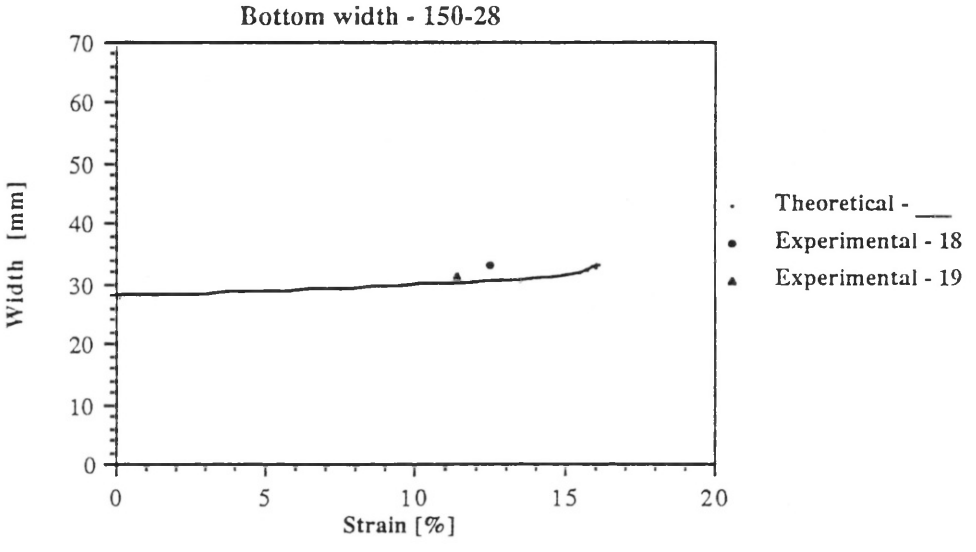


Fig.5.12.

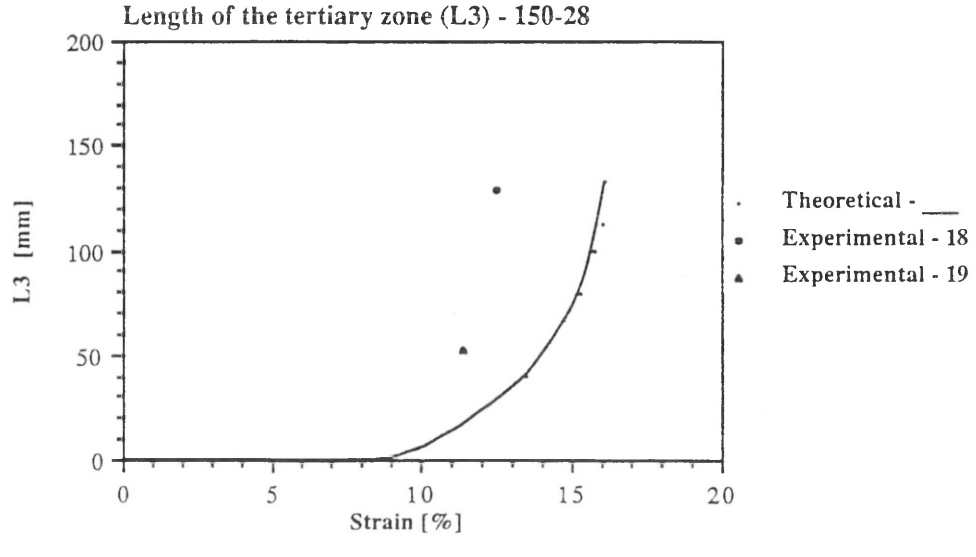


Fig.5.13.

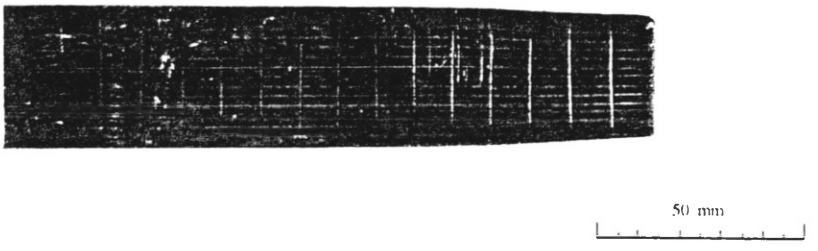
Table.5.2

165 mm x 28 mm Specimen													Experimental data
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
5	165.6	28.14	19.89	173.80	18.90	153.64	18.90	33.05	28.57	60.0500	20.0376	65.00	11.08
13	165.4	28.25	19.84	173.20	18.90	156.87	18.90	33.07	28.95	70.2312	21.5126	102.70	9.64
14	165.1	28.31	19.82	173.00	18.90	163.71	18.90	33.08	28.8	62.0000	48.1719	20.775	5.51
													Theoretical data
L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]			
173.00	28.00	19.00	145.466	19.00	33.00	32.59	243.0045	82.5735	130.755	15.92			



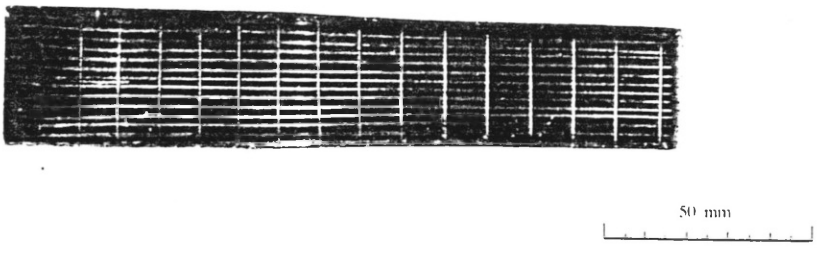
SPECIMEN No.5

Fig.5.14. Deformed Specimen No.5



SPECIMEN No.13

Fig.5.15. Deformed Specimen No.13



SPECIMEN No.14

Fig.5.16. Deformed Specimen No.14

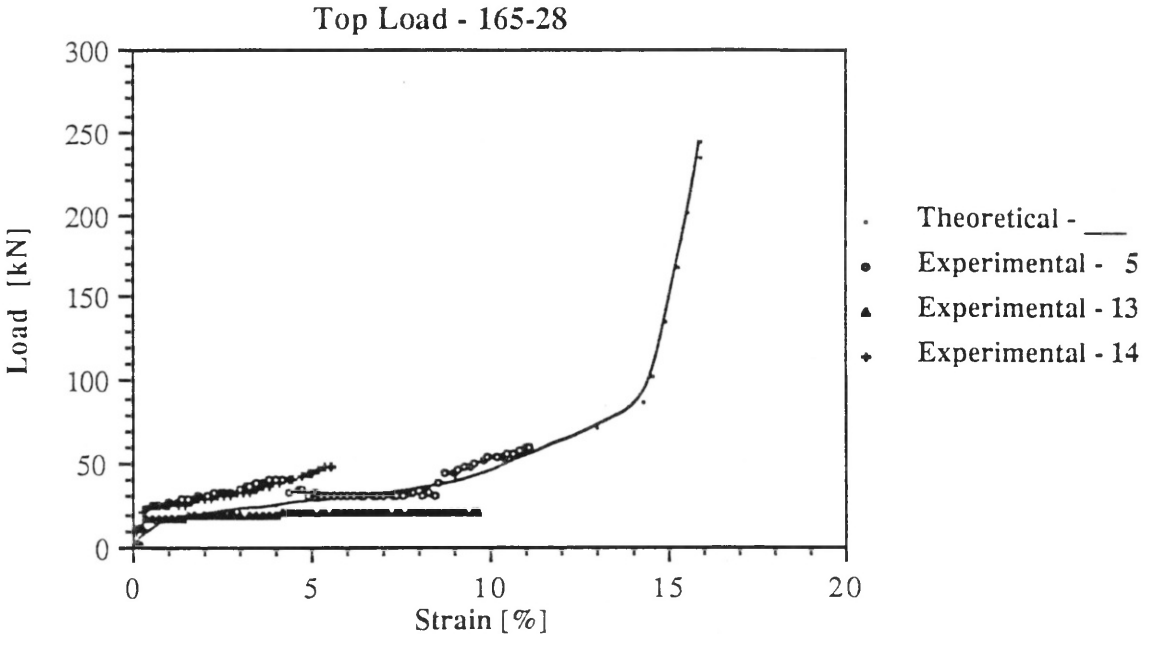


Fig.5.17

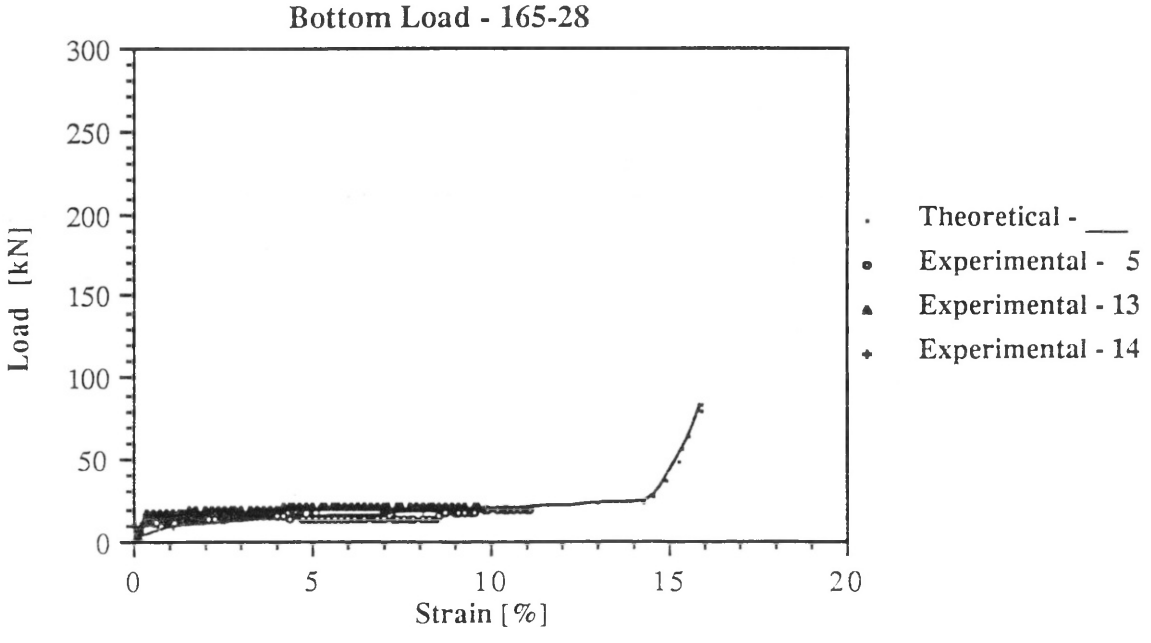


Fig.5.18.

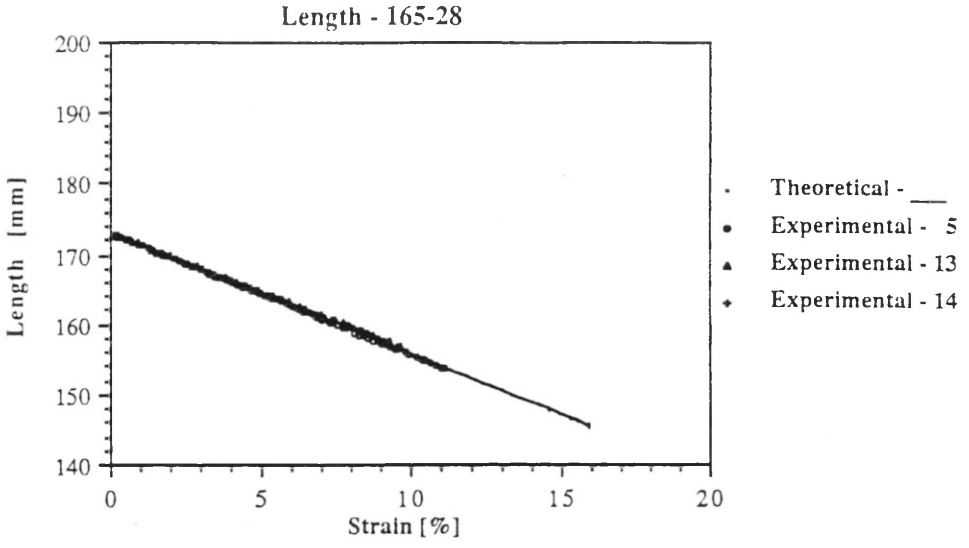


Fig.5.19.

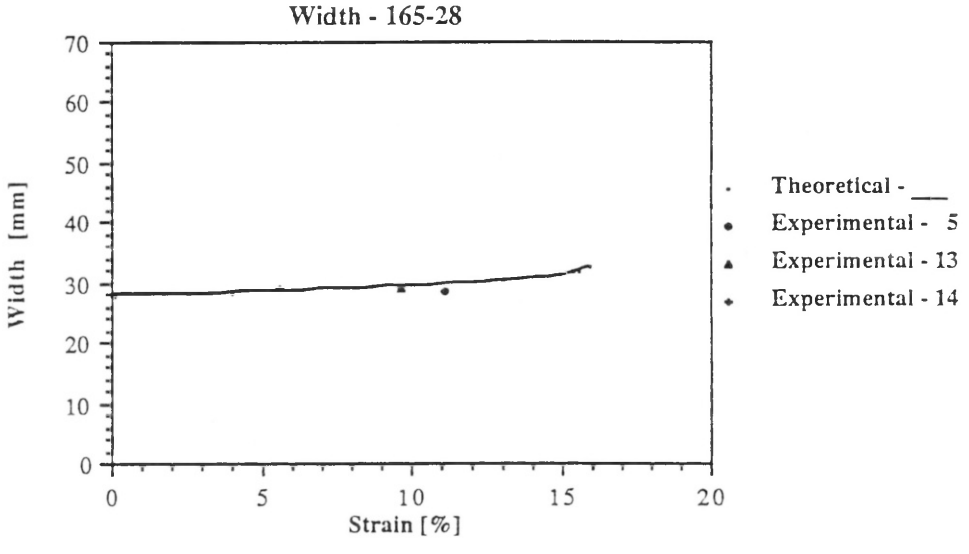


Fig.5.20.

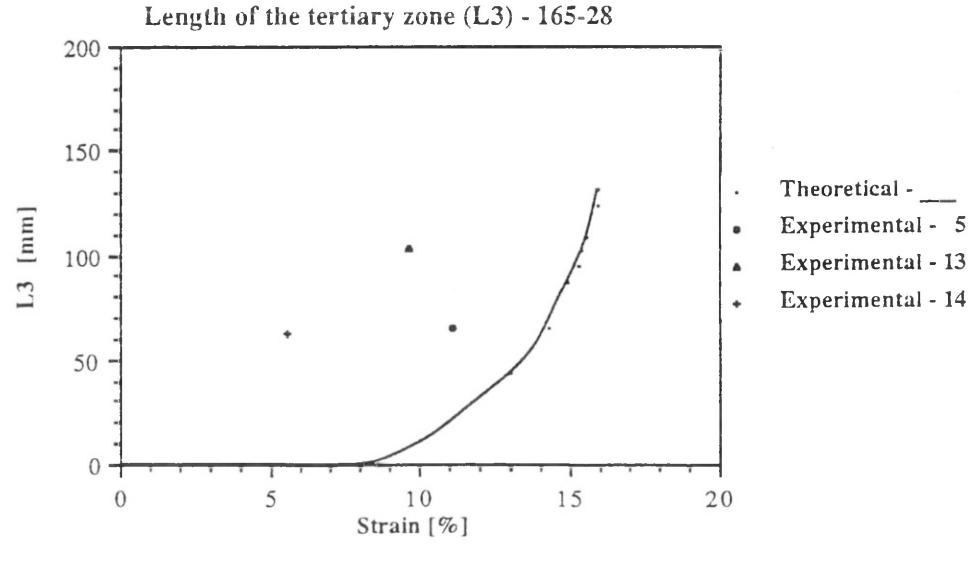
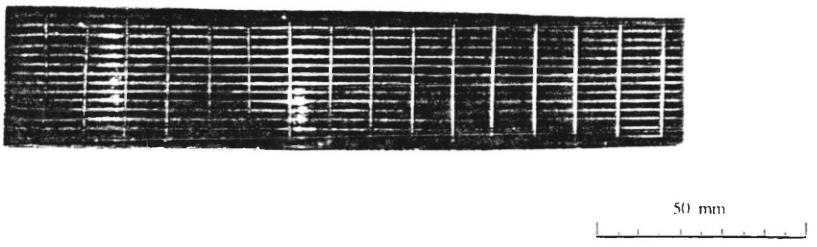


Fig.5.21.

Table.5.3

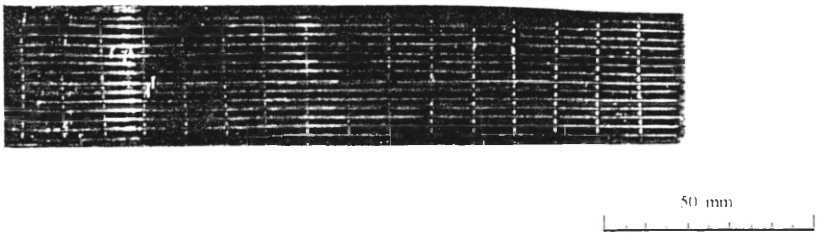
165 mm x 30 mm Specimen													Experimental data
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
15	165.5	30.01	19.82	173.54	18.90	164.69	18.90	33.08	30.50	70.2312	20.7750	103.8	4.9732
16	165.7	30.01	19.79	173.63	18.90	163.91	18.90	33.09	31.00	90.5938	19.3000	111.9	5.4254
17	165.4	30.03	19.81	173.49	18.90	166.74	18.90	33.05	30.35	58.3530	17.8251	80.8	3.7660

										Theoretical data
L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
173.00	30.00	19.00	156.078	19.00	33.00	33.00	242.8785	148.1827	156.078	9.78



SPECIMEN No.15

Fig.5.22. Deformed Specimen No.15



SPECIMEN No.16

Fig.5.23. Deformed Specimen No.16



SPECIMEN No.17

Fig.5.24. Deformed Specimen No.17

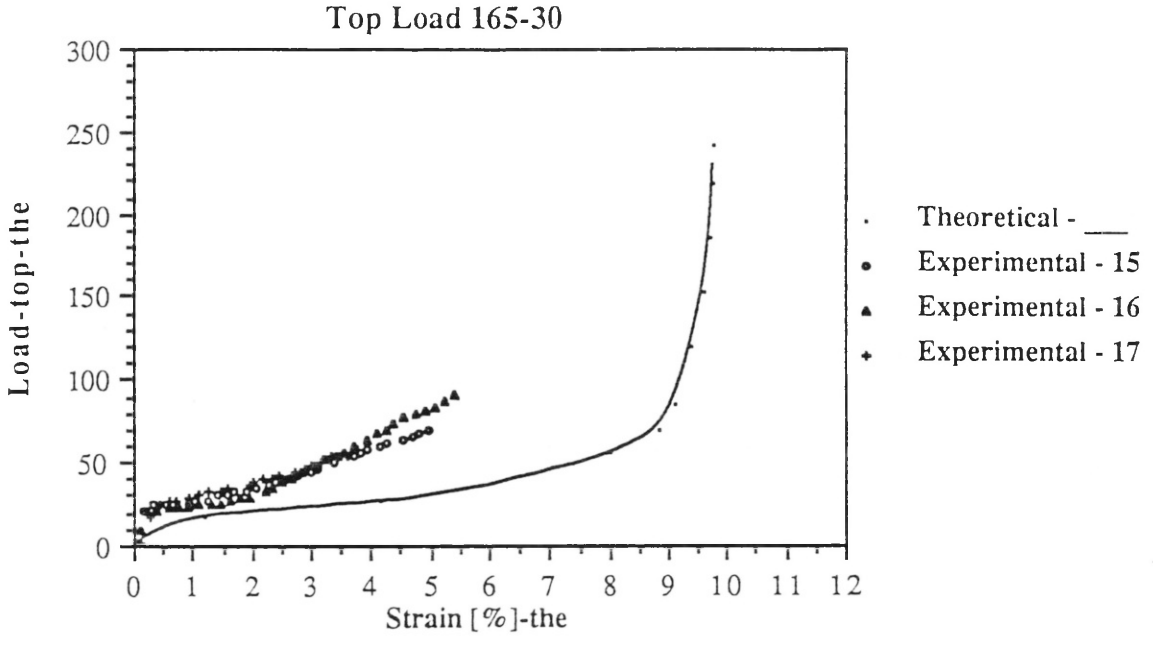


Fig.5.25.

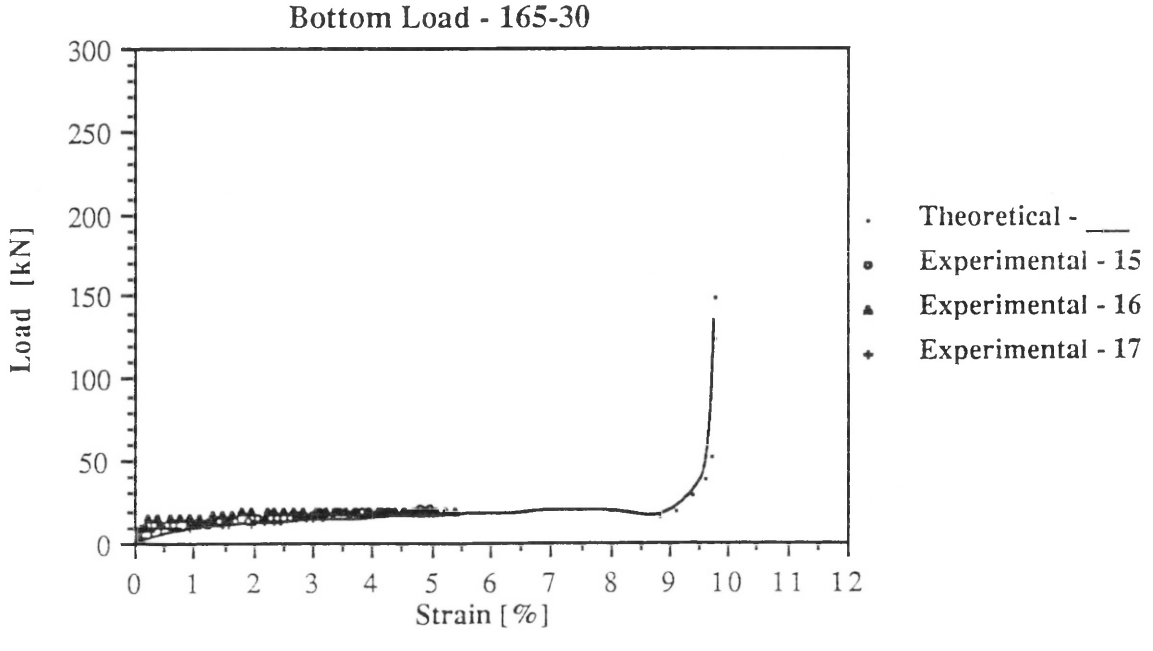


Fig.5.26.

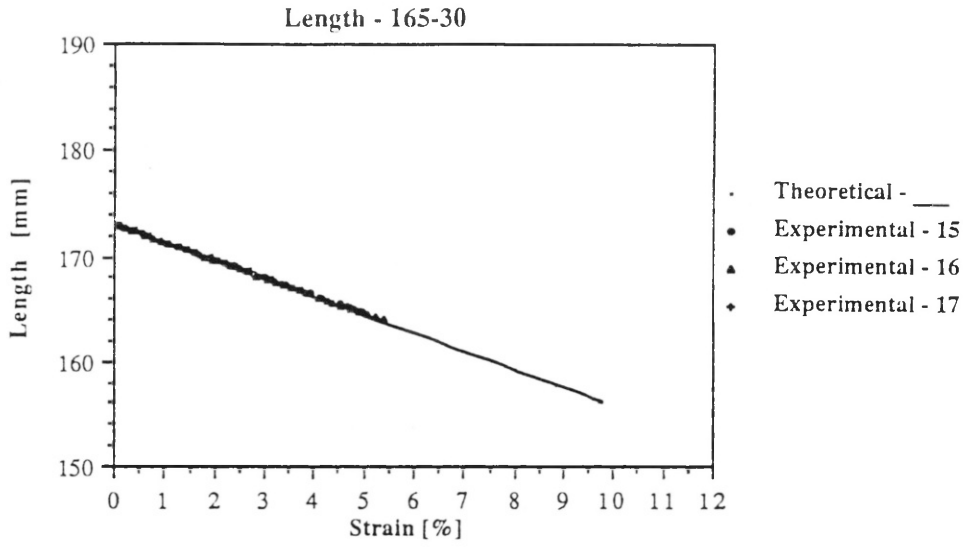


Fig.5.27.

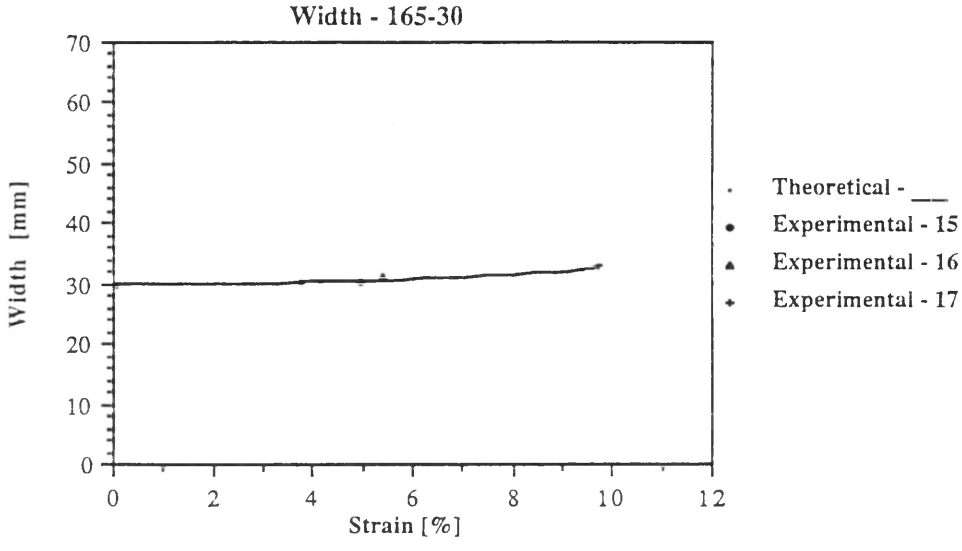


Fig.5.28.

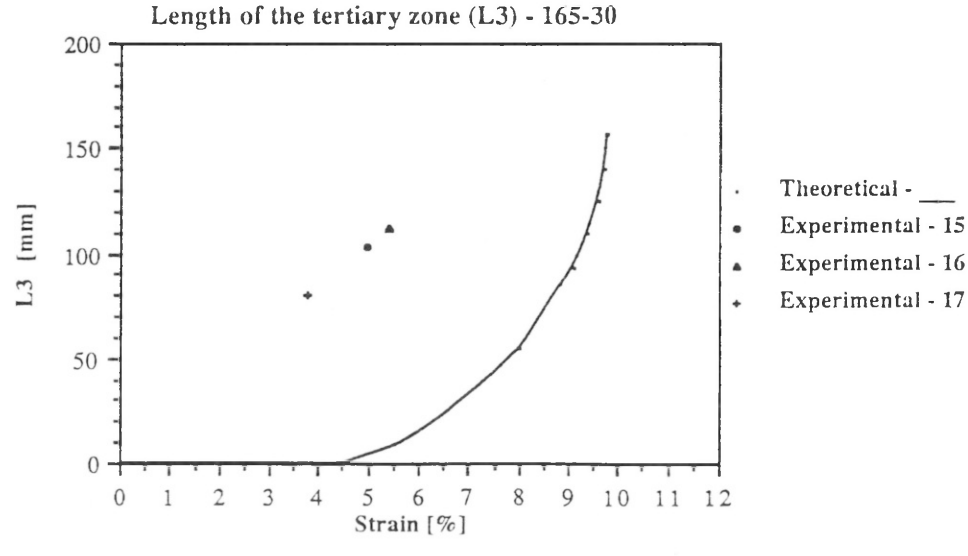


Fig.5.29.

Table.5.4

185 mm x 28 mm Specimen												Experimental data	
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
6	185.3	28.32	19.79	192.28	18.90	163.16	18.90	33.05	30.62	95.6843	31.1001	142.50	14.78
7	185.1	28.21	19.78	192.12	18.90	180.56	18.90	33.05	29.04	62.0550	60.0500	22.25	6.02
8	185.2	28.36	19.78	192.19	18.90	161.99	18.90	33.06	33.06	136.4094	50.2750	161.99	15.36

										Theoretical data	
L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
192.00	28.00	19.00	161.453	19.00	33.00	32.654	242.8095	77.959	145.174	15.91



Fig.5.30. Deformed Specimen No.6

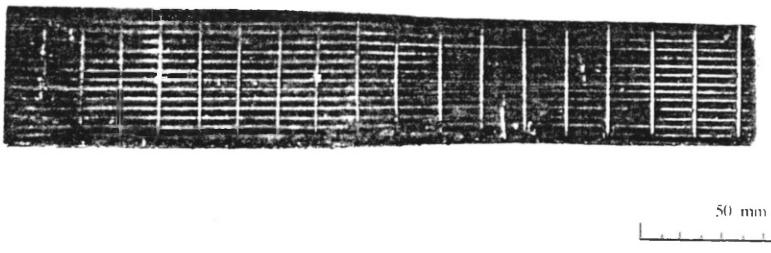


Fig.5.31. Deformed Specimen No.7



Fig.5.32. Deformed Specimen No.8

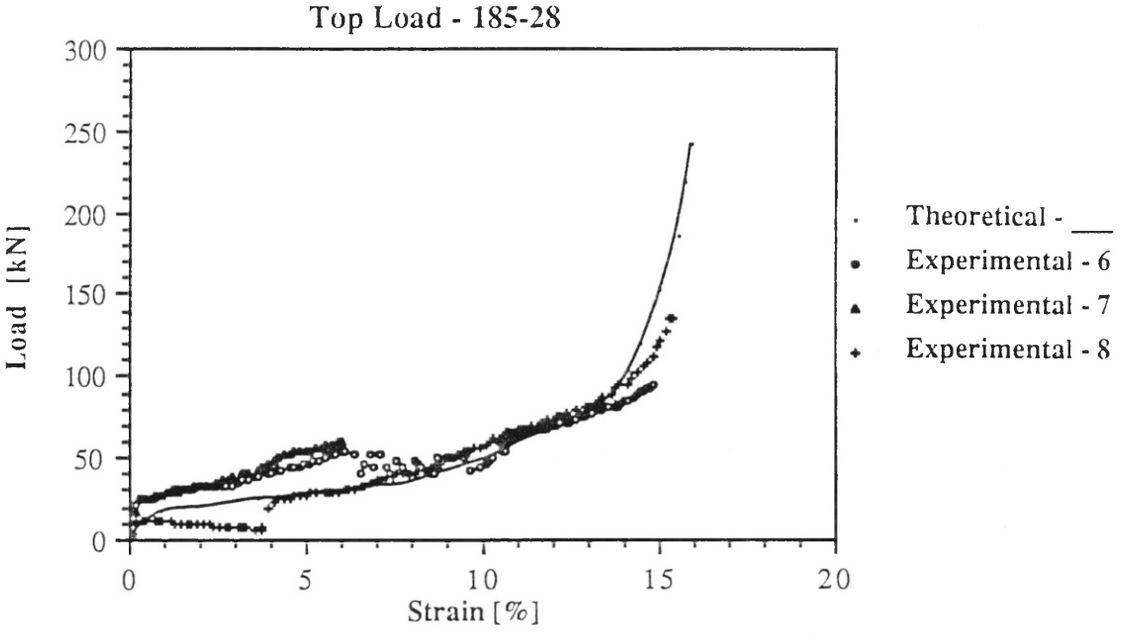


Fig.5.33.

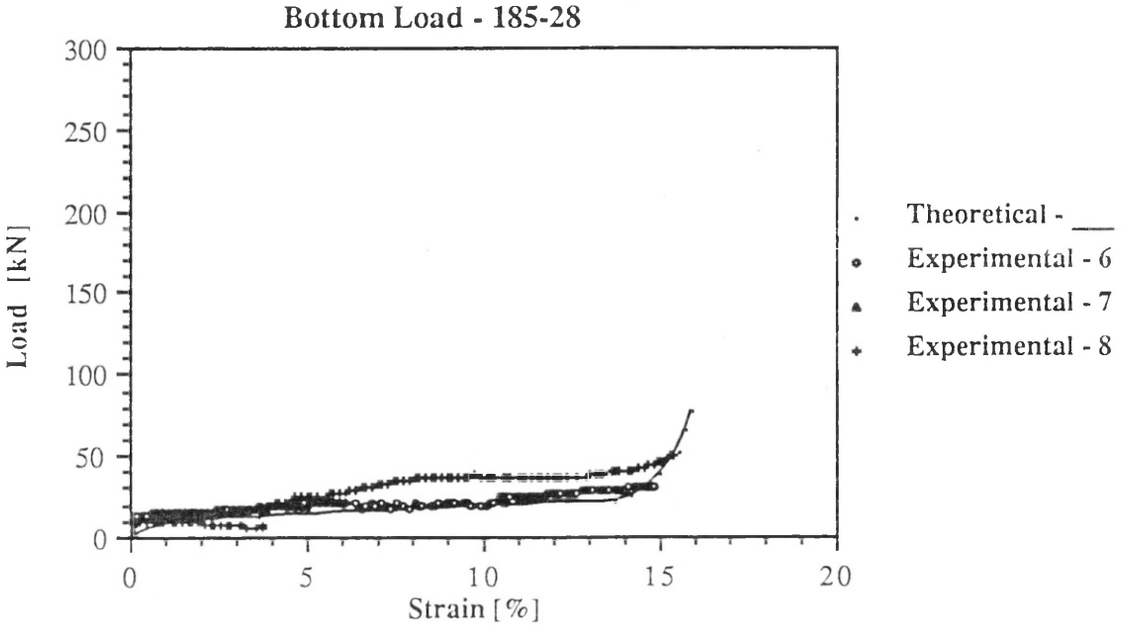


Fig.5.34.

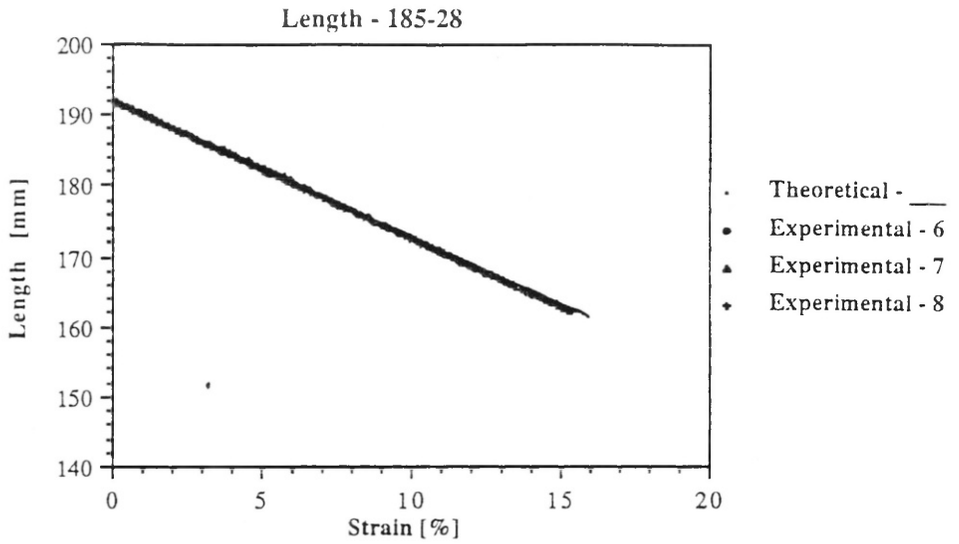


Fig.5.35.

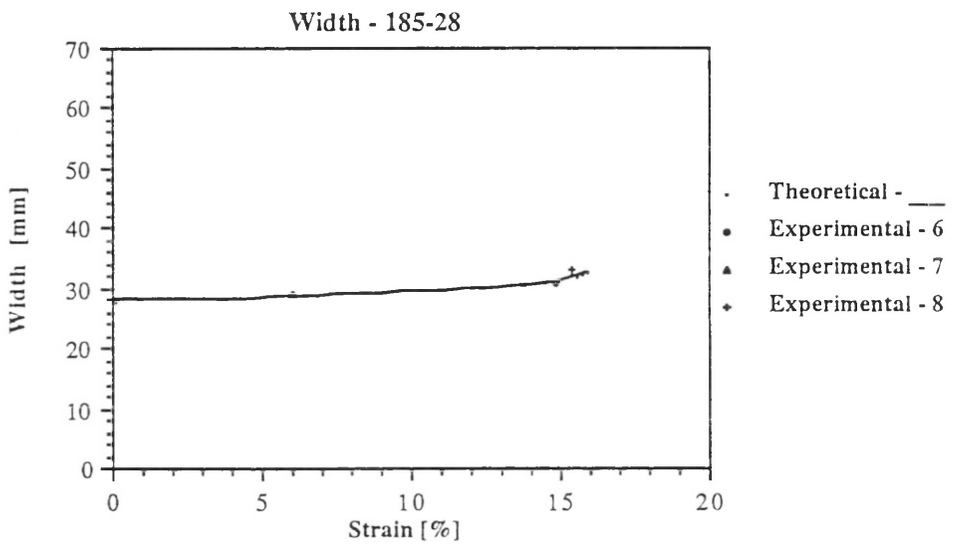


Fig.5.36.

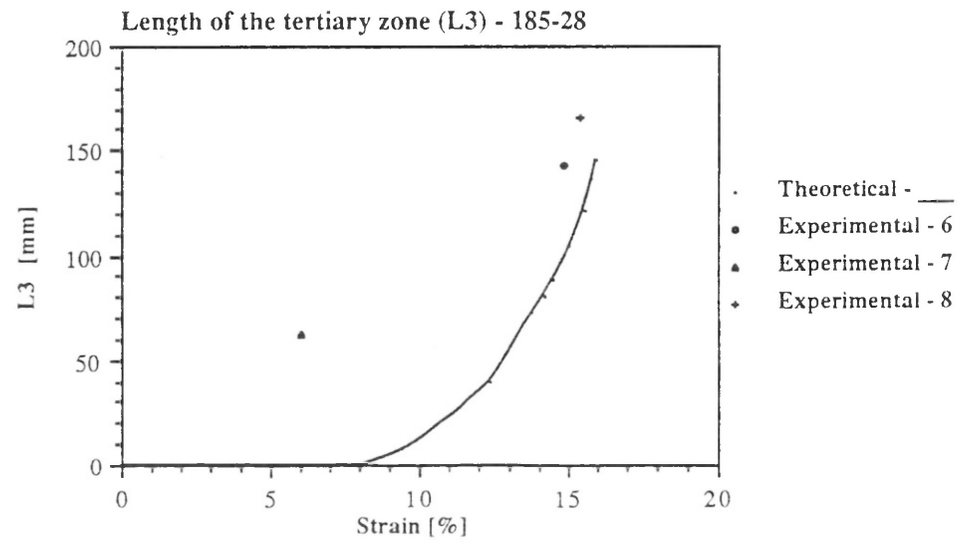


Fig.5.37.

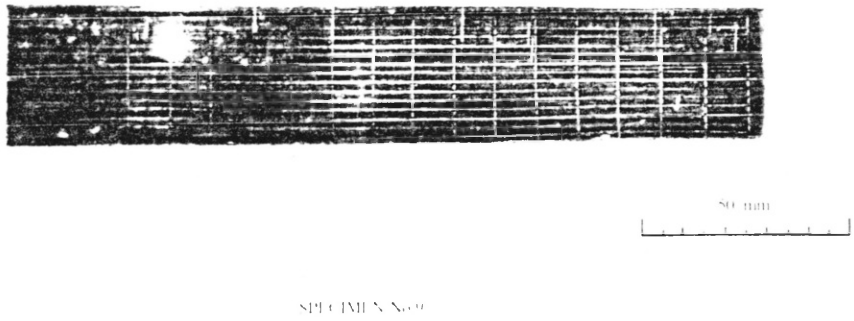
Table.5.5

185 mm x 30 mm Specimen — Experimental data

Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
9	184.8	29.99	19.79	172.82	18.90	174.99	18.90	33.06	31.30	63.4436	38.4751	110.8	8.76
10	185.1	29.88	19.77	173.09	18.90	173.52	18.90	33.07	31.75	88.8967	39.9501	147.2	9.56
11	185.1	29.83	19.83	173.12	18.90	176.16	18.90	33.05	31.25	51.5657	36.2626	84.7	8.16

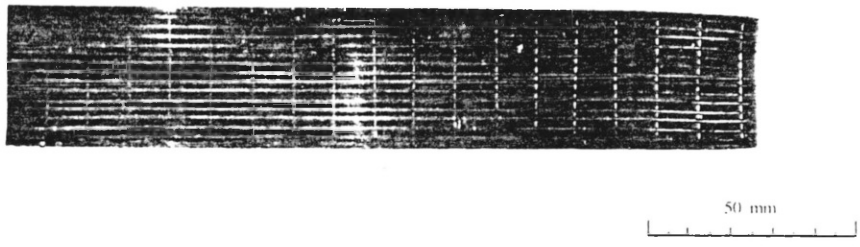
Theoretical data

L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
173.0	30.00	19.00	173.235	19.00	33.00	33.00	234.3872	130.5082	173.235	9.77



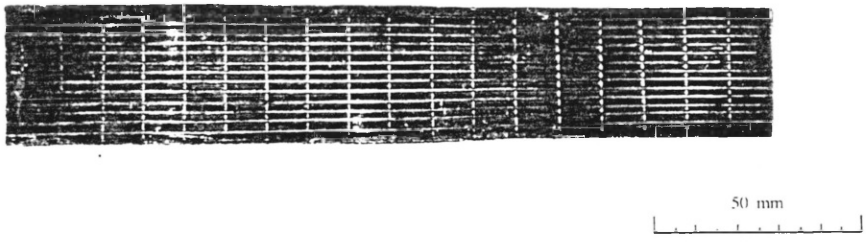
SPECIMEN No.9

Fig.5.38. Deformed Specimen No.9



SPECIMEN No.10

Fig.5.39. Deformed Specimen No.10



SPECIMEN No.11

Fig.5.40. Deformed Specimen No.11

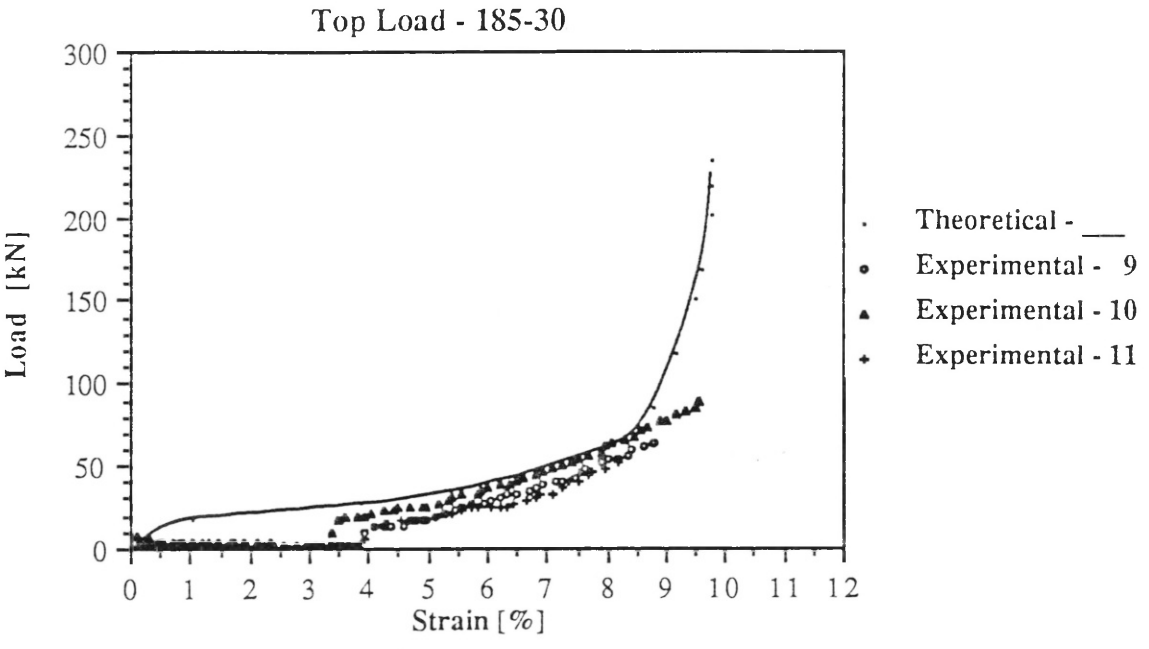


Fig.5.41.

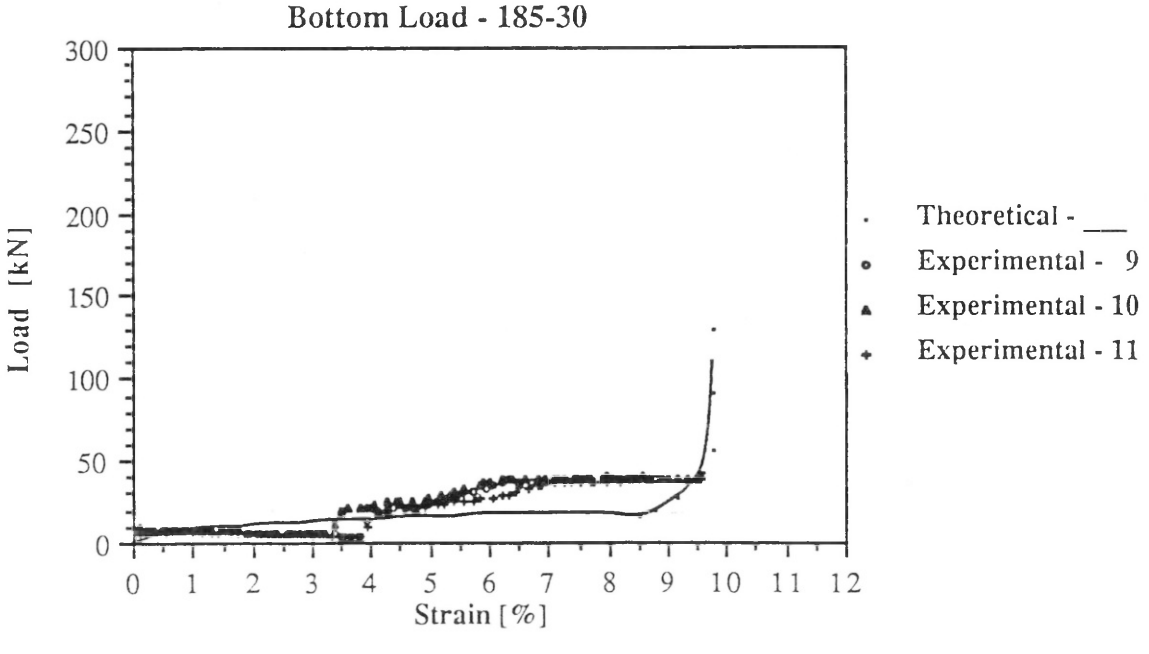


Fig.5.42.

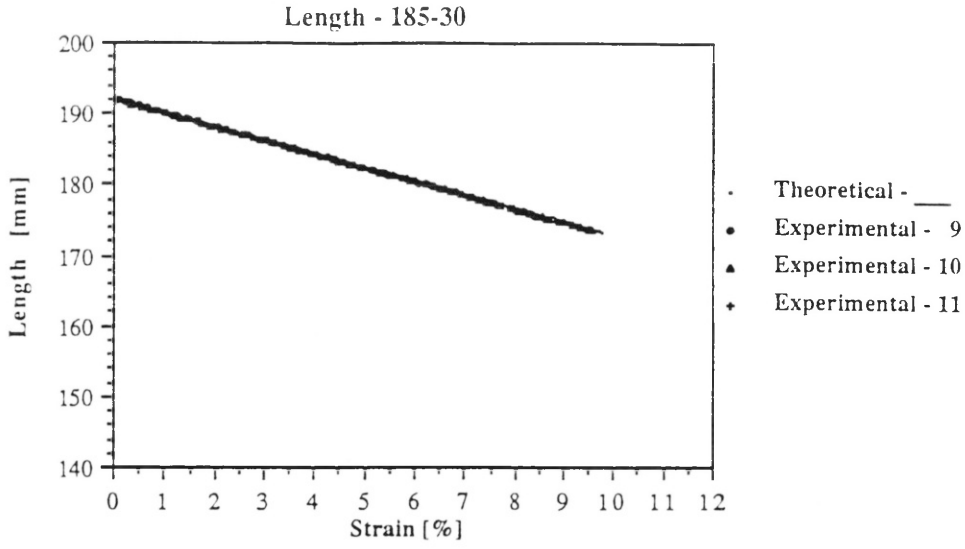


Fig.5.43.

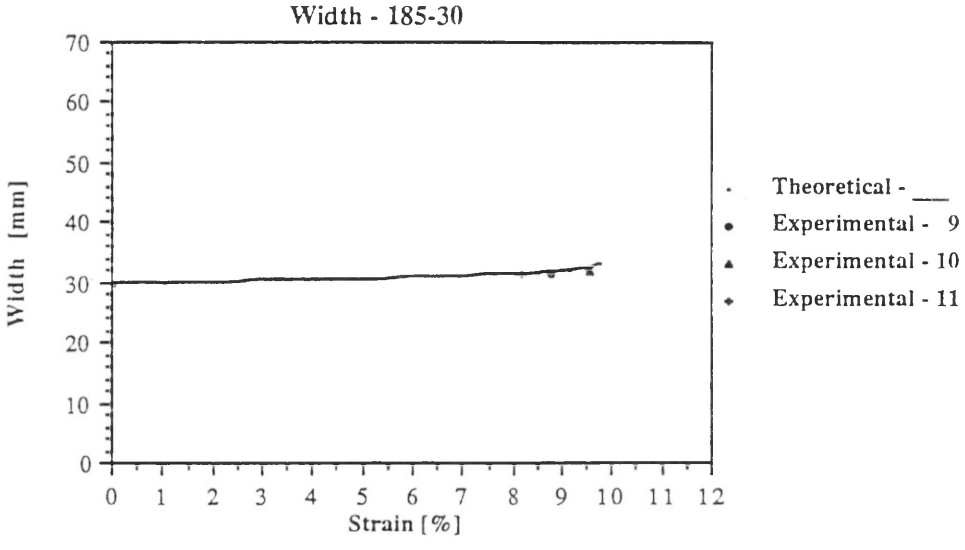


Fig.5.44.

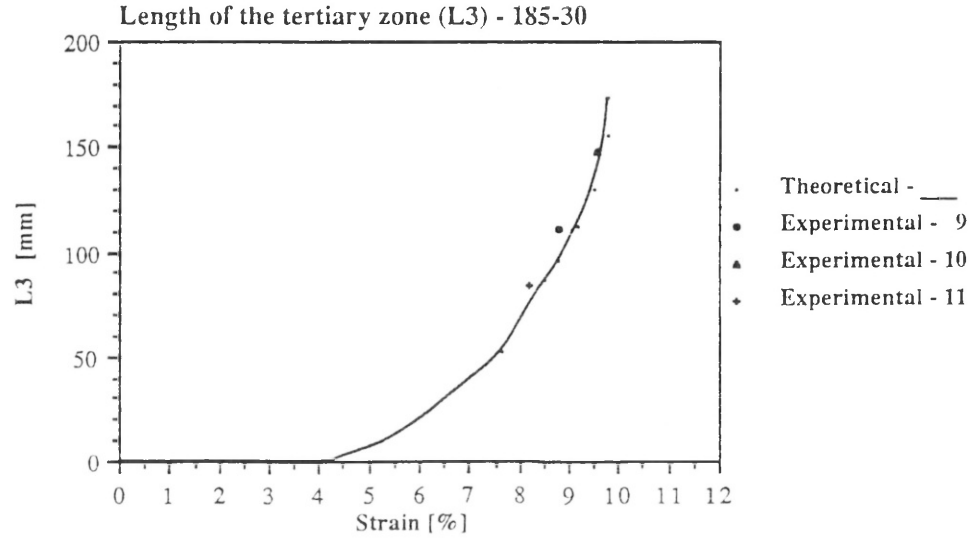
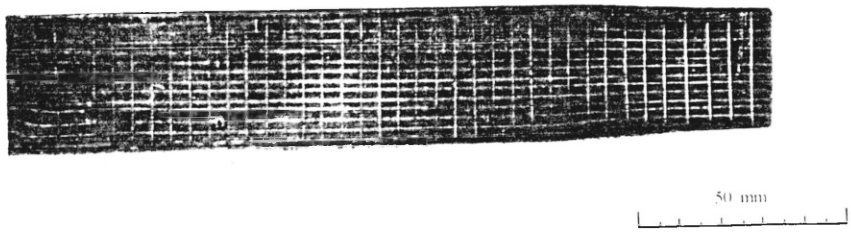


Fig.5.45.

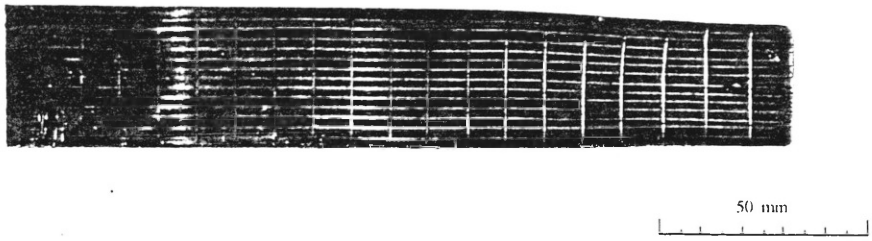
Table.5.6

200 mm x 28 mm Specimen													Experimental data
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
4	199.1	27.84	19.82	206.21	18.90	176.78	18.90	33.05	28.60	77.0374	25.2126	116.00	14.60
12	200.1	28.17	19.78	207.12	18.90	180.70	18.90	33.07	28.75	66.8188	27.4001	111.00	12.70
													Theoretical data
L_i [mm]		W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]		
207.0		28.00	19.00	174.21	19.00	33.00	32.258	242.9324	74.6674	147.67	15.84		



SPECIMEN No.4

Fig.5.46. Deformed Specimen No.4



SPECIMEN No.12

Fig.5.47. Deformed Specimen No.12

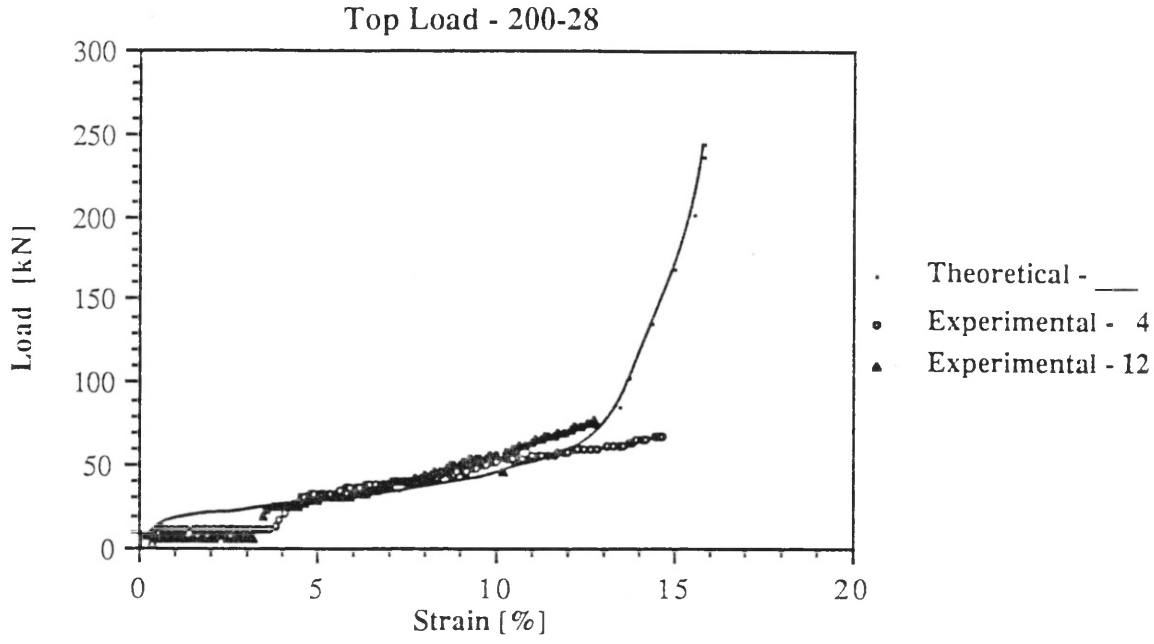


Fig.5.48.

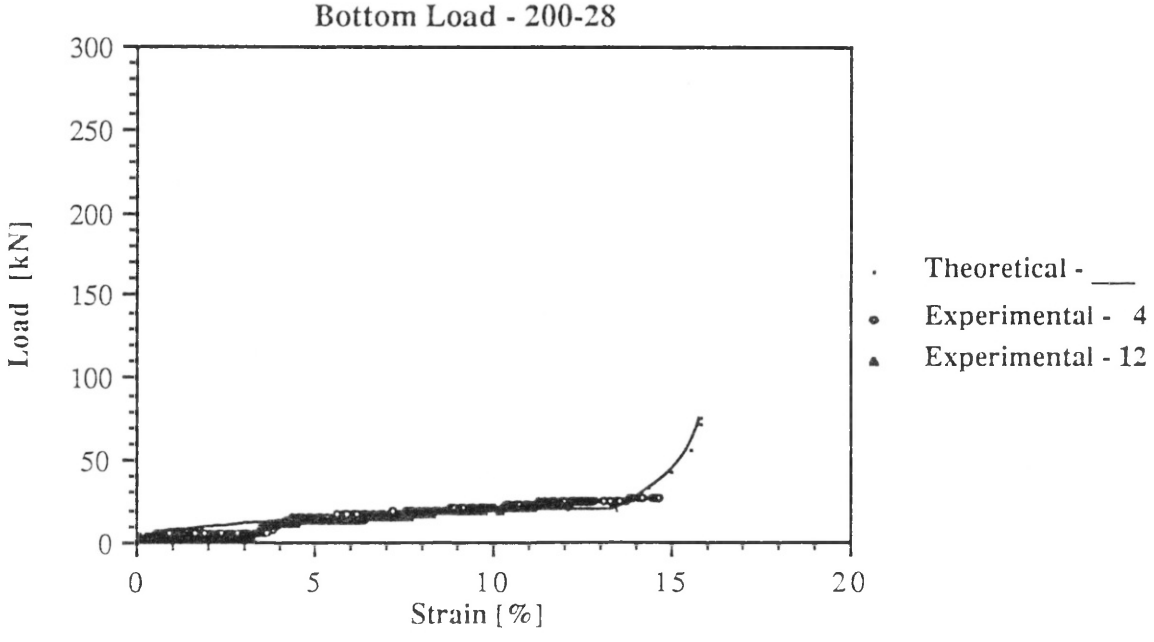


Fig.5.49.

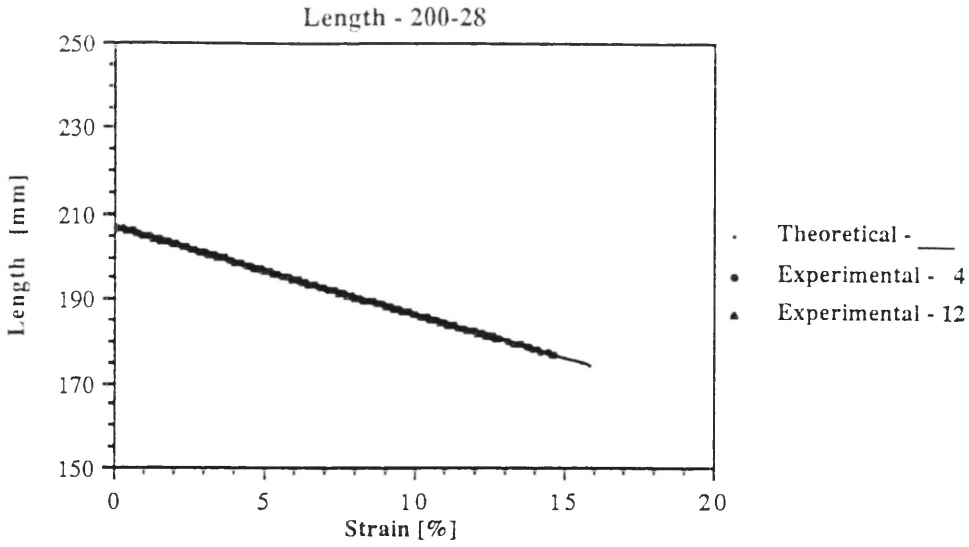


Fig.5.50.

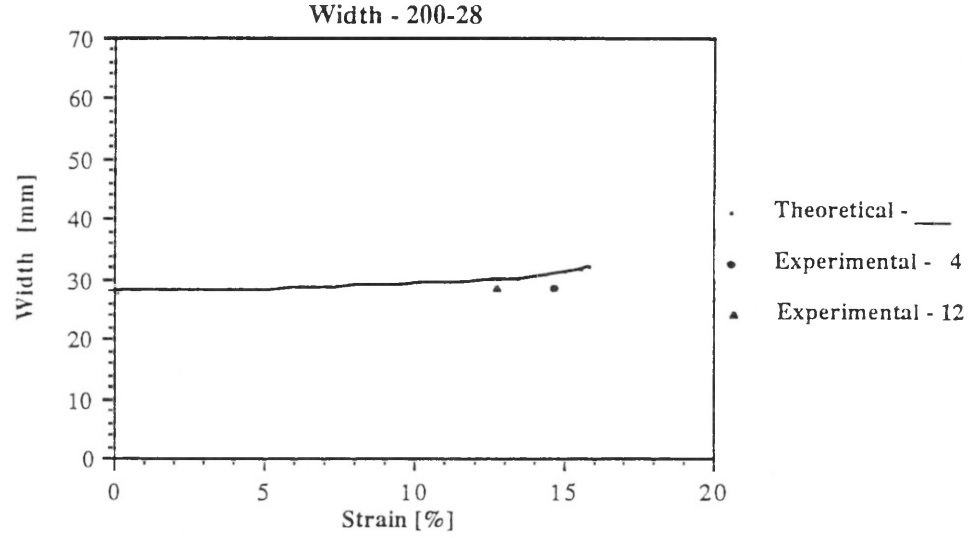


Fig.5.51.

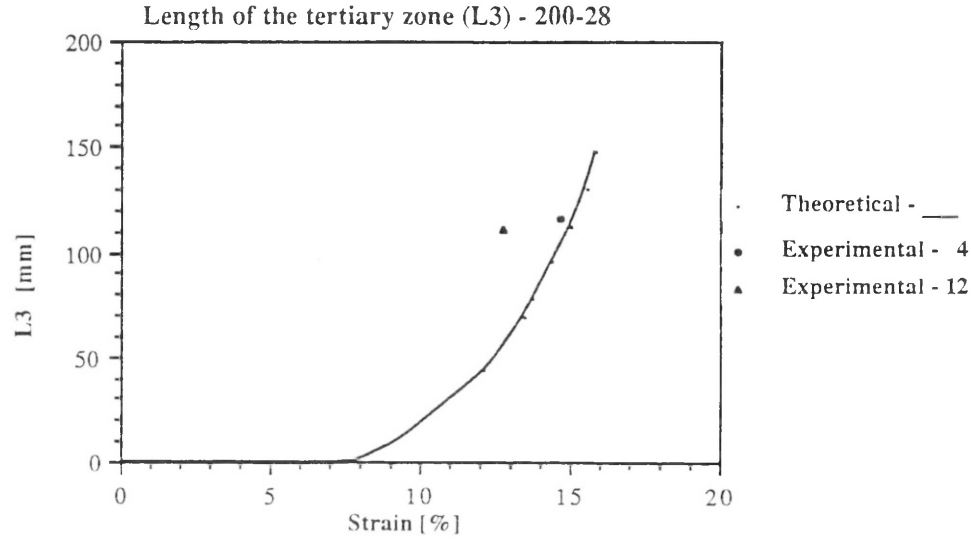
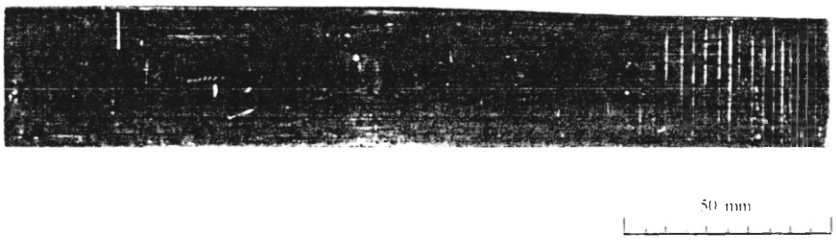


Fig.5.52.

Table.5.7

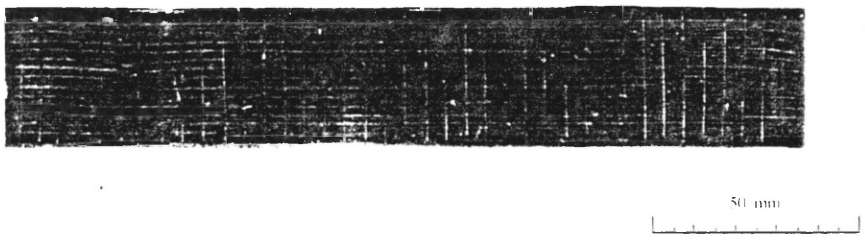
200 mm x 30 mm Specimen												Experimental data
Spec No.	L_i [mm]	W_i [mm]	Th_i [mm]	L_{ind} [mm]	Th_{ind} [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
2	200.0	29.79	19.82	207.10	18.90	193.61	18.90	33.05	30.65	60.0500	19.3000	96.00	6.51
3	199.8	29.68	19.81	206.91	18.90	188.61	18.90	33.07	33.00	131.3186	45.1125	181.00	8.94

Theoretical data										
L_i [mm]	W_i [mm]	Th_i [mm]	L_f [mm]	Th_f [mm]	W_f^{top} [mm]	W_f^{bot} [mm]	Ld_{max}^{top} [kN]	Ld_{max}^{bot} [kN]	L_3 [mm]	ε_{max} [%]
207.0	30.00	19.00	186.907	19.00	33.00	33.00	242.4766	102.7306	186.907	9.71



SPECIMEN No.2

Fig.5.53. Deformed Specimen No.2



SPECIMEN No.3

Fig.5.54. Deformed Specimen No.3

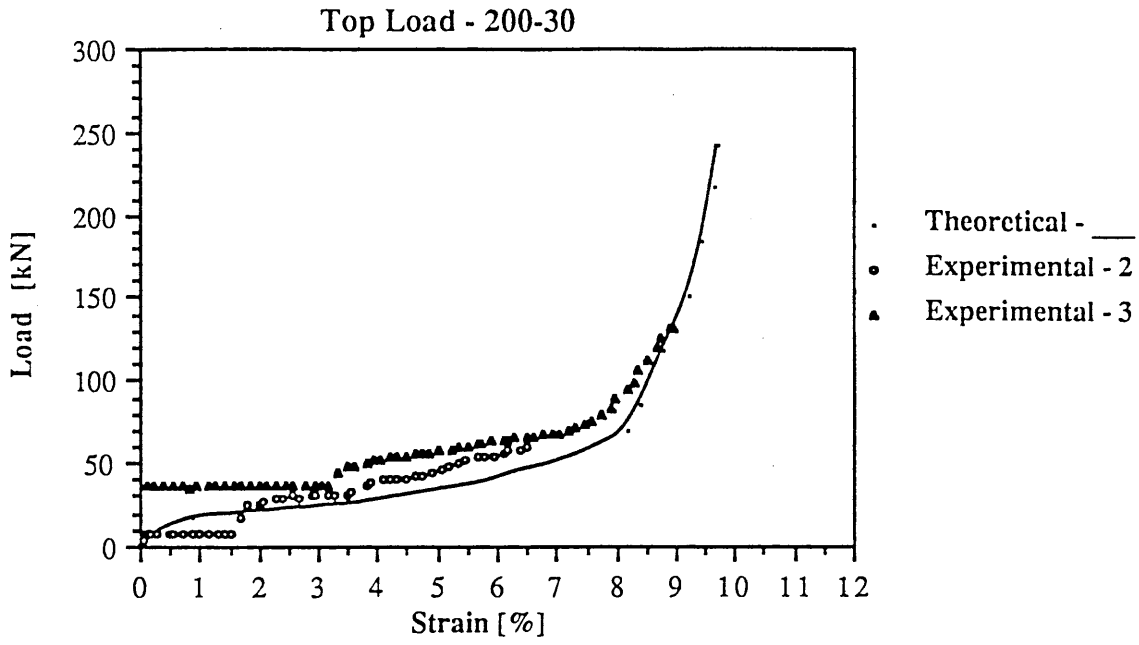


Fig.5.55.

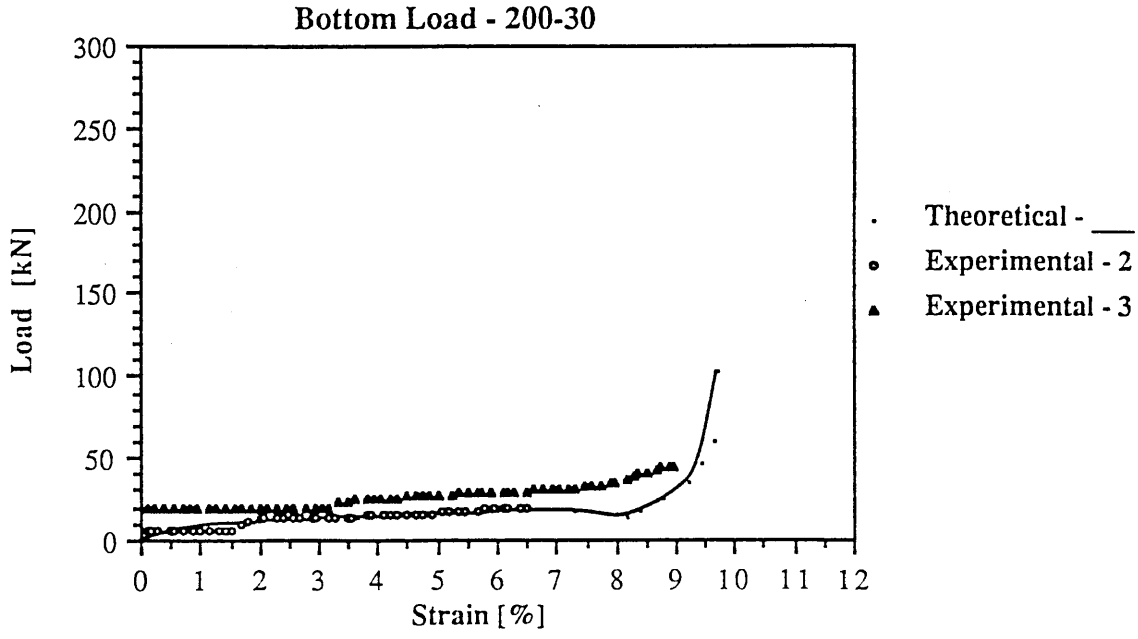


Fig.5.56

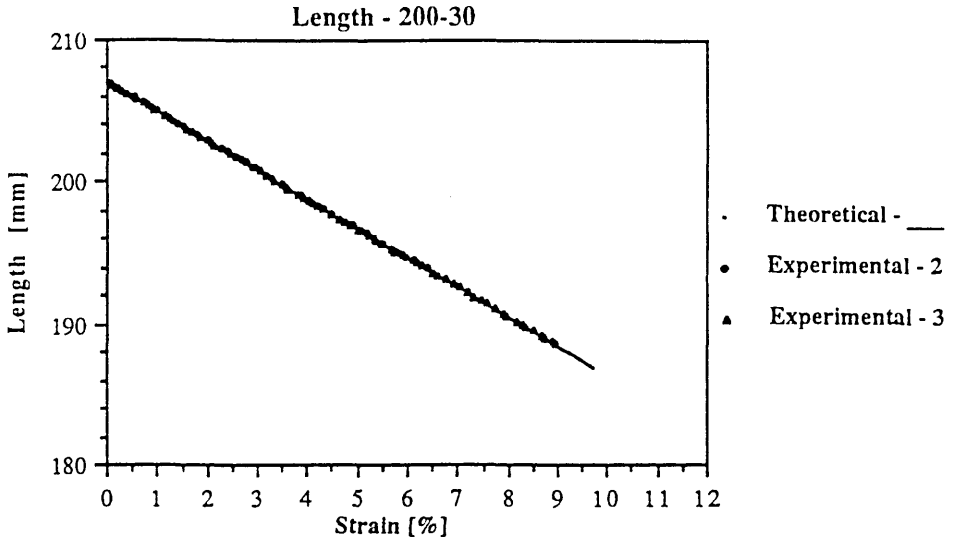


Fig.5.57.

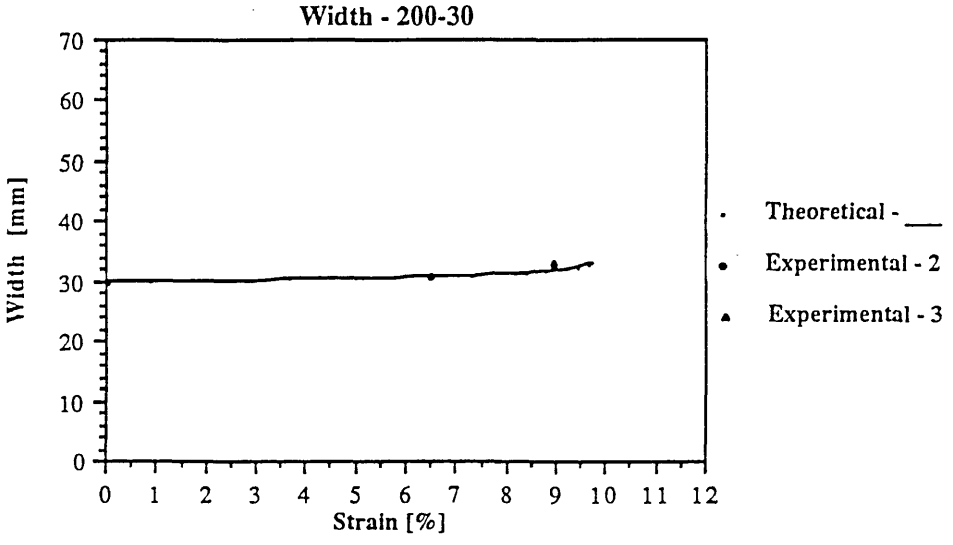


Fig.5.58.

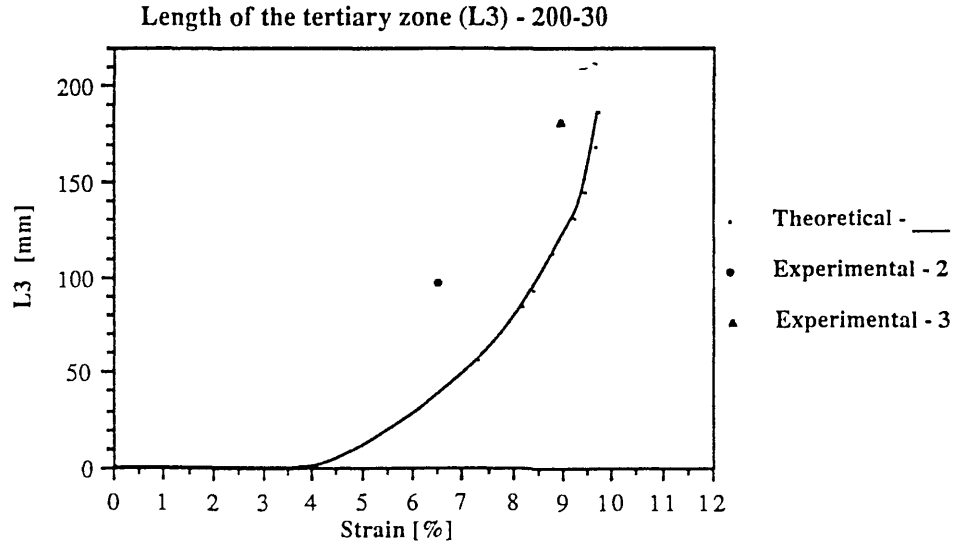


Fig.5.59.

CHAPTER 6

RESULTS AND DISCUSSION

6.1. INTRODUCTION

In this chapter, the application of the computer code presented in *Chapter 3* to industrial examples of Context, Linex and Conform is discussed.

The processes under consideration are of non-steady state type, i.e. the mode of deformation does not remain constant throughout the deformation process, so the problem has to be analysed as a transient one. For such problems the flow velocities are first established for the initial configuration and then these velocities, determined for the nodal points, allow the new position of the mesh to be determined at a subsequent time step Δt, by a suitable updating procedure. With the new boundary and the altered mesh, new flow conditions are established. As each new flow solution starts in an "Eulerian" manner from the present configuration, very large deformations can be readily followed by a simple process of repetition of the solution in updated conditions and, if necessary, updated boundary conditions.

Clearly, for accuracy, small time intervals need to be considered, but as all calculations are restarted at each new configuration the question of incrementing Eulerian type stresses, which often presents difficulty in elastic-plastic analysis, does not arise.

6.2. CASES CONSIDERED AND COMPUTATIONAL CONDITIONS

Case studies are presented in what follows, for the conditions indicated in Table 6.1, to examine the effect of various parameters on the available extrusion pressure for a billet 100 mm x 10 mm cross sectional area. The clamp width is 110 mm.

Two clamped billet lengths (initially loaded lengths) of 240 and 300 mm are assumed, with coefficient of friction 0.1 and 0.2 over the clamp/billet interface. The assumed mean yield stress of the material is constant at 96.5 MPa. This is a reasonable

Table 6.1

Case No.	No. of initially loaded elements	Initially loaded length of billet [mm]	Coefficient of friction μ	Initially applied frictional shear stress τ_{xy} [MPa]	Initial billet width [mm]	Thickness of billet [mm]	Runs (Context, Linex, Conform) No.
1.	250	300	0.1	9.5	100	10	Context-21,Linex-22,Conform-23
2.	200	240	0.1	9.5	100	10	Context-24,Linex-25,Conform-26
3.	250	300	0.1	8.5	100	10	Context-27,Linex-28,Conform-29
4.	250	300	0.1	9.5	95	10	Context-33,Linex-34,Conform-35
5.	250	300	0.2	9.5	100	10	Context-36,Linex-37,Conform-38

representation of high conductivity copper at 800°C [82].

In the model first a lateral pressure of 95 MPa is applied to the 100 mm wide face, in the x-y plane, marginally below the yield stress of the material which produces 9.5 MPa initial shear frictional stress, τ_{xy}, for $\mu = 0.1$.

As the billet end reaches the die face the material gradually fills up the full width of the clamp and interfacial pressure σ_x builds up between the 10 mm edge of billet and the clamp producing frictional shear stress τ_{fr}. This is followed by the gradual increase of interfacial pressures between the billet material and clamp, increasing the frictional shear stress in the x-y plane and on the edge of the billet.

Case No.1 was taken as a basis for comparison with the rest of the theoretically studied cases.

Stresses are presented in dimensionless form, while the obtainable extrusion ratios were calculated from the expression obtained by W. Johnson [39] for axisymmetric extrusion,

$$\sigma_{axial} = \sigma_y (a + b \ln R) \qquad (6.1)$$

where:

σ_{axial} - axial stress on the die face

σ_y - yield stress of the material

$R = A_i/A_f$ - extrusion ratio

A_i - Initial cross-sectional area of the billet

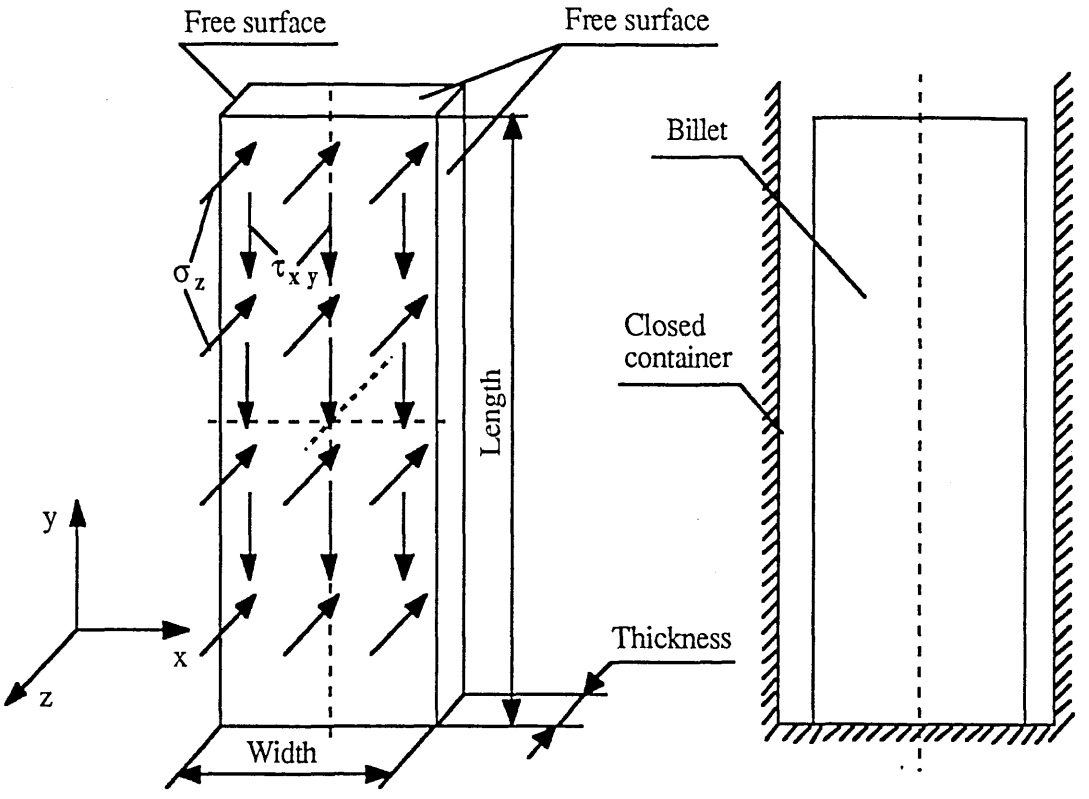
A_f - Final cross-sectional area of the billet

$a = 0.8$ - constant

$b = 1.5$ - constant

Although Equation 6.1 is for axisymmetric extrusion of round billets into round rods, it gives an indication of the feasible extrusion ratios.

As in *Chapter 5*, the initial conditions are those after the lateral indentation of the billet (Fig.6.1.). The indentation itself was fully studied by A.N.Sani [78].



a. Initial conditions b. sketch of the process

Fig.6.1.Initial conditions

Non-workhardening material was considered with yield stress σ_y = **96.5 MPa.** Because of symmetry only one quarter of the billet needs to be modelled. The continuum is divided into 250 bi-linear quadrilateral elements with 286 nodes, as shown in Fig.6.2, and the boundary conditions are shown in Fig.6.3.

A penalty coefficient α equal to 10^8 and a cut-off factor γ of 10^9 were chosen, where the cut-off factor is equal to:

$$\gamma = \frac{2}{3}\frac{\bar{\sigma}}{\dot{\bar{\varepsilon}}} \qquad (6.\ 2)$$

where:

$\bar{\sigma}$ – effective stress

$\dot{\bar{\varepsilon}}$ – effective strain rate

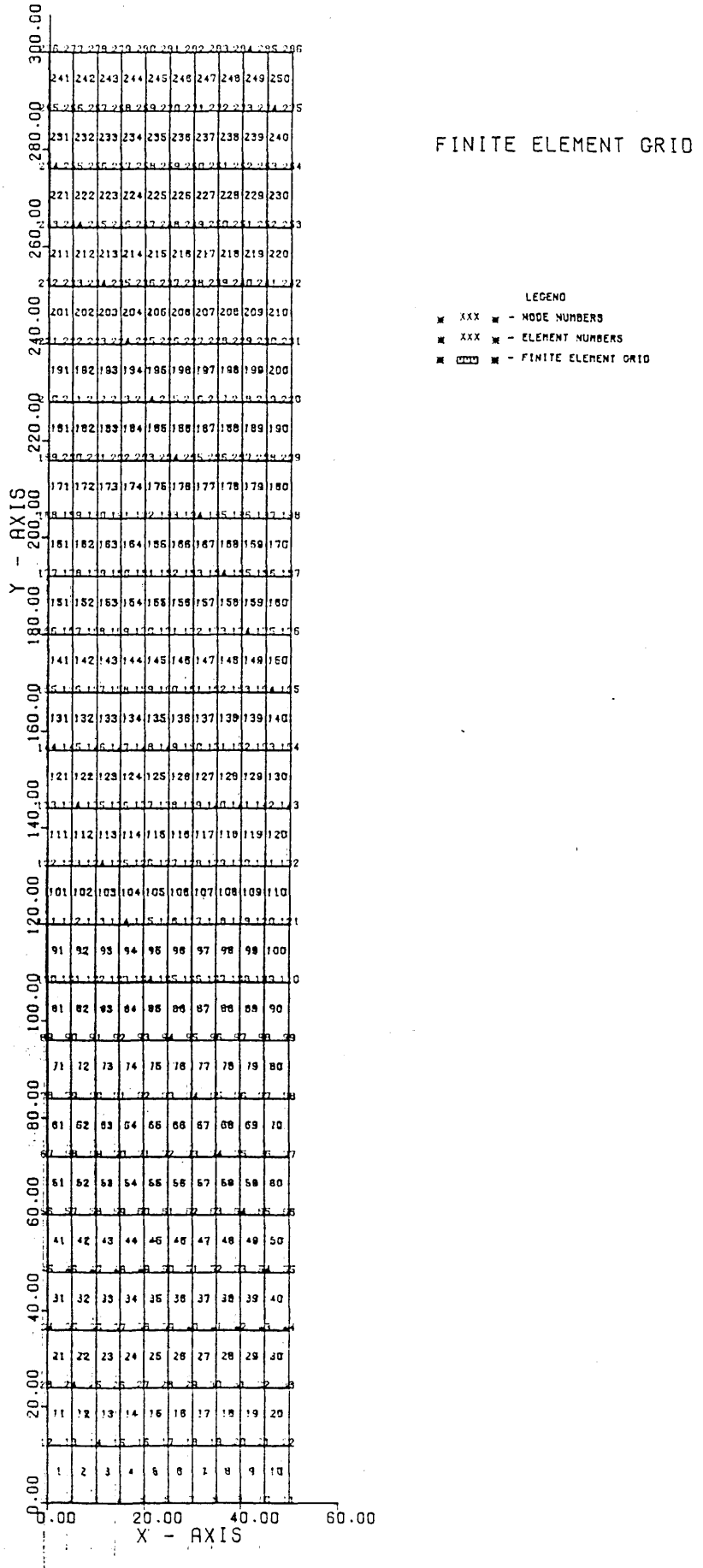


Fig.6.2.Undeformed mesh

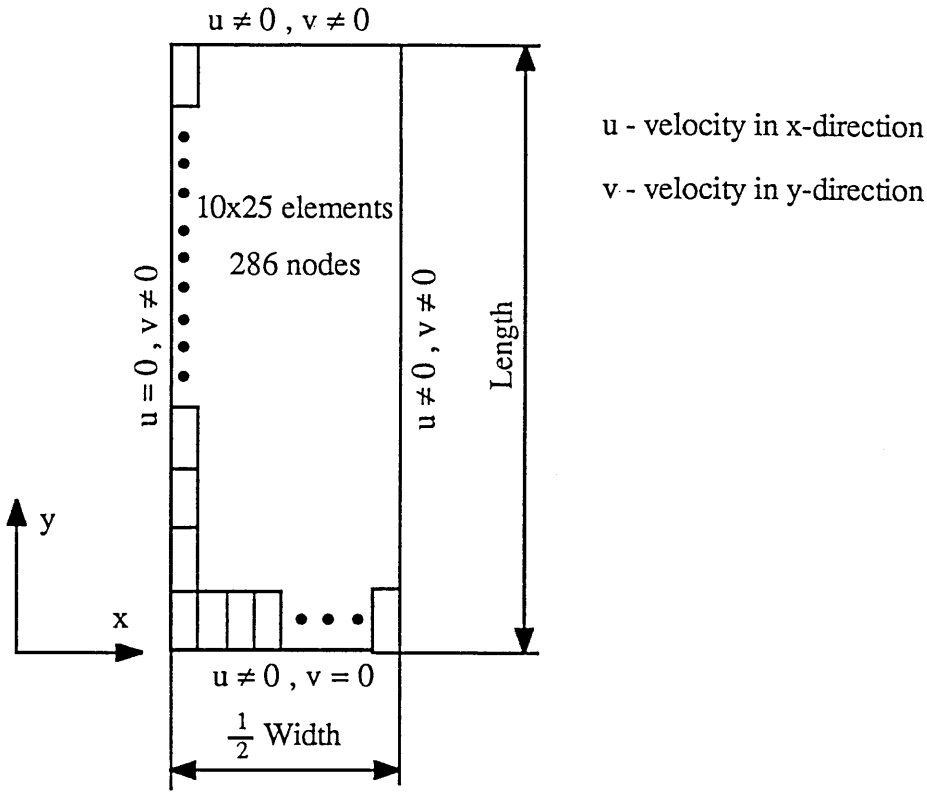


Fig.6.3.Boundary conditions

Time step of 0.02 min was selected as a starting size of an increment. The solution with convergence norm $||\Delta \mathbf{u}||/||\mathbf{u}||$ less than 0.001 was considered acceptable for each step. The average number of iterations for each step was two. The calculations were continued until staedy-state was reached. As indication of a steady state, a difference in effective strain of less than 1% was taken. This state was achieved for thirty or less steps for different cases under different conditions, but for consistency and to make comparison between different runs easier, calculations for all cases were carried out for thirty steps.

6.3. DISCUSSION

In Fig.6.4 to Fig.6.29 the distribution of axial stresses $\sigma_{\mathbf{axial}}$ (stresses in the y-direction), frictional stresses in the x-y plane, τ_{xy}, where indenting load was applied, stresses in the x-direction σ_x and frictional stresses τ_{fr} on the edge of the specimen due to σ_x after some of the nodes have reached the container wall, as well as rise of the above mentioned stresses with the progressing deformation are presented. Comparative graphs of Context-21, Linex-22 and Conform-23 are shown in Fig.6.15 to Fig.6.19. No further graphs about Linex and Conform for the rest of the conditions considered were made because those presented and the rest of the calculations prove that, under same conditions, lowest extrusion ratios can be obtained in Linex and Context is capable of achieving highest

extrusion ratios. Further, concentration was made on comparing results for Context for the five earlier described variations in the process parameters and in Fig.6.20 to Fig.6.62 comparative graphs for these cases are shown. In Fig.6.63 to Fig.6.82 isostrain contours for steps 1 and 30 for Context-21, Linex-22 and Conform-23 and for step 30 for Context-24, Context-27, Context-33 and Context-36 are given as well as isostress contours, again for the same steps and for the same cases, of out-of-plane stress σ_z are shown. Finally, plots of deformed mesh and associated flow patterns for time steps 1, 9 and 30 for Context-21, Linex-22, Conform-23, Context-27, Context-33 and Context-36 are given in Fig.6.83 to Fig.6.103.

In order to make comparisons more general, quantities presented in the above mentioned graphs are made dimensionless. Also, as a rigid plastic model of the material was adopted and because of the high values of the normal stresses obtained,those values of the stresses, which were below the yield point of the material, i.e. the elastic stresses,were neglected.

6.3.1. COMPARISON BETWEEN THE THREE PROCESSES

The main difference in the mechanics of Context, Linex and Conform is in the direction in which the frictional shear stress τ_{fr} acts at the interface between the billet edges and the feed channel. In Context it supplements the frictional shear stress τ_{xy} acting between the **x-y** interface of the billet and channel, in Linex it opposes the billet movement towards the die, while in Conform it acts in opposite directions on the two edges, so its effect is nil.

The industrial process begins by introducing an initial lateral indentation on the billet by the application of stress σ_z slightly bellow the yield stress of the billet σ_y, Fig.6.1-a.

The feed channel is then moved forward with the billet pushed against the die so that the axial pressure σ_{axial} is applied to the end face of the billet. The points of intersection of the bottom curves with the vertical axis in Fig.6.4 to Fig.6.6 represent this axial pressure which initially produces a frictional shear stress τ_{xy} slightly less than 0.1 σ_y if Colomb friction is assumed with a coefficient of friction μ of 0.1. This is shown by the bottom lines in Fig.6.7 to Fig.6.9.

If σ_{axial} produces an axial compressive strain of 1.42 % as shown by the bottom curves, the material begins to deform plastically at the die face. It can flow only in the **x** direction to fill the feed channel, so that a normal stress in **x** direction σ_x develops,

Fig.6.10 to Fig.6.12. Once part of the material fills up completely the channel at compressive strain 6.43 %, the tertiary zone begins to develop, now σ_x being interfacial normal pressure between the billet and the container. As deformation spreads to reach this figure, the tertiary zone extends towards the billet end. For strain of 6.43 % and bigger the end of the zone is indicated by the intersection of the curves with the horizontal axes in Fig.6.13 and Fig.6.14.

The normal stress σ_x produces interfacial shear stress τ_{fr} between the edges of the billet and the feed channel, Fig.6.13 and Fig.6.14. The distribution of this stress is not shown for Conform because it has no effect on the further development of the process. It supplements τ_{xy} in Context and acts against it in Linex.

In practice the billet is further deformed as a result of forcing it with the feed channel against the die, by utilising the friction between billet and channel. This is simulated in the program by applying the increased forward driving interfacial frictional shear stress τ_{xy} on the billet material (its higher value due to the increased normal stress σ_z) in the computations; the results are shown in the illustrations, with the obtained strain increments on the extreme right in every case. With each step the tertiary zone extends further towards the billet end and all stresses increase correspondingly, Fig.6.4 to Fig.6.14. It is interesting to note that almost the largest stresses are reached along the full billet length at a little over 8% strain after the application of 16 time increments. The remaining nine increments in these particular cases have little effect on the stress levels, but the computations, as mentioned earlier, were carried out up to the 30 time steps for consistency. The physical explanation is that, under the given conditions, friction can not be raised further to allow an increase in the level of maximum stress lines; the feed channel slips over the billet surface and the process stops. The maximum extrusion pressures that can be obtained under the given conditions are indicated by the intersection of the top curves with the vertical axes, in Fig.6.4 to Fig.6.6 for the three processes.

The combined effects outlined in the foregoing produce the largest extrusion pressure in Context, at about ten-times the yield stress of the material, and the smallest in Linex at about eight-times the yield stress, as indicated by the intersection of the top curves with the vertical axes in Fig.6.4 and Fig.6.5. The intermediate value is in Conform, at about nine-times the yield stress of the material, Fig.6.6. This is further illustrated in Fig.6.15. The curves become practically parallel to the horizontal axis at just over 8 % strain, indicating that the limiting pressure is just about to be reached.

The extrusion ratios computed from the simple empirical equation (6.1) for the maximum feasible extrusion pressures are unlikely to be the precise ones for the present

billet shape of much greater width than thickness, but they still indicate the large differences actually obtainable by the three methods, Fig.6.16.

Due to the logarithmic relationship between extrusion pressure and extrusion ratio, a relatively modest change in the former produces vast difference in the latter, indicating the increased efficiency of Conform relative to Linex and of Context relative to both.

The resultant axial stress distribution along the billet length is shown in Fig.6.4 to Fig.6.6. Initially the values of the axial stress and its rise with the progressing deformation is the same for all three processes because the tertiary zone is not yet developed and frictional stress on the edges of the billet is not present. Once the tertiary zone is established at about 6% reduction in height a slight difference can be seen in the three graphs for 6.43% deformation. Initially the difference is small because the stresses are not large enough and the length of the tertiary zone is small compared to the total billet length, but with further development of the tertiary region this difference becomes more pronounced, the rate of increase of the axial stresses in Context is greater than in the other two processes, leading to a 10.2% difference in axial stresses on the die face between Context and Conform and 20.9% difference between Context and Linex. The difference in axial stresses on the die face between Conform and Linex is 9.7%. This can be more clearly seen in the comparative graph in Fig.6.7, showing the rise of the axial stress on the die face with progressing deformation.

From the graphs shown in Fig.6.7 to Fig.6.9 it is evident that the rise of the frictional shear stress on the flat sides of the billet (the main frictional drag) up to its limit **k**, where:

$$\mathbf{k} = \frac{\sigma_y}{\sqrt{3}} \qquad \text{(for Von Mises yield criterion)} \qquad (6.3)$$

is quicker in Context, slower in Conform and slowest in Linex.The same is the situation with the stress σ_x for the three processes (Fig.6.10 to Fig.6.12). Due to this stress is the frictional stress on the edges of the billet shown in Fig.6.13 and Fig.6.14. There is not a great difference in the rise and distribution of these stresses, not forgetting of course the opposite signs (see also Fig.6.19 showing the rise of frictional stress on the edges of the specimen at the die face for Linex and Context with progressing deformation), but because of the greater forward driving force in Context the frictional stress has reached its limit, **k**, on a greater length. In Fig.6.13 and Fig.6.14 the curves for 1.42% and 4.29% strains coincide with the horizontal axis. This is because the tertiary zone does not develop until about 6% deformation.

The intersection of the curves with the horizontal axis in Fig.6.13 and Fig.6.14 shows the actual length of the tertiary zone and its development with the deformation process.

From graphs in Fig.6.15 to Fig.6.19 it can be seen again that there is no difference in development and values of the stresses when the tertiary zone is not present.

Difference between the above mentioned stresses obtained by Context, Linex and Conform, after the tertiary region has developed, is going to be much more pronounced if a thicker billet is considered, i.e. when the billet width/billet thickness ratio is smaller. The reason for this is that the frictional shear stress τ_{fr} on the billet edges will act on a greater area and hence a greater force will compliment main frictional drag τ_{xy} in Context and a greater force will act against it in Linex accordingly. However, in order to keep the deformation under plane strain conditions the present billet size was chosen.

From the presented graphs the advantages of Context in terms of the obtainable extrusion ratios over Conform and Linex are clear. For this reason and because the rest of the data show the same trend, no further graphs for Conform and Linex are presented and emphasis is placed on comparing different cases of Context.

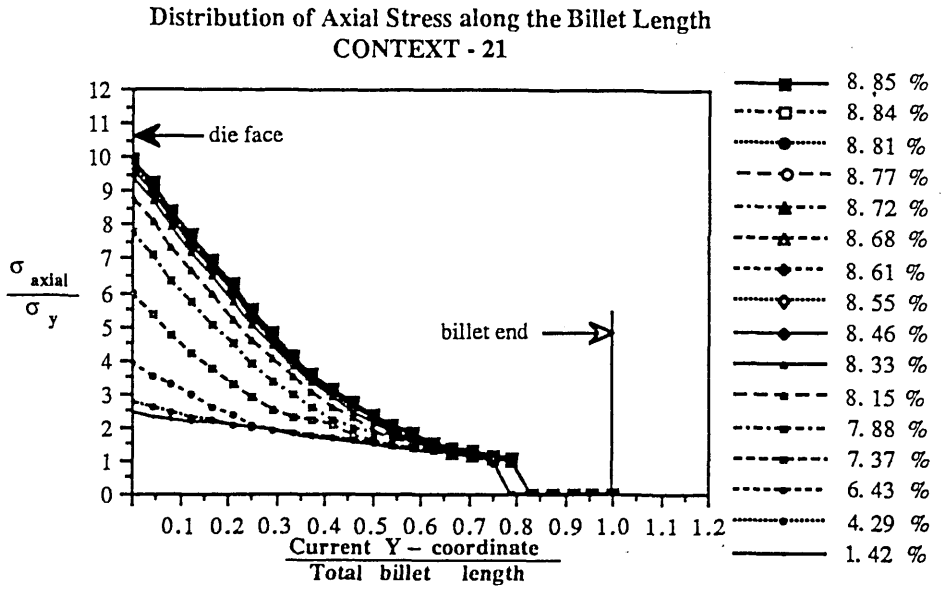


Fig.6.4.

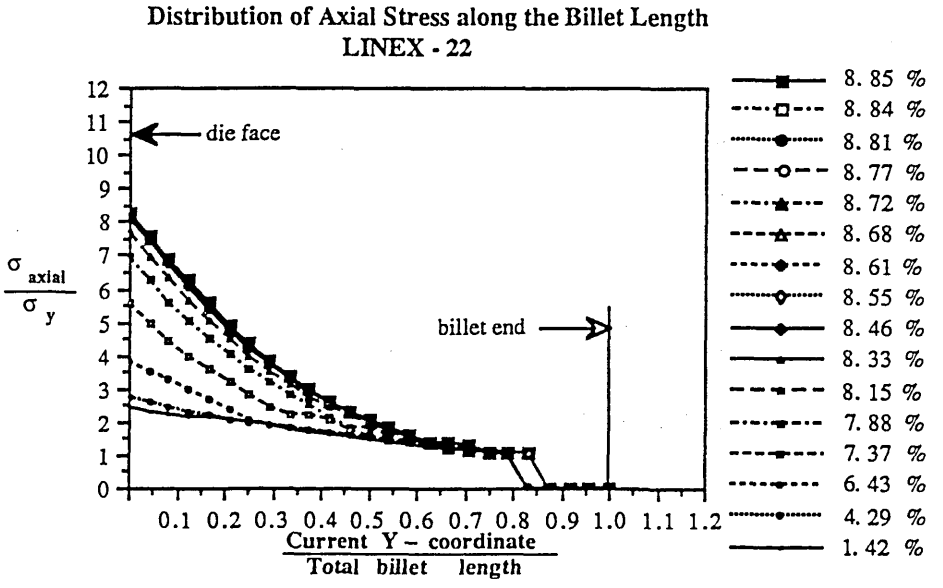


Fig.6.5.

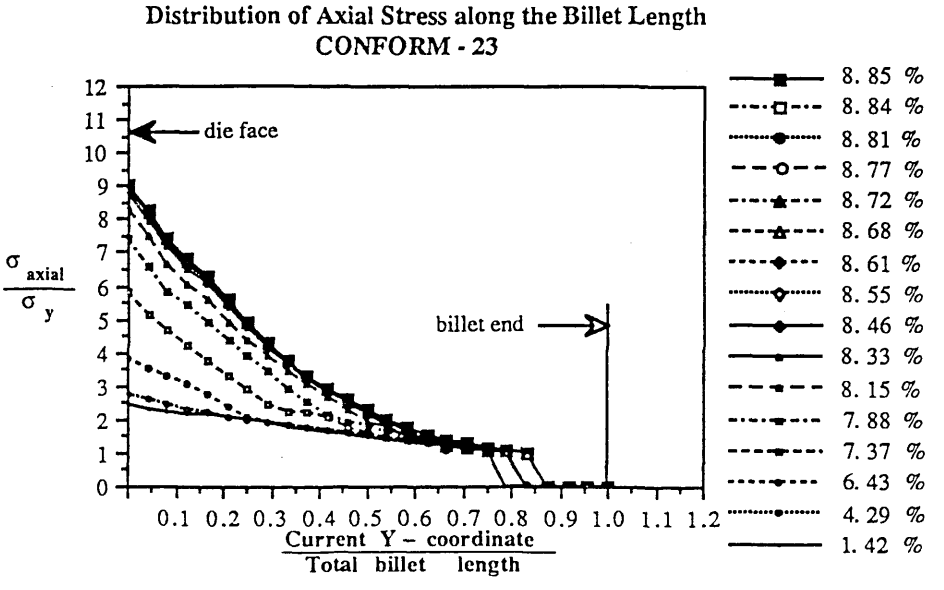


Fig.6.6.

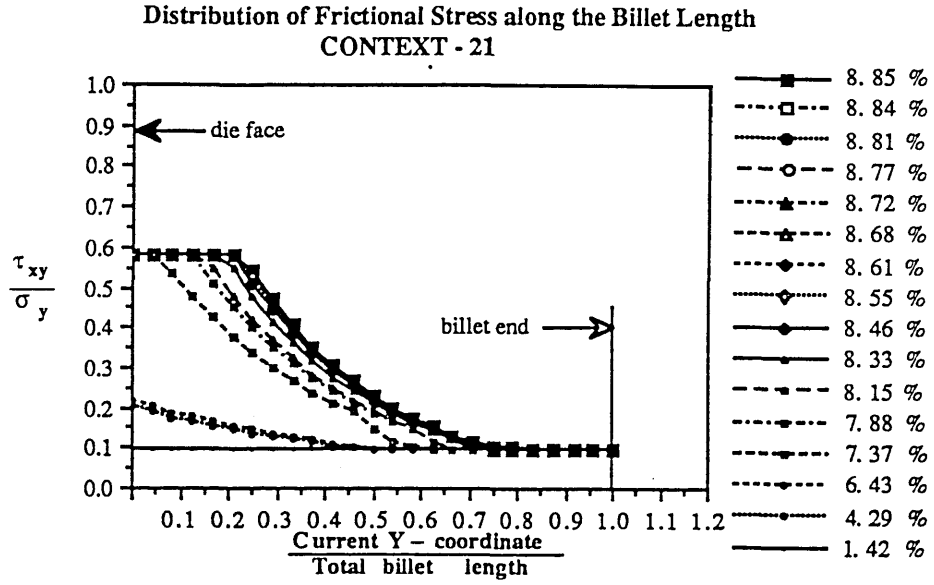


Fig.6.7.

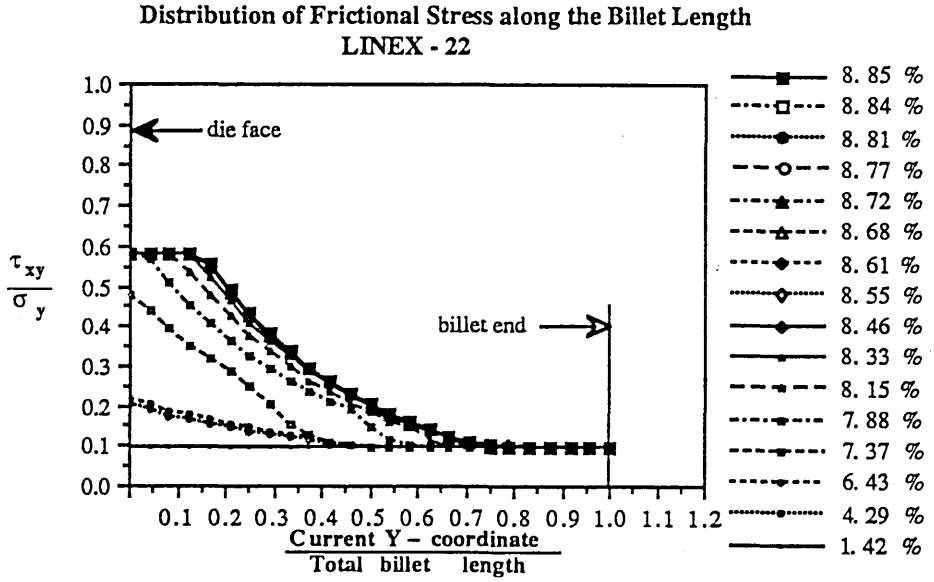


Fig.6.8.

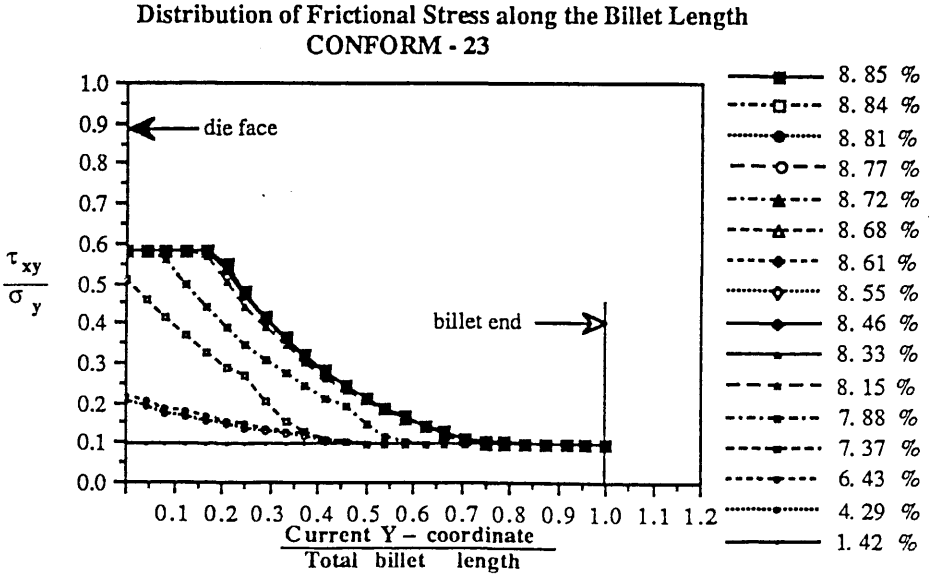


Fig.6.9.

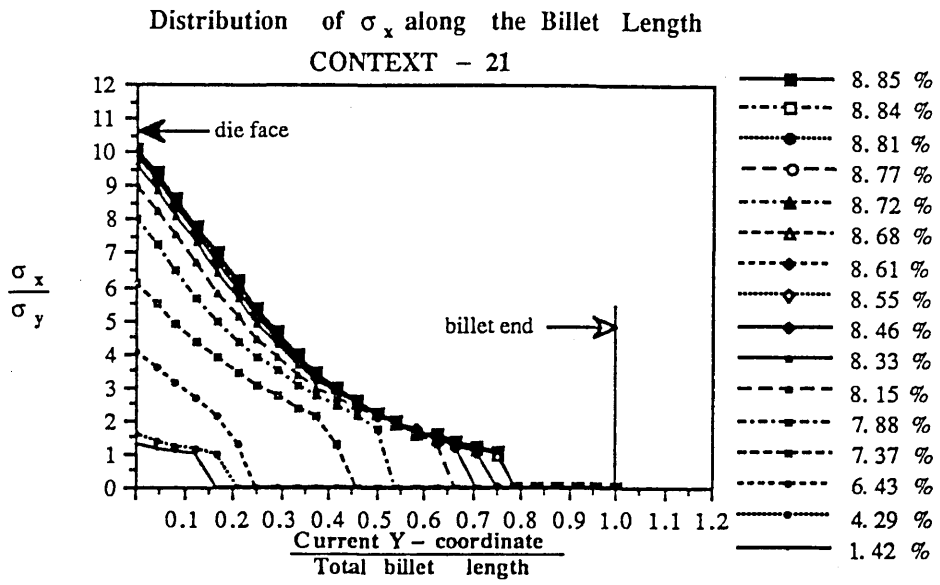


Fig.6.10.

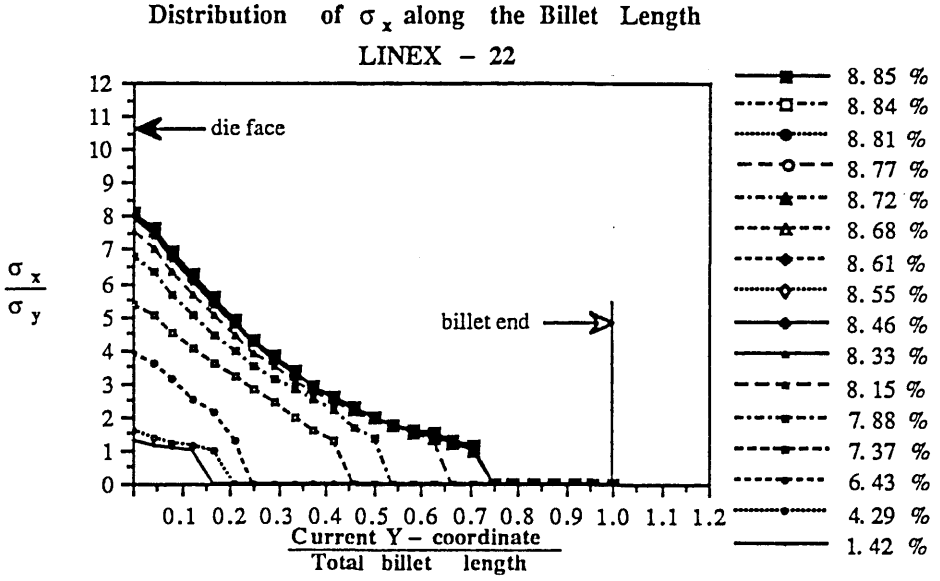


Fig.6.11.

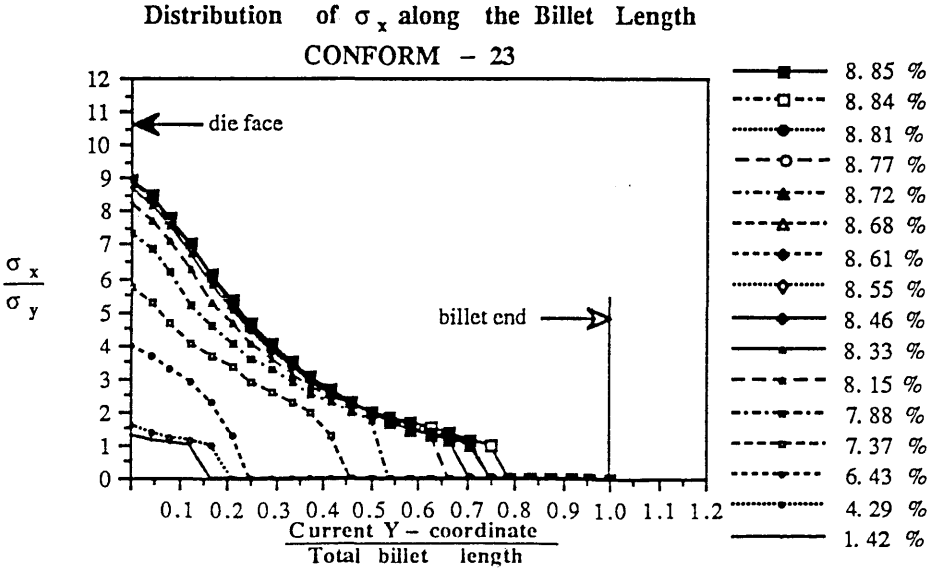


Fig.6.12.

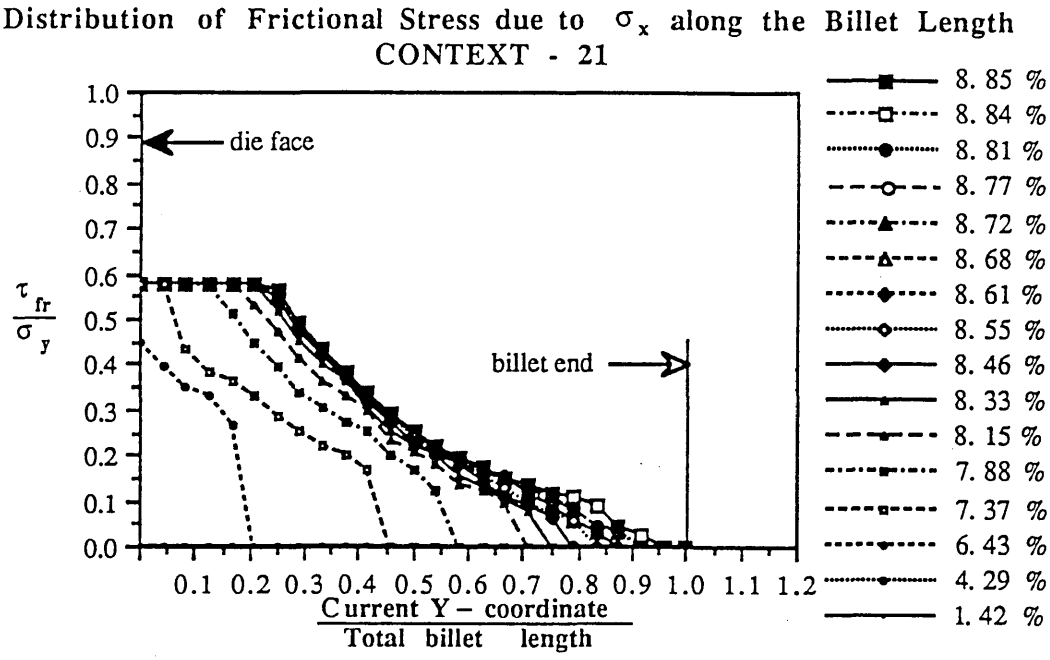


Fig.6.13.

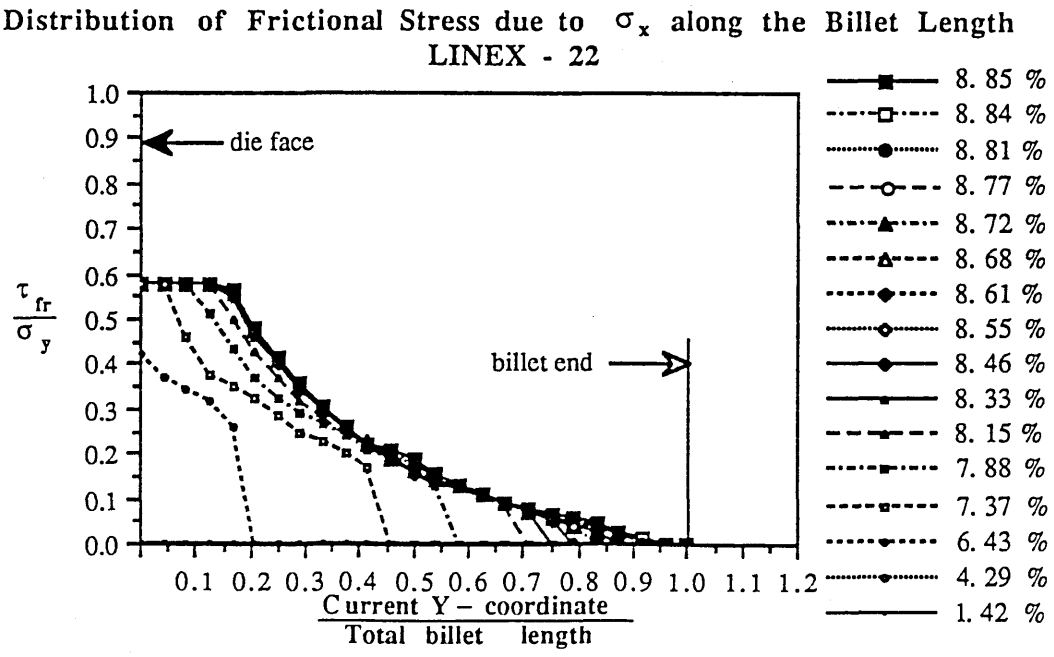


Fig.6.14.

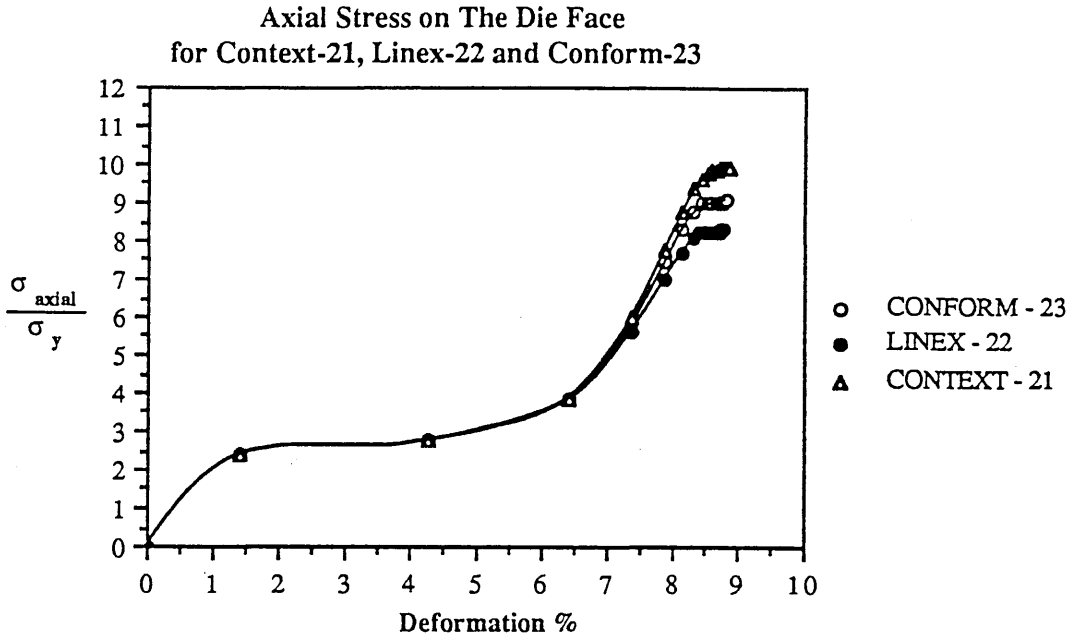


Fig.6.15.

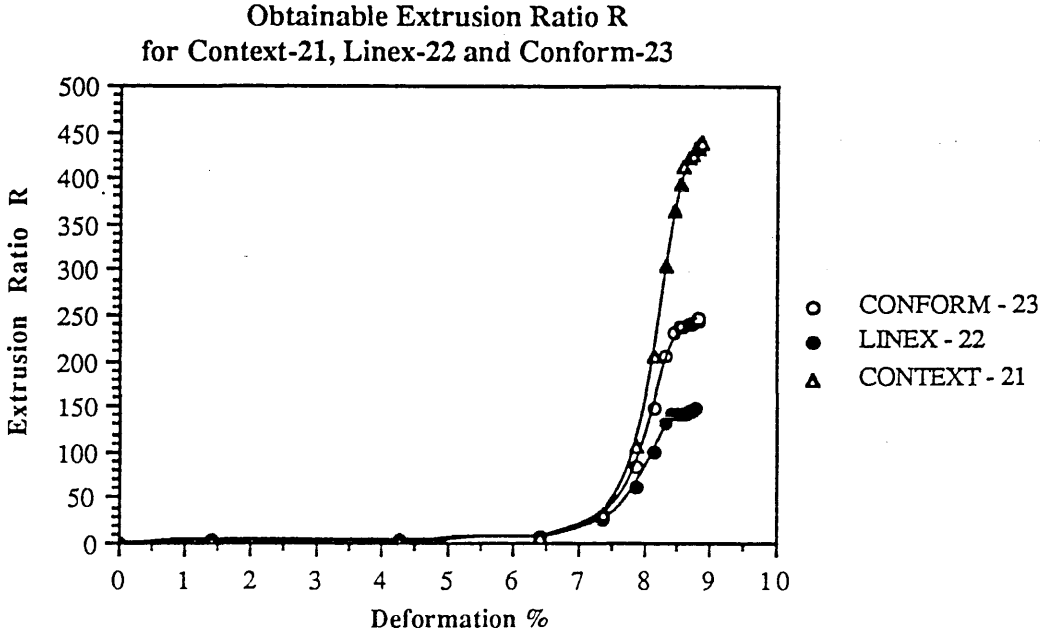


Fig.6.16.

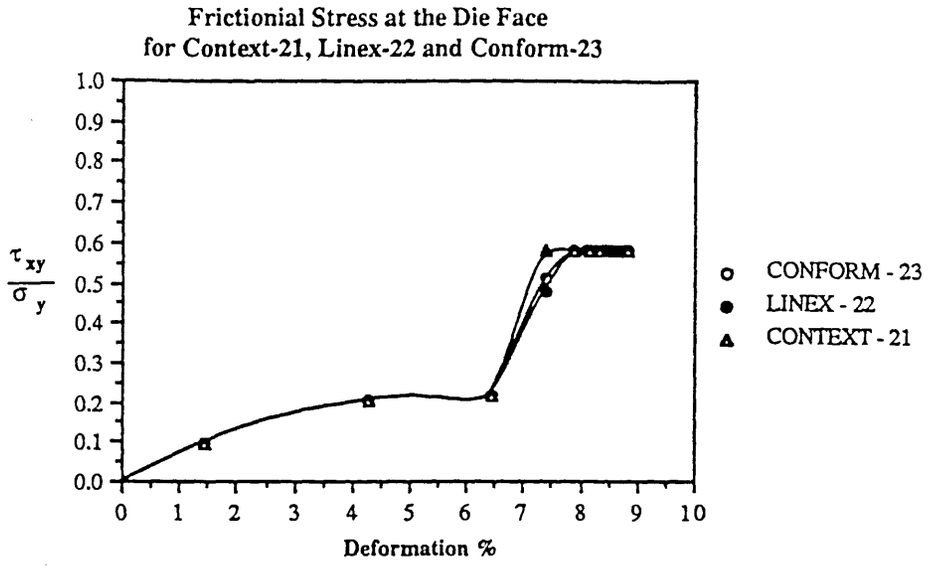


Fig.6.17.

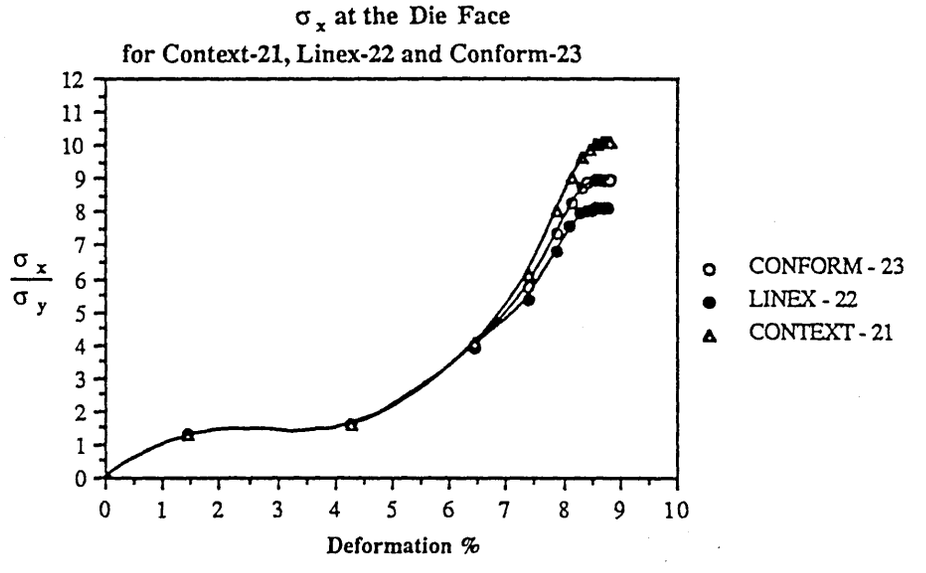


Fig.6.18.

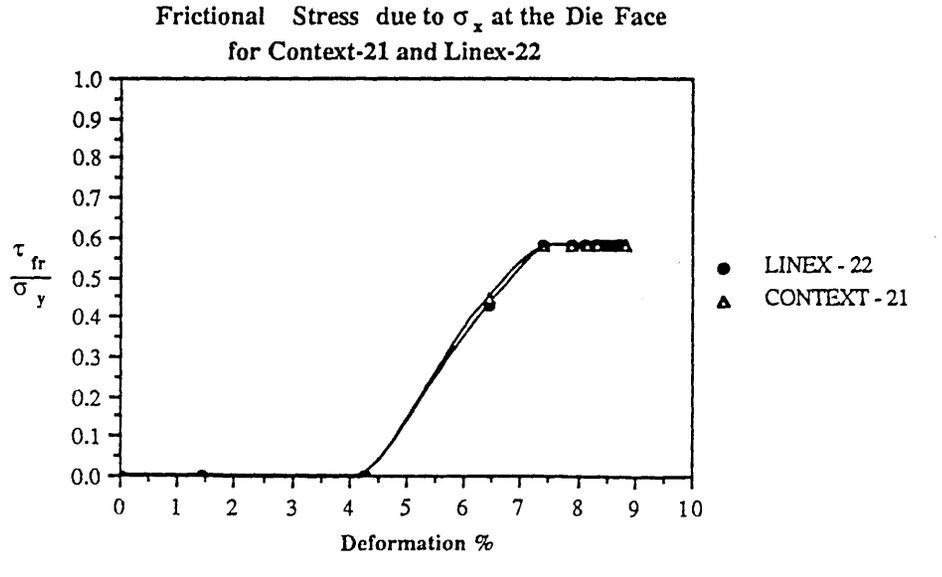


Fig.6.19.

6.3.2. DESIGNING FOR CONTEXT

It is clear from the foregoing that Context is more efficient than either Conform or Linex: it produces significantly larger extrusion ratios for otherwise identical conditions.

Now the effect of the various parameters on process and equipment design will be examined. Although Context will be taken as an example, similar conditions apply to designing for Conform and Linex also.

Comparing the basic Case No.1 - Context-21 with Case No.2 - Context-24, the latter having smaller initially loaded length, Table 6.1, page 124, it can be seen from the graphs presented in Fig.6.4, Fig.6.7, Fig6.20 and Fig.6.21 that, firstly the rise of the axial stress in Context-24 is much slower than in Context-21 and secondly the final value of the obtained axial stress in Context-24 is 43.1% smaller than in Context-21 for 20% difference in initially loaded length. The graph given in Fig.6.56 shows that for Case No.2 - Context-24 lowest axial stress on the die face is available.

If the initially applied dragging frictional stress is reduced by 10.5% in comparison with the basic Case No.1 - Context-21, as in Case No.3 - Context-27, this results in a reduction of the maximum achievable axial stress on the die face by 5.5% (Fig.6.4, Fig.6.7, Fig.6.29 and Fig.6.30). This means that although the initial dragging frictional stress plays its role in obtaining higher extrusion ratios by producing higher axial stress on the die face its importance is not as great as both the geometry of the billet and the container. The reason for this, is that, with the development of the tertiary zone, the growth of the normal stress and the frictional drag can "pick up" speed and compensate for the initially smaller amount of the frictional dragging force. Fig.6.56 gives another indication that there is little difference between the two cases in the manner of rise of the axial stress on the die face.

In Case No.4 - Context-33 the billet width/container width ratio was reduced by 5.5% from 0.91 to 0.86 in comparison with Context-21. This resulted in a reduction of the maximum axial stress on the die face by 7% (Fig.6.4, Fig.6.7, Fig.6.38 and Fig.6.39). On the other hand, the difference in the rise in the axial stress with progressing deformation (Fig.6.56) is more pronounced at the beginning of the process, when the tertiary region is either not developed, or is short in length. This difference diminishes as the tertiary region develops.

Comparison between the obtained axial stresses for different frictional conditions (Case No.5 - Context-36 with $\mu = \mathbf{0.2}$ and Case No.1 - Context-21 with $\mu = \mathbf{0.1}$) shows considerable rise of 48.5 % of the maximum axial stress on the die face with the

higher coefficient of friction. This should be expected as all continuous extrusion processes rely on the frictional drag for extrusion to take place. Therefore, the coefficient of friction is very important parameter in continuous extrusion process. It should be noticed that change of the coefficient of friction changes the pattern of the rise of the axial stress with progressing deformation (Fig.6.47, Fig.6.48 and Fig.6.56). The same is true for the rise of the rest of the compared stresses, i.e frictional stress τ_{xy} (stress in x-y plane), σ_x (stress in x-direction) and frictional stress τ_{fr} on the billet edges and also for extrusion ratios.

Comparing the rise of the length of the tertiary zone, L_3, with the deformation process (Fig.6.62) it can be seen that it develops quicker for Case No.5 - Context-36 which has the higher coefficient of friction. This is not surprising as in Context-36 largest frictional drag is achieved in comparison with the rest of the cases. It should be pointed out that although the length of the tertiary zone for Context-36 is shorter than for Context-21 and Context-27, in the former highest axial stress was obtained due to the quicker rise of the stresses because of the higher frictional dragging stress.

It is interesting to notice the development of the tertiary region for Context-24 and Context-33. It follows similar pattern for both cases, different from the rest of considered cases. In Context-33 larger volume of the container has to be filled because of the smaller billet width/container width ratio. For this reason at the beginning of the deformation process the tertiary zone in Context-33 develops slower than in Context-24. After a certain deformation, when in Context-33 the area on which the main frictional drag acts is sufficiently big and because of the larger loaded length of the billet, the tertiary region begins to develop quicker than in Context-24. As it is expected, Context-24 has the shortest tertiary zone developed as it has the smallest achievable axial stress on the die face.

From the graph in Fig.6.58, which shows obtainable extrusion ratios for all cases of Context, it is clear that Context-36 has the highest achievable extrusion ratio, and its rise with the deformation process differs from the pattern of the rest of the cases. The graph presented in Fig.6.59 was designed in order to make comparison between cases 1, 2, 3 and 4 possible, as they all look as one line in Fig.6.58. From this graph it can be seen that there is 10% difference in obtainable extrusion ratio for Context-33 and Context-27 despite the fact that the difference in maximum axial stress on the die face for these two cases is only 1.5%. This once again emphasises the fact that a small rise in the axial stress on the die face gives substantially greater difference in obtainable extrusion ratios.

In Fig.6.63 to Fig.6.72 isostrain contours of the effective strain for time steps 1 and 30 for Context-21, Linex-22 and Conform-23 are shown as well as isostrain contours of the effective strain for time step 30 for Context-24, Context-27, Context-33 and

Context-36. For all presented cases maximum effective strain is at the bottom central part of the billet. The dead metal zone is not present at the bottom corners of the billet because a closed container is considered, though the strains there are smaller than those in the bottom central part

In Case No.2 - Context-24 no strains are observed in the top unclamped part of the billet, where no plastic deformation is taking place and this region is moving as a whole rigid zone.

Largest deformations are observed in Case No.4 - Context-33, where bigger volume of the container has to be filled in order to develop the tertiary region.

Further in Fig.6.73 to Fig.6.82 isostress contours for the out-of-plane stress σ_z are presented for all cases and steps mentioned above. As with the rest of the stresses, highest out-of-plane stress is observed in Case No.5 - Context-36 and lowest is in Case No.2 - Context-24. Again, in the unclamped part of the billet in Case No.2 - Context-24 very low values of the stress can be found, far below the yield point of the material. Presented stresses have to be taken into account when designing the clamping/driving platens of the container, in order to ensure enough counter-force to oppose those stresses and not to let the container get split, flash formed and the process of continuous extrusion interrupted.

Finally, plots of deformed mesh and flow patterns for time steps 1, 9 and 30 for all cases of Context and for Linex-22 and Conform-23 are given in Fig.6.83 to Fig.6.103. From these it can be seen that once the tertiary region is developed the velocities of the nodes become almost zero and the deformation continues only in the transitional region. The velocities slightly differ from zero, because, as stated in *Chapter 3,* in the model a slight compressibility is present, as the large number can not be assigned to the penalty parameter α in order to avoid locking the mesh. For this reason the Poisson's ratio instead of being 0.5 is in fact 0.49978.

In brief the following observations about different conditions in Context can be made:

The axial stress on the die face is much higher for larger coefficient of friction, Fig.6.56. The pattern in the build-up of all stresses is also different (Fig.6.47 and Fig.6.48), which confirms, as would be expected, the overwhelming significance of this parameter.

The obtainable extrusion ratios under the various assumed conditions are shown in Fig.6.58 and Fig. 6.59. While equation 6.1 can not be expected to give the precise values for the presented cases, the vastly increased value for Context-36 underlines, in an even more pronounced manner, the importance of the coefficient of friction.

The development of the tertiary zone is illustrated in Fig.6.62, while Fig.6.63 to Fig.6.72 give the effective strains. The maximum values are at the bottom central part as would be expected. A further confirmation of the finite element predictions is the relatively large strains shown in Fig.6.71, where the initial billet width had the smallest value, so large strains are necessary to fill the full channel width.

In Fig.6.73 to Fig.6.82 isostress contours for σ_z are shown, which are particularly important for the design of the feed channel for a production machine. The largest stresses on the channel walls occur in Context-36, Fig.6.82, brought about by the large coefficient of friction, while the smallest are in Context-24, Fig.6.79, due to the shorter clamped billet length.

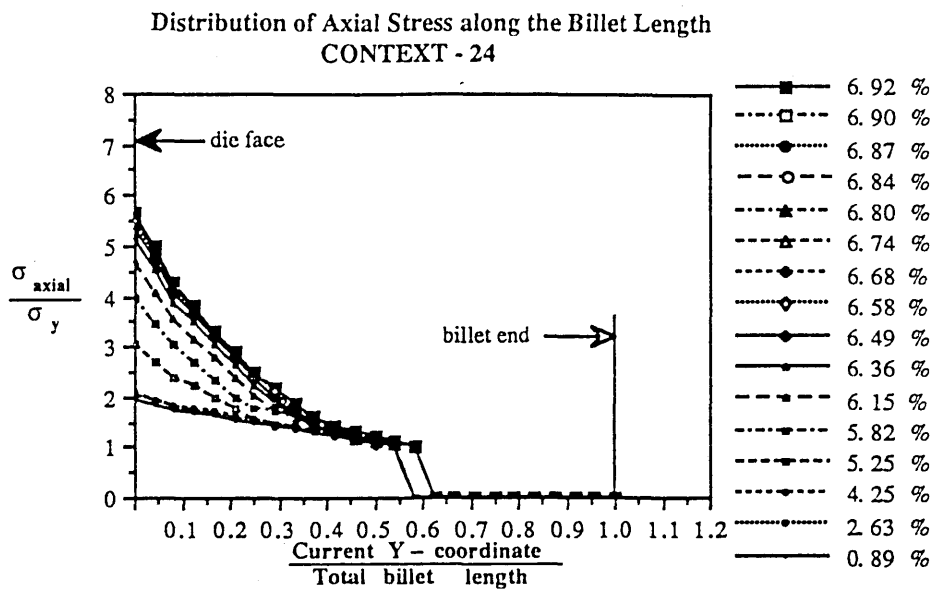


Fig.6.20.

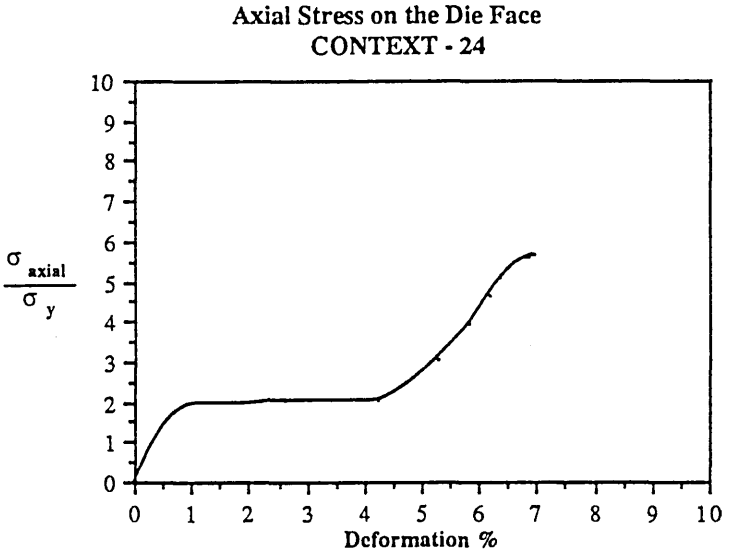


Fig.6.21.

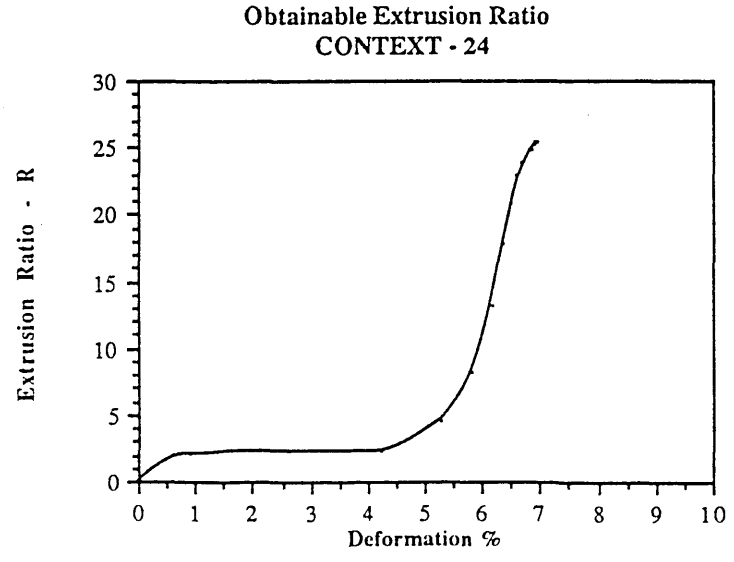


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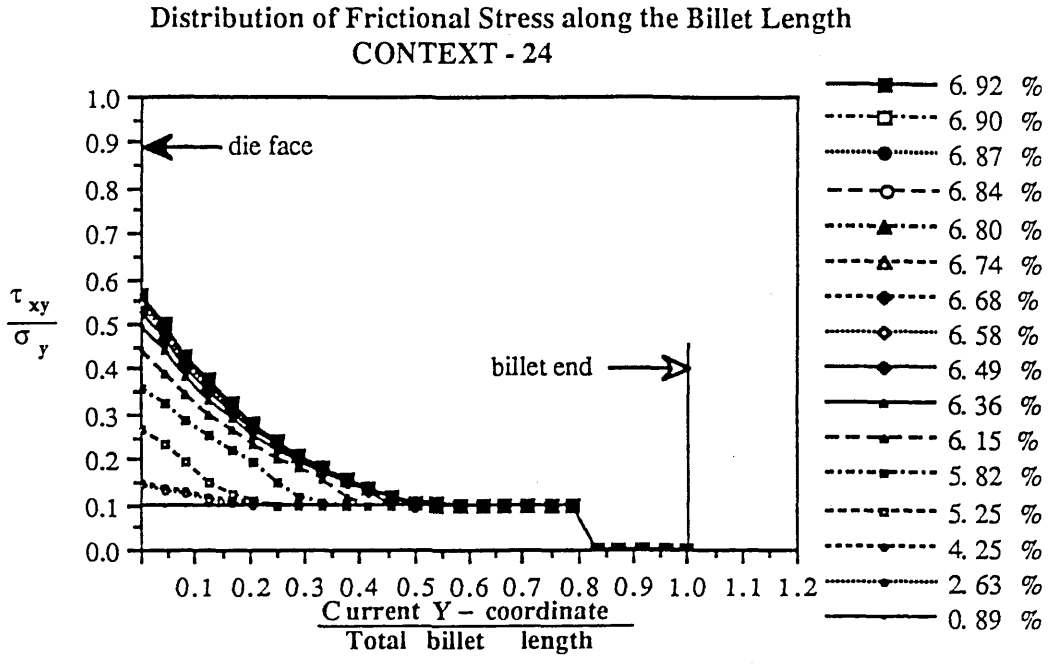


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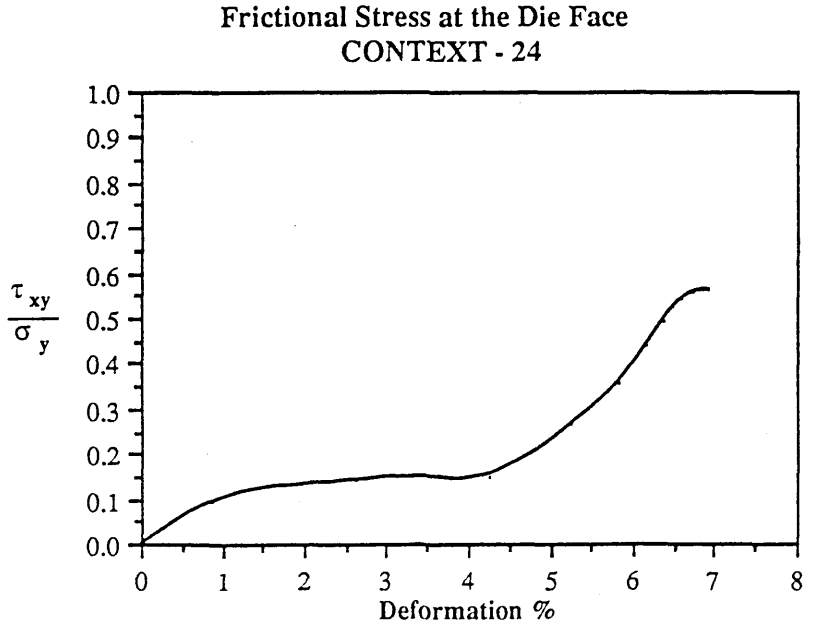


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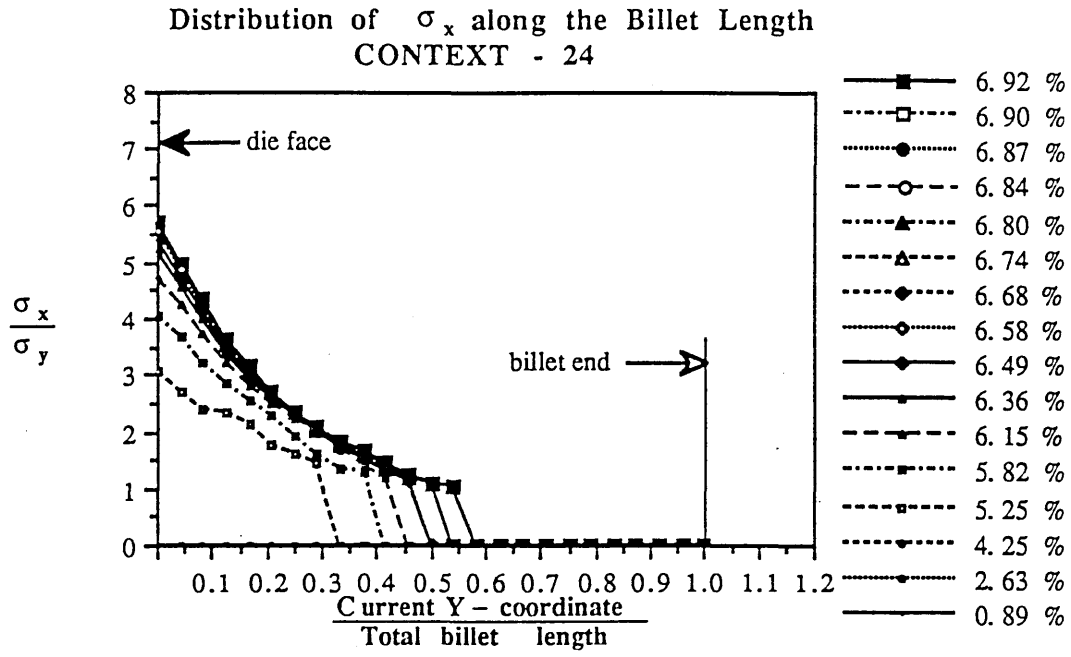


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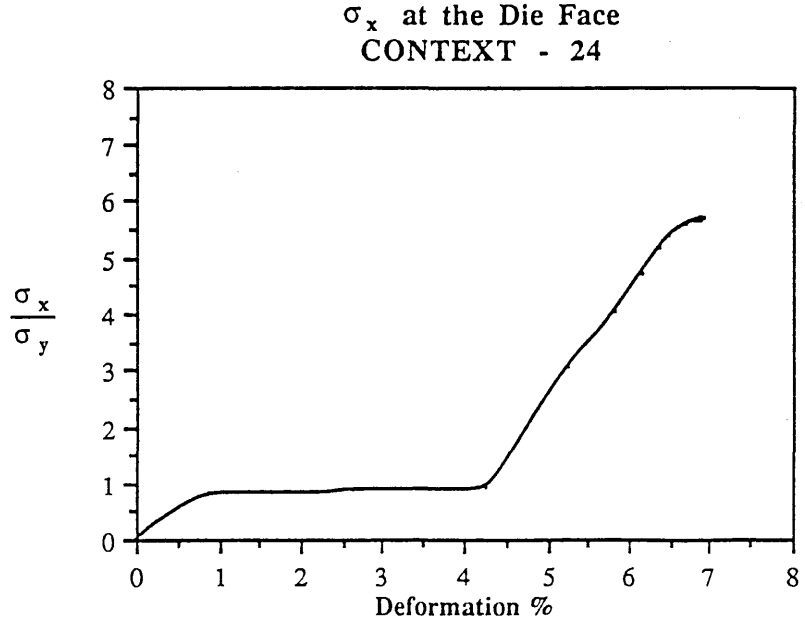


Fig.6.26.

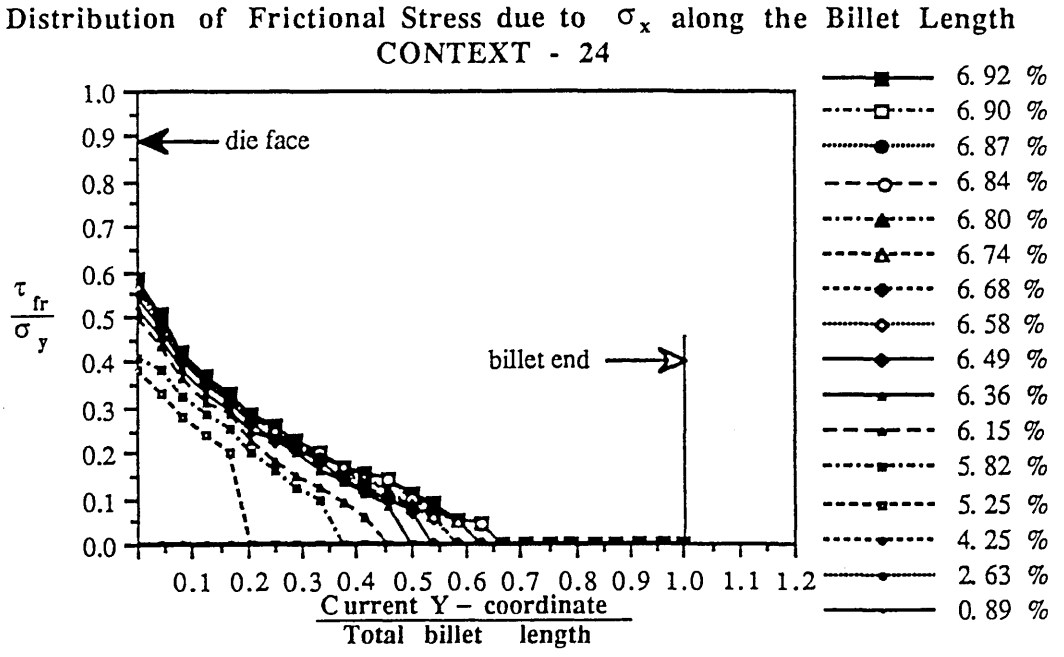


Fig.6.27.

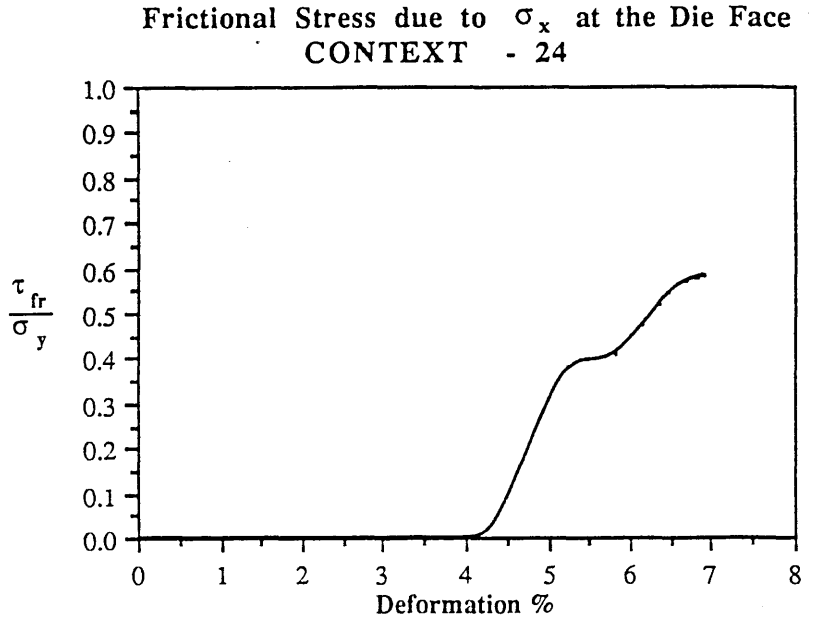


Fig.6.28.

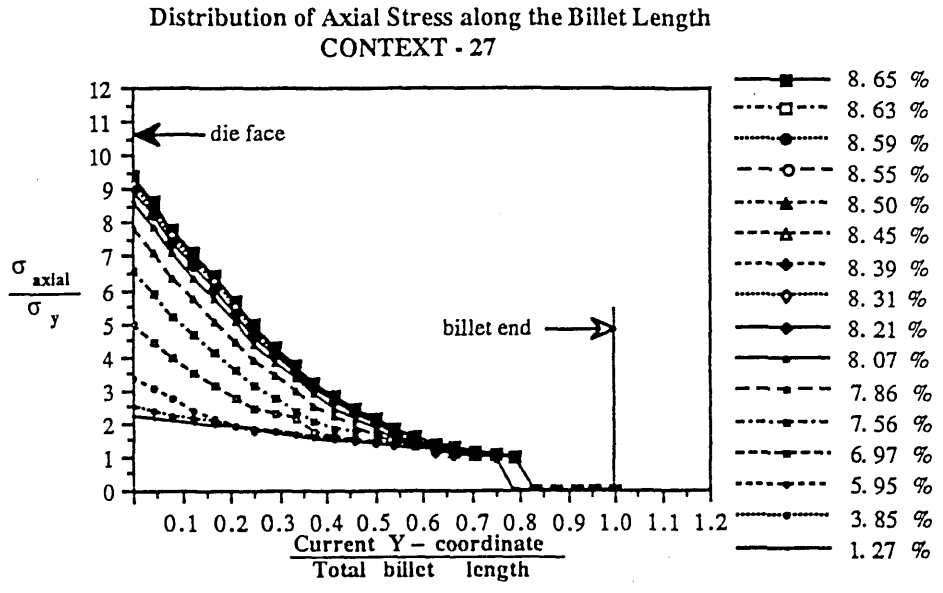


Fig.6.29.

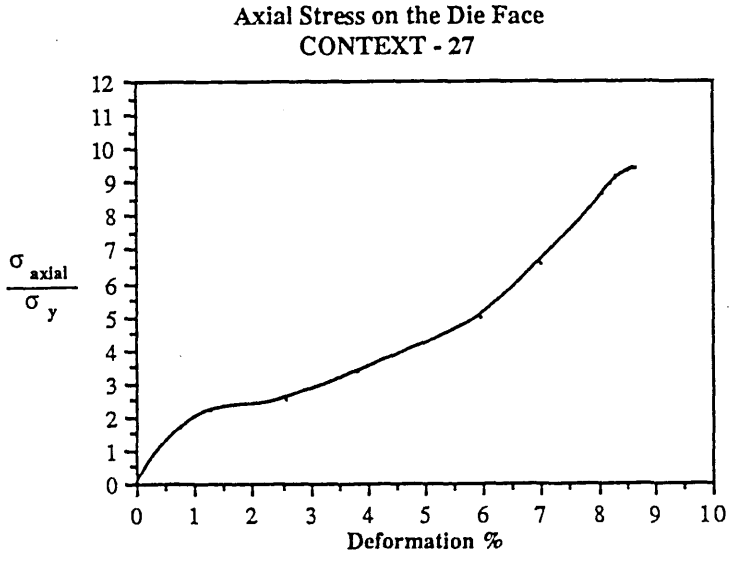


Fig.6.30.

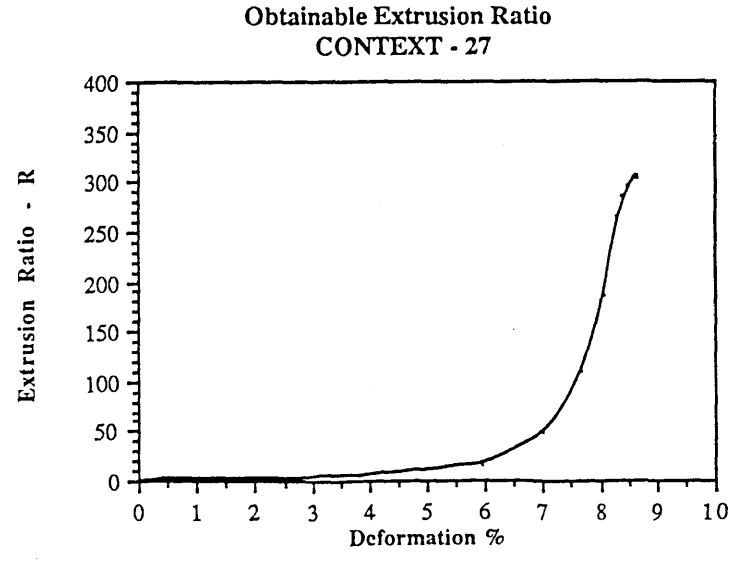


Fig.6.31.

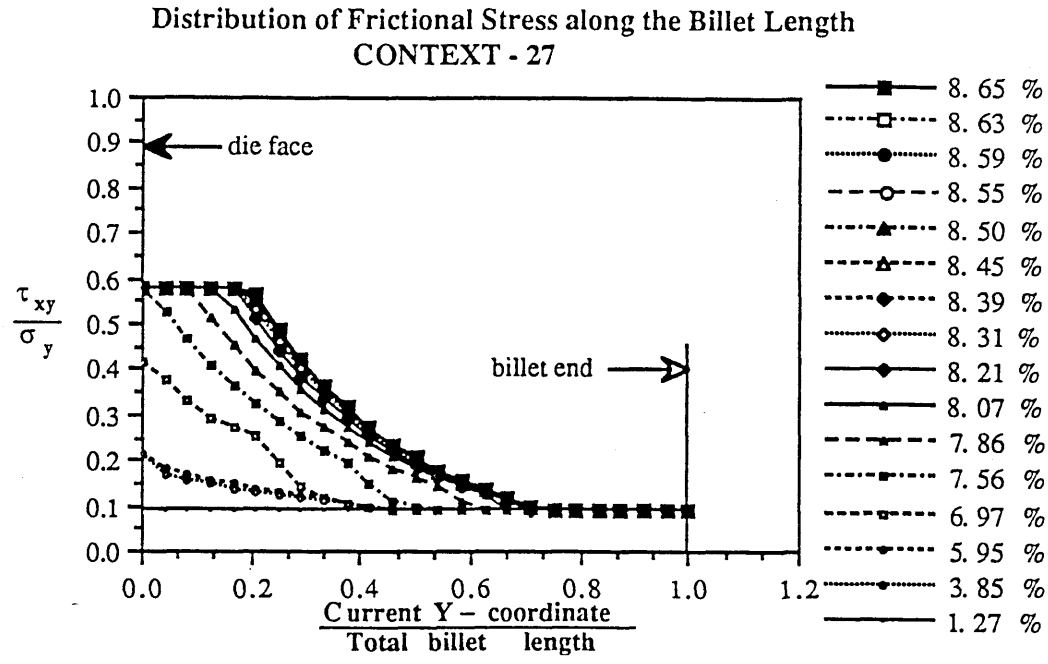


Fig.6.32.

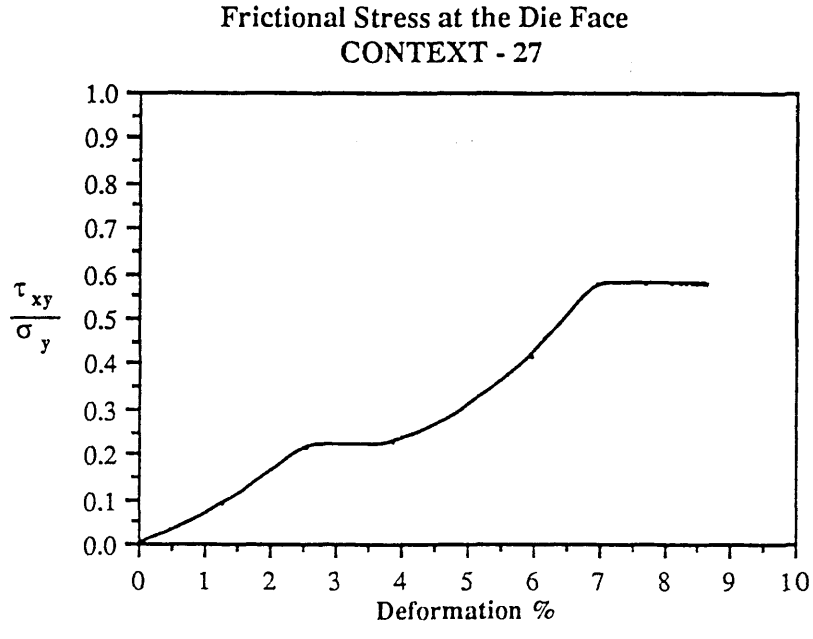


Fig.6.33.

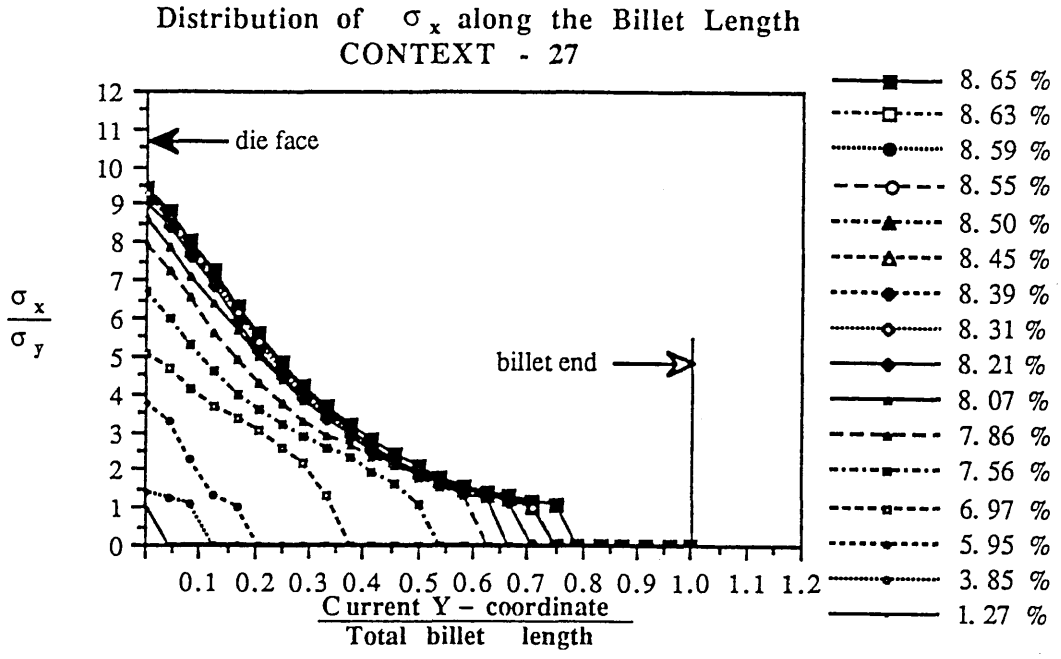


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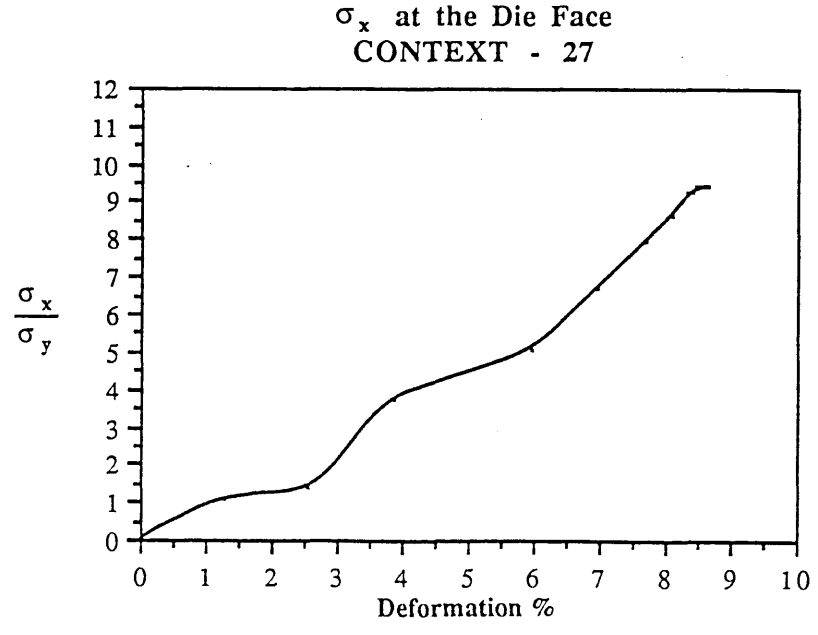


Fig.6.35.

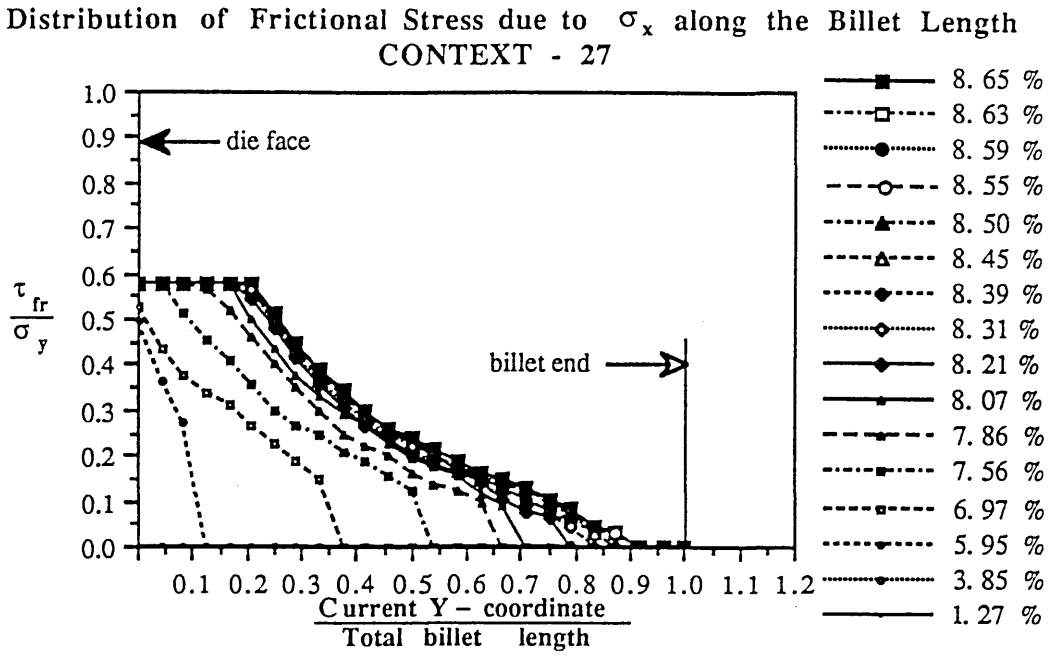


Fig.6.36.

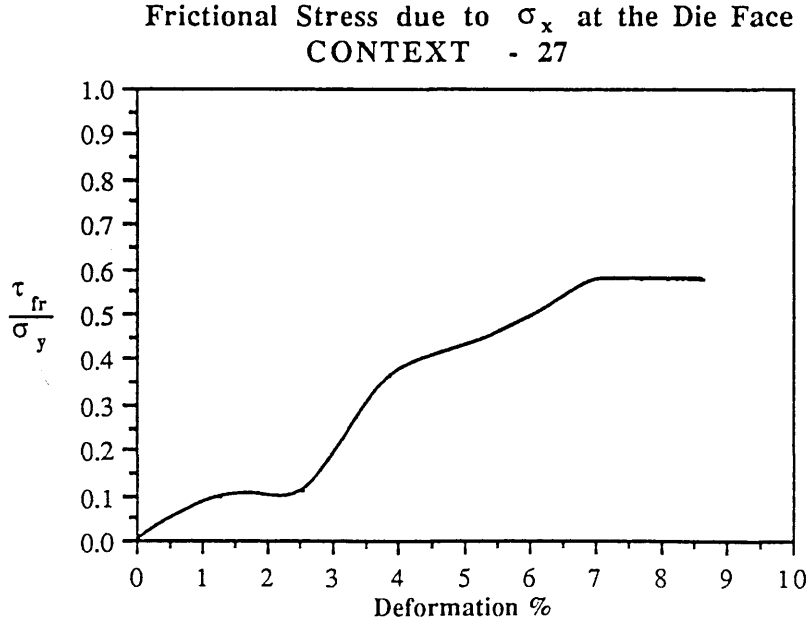


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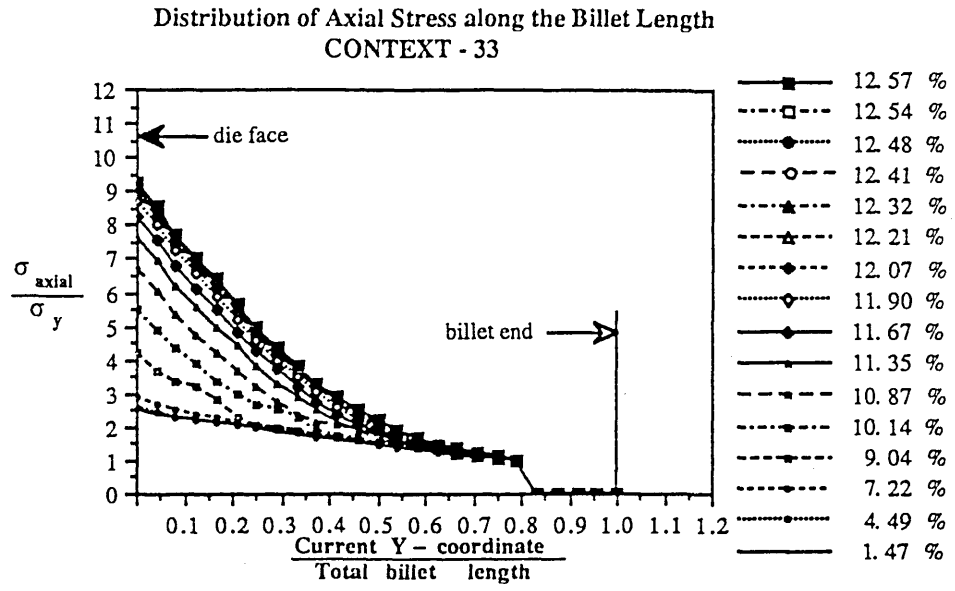


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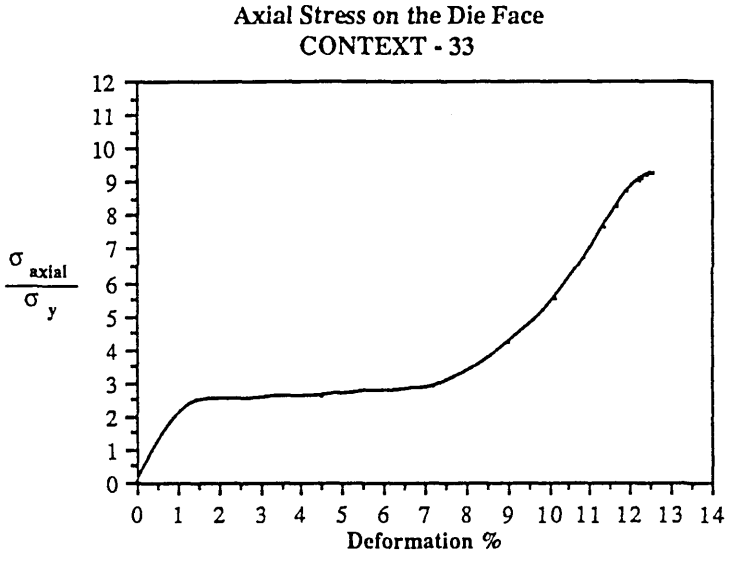


Fig.6.39.

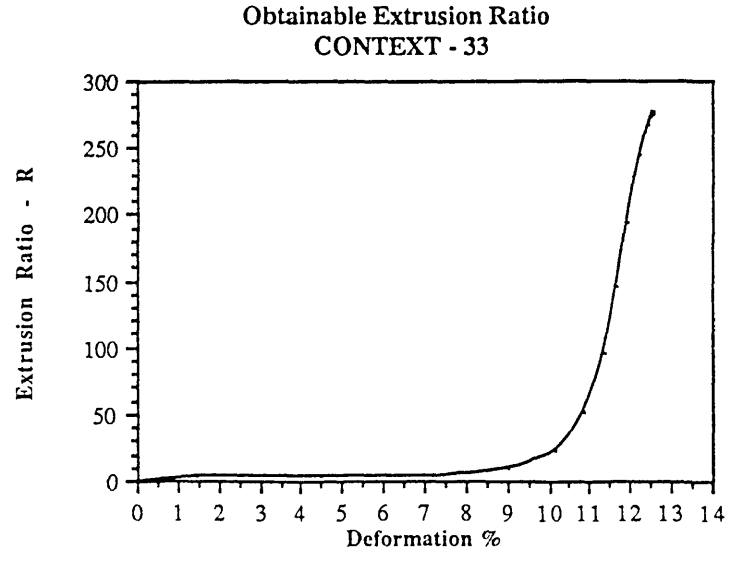


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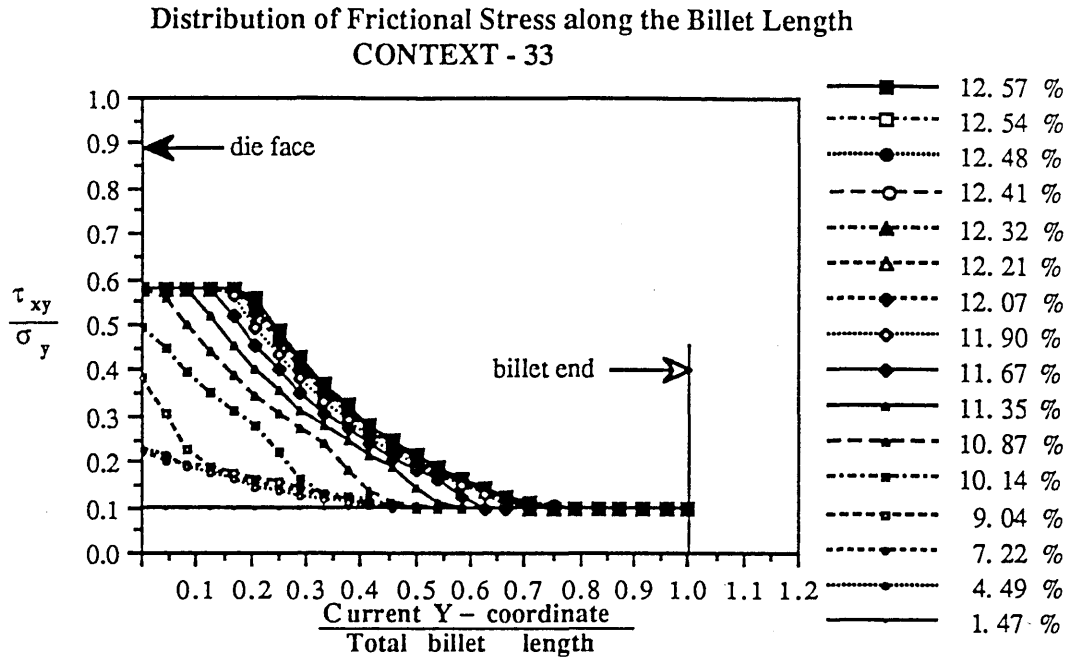


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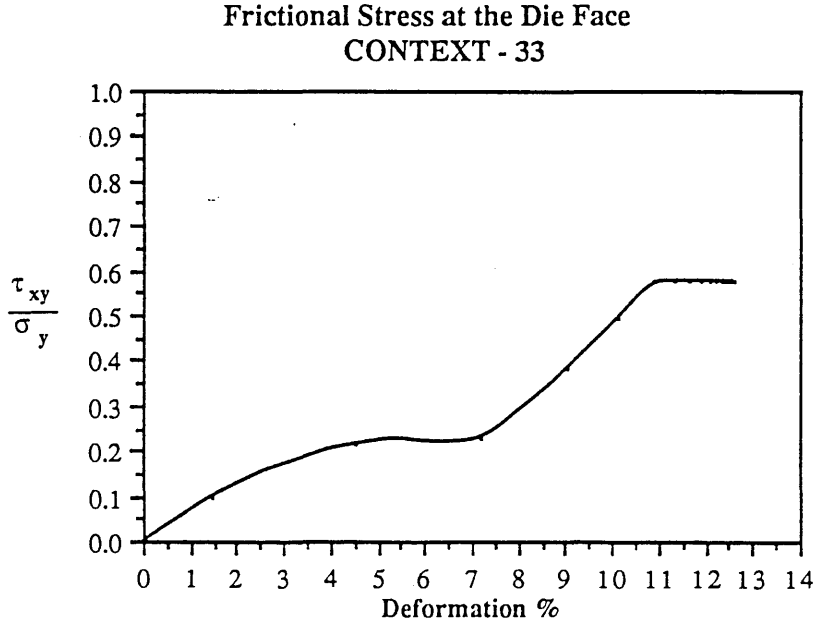


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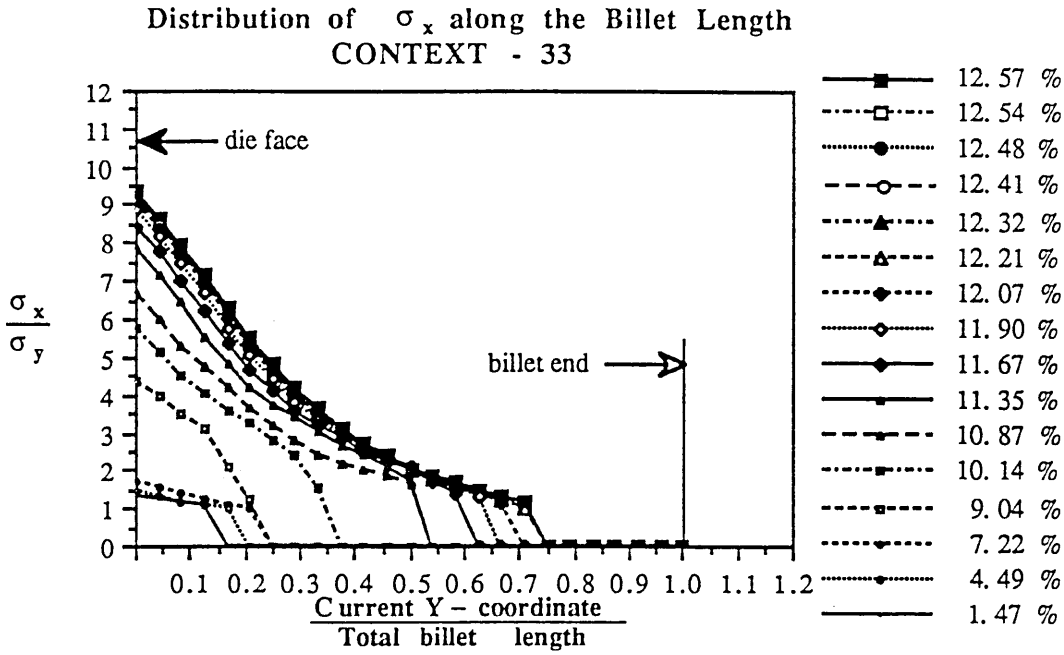


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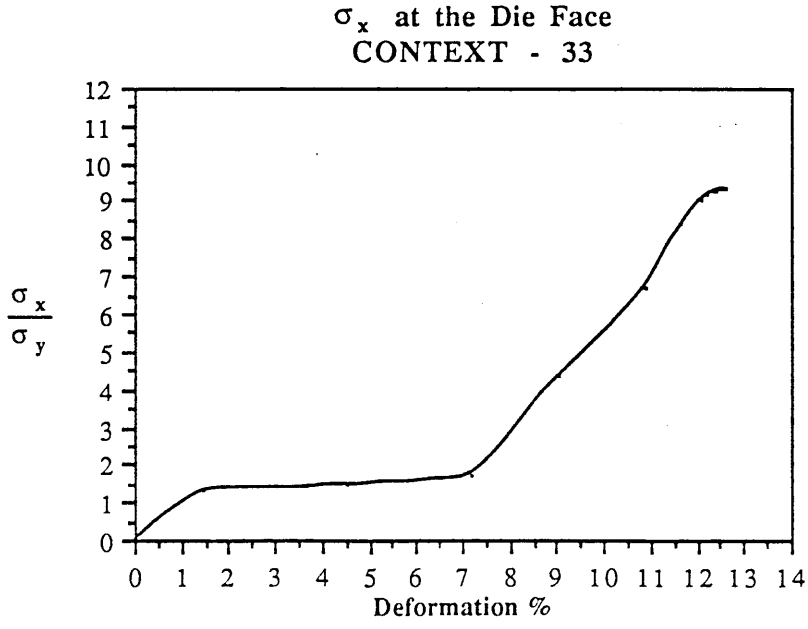


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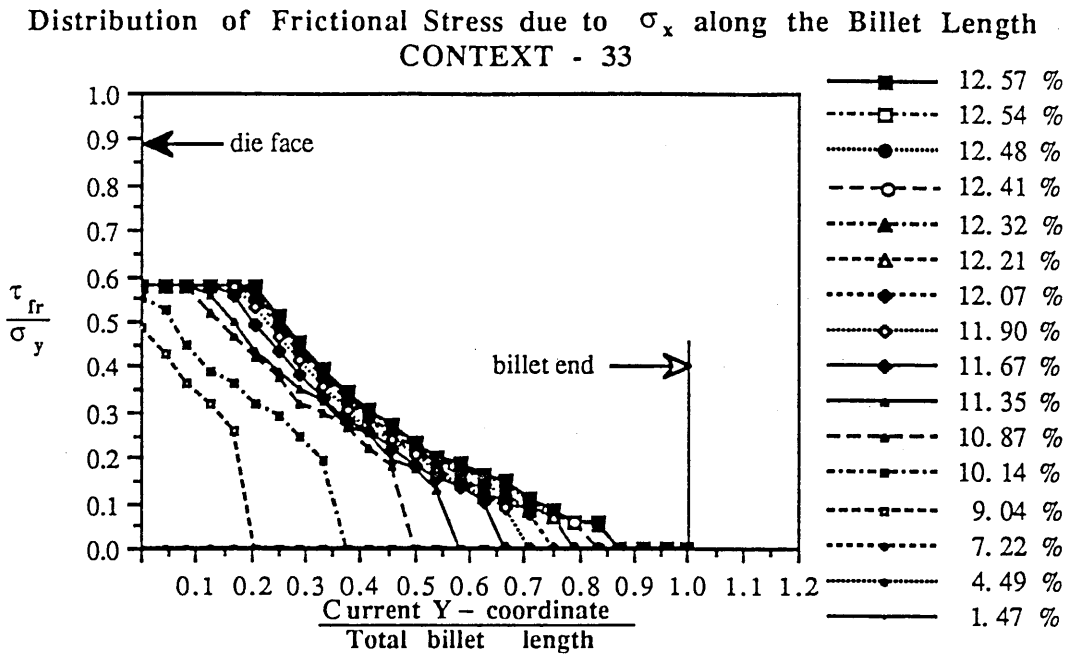


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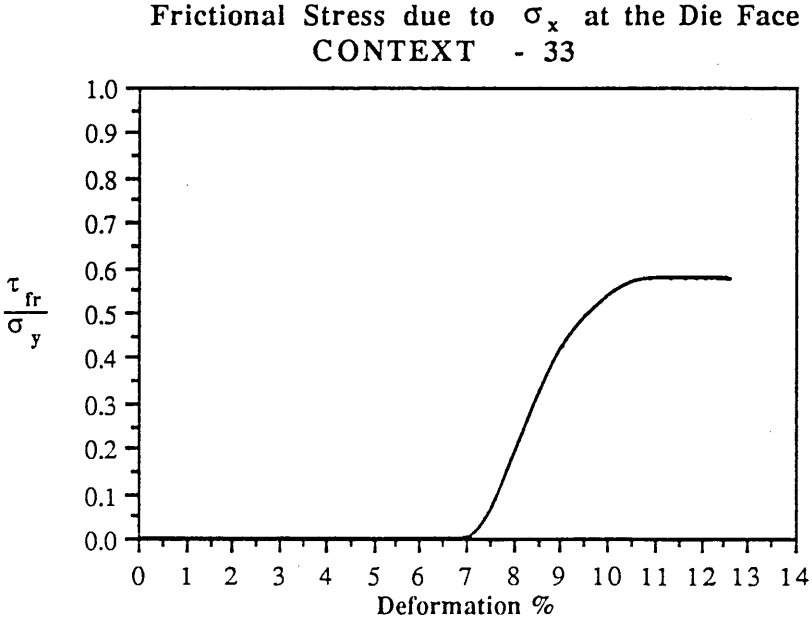


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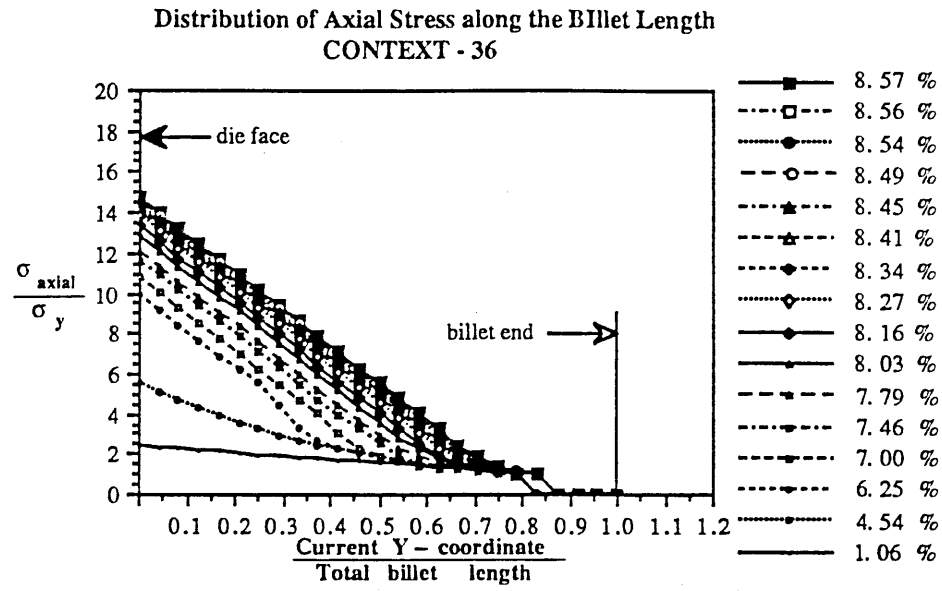


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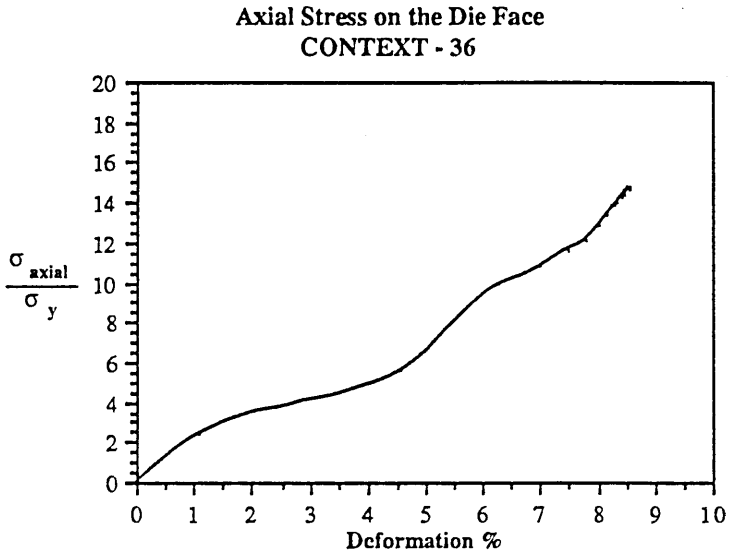


Fig.6.48.

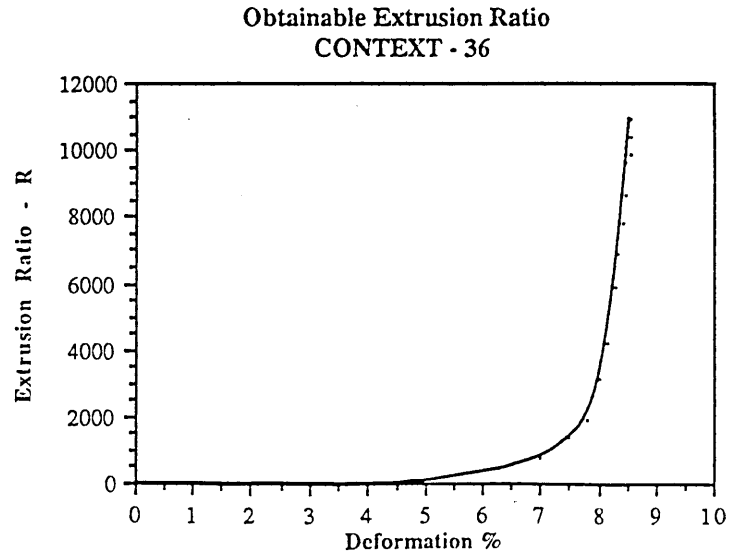


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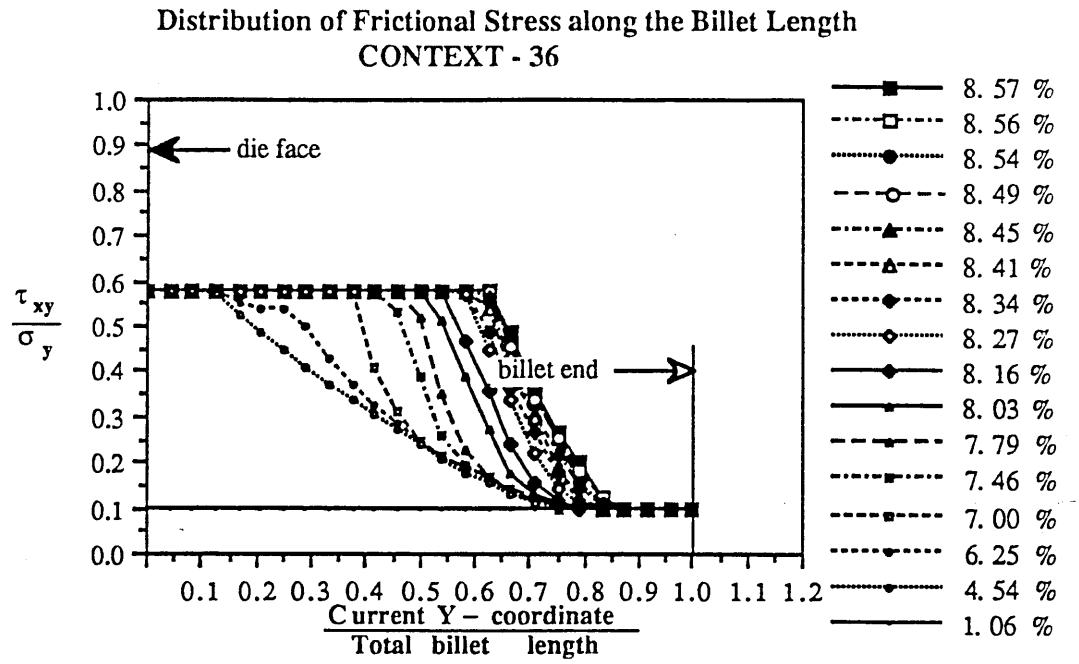


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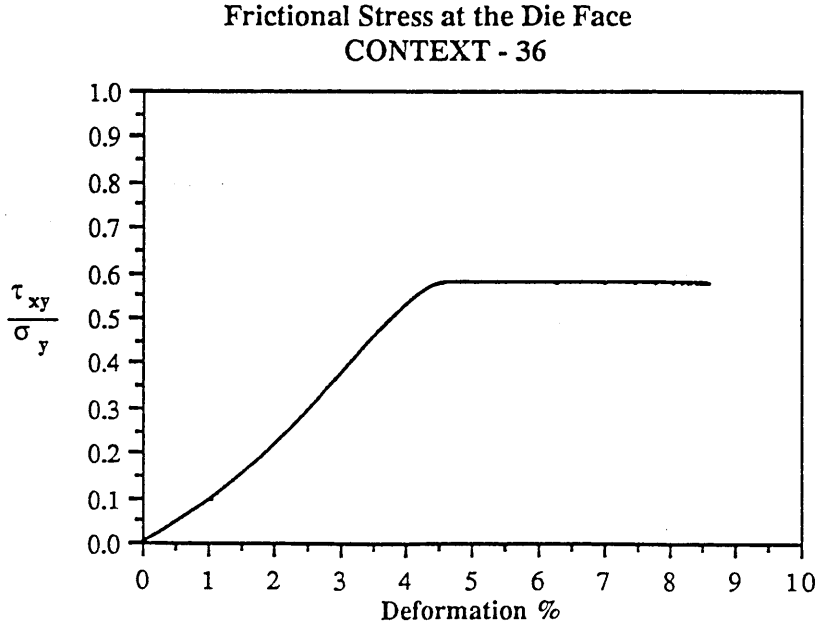


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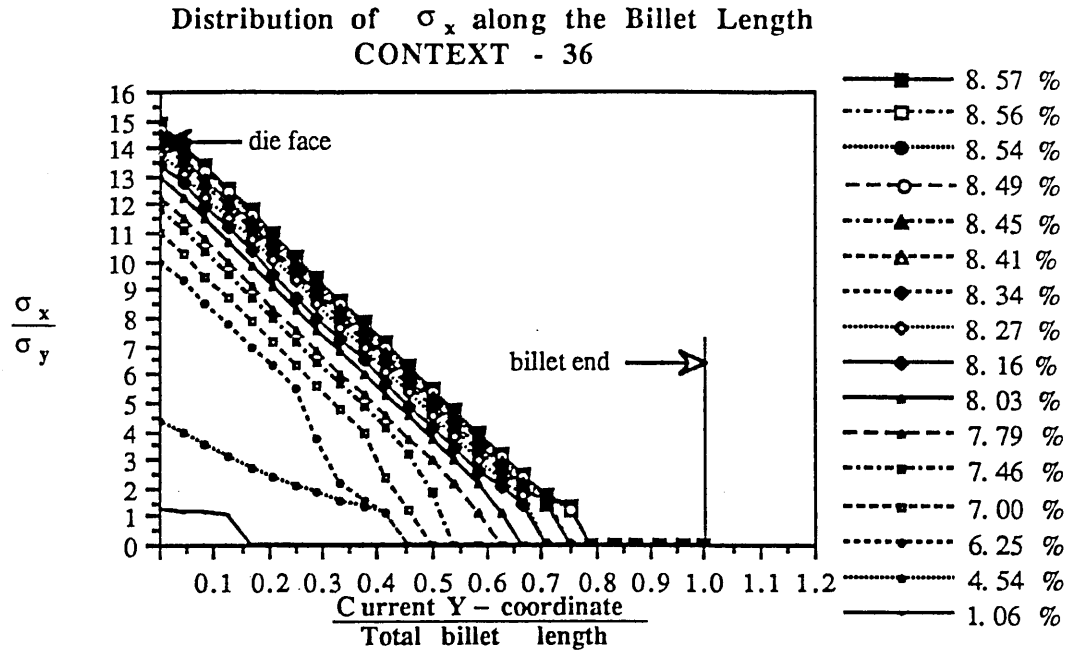


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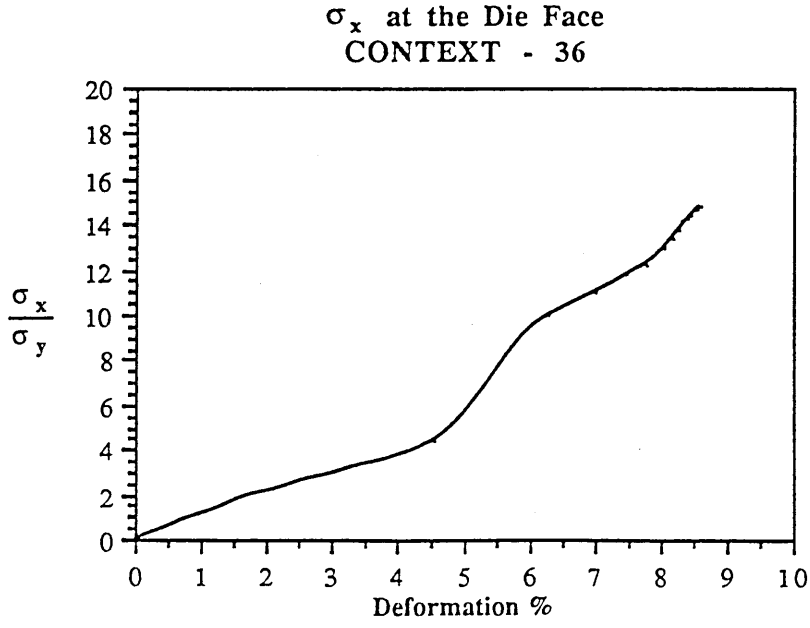


Fig.6.53.

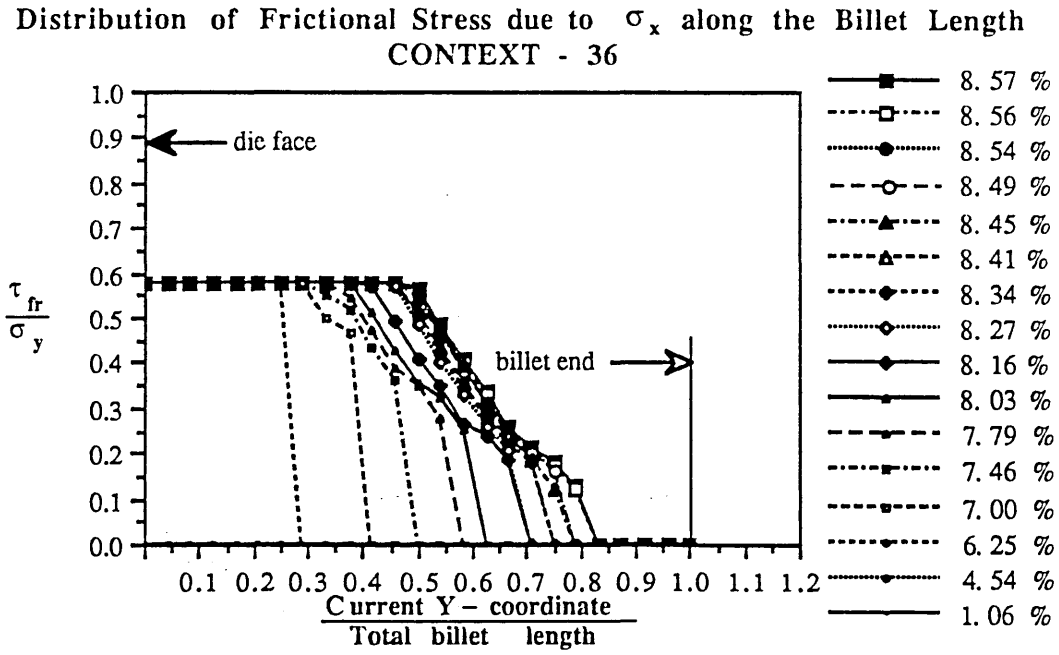


Fig.6.54.

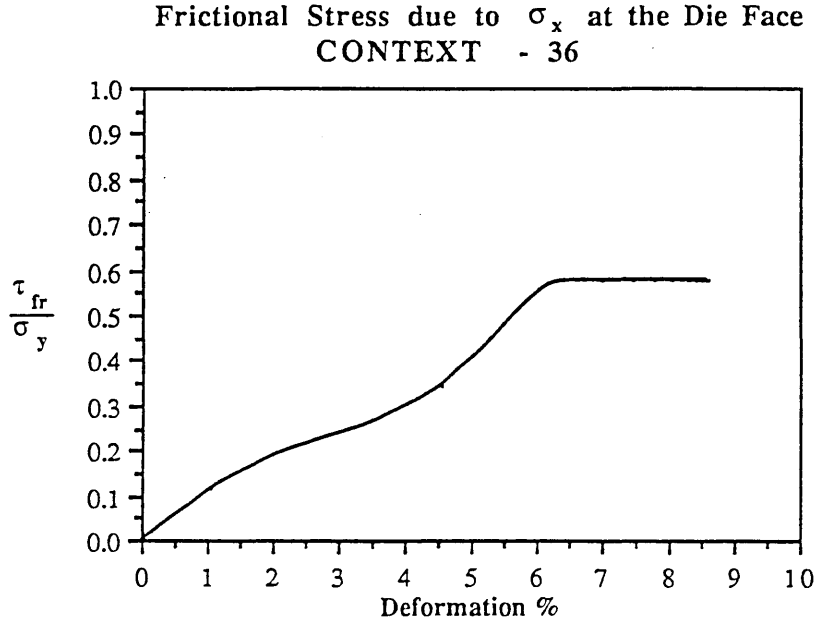


Fig.6.55.

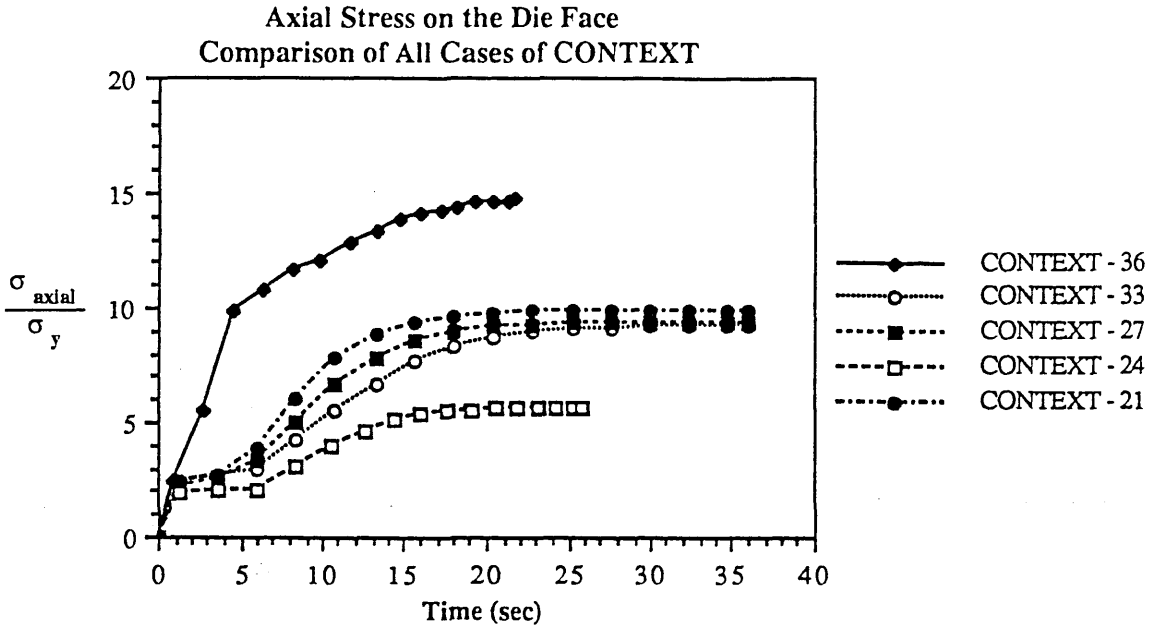


Fig.6.56.

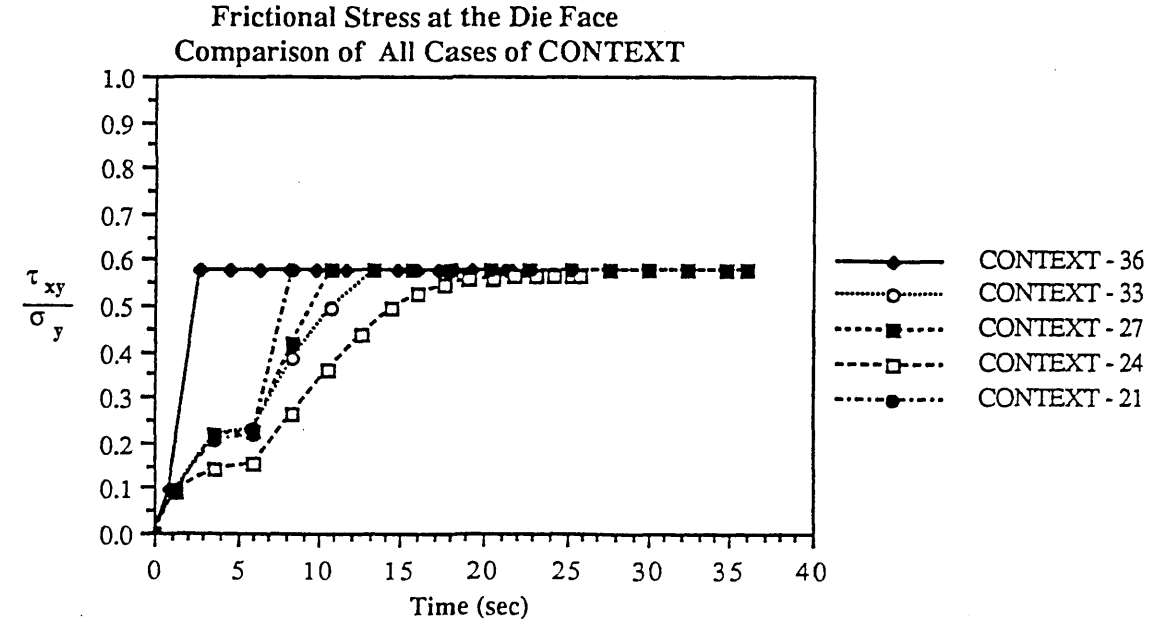


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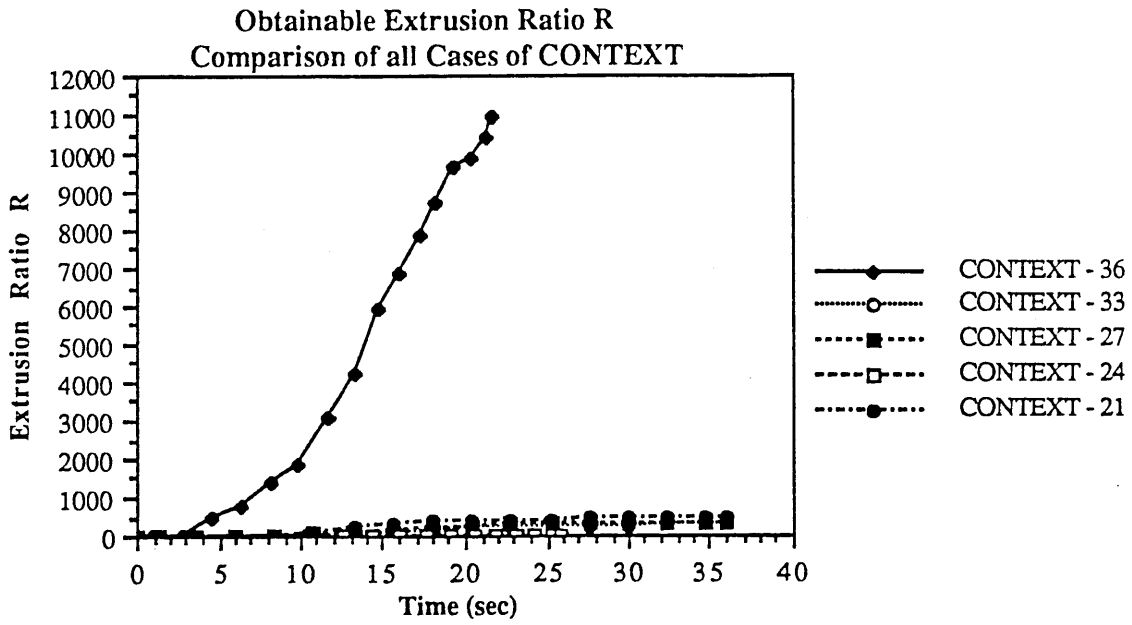


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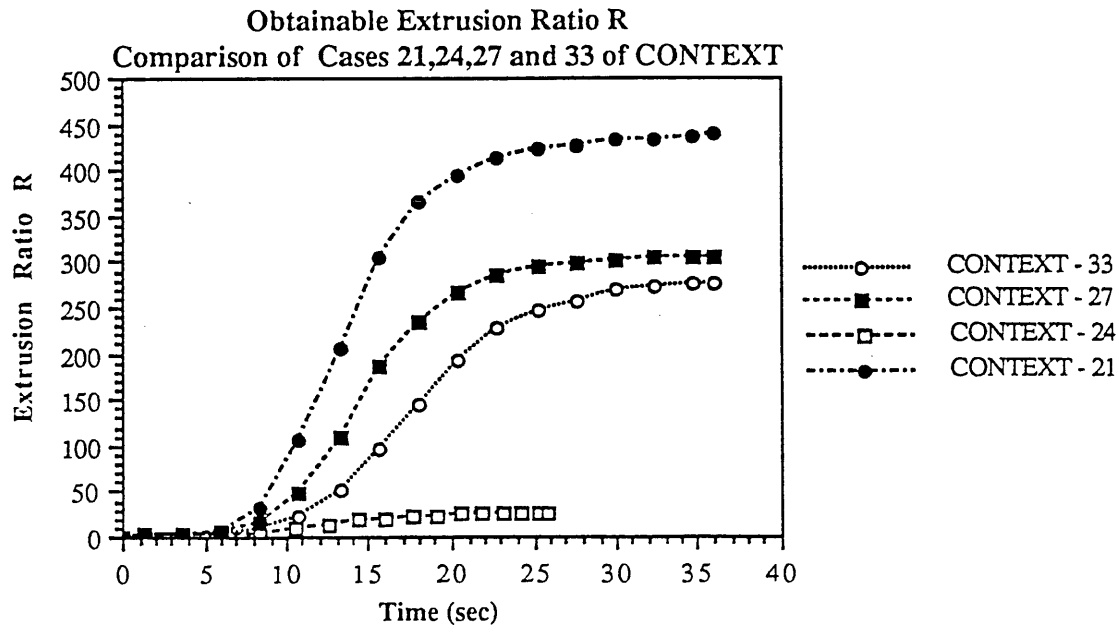


Fig.6.59.

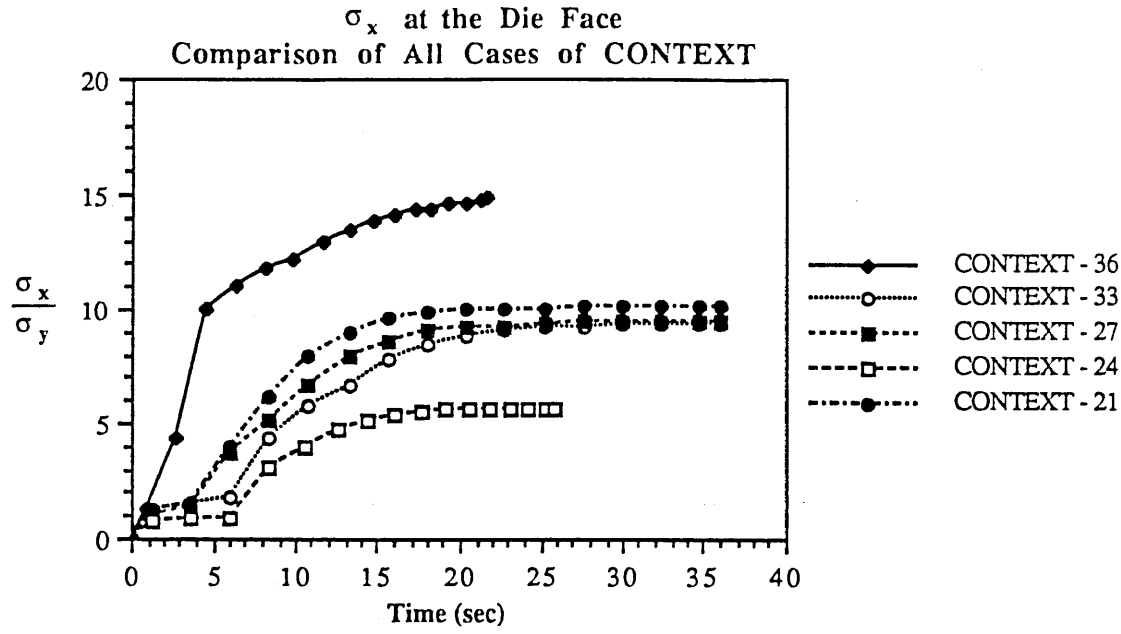


Fig.6.60.

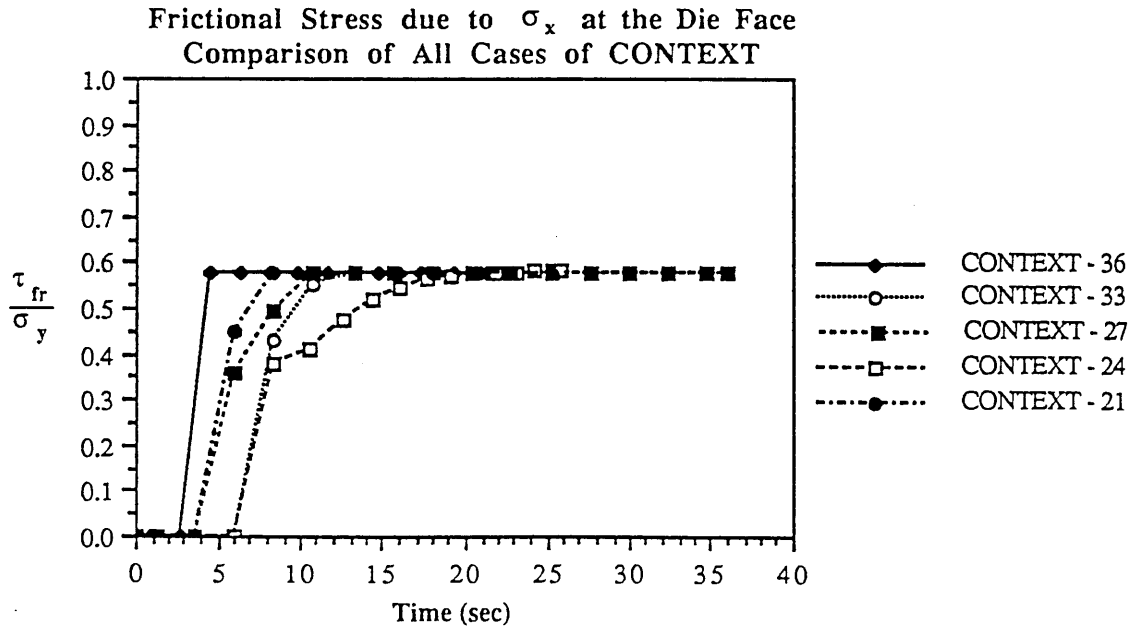


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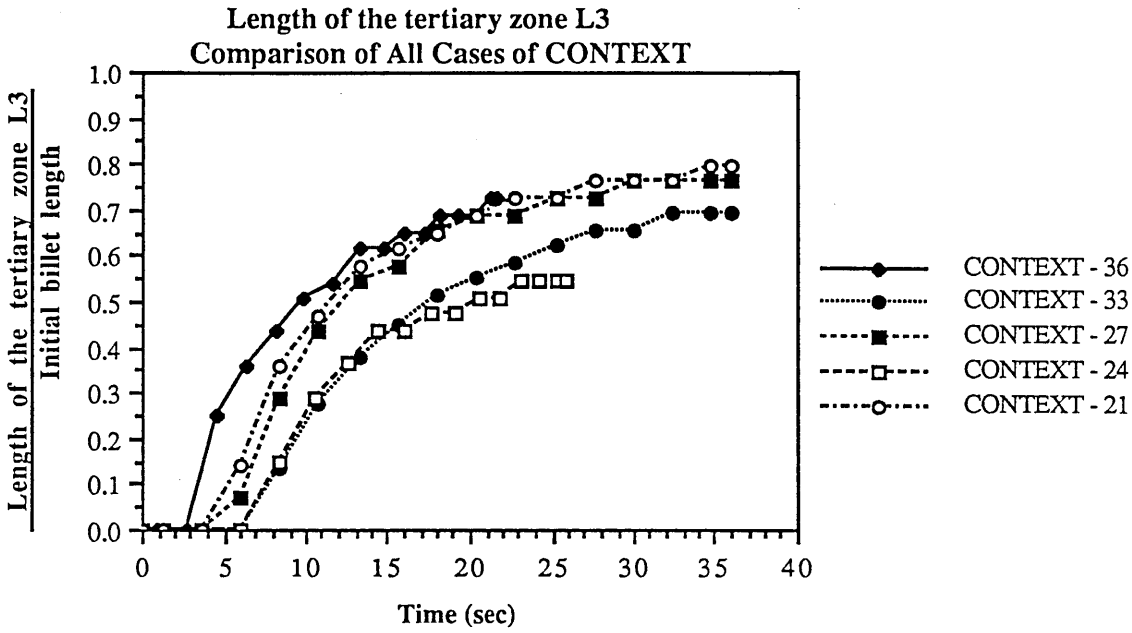
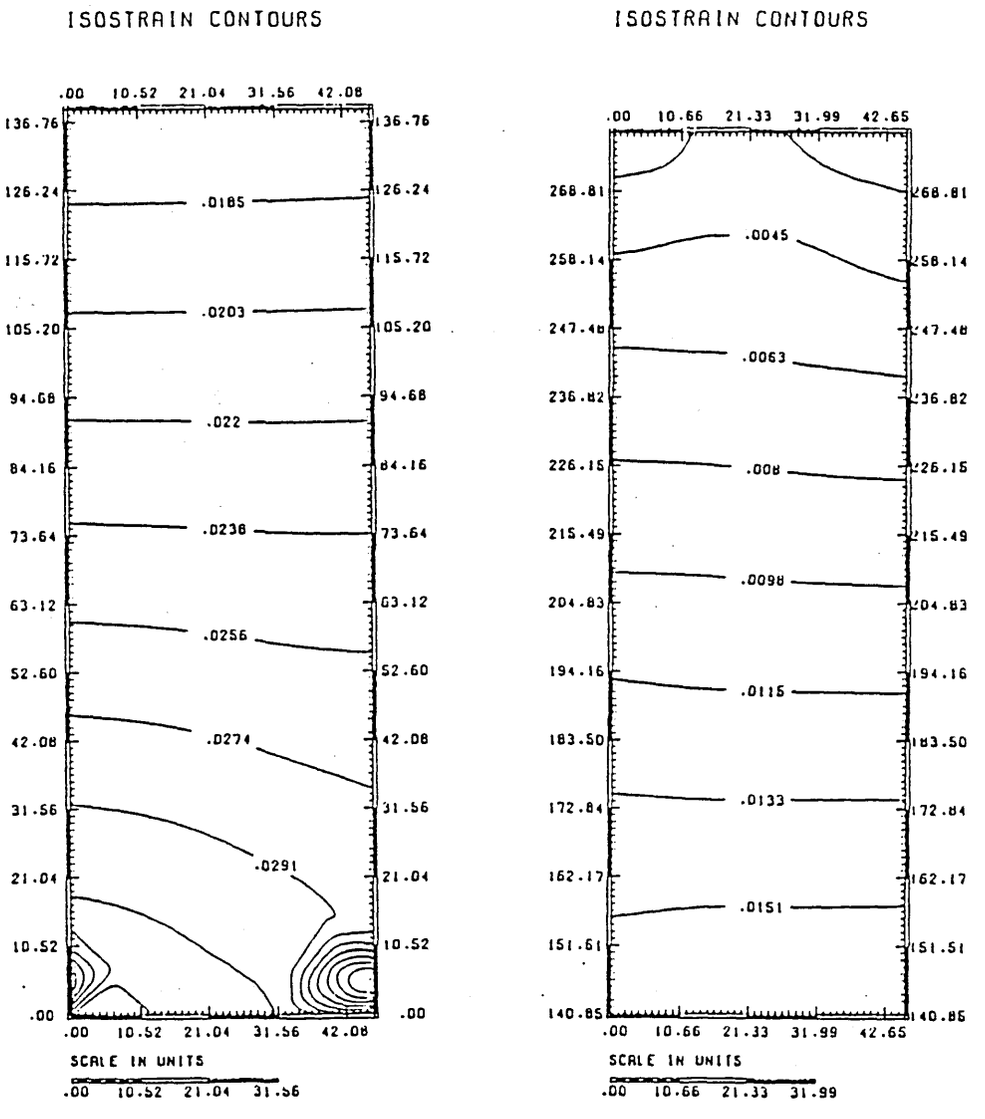

Length of the tertiary zone L3
Comparison of All Cases of CONTEXT
Length of the tertiary zone L3 / Initial billet length
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
30
35
40
Time (sec)
CONTEXT - 36
CONTEXT - 33
CONTEXT - 27
CONTEXT - 24
CONTEXT - 21

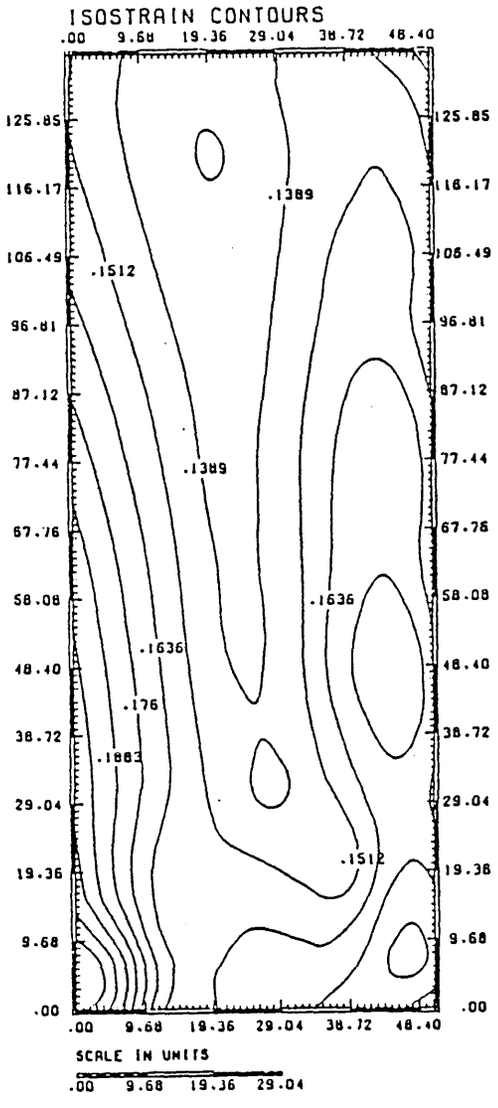
Fig.6.62



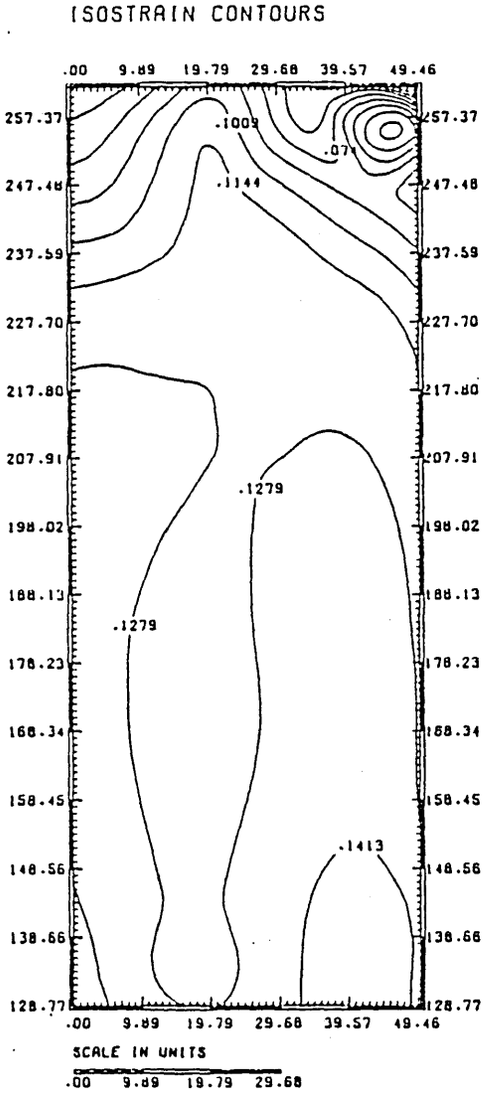
a. Bottom part of the Billet.

b. Top part of the Billet.

Fig.6.63.Isostrain contours of the effective strain for Context-21, time step No.1.

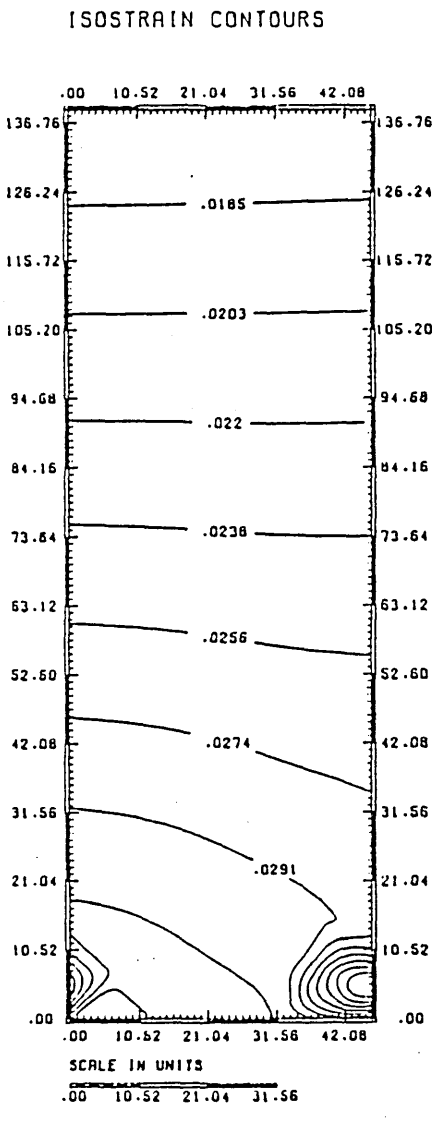


a. Bottom part of the Billet.

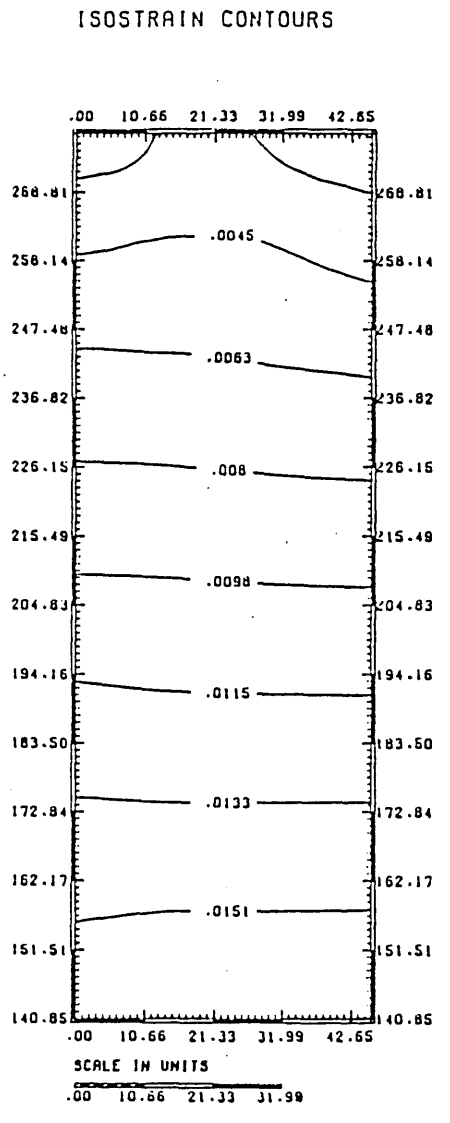


b. Top part of the Billet.

Fig.6.64.Isostrain contours of the effective strain for Context-21, time step No.30.

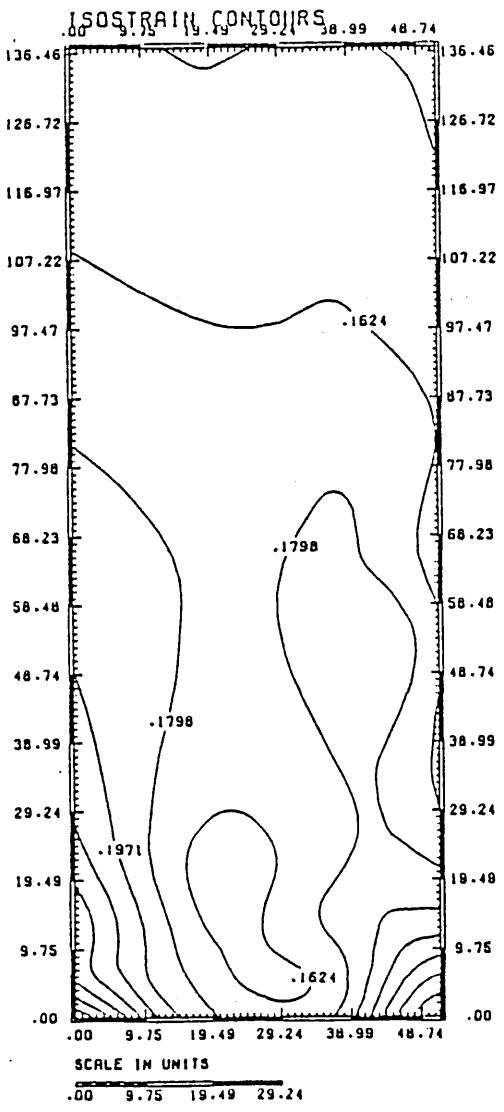


a. Bottom part of the Billet.

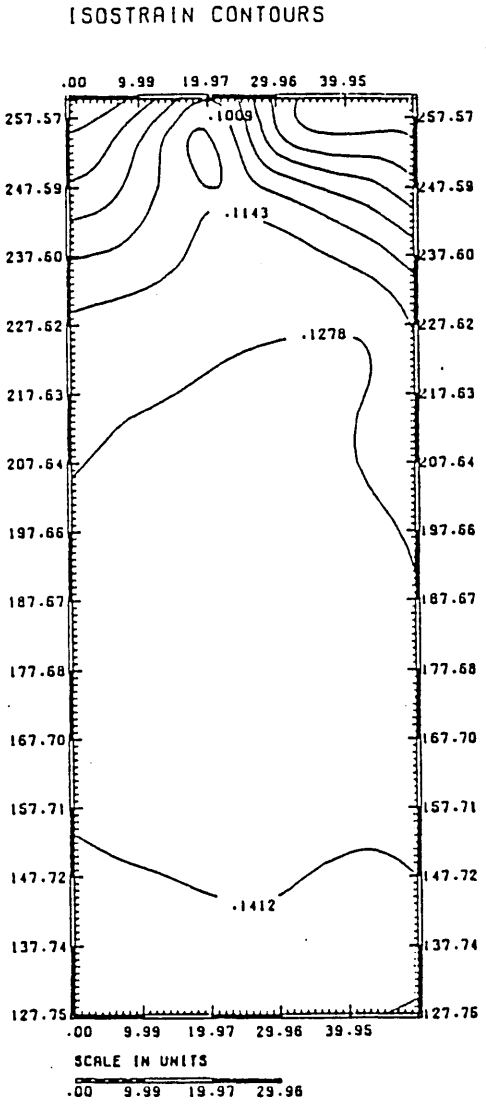


b. Top part of the Billet.

Fig.6.65.Isostrain contours of the effective strain for Linex-22, time step No.1.

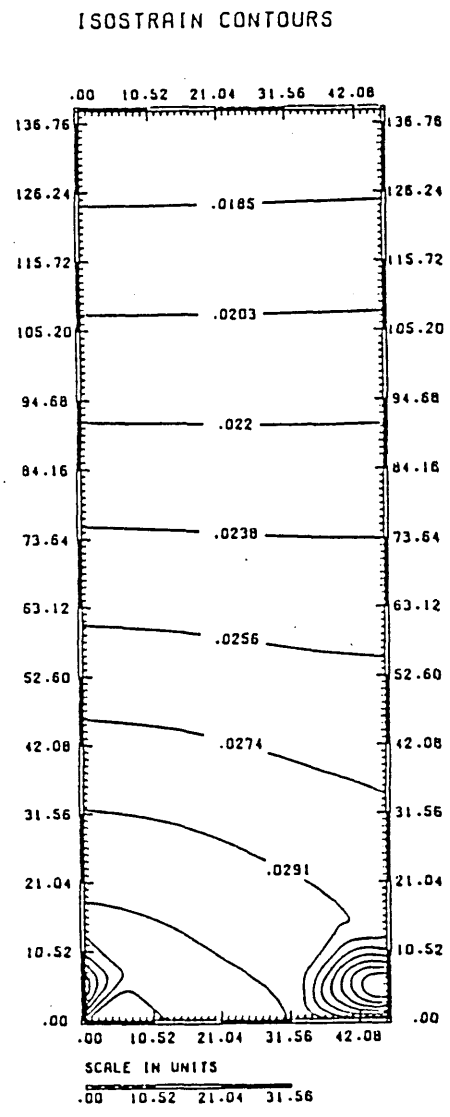


a. Bottom part of the Billet.

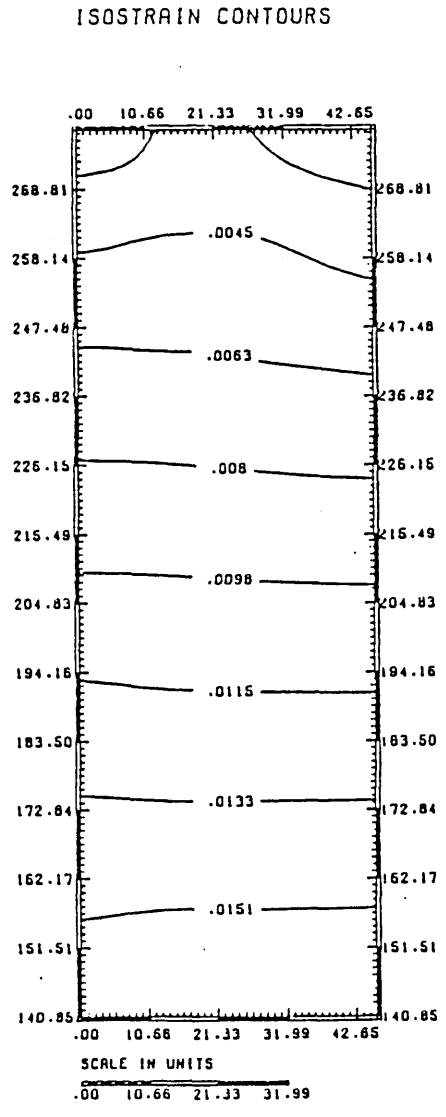


b. Top part of the Billet.

Fig.6.66.Isostrain contours of the effective strain for Linex-22, time step No.30.

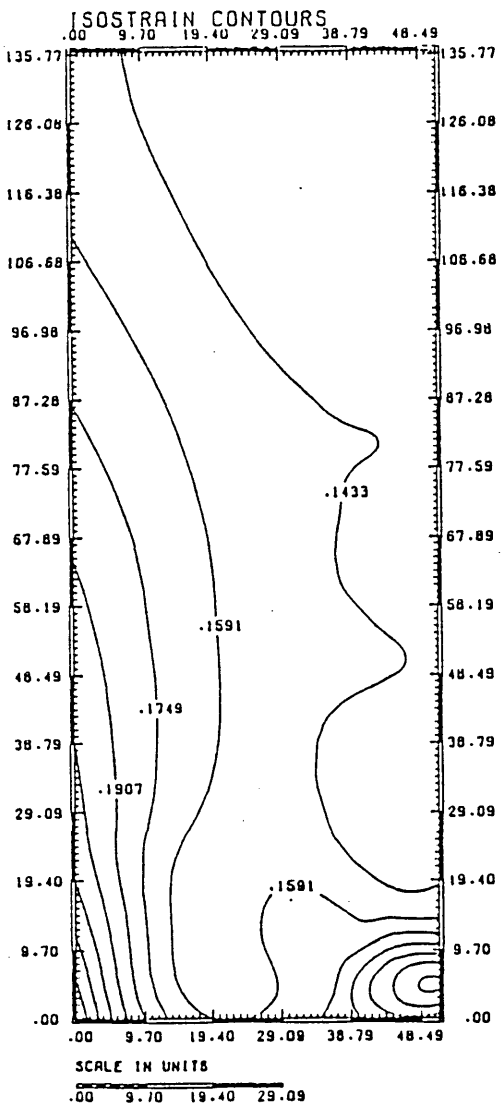


a. Bottom part of the Billet.

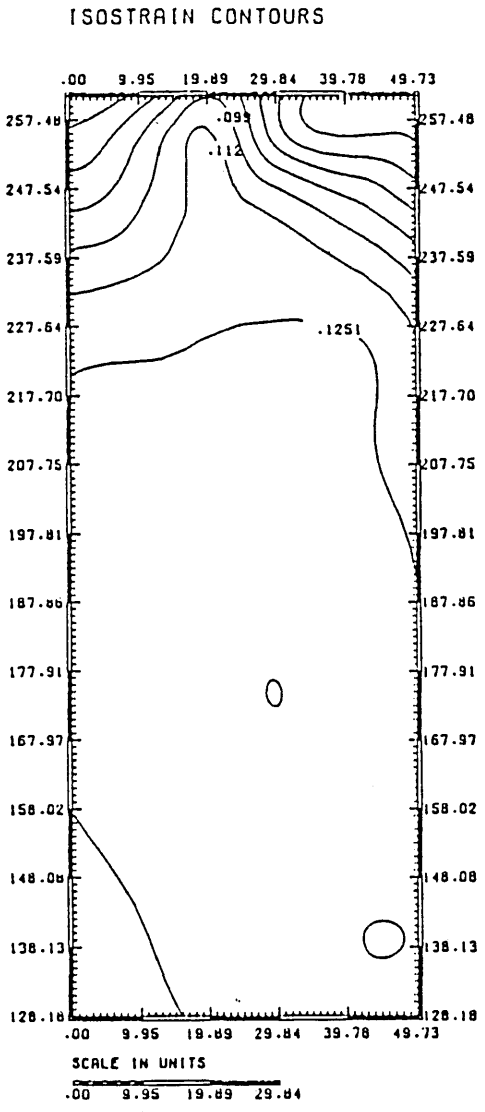


b. Top part of the Billet.

Fig.6.67.Isostrain contours of the effective strain for Conform-23, time step No.1.

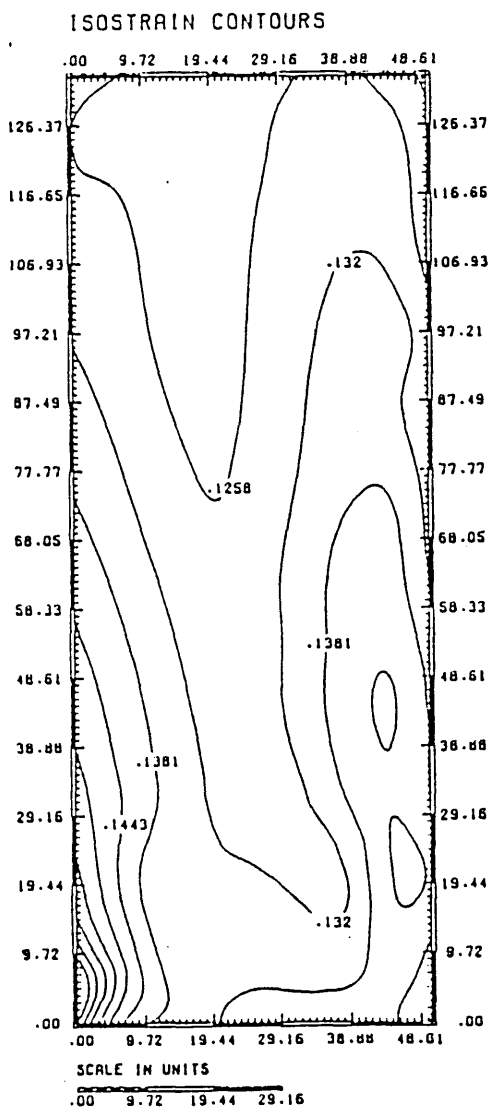


a. Bottom part of the Billet.

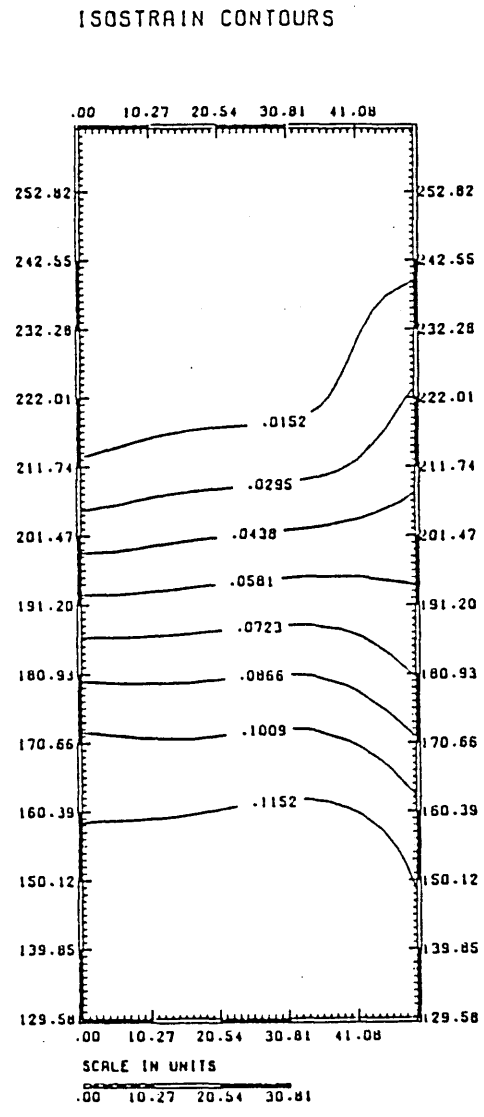


b. Top part of the Billet.

Fig.6.68.Isostrain contours of the effective strain for Conform-23, time step No.30.

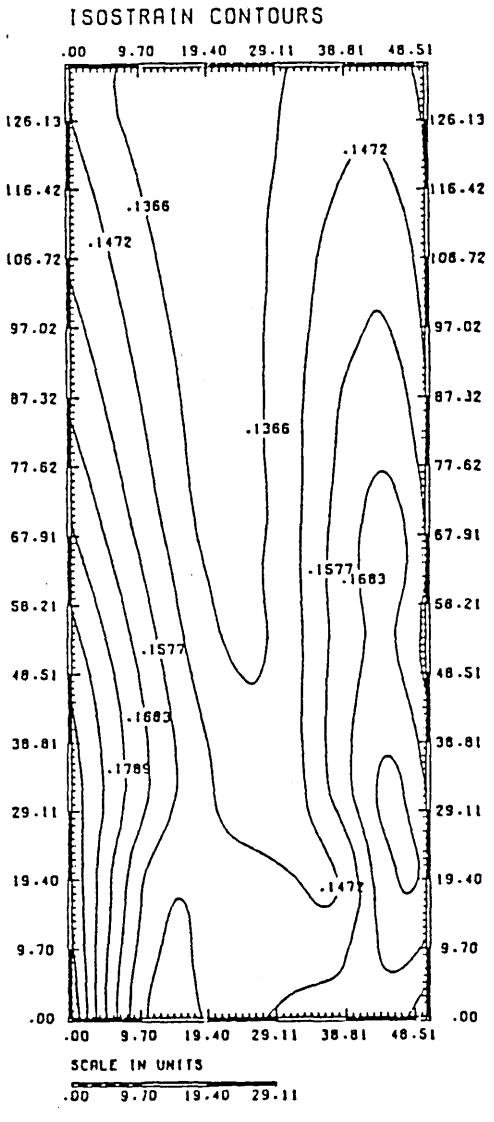


a. Bottom part of the Billet.

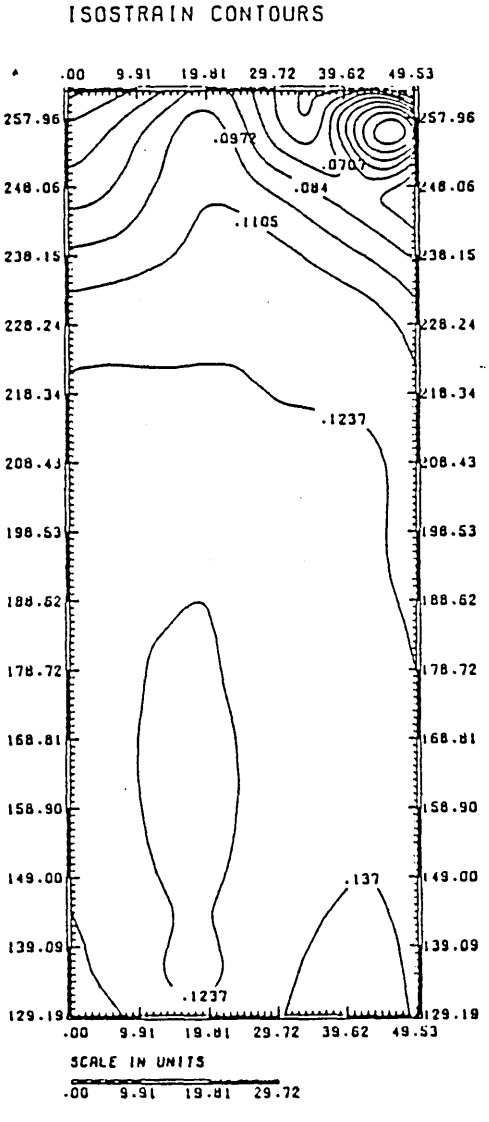


b. Top part of the Billet.

Fig.6.69.Isostrain contours of the effective strain for Context-24, time step No.30.

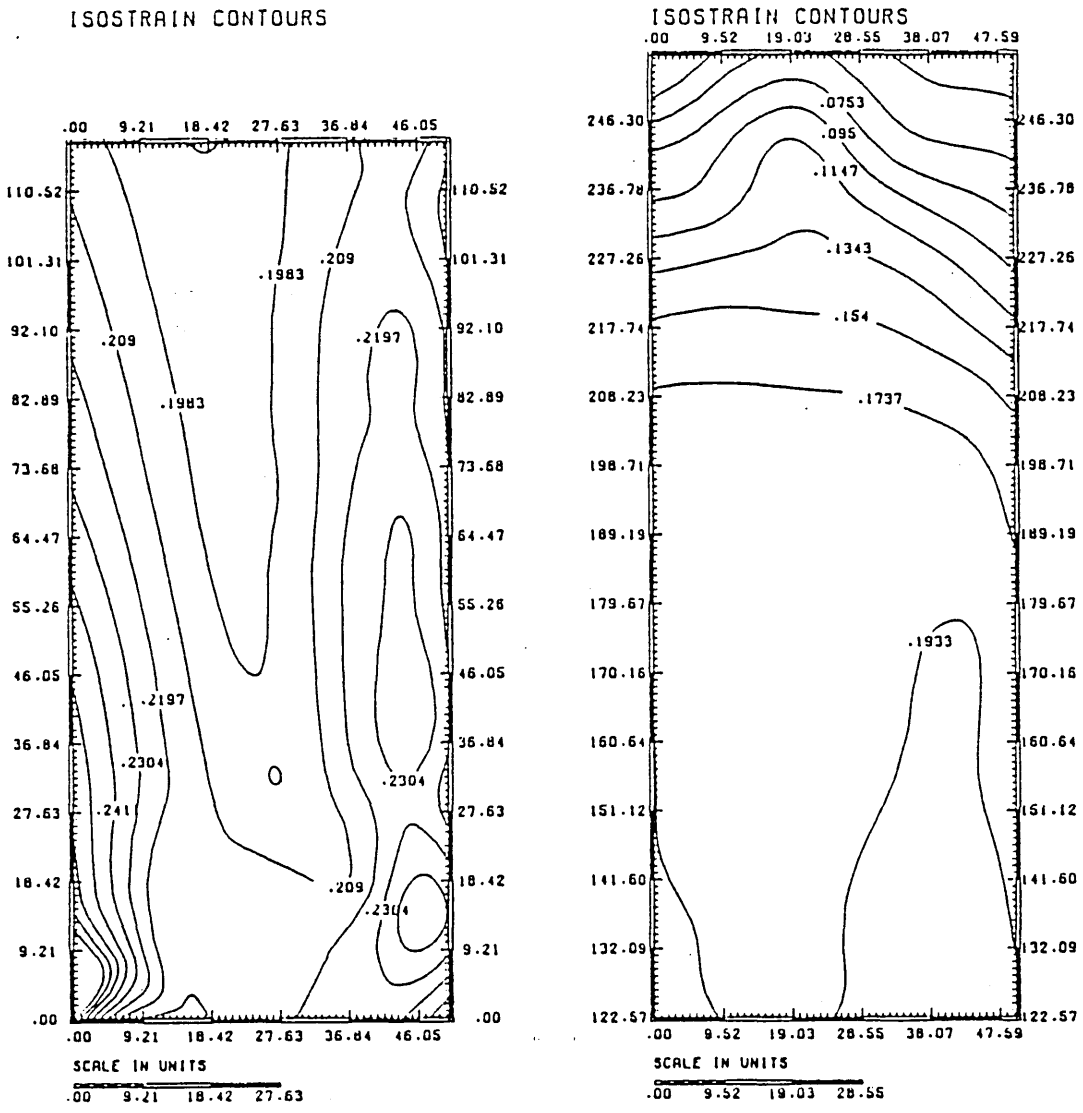


a. Bottom part of the Billet.



b. Top part of the Billet.

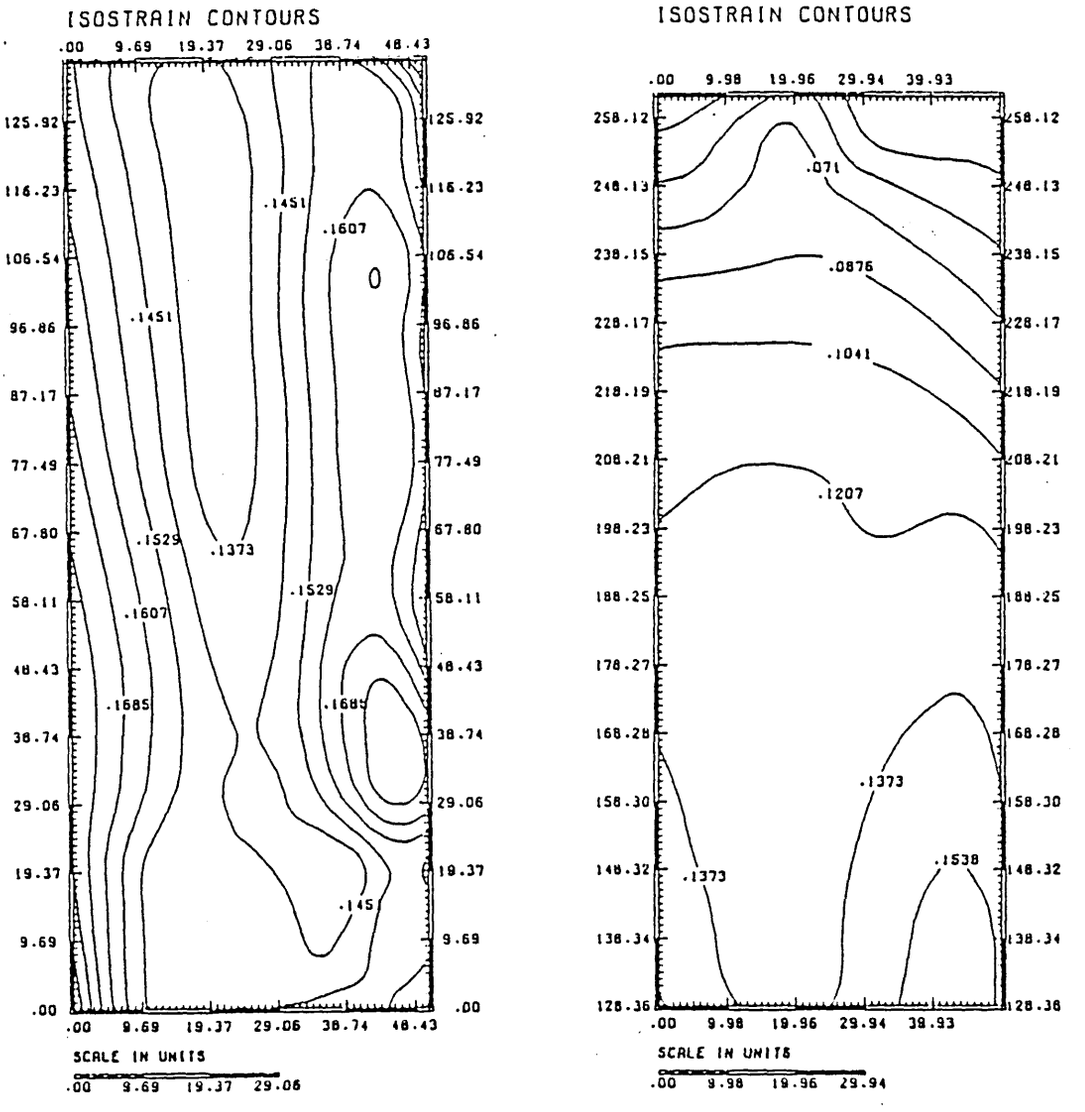
Fig.6.70.Isostrain contours of the effective strain for Context-27, time step No.30.



a. Bottom part of the Billet.

b. Top part of the Billet.

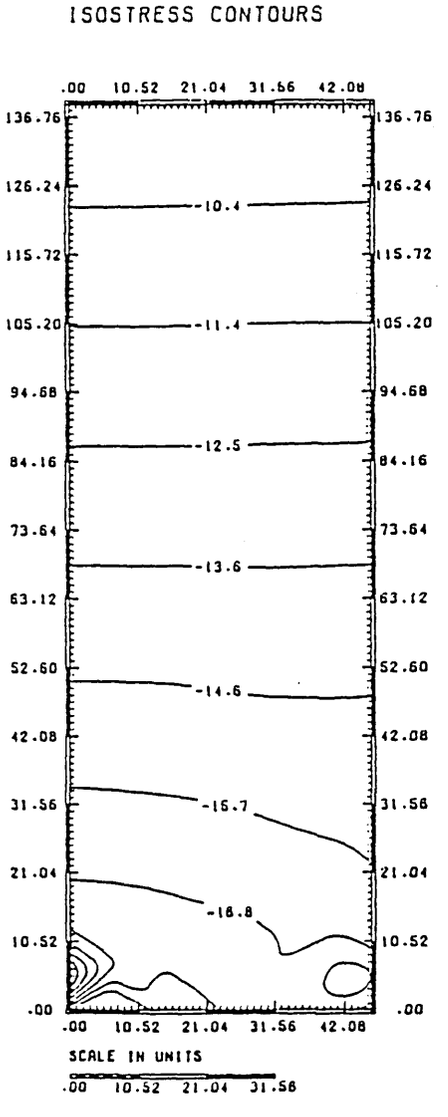
Fig.6.71.Isostrain contours of the effective strain for Context-33, time step No.30.



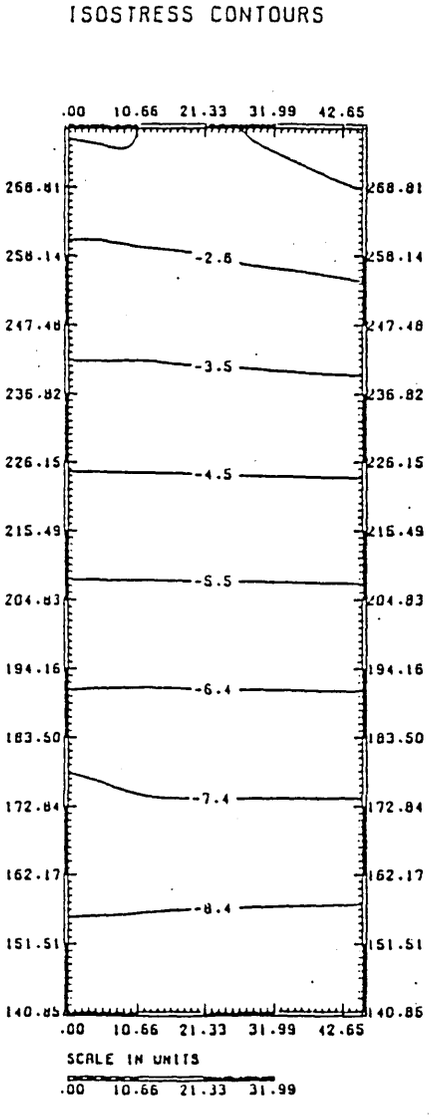
a. Bottom part of the Billet.

b. Top part of the Billet.

Fig.6.72.Isostrain contours of the effective strain for Context-36, time step No.30.

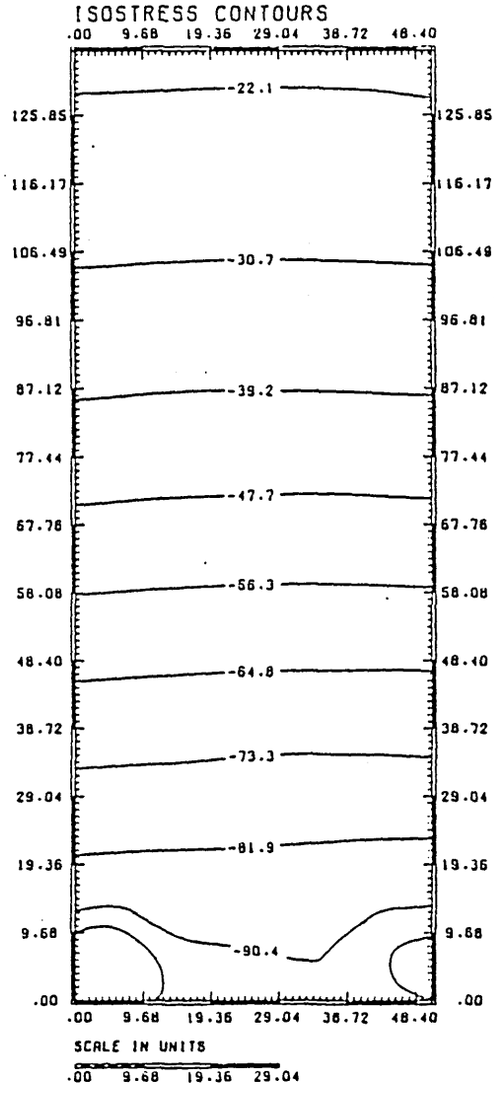


a. Bottom part of the Billet.

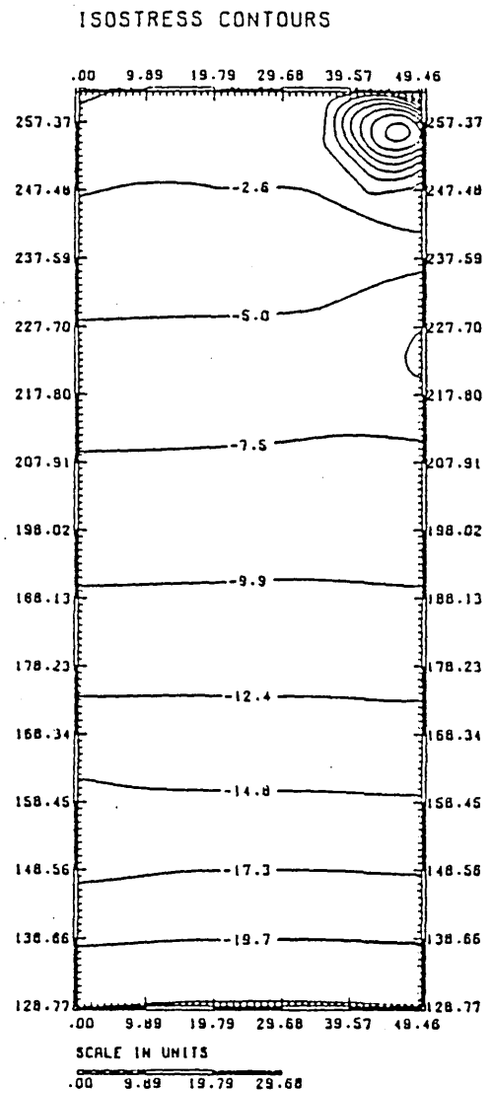


b. Top part of the Billet.

Fig.6.73.Isostress contours of the out-of-plane stress σ_z for Context-21, time step No.1.

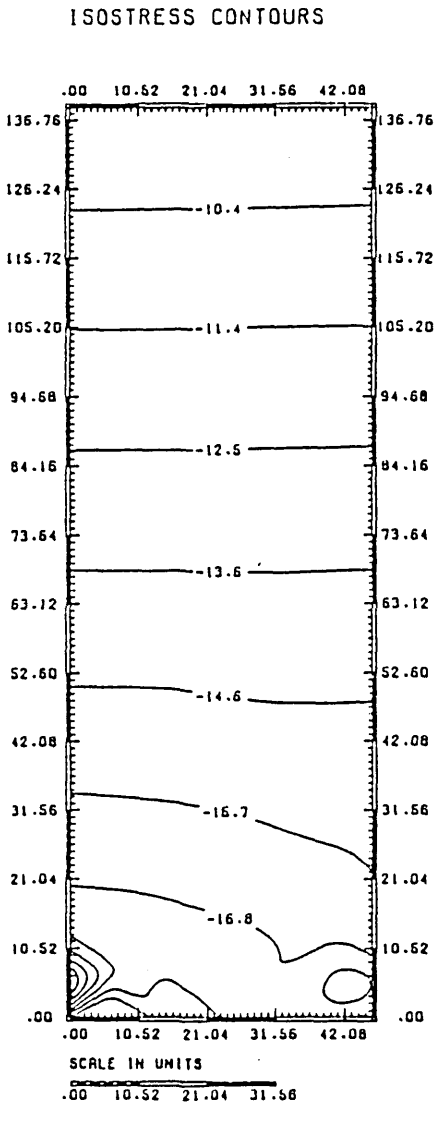


a. Bottom part of the Billet.

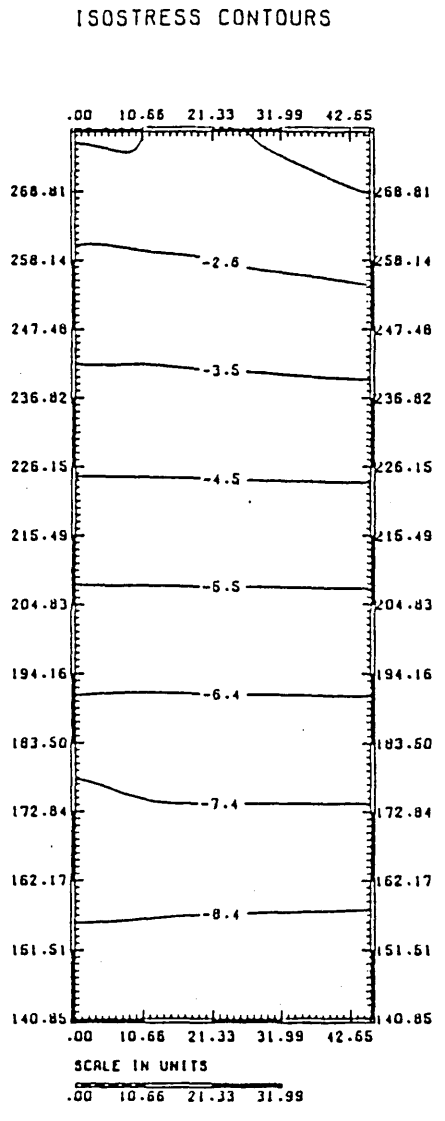


b. Top part of the Billet.

Fig.6.74.Isostress contours of the out-of-plane stress σ_z for Context-21, time step No.30.

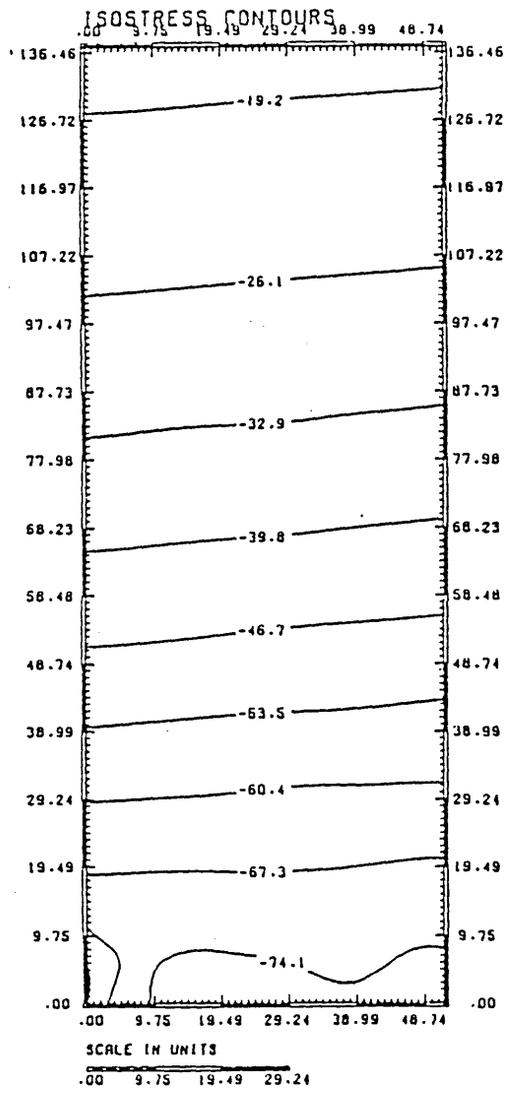


a. Bottom part of the Billet.

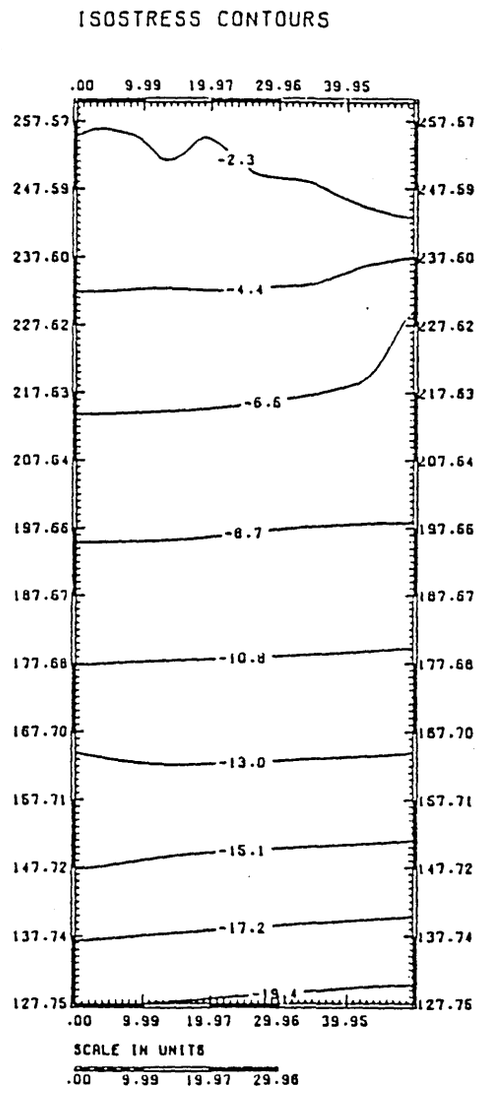


b. Top part of the Billet.

Fig.6.75.Isostress contours of the out-of-plane stress σ_z for Linex-22, time step No.1.

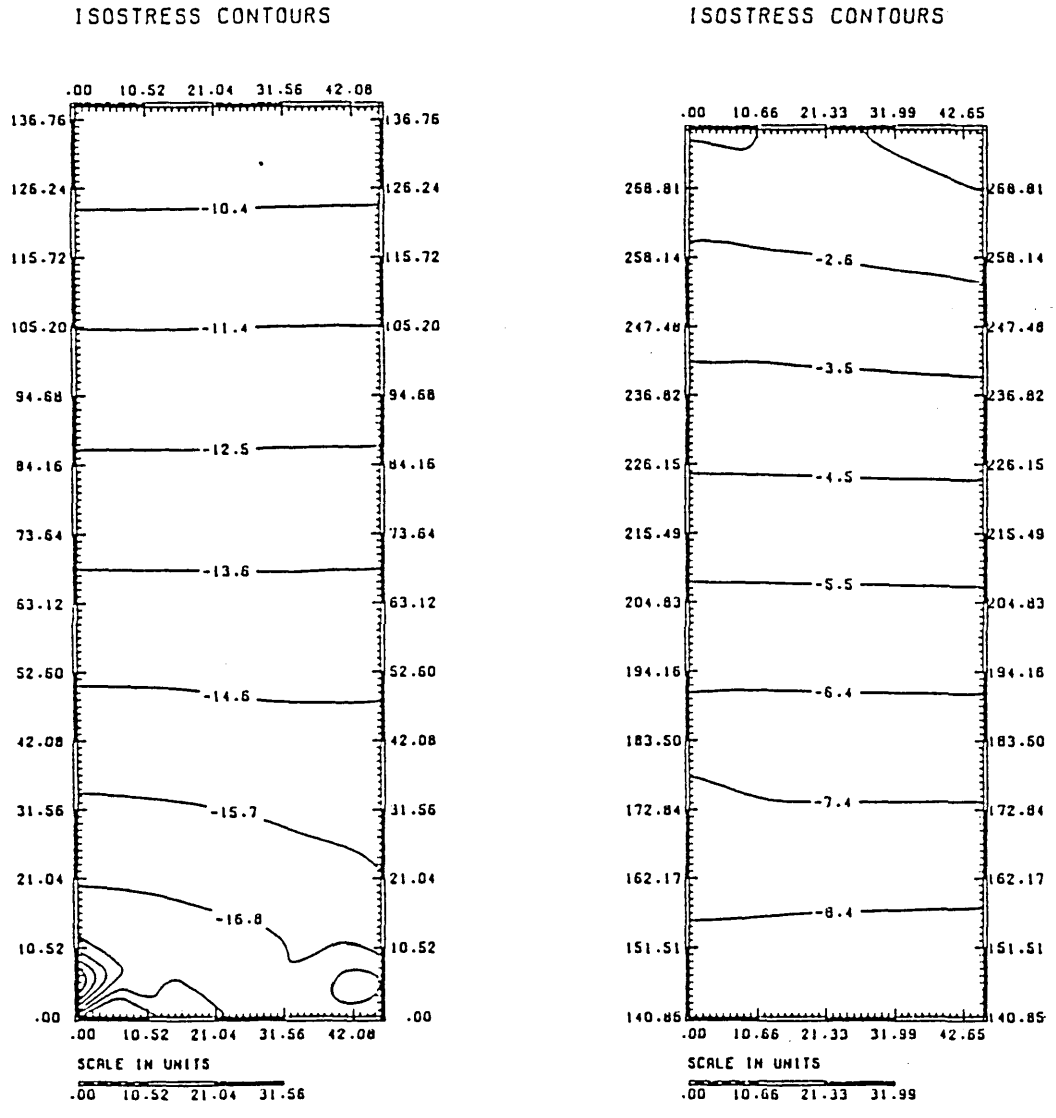


a. Bottom part of the Billet.



b. Top part of the Billet.

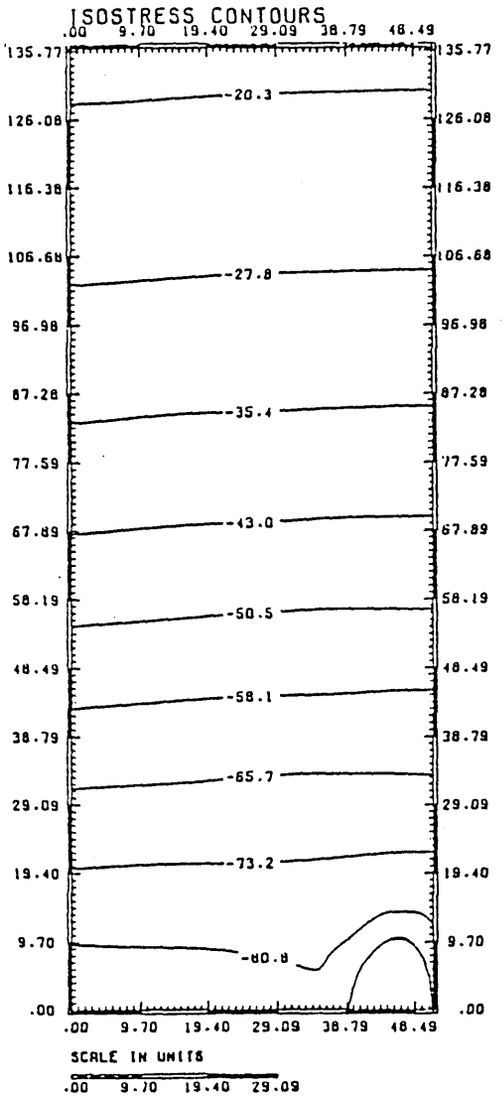
Fig.6.76.Isostress contours of the out-of-plane stress σ_z for Linex-22, time step No.30.



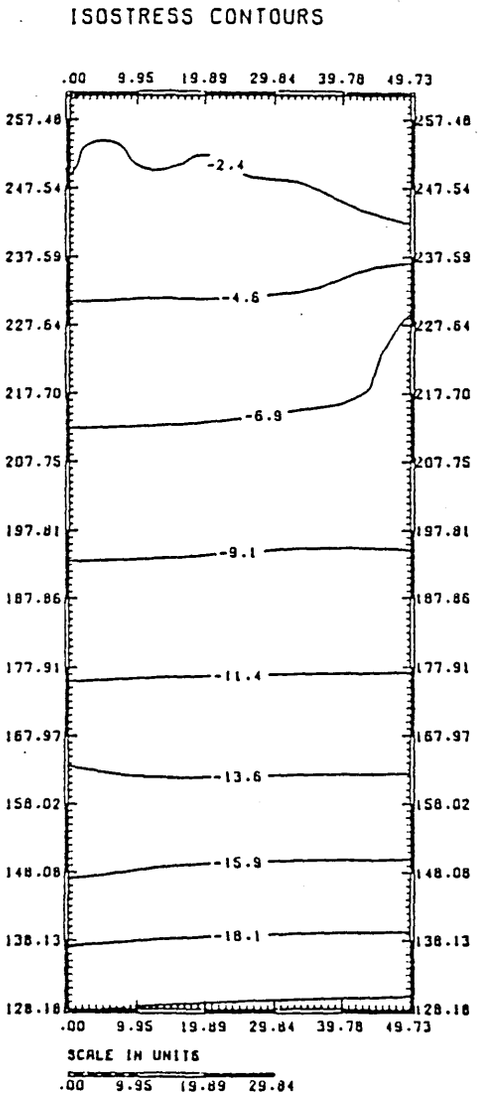
a. Bottom part of the Billet.

b. Top part of the Billet.

Fig.6.77.Isostress contours of the out-of-plane stress σ_z for Conform-23, time step No.1.

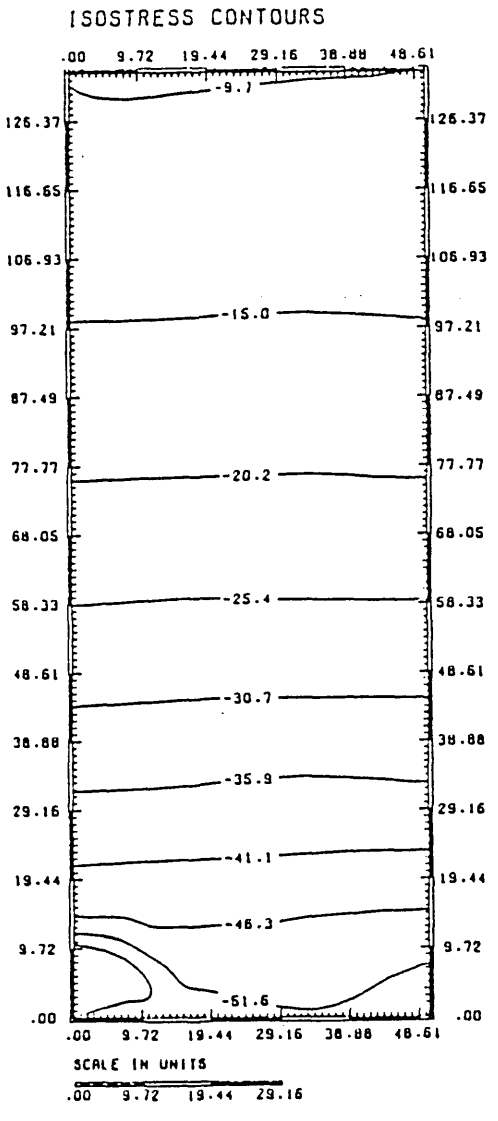


a. Bottom part of the Billet.

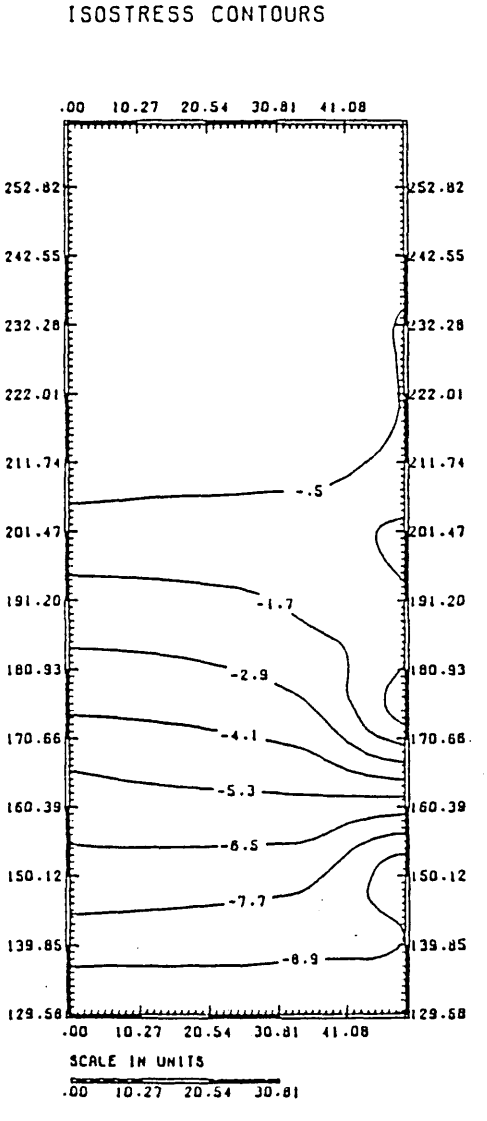


b. Top part of the Billet.

Fig.6.78.Isostress contours of the out-of-plane stress σ_z for Conform-23, time step No.30.

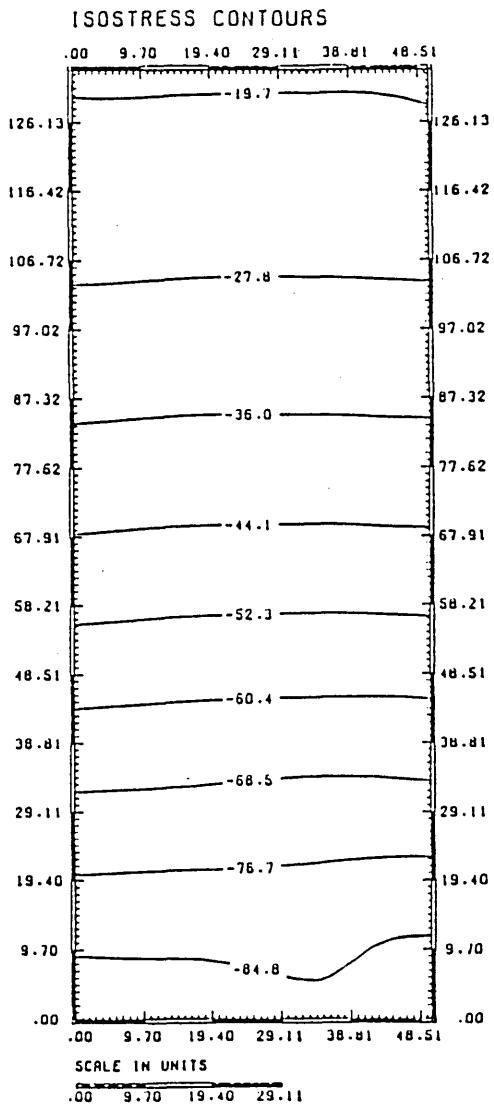


a. Bottom part of the Billet.

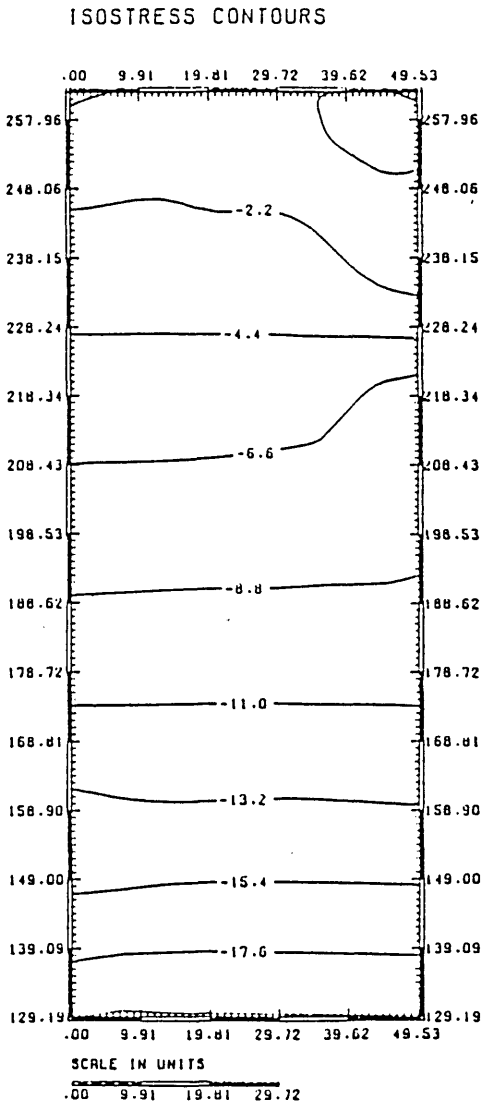


b. Top part of the Billet.

Fig.6.79.Isostress contours of the out-of-plane stress σ_z for Context-24, time step No.30.

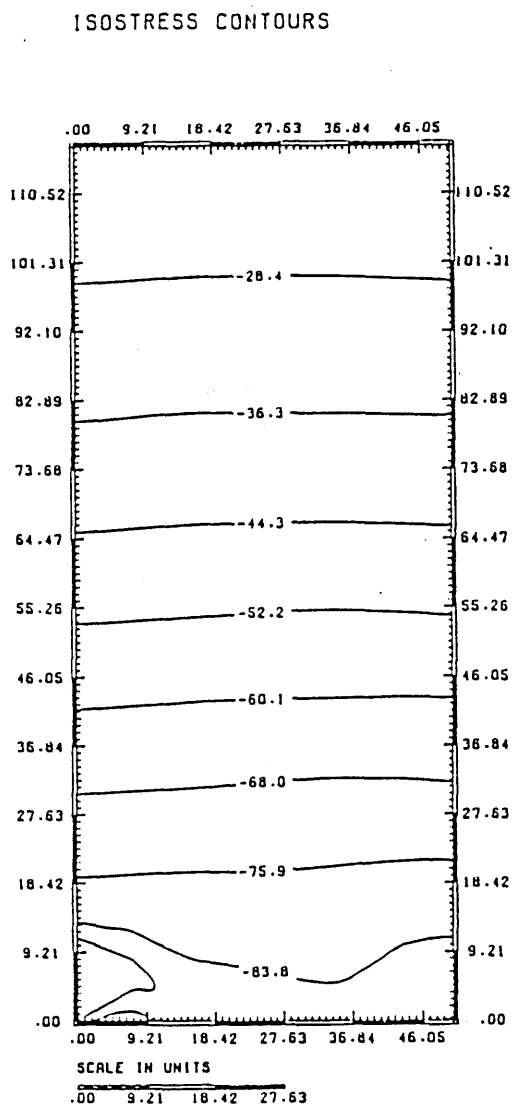


a. Bottom part of the Billet.

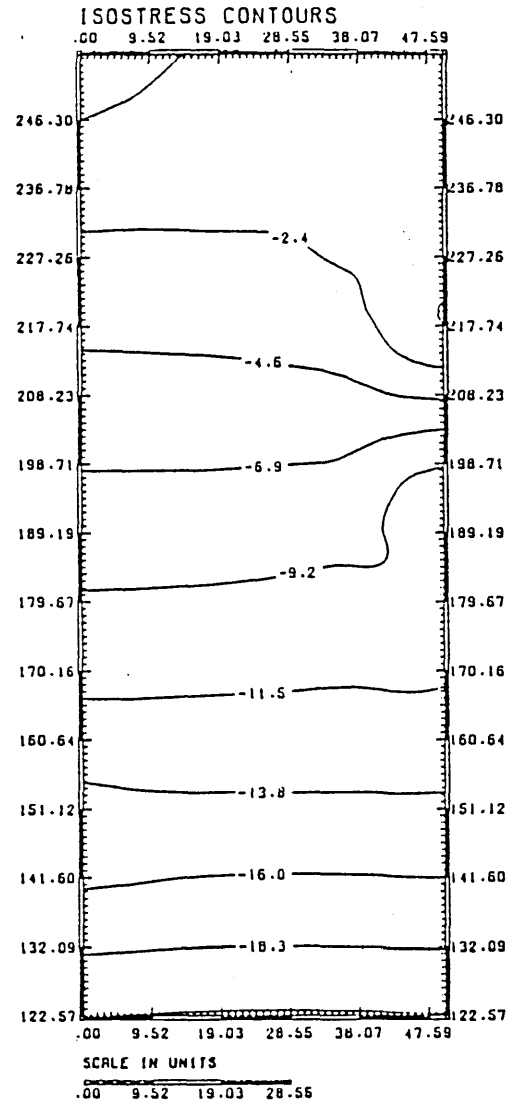


b. Top part of the Billet.

Fig.6.80.Isostress contours of the out-of-plane stress σ_z for Context-27, time step No.30.

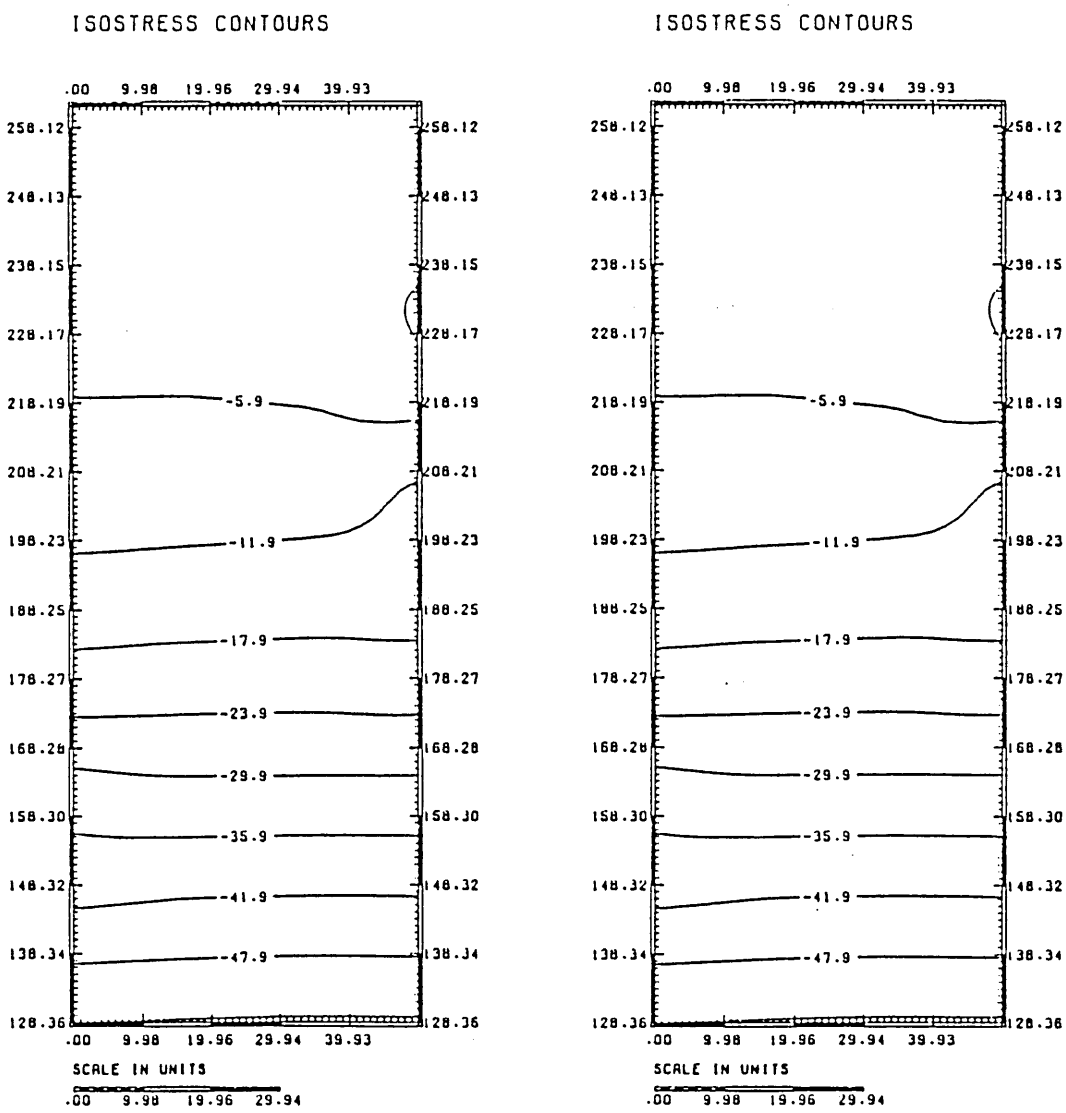


a. Bottom part of the Billet.



b. Top part of the Billet.

Fig.6.81.Isostress contours of the out-of-plane stress σ_z for Context-33, time step No.30.



a. Bottom part of the Billet.

b. Top part of the Billet.

Fig.6.82.Isostress contours of the out-of-plane stress σ_z for Context-36, time step No.30.

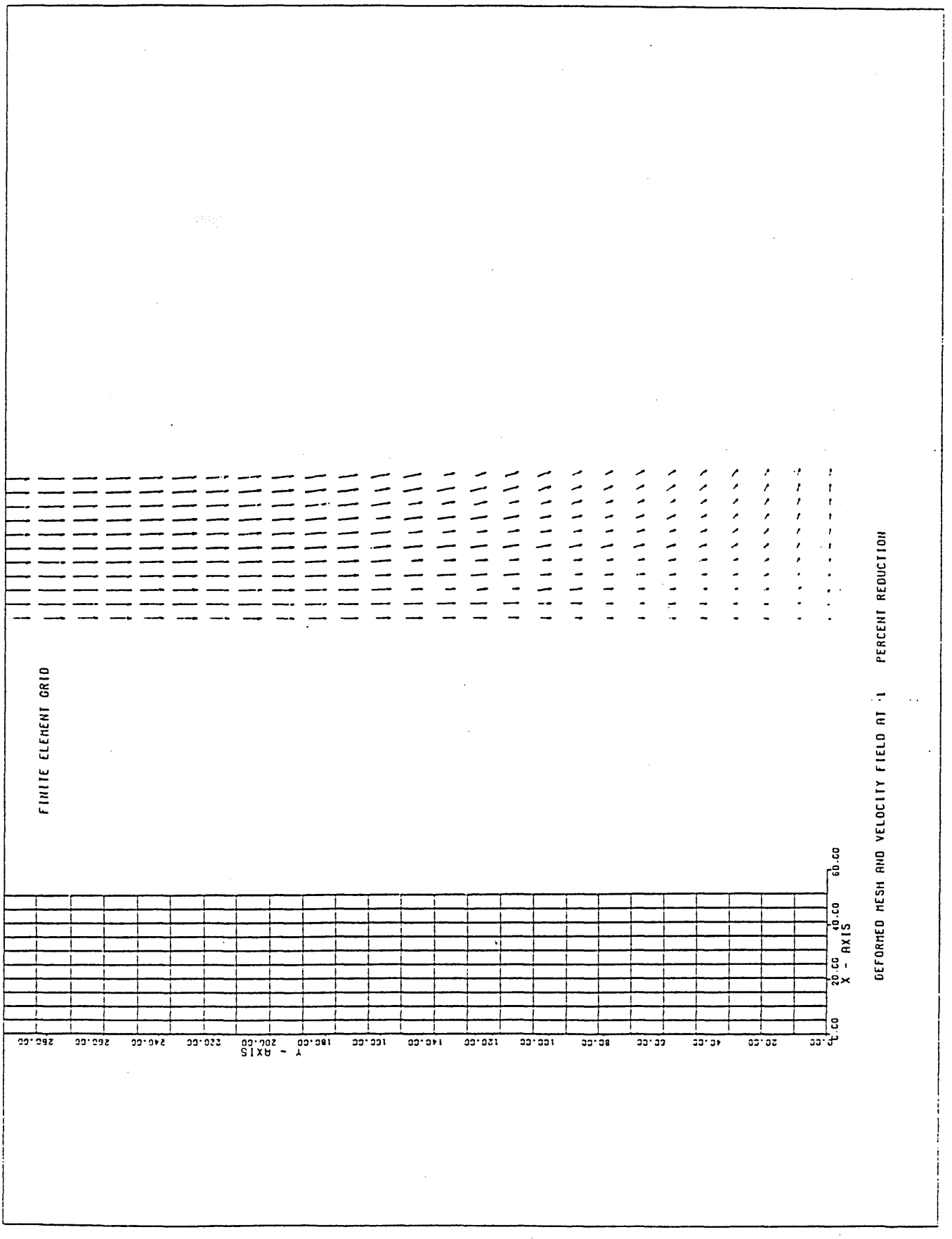


Fig.6.83. Deformed grid and associated velocity field for Context-21, time step No.1, 1.42% rediction in height.

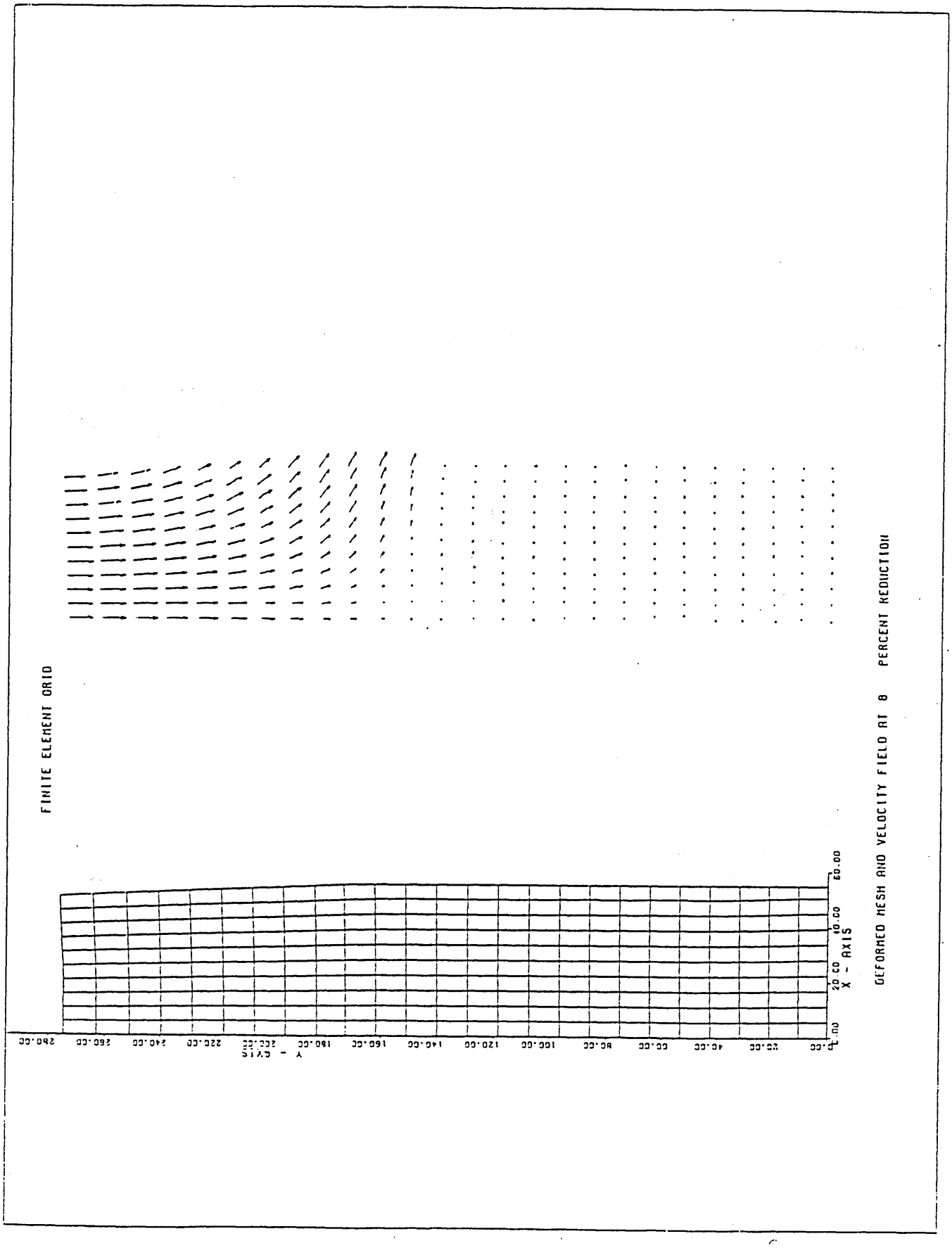


Fig.6.84. Deformed grid and associated velocity field for Context-21, time step No.9, 7.88% rediction in height.

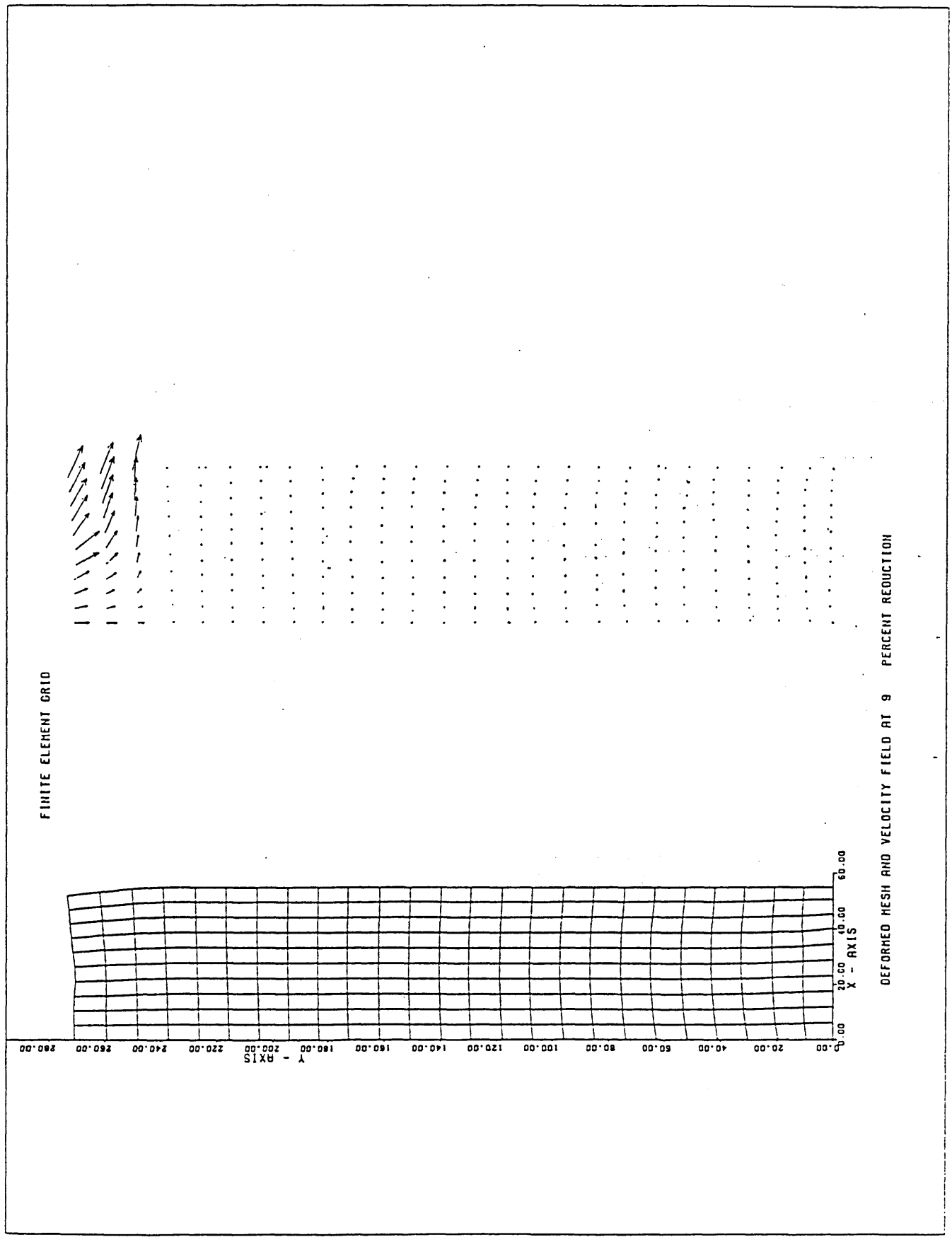


Fig.6.85. Deformed grid and associated velocity field for Context-21, time step No.30, 8.85% rediction in height.

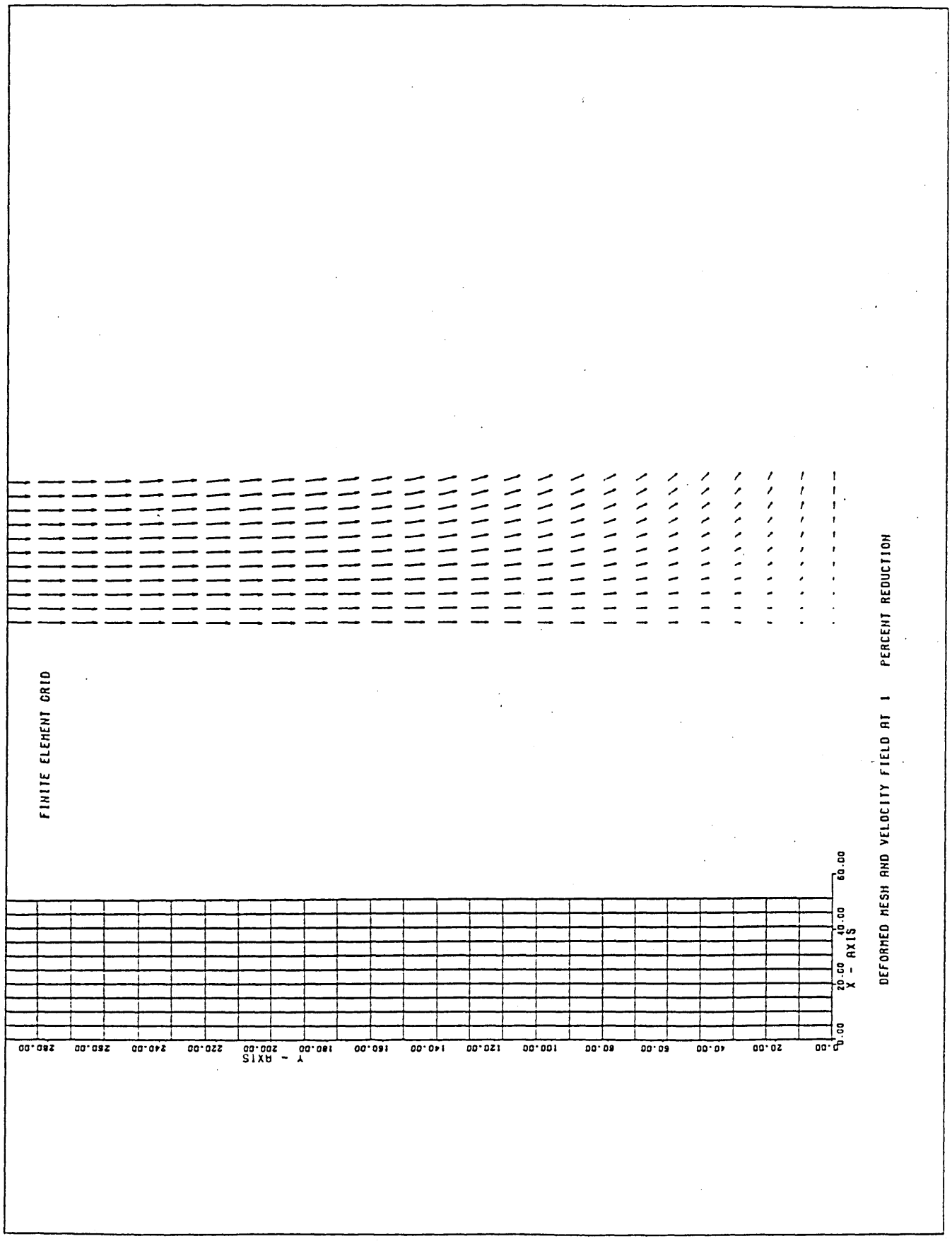


Fig.6.86. Deformed grid and associated velocity field for Linex-22, time step No.1, 1.42% rediction in height.

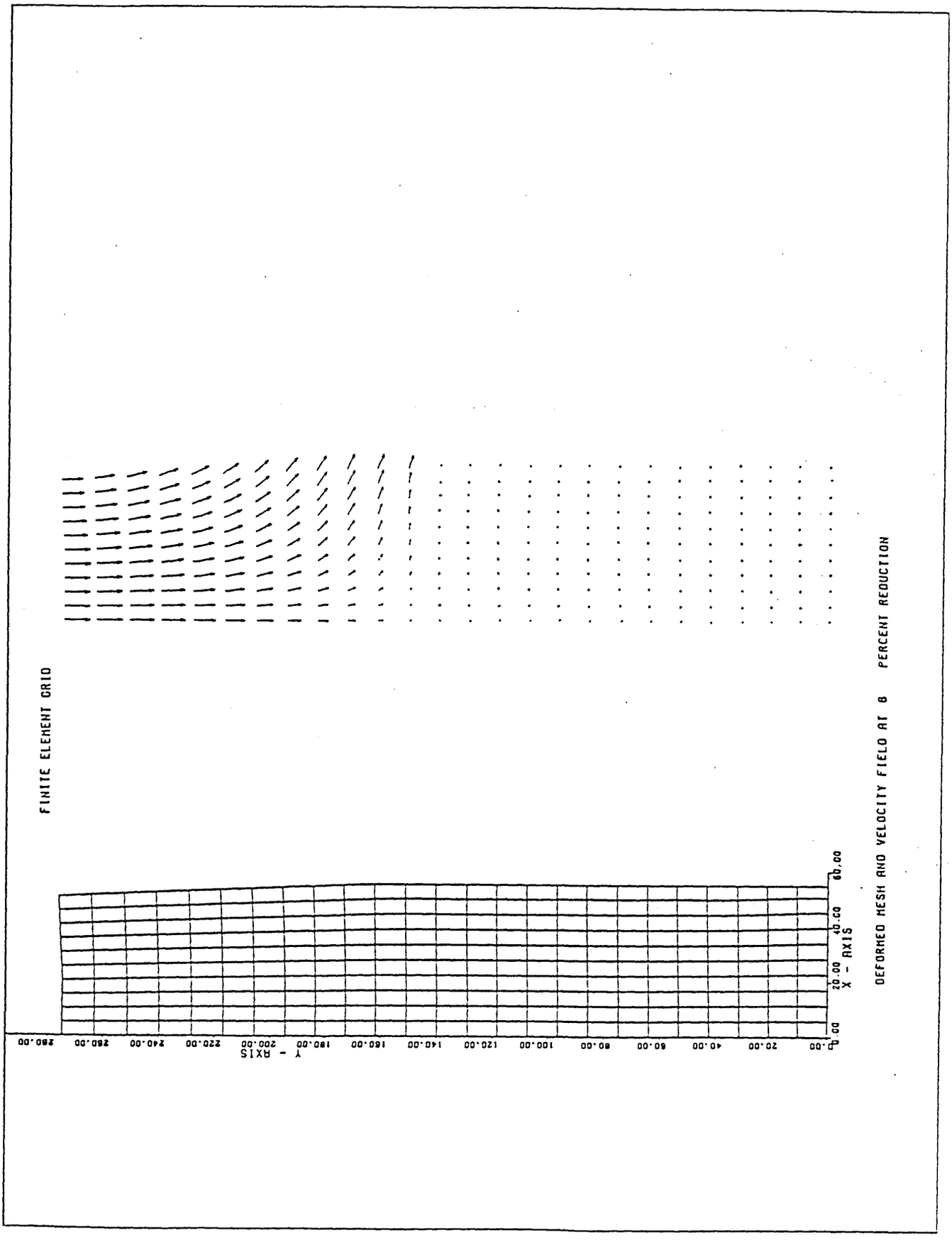


Fig.6.87. Deformed grid and associated velocity field for Linex-22, time step No.9, 7.87% rediction in height.

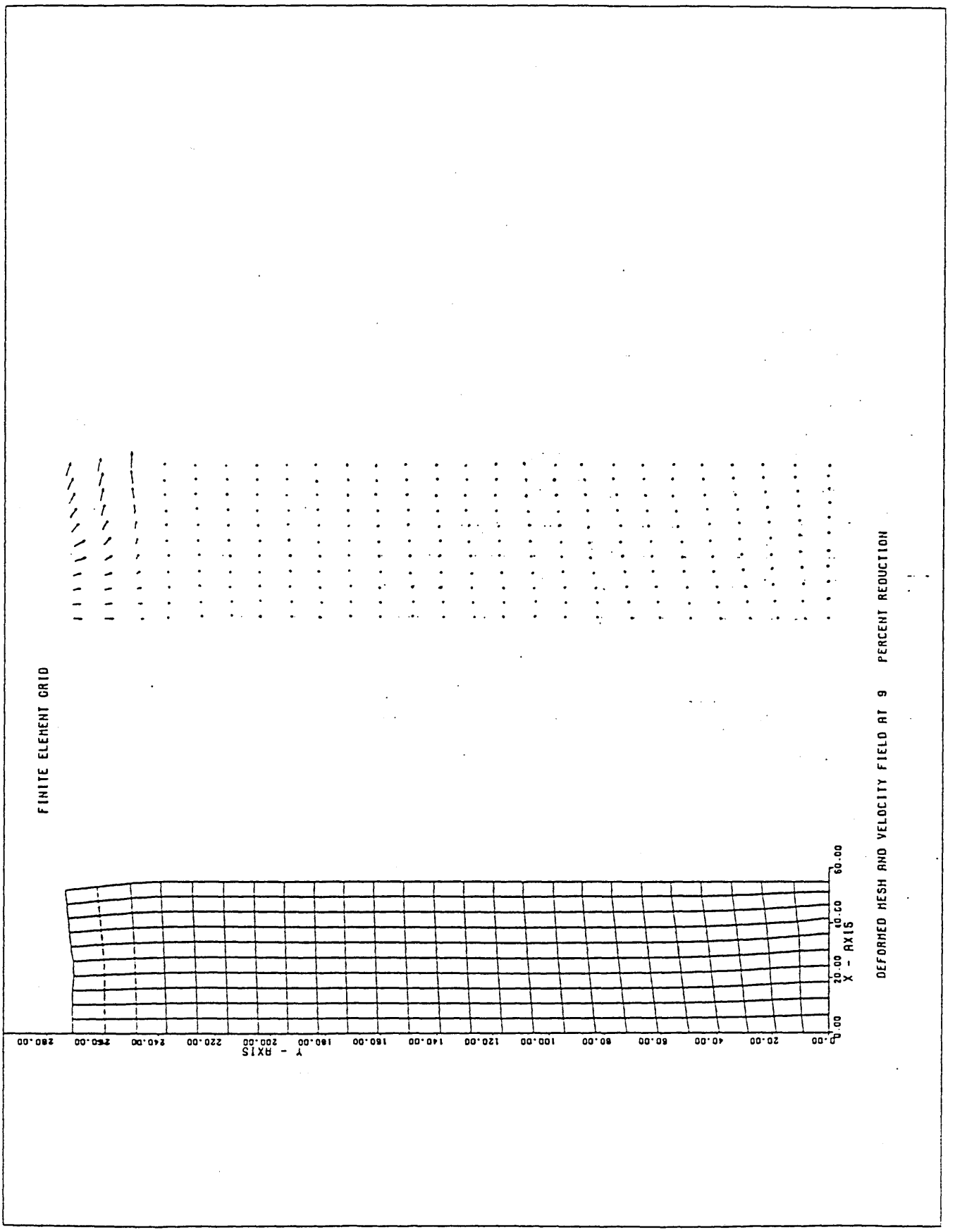


Fig.6.88. Deformed grid and associated velocity field for Linex-22, time step No.30, 8.77% rediction in height.

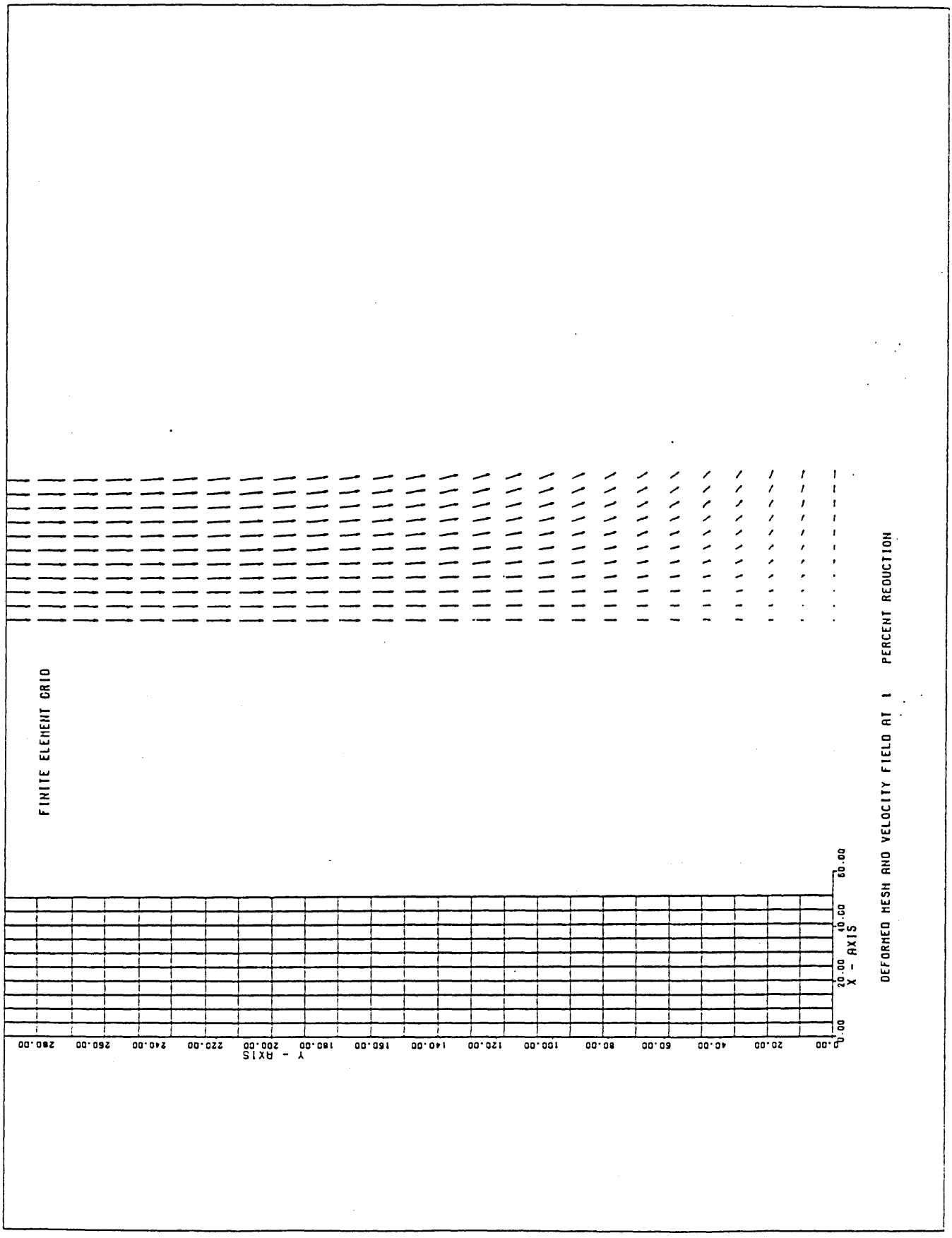


Fig.6.89. Deformed grid and associated velocity field for Conform-23, time step No.1, 1.42% rediction in height.

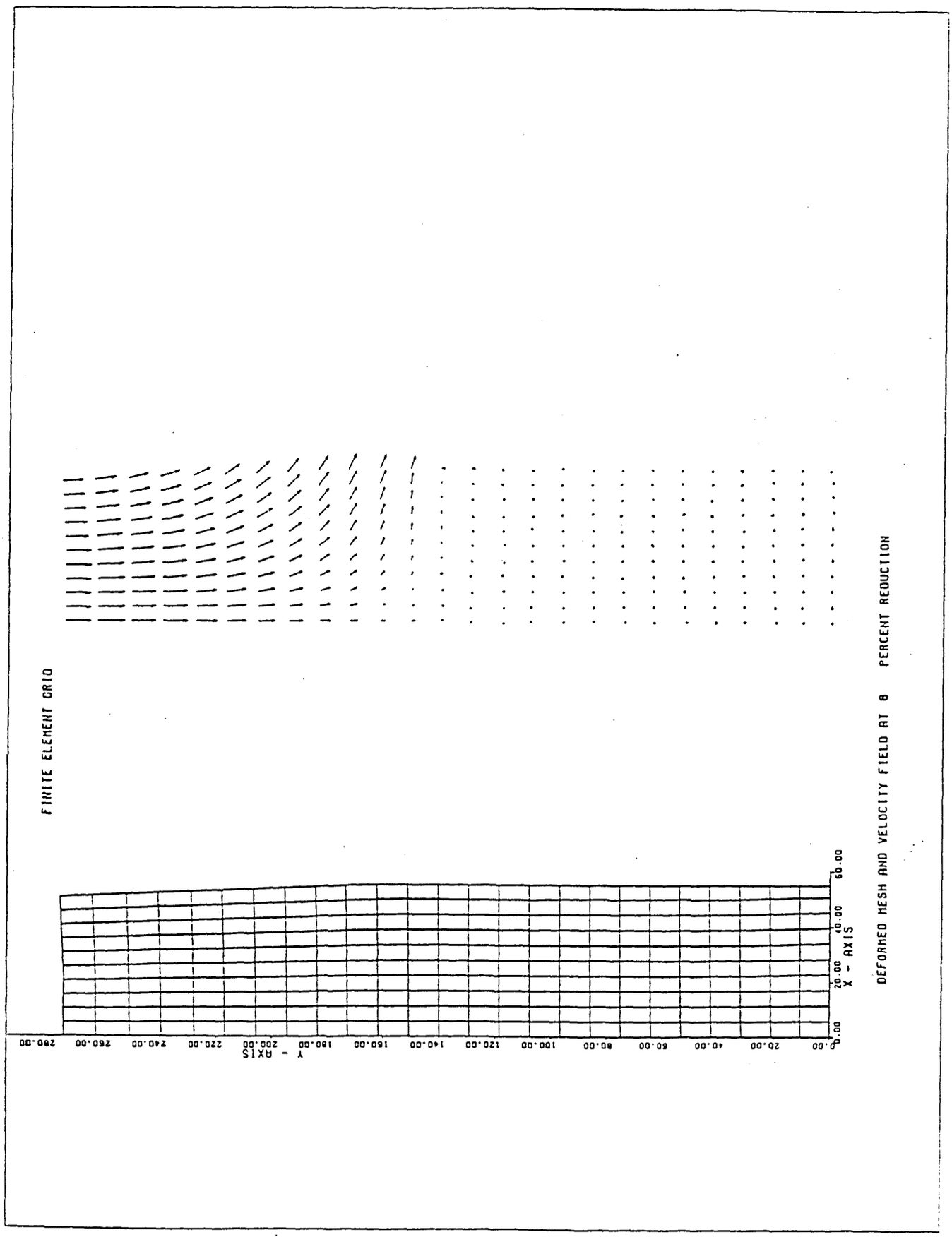


Fig.6.90. Deformed grid and associated velocity field for Conform-23, time step No.9, 7.88% rediction in height.

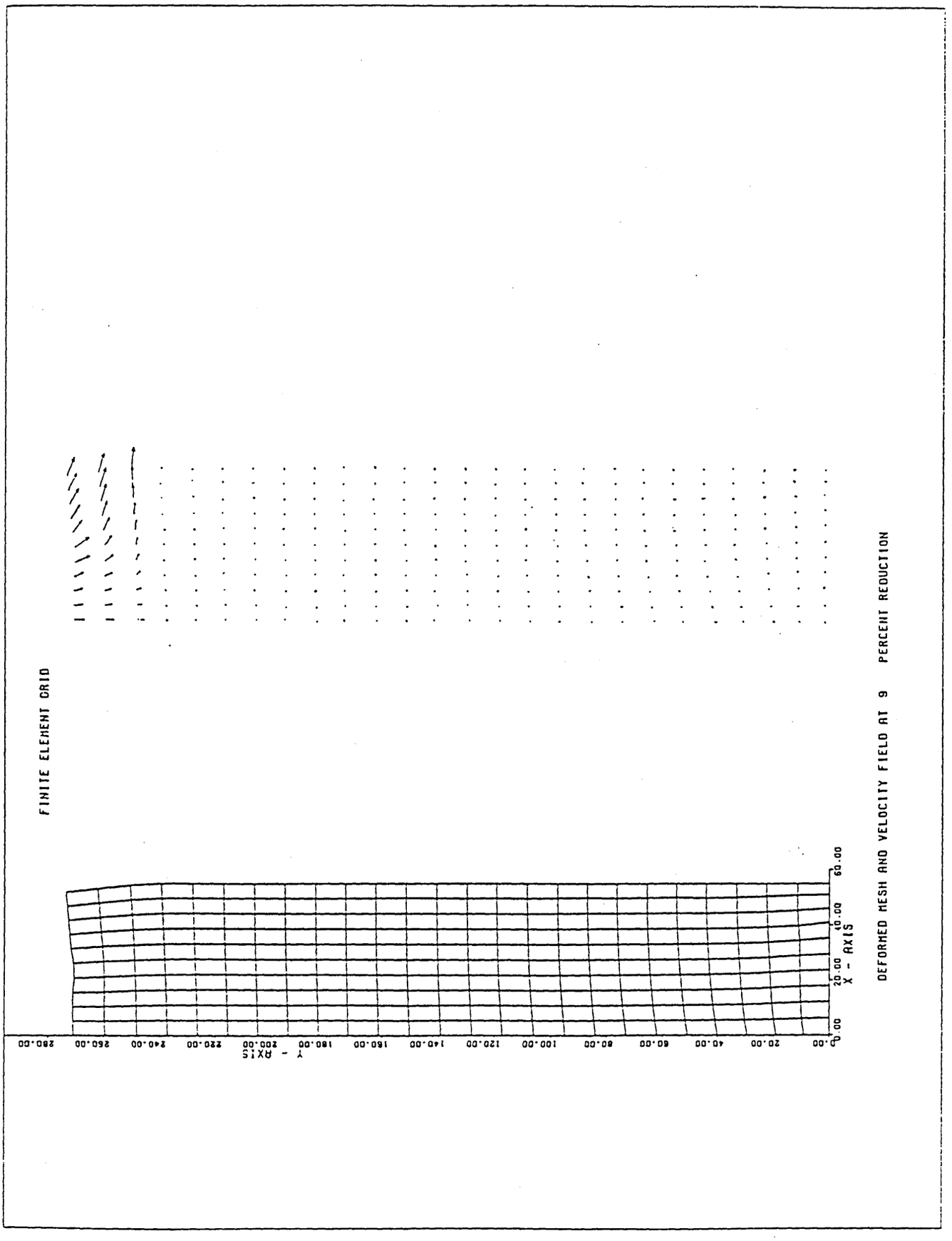


Fig.6.91. Deformed grid and associated velocity field s for Conform-23, time step No.30, 8.81% rediction in height.

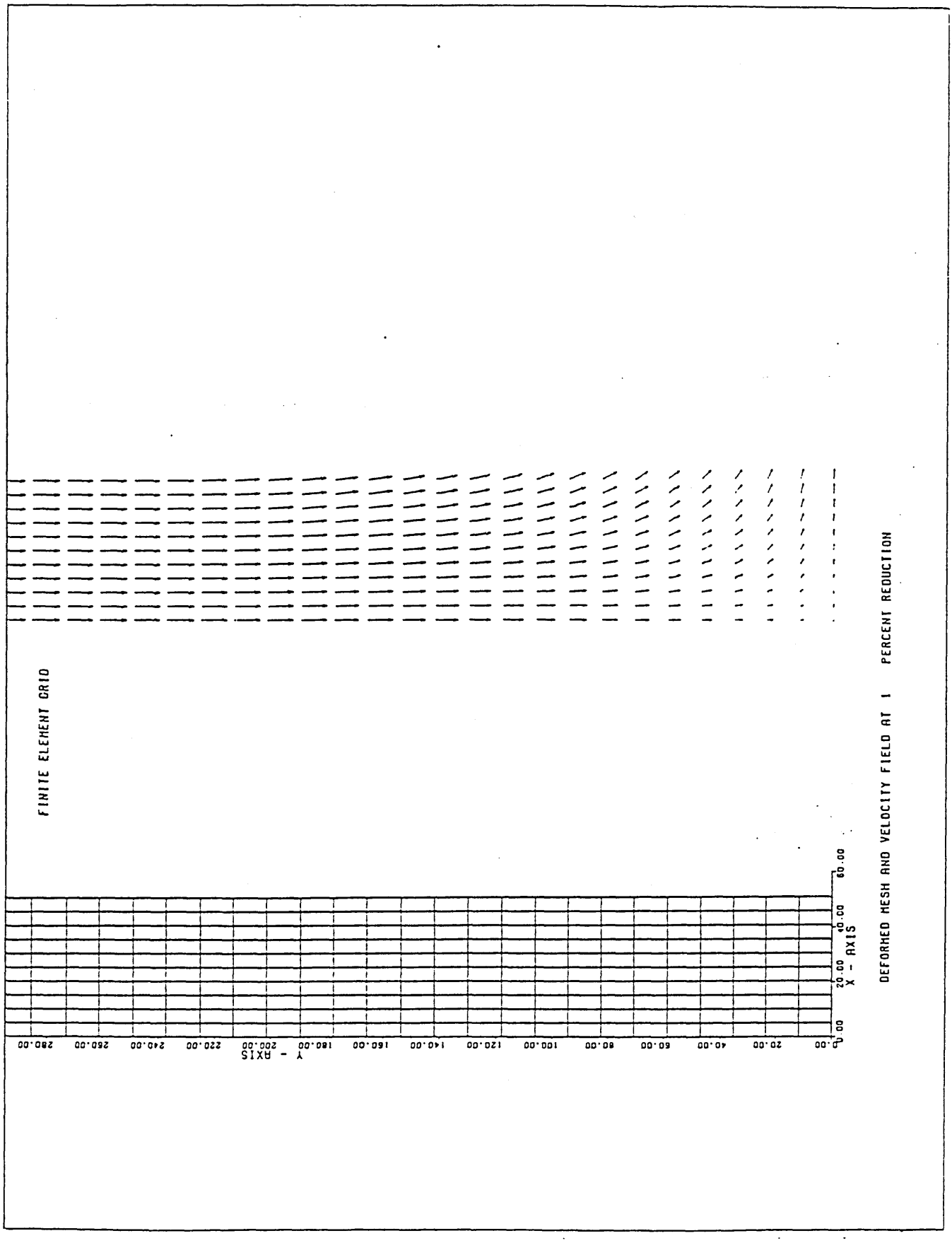


Fig.6.92. Deformed grid and associated velocity field for Context-24, time step No.1, 0.89% rediction in height.

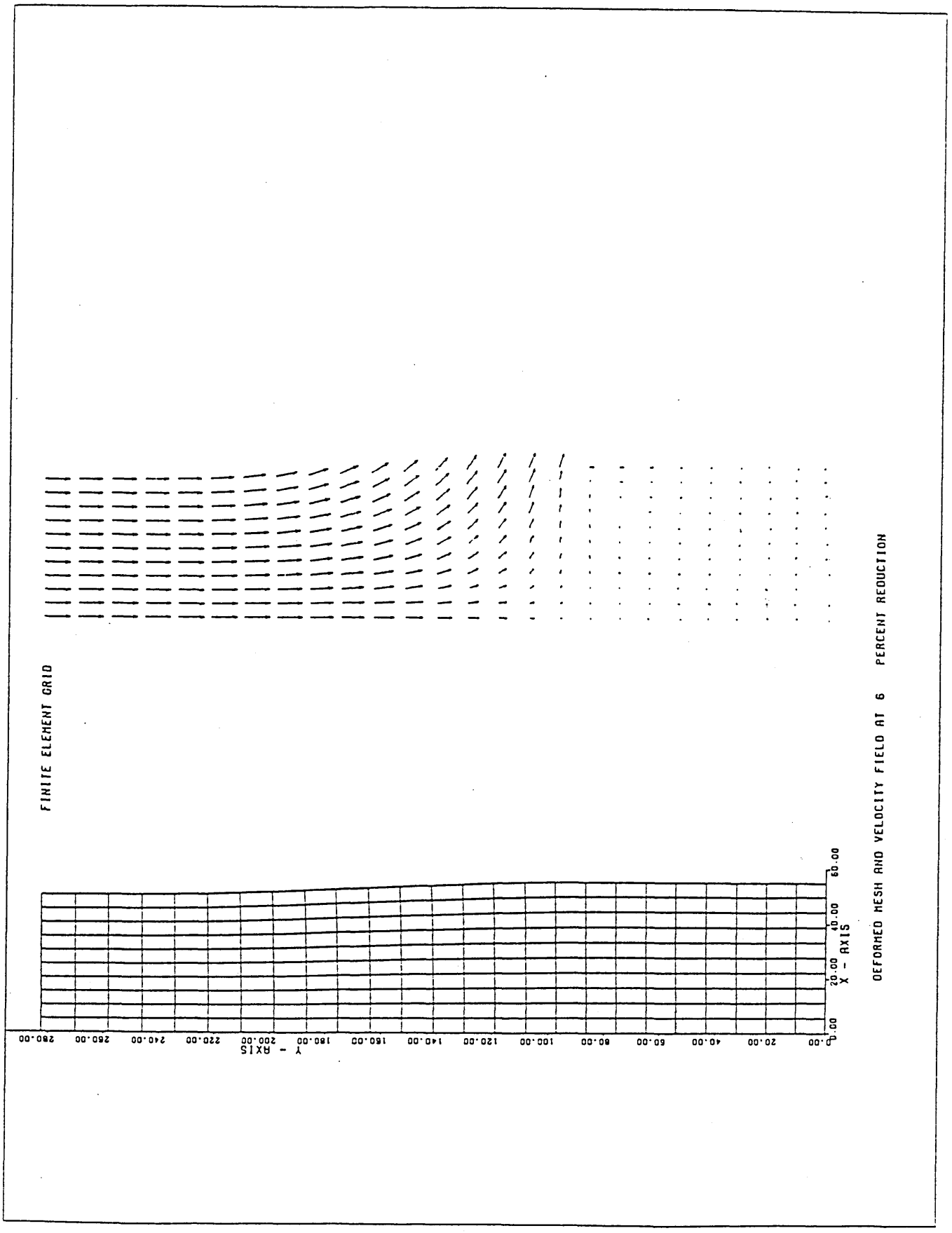


Fig.6.93. Deformed grid and associated velocity field for Context-24, time step No.9, 5.82% rediction in height.

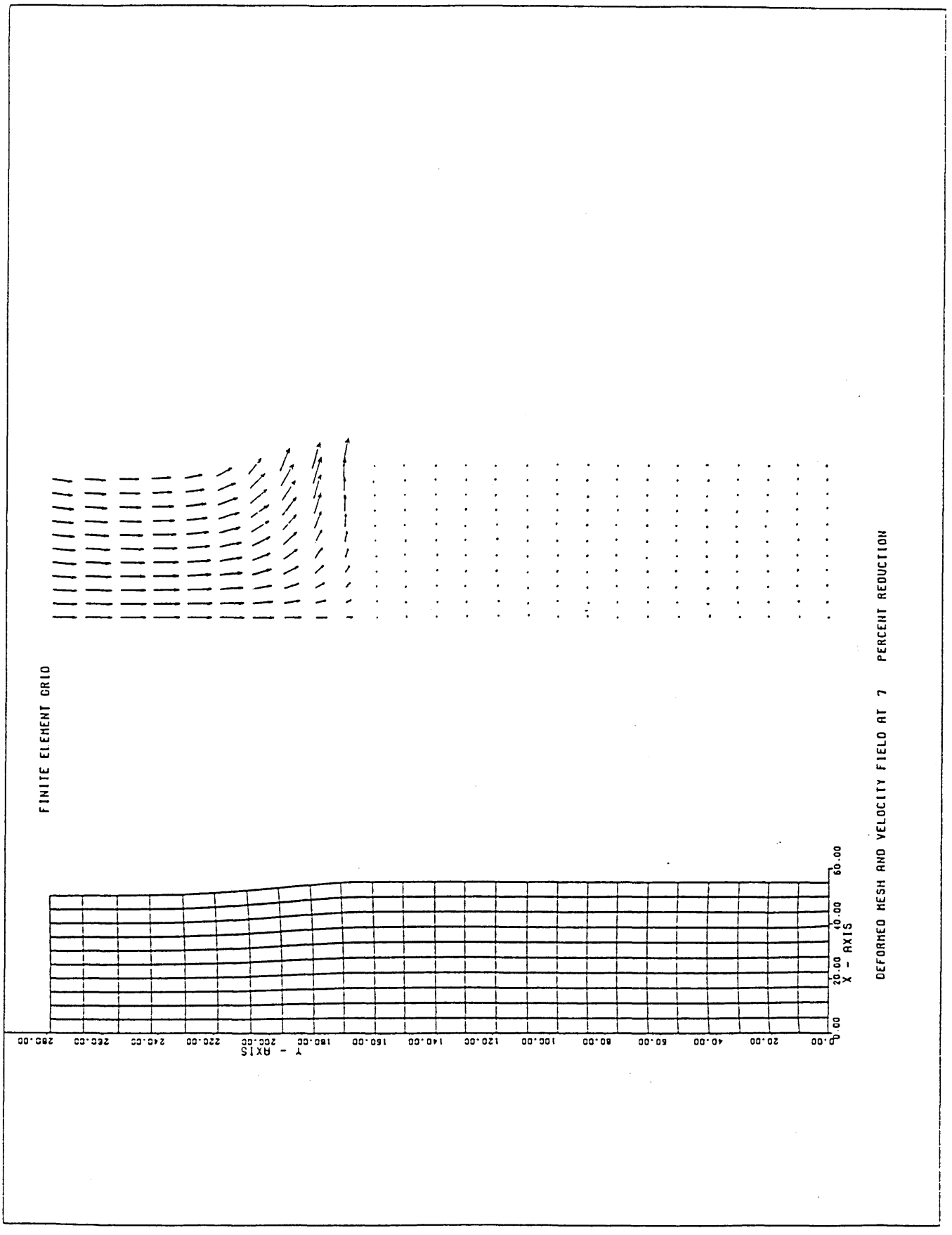


Fig.6.94. Deformed grid and associated velocity field for Context-24, time step No.30, 6.92% rediction in height.

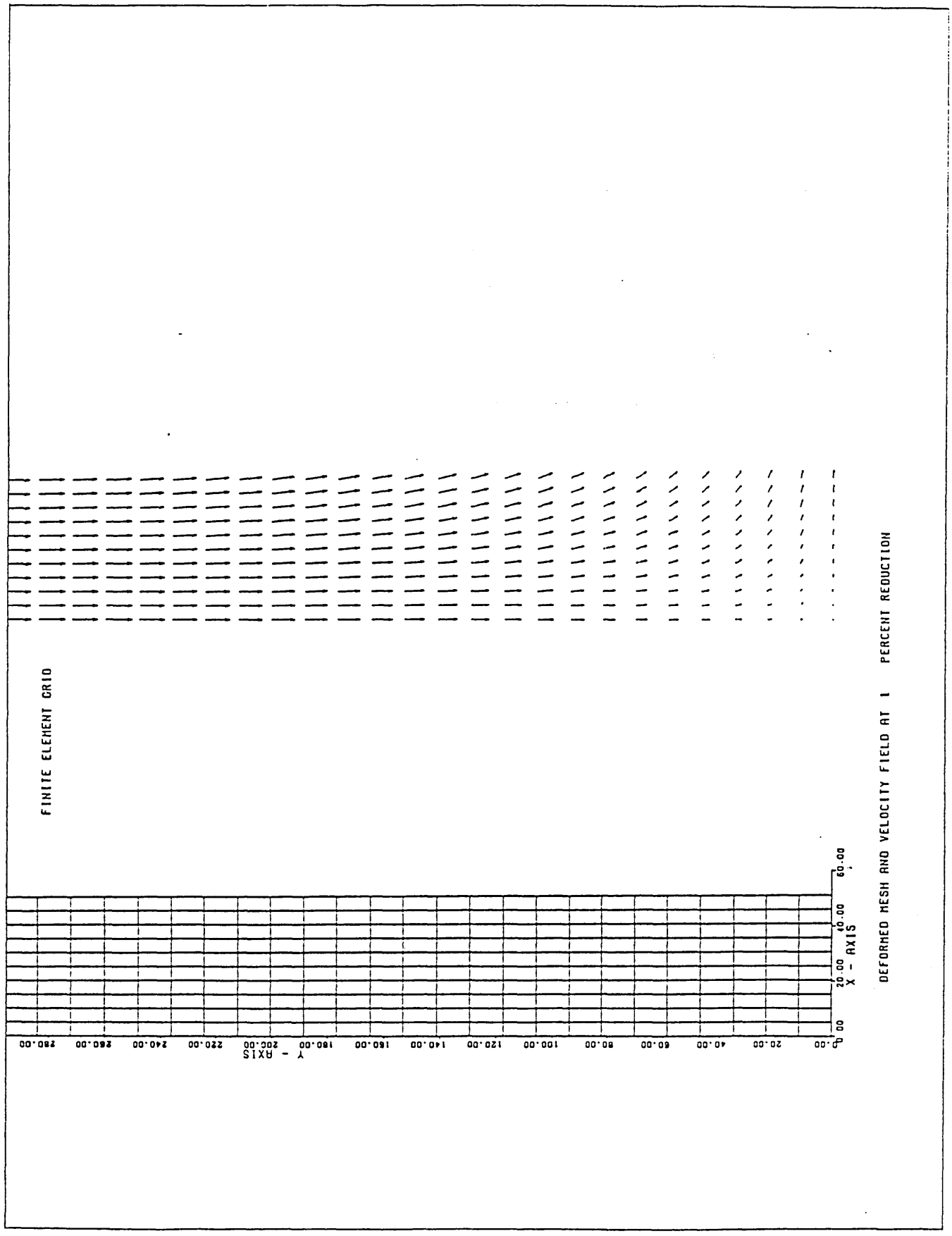


Fig.6.95. Deformed grid and associated velocity field for Context-27, time step No.1, 1.27% rediction in height.

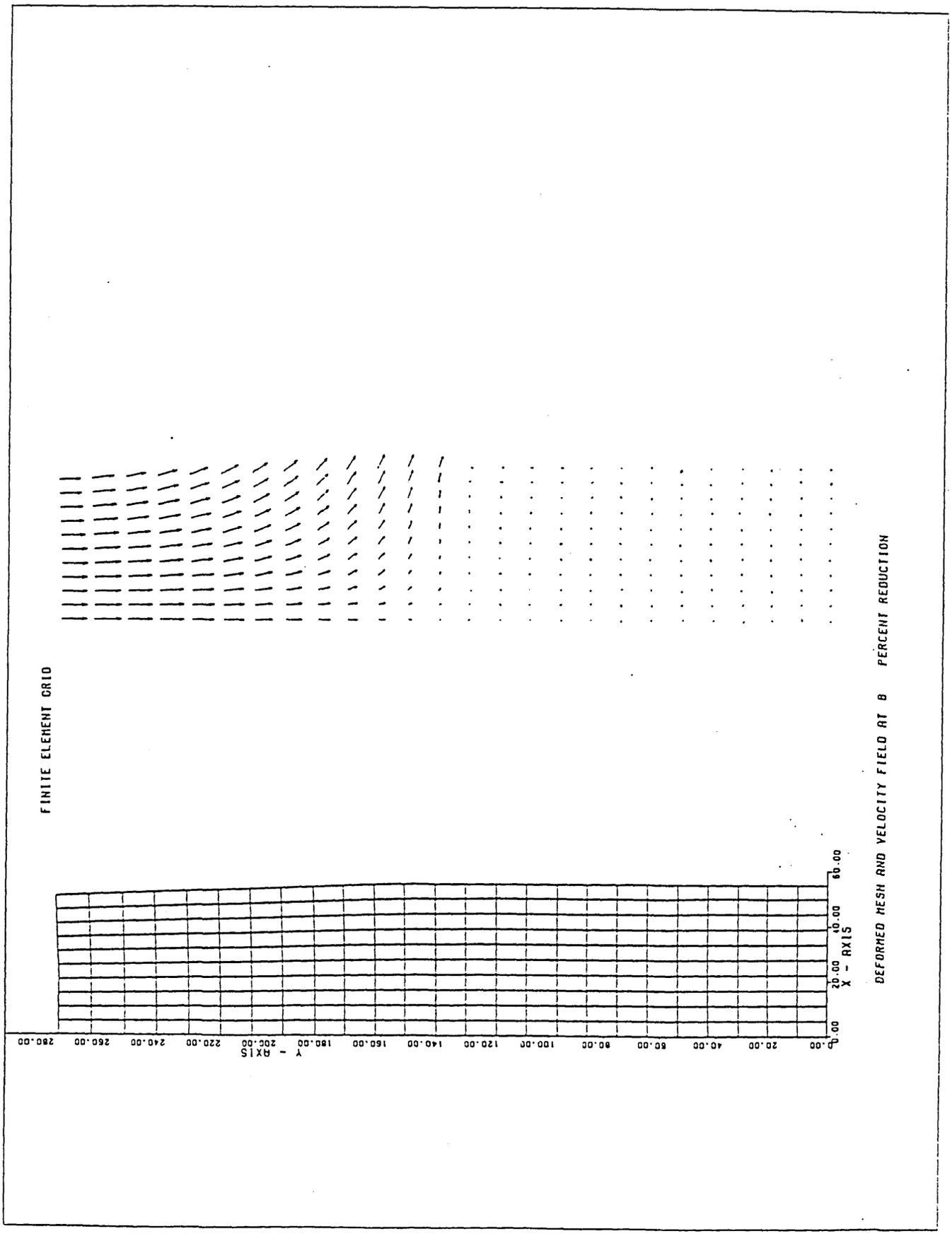


Fig.6.96. Deformed grid and associated velocity field for Context-27, time step No.9, 7.56% rediction in height.

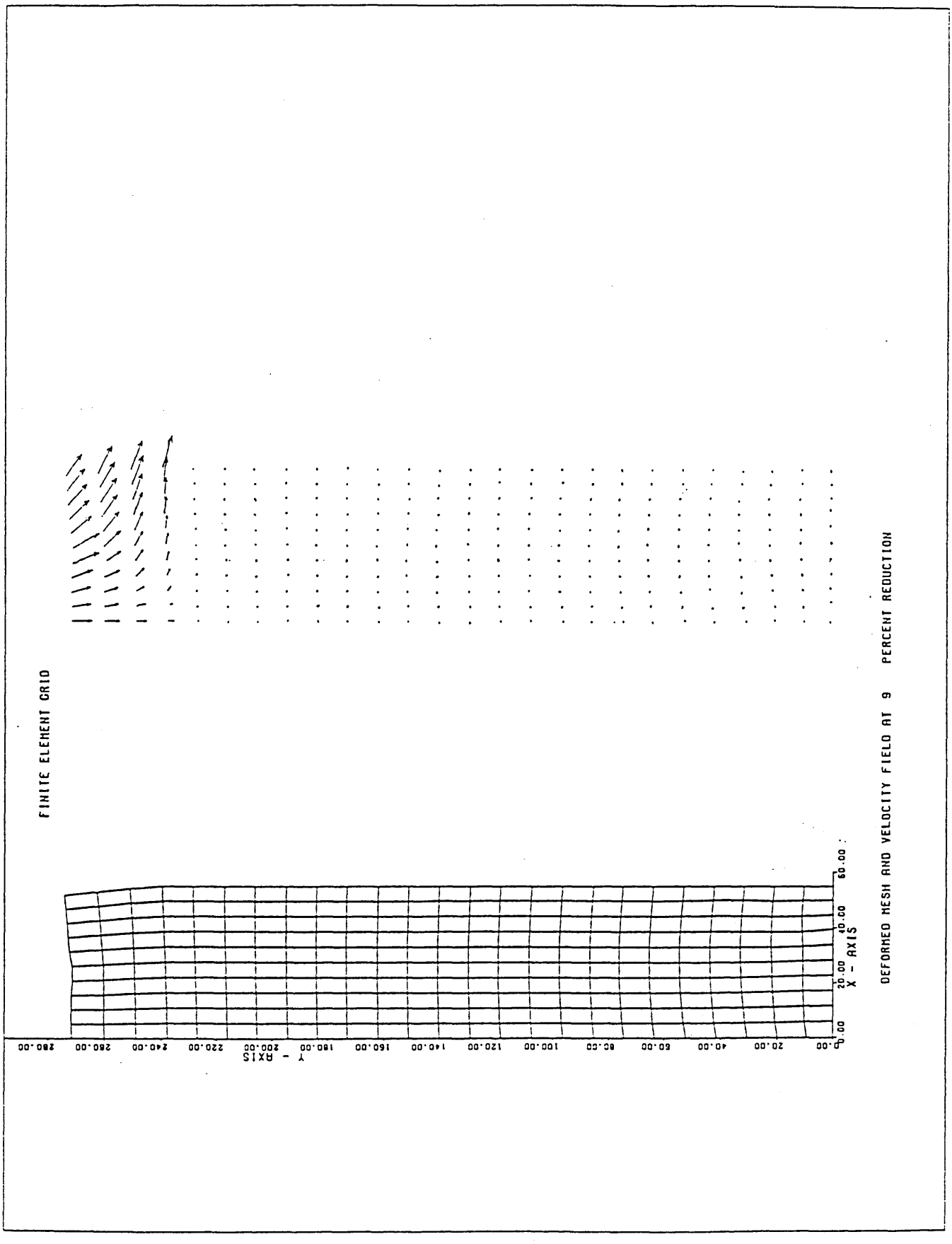


Fig.6.97. Deformed grid and associated velocity field for Context-27, time step No.30, 8.65% rediction in height.

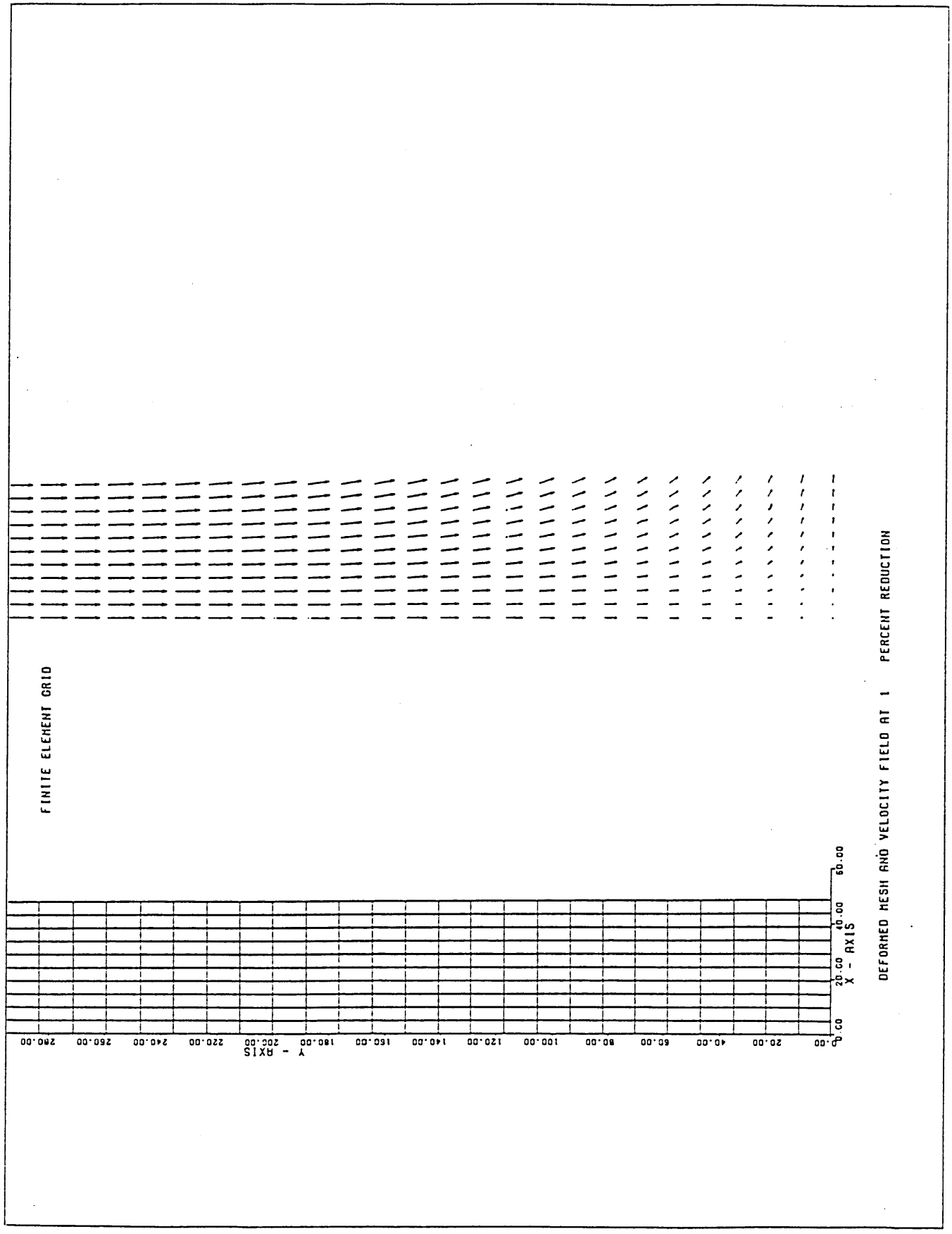


Fig.6.98. Deformed grid and associated velocity field for Context-33, time step No.1, 1.47% rediction in height.

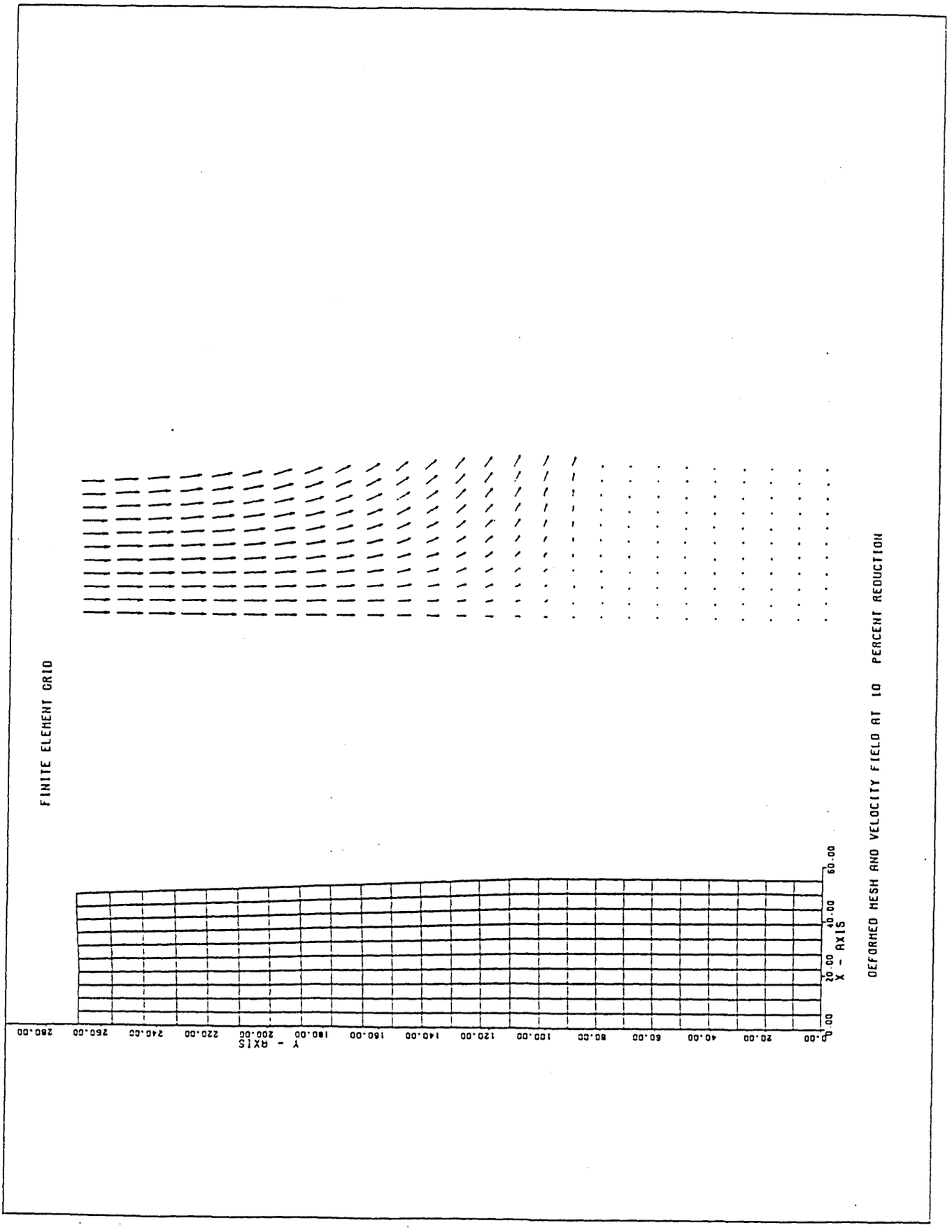


Fig.6.99. Deformed grid and associated velocity field for Context-33, time step No.9, 10.14% rediction in height.

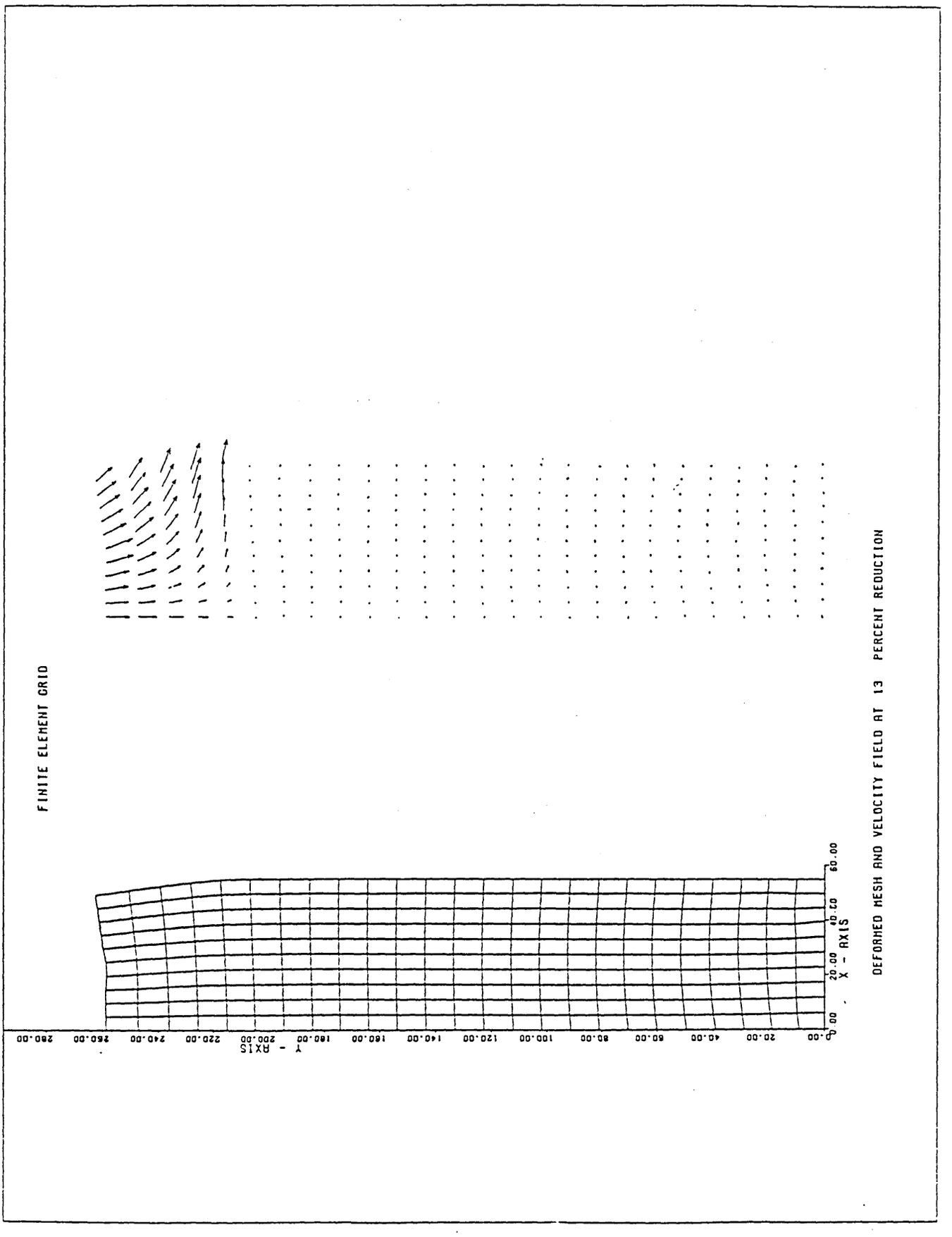


Fig.6.100. Deformed grid and associated velocity field for Context-33, time step No.30, 12.57% rediction in height.

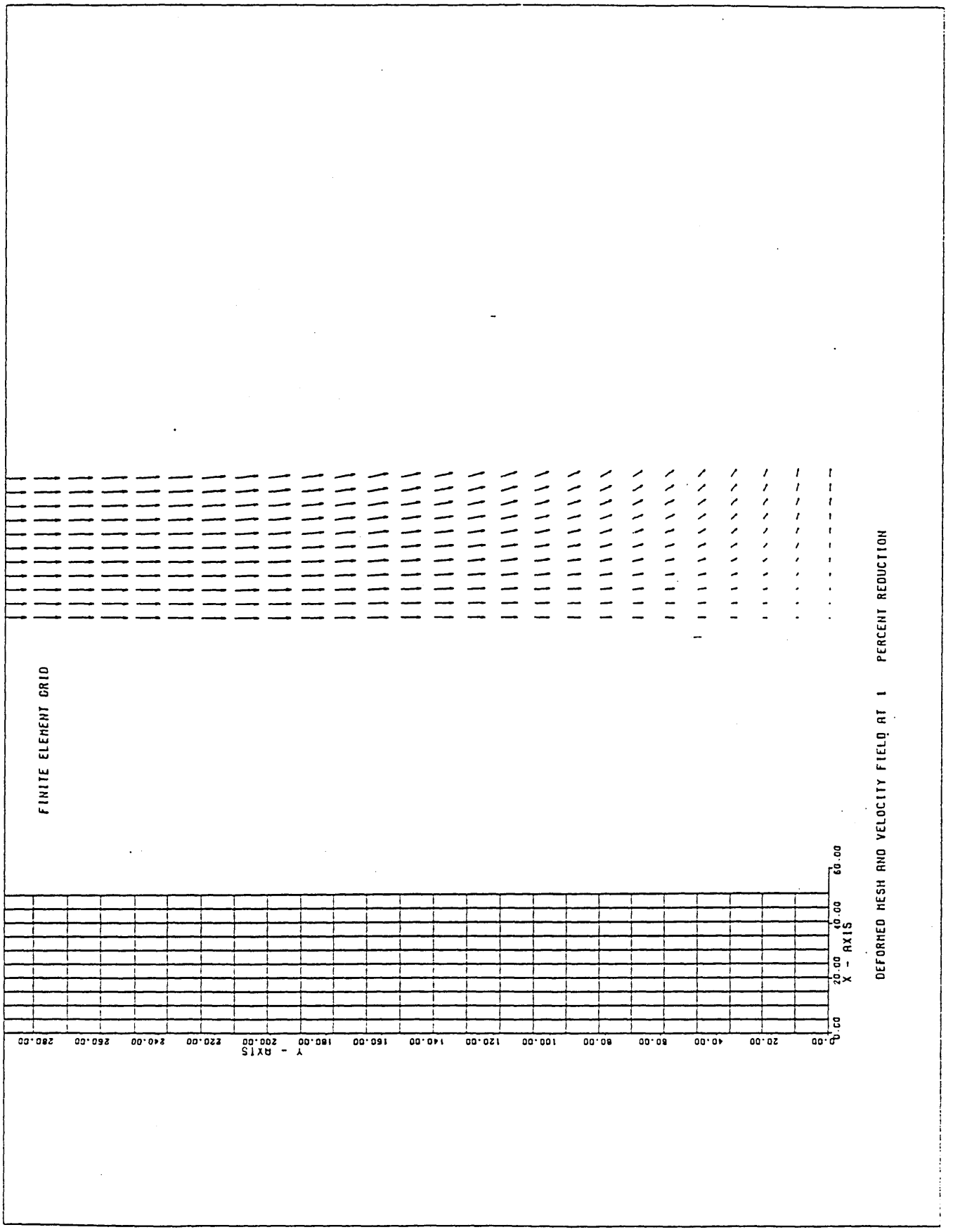


Fig.6.101. Deformed grid and associated velocity field for Context-36, time step No.1, 1.06% rediction in height.

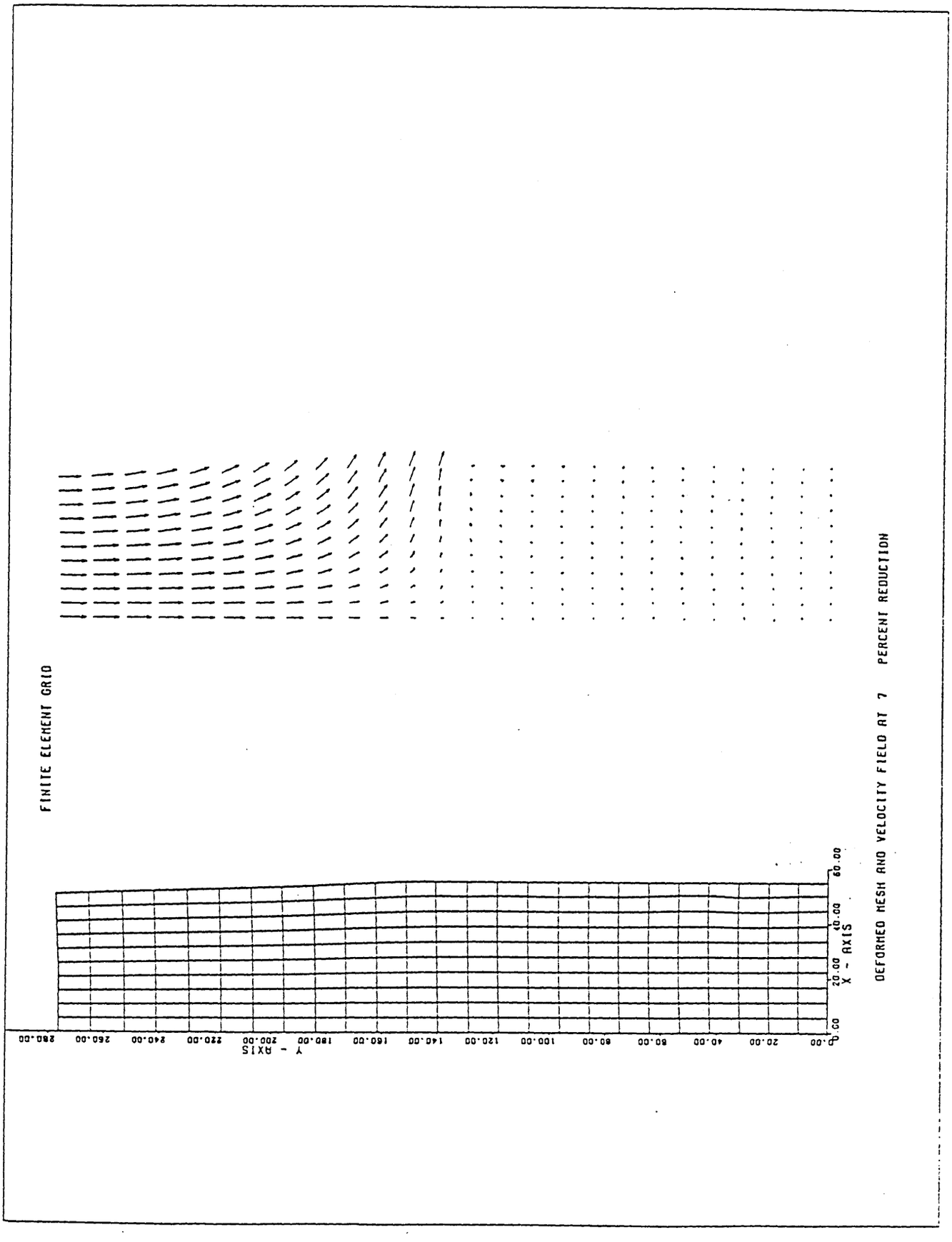


Fig.6.102. Deformed grid and associated velocity field for Context-36, time step No.9, 7.46% rediction in height.

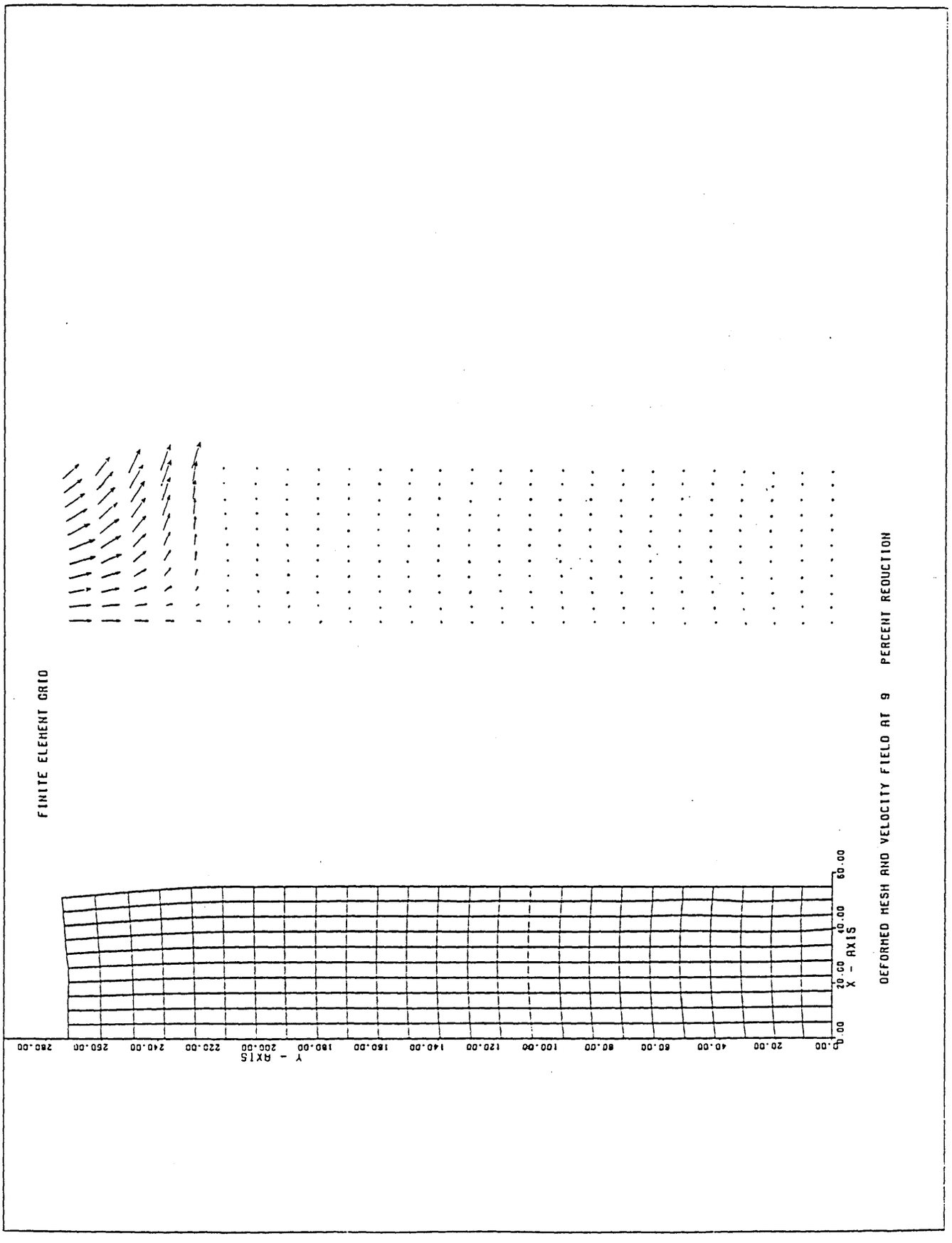


Fig.6.103. Deformed grid and associated velocity field for Context-36, time step No.30, 8.57% rediction in height.

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

7.1. CONCLUSIONS

The main objective of this work was to analyse the development of the stresses and strain fields during continuous extrusion before the steady state is reached, thus predict the obtainable extrusion pressures and provide information for machine design. The finite element method and in particular, rigid-plastic formulation proved to be a suitable choice.

The formulations were presented and computer program was written and implemented using FORTRAN. The formulation chosen as the most adequate was the penalty function approach. The analysis provided information about the detailed mechanics of the process, giving velocity,stress and strain fields. The extrusion pressures, which are in general the only information obtained from relatively complex analyses, are only a small part of the information given by the finite element analysis.

The finite element method was then used to analyse the complex deformation developed during continuous extrusion. Various geometries were analysed and predictions were compared with experimental evidence obtained using existing experimental equipment after the necessary modifications. The experiments were by no means exhaustive, but fulfilled the main objective of providing data to assess the theoretical solutions. The main characteristics of the complex deformation patterns were predicted and found in good agreement with available experimental data.

It would seem, therefore, that the rigid-plastic finite element formulation using the penalty function approach, can be used with success in the analysis of metalforming problems. However, the solutions presented in this thesis are by no means the "exact" and should be judged in the light of the mathematical and physical approximations intrinsic in the model. Indeed, one must be aware of limitations of the model and avoid falling pray to the "Computer equals Oracle" syndrome. For example, if it was desired to predict residual stress distribution in products subjected to large deformations (to predict fatigue strength, for example), then it would be necessary to use an elastic-plastic formulation of the finite

element method.

As for the theoretical analysis of the three continuous extrusion processes, Context, Linex and Conform, the following conclusions can be drawn:

- Context gives the best results in terms of obtainable extrusion ratio in comparison with the other two methods. Also, Conform can be favoured to Linex.

- The coefficient of friction μ plays major role among the other process parameters. By increasing it, the clamped length of the billet, thus the feed channel length, can be greatly reduced, an important consideration in the design of production machines.

- Initially applied lateral indentation, thus dragging frictional force, appears to have an influence on the obtainable axial stress on the die face (and hence on the achievable extrusion ratio) at the beginning of the process, before the stresses have "picked up" speed. After the frictional stress rises relatively quickly and compensates for the initially lower value;

- Width of the billet, yet relative to that of the feed channel, influences the stresses that can be obtained, as long as the tertiary region is not developed, or it is in the initial stages of development. Once it has reached about half the length of the feed channel, the role of the tertiary zone prevails in its influence on stress development and the width of the primary zone starts to loose its importanse.

7.2. SUGGESTIONS FOR FURTHER WORK

A logical extension of the model is the prediction of the temperature distribution developed during deformation.

In order to do that, the temperature development dependent on the energy dissipation in the process must be considered and hence the thermal equilibrium equation must be solved. For plane flow, this equation takes the form:

$$\rho C\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) - K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) - \dot{Q} = 0 \qquad (7.1)$$

where:

ρ – density

C – specific heat

K – thermal conductivity

T – temperature

$\dot{Q} = \sigma'_{ij}\dot{\varepsilon}_{ij}$ – the rate of heath generation

u – velocity component in **x** direction

v – velocity component in **y** direction

The numerical solution of this equation is discussed in standard finite element texts [64]. The problem can be solved either as uncoupled flow [95] or as a coupled flow [97].

Once the temperature distribution is found, it is a simple matter to introduce the dependence of the flow stress of the material on temperature (and strain/strain rate). In order to do this various relations have been proposed [37,51, 77 & 83]. It should also be possible to include the dependence of the thermal properties on the temperature.

The other further obvious extension of the present work is the development of a three dimensional model. This would make it possible to analyse more complicated three dimensional flow problems like the continuous extrusion of round or hexagonal billets or billets with width/thickness ratio close to 1. The basis for this possible extension is provided in *Chapter 2* , and, in the author's opinion, it should not present a great difficulty to implement three dimensional variant in the existing computer code.

REFERENCES

1. Alexanfer, J.M. and Lengyel, B., Hydrostatic Extrusion., Mills & Boon Ltd., London, 1971.

2. Alexander J.M. and Price J.W.H., Finite Element Analysis of Hot Metal Forming., Proc. 18th Int. MTDR Conf., pp. 267-274, London, 1977.

3. Alexander, J.M. and Turner, T.W., A Preliminary Investigation if the Dieless Drawing of Titanium and Some Steels., Proc. of the 15th Int. MTDR Conf., 1975.

4. Arantes E Olivera, E.R.,Theoretical Foundations of Finite Element Method., Int.J.Sols.Structs., 4, p.929,1968.

5. Avitzur, B., Extrolling: A Concept for continuous wire making machines., Soc. of Manufacturing Eng. MF, p.75, 1975.

6. Avitzur, B., Metalforming., Marcel Dekker, U.S.A., 1980.

7. Backofen, W.A., Deformation Processing., Addison-Wasley, U.S.A., 1972.

8. Bathe, K.J. and Wilson, E.L., Numerical Methods in Finite Element Analysis., Prentice-Hall, U.S.A., 1976.

9. Bianchi, J.H. and Sheppard, T., A Comparison of a Viscoplastic Finite Element Model With Slip-Line Field and Upper-Bound Solutions for Non-Hardening Material Subjected to Plane Strain and Axisymmetric Extrusion., Int.J. Mech. Sci., 29, p. 61, 1987.

10. Bicanic, N. and Hinton, E., Spurious Modes in Two Dimensional Isoparametric Elements., Int. J. Num. Meths. Engng., 14, p. 1545, 1979.

11. Chua, P.S., Hot Extrusion of Long Billets., Third Year Project Report, Imperial College, 1977.

12. Chung, T.J., Finite Element Analysis in Fluid Dynamics., McGraw-Hill, U.S.A., 1978.

13. Clode, M.P., The Origin of Defects During Al-Mg-Si Extrusion., Ph.D. Thesis, University of London, 1987.

14. Conner, J.J. and Brebia, C.A., Finite Element Techniques for Fluid Flow., Newnes-Butterworths, U.S.A., 1976.

15. Cook, R.D., Concept and Applications of Finite Element Analysis., John Wiley & Sons, U.S.A., 1981.

16. Cramphorn, A.S., Bramley, A.N., Computer Aided Forging Design With UBET., Proc. 18th Int. MTDR Conf., 1977.

17. Cornfield, G.C. and Johnson R.H., Theoretical Predictions of Plastic Flow in Hot Rolling., J. of Iron and Steel Institute, 211, pp. 567-573, 1973.

18. Davies, A.J., The Finite Element Method., Clarendon Press, U.K., 1980.

19. Desai, C.S., Introduction to the Finite Element Method., Litton Educational Publishing, U.S.A., 1972.

20. Fenner, R.T., Computing for Engineers.,Macmillan, London, 1984.

21. Fenner, R.T., Engineering Elasticity: Applications of Numerical and Analytical Techniques., Ellis Horwood, England, 1986.

22. Fenner, R.T., Finite Element Methods for Engineers., Macmillan, London, 1975.

23. Fried, I., Finite Element Analysis of Incompressible Materials by Residual Energy Balancing., Int. J. Sol. Struct., 10, pp.993-1000, 1976.

24. Fuchs, F.J., Apparatus and Method for Continuous Extrusion., U.S. Patent No.3.740.985, June 1975.

25. Fuchs, F.J., High Pressure Continuous Extrusion., Research report, Western Electrical Co., Princeton, U.S.A., 1974.

26. Gallagher, R.H. et al., Finite Element in Fluids., John Wiley and Sons, U.S.A., 1975. 107

27. Green, D., Continuous Extrusion-Forming of Wire Sections., J. Inst. Metals, 100, p. 295, 1972.

28. Hartley, P., Sturgess, C.E.N. and Rowe, G.W., Friction in Finite Element Analysis of Metalforming Processes., Int. J. Mech. Sci., 21, p. 301, 1979.

29. Hibbit, D.H., Marcal, P.V. and Rice, J.R., A Finite Element Formulation for Problems of Large Strain and Large Displacement., Int. J. Sols. Structs., 6, p. 1069, 1970.

30. Hill, R., The Mathematical Theory of Plasticity., Clarendon Press, U.K., 1950.

31. Hinton, E. and Owen, D.R.J., An Introduction to Finite Element Computations., Pineridge Press, U.K., 1979.

32. Hinton, E. and Owen, D.R.J., Finite Element Programing., Academic Press, U.K., 1977.

33. Hoffman, O. and Sachs, G., Introduction to the Theory of Plasticity for Engineers., McGraw-Hill, U.S.A., 1953.

34. Huebner, K.H., The Finite Element Method for Engineers, John Wiley and Sons, 1975.

35. Hughes, T.J.R., Liu, W.K. and Brooks, A., Finite Element Analysis of Incompressible Viscous Flow by the Penalty Function Formulation., J. of Comp. Physics, 30, pp. 1-60, 1979.

36. Hughes, T.J.R., Taylor, R.L. and Levy, J.E., A Finite Element Method of Incompressible Flow., Proc. Conf. Finite Element Methods in Flow Problems, pp. 1-16, Sta. Margherita, Italy, 1976.

37. Inouye,K.,Studies of the Hot-Working Strength of Steels., Tetsu to Hagano,41, p. 593, 1955.

38. Jain, P.C., Ph.D. Thesis, Univercity of Wales, October, 1976.

39. Johnson, W. and Mellor P.B., Engineering Plasticity., Van Nostrand Reinhold Co., U.K., 1973.

40. Kanazawa, K. and Marcal, P.V., Finite Element Analysis of the Steel Rolling Process., Applivations of Numerical Methods to Forming Processes, AMD, 28, ASME, New York, USA, 1978.

41. Kim, J.H., Analysis of Sheet Metalforming by the finite Element Method., Ph.D. Thesis,University of California, Berkeley, 1977.

42. Kobayashi, S., Metalforming and the Finite Element Method - Past and Future., Proc. 25 Int. Mach. Tool Des. Res. Conf., 1985.

43. Kondylides, A., Forces and Stresses in the Feed Channel During Continuous Extrusion of Long Billets.,M.Sc. Thesis, Imperial College, 1980.

44. Lee, C.H., The Theoretical Analysis of Metalforming Problems in Plane-Strain., J. Appl. Mech., 19, p. 97, 1963.

45. Lee, C.H. and Kobayashi, S., Analysis of Axisymmetric Upsetting and Plane-Strain Side Pressing of Solid Cylinders by the Finite Element Method., Trans. ASME, J. Eng. for Ind., 93, p. 445, 1971.

46. Lee, C.H. and Kobayashi, S., Elasto-Plastic Analysis of Plane-Strain and Axisymmetric Flat Punch Indentation by the Finite Element Method., Int. J. Mech. Sci., 12, pp. 349-370, 1970.

47. Lee, C.H., Masaki, S. and Kobayashi, S., Analysis of Ball Indentation., Int. J. Mech. Sci., 14, pp. 417-426, 1972.

48. Lee, C.H. and Kobayashi, S., Elasto-Plastic Analysis of Plane-Strain and Axisymmetric Flat-Punch Indentation by the Finite Element Method., Int. J. Mech. Sci., 12, p. 349, 1970.

49. Lee, C.H. and Kobayashi, S., New Solutions to Rigid Plastic Deformation Problems Using a Matrix Method., Trans. ASME, J. of Engng. for Ind., 95,pp. 865-873, 1973.

50. Lengyel, B., Continuous Extrusion., Provisional British Patent Specification No. 262, 1976.

51. McGregor, C.W. and Fisher, J.C., Trans. ASME, J. Appl. Mech., 13, All, 1946.

52. Male, A.T. and Cockroft, A., A Method for Determination of the Coefficient of Friction of Metals Under Conditions of Bulk Plastic Deformation., J. Inst. Met., 93, p. 38, 1964-65.

53. Malkus, D.S. and Hughes, T.J.R., Mixed Finite Element Methods - Reduced and Selective Integration Techniques : A Unification of Concepts., Comp. Methods in Appl. Mech. Engng., 15, pp. 63-81, 1978.

54. Man, H.T., Distribution of Stresses in the Feed Chanel During Continuous Extrusion of Long Billets., M.Sc./DIC Thesis, Imperial College, 1981.

55. Matsumo, H., Oh, S.I. and Kobayashi, S., A Note on the Matrix Method of Rigid-Plastic Analysis of Ring Compression., Proc. 18th Int. MTDR Conf., pp. 3-9, 1977.

56. Mitchelle, A.R. and Wait, R., The Finite Element Method in Partial Differential Equations., John Wiley and Sons, U.S.A., 1977.

57. Nagpal, V., On the Solution of Three Dimensional Metalforming Processes., ASME J. Eng. for Ind., 99, p. 624, 1977.

58. Nagtegaal, J.C., Parks, D.M. and Rice, J.R.,On Numerically accurate Finite element Solutions in the Fully Plastic Range., Comp. Meth. Appl. Mech. Eng., 13, pp. 153-178, 1974.

59. Nayak, G.C., Plasticity and Large Deformation Problems by the Finite Element Method., Ph.D. Thesis, University of Wales, Swansea, 1971.

60. Noori, K., Context: A Design Exercise., M.Sc./DIC Thesis, Imperial College, 1979.

61. Norley, J., Ph.D. Thesis, Univrsity of Londodn, 1985.

62. Norrie, D.H. and Devries, G., An Introduction to Finite Element Analysis., Academic Press, U.S.A., 1978.

63. Oden, J.T., A General Theory of Finite Elements., Int. J. Num. Methods, 1, p. 205, 1969.

64. Oden, J.T., Computers and Structures, 8, pp. 445-449, 1978.

65. Oden, J.T., Finite Elements of Nonlinear Continua., McGraw-Hill, U.K., 1972.

66. Oh, S.I., Finite Element Analysis of Metalforming Processes with Arbitrary Shaped Dies., Int. J. Mech. Sci., 24, p. 479, 1982.

67. Osman, F.H. and Bramley, A.N., Metal Flow Prediction in Forging and Extrusion Using UBET., Proc. 20th Int. MTDR Conf., pp. 51-59, 1979.

68. Owen,D.R.J. and Hinton, E., Finite Elements in Plasticity: Theory and Practice., Pineridge Press, U.K., 1980.

69. Perzyna, P., Fundamental Problems in Visco-Plasticity., Academic Press, London, 1966.

70. Park, J.J., Applications of the Finite Element Method to Metalforming Problems., Ph.D. Thesis, University of California, Berkeley, 1982.

71. Pillinger, I., Hartley, P., Sturgess, C.E.N. and Row, G.W., An Elastic-Plastic Three Dimensional Finite Element Analysis of the Upsetting of Rectangular Blocks and Experimental Comparison., Int. J. M.T.D.R., p. 229, 1985.

72. Price J.W.H. and Alexander J.M., A Study of Isotermal Forming or Creep Forming of a Titanium Alloy., 4th NAMRC, Batelle, Columbus, Ohio, USA, 1976.

73. Price J.W.H. and Alexander J.M., The Finite Element Analysis of Two High Temperature Metal Deformation Processes., 2nd Int. Symp. on Finite Elements in Flow Problems, Santa Margharita, Ligure, Italy, 1976.

74. Rebelo, N. and Kobayashi, S., A Coupled Analysis of Viscoplastic Deformation and Heat Transfer : I - Theoretical Consideration and II - Applications., Int. J. Mech. Sci., 22, pp. 699-705, 1980.

75. Rebelo, N. and Kobayashi, S., A Coupled Analysis of Viscoplastic Deformation and Heat Transfer : I - Theoretical Consideration and II - Applications., Int. J. Mech. Sci., 22, pp. 707-718, 1980.

76. Rodriguez, L.A.P., Rigid-Plastic Finite Element Analysys of Some Metal Forming Processes., Ph.D. Thesis, University of London, 1980.

77. Samanta, S.S., Effect of strain Rate on Compressive Strength of Steel at Elevated Temperatures., Proc. Conf. on Deformation Under Hot Working Conditions, University of Sheffield, pp. 122-130, 1966.

78. Sani, A.N., Indentation of Billets in Continuous Extrusion., Ph.D. Thesis, University of London, 1980.

79. Shaari, A.F.B., Lateral Indentation of Long Billets, M.Sc./DIC Thesis, Imperial College, 1984.

80. Sharman F.W., Electricity Council Report R581, 1975.

81. Strang, G. and Fix, G.J., An Analysis of the Finite Element Method., Prentice-Hall, U.S.A., 1973.

82. Suzuki, H., Hashizume, S.,Yabuki, Y., Ishihara, Y., Nakajima, S. and Kenmochi, K., Studies on the Flow Stress of Metals and Alloys., Report of the Institute of Industrial Science, University of Tokyo, 1968.

83. Tay, A.O., Farmer, L.E. and Oxley, P.L.B., A numerical Method for Calculating Temperature Distribution in Metal Working Processes., Int. J. Mech. Sci., 22, pp. 41-57, 1980.

84. Teo, C.K., Continuous Extrusion of Long Billets., Third Year Project Report, Imperial College, 1977.

85. Thomson, E.G.,Yang, C.T. and Kobayashi, S., Mechanics of Plastic Deformation in Metal Processing., Macmillan, U.S.A., 1963.

86. Turner, T.W., Ph.D. Thesis, University of London, 1973.

87. Voorhes, W.G., Extrusion process., U.S. Patent No.3.922.898, December, 1975.

88. Yamada, Y., Yoshimura, N. and Sakurai, T., Plastic Stress-Strain Matrix and its Application for the Solution of Elastic-Plastic Problems by the Finite Element Method., Int. J. Mech. Sci., 10, p. 343, 1968.

89. Zienkiewicz, O.C., The Finite Element Method., 3rd ed., McGraw-Hill, U.K., 1977.

90. Zienkiewicz, O.C., Constrained Variational Principles and Penalty Function Methods in Finite Element Analysis.,Lecture Notes in Mathematics, No. 363, Springer-Verlag, pp. 207-214, 1974.

91. Zienkiewicz, O.C. and Cormeau, I.C., Viscoplasticity, Plasticity and Creep in Elastic Solids: A Unified Numerical Approach., Int. J. Num. Engng., 8, pp. 821-845, 1974.

92. Zienkiewicz, O.C. and Godbole P.N., Penalty Function Approach to Problems of Plastic Flow of Metals with Large Surface Deformation., J. Strain Analysis, 10, pp. 180-183, 1975.

93. Zienkiewicz, O.C. and Godbole P.N., Viscous Incompressible Flow with Special Reference to Non-Newtonian (Plastic) Flow., Finite Elements in Fluids, 1, Ch. 2, pp. 25-71, 1975.

94. Zienkiewicz, O.C. and Hinton, E., Reduced Integration, Fuction Smoothing and Non-Conformity in Finite Element Analysis., J. Franklin Inst., 302, pp. 443-461, 1976.

95. Zienkiewicz, O.C., Jain, P.C. and Onate, E., Flow of Solids During Forming and Extrusion. Some Aspects of Numerical Solutions., University College of Swansea, Report C/R/283/76, 1976.

96. Zienkiewicz, O.C. and Onate, E., Finite Element Solution of Metal Forming Using the Plastic Flow Approach., Proc. Int. Congr. Num. Meths. Engng., Paris, France, 1978.

97. Zienkiewicz, O.C., Onate, E. and Henrich, J.C., Plastic Flow in Metal Forming, I-Coupeled Thermal behaviour in Extrusion, II-Thin sheet forming., Applications of Numerical Metjods to forming Processes, AMD, 28, ASME, New York, USA, 1978.

APPENDICES

APPENDIX 1

NUMERICAL INTEGRATION

Throughout the FEM various matrices are found by integrating the products of other matrices that vary over the element space. Typically the element stiffness matrix is:

$$[k] = \int_V [B]^t [D][B]dV \qquad (A1.1)$$

where **[B]** - matrix is a function of a spatial variables. As described in *Chapter 2*, **[B]** is obtained from the interpolation matrix **[N]** and is, therefore, a combination of polynomials.

For simple elments the integration can be carried out explicitly. However, for the more complicated elements it becomes impractical to do this and each element is integrated numerically within the program as required.

There are various types of numerical integration methods available, the simplest being the trapezoidal, or Simpson's rule. All forms of numerical integration involve calculating the **[B]** matrix at various points within the element and then summing these to obtain the integration. Integrating a polynomial of degree **n**, using Simpson's rule, requires evaluation of the function being integrated at **n+1** points.

The fewer are the points at which the function has to be evaluated, the more efficient is the numerical integration process. The most efficient rules for integrating polynomials are the various Gaussian Quadrature formulae. Using these a polynomial of degree **2n-1** can be integrated by evaluating the function at only **n** points. This makes it about twice as efficient as Simpson's rule.

The basic form of Gaussian Quadrature is:

$$\int f(x)dx = \sum_{i=1}^{n} f(x_i) w_i \qquad (A1.2)$$

where the integration is replaced by a summation. The function is evaluated at various points, x_i, known as quadrature points. When the function has been evaluated at these points it is multiplied by weighting functions w_i. There are tables of quadrature points x_i and associated weighting functions for various values of **n**. These are usually given for integration limits of **-1** to **+1**, so that:

$$\int_{-1}^{+1} f(\xi)d\xi = \sum_{i=1}^{n} f(\xi_i)w_i \qquad \text{(A1.3)}$$

where ξ_i are the qudrature points when the limits are **-1** to **+1**.

It was shown in Section 2.2.10.2 - *Chapter 2* that the interpolation matrix (and hence the **[B]** - matrix) is set up for isoparametric elements on a 2 x 2 basis square or, if in three dimensions, on a 2 x 2 x 2 basic cube. When this is done the integration limits for isoparametric elements are **-1** to **+1** for all variables. The numerical integration then becomes, for the three dimensional brick:

$$\int_{-1}^{+1}\int_{-1}^{+1}\int_{-1}^{+1} [B(\xi_1, \xi_2, \xi_3)]^t [D] [B(\xi_1, \xi_2, \xi_3)] |[J(\xi_1, \xi_2, \xi_3)]| d\xi_1 d\xi_2 d\xi_3 =$$
$$= \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} [B(\xi_1, \xi_2, \xi_3)]^t [D] [B(\xi_1, \xi_2, \xi_3)] |[J(\xi_1, \xi_2, \xi_3)]| w_i w_j w_k \qquad \text{(A1.4)}$$

In practice **l**, **m** and **n** usually have the same value.

Triangular or tetrahedral elements can also be integrated in a similar manner except that different integration points and weighting functions are used. These are usually known as Gauss-Radau formulae.

APPENDIX 2

THEORY OF PLASTICITY IN BRIEF

In order to formulate a theory which describes elasto-plastic material deformation three requirements have to be met:

- An explicit relationship between stress and strain must be formulated to describe material behaviour under elastic conditions;
- A yield criterion indicating the stress level at which plastic flow starts must be postulated;
- A relationship between stress and strain must be developed for post yield behaviour.

So, according to the above, before the onset of plastic yielding the stress-strain relationship is expressed as:

$$\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl} \qquad \text{(A2.1)}$$

where:

σ_{ij} – stress components

ε_{kl} – strain components

C_{ijkl} – tensor of elastic constnts, and for isotropic material

$$C_{ijkl} = \lambda\delta_{ij}\delta_{kl} + \mu\delta_{ik}\delta_{jl} + \mu\delta_{il}\delta_{jk}\,*$$

where: λ,μ - Lamé constants

$$\delta_{ij} = \begin{cases} 0 & \text{if} \quad i = j \\ 1 & \text{if} \quad i \neq j \end{cases} \quad \text{– Kronecker delta}$$

**In this type of notation, Einstein's summation is employed. It is explicitly assumed that a summation from 1 to 3 is performed over any index which is repeated in any term of an expression. Also indices 1,2,3 reffer to cartesian coordinates x,y,z respectively. Note that* $\sigma_{11} = \sigma_{xx} = \sigma_x$, $\sigma_{12} = \sigma_{xy} = \tau_{xy}$ *etc.*

The yield criterion can be written in the general form:

$$f(\sigma_{ij}) = k(\kappa) \qquad (A\ 2.2)$$

where:

f – function of σ_{ij}

κ – material parameter to be determined experimentaly

Any yield criterion is independent of the orientation of the coordinate system employed and therefore it is a function of the three stress invariants only:

$$J_1 = \sigma_{ij}\ \sigma_{ij}$$

$$J_2 = \frac{1}{2}\sigma_{ij}\ \sigma_{ij} \qquad (A2.3)$$

$$J_3 = \frac{1}{2}\sigma_{ij}\ \sigma_{jk}\ \sigma_{ki}$$

Experimental observations indicate that the plastic deformation of metals is essentially independent of hydrostatic pressure. Thus the yield function can be written in the form:

$$f(J'_2, J'_3) = k(\kappa) \qquad (A\ 2.4)$$

where:

J'_2 & J'_3 are the second and third invariants of the deviatoric stresses defined as:

$$\sigma'_{ij} = \sigma_{ij} - \frac{1}{3}\delta_{ij}\ \sigma_{kk}$$

One of the most popular and most widely used yield criterion in metalforming is that of Von Mises, which can be expressed as:

$$\sqrt{J'_2} = k(\kappa) \qquad (A2.5)$$

J'_2 can be explicitly written as:

$$J'_2 = \frac{1}{2}\sigma_{ij}\sigma_{ij} = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right] =$$

$$= \frac{1}{2}\left(\sigma'^2_x + \sigma'^2_y + \sigma'^2_z\right) + \tau^2_{xy} + \tau^2_{yz} + \tau^2_{zx} \qquad (A2.6)$$

The equivalent (or effective) stress can be written as:

$$\bar{\sigma} = \sqrt{3J'_2} = \sqrt{3}\,k \qquad \text{(A 2.7)}$$

or

$$\bar{\sigma} = \sqrt{\frac{3}{2}\sigma'_{ij}\,\sigma'_{ij}} \qquad \text{(A 2.8)}$$

After initial yielding, the stress level at which further plastic deformation occurs may be dependent on the current degree of plastic straining, work-hardening or strain-hardening. In Fig.A2-1. two alternative models are illustrated. Fig.A2-1.a. presents a perfectly plastic material where the yield stress level does not depend in any way on the degree of plastification. Fig.A2-1.b. shows isotropic strain hardening material where the subsequent yield surfaces are uniform expansion of the original yield curve. The progressive development of the yield surface can be defined by relating the shear yield stress **k** to the plastic deformation by means of the hardening parameter κ. Now introducing the equivalent (or effective) plastic strain defined incrementally as:

$$d\varepsilon^p = \sqrt{\frac{2}{3}\varepsilon^p_{ij}\,\varepsilon^p_{ij}} \qquad \text{(A2.9)}$$

and noting that

$$d\varepsilon'_{ij} = d\varepsilon'^{p}_{ij} \qquad \text{(A 2.10)}$$

when the assumption that yielding is independent of the hydrostatic stress is valid, the following expression for the equivalent strain can be written:

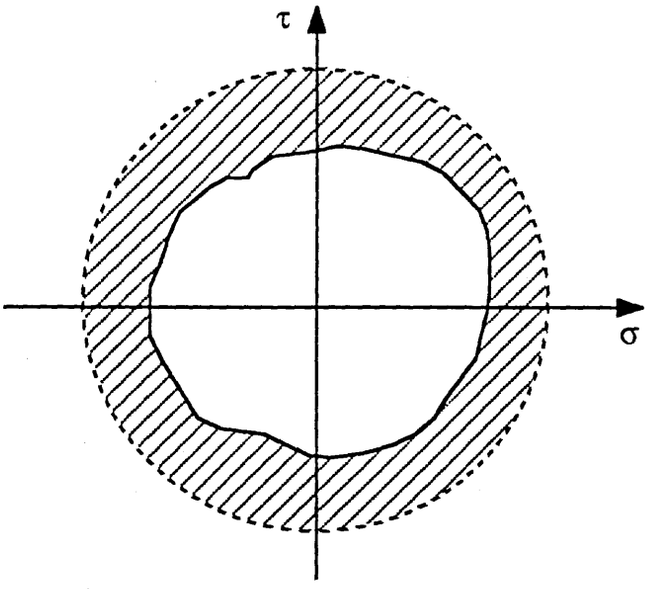
$$d\varepsilon^p = \sqrt{\frac{2}{3}\varepsilon'^{p}_{ij}\,\varepsilon'^{p}_{ij}} \qquad \text{(A 2.11)}$$

Then the hardening parameter can be defined [39] as:

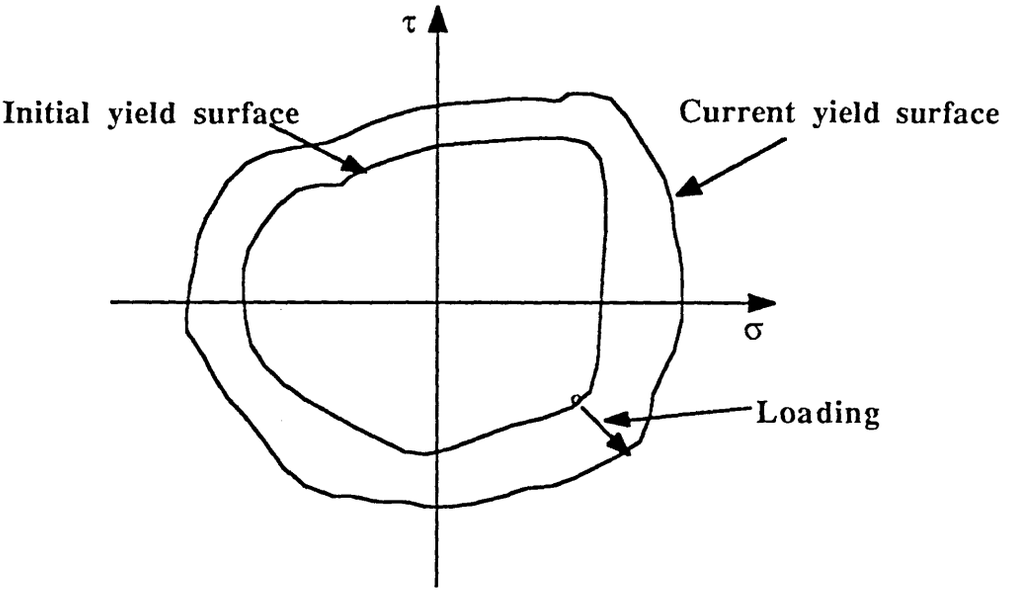
$$\kappa = \bar{\varepsilon}^p \qquad \text{(A 2.12)}$$

where $\bar{\varepsilon}^p$ is the result of integrating $d\varepsilon^p$ (Eqn . A2.9) over the strain path. This behaviour is known as strain hardening. Stress states for which **f=k** (see Eqn.(A2.2)) represent plastic states, while elastic behaviour is characterised by **f<k**. In the plastic state the incremental change in the yield function due to an incremental stress change is:

$$df = \frac{\partial f}{\partial \sigma_{ij}}\,d\sigma_{ij} \qquad \text{(A 2.13)}$$



a. Perfectly plastic material



b. Isotropic strain-hardening material

Fig.A2-1. Representation of the Strain-Hardening Behaviour

Then if:

df < 0 - elastic unloading occurs (elastic behaviour)

df = 0 - neutral loading (plastic behaviour for a perfectly plastic material)

df > 0 - plastic loading (plastic behaviour for a strain hardening material)

After initial yielding the material behaviour will be partly elastic and partly plastic, so that the total strain can be presented as:

$$d\varepsilon_{ij} = d(\varepsilon_{ij})^{E} + d(\varepsilon_{ij})^{P} \qquad (A2.14)$$

The elastic strain increment is related to the stress increment by Eqn.(A2.1) and decomposing the stress terms into their deviatoric and hydrostatic components this relationship can be rewritten as:

$$d(\varepsilon_{ij})^{E} = \frac{d\sigma'_{ij}}{2\mu} + \frac{(1-2\nu)}{E}\delta_{ij}\, d\sigma_{kk} \qquad (A2.15)$$

Further assumption on the material behaviour must be made in order to establish a relationship between the plastic strain increment and the stress increment. The adopted assumption is that the plastic strain increment is proportional to the stress gradient of a quantity called plastic potential **F** (where $\mathbf{F} = F(\sigma_{ij})$) so that:

$$d(\varepsilon_{ij})^{P} = \frac{\partial F}{\partial \sigma_{ij}} \qquad (A2.16)$$

where: $d\lambda$ - is a proportionality constant called the plastic multiplier [39].

Equation (A2.15) is known as a flow rule since it governs the plastic flow after yielding.

The potential **F** must be a function of J'_2 and J'_3 [68] and as so the relationship **f = F** has been offered. The identity **f = F** is a valid one since it has been postulated that both are functions of J'_2 and J'_3 and such an assumption gives rise to an associated theory of plasticity in which case Eqn.(A2.15) becomes:

$$d(\varepsilon_{ij})^{P} = \frac{\partial f}{\partial \sigma_{ij}} \qquad (A2.17)$$

For the particular case of $f = J'_2$ we have:

$$\frac{\partial f}{\partial \sigma_{ij}} = \frac{\partial J_2'}{\partial \sigma_{ij}} = \sigma'_{ij} \qquad \text{(A 2.18)}$$

Hence Eqn. (A2.16) becomes:

$$d(\varepsilon_{ij}) = d\lambda\, \sigma'_{ij} \qquad \text{(A 2. 19)}$$

known as Prandtl-Reuss equations [39]. Using Eqns. (A2.14), (A2.15) and (A2.17) the complete incremental relationship between stress and strain for elasto-plastic deformation is found as:

$$d\varepsilon_{ij} = \frac{d\sigma'_{ij}}{2\mu} + \frac{(1-2\nu)}{E}\delta_{ij} d\sigma_{kk} + d\sigma \frac{\partial f}{\partial \sigma_{ij}} \qquad \text{(A2.20)}$$

Now let us consider the uniaxial testing of an elasto-plastic material, which produces a stress –strain curve shown in Fig.A2–2. In this case $\sigma_1 = \sigma$, $\sigma_2 = \sigma_3 = 0$ and $d(\varepsilon_1)^p = d\varepsilon^p$ $(d\varepsilon_2)^p = (d\varepsilon_3)^p = (-1/2)\, d\varepsilon^p$ since due to incompressibility $\nu = 0.5$ ($d\varepsilon^p$ is the plastic strain increment in the direction of loading). Thus from Eqns. (A2.8) and (A2.9) we get:

$$\bar{\sigma} = \sigma \qquad \text{(A 2.21)}$$

$$d\bar{\varepsilon}^p = d\varepsilon^p \qquad \text{(A2.22)}$$

respectively.

The behaviour of the material is initially elastic and is characterised by the elastic modulus **E**. Afterwards the material response is elasto-plastic with a local tangent to the curve continuously varying which is called the elasto-plastic modulus E_T.

The hardening law $k = k(\kappa)$ could be expressed in terms of equivalent stress $\bar{\sigma}$ and for the strain hardening hypothesis (see Eqn.(A2.12)) we obtain:

$$\bar{\sigma} = H(\bar{\varepsilon}^p) \qquad \text{(A 2.23)}$$

After differentiation

$$\frac{d\sigma}{d\bar{\varepsilon}^p} = H'(\bar{\varepsilon}^p) \qquad \text{(A 2.24)}$$

Using Eqns.(A2.21) and (A2.22) the last equation becomes:

$$H'(\bar{\varepsilon}^p) = \frac{d\sigma}{d\varepsilon^p} = \frac{d\sigma}{d\varepsilon - d\varepsilon^e} = \frac{1}{\frac{d\varepsilon}{d\sigma} - \frac{d\varepsilon^e}{d\sigma}} \qquad (A\ 2.25)$$

or referring to Fig.A2-2.:

$$H' = \frac{E_T}{1 - \frac{E_T}{E}} \qquad (A\,2.26)$$

Thus hardening function **H'** can be determined experimentally from a uniaxial test.

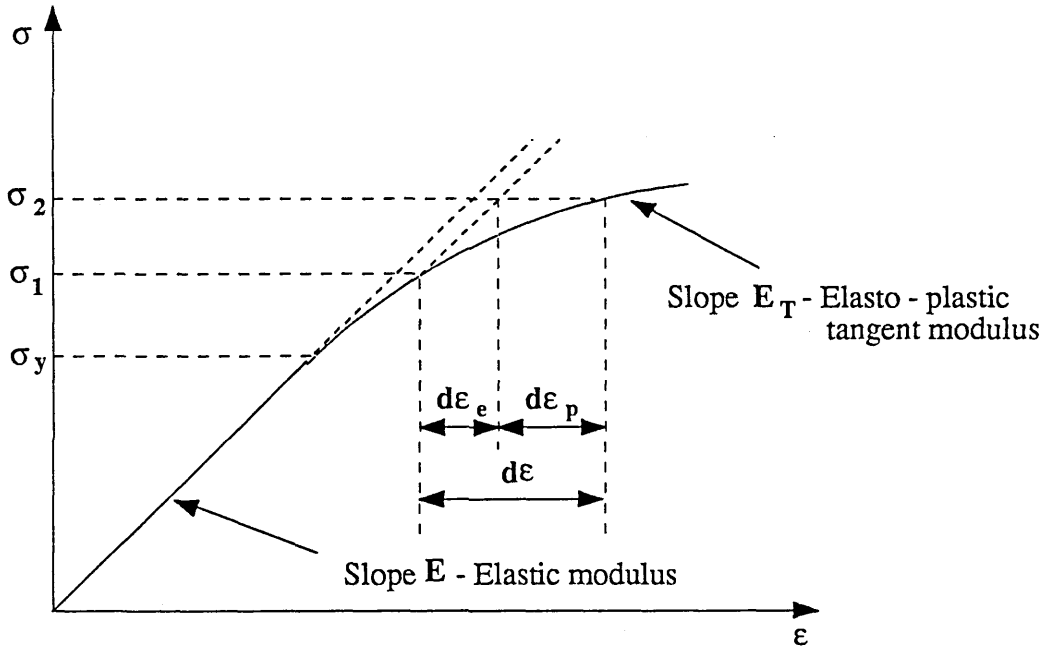


Fig.A2-2. Elasto-Plastic Strain Hardening Behaviour for the Uniaxial Case

MATRIX FORMULATION

The yield function first defined in Eqn. (A2.2) can be rewritten as:

$$f(\underset{\sim}{\sigma}) = k(\kappa) \qquad (A\,2.27)$$

where:

$\underset{\sim}{\sigma}$ – is the stress vector

κ – the hardening parameter

From Eqn.(A2.12):

$$d\kappa = d\underset{\sim}{\varepsilon}^p \qquad (A\,2.28)$$

Rearrangenig Eqn. (A2.27) we have:

$$\underset{\sim}{F}(\underset{\sim}{\sigma}, k) = f(\underset{\sim}{\sigma}) - k(\kappa) \qquad \text{(A 2.29)}$$

Differentiating the last equation we get:

$$d\underset{\sim}{F} = \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\sigma}} d\,\underset{\sim}{\sigma} + \frac{\partial \underset{\sim}{F}}{\partial \kappa} d\kappa = 0 \qquad \text{(A 2.30)}$$

or

$$\underset{\sim}{a}^{t}\, d\underset{\sim}{\sigma} - A d = 0 \qquad \text{(A2.31)}$$

where $\underset{\sim}{a}^{t}$ and A are defined as:

$$\underset{\sim}{a}^{t} = \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\sigma}} = \left\{ \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\sigma}_x}, \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\sigma}_y}, \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\sigma}_z}, \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\tau}_{xy}}, \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\tau}_{yz}}, \frac{\partial \underset{\sim}{F}}{\partial \underset{\sim}{\tau}_{zx}} \right\} \qquad \text{(A 2.32)}$$

$$A = -\frac{1}{d\lambda} \frac{\partial \underset{\sim}{F}}{\partial \kappa} d\kappa \qquad \text{(A2.33)}$$

The vector $\underset{\sim}{a}$ is called the flow vector. Equation (A2.20) can be now rewritten as:

$$d\{\varepsilon\} = [D^{E}]^{-1} d\{\sigma\} + d\lambda \frac{\partial [F]}{\partial \{\sigma\}} \qquad \text{(A2 .34)}$$

where:

$\underset{\sim}{D}^{E}$ – matrix of elastic constants and:

$$\underset{\sim}{D}^{E} = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1 & \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 0 & 0 & 0 \\ \frac{\nu}{1-\nu} & 1 & \frac{\nu}{1-\nu} & 0 & 0 & 0 \\ \frac{\nu}{1-\nu} & \frac{\nu}{1-\nu} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{(1-2\nu)}{2(1-\nu)} \end{bmatrix} \qquad \text{(A 2.35)}$$

where: E - elastic modulus

ν - Poisson's ratio.

Premultiplying both sides of the last equation by $\underline{d}_D^t = \underset{\sim}{a}^t \underline{D}$ and eliminating $\underset{\sim}{a}^t d\underset{\sim}{\sigma}$ using Eqn. (A2.31), the plastic multiplier $d\lambda$ can be obtained as:

$$d\lambda = \frac{1}{\left(A + \underset{\sim}{a}^t \underline{D}^E \underset{\sim}{a}\right)} \underset{\sim}{a}^t \underline{d}_D \, d\underset{\sim}{\varepsilon} \qquad \text{(A 2.36)}$$

Substituting now Eqn.(A2.36)into Eqn.(A2.34) the complete elasto-plastic stress-strain relationship is obtained as:

$$d\underset{\sim}{\sigma} = \underline{D}^{EP} \, d\underset{\sim}{\varepsilon} \qquad \text{(A 2.37)}$$

with

$$\underline{D}^{EP} = \underline{D}^E - \frac{\underline{d}_D \, \underline{d}_D^t}{A + \underline{d}_D^t \underset{\sim}{a}} \; ; \; \underline{d}_D = \underline{D}^E \underset{\sim}{a} \qquad \text{(A 2.38)}$$

Now the scalar term A must be determined. As the work-hardening hypothesis is more general than the strain hardening hypothesis, the former is going to be used. The work-hardening hypothesis postulates that the degree of work hardening is a function of the total plastic work W_p. Then:

$$\kappa = W_p \qquad \text{(A 2.39)}$$

where

$$W_p = \int \sigma_{ij} \, d(\varepsilon_{ij})^p \qquad \text{(A 2.40)}$$

Therefore from Eqn.(A2.39) after differentiating we obtain:

$$d\kappa = \underset{\sim}{\sigma}^t d\underset{\sim}{\varepsilon}^p \qquad \text{(A2.41)}$$

Equation (A2.23) can be rewritten as:

$$\underline{F}\,(\underset{\sim}{\sigma}, \kappa) = f(\underset{\sim}{\sigma}) - \sigma_y(k) = 0 \qquad \text{(A 2.42)}$$

since the uniaxial yield stress $\sigma_y = \sqrt{3}\,k$ for the von Mises yield criterion .

Thus from Eqn.(A2.33)

$$A = -\frac{1}{d\lambda} \frac{\partial \underline{F}}{\partial \kappa} d\kappa = \frac{1}{d\lambda} \frac{d\sigma_y}{d\kappa} d\kappa \qquad \text{(A2.43)}$$

The full differential can be used in the last term since σ_y is a function only of κ.

Using normality condition in Eqn.(A2.41) to express $d\underset{\sim}{\varepsilon}^p$ we have:

$$d\kappa = \underset{\sim}{\sigma}^t d\underset{\sim}{\varepsilon}^p = \underset{\sim}{\sigma}^t d\lambda\, \underset{\sim}{a} = d\lambda\, \underset{\sim}{a}^t \underset{\sim}{\sigma} \qquad \text{(A 2.44)}$$

For the uniaxial case $\underset{\sim}{\sigma} = \bar{\sigma} = \sigma_y$ and $d\underset{\sim}{\varepsilon}^p = d\bar{\varepsilon}^p$ where $\bar{\sigma}$ & $\bar{\varepsilon}^p$ are equivalent stress and equivalent strain respectively. Thus Eqn.(A2.44) becomes:

$$d\kappa = \sigma_y\, d\bar{\varepsilon}^p = d\lambda\, \underset{\sim}{a}^t \underset{\sim}{\sigma} \qquad \text{(A2.45)}$$

Also from Eqn.(A2.24)

$$\frac{d\bar{\sigma}}{d\bar{\varepsilon}^p} = \frac{d\sigma_y}{d\bar{\varepsilon}^p} = H' \qquad \text{(A 2.46)}$$

Applying Euler's theorem for homogeneous functions from Eqn.(A2.42) we can write:

$$\frac{\partial f}{\partial \underset{\sim}{\sigma}}\, \underset{\sim}{\sigma} = \sigma_y \qquad \text{(A 2.47)}$$

or from Eqn.(A2.32)

$$\underset{\sim}{a}^t \underset{\sim}{\sigma} = \sigma_y \qquad \text{(A2.48)}$$

Substituting Eqns. (A2.46) and (A2.48) into Eqns. (A2.45) and (A2.43) respectively it can be obtained:

$$d\lambda = d\,\bar{\varepsilon}^p$$

$$A = H' \qquad \text{(A 2.49)}$$

Thus A is obtained to be the local slope of the uniaxial stress-plastic strain curve and it can be determined experimentally from Eqn.(A2.26).

APPENDIX 3

COMPUTER PROGRAM

A3.1. INTRODUCTION

Final version of the finite element formulation presented in *Chapter 3* in the thesis is given in what follows. The program is written in standard FORTRAN and, with exeption of plotting routines, is machine independent. Single precision was used throughout. This was found to give enough accuracy when using the CDC 6500 computer in Imperial College Computer Centre (ICCC).

A3.2. GENERAL DSESCRIPTION OF THE PROGRAM

The program is divided into a number of subroutines and a master program, which controls the flow operation (Fig.A3.1). The program uses bi-linear quadrilateral elements with numerical integration, however other kinds of elements could be easily implemented.

The program is built around a band solver which, although not the most sophisticated, is the most simple to implement. The author believes that the argument for simplicity is very strong and it should be the over-riding aim when not very severe economical pressures are present. Thus the programs are by no means the most efficient that could have been written and from this point of view they can be greatly improved. However, this is beyond the scope of this work and will be left to potential users.

The listing of the program presented at the end of this appendix is compiled copy and, therefore, free of programming errors. Comment cards have been used generously and it is hoped that they make the program self-explanatory to any one fluent in the FORTRAN lenguage.

The program is designed to solve non-steady state problems in a quasistatic manner using penalty function formulation. Both plane strain and axisymmetric problems can be treated as well as hardening and non-hardening materials.

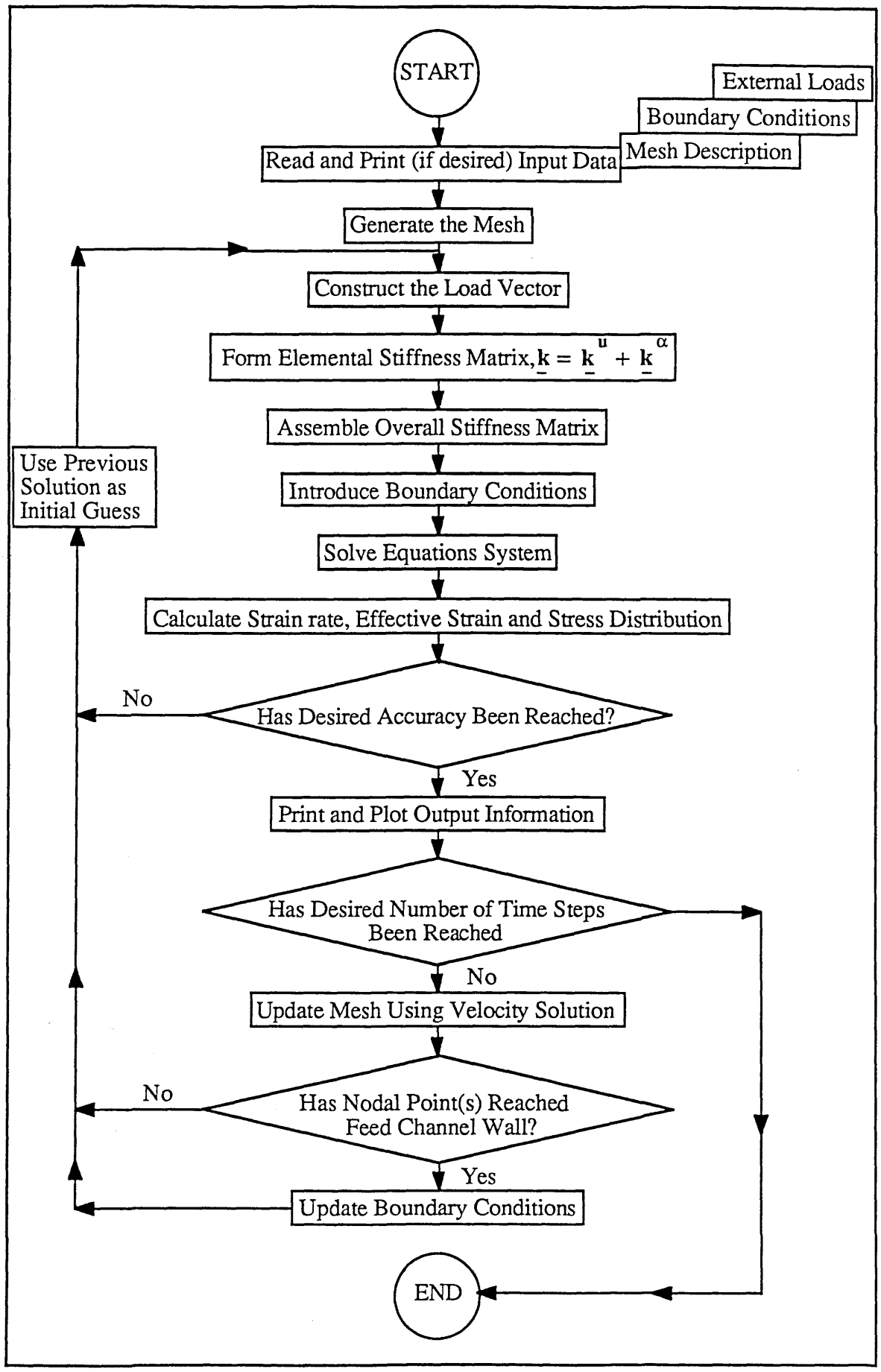


Fig.A3.1. Flow Chart of the Finite Element Code 'FEFF2D'.

The mesh is updated for each step and boundary conditions are checked and altered accordingly if necessary. The program has facilities for plotting the deformed geometry and velocity fields at different stages of calculation. Part of the output of the program is provided in a form suitable for contouring and using existing computer packages in ICCC.

A3.3. PROGRAMM TERMINOLOGY

Here is the meaning of the main variables of the program:

Variable	Place in labelled common	Definition
NP	/BLK1/	Number of nodal points
NE	/BLK1/	Number of elements
NB	/BLK1/	Nodal points with boundary conditions (Number of restrained nodes)
NPC	/BLK1/	Number of loaded nodes with point loads
NMAT	/BLK1/	Number of element material types
NEQ	/BLK1/	Number of equations
NBAND	/BLK1/	Bandwidth
TITLE(8)	/BLK1/	Title array
NBF	/BLK1/	Number of nodes where reactions are calculated
XMAX	/BLK1/	Half width of the feed channel
COORD(NP,2)	/BLK2/	Nodal point coordinates array
NOP(NE,4)	/BLK2/	Element connection array
IMAT(NE)	/BLK2/	Element material type array
ELOAD(NE,8)	/BLK2/	Nodal loads array in x and y directions
NELM	/BLK2/	Number of initially loaded elements
YIELD(4)	/BLK3/	Different materials yield stress array
NBC(NB)	/BLK3/	Array of restrained nodes
NREST(NB)	/BLK3/	Boundary condition type
NQ(NPC)	/BLK3/	Nodes loaded with point loads array
R(NPC,2)	/BLK3/	Nodal loads array
XPRE(NB)	/BLK3/	x(r) velocity imposed at nodal points
YPRE(NB)	/BLK3/	y(z) velocity imposed at nodal points

Variable	Place in labelled common	Definition
NF(NBF)	/BLK3/	Array of nodes where reactions are calculated
SIGZ1	/BLK3/	Maximum stress in z direction for the current step
STR(NE,6)	/BLK5/	Stress array
EPS(NE,6)	/BLK5/	Strain rate array
VEL(2,NP)	/BLK5/	Velocity array
TEPS(NE)	/BLK5/	Effective strain vector
STREF(NE)	/BLK5/	Effective stress vector
STRFR(NE)	/BLK5/	Frictional stress vector
ALPHA	/A/	Penalty coefficient
VRIG	/A/	Cut-off factor
IPLAX	/A/	Identifier = 0 --> for plane strain ≠ 0 --> for axisymmetric
LLMM	/A/	Drawing subroutine control variable = 0 --> draw deformed mesh and velocity field for every other time step = 1 --> draw undeformed mesh only and stop
NEDGE	/A/	Number of loaded edges
NEDGE1	/A/	Number of loaded edges in the previous time step
FMU	/A/	Coefficient of friction
NEX	/A/	Number of elements in x direction
NEY	/A/	Number of elements in y direction
NPX	/A/	Number of nodal points in x direction
NPY	/A/	Number of nodal points in y direction
DX	/A/	Billet dimension in x direction
DY	/A/	Billet dimension in y direction
INTF	/B/	Number of nodal points on the free surface
NINTF(I) (where I=NPX+ +NPY-NB)	/B/	Nodes on the free surface array
NSTEP	/B/	Number of time steps for which the calculations are to be carried on

Variable	Place in labelled common	Definition
STEP	/B/	Value of the time step
ISTEP	/B/	Step number counter
NPRES	/B/	Distributed load control variable
XMIN	/B/	Initially loaded billet length
THIC	/B/	Billet thickness
ITY	/B/	Process identifier = 0 --> Linex = 1 --> Context = 2 --> Conform
SK(I,J) (where I=NEQ J=NBAND)	/C/	Master stiffness matrix
R1(NEQ)	/C/	Load vector. After elimination the space is used for the solution vector.
EST(I,J) (where I=2*NBF J=2*NBAND)	/C/	Array containing stiffness equations for reaction calculations
FX(NBF)	/C/	Nodal reacton force in x direction vector
FY(NBF)	/C/	Nodal reacton force in y direction vector
FPUR(NBF)	/C/	Nodal loads array of the nodes where reactions are calculated
LITER	/C/	Number of iterations per step counter

```
      PROGRAM FEFF2D (DATAIN,DATAOUT,TAPE5=DATAIN,TAPE6,TAPE4,TAPE3,TAPE
     * 62)
C*************************************************************************
C* THIS PROGRAM IS DESIGNED TO SLVE NONSTEADY-STATE PROBLEMS IN          *
C* METAL FORMING USING THE FINITE ELEMENT METHOD.                        *
C* THE MATERIAL IS ASSUMED TO BE RIGID-PLASTIC AND INCOMPRESSIBLE,       *
C* THIS LATTER CONSTRAINT BEING INTRODUCED BY MEANS OF A PENALTY         *
C* FUNCTION.                                                             *
C* THE PROGRAM USES BILINEAR ISOPARAMETRIC ELEMENTS WITH                 *
C* REDICED/SELECTIVE INTEGRATION.                                        *
C*************************************************************************
C
C             ------------------------------------------------------------
C             ]        BRANIMIR B. GERGINOV, BENG(MECH),M.SC.           [
C             ]     DEPARTMENT OF MATERIALS, IMPERIAL COLLEGE           [
C             ]              UNIVERSITY OF LONDON                       [
C             ]           THIS VERSION - 20 NOVEMBER 1988               [
C             ------------------------------------------------------------
C
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DX
     * ,DY
      COMMON/B/INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      OPEN(UNIT=5,FILE='DATAIN',STATUS='OLD')
C
C.....READ NECESSARY INPUT INFORMATION
C
      CALL START (2)
      ISTEP = 1
      NPAGE = 0
      WRITE(6,1000)
      CALL PRELIM
C
C.....CALCULATE BANDWIDTH AND NUMBER OF EQUATIONS.
C
      NEQ = NP*2
      J = 0
      DO 20 N = 1,NE
      DO 20 I = 1,4
      DO 10 L = 1,4
      KK = IABS(NOP(N,I)-NOP(N,L))
      IF (KK-J.LE.0) GOTO 10
      J = KK
   10 CONTINUE
   20 CONTINUE
      NBAND = 2*(J+1)
      NLIN = 0
      DO 30 N = 1,NE
   30 TEPS(N) = 0.0
C
C.....READ THE EXTERNAL LOADS IF ANY. FORM LOAD VECTOR.
C
      NITER = 0
   45 WRITE(6,1010) ISTEP,STEP
      WRITE(3,1010) ISTEP,STEP
   40 CALL LOAD
C
```

```
C.....FORM AND SOLVE THE EQUATION SYSTEM.
C
      CALL FORMK
      CALL SOLVE
      CALL CONVER (NCONV)
      IF (NCONV.EQ.1) GOTO 50
      IF (NLIN.EQ.1) GOTO 50
      IF (NITER.EQ.12) GOTO 50
      NITER = NITER+1
      GOTO 40
C
C.....CALCULATE FORCES AT BOUNDARY NODAL POINTS IF REQUIRED.
C
   50 CALL CFORC
      CALL STRAIN
C
C.....WRITE RESULTS
C
      CALL MODMES
      CALL UPBOUND
      CALL DOUT
      WRITE(6,1020) ISTEP
      IF (ISTEP.GE.NSTEP) GOTO 60
      ISTEP = ISTEP+1
      NITER = 1
      LITER = 1
      NCONV = 0
      GOTO 45
   60 CALL ENPLOT
C
 1000 FORMAT (1H ,6("PROGRAM 'FEFF2D' ** "),/,1H ,120(1H-),///)
 1010 FORMAT (1H ,33X,"STEP NO.",I3,/1H ,33X,12(1H-),/1H ,20X,"STEP INCR
     * EMENT IS NSTEP = ",E10.4,//)
 1020 FORMAT (1H ,//,1H ,25X,22(1H-),/,1H ,25X,"- END OF STEP NO.",I3,"
     * -",/,1H ,25X,22(1H-),/,1H ,120(1H_),//)
      STOP
      END
C
C************************  END OF THE MAIN PROGRAM  ************************
C
      SUBROUTINE PRELIM
C
C.....THIS SUBROUTINE READ AND PRINT THE NECESSARY INPUT DATA
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DX
     * ,DY
      COMMON/B/INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
C
C.....READ TITLE AND CONTROL VARIABLES.
C
      READ(5,1070) TITLE
      READ(5,1005) ALPHA
      READ(5,1005) VRIG
      READ(5,1006) ITY
      WRITE(6,1140) TITLE
      IF (ITY.EQ.0) WRITE(6,1145)
      IF (ITY.EQ.1) WRITE(6,1146)
```

```
      IF (ITY.EQ.2) WRITE(6,1147)
C
C.....GENERATE THE MESH.
C
      CALL GRID
      READ(5,1020) NB,NPC,NBF,NMAT,I1,IPLAX,INTF,XMAX
      READ(5,1025) NEDGE
      READ(5,1015) FMU
      READ(5,1025) NPRES
      READ(5,1007) THIC
      NELM = (NEDGE*NEX)/(2*NEX+1)
      XMIN = CORD(NOP(NELM,3),2)
      IF (IPLAX.EQ.0) WRITE(6,1090) IPLAX
      IF (IPLAX.EQ.1) WRITE(6,1110) IPLAX
      WRITE(6,1100) NP,NE,NB,NPC,NBF,NMAT,I1,XMAX
      READ(5,1000) NSTEP,STEP
      WRITE(6,1010) NSTEP,STEP
      WRITE(6,1260) ALPHA
      WRITE(6,1220) VRIG
      WRITE(6,1230) FMU
      WRITE(6,1270) XMIN
      WRITE(6,1240) NPRES
      WRITE(6,1250) NEDGE
      WRITE(6,1280) THIC
C
C.....READ MATERIAL INFORMATION.
C
      READ(5,1120) (N,YIELD(N),L=1,NMAT)
      WRITE(6,1210)
      WRITE(6,1130)
      WRITE(6,1080) (N,YIELD(N),N=1,NMAT)
C
C.....READ ELEMENTS INFORMATION
C
      READ(5,1040) (N,IMAT(N),L=1,NE)
C
C.....READ BOUNDARY CONDITIONS
C
      READ(5,1050) (NBC(I),NREST(I),XPRE(I),YPRE(I),I=1,NB)
      IF (INTF.EQ.0) GOTO 10
      READ(5,1060) (NINTF(I),I=1,INTF)
   10 IF (NBF.EQ.0) GOTO 20
      READ(5,1060) (NF(I),I=1,NBF)
C
C.....PRINT INPUT INFORMATION IF REQUIRED
C
   20 IF (I1.EQ.0) GOTO 30
      WRITE(6,1160)
      WRITE(6,1030) (N,(CORD(N,M),M=1,2),N=1,NP)
      WRITE(6,1170)
      WRITE(6,1035)(N,(NOP(N,M),M=1,4),IMAT(N),(NOGP(N,K),K=1,4),N=1,NE)
   30 IF (INTF.EQ.0) GOTO 40
      WRITE(6,1200)
      WRITE(6,1150) (NINTF(I),I=1,INTF)
   40 IF (NBF.EQ.0) GOTO 50
      WRITE(6,1190)
      WRITE(6,1150) (NF(I),I=1,NBF)
   50 WRITE(6,1180)
      WRITE(6,1055) (NBC(I),NREST(I),XPRE(I),YPRE(I),I=1,NB)
      RETURN
C
```

```
 1000 FORMAT (I5,F7.4)
 1005 FORMAT (E10.2)
 1007 FORMAT (F8.3)
 1006 FORMAT (I5)
 1010 FORMAT (1H ,"NSTEP=",I3,2X,"INCREMENT=",E12.5,/)
 1015 FORMAT (F5.2)
 1020 FORMAT (7I5,F8.3)
 1025 FORMAT (I5)
 1030 FORMAT (I5,2F12.3)
 1035 FORMAT (10I5)
 1040 FORMAT (2I5)
 1045 FORMAT (6I5)
 1050 FORMAT (2I5,2F7.3)
 1055 FORMAT (2I10,1X,2F10.2)
 1060 FORMAT (16I5)
 1070 FORMAT (8A10)
 1080 FORMAT (1H ,I4,F12.2,/)
 1090 FORMAT(1H ,"PLANE-STRAIN PROBLEM   'IPLAX' = ",I2,/,1H ,20(1H*),/)
 1100 FORMAT (1H ,"NUMBER OF NODES=",I3,//,1H ,"NUMBER OF ELEMENTS=",I3,
     * //,1H ,"NUMBER OF NODES WITH BOUNDARY CONDITIONS=",I3,//,1H ,"NUMB
     * ER OF LOADED NODES=",I3,//,1H ,"NUMBER OF NODES WHERE REACTIONS AR
     * E CALCULATED=",I3,//,1H ,"NUMBER OF MATERIALS=",I3,//,1H ,"PRINT C
     * ONTROL VARIABLE (I1)=",I2,//,1H ,"MAXIMUM DIMENSION OF THE CONTAIN
     * ER IN 'X' DIRECTION IS   'XMAX' = ",F8.3,/)
 1110 FORMAT(1H0,"AXISYMMETRIC PROBLEM   'IPLAX' = ",I2,/,1H ,20(1H*),/)
 1120 FORMAT (I5,F6.2)
 1130 FORMAT (1H ,2X,"MAT",3X,"YIELD POINT")
 1140 FORMAT (1H ,8A10,/,1H ,120(1H,//)
 1145 FORMAT(1H ,"PROCESS UNDER CONSIDERATION IS 'LINEX' - ITY = 0",/)
 1146 FORMAT(1H ,"PROCESS UNDER CONSIDERATION IS 'CONTEXT' - ITY = 1",/)
 1147 FORMAT(1H ,"PROCESS UNDER CONSIDERATION IS 'CONFORM' - ITY = 2",/)
 1150 FORMAT (1H ,20I5)
 1160 FORMAT (1H ,"NODES",3X,"COORD X(R)",3X,"COORD Y(Z)")
 1170 FORMAT(1H ,/,1H ,"ELEMENT",6X,"NODES",8X,"IMAT",4X,"GAUSS POINTS")
 1180 FORMAT (1H ,/,1H ,"BOUNDARY CONDITIONS",/,1H ,19(1H_),//,1H ,5X,"N
     * ODES",4X,"CONDITION",3X,"XPRE",6X,"YPRE")
 1190 FORMAT (1H ,/,1H ,"THE NODAL POINTS AT WHICH FORCE CALCULATIONS AR
     * E DEZIRED")
 1200 FORMAT (1H ,/,1H ,"THE NODAL POINTS AT THE FREE SURFACE")
 1210 FORMAT (1H ,"MATERIAL PROPERTIES",/,1H ,19(1H_),/)
 1220 FORMAT (1H ,"CUT OFF VALUE USED IN 'D' MATRIX   'VRIG' =",E10.2,/)
 1230 FORMAT (1H ,"COEFFICIENT OF FRICTION 'FMU' =",F5.2,/)
 1240 FORMAT (1H ,"DISTRIBUTED LOAD CONTROL VARIABLE   'NPRES' =",I3,/)
 1250 FORMAT (1H ,"NUMBER OF INITIALLY LOADED EDGES   'NEDGE' =",I5,/)
 1260 FORMAT (1H ,"PENALTY NUMBER   'ALPHA' =",E10.2,/)
 1270 FORMAT (1H ,"LENGTH OF THE BILLET LOADED WITH DRAGGING FRICTIONAL
     * FORCE   'XMIN' =",F8.3,/)
 1280 FORMAT (1H ,"THICKNESS OF THE ELEMENT   'THIC' =",F7.2,/)
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+
C
      SUBROUTINE GRID
C
C.....THIS SUBROUTINE COMPUTES THE COORDINATES OF THE NODAL POINTS FOR GIVEN
C.....DIMENSIONS OF THE BILLET AND ESTABLISHES THE ELEMENT CONNECTIONS.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/D/ NCONV,LITER
```

```
      DIMENSION C(2)
C
C.....READ THE INPUT INFORMATION
C
      READ (5,1000) DX,DY,NEX,NEY,LLMM
      NPX = NEX+1
      NPY = NEY+1
      NE = NEX*NEY
      NP = NPX*NPY
      DO 10 I = 1,NP
      DO 10 J = 1,2
   10 CORD(I,J) = 0.0
      DIMX = DX/NEX
      DIMY = DY/NEY
C
C.....COMPUTE THE COORDINATES OF THE NODAL POINTS.
C
      KNT = 1
      CORD(1,1) = 0.0
      CORD(1,2) = 0.0
      DO 30 I = 2,NP
      KK = (KNT/NPX)*NPX
      IF(KK.EQ.KNT) GOTO 20
      CORD(I,1) = CORD(I-1,1)+DIMX
   20 KNT = KNT+1
      IF (KNT.LE.NPX) GOTO 30
      CORD(I,2) = CORD(I-NPX,2)+DIMY
   30 CONTINUE
C
C.....ESTABLISH THE ELEMENT CONNECTION ARRAY
C
      L = 0
      KNT = 0
      DO 40 I = 1,NE
      L = L+1
      KNT = KNT+1
      NOP(I,1) = L
      NOP(I,2) = L+1
      NOP(I,3) = L+1+NPX
      NOP(I,4) = L+NPX
      IF (KNT.NE.NEX) GOTO 40
      KNT = 0
      L = L+1
   40 CONTINUE
      IF (LLMM) 60,60,70
   60 WRITE(6,1010)
      WRITE(6,1020)(N,(CORD(N,M),M=1,2),N=1,NP)
      WRITE(6,1030)
      WRITE(6,1040)(N,(NOP(N,M),M=1,4),N=1,NE)
      CALL DRAW
      CALL ENPLOT
      STOP
   70 RETURN
C
 1000 FORMAT(2F10.3,3I5)
 1010 FORMAT(1H ,"NODES",3X,"COORD X(R)",3X,"COORD Y(Z)",/1H ,27(1H-),/)
 1020 FORMAT(I5,2F12.3)
 1030 FORMAT(1H ,"ELEMENT",6X,"NODES",/,1H ,25(1H-),/)
 1040 FORMAT (1H ,5I5)
      END
C
```

```
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+
C
      SUBROUTINE LOAD
C
C.....THIS SUBROUTINE FORMS THE LOAD VECTOR R1
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      COMMON/A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DX
     * ,DY
      COMMON/B/INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
C
C.....ZERO LOAD ARRAY
C
      DO 10 J = 1,NEQ
   10 R1(J) = 0.0
      IF (NPC.EQ.0.AND.NITER.GT.0.AND.NEDGE.EQ.0) RETURN
      IF (ISTEP.EQ.1.AND.NITER.EQ.1) GOTO 50
      IF (NITER.GT.1) GOTO 50
C
C.....CHECK TYPE OF THE LOADING
C
      IF (NPC.EQ.0.AND.NEDGE.EQ.0) GOTO 110
      IF (NPC.EQ.0) GOTO 30
      IF (IPLAX.EQ.0) WRITE(6,1000)
      IF (IPLAX.EQ.1) WRITE(6,1005)
      DO 20 N = 1,NPC
      READ(5,1010) NQ(N),(R(N,K),K=1,2)
      WRITE(6,1030) NQ(N),(R(N,K),K=1,2)
   20 CONTINUE
   30 IF (NEDGE.EQ.0) GOTO 50
C
C.....DISTRIBUTED LOADING
C
      DO 40 N = 1,NE
      DO 40 J = 1,8
   40 ELOAD(N,J) = 0.0
      CALL SURF
   50 IF (NPC.EQ.0) GOTO 70
      DO 60 N = 1,NPC
      DO 60 K = 1,2
      IC = (NQ(N)-1)*2+K
   60 R1(IC) = R(N,K)+R1(IC)
   70 IF (NEDGE.EQ.0) GOTO 120
      NNE = 4
      DO 100 N = 1,NE
      DO 90 J = 1,NNE
      NLOCAL = NOP(N,J)
      DO 80 MM = 1,2
      IC = (NLOCAL-1)*2+MM
      JC = (J-1)*2+MM
   80 R1(IC) = R1(IC)+ELOAD(N,JC)
   90 CONTINUE
  100 CONTINUE
      IF (R1(NPN).EQ.0) R1(NPN)=R1(NPN-2)
      GOTO 120
  110 WRITE(6,1020)
  120 RETURN
```

```
C
 1000 FORMAT (1H ,/,1H ,"PRESCRIBED EXTERNAL LOADS",/,1H ,25(1H_),//,"NO
   * DES",3X,"FORCE-X",3X,"FORCE-Y")
 1005 FORMAT (1H ,"PRESCRIBED EXTERNAL LOADS",//,"NODES",3X,"FORCE-R",
   * 3X,"FORCE-Z")
 1010 FORMAT (I5,2F7.3)
 1020 FORMAT (1H ,/,1H ,"NO EXTERNAL LOADS PRESCRIBED")
 1030 FORMAT (I5,2F10.3)
 1040 FORMAT(/,1H ,"EQUIVALENT NODE LOADS DUE TO DISTRIBUTED LOADS BEFOR
   * E CONDENSATION")
 1050 FORMAT (1H ,"NODE,NO.",11(6X,I3,2X))
 1060 FORMAT (1H ,"FORCE-X ",11(F11.2))
 1070 FORMAT (1H ,"FORCE-Y ",11(F11.2))
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE SURF
C
C.....THIS SUBROUTINE CALCULATES THE NODAL LOADS DUE TO SURFACE LOADING
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
   * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
   * ,STRFR(250)
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      DIMENSION NOPRS(550,3),PRESS(3,2),ELCOD(20,30),SHP(3,9),PGASH(2),D GASH(2), XL
   * (1),YL(1),SG(9),TG(9),WG(9),NEASS(550),PRES(550,4)
      IF (NITER.GT.0) GOTO 180
      DO 190 I=1,275
      DO 190 J=1,4
  190 PRES(I,J) = 0.0
      KDGE = 0
  180 NODEG = 2
      NODFN = 2
      NELEM = NEDGE+NEX
      NEDGE1 = NEDGE
      IF (NELM.GE.NE) GOTO 240
      KEE = 0
      DO 210 NL=NE,NELEM,-NEX
      IF (CORD(NOP(NL,3),2).GT.XMIN) GOTO 210
      KEE = NL-NEDGE1
      NEDGE = NEDGE+KEE
      MEDGE = NEASS(NEDGE1)+1
      DO 220 JEDGE=MEDGE,NEDGE
      SK = YIELD(IMAT(JEDGE))/SQRT(3.)
      NEASS(JEDGE) = JEDGE
      NOPRS(NEASS(JEDGE),1) = NOP(JEDGE,4)
      NOPRS(NEASS(JEDGE),2) = NOP(JEDGE,3)
      DO 230 KEK=1,2
      PRES(NEASS(JEDGE),KEK) = ABS(STR(NEASS(JEDGE),3))*FMU
      IF (PRES(NEASS(JEDGE),KEK).GT.SK) PRES(NEASS(JEDGE),KEK) = SK
 230 IF(ABS(PRES(NEASS(JEDGE),KEK)).LT.ABS(PRESIN)) PRES(NEASS(JEDGE),K
   * EK) = PRESIN
 220 CONTINUE
 210 CONTINUE
 240 XL(1) = 1.
      YL(1) = 1.
```

```
      WRITE(6,1000)
      IF (ISTEP.LE.1) GOTO 330
C
C.....IMPOSE THE FRICTIONAL FORCE ON THE ELEMENT EDGE (IF NECESSARY) IF THE
C.....WHOLE ELEMENT EDGE HAS RICHED THE CONTAINER WALL.
C
      KKK = NEX*2+1
      LEDGE = 1
      DO 150 NEL=1,NELM,NEX
      LKK = NEL-1
      DO 300 LEL=1,KKK,2
      IF (LEL.NE.1) GOTO 310
      LLK = LKK+1
      SK = YIELD(IMAT(LLK))/(SQRT(3.))
      PRES(LEDGE,1) = 0.0
      PRES(LEDGE,2) = 0.0
      PRES(LEDGE,3) = ABS(STR(LLK,3))*FMU
      IF (PRES(LEDGE,3).GT.SK) PRES(LEDGE,3) = SK
      IF (PRES(LEDGE,3).LT.PRESIN) PRES(LEDGE,3) = PRESIN
      PRES(LEDGE,4) = ABS(STR(LLK,3))*FMU
      IF (PRES(LEDGE,4).GT.SK) PRES(LEDGE,4) = SK
      IF (PRES(LEDGE,4).LT.PRESIN) PRES(LEDGE,4) = PRESIN
      STRFR(LLK) = PRES(LEDGE,4)
      LEDGE = LEDGE+1
      LEDGEL = LEDGE+1
      GOTO 300
  310 LLE = LEL+1
      LLK = LKK+(LLE/2)-1
      SK = YIELD(IMAT(LLK))/(SQRT(3.))
      DO 320 LKL=3,4
      IAA = LKL-2
      PRES(LEDGE,IAA) = ABS(STR(LLK,3))*FMU
      PRES(LEDGE,LKL) = 0.0
      IF (PRES(LEDGE,IAA).GE.PRESIN) GOTO 340
      PRES(LEDGE,IAA) = PRESIN
  340 IF (PRES(LEDGE,IAA).GT.SK) PRES(LEDGE,IAA) = SK
      PRES(LEDGEL,IAA) = 0.0
      PRES(LEDGEL,LKL) = ABS(STR(LLK,3))*FMU
      IF (PRES(LEDGEL,LKL).GE.PRESIN) GOTO 350
      PRES(LEDGEL,LKL) = PRESIN
  350 IF (PRES(LEDGEL,LKL).GT.SK) PRES(LEDGEL,LKL) = SK
      STRFR(LLK) = PRES(LEDGEL,LKL)
      IF (LEL.LT.KKK) GOTO 320
      IF (CORD(NOP(LLK,2),1).NE.XMAX.OR.CORD(NOP(LLK,3),1).NE.XMAX) GOTO
     * 320
      FRIC = ABS(STR(LLK,1))*FMU
      IF (FRIC.GT.SK) FRIC = SK
      IF (ITY.EQ.0) PRES(LEDGEL,LKL) = PRES(LEDGEL,LKL)+FRIC
      IF (ITY.EQ.1) PRES(LEDGEL,LKL) = PRES(LEDGEL,LKL)-FRIC
C.....IF (ITY.EQ.2) THEN CONFORM IS UNDER CONSIDERATION AND THERE IS NO
C.....NEED TO CHANGE THE VALUE OF PRESS(LEDGEL,LKL)
  320 CONTINUE
      LEDGE = LEDGE+2
      LEDGEL = LEDGE+1
  300 CONTINUE
  150 CONTINUE
      IF (NELM.GE.NE) GOTO 330
      DO 400 IST=NELM+1,NE
  400 STRFR(IST) = 0.0
C
C.....LOOP OVER EACH LOADED EDGE
```

```
C
 330 WRITE(6,*) 'NEDGE = ',NEDGE
     DO 80 IEDGE = 1,NEDGE
     IF (ISTEP.GT.1) GOTO 130
C
C.....READ DATA LOCATING THE EDGE AND APPLIED LOAD.
C
     READ(5,1010) NEASS(IEDGE),(NOPRS(IEDGE,IODEG),IODEG=1,NODEG)
     READ(5,1030) ((PRESS(IODEG,IDOFN),IODEG=1,NODEG),IDOFN = 1,2)
     DO 110 IDOFN=1,2
     DO 110 IODEG=1,NODEG
     IA = (IDOFN-1)*2+IODEG
 110 PRES(IEDGE,IA) = PRESS(IODEG,IDOFN)
     IF (IEDGE.NE.NEDGE) GOTO 370
     DO 360 ILE=2,3
 360 IF (PRES(IEDGE,ILE).NE.0.) PRESIN=PRES(IEDGE,ILE)
     WRITE(6,*)'PRESIN = ',PRESIN
 370 GOTO 90
 130 DO 120 IDOFN=1,2
     DO 120 IODEG=1,NODEG
     IA = (IDOFN-1)*2+IODEG
 120 PRESS(IODEG,IDOFN) = PRES(IEDGE,IA)
  90 WRITE(6,1020) NEASS(IEDGE),(NOPRS(IEDGE,IODEG),IODEG=1,NODEG)
     WRITE(6,1030) ((PRESS(IODEG,IDOFN),IODEG=1,NODEG),IDOFN = 1,2)
C
C.....COORDINATES OF THE NODES OF THE ELEMENT EDGE.
C
     DO 280 IDOFN=1,2
     DO 280 IODEG=1,NODEG
     IA = (IDOFN-1)*2+IODEG
 280 PRES(NEASS(IEDGE),IA) = PRESS(IODEG,IDOFN)
     DO 10 IODEG = 1,NODEG
     LNODE = NOPRS(IEDGE,IODEG)
     DO 10 IDIME = 1,2
  10 ELCOD(IDIME,IODEG) = CORD(LNODE,IDIME)
C
C.....ENTER LOOP FOR NUMERICAL INTEGRATION.
C
     NINT = 2
     CALL PGAUSS(NINT,LINT,SG,TG,WG)
     DO 70 IGAUSS = 1,NINT
C
C.....EVALUATE SHAPE FUNCTION AT SAMPLING POINTS.
C
     CALL SHAPE(SG(IGAUSS),-1.,XL,YL,SHP,DETJAC,2,ELD)
     RBAR = 0.0
     DO 20 KI = 1,NODEG
  20 RBAR = RBAR+SHP(3,KI)*ELCOD(1,KI)
     IF (IPLAX.EQ.0) RBAR = 1.0
C
C.....CALCULATE THE COMPONENTS OF THE EQUOVALENT NODEL LOADS.
C
     DO 30 IDOFN = 1,2
     PGASH(IDOFN) = 0.0
     DGASH(IDOFN) = 0.0
     DO 30 IODEG = 1,NODEG
     PGASH(IDOFN) = PGASH(IDOFN)+PRESS(IODEG,IDOFN)*SHP(3,IODEG)
  30 DGASH(IDOFN) = DGASH(IDOFN)+SHP(1,IODEG)*ELCOD(IDOFN,IODEG)
     DVOLU = WG(IGAUSS)*RBAR
     PXCOM = DGASH(1)*PGASH(2)-DGASH(2)*PGASH(1)
     PYCOM = DGASH(1)*PGASH(1)+DGASH(2)*PGASH(2)
```

```
C
C.....ASSOSIATE THE EQUIVALENT NODAL EDGE LOADS WITH AN ELEMENT.
C
      NNE = 4
      DO 40 INODE = 1,NNE
      NLOCA = NOP(NEASS(IEDGE),INODE)
      IF (NLOCA.EQ.NOPRS(IEDGE,1)) GO TO 50
   40 CONTINUE
   50 JNODE = INODE+NODEG-1
      KOUNT = 0
      DO 60 KNODE = INODE,JNODE
      KOUNT = KOUNT+1
      NGASH = (KNODE-1)*NODFN+1
      MGASH = (KNODE-1)*NODFN+2
      IF(KNODE.GT.NNE) NGASH = 1
      IF(KNODE.GT.NNE) MGASH = 2
      ELOAD(NEASS(IEDGE),NGASH) = ELOAD(NEASS(IEDGE),NGASH)+SHP(3,KOUNT)
     * *PXCOM*DVOLU
   60 ELOAD(NEASS(IEDGE),MGASH) = ELOAD(NEASS(IEDGE),MGASH)+SHP(3,KOUNT)
     * *PYCOM*DVOLU
   70 CONTINUE
   80 CONTINUE
      IF (ISTEP.GT.1) GOTO 420
      DO 410 IST=1,NELM
  410 STRFR(IST) = PRESIN
      IF (NELM.GE.NE) GOTO 420
      DO 430 IST=NELM+1,NE
  430 STRFR(IST) = 0.0
  420 RETURN
C
 1000 FORMAT (1H ,/,1H ,"LIST OF LOADED EDGES AND APPLIED LOADS")
 1010 FORMAT(3I5)
 1020 FORMAT(1H ,I10,5X,2I5)
 1030 FORMAT(4F10.3)
 1270 FORMAT (1H ,"LENGTH OF THE BILLET LOADED WITH DRAGGING FRICTIONAL
     * FORCE  'XMIN' =",F8.3,/)
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE FORMK
C
C.....THIS SUBROUTINE FORMS THE OVERALL STIFFNESS MATRIX
C.....AND STORES IT IN A RECTANGULAR FORM.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      DIMENSION SE(8,8)
C
C.....INITIALIZE THE ARRAYS
C
      DO 10 N = 1,NEQ
      DO 10 M = 1,NBAND
   10 SK(N,M) = 0.0
C
C.....SCAN ELEMENTS
C
      WRITE(3,1010) NITER
```

```
 160 DO 80 II = 1,NE
      CALL QUAD2 (SE,II)
C
C.....FORM THE STIFFNESS MATRIX SK
C
C
C.....FIRST ROWS
C
      DO 70 JJ = 1,4
      NROWB = (NOP(II,JJ)-1)*2
      IF (NROWB) 70,20,20
  20 DO 60 J = 1,2
      NROWB = NROWB+1
      I = (JJ-1)*2+J
C
C.....THEN COLUMNS
C
      DO 50 KK = 1,4
      NCOLB = (NOP(II,KK)-1)*2
      DO 40 K = 1,2
      L = (KK-1)*2+K
      NCOL = NCOLB+K+1-NROWB
C
C.....SKIP STORING IF BELOW BAND
C
      IF (NCOL) 40,40,30
  30 SK(NROWB,NCOL) = SK(NROWB,NCOL)+SE(I,L)
  40 CONTINUE
  50 CONTINUE
  60 CONTINUE
  70 CONTINUE
  80 CONTINUE
C
C.....PREPARATION FOR FORCE CALCULATION
C.....STORE THE THE ROWS OF SK WHICH ARE NECESSARY
C
      IF (NBF.EQ.0) GOTO 140
      NBAND2 = 2*NBAND-1
      DO 90 I = 1,NBF
      IY  = 2*I
      IX = IY -1
      DO 90 J = 1,NBAND2
      EST(IY ,J) = 0.0
  90 EST(IX ,J) = 0.0
      DO 130 I = 1,NBF
      II = NF(I)
      IY  = 2*II
      IX = IY -1
      IIY  = 2*I
      IIX = IIY -1
      DO 100 J = NBAND,NBAND2
      JJ = J-NBAND+1
      EST(IIX ,J) = SK(IX ,JJ)
 100 EST(IIY ,J) = SK(IY ,JJ)
      DO 120 J = 1,NBAND
      NR = IX -J+1
      NZ = IY -J+1
      JJ = NBAND-J+1
      IF (NR.LE.0) GOTO 110
      EST(IIX ,JJ) = SK(NR,J)
 110 IF (NZ.LE.0) GOTO 120
```

```
      EST(IIY ,JJ) = SK(NZ,J)
  120 CONTINUE
      FPUR(IIX ) = R1(IX )
  130 FPUR(IIY ) = R1(IY )
C
C.....INSERT DISPLACEMENT BOUNDARY CONDITIONS
C
  140 DO 150 N = 1,NB
      I = NBC(N)
      IX = 2*I-1
      IY  = IX +1
      NC = NREST(N)
C
C.....CHECK IF THE X-VELOCITY IS PRESCRIBED
C
      IF (NC.EQ.1.OR.NC.EQ.11) CALL CONDE (IX ,XPRE(N))
C
C.....CHECK IF THE Y-VELOCITY IS PRESCRIBED
C
      IF (NC.EQ.2.OR.NC.EQ.11) CALL CONDE (IY ,YPRE(N))
  150 CONTINUE
  170 RETURN
C
 1000 FORMAT (1H ,5(1X,"SK(",I3,",",I2,")=",E12.6))
 1010 FORMAT (1H ,"ITERATION NO.",I3)
 1020 FORMAT (1H ,120(1H=),/,1H ,"ELEMENTS OF THE STIFFNESS MATRIX SK",/
     * ,1H ,35(1H-),//)
 1030 FORMAT(1H ,7(I3,",",I2,"=",E10.4,1X))
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE QUAD2 (SE,IEL)
C
C.....THIS SUBROUTINE FORMS THE ELEMENTAL STIFNESS MATRIX.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/ A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      COMMON/D/ NCONV,LITER
      DIMENSION D(4,4),SE(8,8),A(4,8),XL(4),YL(4)
      DIMENSION B(4,8),SHP(3,9),SG(9),WG(9),TG(9),ELD(2,9)
C
C.....INITIALIZE THE ARRAYS
C
      N = IEL
      NNE = 4
      NNE2 = NNE*2
      DO 10 I = 1,4
      DO 10 J = 1,4
   10 D(I,J) = 0.0
      DO 20 I = 1,NNE2
      DO 20 J = 1,NNE2
   20 SE(I,J) = 0.0
   25 DO 30 MM = 1,NNE
      XL(MM) = CORD(NOP(N,MM),1)
```

```
  30 YL(MM) = CORD(NOP(N,MM),2)
      NINT = 2
      IPEN = 0
C
C.....COMPUTE GAUSS POINTS AND WEIGHT FACTORS.
C
  40 CALL PGAUSS (NINT,LINT,SG,TG,WG)
C
C.....FORM STRAIN-DISPLACEMENT MATRIX B.
C
      DO 200 L = 1,LINT
      XBAR = 0.0
      DO 50 NN = 1,3
      DO 50 LL = 1,NNE
  50 SHP(NN,LL) = 0.0
      CALL SHAPE (SG(L),TG(L),XL,YL,SHP,DETJAC,NNE,ELD)
      IF (DETJAC) 60,60,70
  60 WRITE(6,1000) N
      WRITE(6,1010)
      WRITE(6,1020) (LH,(CORD(LH,LT),LT=1,2),LH=1,NP)
      LLMM=1
      CALL DRAW
      CALL ENPLOT
      STOP
  70 DO 80 LI = 1,NNE
      J = 2*LI
      I = J-1
      B(1,I) = SHP(1,LI)
      B(1,J) = 0.0
      B(2,I) = 0.0
      B(2,J) = SHP(2,LI)
      B(3,I) = 0.0
      B(3,J) = 0.0
      B(4,I) = B(2,J)
  80 B(4,J) = B(1,I)
C
C.....IN CASE OF PLANE STRAIN ANALYSIS DO NOT INCLUDE
C.....THE NORMAL STRAIN COMPONENT
C
      IF (IPLAX.EQ.0) GOTO 130
      DO 90 KI = 1,NNE
  90 XBAR = XBAR+SHP(3,KI)*XL(KI)
C
C.....EVALUTE THE HOOP STRAIN-DISPLACEMENT RELATIONSHIP
C
      IF (XBAR.GT.0.00000001) GOTO 110
C
C.....FOR THE CASE OF ZERO RADIUS EQUATE RADIAL TO HOOP STRAIN
C
      DO 100 KI = 1,NNE2
 100 B(3,KI) = B(1,KI)
      GOTO 130
C
C.....NON-ZERO RADIUS
C
 110 DUMA = 1./XBAR
      DO 120 KI = 1,NNE
      LH = 2*KI-1
 120 B(3,LH) = SHP(3,KI)*DUMA
C
C.....FORM THE PENALTY MATRIX.
```

```
C
 130 IF (IPEN.EQ.0) GOTO 150
     DO 140 I = 1,4
     DO 140 J = 1,4
     D(I,J) = ALPHA
 140 IF (I.EQ.4.OR.J.EQ.4) D(I,J) = 0.0
     GOTO 160
C
C.....FORM THE STRESS-STRAIN MATRIX
 150 IF (NITER.EQ.0) EPSR = 1.0
     IF (NITER.GT.0) CALL STRA (L,NNE,N,B,EPSR)
     LL = IMAT(N)
     YYLD = YIELD(LL)
     DUM3 = 2.*YYLD/(3.*EPSR)
     IF (DUM3.GE.VRIG) DUM3 = VRIG
     D(1,1) = DUM3
     D(2,2) = DUM3
     D(3,3) = DUM3
     D(4,4) = DUM3/2.
C
C.....COMPUTE THE PRODUCT D*B
C
 160 DO 170 I = 1,4
     DO 170 J = 1,NNE2
     A(I,J) = 0.0
     DO 170 K = 1,4
 170 A(I,J) = A(I,J)+D(I,K)*B(K,J)
C
C.....COMPUTE [B**T * (D*B)] AND ADD CONTRIBUTION TO ELEMENT STIFFNESS
C
     IF (IPLAX.EQ.0) XBAR = 1.0
     WT = XBAR*WG(L)*DETJAC*THIC
     DO 190 NROW = 1,NNE2
     DO 190 NCOL = NROW,NNE2
     DUM2 = 0.0
     DO 180 LI = 1,4
 180 DUM2 = DUM2+B(LI,NROW)*A(LI,NCOL)
     SE(NROW,NCOL) = SE(NROW,NCOL)+DUM2*WT
 190 CONTINUE
 200 CONTINUE
     IPEN = IPEN+1
     NINT = 1
     IF (IPEN.EQ.1) GOTO 40
C
C.....COMPLETE SE BY SYMMETRY
C
     DO 210 K = 2,NNE2
     DO 210 L = 1,K
 210 SE(K,L) = SE(L,K)
     RETURN
C
1000 FORMAT (//,"PROGRAM WAS HALTED IN SUBROUTINE QUAD2",//,"ELEMENT",I
   * 5,2X,"HAS ZERO OR NEGATIVE AREA")
1010 FORMAT (1H ,"COORDINATES AT THE TIME OF HALTING")
1020 FORMAT (1H ,I10,2F10.4)
1070 FORMAT (1H ,/,1H ,"ELEMENT NO. ",I3," SE(I,J)=",)
1080 FORMAT (1H ,8(I1,",",I1,"=",E10.4,2X))
     END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
```

```
      SUBROUTINE PGAUSS (L,LINT,R,Z,W)
C
C.....GAUSS POINTS AND WEIGHTS FOR TWO DIMENSIONS
C
      REAL LR(9),LZ(9),LW(9),R(9),Z(9),W(9)
      DATA LR/-1.,1.,1.,-1.,0.,-1.,0.,-1.,0./
      DATA LZ/-1.,-1.,1.,1.,-1.,0.,1.,0.,0./
      DATA LW/4*25.,4*40.,64./
      LINT = L*L
      IF (L.EQ.1) GOTO 10
      IF (L.EQ.2) GOTO 20
      IF (L.EQ.3) GOTO 40
C
C.....1 X 1 INTEGRATION
C
   10 R(1) = 0.
      Z(1) = 0.
      W(1) = 2.
      RETURN
C
C.....2 X 2 INTEGRATION
C
   20 G = 1./SQRT(3.)
      DO 30 I = 1,4
      R(I) = G*LR(I)
      Z(I) = G*LZ(I)
   30 W(I) = 1.
      RETURN
C
C.....3 X 3 INTEGRATION
C
   40 G = SQRT(0.6)
      H = 1./81.
      DO 50 I = 1,9
      R(I) = G*LR(I)
      Z(I) = G*LZ(I)
   50 W(I) = H*LW(I)
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE SHAPE (SS,TT,XL,YL,SHP,DETJAC,NNE,ELD)
C
C.....SHAPE FUNCTION SUBROUTINE FOR TWO DIMENSIONAL ELEMENTS
C
      REAL SHP(3,9),XL(4),YL(4),S(4),T(4),JAC(2,2),ELD(2,9)
      DATA S/-0.5,0.5,0.5,-0.5/,T/-0.5,-0.5,0.5,0.5/
C
C.....FORM 4 NODE QUADRILATERAL SHAPE FUNCTION
C
      DO 10 I = 1,4
      SHP(3,I) = (0.5+S(I)*SS)*(0.5+T(I)*TT)
      SHP(1,I) = S(I)*(0.5+T(I)*TT)
      SHP(2,I) = T(I)*(0.5+S(I)*SS)
      ELD(1,I) = SHP(1,I)
   10 ELD(2,I) = SHP(2,I)
C
C.....CONSTRUCT THE JACOBIAN, ITS INVERSE AND ITS DETERMINANT
C
      DO 20 I = 1,2
```

```
      DO 20 J = 1,2
   20 JAC(I,J) = 0.0
      DO 30 K = 1,NNE
      JAC(1,1) = JAC(1,1)+SHP(1,K)*XL(K)
      JAC(1,2) = JAC(1,2)+SHP(1,K)*YL(K)
      JAC(2,1) = JAC(2,1)+SHP(2,K)*XL(K)
   30 JAC(2,2) = JAC(2,2)+SHP(2,K)*YL(K)
      DETJAC = JAC(1,1)*JAC(2,2)-JAC(1,2)*JAC(2,1)
      IF (DETJAC.LE.0) RETURN
      DUM1 = JAC(1,1)/DETJAC
      JAC(1,1) = JAC(2,2)/DETJAC
      JAC(2,1) = -JAC(2,1)/DETJAC
      JAC(1,2) = -JAC(1,2)/DETJAC
      JAC(2,2) = DUM1
C
C.....FORM GLOBAL DERIVATIVES
      DO 40 I = 1,NNE
      TP = SHP(1,I)*JAC(1,1)+SHP(2,I)*JAC(1,2)
      SHP(2,I) = SHP(1,I)*JAC(2,1)+SHP(2,I)*JAC(2,2)
   40 SHP(1,I) = TP
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE STRA (L,NNE,M,BA,EPSR)
C
C.....THIS SUBROUTINE CALCULATES THE STRAINS AT THE GAUSS POINTS
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DX
     * ,DY
      COMMON/B/INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      COMMON/D/ NCONV,LITER
      DIMENSION BA(4,8),E(4),RA(8)
      NK = NNE
      NK2 = NK*2
      DO 10 J = 1,NK
      KK = NOP(M,J)
      KI = (J-1)*2
      DO 10 JJ = 1,2
      IJ = JJ+KI
   10 RA(IJ) = VEL(JJ,KK)
      DO 20 KK = 1,4
      E(KK) = 0.0
      DO 20 J = 1,NK2
   20 E(KK) = E(KK)+BA(KK,J)*RA(J)
      GOTO 50
   40 EPSR = RBAR(E(1),E(2),E(3),E(4))
      EPSR1 = E(1)+E(2)+E(3)
      KK = IMAT(M)
      IF (NITER.EQ.0) YYLD = YIELD(KK)
      IF (NITER.NE.0) YYLD = STREF(M)
      DO 30 I=1,4
      DEG(NOGP(M,L),I) = E(I)*STEP
      STRG(NOGP(M,L),I) = 2.*YYLD/(3.*EPSR)*E(I)+ALPHA*EPSR1
```

```
   30 CONTINUE
   50 RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE CONDE (N,U)
C
C.....THIS SUBROUTINE PERFORMS THE MATRIX CONDENSATION WHEN
C.....THE VALUE OF A COMPONENT OF X IN AX=B IS SPECIFIED.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      DO 10 M = 2,NBAND
      KK = M+N-1
      IF (KK.GT.NEQ) GOTO 10
      R1(KK) = R1(KK)-SK(N,M)*U
   10 CONTINUE
      DO 20 M = 2,NBAND
      K = N-M+1
      IF (K.LE.0) GOTO 20
      R1(K) = R1(K)-SK(K,M)*U
      SK(K,M) = 0.0
   20 SK(N,M) = 0.0
      SK(N,1) = 1.
      R1(N) = U
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE SOLVE
C
C.....THIS SUBROUTINE PERFORMS THE SOLUTION OF THE EQUATION SYSTEM AX=B.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      COMMON/A/ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DX
     * ,DY
      IF (NITER.EQ.2.OR.NITER.EQ.0) GOTO 120
      GOTO 140
  120 WRITE(6,1040)
      KL=0
      DO 130 IL=1,NP,NPX
      JL=IL+NPX-1
      KL=KL+1
      KLL=KL+2*NPX-2
      ML=KL+1
      MLL=ML+2*NPX-2
      WRITE(6,1050)(LM,LM=IL,JL)
      WRITE(6,1060)(R1(LLK),LLK=KL,KLL,2)
      WRITE(6,1070)(R1(LLM),LLM=ML,MLL,2)
      WRITE(6,*)'                                      '
  130 KL=MLL
      WRITE(3,1020)
      WRITE(3,1030)((I,J,SK(I,J),J=1,NBAND),I=1,NEQ)
C
C.....REDUCE MATRIX
C
```

```
 140 DO 50 N = 1,NEQ
      I = N
      DO 40 L = 2,NBAND
      I = I+1
      IF (SK(N,L)) 10,40,10
  10 C = SK(N,L)/SK(N,1)
      J = 0
      DO 30 K = L,NBAND
      J = J+1
      IF (SK(N,K)) 20,30,20
  20 SK(I,J) = SK(I,J)-C*SK(N,K)
  30 CONTINUE
      SK(N,L) = C
C
C.....AND LOAD VECTOR FOR EACH EQUATION.
C
      R1(I) = R1(I)-C*R1(N)
  40 CONTINUE
  50 R1(N) = R1(N)/SK(N,1)
C
C.....BACK SUBSTITUTION
C
      N = NEQ
  60 N = N-1
      IF (N) 100,100,70
  70 L = N
      DO 90 K = 2,NBAND
      L = L+1
      IF (SK(N,K)) 80,90,80
  80 R1(N) = R1(N)-SK(N,K)*R1(L)
  90 CONTINUE
      GOTO 60
  100 RETURN
C
 1020 FORMAT (1H ,120(1H=),/,1H ,"ELEMENTS OF THE STIFFNESS MATRIX SK",/
    * ,1H ,35(1H-),//)
 1030 FORMAT(1H ,7(I3,",",I2,"=",E10.4,1X))
 1040 FORMAT(/,1H ,"EQUIVALENT NODE LOADS DUE TO DISTRIBUTED LOADS",/)
 1050 FORMAT (1H ,"NODE,NO.",11(6X,I3,2X))
 1060 FORMAT (1H ,"FORCE-X ",11(F11.2))
 1070 FORMAT (1H ,"FORCE-Y ",11(F11.2))
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE CFORC
C
C.....THIS SUBROUTINE DETERMINES FORCES ON THE BOUNDARIES.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
    * YPRE(60),NF(25),SIGZ1
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      IF (NBF.LE.0) GOTO 50
      NBAND2 = 2*NBAND-1
      DO 40 I = 1,NBF
      IX = 2*NF(I)-1
      IIY  = 2*I
      IIX = IIY -1
      SUMR = 0.0
      SUMZ = 0.0
```

```
      DO 30 J = 1,NBAND2
      JX  = IX +J-NBAND
      JY  = JX +1
      IF (JX .GT.NEQ) GOTO 20
      IF (JX .LE.0) GOTO 10
      SUMR = SUMR+EST(IIX ,J)*R1(JX )
   10 IF (JY .LE.0) GOTO 30
   20 IF (JY .GT.NEQ) GOTO 30
      SUMZ = SUMZ+EST(IIY ,J)*R1(JY )
   30 CONTINUE
      FX(I) = SUMR-FPUR(IIX )
      FY(I) = SUMZ-FPUR(IIY )
   40 CONTINUE
   50 RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE STRAIN
C
C.....THIS SUBROUTINE CALCULATES STRAINS, STRESSES AND COORDINATES.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      COMMON/D/ NCONV,LITER
      DIMENSION SHP(3,9),SG(9),TG(9),WG(9),U(2,9)
      DIMENSION XL(9),YL(9),E(6)
      IF(ISTEP.NE.1) GOTO 130
      DO 120 I=1,NE
      TEPS(I) = 0.0
      DO 120 J=1,6
  120 STR(I,J) = 0.0
  130 NNE = 4
      DO 100 N = 1,NE
      DO 10 MM = 1,NNE
      XL(MM) = CORD(NOP(N,MM),1)
      YL(MM) = CORD(NOP(N,MM),2)
      U(1,MM) = VEL(1,NOP(N,MM))
   10 U(2,MM) = VEL(2,NOP(N,MM))
      L = 1
      CALL PGAUSS(L,LINT,SG,TG,WG)
      DO 20 NN = 1,3
      DO 20 LL = 1,NNE
   20 SHP(NN,LL) = 0.0
C
C.....COMPUTE ELEMENT SHAPE FUNCTIONS.
C
      CALL SHAPE(SG(L),TG(L),XL,YL,SHP,DETJAC,NNE,ELD)
C
C.....COMPUTE COORDINATES AND STRAINS.
C
      DO 30 I = 1,6
   30 E(I) = 0.0
      XBAR = 0.0
      YBAR = 0.0
```

```
      DO 40 J = 1,NNE
      XBAR = XBAR+SHP(3,J)*XL(J)
   40 YBAR = YBAR+SHP(3,J)*YL(J)
      DO 70 J = 1,NNE
      E(1) = E(1)+SHP(1,J)*U(1,J)
      E(2) = E(2)+SHP(2,J)*U(2,J)
C
C.....FOR THE CASE OF ZERO RADIUS EQUATE RADIAL TO HOOP STRAIN
C
      IF (XBAR.GT.0.0000001) GOTO 50
      E(3) = E(1)
      GOTO 60
   50 E(3) = E(3)+SHP(3,J)/XBAR*U(1,J)
   60 IF (IPLAX.EQ.0) E(3) = 0.0
   70 E(4) = E(4)+SHP(1,J)*U(2,J)+SHP(2,J)*U(1,J)
      DO 80  J = 1,4
   80 EPS(N,J) = E(J)
      EPS(N,6) = RBAR(E(1),E(2),E(3),E(4))
      EPS(N,5) = E(1)+E(2)+E(3)
      KK = IMAT(N)
      YYLD = YIELD(KK)
      Z = STR(N,5)
      DO 90 I = 1,4
   90 STR(N,I) = 2.*YYLD/(3.*EPS(N,6))*EPS(N,I)+ALPHA*EPS(N,5)
      STR(N,5) = STR(N,5)+ALPHA*EPS(N,5)
      TEPS(N) = TEPS(N)+EPS(N,6)*STEP
      IF (N.NE.1) GOTO 140
      SIGZ1 = Z/STR(N,5)
  140 SIGZ2 = Z/STR(N,5)
      IF (SIGZ1.LT.SIGZ2) SIGZ1=SIGZ2
      STREF(N) = SQRT(3./2.*(((STR(N,1)-STR(N,5))**2+(STR(N,2)-STR(N,5))
     * **2)/2.+STR(N,4)**2))
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE DOUT
C
C.....THIS SUBROUTINE PRINTS OUT CALCULATED RESULTS.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      WRITE(6,1080)
C
C.....PRINT NODAL POSITIONS AND VELOCITY DISTRIBUTION FOR THIS STEP
C
      IF (LLMM.EQ.1) GOTO 10
      IF (ISTEP.EQ.1.OR.ISTEP.EQ.NSTEP) GOTO 10
      IF (((ISTEP-1)/2)*2.NE.(ISTEP-1)) GOTO 20
   10 RED = ((DY-CORD(NP,2))/DY)*100.
      WRITE(6,1000) TITLE
      WRITE(6,1010) RED
      IF (IPLAX.EQ.0) WRITE(6,1025)
```

```
      IF (IPLAX.EQ.1) WRITE(6,1030)
      WRITE(6,1020)
      WRITE(6,1040) (N,(CORD(N,M),M=1,2),(VEL(M,N),M=1,2),N=1,NP)
      WRITE(6,1020)
C
C.....PLOT THE DEFORMED MESH.
C
      CALL DRAW
C
C.....WRITE STRAIN-RATE DISTRIBUTION
C
      WRITE(6,1080)
      IF (IPLAX.EQ.0) WRITE(6,1110)
      IF (IPLAX.EQ.1) WRITE(6,1100)
      WRITE(6,1120)
      WRITE(6,1130) (N,(EPS(N,J),J=1,6),TEPS(N),N=1,NE)
C
C.....WRITE STRESS DISTRIBUTION
C
      WRITE(6,1080)
      IF (IPLAX.EQ.0) WRITE(6,1140)
      IF (IPLAX.EQ.1) WRITE(6,1150)
      WRITE(6,1120)
      WRITE(6,1160)(N,(STR(N,J),J=1,5),STREF(N),STRFR(N),N=1,NE)
      WRITE(6,1080)
C
C.....WRITE FORCES AT NODES IF DESIRED.
C
      IF (NBF.LE.0) GOTO 20
      WRITE(6,1060)
      WRITE(6,1070) (NF(I),FX(I),FY(I),I=1,NBF)
      WRITE(6,1080)
      WRITE(6,1080)
C  20 CALL FOLD
      WRITE(4,1240) ISTEP
      WRITE(4,1250)(CORD(NOP(I,3),1),CORD(NOP(I,3),2),(EPS(I,J),J=1,4),I
     * =1,NE)
      WRITE(4,1260)
      WRITE(4,1250)(CORD(NOP(I,3),1),CORD(NOP(I,3),2),(STR(I,J),J=1,4),S
     * TRFR(I),I=1,NE)
   20 RETURN
C
 1000 FORMAT (1H ,8A10,/)
 1010 FORMAT (1H ,"NODAL COORDINATES AT",F6.2,"  PERCENT REDUCTION",/,1H
     *  ,45(1H*),/)
 1025 FORMAT (1H ,6X,"NODES",3X,"COORD-X",3X,"COORD-Y",7X,"VEL-X",10X,"V
     * EL-Y")
 1020 FORMAT (1H ,130(1H-),/)
 1030 FORMAT (1H ,6X,"NODES",3X,"COORD-R",3X,"COORD-Z",20X,"VEL-R",5X,
     * "VEL-Z")
 1040 FORMAT (1H ,I10,1X,2F10.3,2E15.6)
 1055 FORMAT (1H ,15X,"NUMBER OF ITERATIONS",I3,//1H ,4X,"NODES",7X,"VEL
     * OC-X",8X,"VELOC-Y")
 1060 FORMAT (1H ,"FORCES CALCULATED AT BOUNDARY NODES",/1H ,34(1H_),//,
     * 1H ,5X,"NODES",5X,"FORCE-X",3X,"FORCE-Y")
 1070 FORMAT (1H ,I10,2X,2E10.3)
 1080 FORMAT (1H ,130(1H*),/)
 1100 FORMAT (1H ,3X,"ELEMENTS",6X,"R-ST.RATE",7X,"Z-ST.RATE",7X,"O-ST.R
     * ATE",6X,"RZ-ST.RATE",9X,"COMPRE",6X,"EF-ST.RATE",6X,"EF-STRAIN")
 1110 FORMAT (1H ,3X,"ELEMENTS",6X,"X-ST.RATE",7X,"Y-ST.RATE",7X,"Z-ST.R
     * ATE",6X,"XY-ST.RATE",6X,"COMPRE",9X,"EF-ST.RATE",6X,"EF-STRAIN")
```

```
1120 FORMAT (1H ,130(1H-),/)
1130 FORMAT (1H ,I10,4E16.4,E15.4,E16.4,E15.4)
1140 FORMAT (1H ,3X,"ELEMENTS",6X,"X-STRESS",7X,"Y-STRESS",7X,"Z-STRESS
   * ",6X,"XY-STRESS",5X,"HYD-STRESS",6X,"EF-STRESS",6X,"FR-STRESS")
1150 FORMAT (1H ,3X,"ELEMENTS",6X,"R-STRESS",7X,"Z-STRESS",7X,"O-STRESS
   * ",6X,"RZ-STRESS",5X,"HYD-STRESS")
1160 FORMAT (1H ,I10,7E15.5)
1170 FORMAT (8(2X,E12.6))
1180 FORMAT (1H ,"STEP NO.",I5,//,1H ,"STRAIN INCREMENT ON GAUSS POINTS
   *  - DEG(NGP,4)")
1190 FORMAT (1H ,/,2X,"STRAINS ON GAUSS POINTS - EG(NGP,4)")
1200 FORMAT (1H ,/,2X,"STRESSES ON GAUSS POINTS - STRG(NGP,4)")
1220 FORMAT(1H ,"GAUSS POINT NO.",3X,"G.P.COORD X",3X,"G.P.COORD Y",/,1
   * H ,15(1H-),3X,11(1H-),3X,11(1H-))
1230 FORMAT (I8,13X,F7.4,7X,F7.4)
1240 FORMAT (1H ,"STEP NO.",I3,//,1H ,"STRAIN RATES - EPS(NE,4)")
1250 FORMAT (7(2X,E12.6))
1260 FORMAT (1H ,/,2X,"STRESSES - STR(NE,4)")
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE DRAW
C
C.....THIS SUBROUTINE PLOTS THE DEFORMED MESH.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
   * ,STRFR(250)
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      COMMON/E/ FMAX
      DIMENSION X(20),Y(20)
      IF (ISTEP.GT.1) CALL NEWPAGE
      IF (NPAGE.EQ.1) CALL NEWPAGE
      IF (LLMM) 80,80,90
  80 RED = ((DY-CORD(NP,2))/DY)*100.
  90 CALL SYMBOL (6.0,15.0,0.14,'FINITE ELEMENT GRID',0.0)
      CALL SYMBOL (3.0,0.0,0.14,'DEFORMED MESH AND VELOCITY FIELD AT
   *   PERCENT REDUCTION',0.0)
      IF (LLMM.EQ.1) GOTO 100
      CALL NUMBER (8.1,0.0,0.14,RED,0.0,-1)
 100 CALL PLOT (2.0,1.0,-3)
      DO 10 I = 1,5
      X(I) = 0.0
  10 Y(I) = 0.0
      X(5) = CORD(NP,1)
      Y(5) = CORD(NP,2)
      CALL SCALE (X,3.0,5,1)
      CALL SCALE (Y,15.0,5,1)
      CALL AXIS (0.0,0.0,'X - AXIS',-1,3.0,0.0,X(6),X(7))
      CALL AXIS (0.0,0.0,'Y - AXIS',1,15.0,90.0,Y(6),Y(7))
      DO 30 N = 1,NE
      DO 20 J = 1,4
      X(J) = CORD(NOP(N,J),1)
  20 Y(J) = CORD(NOP(N,J),2)
      X(5) = CORD(NOP(N,1),1)
      Y(5) = CORD(NOP(N,1),2)
      CALL LINE (X,Y,5,1,0,1)
      IF (LLMM.NE.1) GOTO 30
```

```
      CALL PEN(4)
      IF (N.GE.10) GOTO 130
      X1 = (X(2)-(X(2)-X(1))/2.)/X(7)-0.035
      GOTO 150
  130 IF(N.GE.100) GOTO 140
      X1 = (X(2)-(X(2)-X(1))/2.)/X(7)-0.07
      GOTO 150
  140 X1 = (X(2)-(X(2)-X(1))/2.)/X(7)-0.105
  150 Y1 = (Y(4)-((Y(4)-Y(1))/2.0))/Y(7)
      XN = N
      CALL NUMBER (X1,Y1,0.07,XN,0.0,-1)
      CALL PEN(1)
   30 CONTINUE
      IF (LLMM.NE.1) GOTO 120
      CALL PEN(2)
      DO 110 IL = 1,NP
      IF (IL.GE.10) GOTO 160
      XX = CORD(IL,1)/X(7)-0.03
      GOTO 180
  160 IF (IL.GE.100) GOTO 170
      XX = CORD(IL,1)/X(7)-0.065
      GOTO 180
  170 XX = CORD(IL,1)/X(7)-0.1
  180 YY = CORD(IL,2)/Y(7)
      XIL = IL
      CALL NUMBER (XX,YY,0.07,XIL,0.0,-1)
  110 CONTINUE
      CALL PEN(1)
      CALL PLOT (16.0,11.8,-3)
      CALL SYMBOL (0.875,0.63,0.07,'LEGEND',0.0)
      CALL PEN(2)
      CALL SYMBOL (0.0,0.42,0.07,11,0.0,-1)
      CALL SYMBOL (0.07,0.42,0.07,' XXX ',0.0)
      CALL SYMBOL (0.56,0.42,0.07,11,0.0,-1)
      CALL PEN(1)
      CALL SYMBOL (0.63,0.42,0.07,' - NODE NUMBERS',0.0)
      CALL PEN(4)
      CALL SYMBOL (0.0,0.21,0.07,11,0.0,-1)
      CALL SYMBOL (0.07,0.21,0.07,' XXX ',0.0)
      CALL SYMBOL (0.56,0.21,0.07,11,0.0,-1)
      CALL PEN(1)
      CALL SYMBOL (0.63,0.21,0.07,' - ELEMENT NUMBERS',0.0)
      CALL SYMBOL (0.0,0.0,0.07,11,0.0,-1)
      CALL SYMBOL (0.21,0.0,0.07,0,0.0,-1)
      CALL SYMBOL (0.28,0.0,0.07,0,0.0,-1)
      CALL SYMBOL (0.35,0.0,0.07,0,0.0,-1)
      CALL SYMBOL (0.56,0.0,0.07,11,0.0,-1)
      CALL SYMBOL (0.63,0.0,0.07,' - FINITE ELEMENT GRID',0.0)
      IF (LLMM.GE.1) RETURN
C
C.....CALCULATE SCALING FACTOR.
C
  120 VMAX1 = ABS(VEL(2,1))
      DO 40 I=2,NP
      DUMY = ABS(VEL(2,I))
      VMAX = AMAX1(VMAX1,DUMY)
      VMAX1=VMAX
   40 CONTINUE
      WRITE(6,*)'** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** '
      WRITE(6,*)'VMAX1 = ',VMAX1
      IF (ISTEP.GT.1) GOTO 200
```

```
      FMAX = 250.
  200 IF (VMAX1.LT.FMAX) VMAX1 = FMAX
      WRITE(6,*)'FMAX = ',FMAX,'  **  VMAX1 = ',VMAX1
      WRITE(6,*)'** ** ** ** ** ** ** ** ** ** ** ** ** ** ** '
      VMAX1 = VMAX1+VMAX1*0.1
      SF = 10.0/VMAX1
  190 DO 50 I = 1,NP
      DO 50 J = 1,2
   50 VEL(J,I) = VEL(J,I)*SF
      Y(3) = Y(6)
      X(3) = X(6)
      X(4) = X(7)
      Y(4) = Y(7)
      CALL PLOT (7.5,0.0,-3)
      AL = 20.*3.14159/180.
      CALL PEN(2)
      DO 70 I = 1,NP
      X(1) = CORD(I,1)
      Y(1) = CORD(I,2)
      X(2) = X(1)+VEL(1,I)
      Y(2) = Y(1)+VEL(2,I)
      CALL LINE (X,Y,2,1,0,1)
      PI = 3.14159
      IF (VEL(1,I).EQ.0..AND.VEL(2,I).EQ.0.) GOTO 70
      IF (VEL(1,I).EQ.0..AND.VEL(2,I).LT.0.) PHI = -PI/2.
      IF (VEL(1,I).EQ.0..AND.VEL(2,I).GT.0.) PHI = PI/2.
      IF (VEL(2,I).EQ.0..AND.VEL(1,I).GT.0.) PHI = 0.
      IF (VEL(2,I).EQ.0..AND.VEL(1,I).LT.0.) PHI = PI
      IF (VEL(1,I).NE.0..AND.VEL(2,I).NE.0.) PHI = ATAN(VEL(2,I)/
     * VEL(1,I))
      IF (VEL(1,I).LT.0..AND.VEL(2,I).LT.0.) PHI = PHI+PI
      IF (VEL(1,I).LT.0..AND.VEL(2,I).GT.0.) PHI = PHI+PI
      VELO = SQRT(VEL(1,I)**2+VEL(2,I)**2)
      D = VELO*0.2
      X(1) = X(2)
      Y(1) = Y(2)
      X(2) = X(1)-COS(PHI-AL)*D/COS(AL)
      Y(2) = Y(1)-SIN(PHI-AL)*D/COS(AL)
      CALL LINE (X,Y,2,1,0,1)
      X(2) = X(1)-COS(PHI+AL)*D/COS(AL)
      Y(2) = Y(1)-SIN(PHI+AL)*D/COS(AL)
      CALL LINE (X,Y,2,1,0,1)
      DO 60 J = 1,2
   60 VEL(J,I) = VEL(J,I)/SF
   70 CONTINUE
      CALL PEN(1)
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE UPBOUND
C
C.....THIS SUBROUTINE IMPOSES THE INSTANTANEOUS BOUNDARY CONDITIONS.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
```

```
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      J = 1
      KOUNT = 0
C
C.....FIRST FOR THE RESTRAINED NODES
C
   DO 10 I=1,NB
C
C.....CHECK IF THE BOUNDARY NODE IS RESTRAINED IN 'X' DIRECTION
C
      IF(NREST(I).EQ.1.OR.NREST(I).EQ.11) GOTO 10
C
C.....CHECK IF THE BILLET MATERIAL HAS RICHED THE CONTAINER WALL
C
      IF (CORD(NBC(I),J).LT.XMAX) GOTO 10
C
C.....CHECK IF THE ACTUAL COORDINATE OF THE NODE IS MORE THAN 5% XMAX
C.....IF 'YES' STOP THE PROGRAM, IF 'NO' CARRY ON.
C
      KOUNT = KOUNT+1
      CCC = CORD(NBC(I),J)/XMAX
      C1C = 1.05
      IF(CCC.LE.C1C) GOTO 30
      LLMM = 1
      WRITE(6,1010) NBC(I),CORD(NBC(I),J),ISTEP
      WRITE(6,1050)
      CALL DOUT
      CALL ENPLOT
      STOP
  30 WRITE(6,1000) NBC(I),CORD(NBC(I),J)
C
C.....IN CASE THE ACTUAL 'X' COORDINATE EXCEEDS THE MAXIMUM
C.....ALLOWED DIMENSION, SET IT EQUAL TO THE LATTER.
C
      CORD(NBC(I),J) = XMAX
      NREST(I) = 11
      XPRE(I) = 0.0
      YPRE(I) = 0.0
  10 CONTINUE
C
C.....SECOND FOR THE NODES ON THE FREE SURFACE
C
      KCOUNT=0
      DO 20 K=1,INTF
      IF(CORD(NINTF(K),J).LT.XMAX) GOTO 20
      KCOUNT = KCOUNT+1
      CCD = CORD(NINTF(K),J)/XMAX
      C1D = 1.05
      IF(CCD.LE.C1D) GOTO 40
      LLMM = 1
      WRITE(6,1010) NINTF(K),CORD(NINTF(K),J),ISTEP
      WRITE(6,1050)
      CALL DOUT
      CALL ENPLOT
      STOP
  40 WRITE(6,1000) NINTF(K),CORD(NINTF(K),J)
      CORD(NINTF(K),J) = XMAX
      NB = NB+1
      NBC(NB) = NINTF(K)
      NREST(NB) = 1
```

```
      XPRE(NB) = 0.0
      YPRE(NB) = 0.0
   20 CONTINUE
      IF (KOUNT.EQ.0.AND.KCOUNT.EQ.0) GOTO 70
      INTF = INTF-KCOUNT
      DO 50 MK=1,INTF
      ML = MK+KCOUNT
      NINTF(MK) = NINTF(ML)
   50 CONTINUE
      IN = INTF+1
      IO = INTF+KCOUNT
      DO 60 KM = IN,IO
   60 NINTF(KM) = 0
      WRITE(6,1040)
      WRITE(6,1020)(NBC(L),NREST(L),XPRE(L),YPRE(L),L=1,NB)
      WRITE(6,1030)(NINTF(LL),LL=1,INTF)
      IF (SIGZ1.LT.1.) GOTO 70
      IF (SIGZ1.GT.1.8) SIGZ1=1.8
      IF (SIGZ1.LT.1.2) SIGZ1=1.2
      STEP = STEP/SIGZ1
      IF (STEP.LT.0.005) STEP = 0.005
   70 RETURN
C
 1000 FORMAT (1H ,/,1H ,"ACTUAL BOUNDARY COORDINATE OF NODE",I4,2X,"IS",F8.3)
     * F8.3)
 1010 FORMAT (1H ,"ACTUAL BOUNDARY COORDINATE OF NODE",I4,2X,"IS",E9.3,"
     *  WHICH IS MORE THAN 5% GREATER THAN XMAX. SMALLER TIME STEP MUST B
     * E CHOSEN.",/,1H ,"OTHERWISE THE RESULTS WILL BE UNREALISTIC. FOR T
     * HIS REASON THE PROGRAM WAS HALTED IN SUBROUTINE 'UPBOUND' AT STEP
     * NO.",I3)
 1020 FORMAT (1H ,I5,9X,I2,6X,F5.2,2X,F5.2)
 1030 FORMAT (1H ,/,1H ,"BOUNDARY NODES ON THE FREE SURFACE",/,1H ,2015,
     * /)
 1040 FORMAT (1H ,/,1H ,"NODE NO.",2X,"BOUND.COND.",2X,"XPRE",3X,"YPRE",
     * /,1H ,"________",2X,"___________",2X,"____",3X,"____")
 1050 FORMAT (1H ,/,1H ,"LISTING OF ALL COMPUTED PARAMETERS AT THE TIME
     *  OF HALTING",/,1H ,/)
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE CONVER(NCONV)
C
C.....THIS SUBROUTINE CHECKS THE CONVERGENCE.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/C/ SK(572,50),R1(572),EST(70,80),FX(40),FY(40),FPUR(50),LITER
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      DIMENSION RC(572)
      EQUIVALENCE (SK,RC)
      NCONV = 0
      IF (NITER.EQ.0) GOTO 30
      DO 10 N = 1,NP
      NZ = 2*N
      NR = NZ-1
      RC(NZ) = VEL(2,N)
   10 RC(NR) = VEL(1,N)
      ACONV1 = 0.
      ACONV2 = 0.
      DO 20 I = 1,NP
```

```
      IY = I*2
      IX = IY -1
      DVZ = R1(IY )-RC(IY )
      DVR = R1(IX )-RC(IX )
      ACONV2 = ACONV2+(DVR**2+DVZ**2)
      ACONV1 = ACONV1+(RC(IY )**2+RC(IX )**2)
   20 CONTINUE
      VCONV = SQRT(ACONV2/ACONV1)
      IF (ABS(VCONV).LE.0.001) NCONV = 1
      WRITE(6,1000) NITER,VCONV
   30 DO 40 K = 1,NP
      DO 40 M = 1,2
      IC = (K-1)*2+M
      VEL(M,K) = R1(IC)
   40 CONTINUE
      RETURN
C
 1000 FORMAT (1H ,"NITER = ",I2," ; VCONV = ",E10.4)
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      SUBROUTINE MODMES
C
C.....THIS SUBROUTINE MODIFIES THE DISTORTED MESH.
C
      COMMON/BLK1/ NP,NE,NB,NPC,NMAT,NEQ,NBAND,NITER,TITLE(8),NBF,XMAX
      COMMON/BLK2/ CORD(286,2),NOP(250,4),IMAT(250),ELOAD(250,8),NELM
      COMMON/BLK3/ YIELD(4),NBC(60),NREST(60),NQ(286),R(286,2),XPRE(60),
     * YPRE(60),NF(25),SIGZ1
      COMMON/BLK5/ STR(250,6),EPS(250,6),VEL(2,286),TEPS(250),STREF(250)
     * ,STRFR(250)
      COMMON/A/ ALPHA,VRIG,IPLAX,LLMM,NEDGE,NEDGE1,FMU,NEX,NEY,NPX,NPY,DY
      COMMON/B/ INTF,NINTF(50),NSTEP,STEP,ISTEP,NPRES,NPAGE,XMIN,THIC,ITY
      COMMON/D/ NCONV,LITER
C
C.....MODIFY COORDINATES.
C
      DO 10 I = 1,NP
      DO 10 J = 1,2
   10 CORD(I,J) = CORD(I,J)+VEL(J,I)*STEP
   80 RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
      FUNCTION RBAR(RX,RY,RZ,RXY)
C
C.....THIS FUNCTION CALCULATES EFFECTIVE STRAIN RATE.
C
      S1 = RX*RX
      S2 = RY*RY
      S3 = RZ*RZ
      S4 = RXY*RXY
      RBAR = 2.*SQRT(3.*(S1+S2+S3)/2.+(3.*S4/4.))/3.
      RETURN
      END
C
C*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*
C
```

APPENDIX 4

LABMASTER DATA COLLECTION

The experimental data from the tests were collected using PC-Mate Labmaster which converts the IBM-PC into an analogue/digital and digital/analogue converter. The Labmaster consists of a daughter board which performs the actual conversion of analogue data to digital data; the information is then in a suitable form to signal the computer, via a ribbon cable, to the mother board. Unlike the daughter board which resides outside the computer, the mother board slots into the IBM-PC bus. The Labmaster is a very versatile accessory and is described in full in [89]. In the following section the configuration used and the collection program are documented.

IBM-PC

The computer used for data collection had twin disk drives and expended 512K memory. It also had a graphics card to enable high resolution display of the recorded data.

MOTHER BOARD

Residing in one of the expansion slots in the IBM bus, the mother board was selected to operate the I/O (input/output) mapped mode where it responds to commands in the 8088 CPU. This selection is made using switches on the mother board. The mother board requires 16 address locations which are necessary because of the multiple functions the board provides. There are numerous locations for the board to reside, but for the purpose of these tests the starting address recommended by Tecmar was used: that is 017OH (1808 decimal).

The 8088 CPU uses only an 8 bit data path and is only considered a 16 bit computer because within the IC it uses 16 Bits. Therefore, when reading data to the computer it must be undertaken in two parts. First, the lower 8 bits of data resets the Done and Overrun bits of the A/D. An Overrun bit is set when the computer does not have quite enough time to

move all the data to computer memory before the next data is available and so invalidates the data.

The mother board also carries an AMD 9513 timer which was used as a real time base for data collection.

DAUGHTER BOARD

The major function of this board is to perform the actual conversion from analogue to digital data. The data signals and control signals are all jumper selectable and are discussed in the following section.

The Labmaster allows, through programming, an automatic channel increment which permits up to 8 different input channels to be sampled. The starting channel is selected through software and the final channel through SW1D (Fig.A4.2) by selecting the correct switch configuration. The jumper selections made are shown in Fig.A4.2. These selections were for differential input, bipolar input in the -10 to +10 volts regime. The analogue amplifications were performed on an "in-house" designed op-amp circuit which is presented in Fig.A4.1.

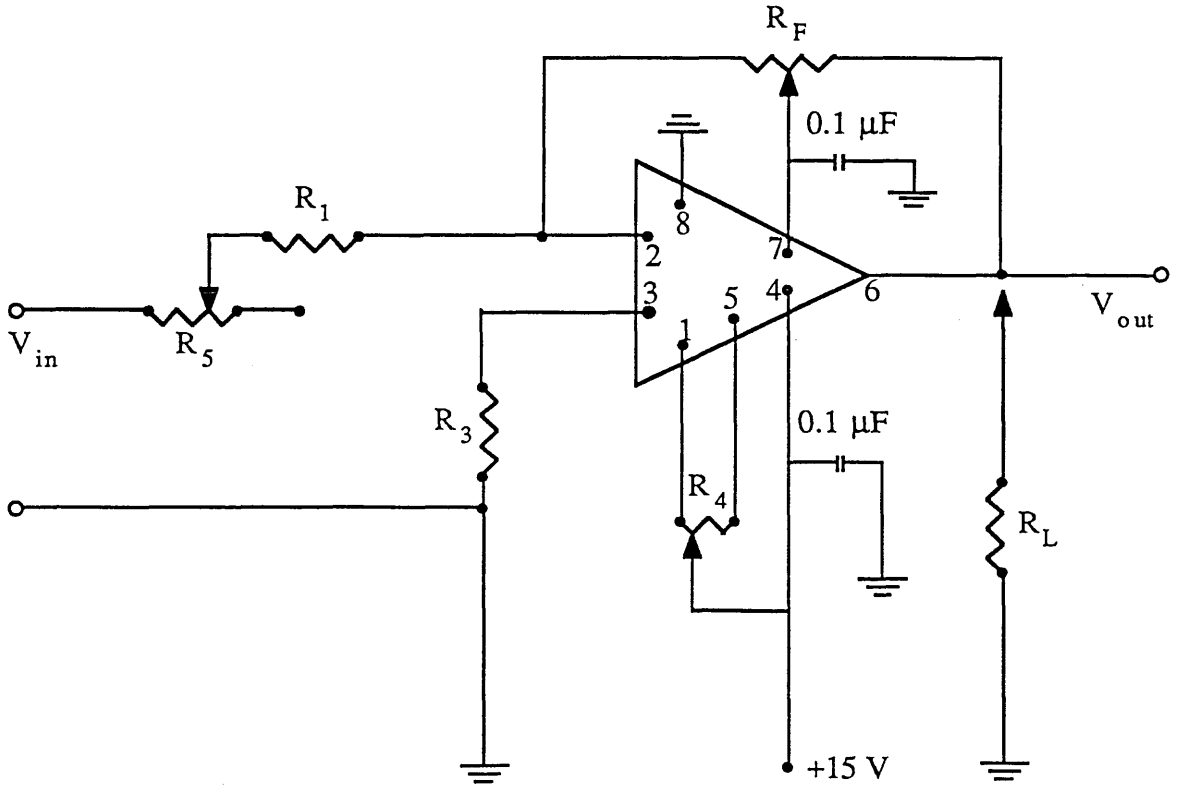


Fig.A4.1.

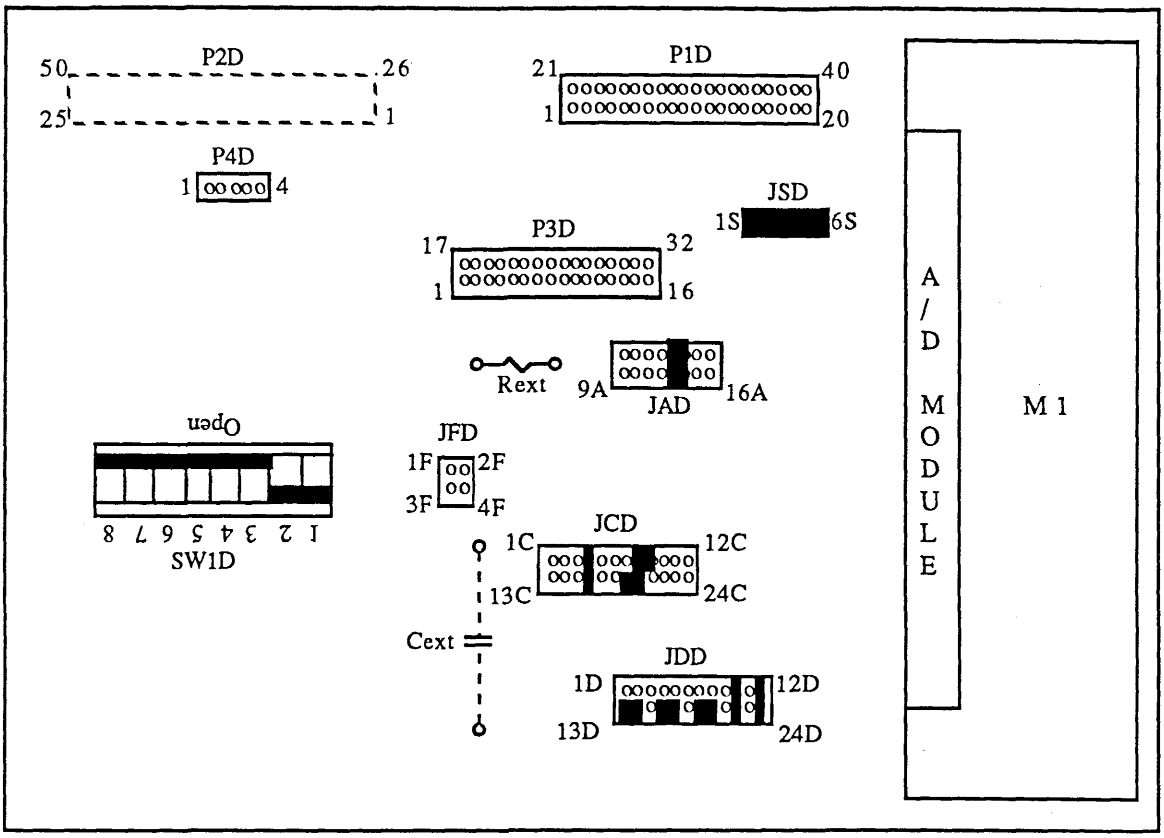


Fig.A4.2.

PROGRAMMING

The listing of the computer program used for operating the Labmaster in the required mode and to collect and store the data collected is given below. All programming was in BASIC.

```
1  REM-----------------------------------------------------------------------------------
2  REM ~                          PROGRAM "CONTEXT"                                     ~
3  REM ~       For Collecting and Storing Data by means of IBM-PC and Labmaster         ~
3  REM ~          B.GERGINOV - Department of Materials - November 1988                  ~
4  REM-----------------------------------------------------------------------------------
10 KEY OFF:SCREEN 0,1,0  :COLOR 0,2,2
20 KEY 1,"A"+CHR$(13)
30 KEY 2,"RUN"+CHR$(13)
40 KEY 3,"C"+CHR$(13)
50 KEY 4,"D"+CHR$(13)
60 KEY 5,"E"+CHR$(13)
70 KEY 6,"F"+CHR$(13)
80 KEY 7,"G"+CHR$(13)
90 KEY 8,"H"+CHR$(13)
100 KEY 9,"I"+CHR$(13)
110 KEY 10,"J"+CHR$(13)
120 CLS:ON ERROR GOTO 3460:REM POKE-MAIN3
130  DEF FNCONV(X)=X-6*INT(X/16)
```

```
140 LET SZ = -1
150 SCREEN 0,1,0:COLOR 0,2,2
160 CLS:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
170 PRINT"DO YOU WANT TO START NEW TEST OR TO EXAMINE AN OLD DATA FILE?" :PRINT
180 PRINT"         ** FOR A NEW TEST HIT 'T' ** ":PRINT
190 PRINT"    ** TO EXAMINE AN OLD DATA FILE HIT 'O' ** ":PRINT
200 PRINT"            ** TO QUIT THE PROGRAM HIT 'Q' **      ":PRINT:INPUT"MAKE YOUR
CHOICE --->    ";G$
210 IF G$="T" GOTO 250
220 IF G$="O" GOTO 730
230 IF G$="Q" GOTO 600
240 CLS:BEEP:BEEP:GOTO 170
250 CLS:PRINT:PRINT:PRINT:PRINT:PRINT:PRINT
260 PRINT"              CCCC     OOO     N   N  TTTTT  EEEEE    X    X   TTTTT"
270 PRINT"            C         O   O    NN  N    T    E          X X      T"
280 PRINT"            C         O   O    N N N    T    EEEE        X       T"
290 PRINT"            C         O   O    N  NN    T    E          X X      T"
300 PRINT"              CCCC     OOO     N   N    T    EEEEE    X    X     T"
310 PRINT:PRINT
320 PRINT"         EEEEE  X   X  TTTTT   RRRR     U   U   SSSS    I    OOO   N   N"
330 PRINT"         E       X X     T     R   R    U   U   S       I   O   O  NN  N
340 PRINT"         EEEE     X      T     RRRR     U   U    SSS    I   O   O  N N N
350 PRINT"         E       X X     T     R   R    U   U       S   I   O   O  N  NN
360 PRINT"         EEEEE  X   X    T     R   R     UUU    SSSS    I    OOO   N   N
370 PRINT:PRINT
380 B$=INKEY$: IF B$="" THEN 380
390 M=10
400 IF M=0 GOTO 420
410 M=M+6*INT(M/10)
420 RTZ=10
430 H=50
440 HH=H+6*INT(H/10):H=(RTZ*60)+H
450 GOSUB 3590
460 LET AX= H :AT=(557/H)
470 BP=H/(6*ST)
480 IF BP<7.5 THEN GOTO 500
490 PRINT:PRINT:PRINT:GOTO 510
500 BP=H/(.6*ST)
510 GOSUB 780  :REM Enter filename program
520 GOSUB 3880 : REM CHECK ZEROS OF THE CALIBRATION
530 COLOR 14,1,1:CLS
540 GOSUB 950  :REM Screen plot while extruding
550 GOSUB 1800 :REM Rescale program
560 GOSUB 2520 :REM Store data on disk
570 GOSUB 2700 :REM Find maximum load
580 GOSUB 2870:REM Printer program
590 GOTO 150
600 END
610 M=10
620 IF M=0 GOTO 640
630 M=M+6*INT(M/10)
640 RTZ=10
650 H=50
660 HH=H+6*INT(H/10):H=(RTZ*60)+H
670 GOSUB 3590
680 LET AX= H :AT=(557/H)
690 BP=H/(6*ST)
700 IF BP<7.5 THEN GOTO 720
710 PRINT:PRINT:PRINT:GOTO 730
720 BP=H/(.6*ST)
730 GOSUB 4910:REM RE-ENTER DATA
```

```
740 GOSUB 2690:REM FIND MAXIMUM LOAD
750 GOSUB 2860:REM PRINTER PROGRAM
760 GOSUB 4510:REM SCREEN PLOT AFTER EXTRUDING
770 GOTO 150
780 REM*************************************************************************
790 REM***************      FILENAME SUBROUTINE      **********************
800 REM*************************************************************************
810 CLS:PRINT:PRINT
820 PRINT"As part of this program data is stored in a sequential file on a diskette in"
830 PRINT "disk drive B. To continue with this program it is necessary to specify a"
840 PRINT "filename which must have the following format :- ":PRINT
850 PRINT TAB(24) "B:********.DAT":PRINT :PRINT:PRINT
860 PRINT "Before entering a filename make sure a diskette is in drive B which has "
870 PRINT "been correctly formatted"
880 PRINT "An asterisk in the above format indicates any alphanumeric character "
890 LOCATE 8,1:INPUT"Enter filename ---->>";A$
900 IF MID$(A$,1,1)<> "B" OR MID$(A$,2,1)<> ":" OR MID$(A$,11,1)<>"." OR
MID$(A$,12,3)<>"DAT" THEN CLS:PRINT "FILENAME FORMAT ERROR": FOR I = 1 TO 10
:BEEP:BEEP:NEXT I:GOTO 810
910 RETURN
920 REM*************************************************************************
930 REM************  SCREEN PLOT WHILE EXTRUDING SUBRIUTINE  *************
940 REM*************************************************************************
950 COLOR 0,2,2:CLS:PRINT :PRINT
960 PRINT:PRINT:PRINT:PRINT:PRINT
970 PRINT:PRINT"                    PRESS 'F1'  TO START TEST"
980 PRINT:PRINT"                    PRESS 'F10' TO STOP  TEST"
990 BUM$=INKEY$:IF BUM$="A" GOTO 1010
1000 GOTO 990
1010  SCREEN 2,0,0 :CLS
1020 LOCATE 25,1:PRINT TAB(3)" "TAB(6)"0" TAB(10)"0"
1030 LOCATE 25,40:PRINT"Time (sec)"
1040 LOCATE 25,75:PRINT STR$(AX)
1050 LOCATE 1,1:PRINT "    mm  kN "
1060 LOCATE 2,1:PRINT "   100 500"
1070  LINE (51,10)-(51,190)
1080  LINE (82,10)-(82,190)
1090  LINE -(639,190)
1100 FOR K = 82 TO 639 STEP BP:LINE (K,190)-(K,193):NEXT K
1110 FOR K =190 TO 10 STEP -18: LINE (79,K)-(82,K):NEXT K
1120 FOR K= 190 TO 10 STEP -18:LINE (49,K) - (52,K):NEXT K
1130 REM
1140 REM SET UP A.D.C FOR AUTO-INCREMENTING MODE
1150 REM
1160 OUT 1812,128:OUT 1813,255:OUT 1814,0
1170 IF INP(1812)< 128 THEN 1170
1180 X= INP(1814):OUT 1812,0:OUT 1813,0
1190 REM
1200 REM SET UP COUNTER 1 FOR TIME OF DAY MODE
1210 REM
1220 OUT 1817,23:OUT 1816,3:OUT 1816,129
1230 OUT 1817,1 :OUT 1816,57:OUT 1816,31
1240 OUT 1816,0:OUT 1816,0
1250 OUT 1817,2:OUT 1816,57:OUT 1816,16
1260 OUT 1816,0:OUT 1816,0
1270 OUT 1817,71
1280 OUT 1817,9: OUT 1816,0:OUT 1816,0
1290 OUT 1817,10: OUT 1816,0:OUT 1816,0
1300 REM
1310 REM DATA COLLECTION BEGINS
1320 REM
```

```
1330 LS=1
1340 DEF SEG=&H2000:OUT 1817,39
1350 FOR I= 0 TO 64000! STEP 10
1360 FOR J=0 TO 4 STEP 2
1370 OUT 1814,0
1380 IF INP(1812) < 128 THEN 1380
1390 POKE (I+J),INP(1813):POKE (I+J+1),INP(1814)
1400 NEXT J
1410 OUT 1817,163:OUT 1817,17:POKE(I+6),INP(1816):POKE(I+7),INP(1816)
1420 FX=PEEK(I+6):FY=PEEK(I+7):IF FX+FY=0 THEN OUT 1817,162
1430 OUT 1817,18:POKE(I+8),INP(1816):POKE(I+9),INP(1816)
1440 IF PEEK(I+8)>=M THEN GOTO 1450 ELSE GOTO 1460
1450 IF PEEK(I+7)>=HH THEN GOTO 1780
1460  REM Timer
1470  SH = FNCONV(PEEK(I+6)):REM THS
1480 SI = FNCONV(PEEK(I+7)):REM SEC
1490 SQ = FNCONV(PEEK(I+8)):REM MIN
1500  REM Change into time units - Y axis
1510  SJ =82 + INT (((SQ*60)+SI+(SH/100))*AT)
1520  REM Change into load units - Y axis
1530 REM  SVB = ((PEEK(I+1)*256)+PEEK(I))/409.6:  REM SO-FOR BOTTOM LOAD CELL
1540 REM  SVD = ((PEEK(I+5)*256)+PEEK(I+4))/409.6:REM SM-FOR DISPL. TRANSDUCER
1550 REM  SVT = ((PEEK(I+3)*256)+PEEK(I+2))/409.6:REM SN-FOR TOP LOAD CELL
1560 REM  PRINT SVT,SVB,SVD
1570  SO = 190 - INT((((PEEK(I+1)*256)+PEEK(I))*((-302.08)/409.6)+1447.1)*(180/500))
1580  REM Change into displacement uints Y-axis
1590  SM = 190 - INT((((PEEK(I+5)*256)+PEEK(I+4))*((-40.046)/409.6)+201.58)*(180/100))
1600  SN = 190 - INT((((PEEK(I+3)*256)+PEEK(I+2))*((-695.04)/409.6)+3290.9)*(180/500))
1610 IF LS=ST GOTO 1630
1620 LS=LS+1:GOTO 1360
1630 LS=1
1640  REM PLOT LOAD AGAINST TIME
1650  PSET (SJ,SO)
1660  REM PLOT DISPLACEMENT AGAINST TIME
1670  PSET (SJ,SM)
1680  PSET (SJ,SN)
1690 TLC=536.111112-SN/(180/500): BLC=530.555556-SO/(180/500): DIS=104.444445-SM/(180/100)
1700 LOCATE 1,50: PRINT"| T.L.C. | B.L.C. | DISPL. |"
1710 LOCATE 2,50: PRINT"|--------|--------|--------|"
1720 LOCATE 3,50: PRINT"|      |      |      |"
1730 LOCATE 3,52: PRINT USING "###.##";TLC
1740 LOCATE 3,61: PRINT USING "###.##";BLC
1750 LOCATE 3,70: PRINT USING "###.##";DIS
1760 TIT$=INKEY$:IF TIT$="J" GOTO 1780
1770 NEXT I
1780 RETURN
1790 REM*************************************************************************
1800 REM***************    RESCALE SUBROUTINE    ***************************
1810 REM*************************************************************************
1820 LOCATE 1,40:PRINT "Press any key to continue ":B$=INKEY$:IF B$="" THEN 1820
1830 LOCATE 1,40:INPUT "RESCALE (YES OR NO) ";B$:IF B$ <>"YES" THEN GOTO 2500
1840 LOCATE 1,40:INPUT "ENTER MAX TIME (SEC)   ";MT
1850 LOCATE 1,40:INPUT "ENTER TIME OFFSET (SEC) ";OT
1860 FOR I= 0 TO 64000! STEP 10
1870 SH = FNCONV(PEEK(I+6)):REM THS
1880 SI = FNCONV(PEEK(I+7)):REM SEC
1890 SQ = FNCONV(PEEK(I+8)):REM MIN
1900 SJ = ((SQ*60)+SI +(SH/100))
1910 IF SJ >= OT THEN  GOTO 1950
1920 NEXT I
1930 LOCATE 1,40:PRINT "TIME OFFSET NOT FOUND "
```

```
1940 FOR MI =0 TO 100:NEXT MI:GOTO 1830
1950 LET OT=SJ:OL = ((PEEK(I+1)*256)+PEEK(I)):REM MIN LOAD
1960 OP =((PEEK(I+3)*256)+PEEK(I+2)):REM MIN  PRESSURE
1970 OD =((PEEK(I+5)*256)+PEEK(I+4)):REM MIN DISPLACEMENT
1980 MOL =INT(OL*((-302.08)/409.6)+1447.1):OL=INT(MOL*(180/500))
1990 MOP =INT(OP*((-40.046)/409.6)+201.58):OP=INT(MOP*(180/100))
2000 NOD =INT(OD*((-695.04)/409.6)+3290.9):OD=INT(NOD*(180/500))
2010 MAL=INT(OL):MAP=INT(OP)
2020 NAD=INT(OD*10):AT=(557/(MT-OT)):SZ=-1
2030 PDM=(((INT(180/NAD))*10)+NOD)
2040 PLM=INT((180/MAL)+MOL)
2050 PPL=INT((180/MAP)+MOP)
2060 NT=(INT(557/AT)+OT)
2070 SCREEN 2,0,0:CLS
2080 LOCATE 25,1:PRINT STR$(MOP)
2090 LOCATE 25,4:PRINT STR$(NOD)
2100 LOCATE 25, 9:PRINT STR$(MOL)
2110 LOCATE 25,75:PRINT STR$(MT)
2120 LOCATE 25,40:PRINT "Time (sec)"
2130 LOCATE 25,11:PRINT  STR$(OT)
2140 LOCATE 1,1:PRINT "  P   D   L =MN : D = mm : P =MN/(M^2)"
2150 LOCATE 1,80:PRINT STR$(PPL)
2160 LOCATE 2,4:PRINT STR$(PDM)
2170 LOCATE 2,9:PRINT STR$(PLM)
2180 LINE (27,10)-(27,190)
2190 LINE (59,10)-(59,190)
2200 LINE (82,10)-(82,190)
2210 LINE -(639,190)
2220 FOR K= 82 TO 639 STEP (AT*ST) :LINE (K,190) - (K,193):NEXT K
2230 FOR K =190 TO 10 STEP -MAL: LINE (79,K)-(82,K):NEXT K
2240 FOR K= 190 TO 10 STEP -NAD:LINE (56,K) - (59,K):NEXT K
2250 FOR K = 190 TO 10 STEP -MAP:LINE (24,K)-(27,K):NEXT K
2260 FOR I= 0 TO 64000! STEP 10
2270  REM Timer
2280  SH = FNCONV(PEEK(I+6)):REM THS
2290 SI = FNCONV(PEEK(I+7)):REM SEC
2300 SQ = FNCONV(PEEK(I+8)):REM MIN
2310  RS =((SQ*60)+SI+(SH/100))
2320  REM Change into time units - Y axis
2330  SJ =82 + INT((((SQ*60)+SI+(SH/100)) -OT)*AT)
2340 IF SJ>=639 GOTO 2490
2350  REM Change into load units - Y axis
2360  SO = 190 - INT(((PEEK(I+1)*256)+PEEK(I))*((-302.08)/409.6)+1447.1)*(180/500)
2370  REM Change into pressure units Y-axis
2380  SM = 190 - INT(((PEEK(I+5)*256)+PEEK(I+4))*((-40.046)/409.6)+201.58)*(180/100)
2390  REM Change into displacement uints Y-axis
2400  SN = 190 - INT(((PEEK(I+3)*256)+PEEK(I+2))*((-695.04)/409.6)+3290.9)*(180/500)
2410 IF SJ<82 THEN GOTO 2480
2420  REM PLOT LOAD AGAINST TIME
2430  PSET (SJ,SO)
2440  REM PLOT PRESSURE AGAINST TIME
2450  PSET (SJ,SN)
2460  REM PLOT DISPLACEMENT AGAINST TIME
2470  PSET (SJ,SM)
2480 NEXT I
2490 GOTO 1820
2500 RETURN
2510  LOCATE 1,40:INPUT "PRESS ANY KEY TO CONTINUE";B$
2520 SCREEN 0,1,0,0: COLOR 14,1,1:CLS:PRINT:PRINT
2530 PRINT TAB(10)"Storing data on disk using filename ---->> ";A$
2540 PRINT:PRINT TAB(10) "Have a cup of coffee        "
```

```
2550 REM*************************************************************************
2560 REM************  DATA STORAGE SUBROUTINE  ************************
2570 REM*************************************************************************
2580 OPEN A$ FOR OUTPUT AS #1
2590 FOR K =0 TO  I STEP 10
2600 SO=PEEK(K): SA=PEEK(K+1)
2610 SB=PEEK(K+2) :SC=PEEK(K+3)
2620 SD=PEEK(K+4) :SE=PEEK(K+5)
2630 SF=PEEK(K+6) :SG=PEEK(K+7)
2640 SH=PEEK(K+8) :SI=PEEK(K+9)
2650 WRITE #1,SO,SA,SB,SC,SD,SE,SF,SG,SH,SI
2660 NEXT K
2670 CLOSE #1
2680 RETURN
2690 REM*************************************************************************
2700 REM***************  MAX LOAD SUBROUTINE  ************************
2710 REM*************************************************************************
2720 LET MOK =0
2730 FOR K= 0 TO I STEP 10
2740 MAXL = ((PEEK(K+3)*256+PEEK(K+2))/409.6)*(-695.04)+3290.9
2750 IF MAXL =< MOK THEN GOTO 2840
2760 LET MOK = MAXL
2770 LET DER = K
2780 MAXP = ((PEEK(K+1)*256+PEEK(K))/409.6)*(-302.08)+1447.1
2790 MAXD = ((PEEK(K+5)*256+PEEK(K+4))/409.6)*(-40.046)+201.58
2800 MSEA=((FNCONV(PEEK(K+6)))/100)
2810 MSEB=FNCONV(PEEK(K+7))
2820 MSED=((FNCONV(PEEK(K+8)))*60)
2830 MSEC=MSEA+MSEB+MSED
2840 NEXT K
2850 RETURN
2860 REM*************************************************************************
2870 REM************  PRINTER SUBROUTINE  ****************************
2880 REM*************************************************************************
2890 CLS
2900 PRINT :PRINT
2910 PRINT "*************************************************************************"
2920 PRINT "************************* RESULTS ************************************"
2930 PRINT "*************************************************************************"
2940 PRINT :PRINT
2950 PRINT "The results of this test are stored in the file ";A$
2960 PRINT
2970 PRINT "The values at maximum Load were -:"
2980 PRINT "Load at Top Load Cell     =";MOK;"(kN)"
2990 PRINT "Load at Bottom Load Cell =";MAXP;"(kN)"
3000 PRINT "Displacement              =";MAXD;"(mm)"
3010 PRINT "Time Elasped              =";MSEC;"(sec)":PRINT:PRINT
3020 INPUT"Do you require output of the calculated values on disk (YES/NO)";V$
3030 IF V$="YES" THEN GOSUB 5380
3040 INPUT"Do you require printout of the data obtained (YES/NO)";B$
3050 IF B$<>"YES" THEN GOTO 3440
3060 LPRINT "*************************************************************************"
3070 LPRINT CHR$(14);TAB(16)" RESULTS "
3080 LPRINT "*************************************************************************"
3090 LPRINT CHR$(27);CHR$(70);
3100 LPRINT "The results of this test are stored in the file ";A$
3110 LPRINT
3120 LPRINT "The values at maximum load are :-"
3130 LPRINT "Load at Top Load Cell   =";MOK;"(kN)"
3140 LPRINT "Load at Bottom Load Cell =";MAXP;"(kN)"
3150 LPRINT "Displacement          =";MAXD;"(mm)"
```

```
3160 LPRINT "Time Elasped          =";MSEC;"(sec)":PRINT:PRINT
3170 LPRINT"       "
3180 LPRINT"       "
3190 LPRINT
3200 LPRINT CHR$(27);CHR$(48);
3210 LPRINT CHR$(15);
3220 G$="*  T.L.C.       B.L.C.      DISPLACEMENT      TIME     *"
3230 H$="*     T.L.C.       B.L.C.      DISPLACEMENT      TIME     *"
3240 K$="*  (kN)          (kN)          (mm)          (sec)    *"
3250 J$="*     (kN)          (kN)          (mm)          (sec)    *"
3260 WIDTH "LPT1:",132
3270 LPRINT G$+H$;
3280 LPRINT K$+J$
3290 FOR K = 0 TO I STEP 20
3300 SA = ((FNCONV(PEEK(K+6)))/100)+FNCONV(PEEK(K+7))+((FNCONV(PEEK(K+8))*60))
3310 SA1 = ((FNCONV(PEEK(K+16)))/100)+FNCONV(PEEK(K+17))+((FNCONV(PEEK(K+18)))*60)
3320 SP  = (((PEEK(K+1)*256)+PEEK(K))/409.6)*(-302.08)+1447.1
3330 SL  = (((PEEK(K+3)*256)+PEEK(K+2))/409.6)*(-695.04)+3290.9
3340 SD  = (((PEEK(K+5)*256)+PEEK(K+4))/409.6)*(-40.046)+201.58
3350 SP1 = (((PEEK(K+11)*256)+PEEK(K+10))/409.6)*(-302.08)+1447.1
3360 SL1 = (((PEEK(K+13)*256)+PEEK(K+12))/409.6)*(-695.04)+3290.9
3370 SD1 = (((PEEK(K+15)*256)+PEEK(K+14))/409.6)*(-40.046)+201.58
3380 IF SP<=0 THEN SP=0:IF SL<=0 THEN SL=0:IF SD<=1.55 THEN SD=0
3390 IF SP1<=0 THEN SP1=0:IF SL1<=0 THEN SL1=0:IF SD1<=1.55 THEN SD1=0
3400 LPRINT USING "###.####       "; SL, SP,SD,SA,SL1,SP1,SD1,SA1
3410 NEXT K
3420 LPRINT
3430 LPRINT  CHR$(18);
3440 RETURN
3450 LOCATE 8,19: PRINT"|          |          |          |"
3460 IF (ERR<>61) THEN CLS:PRINT"ERROR OCCURED IN THE PROGRAM":REM END
3470 A=ERR:B=ERL
3480 PRINT A,B
3490 PRINT"TO CONTINUE FROM THE BEGINING OF THE POGRAM HIT ANY
KEY":PRINT"OTHERWISW PRESS SIMULTANEOUSLY Ctrl+Braek KEYS"
3500 Z$=INKEY$:IF INKEY$="" THEN 3500
3510 RESUME 150
3520 CLS:PRINT
3530 PRINT "Diskette storage space is full":PRINT
3540 PRINT "Insert new diskette into disk drive B"
3550 PRINT :PRINT :PRINT
3560 PRINT "PRESS ANY KEY TO CONTINUE "
3570 KT$=INKEY$:IF KT$="" THEN 3570
3580 RESUME 2570
3590 REM ##########################################################################
3600 REM ########################## STALL CALCS ##########################
3610 REM ##########################################################################
3620 IF H<60 THEN ST=1
3630 IF H<120 AND H>=60 THEN ST=2
3640 IF H<180 AND H>=120 THEN ST=3
3650 IF H<240 AND H>=180 THEN ST=4
3660 IF H<300 AND H>=240 THEN ST=5
3670 IF H<360 AND H>=300 THEN ST=6
3680 IF H<420 AND H>=360 THEN ST=7
3690 IF H<480 AND H>=420 THEN ST=8
3700 IF H<540 AND H>=480 THEN ST=9
3710 IF H<600 AND H>=540 THEN ST=10
3720 IF H<660 AND H>=600 THEN ST=11
3730 IF H<720 AND H>=660 THEN ST=12
3740 IF H<780 AND H>=720 THEN ST=13
3750 IF H<840 AND H>=780 THEN ST=14
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```
3760 IF H<900 AND H>=840 THEN ST=15
3770 IF H<960 AND H>=900 THEN ST=16
3780 IF H<1040 AND H>=960 THEN ST=17
3790 IF H<1100 AND H>=1040 THEN ST=18
3800 IF H<=1100 THEN GOTO 3820
3810 CLS:PRINT:PRINT:PRINT:PRINT"        DATA COLLECTION TIME TOO LONG--------
PLEASE RE-ENTER":PRINT:GOTO 390
3820 RETURN
3830 INPUT"        DO YOU WANT TO START A NEW TEST (YES/NO)";T$
3840 IF T$="YES" GOTO 150
3850 PRINT:INPUT"        DO YOU WANT TO EXAMINE AN OLD DATA FILE (YES/NO)";F$
3860 IF F$="YES" GOTO 730
3870 RETURN
3880 REM ************************************************************************
3890 REM ******************** ZERO CHECK SUBROUTINE ************************
3900 REM ************************************************************************
3910 CLS
3920 PRINT:PRINT"   CHEK THE ZEROS OF THE CALIBRATION BEFORE STARTING THE
TEST"
3930 BEEP:BEEP:BEEP
3940 PRINT:PRINT"WHEN SATISFIED WITH THE ZEROS OF THE CALIBRATION PRESS ANY
KEY TO CONTINUE"
3950 LOCATE 5,19: PRINT"_____________________________________________"
3960 LOCATE 6,19: PRINT"|                |                |                |"
3970 LOCATE 7,19: PRINT"|   TOP L.C.     |  BOTTOM L.C.   | DISPL. TRANS.  |"
3980 LOCATE 8,19: PRINT"|                |                |                |"
3990 LOCATE 9,19: PRINT"_____________________________________________"
4000 LOCATE 10,19:PRINT"|                |                |                |"
4010 LOCATE 11,19:PRINT"|                |                |                |"
4020 LOCATE 12,19:PRINT"|                |                |                |"
4030 LOCATE 13,19:PRINT"_____________________________________________"
4040 LOCATE 14,19:PRINT"|                |                |                |"
4050 LOCATE 15,19:PRINT"|  IN VOLTS      |   IN VOLTS     |   IN VOLTS     |"
4060 LOCATE 16,19:PRINT"_____________________________________________"
4070 LOCATE 17,19:PRINT"|                |                |                |"
4080 LOCATE 18,19:PRINT"|                |                |                |"
4090 LOCATE 19,19:PRINT"_____________________________________________"
4100 LOCATE 20,19:PRINT"|                |                |                |"
4110 LOCATE 21,19:PRINT"|                |                |                |"
4120 LOCATE 22,19:PRINT"_____________________________________________"
4130 OUT 1812,128:OUT 1813,255:OUT 1814,0
4140 IF INP(1812)< 128 THEN 4140
4150 X= INP(1814):OUT 1812,0:OUT 1813,0
4160 OUT 1817,23:OUT 1816,3:OUT 1816,129
4170 OUT 1817,1 :OUT 1816,57:OUT 1816,31
4180 OUT 1816,0:OUT 1816,0
4190 OUT 1817,2:OUT 1816,57:OUT 1816,16
4200 OUT 1816,0:OUT 1816,0
4210 OUT 1817,71
4220 OUT 1817,9: OUT 1816,0:OUT 1816,0
4230 OUT 1817,10: OUT 1816,0:OUT 1816,0
4240 DEF SEG=&H2000:OUT 1817,39
4250 FOR I= 0 TO 64000! STEP 10
4260 FOR J=0 TO 4 STEP 2
4270 OUT 1814,0
4280 IF INP(1812) < 128 THEN 4280
4290 POKE (I+J),INP(1813):POKE (I+J+1),INP(1814)
4300 NEXT J
4310 OUT 1817,163:OUT 1817,17:POKE(I+6),INP(1816):POKE(I+7),INP(1816)
4320 FX=PEEK(I+6):FY=PEEK(I+7):IF FX+FY=0 THEN OUT 1817,162
4330 OUT 1817,18:POKE(I+8),INP(1816):POKE(I+9),INP(1816)
```

```
4340  SVT = ((PEEK(I+3)*256)+PEEK(I+2))/409.6
4350  SVB = ((PEEK(I+1)*256)+PEEK(I))/409.6
4360  SVD = ((PEEK(I+5)*256)+PEEK(I+4))/409.6
4370 SVT1 = SVT*(-695.04)+3290.9
4380 SVB1 = SVB*(-302.08)+1447.1
4390 SVD1 = SVD*(-40.046)+201.58
4400 TOP = 4.746094-SVT:BOT = 4.797363-SVB: DIS = 4.996338-SVD
4410 LOCATE 21,23:PRINT USING"##.####";TOP:LOCATE 21,39:PRINT
USING"##.####";BOT:LOCATE 21,55:PRINT USING "##.####";DIS
4420 LOCATE 11,23:PRINT USING"###.####";SVT1:LOCATE 11,39:PRINT
USING"###.####";SVB1:LOCATE 11,55:PRINT USING "###.####";SVD1
4430 LOCATE 18,22:PRINT USING"##.######";SVT
4440 LOCATE 18,39:PRINT USING"##.######";SVB
4450 LOCATE 18,55:PRINT USING"##.######";SVD
4460 B$ = INKEY$: IF B$ <>"" THEN 4500
4470 LS=LS+1:GOTO 4260
4480 LS=1
4490 NEXT I
4500 RETURN
4510 REM*************************************************************************
4520 REM********** SCREEN PLOT AFTER EXTRUDING SUBROUTINE ************
4530 REM*************************************************************************
4540 CLS:INPUT"Do you want a Plot of Loads and Diaplacement vs Time (YES/NO)";JK$
4550 IF JK$<>"YES" AND JK$<>"NO" GOTO 4540
4560 IF JK$<>"YES" GOTO 4900
4570 SCREEN 2,0,0 :CLS
4580 LOCATE 25,1:PRINT TAB(3)" "TAB(6)"0" TAB(10)"0"
4590 LOCATE 25,40:PRINT "Time (sec)"
4600 LOCATE 25,75:PRINT STR$(AX)
4610 LOCATE 1,1:PRINT "    mm  kN "
4620 LOCATE 2,1:PRINT "    100 500"
4630 LINE (51,10)-(51,190)
4640 LINE (82,10)-(82,190)
4650 LINE -(639,190)
4660 FOR K= 82 TO 639 STEP BP : LINE (K,190) - (K,193):NEXT K
4670 FOR K =190 TO 10 STEP -9 : LINE (79,K)-(82,K):NEXT K
4680 FOR K= 190 TO 10 STEP -9 : LINE (49,K) - (52,K):NEXT K
4690 FOR K=0 TO I STEP 10
4700 REM Timer
4710 SH = FNCONV(PEEK(K+6)):REM THS
4720 SI = FNCONV(PEEK(K+7)):REM SEC
4730 SQ = FNCONV(PEEK(K+8)):REM MIN
4740 REM Change into time units - Y axis
4750  SJ =82 + INT((((SQ*60)+SI+(SH/100))*AT)-AO)
4760 REM Change into load units - Y axis
4770  SO = 190 - INT((((PEEK(K+1)*256)+PEEK(K))*((-302.08)/409.6)+1447.1)*(180/500)):IF
SO>=190 THEN SO=190
4780 REM Change into pressure units Y-axis
4790  SN = 190 - INT((((PEEK(K+3)*256)+PEEK(K+2))*((-695.04)/409.6)+3290.9)*(180/500)):IF
SN>=190 THEN SN=190
4800 REM Change into displacement uints Y-axis
4810  SM = 190 - INT((((PEEK(K+5)*256)+PEEK(K+4))*((-40.046)/409.6)+201.58)*(180/100)):IF
SM>=(190-2.01) THEN SM=190
4820 REM PLOT LOAD AGAINST TIME
4830 PSET (SJ,SO)
4840 REM PLOT PRESSURE AGAINST TIME
4850 PSET (SJ,SN)
4860 REM PLOT DISPLACEMENT AGAINST TIME
4870 PSET (SJ,SM)
4880 NEXT K
4890 SSS$=INKEY$ : IF SSS$="" THEN 4890
```

```
4900 RETURN
4910 REM*************************************************************************
4920 REM**************  RE-ENTER SUBROUTINE  ***************************
4930 REM*************************************************************************
4940 CLS : SCREEN 0,1,0 : COLOR 0,2,2
4950 CLS:PRINT :PRINT: PRINT
4960 PRINT "You have chosen to examine data which has previously been stored on disk."
4970 PRINT "To continue with this program insert the disk,which contains the file you wish"
4980 PRINT "to examine,into disk drive B. When you have done this press any key to continue"
4990 K$=INKEY$:IF K$="" THEN 4990
5000 CLS : PRINT : PRINT "The following data files are on your diskette -:
5010 FILES "B:????????.DAT"
5020 LOCATE 19,1: PRINT"To continue with this program it is necessary to specify the name of the file"
5030 LOCATE 20,1: PRINT "you wish to examine.The name of which must have the following format :-"
5040 LOCATE 21,1:PRINT TAB(24)"B:********.DAT":PRINT :PRINT
5050 LOCATE 24,1:PRINT"An asterisk in the above format indicates any alphanumeric character"
5060 LOCATE 22,1:INPUT "Enter filename ---->>";A$
5070 IF MID$(A$,1,1)<> "B" OR MID$(A$,2,1) <> ":" OR MID$(A$,11,1) <> "." OR MID$(A$,12,3)
<>"DAT" THEN CLS: FOR G= 0 TO 10:BEEP:PRINT "FILENAME FORMAT ERROR ":BEEP:NEXT
G: GOTO 5040
5080 DEF SEG=&H2000
5090 OPEN A$ FOR INPUT AS #1
5100 FOR I = 0 TO 64000! STEP 10
5110 IF EOF(1)  THEN GOTO 5190
5120 INPUT #1,SO,SA,SB,SC,SD,SE,SF,SG,SH,SI
5130 POKE I,SO:POKE I+1,SA
5140 POKE I+2,SB:POKE I+3,SC
5150 POKE I+4,SD:POKE I+5,SE
5160 POKE I+6,SF:POKE I+7,SG
5170 POKE I+8,SH:POKE I+9,SI
5180 NEXT I
5190 CLOSE #1
5200 LET I=I-10:LET M=SH:LET H=SG
5210 TI=FNCONV(H):IT=FNCONV(M)
5220 TF=M+6*INT(M/10):FI=H+6*INT(H/10)
5230 H=(IT*60)+TI:LET AX=H:LET AT=(557/H)
5240 GOSUB 3590
5250 BP=H/(6*ST)
5260 IF BP<7.5 THEN GOTO 5280
5270 GOTO 5290
5280 BP=H/(.6*ST)
5290 RETURN
5300 IF (ERR<>61) THEN END
5310 CLS:PRINT
5320 PRINT "Diskette storage space is full":PRINT
5330 PRINT "Insert new diskette into disk drive B"
5340 PRINT :PRINT :PRINT
5350 PRINT "PRESS ANY KEY TO CONTINUE "
5360 KT$=INKEY$:IF KT$="" THEN 5360
5370 RESUME 2510
5380 REM *************************************************************************
5390 REM **************  DISK STORAGE OF THE COMPUTED RESULTS  *********
5400 REM *************************************************************************
5410 GOTO 5430
5420 BEEP:BEEP:BEEP
5430 CLS:PRINT:PRINT:PRINT:PRINT"    ENTER THE FILENAME UNDER WHICH YOUR FILES
WILL BE SOTRED ON THE DISK":PRINT:PRINT"       THE FILE NAME MUST BE OF FORMAT
'A:**'":PRINT
5440 PRINT"   WHERE AN ASTERISK IS ANY ALPHANUMERIC CHARACTER":PRINT
5450 INPUT"   *****ENTER THE FILENAME NOW -->";D$
5460 DV=LEN(D$):IF DV<>4 THEN GOTO 5420
```

```
5470 EXT$=".RES"
5480 TIT$="-TITLE"
5490 TOP$="-TOP"
5500 BOT$="-BOT"
5510 DIS$="-DISPL"
5520 TIM$="-TIME"
5530 TOT$="-PRINT"
5540 N1$=D$+TIT$+EXT$
5550 N2$=D$+TOP$+EXT$
5560 N3$=D$+BOT$+EXT$
5570 N4$=D$+DIS$+EXT$
5580 N5$=D$+TIM$+EXT$
5590 N6$=D$+TOT$+EXT$
5600 OPEN N2$ FOR OUTPUT AS #2:OPEN N3$ FOR OUTPUT AS #3:OPEN N4$ FOR OUTPUT
AS #4:OPEN N5$ FOR OUTPUT AS #5:OPEN N6$ FOR OUTPUT AS #6
5610 PRINT #6,"*************************************************************************"
5620 PRINT #6,"                                    RESULTS "
5630 PRINT #6,"*************************************************************************"
5640 PRINT #6,"          "
5650 PRINT #6,"The results of this test are stored in the file ";A$
5660 PRINT #6,"      "
5670 PRINT #6,"The values at maximum load are :-"
5680 PRINT #6,"Load at Top Load Cell   =";MOK;"(kN)"
5690 PRINT #6,"Load at Bottom Load Cell =";MAXP;"(kN)"
5700 PRINT #6,"Displacement          =";MAXD;"(mm)"
5710 PRINT #6,"Time Elasped          =";MSEC;"(sec)":PRINT:PRINT
5720 PRINT #6,"      "
5730 PRINT #6,"      "
5740 PRINT #6,"      "
5750 G$="*  T.L.C.   B.L.C.  DISPLACEMENT  TIME *"
5760 H$="*  T.L.C.   B.L.C.  DISPLACEMENT  TIME *"
5770 K$="*   (kN)     (kN)      (mm)    (sec) *"
5780 J$="*   (kN)     (kN)      (mm)    (sec) *"
5790 PRINT #6,G$+H$
5800 PRINT #6,K$+J$
5810 FOR K = 0 TO I STEP 20
5820 SA = ((FNCONV(PEEK(K+6)))/100)+FNCONV(PEEK(K+7))+((FNCONV(PEEK(K+8))*60))
5830 SA1 = ((FNCONV(PEEK(K+16)))/100)+FNCONV(PEEK(K+17))+((FNCONV(PEEK(K+18)))*60)
5840 SP  = (((PEEK(K+1)*256)+PEEK(K))/409.6)*(-302.08)+1447.1
5850 SL  = (((PEEK(K+3)*256)+PEEK(K+2))/409.6)*(-695.04)+3290.9
5860 SD  = (((PEEK(K+5)*256)+PEEK(K+4))/409.6)*(-40.046)+201.58
5870 SP1 = (((PEEK(K+11)*256)+PEEK(K+10))/409.6)*(-302.08)+1447.1
5880 SL1 = (((PEEK(K+13)*256)+PEEK(K+12))/409.6)*(-695.04)+3290.9
5890 SD1 = (((PEEK(K+15)*256)+PEEK(K+14))/409.6)*(-40.046)+201.58
5900 IF SP<=0 THEN SP=0:IF SL<=0 THEN SL=0:IF SD<=1.55 THEN SD=0
5910 IF SP1<=0 THEN SP1=0:IF SL1<=0 THEN SL1=0:IF SD1<=1.55 THEN SD1=0
5920 PRINT #6,USING "###.####   "; SL, SP,SD,SA,SL1,SP1,SD1,SA1
5930 PRINT #2,USING"###.####";SL
5940 PRINT #3,USING"###.####";SP
5950 PRINT #4,USING"###.####";SD
5960 PRINT #5,USING"###.####";SA
5970 PRINT #2,USING"###.####";SL1
5980 PRINT #3,USING"###.####";SP1
5990 PRINT #4,USING"###.####";SD1
6000 PRINT #5,USING"###.####";SA1
6010 NEXT K
6020 CLOSE
6030 RETURN
```

APPENDIX 5

EXPERIMENTAL DATA

In this Appendix the raw experimental data (i.e.: loads on top and bottom load cells, punch displacement and time) obtained during the Context simulation, together with the graphical representation of this data, are presented. The results are given in the order in which they were conducted, however experiment number one is omitted as the run failed due to equipment failure.

The meaning of the symbols in the Tables below are:

T.L.C. - Load on the Top Load Cell

B.L.C. - Load on the Bottom Load Cell

****

RESULTS - SPECIMEN No.2

****

The results of this test are stored in the file B:29-12-02.DAT

The values at maximum load are :-

Load at Top Load Cell = 60.05005 (kN)

Load at Bottom Load Cell = 19.30005 (kN)

Displacement = 14.93982 (mm)

Time Elasped = 25.42 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	4.4314	0.1251	1.6433	7.5300
7.4468	6.0250	1.7411	7.9200	7.4468	6.7626	1.9366	8.3100
7.4468	6.0250	2.1321	8.6900	7.4468	6.0250	2.5232	9.0800
7.4468	6.0250	2.7188	9.4600	7.4468	6.0250	3.0121	9.8500
7.4468	6.0250	3.3054	10.2400	7.4468	6.0250	3.5987	10.6300
7.4468	6.0250	3.8920	11.0200	7.4468	6.0250	4.1853	11.4100
7.4468	6.0250	4.4786	11.8000	7.4468	6.0250	4.6741	12.1800
17.6282	9.7125	5.0652	12.5700	24.4155	11.9250	5.2607	12.9600
26.1125	12.6626	5.6518	13.3500	27.8093	13.4000	5.8474	13.7500
29.5061	13.4000	6.2384	14.1300	29.5061	13.4000	6.4340	14.5300
31.2031	12.6626	6.8250	14.9200	29.5061	13.4000	7.0206	15.3100
31.2031	13.4000	7.5094	15.7000	31.2031	13.4000	7.6072	16.0900
31.2031	13.4000	8.0960	16.4800	31.2031	13.4000	8.2916	16.8700
31.2031	13.4000	8.6826	17.2600	32.8999	14.1376	8.8782	17.6500
36.2937	14.8751	9.3670	18.0400	37.9905	14.8751	9.4648	18.4300
39.6875	15.6125	9.9536	18.8200	41.3843	15.6125	10.1492	19.2100
41.3843	15.6125	10.4425	19.6000	41.3843	15.6125	10.7358	19.9900
43.0813	16.3501	11.1268	20.3800	43.0813	16.3501	11.3224	20.7600
44.7781	16.3501	11.6157	21.1500	46.4749	17.0875	12.0068	21.5400
48.1719	17.0875	12.2023	21.9300	49.8687	17.8251	12.5934	22.3200
51.5657	17.8251	12.7889	22.7100	53.2625	17.8251	13.1800	23.0900
53.2625	18.5626	13.4733	23.4800	54.9592	18.5626	13.7666	23.8700
56.6563	18.5626	14.0599	24.2600	58.3530	19.3000	14.2554	24.6500
58.3530	19.3000	14.6465	25.0300	60.0500	19.3000	14.9398	25.4200
46.4749	17.0875	15.2331	25.8100	46.4749	17.0875	15.6242	26.2000
44.7781	17.0875	15.8197	26.5900	44.7781	17.0875	16.2108	26.9700
43.0813	16.3501	16.2108	27.3600	41.3843	16.3501	16.3086	27.7500
41.3843	16.3501	16.3086	28.1400	41.3843	16.3501	16.2108	28.5300
41.3843	16.3501	16.3086	28.9200	41.3843	16.3501	16.2108	29.3100
41.3843	15.6125	16.3086	29.6900	41.3843	16.3501	16.2108	30.0800
41.3843	15.6125	16.3086	30.4700	41.3843	16.3501	16.3086	30.8600
39.6875	16.3501	16.2108	31.2500	41.3843	16.3501	16.3086	31.6400
39.6875	16.3501	16.2108	32.0200	39.6875	16.3501	16.2108	32.4100
39.6875	16.3501	16.3086	32.8000	39.6875	16.3501	16.2108	33.1900
39.6875	15.6125	16.3086	33.5700	41.3843	16.3501	16.2108	33.9600
39.6875	15.6125	16.3086	34.3500	39.6875	15.6125	16.2108	34.7400
39.6875	16.3501	16.8952	35.1300	39.6875	15.6125	16.3086	35.5200
39.6875	16.3501	16.2108	35.9000	39.6875	15.6125	16.3086	36.2900
39.6875	15.6125	16.3086	36.6800	39.6875	15.6125	16.3086	37.0700
39.6875	16.3501	16.3086	37.4600	39.6875	16.3501	16.2108	37.8400
39.6875	15.6125	16.3086	38.2300	39.6875	16.3501	16.2108	38.6200
39.6875	15.6125	16.3086	39.0100	39.6875	16.3501	16.3086	39.4000
39.6875	15.6125	16.3086	39.7900	39.6875	15.6125	16.3086	40.1700
39.6875	15.6125	16.2108	40.5600	39.6875	15.6125	16.2108	40.9500
39.6875	15.6125	16.3086	41.3300	39.6875	15.6125	16.2108	41.7200
39.6875	15.6125	16.3086	42.1100	39.6875	15.6125	16.3086	42.4900
39.6875	15.6125	16.2108	42.8800	39.6875	15.6125	16.3086	43.2700
39.6875	15.6125	16.3086	43.6500	39.6875	15.6125	16.2108	44.0400
39.6875	15.6125	16.3086	44.4300	39.6875	15.6125	16.3086	44.8100
39.6875	15.6125	16.3086	45.2000	36.2937	14.8751	16.2108	120.3400
36.2937	14.8751	16.3086	120.7300	36.2937	14.8751	16.3086	121.1200
36.2937	14.8751	16.3086	121.5100	36.2937	15.6125	16.2108	121.9100
36.2937	15.6125	16.2108	122.3000	36.2937	14.8751	16.3086	122.6900
36.2937	14.8751	16.2108	123.0900	36.2937	14.8751	16.3086	123.4800
36.2937	14.8751	16.3086	123.8700	36.2937	14.8751	16.3086	124.2600

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
36.2937	14.8751	16.3086	124.6600	36.2937	14.8751	16.3086	125.0500
36.2937	14.8751	16.2108	125.4400	36.2937	14.8751	16.3086	125.8400
36.2937	14.8751	16.3086	126.2300	36.2937	14.8751	16.2108	126.6200
37.9905	14.8751	16.3086	127.0200	36.2937	14.8751	16.3086	127.4100
36.2937	14.8751	16.2108	127.8000	36.2937	14.8751	16.3086	128.1900
36.2937	14.8751	16.2108	128.5900	36.2937	14.8751	16.3086	128.9800
36.2937	14.8751	16.3086	129.3700	36.2937	14.8751	16.2108	129.7600
36.2937	14.8751	16.3086	130.1600	36.2937	14.8751	16.3086	130.5500
36.2937	14.8751	16.3086	130.9500	36.2937	14.8751	16.3086	131.3500
36.2937	15.6125	16.3086	131.7400	36.2937	14.8751	16.2108	132.1400
36.2937	14.8751	16.3086	132.5400	36.2937	14.8751	16.3086	132.9300
36.2937	14.8751	16.3086	133.3300	36.2937	14.8751	16.2108	133.7200
36.2937	14.8751	16.2108	134.1200	36.2937	14.8751	16.3086	134.5200
36.2937	14.8751	16.3086	134.9100	36.2937	14.8751	16.3086	135.3100
36.2937	14.8751	16.3086	135.7100	36.2937	14.8751	16.2108	136.1000
36.2937	14.8751	16.3086	136.5000	36.2937	14.8751	16.3086	136.8900
36.2937	14.8751	16.3086	137.2900	36.2937	14.8751	16.2108	137.6800
36.2937	14.8751	16.2108	138.0800	36.2937	14.8751	16.3086	138.4800
36.2937	14.8751	16.3086	138.8700	36.2937	14.8751	16.3086	139.2700
36.2937	14.8751	16.3086	139.6600	36.2937	14.8751	16.2108	140.0600
36.2937	14.8751	16.3086	140.4500	36.2937	14.8751	16.3086	140.8500
36.2937	14.8751	16.3086	141.2500	36.2937	14.8751	16.3086	141.6400
36.2937	14.8751	16.2108	142.0400	36.2937	14.8751	16.3086	142.4300
36.2937	14.8751	16.3086	142.8300	36.2937	14.8751	16.3086	143.2200
36.2937	14.8751	16.2108	143.6200	36.2937	14.8751	16.3086	144.0200
36.2937	14.8751	16.3086	144.4100	36.2937	14.8751	16.3086	144.8100
36.2937	14.8751	16.3086	145.2000	36.2937	14.8751	16.2108	145.6000
36.2937	14.8751	16.3086	145.9900	36.2937	14.8751	16.3086	146.3900
36.2937	14.8751	16.3086	146.7900	36.2937	14.8751	16.3086	147.1800
36.2937	14.8751	16.2108	147.5800	36.2937	14.8751	16.3086	147.9700
36.2937	14.8751	16.3086	148.3700	36.2937	14.8751	16.3086	148.7600
36.2937	14.8751	16.2108	149.1600	36.2937	14.8751	16.2108	149.5600
36.2937	14.8751	16.2108	149.9500	36.2937	14.8751	16.3086	150.3500
36.2937	14.8751	16.3086	150.7400	36.2937	14.8751	16.2108	151.1400
36.2937	14.8751	16.2108	151.5300	36.2937	14.8751	16.3086	151.9300
36.2937	14.8751	16.3086	152.3300	36.2937	14.8751	16.3086	152.7200
36.2937	14.8751	16.2108	153.1200	36.2937	14.8751	16.3086	153.5100
36.2937	14.8751	16.3086	153.9100	36.2937	14.8751	16.3086	154.3100
36.2937	14.8751	16.3086	154.7000	36.2937	14.8751	16.2108	155.1000
36.2937	14.8751	16.2108	155.4900	36.2937	14.8751	16.2108	155.8900
34.5969	14.8751	16.3086	156.2900	36.2937	14.8751	16.3086	156.6900
36.2937	14.8751	16.3086	157.0800	36.2937	14.8751	16.3086	157.4800
36.2937	14.8751	16.2108	157.8700	36.2937	14.8751	16.2108	158.2700
36.2937	14.8751	16.3086	158.6700	36.2937	14.8751	16.4063	159.0600
36.2937	14.8751	16.3086	159.4600	36.2937	14.8751	16.3086	159.8600

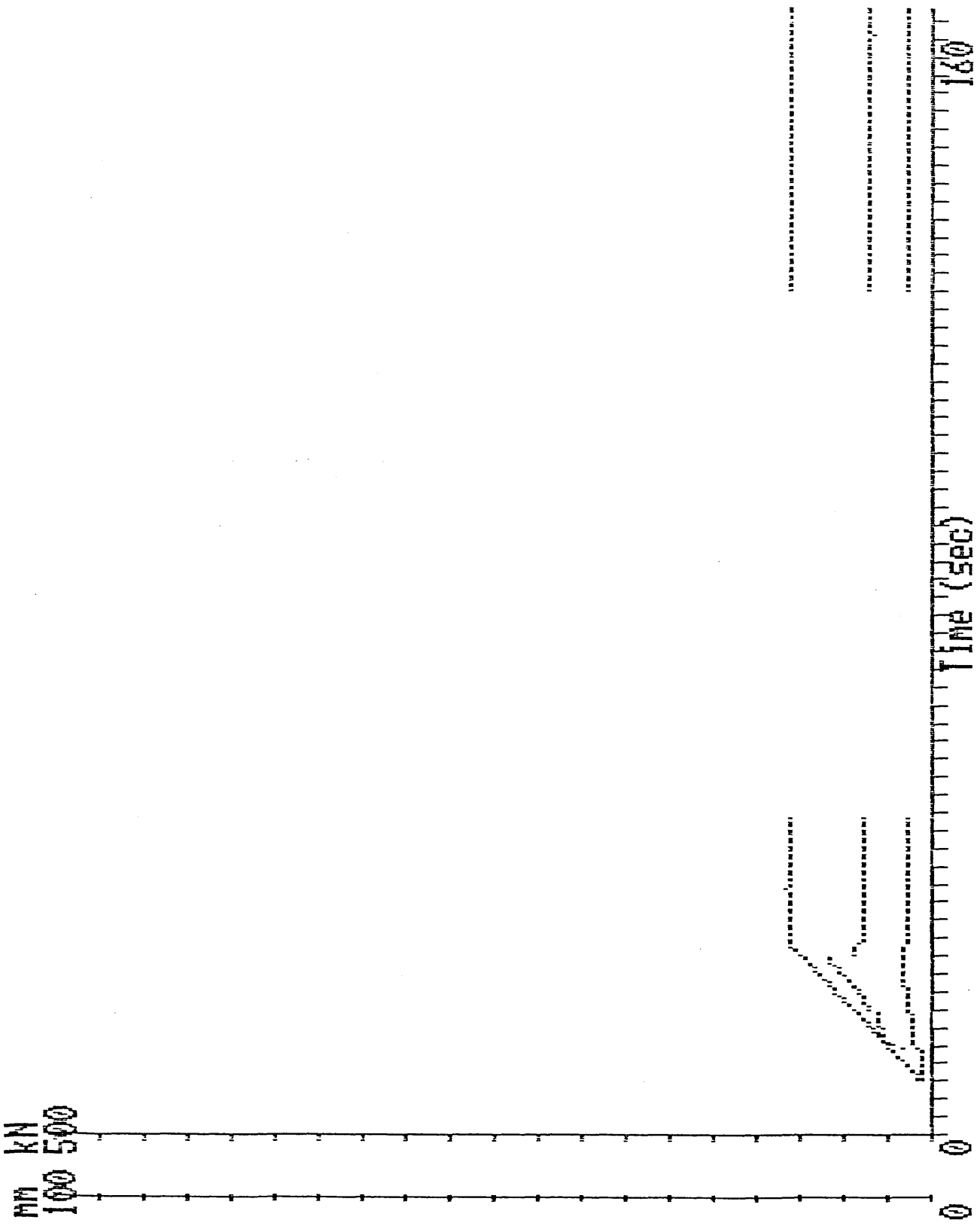


Fig.A5.1. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.2

****

RESULTS - SPECIMEN No.3

****

The results of this test are stored in the file B:04-01-03.DAT

The values at maximum load are :-

Load at Top Load Cell = 131.3186 (kN)

Load at Bottom Load Cell = 44.37512 (kN)

Displacement = 26.08543 (mm)

Time Elasped = 61.48 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	0.0000	9.8600
0.0000	0.0000	0.0000	10.2500	0.0000	0.0000	0.0000	10.6400
0.0000	0.0000	0.0000	11.0300	0.0000	0.0000	0.0000	11.4300
0.0000	0.0000	0.0000	11.8200	0.0000	0.0000	0.0000	12.2000
0.0000	0.0000	0.0000	12.6000	0.0000	0.0000	0.0000	12.9900
0.0000	0.0000	0.0000	13.3800	0.0000	0.0000	0.0000	13.7700
0.0000	0.0000	0.0000	14.1600	0.0000	0.0000	0.0000	14.5500
0.0000	0.0000	0.0000	14.9400	0.0000	0.0000	0.0000	15.3300
0.0000	0.0000	0.0000	15.7200	0.0000	0.0000	0.0000	16.1100
0.0000	0.0000	0.0000	16.5000	0.0000	0.0000	0.0000	16.8900
0.0000	0.0000	0.0000	17.2800	0.0000	0.0000	0.0000	17.6700
0.0000	0.0000	0.0000	18.0600	0.0000	0.0000	0.0000	18.4500
0.0000	0.0000	0.0000	18.8500	0.0000	0.0000	0.0000	19.2400
0.0000	0.0000	0.0000	19.6300	0.0000	0.0000	0.0000	20.0200
0.0000	0.0000	0.0000	20.4100	0.0000	0.0000	0.0000	20.8000
0.0000	0.0000	0.0000	21.1800	0.0000	0.0000	0.0000	21.5700
0.0000	0.0000	0.0000	21.9600	0.0000	0.0000	0.0000	22.3500
0.0000	0.0000	0.0000	22.7400	4.4314	0.1251	1.5455	23.1300
7.4468	7.5001	1.5455	23.5100	15.9312	11.1876	1.5455	23.9000
19.3250	12.6626	1.5455	24.2900	22.7188	14.1376	1.5455	24.6800
22.7188	14.8751	1.5455	25.0700	24.4155	15.6125	1.5455	25.4500
26.1125	15.6125	1.5455	25.8400	26.1125	15.6125	1.5455	26.2300
26.1125	15.6125	1.6433	26.6200	26.1125	16.3501	1.6433	27.0100
27.8093	16.3501	1.6433	27.4000	26.1125	16.3501	1.6433	27.7900
26.1125	15.6125	1.6433	28.1700	27.8093	16.3501	1.7411	28.5600
26.1125	16.3501	1.9366	28.9500	27.8093	16.3501	1.9366	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. ** (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
27.8093	16.3501	2.1321	29.7300	27.8093	17.0875	2.3277	30.1200
29.5061	17.0875	2.5232	30.5100	29.5061	17.0875	2.9143	30.9000
29.5061	17.8251	3.1098	31.2900	31.2031	17.8251	3.5987	31.6800
31.2031	17.8251	3.6964	32.0600	34.5969	19.3000	4.0875	32.4500
37.9905	20.7750	4.2831	32.8400	37.9905	20.7750	4.5764	33.2300
39.6875	21.5126	4.9674	33.6200	41.3843	21.5126	5.1630	34.0100
41.3843	21.5126	5.5540	34.3900	43.0813	22.2501	5.7496	34.7800
43.0813	22.2501	6.0429	35.1700	43.0813	22.2501	6.4340	35.5600
43.0813	22.9875	6.7273	35.9500	44.7781	22.9875	7.0206	36.3300
36.2937	20.0376	7.3139	36.7200	36.2937	20.0376	7.7049	37.1100
36.2937	20.0376	7.9983	37.5000	36.2937	20.0376	8.2916	37.8900
36.2937	20.0376	8.5849	38.2800	36.2937	19.3000	8.8782	38.6700
36.2937	20.0376	9.2692	39.0500	34.5969	20.0376	9.4648	39.4400
36.2937	19.3000	9.7581	39.8300	36.2937	19.3000	10.1492	40.2200
36.2937	19.3000	10.3447	40.6000	36.2937	19.3000	10.7358	40.9900
36.2937	19.3000	11.0291	41.3800	36.2937	19.3000	11.3224	41.7600
36.2937	19.3000	11.6157	42.1500	36.2937	19.3000	11.9090	42.5400
36.2937	19.3000	12.2023	42.9200	36.2937	19.3000	12.4956	43.3100
36.2937	19.3000	12.8867	43.7000	36.2937	19.3000	13.0822	44.0800
36.2937	19.3000	13.4733	44.4700	36.2937	19.3000	13.8644	44.8600
36.2937	19.3000	14.0599	45.2400	36.2937	19.3000	14.3532	45.6300
44.7781	22.9875	14.6465	46.0200	48.1719	23.7251	14.9398	46.4000
48.1719	24.4625	15.2331	46.7900	49.8687	24.4625	15.6242	47.1800
51.5657	25.2001	15.8197	47.5600	51.5657	25.2001	16.1130	47.9500
53.2625	25.9376	16.4063	48.3400	53.2625	25.9376	16.6997	48.7200
54.9592	26.6750	16.9930	49.1100	56.6563	26.6750	17.3840	49.5000
56.6563	27.4126	17.5796	49.8800	56.6563	27.4126	17.7751	50.2700
58.3530	27.4126	18.1662	50.6600	58.3530	27.4126	18.5573	51.0400
60.0500	28.1500	18.7528	51.4300	60.0500	28.1500	19.1439	51.8200
61.7468	28.1500	19.4372	52.2000	61.7468	28.8876	19.6327	52.5900
63.4436	28.8876	19.9260	52.9700	63.4436	28.8876	20.3171	53.3600
63.4436	29.6251	20.5126	53.7500	65.1406	29.6251	20.7082	54.1300
65.1406	29.6251	21.1970	54.5200	65.1406	30.3625	21.3925	54.9100
66.8374	30.3625	21.6859	55.2900	68.5344	30.3625	22.0769	55.6800
68.5344	31.1001	22.2725	56.0700	70.2312	31.1001	22.5658	56.4500
71.9280	31.1001	22.8591	56.8400	73.6250	32.5751	23.1524	57.2300
75.3218	32.5751	23.3479	57.6100	78.7156	33.3126	23.7390	58.0000
83.8062	34.0500	24.0323	58.3800	88.8967	35.5250	24.2278	58.7700
93.9875	37.0001	24.6189	59.1600	99.0781	38.4751	24.8144	59.5400
105.8655	39.9501	25.0100	59.9300	112.6531	40.6876	25.3033	60.3200
119.4407	42.1626	25.5966	60.7000	126.2280	43.6376	25.7921	61.0900
131.3186	44.3751	26.0854	61.4800	131.3186	45.1125	26.1832	61.8800
129.6218	45.1125	26.0854	62.2700	127.9250	44.3751	26.1832	62.6600
126.2280	44.3751	26.1832	63.0600	126.2280	44.3751	26.0854	63.4500
126.2280	44.3751	26.1832	63.8400	126.2280	44.3751	26.0854	64.2300
124.5313	44.3751	26.1832	64.6300	124.5313	44.3751	26.1832	65.0200
124.5313	44.3751	26.0854	65.4100	124.5313	44.3751	26.1832	65.8000
124.5313	44.3751	26.1832	66.2000	124.5313	44.3751	26.1832	66.5900
122.8342	44.3751	26.1832	66.9800	122.8342	44.3751	26.0854	67.3800
122.8342	44.3751	26.1832	67.7700	122.8342	44.3751	26.1832	68.1600
122.8342	44.3751	26.0854	68.5500	122.8342	44.3751	26.2810	68.9500
122.8342	44.3751	26.1832	69.3400	122.8342	44.3751	26.1832	69.7300
122.8342	44.3751	26.1832	70.1200	122.8342	44.3751	26.1832	70.5200
121.1375	44.3751	26.1832	70.9200	121.1375	44.3751	26.0854	71.3100
121.1375	44.3751	26.1832	71.7100	121.1375	44.3751	26.2810	72.1000
121.1375	43.6376	26.1832	72.5000	121.1375	43.6376	26.1832	72.9000

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec)	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
121.1375	44.3751	26.1832	73.2900	121.1375	44.3751	26.1832	73.6900
119.4407	43.6376	26.2810	74.0900	121.1375	43.6376	26.2810	74.4800
121.1375	43.6376	26.1832	74.8800	121.1375	43.6376	26.0854	75.2800
121.1375	44.3751	26.1832	75.6700	119.4407	43.6376	25.9877	76.0700
121.1375	43.6376	26.2810	76.4600	121.1375	43.6376	26.1832	76.8600
112.6531	42.9000	26.1832	151.7600	112.6531	42.9000	26.1832	152.1500
112.6531	42.9000	26.1832	152.5500	110.9563	42.9000	26.1832	152.9400
112.6531	42.9000	26.1832	153.3400	110.9563	42.9000	26.1832	153.7300
112.6531	42.9000	26.2810	154.1300	110.9563	42.9000	26.2810	154.5200
112.6531	42.9000	26.1832	154.9200	110.9563	42.9000	26.1832	155.3200
110.9563	42.9000	26.1832	155.7100	110.9563	42.9000	26.1832	156.1100
110.9563	42.9000	26.2810	156.5000	112.6531	42.9000	26.1832	156.9000
112.6531	42.9000	26.1832	157.3000	110.9563	42.9000	26.1832	157.6900
110.9563	42.9000	26.2810	158.0900	110.9563	42.9000	26.1832	158.4800
110.9563	42.9000	26.1832	158.8800	110.9563	42.9000	26.1832	159.2800
112.6531	42.9000	26.1832	159.6700	110.9563	42.9000	26.1832	160.0700
110.9563	42.9000	26.2810	160.4700	110.9563	42.9000	26.1832	160.8600
110.9563	42.9000	26.1832	161.2600	110.9563	42.9000	26.1832	161.6500
110.9563	42.9000	26.1832	162.0500	110.9563	42.1626	26.1832	162.4500
110.9563	42.1626	26.1832	162.8400	110.9563	42.9000	26.1832	163.2400
110.9563	42.9000	26.1832	163.6300	110.9563	42.9000	26.1832	164.0300
110.9563	42.9000	26.2810	164.4300	110.9563	42.9000	26.2810	164.8200
110.9563	42.9000	26.1832	165.2200	110.9563	42.9000	26.1832	165.6100
110.9563	42.9000	26.1832	166.0100	110.9563	42.1626	26.1832	166.4000
110.9563	42.1626	26.2810	166.8000	110.9563	42.9000	26.1832	167.2000
110.9563	42.9000	26.1832	167.5900	110.9563	42.9000	26.1832	167.9900
110.9563	42.1626	26.1832	168.3800	110.9563	42.9000	26.2810	168.7800
110.9563	42.9000	26.1832	169.1700	110.9563	42.9000	26.1832	169.5700
110.9563	42.9000	26.1832	169.9700	110.9563	42.1626	26.1832	170.3600
110.9563	42.9000	26.2810	170.7600	110.9563	42.9000	26.1832	171.1500
110.9563	42.1626	26.1832	171.5500	110.9563	42.9000	26.1832	171.9500

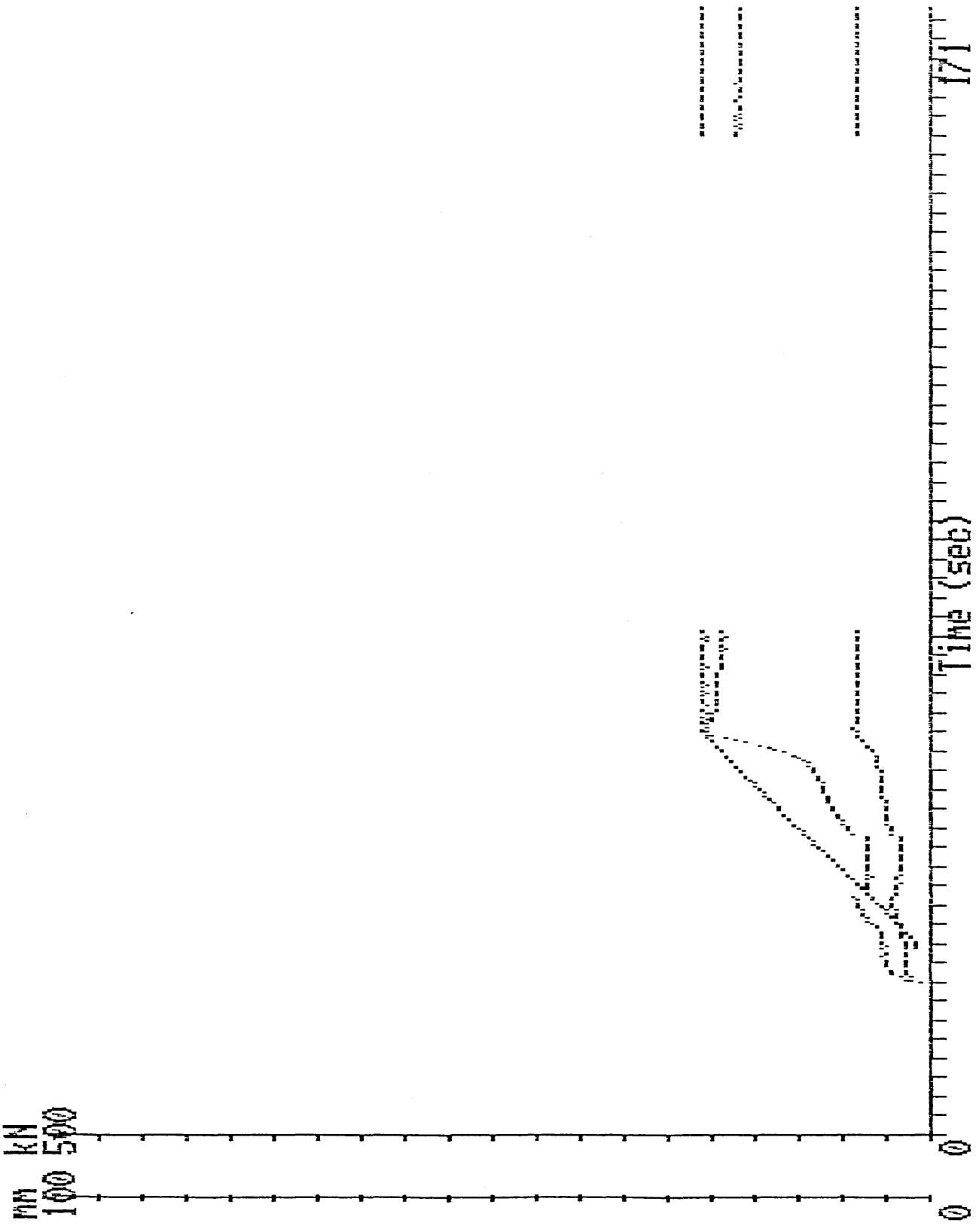


Fig.A5.2. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.3.

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RESULTS - SPECIMEN No.4

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The results of this test are stored in the file B:04-01-04.DAT

The values at maximum load are :-

Load at Top Load Cell = 66.8374 (kN)

Load at Bottom Load Cell = 26.67505 (kN)

Displacement = 31.56047 (mm)

Time Elasped = 46.72 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5700
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.6000	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	1.7411	7.5400
0.0000	0.0000	2.0344	7.9300	1.0376	1.6001	2.3277	8.3100
9.1438	6.0250	2.6210	8.7000	12.5374	6.7626	2.8165	9.0800
12.5374	6.0250	3.1098	9.4700	10.8406	6.7626	3.5009	9.8600
10.8406	6.0250	3.7942	10.2500	12.5374	6.0250	4.0875	10.6400
10.8406	6.0250	4.2831	11.0300	10.8406	6.7626	4.6741	11.4200
10.8406	6.7626	4.9674	11.8100	10.8406	6.0250	5.2607	12.1900
12.5374	6.7626	5.5540	12.5800	12.5374	6.7626	5.8474	12.9700
12.5374	6.7626	6.2384	13.3600	12.5374	6.7626	6.5317	13.7500
12.5374	6.7626	6.8250	14.1400	12.5374	6.7626	7.1183	14.5300
12.5374	6.7626	7.4116	14.9200	12.5374	6.7626	7.7049	15.3100
12.5374	6.7626	7.9983	15.7000	12.5374	6.7626	8.3893	16.0800
12.5374	6.7626	8.5849	16.4700	12.5374	6.7626	8.9759	16.8600
12.5374	6.7626	9.1715	17.2500	14.2344	7.5001	9.5625	17.6400
17.6282	9.7125	9.7581	18.0300	21.0217	11.1876	10.1492	18.4200
24.4155	13.4000	10.3447	18.8100	27.8093	14.8751	10.6380	19.2000
31.2031	15.6125	10.9313	19.5900	31.2031	15.6125	11.2246	19.9800
32.8999	15.6125	11.5179	20.3700	32.8999	16.3501	11.8112	20.7600
32.8999	16.3501	12.1045	21.1400	32.8999	16.3501	12.3978	21.5300
32.8999	16.3501	12.6911	21.9200	32.8999	16.3501	13.0822	22.3100
34.5969	17.0875	13.3755	22.7000	36.2937	17.0875	13.6688	23.0800
36.2937	17.0875	13.8644	23.4700	36.2937	17.0875	14.2554	23.8600
36.2937	17.8251	14.4510	24.2500	37.9905	17.8251	14.7443	24.6400
37.9905	17.8251	15.0376	25.0200	37.9905	17.8251	15.4287	25.4100
37.9905	17.8251	15.7220	25.8000	37.9905	17.8251	15.9175	26.1900
39.6875	17.8251	16.3086	26.5800	39.6875	18.5626	16.5041	26.9600
39.6875	17.8251	16.8952	27.3500	39.6875	18.5626	17.1885	27.7400
39.6875	18.5626	17.4818	28.1300	41.3843	19.3000	17.6773	28.5200
41.3843	19.3000	18.0684	28.9100	43.0813	19.3000	18.3617	29.2900

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
43.0813	19.3000	18.6550	29.6800	43.0813	20.0376	19.0461	30.0700
44.7781	20.0376	19.2416	30.4600	44.7781	20.0376	19.6327	30.8500
44.7781	20.7750	19.8282	31.2300	46.4749	20.7750	20.1216	31.6200
46.4749	20.7750	20.4149	32.0100	46.4749	20.7750	20.7082	32.4000
48.1719	21.5126	21.0015	32.7900	48.1719	21.5126	21.2948	33.1700
49.8687	21.5126	21.6859	33.5600	49.8687	22.2501	21.8814	33.9500
51.5657	22.2501	22.2725	34.3400	51.5657	22.2501	22.3702	34.7300
53.2625	22.2501	22.8591	35.1100	53.2625	22.9875	23.0546	35.5000
53.2625	22.9875	23.3479	35.8900	54.9592	23.7251	23.6412	36.2800
54.9592	23.7251	23.8368	36.6600	54.9592	23.7251	24.2278	37.0500
56.6563	23.7251	24.4234	37.4400	56.6563	23.7251	24.9122	37.8300
56.6563	24.4625	25.1078	38.2100	56.6563	24.4625	25.4011	38.6000
56.6563	24.4625	25.6944	38.9900	58.3530	24.4625	25.9877	39.3800
58.3530	25.2001	26.2810	39.7700	58.3530	24.4625	26.4765	40.1500
60.0500	24.4625	26.9653	40.5400	60.0500	25.2001	27.1609	40.9300
60.0500	25.2001	27.4542	41.3100	60.0500	25.2001	27.8453	41.7000
60.0500	25.2001	27.9430	42.0800	60.0500	25.2001	28.3341	42.4700
61.7468	25.2001	28.7252	42.8600	61.7468	25.2001	28.8230	43.2400
61.7468	25.2001	29.2140	43.6300	61.7468	25.9376	29.5073	44.0200
61.7468	25.9376	29.7029	44.4000	63.4436	25.9376	30.0939	44.7900
63.4436	26.6750	30.2895	45.1700	65.1406	26.6750	30.5828	45.5600
65.1406	26.6750	30.9739	45.9500	65.1406	26.6750	31.1694	46.3300
66.8374	26.6750	31.5605	46.7200	66.8374	27.4126	31.7560	47.1100
66.8374	27.4126	31.9516	47.4900	63.4436	26.6750	32.1471	47.8800
61.7468	25.9376	32.1471	48.2700	61.7468	25.9376	32.1471	48.6500
61.7468	25.9376	32.1471	49.0400	61.7468	25.2001	32.0493	49.4200
60.0500	25.2001	32.1471	49.8100	60.0500	25.2001	32.1471	50.2000
60.0500	25.9376	32.1471	50.5800	60.0500	25.2001	32.1471	50.9700
60.0500	25.2001	32.1471	51.3600	60.0500	25.2001	32.2449	51.7400
58.3530	25.2001	32.2449	52.1300	58.3530	25.2001	32.1471	52.5200
58.3530	25.2001	32.2449	52.9000	58.3530	25.2001	32.1471	53.2900
58.3530	25.2001	32.1471	53.6800	58.3530	25.2001	32.2449	54.0600
58.3530	24.4625	32.1471	54.4500	58.3530	24.4625	32.1471	54.8300
58.3530	24.4625	32.2449	55.2200	56.6563	24.4625	32.0493	55.6100
56.6563	24.4625	32.2449	55.9900	56.6563	24.4625	32.1471	56.3800
56.6563	24.4625	32.1471	56.7700	56.6563	24.4625	32.2449	57.1500
56.6563	24.4625	32.1471	57.5400	56.6563	24.4625	32.1471	57.9200
56.6563	24.4625	32.2449	58.3100	56.6563	24.4625	32.1471	58.7000
56.6563	23.7251	32.2449	59.0800	54.9592	24.4625	32.1471	59.4700
54.9592	23.7251	32.1471	59.8600	54.9592	23.7251	32.2449	60.2400
54.9592	23.7251	32.1471	60.6300	54.9592	23.7251	32.1471	61.0100
54.9592	23.7251	32.1471	61.4100	54.9592	23.7251	32.1471	61.8000
54.9592	23.7251	32.2449	62.1900	54.9592	23.7251	32.1471	62.5900
54.9592	23.7251	32.1471	62.9800	54.9592	23.7251	32.2449	63.3700
53.2625	23.7251	32.2449	63.7700	53.2625	23.7251	32.1471	64.1600
53.2625	23.7251	32.1471	64.5500	53.2625	22.9875	32.2449	64.9400
53.2625	22.9875	32.1471	65.3400	53.2625	22.9875	32.1471	65.7300
53.2625	22.9875	32.2449	66.1200	53.2625	22.9875	32.1471	66.5200
53.2625	22.9875	32.1471	66.9100	44.7781	19.3000	32.2449	141.8000
44.7781	19.3000	32.2449	142.1900	44.7781	19.3000	32.1471	142.5900
44.7781	20.0376	32.1471	142.9900	44.7781	20.0376	32.1471	143.3800
44.7781	19.3000	32.2449	143.7800	44.7781	19.3000	32.2449	144.1700
44.7781	19.3000	32.2449	144.5700	44.7781	20.0376	32.1471	144.9600
44.7781	19.3000	32.1471	145.3600	44.7781	20.0376	32.2449	145.7500
44.7781	19.3000	32.2449	146.1400	44.7781	19.3000	32.2449	146.5400
44.7781	19.3000	32.1471	146.9400	43.0813	20.0376	32.1471	147.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
43.0813	19.3000	32.1471	147.7300	44.7781	19.3000	32.2449	148.1200
43.0813	19.3000	32.2449	148.5200	43.0813	19.3000	32.2449	148.9100
43.0813	20.0376	32.1471	149.3100	44.7781	19.3000	32.1471	149.7000
44.7781	19.3000	32.2449	150.1000	43.0813	19.3000	32.2449	150.4900
43.0813	19.3000	32.2449	150.8900	43.0813	19.3000	32.1471	151.2800
43.0813	19.3000	32.1471	151.6800	43.0813	19.3000	32.1471	152.0700
44.7781	19.3000	32.2449	152.4700	43.0813	19.3000	32.2449	152.8600
43.0813	19.3000	32.2449	153.2600	43.0813	19.3000	32.1471	153.6600
44.7781	19.3000	32.1471	154.0500	43.0813	19.3000	32.1471	154.4500
44.7781	19.3000	32.1471	154.8400	43.0813	19.3000	32.2449	155.2400
43.0813	19.3000	32.2449	155.6400	43.0813	19.3000	32.2449	156.0300
43.0813	19.3000	32.1471	156.4300	43.0813	19.3000	32.1471	156.8200
43.0813	19.3000	32.1471	157.2200	44.7781	19.3000	32.1471	157.6200
43.0813	19.3000	32.1471	158.0100	43.0813	19.3000	32.2449	158.4100
43.0813	19.3000	32.2449	158.8100	43.0813	19.3000	32.2449	159.2000
43.0813	19.3000	32.2449	159.6000	43.0813	19.3000	32.0493	160.0000
43.0813	19.3000	32.1471	160.3900	43.0813	19.3000	32.1471	160.7900
43.0813	19.3000	32.1471	161.1800	43.0813	19.3000	32.2449	161.5800
43.0813	19.3000	32.2449	161.9800	43.0813	19.3000	32.2449	162.3700
43.0813	19.3000	32.2449	162.7700	43.0813	19.3000	32.1471	163.1700

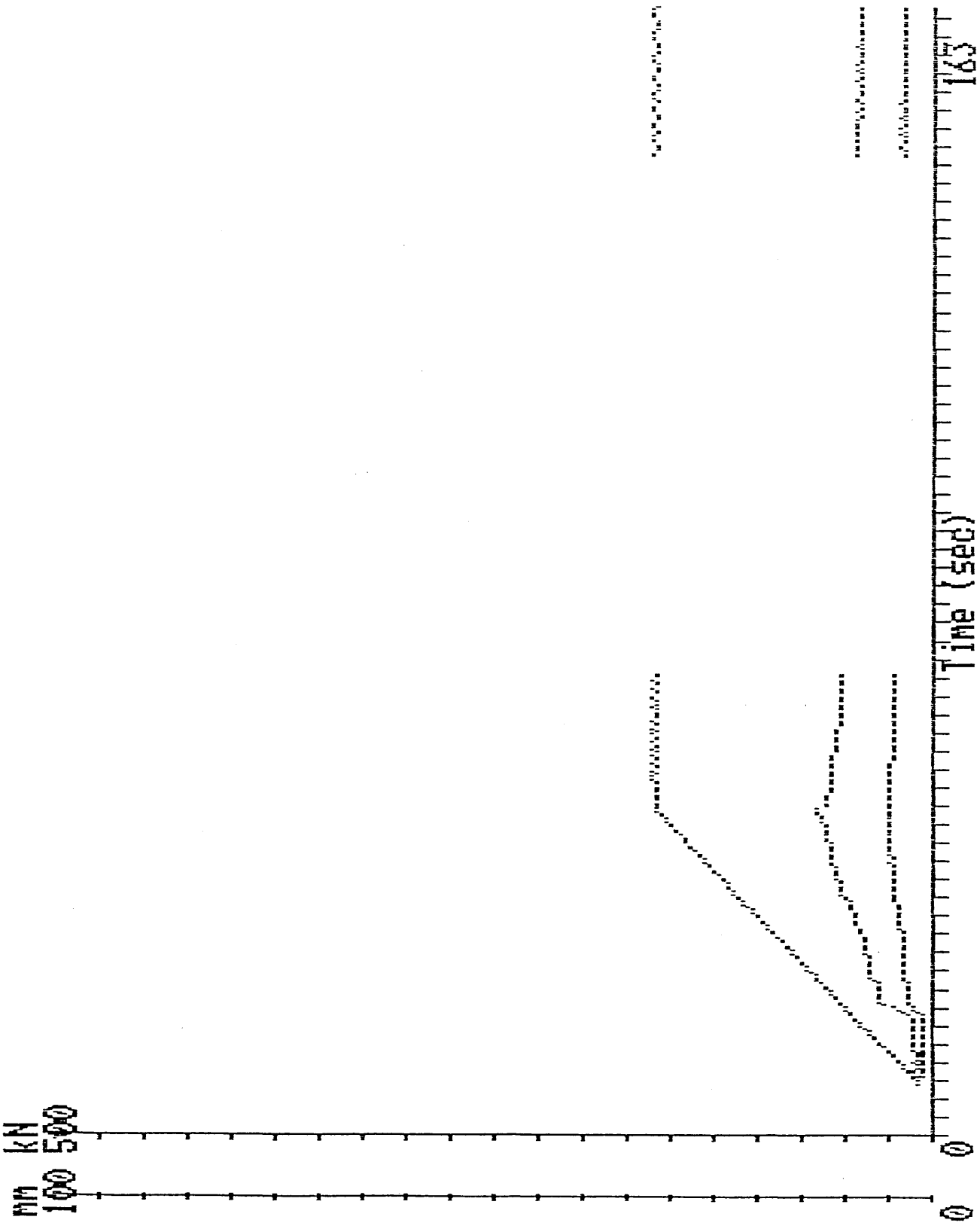


Fig.A5.3. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.4.

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RESULTS - SPECIMEN No.5

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The results of this test are stored in the file B:06-01-05.DAT

The values at maximum load are :-

Load at Top Load Cell = 60.05005 (kN)

Load at Bottom Load Cell = 20.0376 (kN)

Displacement = 22.76131 (mm)

Time Elasped = 42.13 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5700
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.6000	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5400
0.0000	0.0000	0.0000	7.9300	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4800	0.0000	0.0000	0.0000	9.8700
0.0000	0.0000	0.0000	10.2600	0.0000	0.0000	0.0000	10.6500
0.0000	0.0000	0.0000	11.0400	0.0000	0.0000	0.0000	11.4300
0.0000	0.0000	0.0000	11.8200	0.0000	0.0000	0.0000	12.2100
0.0000	0.0000	0.0000	12.6000	0.0000	0.0000	0.0000	12.9900
0.0000	0.0000	0.0000	13.3800	0.0000	0.0000	0.0000	13.7700
0.0000	0.0000	0.0000	14.1600	0.0000	0.0000	0.0000	14.5500
0.0000	0.0000	1.6433	14.9400	0.0000	0.0000	1.9366	15.3300
0.0000	0.0000	2.3277	15.7200	0.0000	0.0000	2.5232	16.1100
0.0000	0.0000	2.9143	16.5100	0.0000	0.0000	3.2076	16.9000
0.0000	0.0000	3.5987	17.2900	2.7344	0.1251	3.8920	17.6800
12.5374	8.2375	3.9897	18.0700	22.7188	11.9250	4.1853	18.4600
24.4155	11.9250	4.4786	18.8500	26.1125	11.9250	4.6741	19.2400
26.1125	11.9250	5.1630	19.6300	27.8093	12.6626	5.3585	20.0200
27.8093	12.6626	5.7496	20.4100	29.5061	12.6626	5.9451	20.8000
29.5061	12.6626	6.3362	21.1800	29.5061	13.4000	6.6295	21.5700
31.2031	13.4000	6.8250	21.9600	31.2031	13.4000	7.2161	22.3500
32.8999	14.1376	7.5094	22.7400	32.8999	14.1376	7.9005	23.1200
32.8999	14.1376	8.0960	23.5100	32.8999	14.8751	8.3893	23.9000
34.5969	14.8751	8.7804	24.2900	36.2937	14.8751	9.0737	24.6800
36.2937	14.8751	9.3670	25.0700	37.9905	15.6125	9.6603	25.4500
37.9905	15.6125	9.9536	25.8400	39.6875	16.3501	10.2469	26.2300
39.6875	16.3501	10.5402	26.6200	41.3843	16.3501	10.9313	27.0100
32.8999	14.1376	11.2246	27.4000	34.5969	14.8751	11.6157	27.7800
34.5969	14.1376	11.8112	28.1700	31.2031	13.4000	12.2023	28.5600
32.8999	13.4000	12.4956	28.9500	31.2031	13.4000	12.7889	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
31.2031	12.6626	13.0822	29.7300	31.2031	13.4000	13.3755	30.1100
31.2031	13.4000	13.7666	30.5000	31.2031	13.4000	14.0599	30.8900
31.2031	12.6626	14.3532	31.2800	31.2031	12.6626	14.6465	31.6700
31.2031	12.6626	14.8421	32.0600	31.2031	12.6626	15.3309	32.4400
31.2031	12.6626	15.5264	32.8300	31.2031	12.6626	15.8197	33.2200
31.2031	12.6626	16.2108	33.6100	31.2031	12.6626	16.4063	34.0000
31.2031	12.6626	16.7974	34.3800	32.8999	12.6626	17.0907	34.7700
32.8999	12.6626	17.2863	35.1600	31.2031	12.6626	17.7751	35.5500
32.8999	12.6626	18.0684	35.9400	31.2031	12.6626	18.3617	36.3200
37.9905	14.8751	18.5573	36.7100	44.7781	17.0875	18.8506	37.1000
44.7781	17.0875	19.2416	37.4900	46.4749	17.8251	19.4372	37.8700
48.1719	17.8251	19.8282	38.2600	48.1719	17.8251	20.0238	38.6500
49.8687	17.8251	20.3171	39.0400	51.5657	18.5626	20.7082	39.4200
53.2625	18.5626	20.9037	39.8100	53.2625	18.5626	21.2948	40.2000
54.9592	18.5626	21.6859	40.5900	56.6563	19.3000	21.7836	40.9700
56.6563	19.3000	22.1747	41.3600	58.3530	19.3000	22.4680	41.7500
60.0500	20.0376	22.7613	42.1300	60.0500	20.0376	22.9568	42.5200
58.3530	19.3000	23.1524	42.9000	58.3530	19.3000	23.2502	43.2900
56.6563	19.3000	23.1524	43.6800	56.6563	19.3000	23.1524	44.0600
56.6563	19.3000	23.1524	44.4500	56.6563	19.3000	23.0546	44.8300
56.6563	18.5626	23.1524	45.2200	56.6563	18.5626	23.1524	45.6100
54.9592	18.5626	23.1524	45.9900	56.6563	18.5626	23.1524	46.3800
56.6563	18.5626	23.1524	46.7700	54.9592	18.5626	23.1524	47.1500
54.9592	18.5626	23.2502	47.5400	54.9592	18.5626	23.1524	47.9300
54.9592	18.5626	23.0546	48.3100	54.9592	18.5626	23.3479	48.7000
54.9592	18.5626	23.2502	49.0800	54.9592	18.5626	23.1524	49.4700
54.9592	18.5626	23.0546	49.8600	54.9592	18.5626	23.1524	50.2400
54.9592	18.5626	23.1524	50.6300	54.9592	18.5626	23.0546	51.0100
54.9592	18.5626	23.1524	51.4000	54.9592	18.5626	23.2502	51.7900
53.2625	18.5626	23.1524	52.1700	53.2625	18.5626	23.2502	52.5600
53.2625	18.5626	23.1524	52.9500	53.2625	18.5626	23.0546	53.3300
53.2625	17.8251	23.2502	53.7200	53.2625	17.8251	23.2502	54.1000
53.2625	17.8251	23.1524	54.4900	53.2625	17.8251	23.1524	54.8800
53.2625	18.5626	23.1524	55.2600	53.2625	17.8251	23.1524	55.6500
53.2625	17.8251	23.1524	56.0400	53.2625	17.8251	23.2502	56.4200
53.2625	17.8251	23.1524	56.8100	53.2625	17.8251	23.0546	57.2000
53.2625	17.8251	23.2502	57.5800	53.2625	17.8251	23.0546	57.9700
53.2625	17.8251	23.1524	58.3600	53.2625	17.8251	23.2502	58.7400
53.2625	17.8251	23.1524	59.1300	53.2625	17.8251	23.1524	59.5100
53.2625	17.8251	23.2502	59.9000	53.2625	17.8251	23.1524	60.2900
51.5657	17.8251	23.1524	60.6700	53.2625	17.8251	23.2502	61.0600
53.2625	17.8251	23.1524	61.4500	53.2625	17.8251	23.1524	61.8500
51.5657	17.8251	23.3479	62.2400	51.5657	17.8251	23.1524	62.6300
51.5657	17.8251	23.1524	63.0300	51.5657	17.8251	23.2502	63.4200
51.5657	17.8251	23.1524	63.8100	51.5657	17.8251	23.1524	64.2100
43.0813	15.6125	23.1524	139.1000	44.7781	15.6125	23.1524	139.5000
43.0813	15.6125	23.2502	139.8900	43.0813	15.6125	23.2502	140.2900
43.0813	15.6125	23.1524	140.6800	43.0813	15.6125	23.1524	141.0800
43.0813	15.6125	23.2502	141.4700	44.7781	15.6125	23.2502	141.8700
43.0813	15.6125	23.1524	142.2600	44.7781	15.6125	23.1524	142.6600
43.0813	15.6125	23.2502	143.0500	43.0813	15.6125	23.2502	143.4500
43.0813	15.6125	23.2502	143.8400	43.0813	15.6125	23.1524	144.2400
43.0813	15.6125	23.1524	144.6300	43.0813	15.6125	23.2502	145.0300
43.0813	15.6125	23.2502	145.4200	43.0813	15.6125	23.1524	145.8200
44.7781	15.6125	23.1524	146.2100	43.0813	15.6125	23.2502	146.6100
43.0813	15.6125	23.2502	147.0000	43.0813	15.6125	23.1524	147.4000

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
43.0813	15.6125	23.1524	147.7900	43.0813	15.6125	23.2502	148.1900
43.0813	15.6125	23.2502	148.5800	43.0813	14.8751	23.1524	148.9800
43.0813	15.6125	23.1524	149.3700	43.0813	15.6125	23.1524	149.7700
43.0813	15.6125	23.2502	150.1600	43.0813	14.8751	23.2502	150.5600
43.0813	14.8751	23.2502	150.9600	43.0813	15.6125	23.1524	151.3500
43.0813	14.8751	23.1524	151.7500	43.0813	15.6125	23.2502	152.1400
43.0813	14.8751	23.2502	152.5400	43.0813	14.8751	23.1524	152.9300
43.0813	15.6125	23.1524	153.3300	43.0813	15.6125	23.1524	153.7200
43.0813	14.8751	23.2502	154.1200	43.0813	14.8751	23.2502	154.5200
43.0813	14.8751	23.2502	154.9100	43.0813	15.6125	23.1524	155.3100
43.0813	15.6125	23.1524	155.7000	43.0813	15.6125	23.1524	156.1000
43.0813	14.8751	23.2502	156.5000	43.0813	14.8751	23.2502	156.8900
43.0813	14.8751	23.1524	157.2900	43.0813	14.8751	23.1524	157.6900
43.0813	14.8751	23.1524	158.0800	43.0813	14.8751	23.1524	158.4800
43.0813	14.8751	23.2502	158.8700	43.0813	14.8751	23.2502	159.2700
43.0813	14.8751	23.1524	159.6700	43.0813	15.6125	23.1524	160.0600
43.0813	14.8751	23.1524	160.4600	43.0813	14.8751	23.1524	160.8600

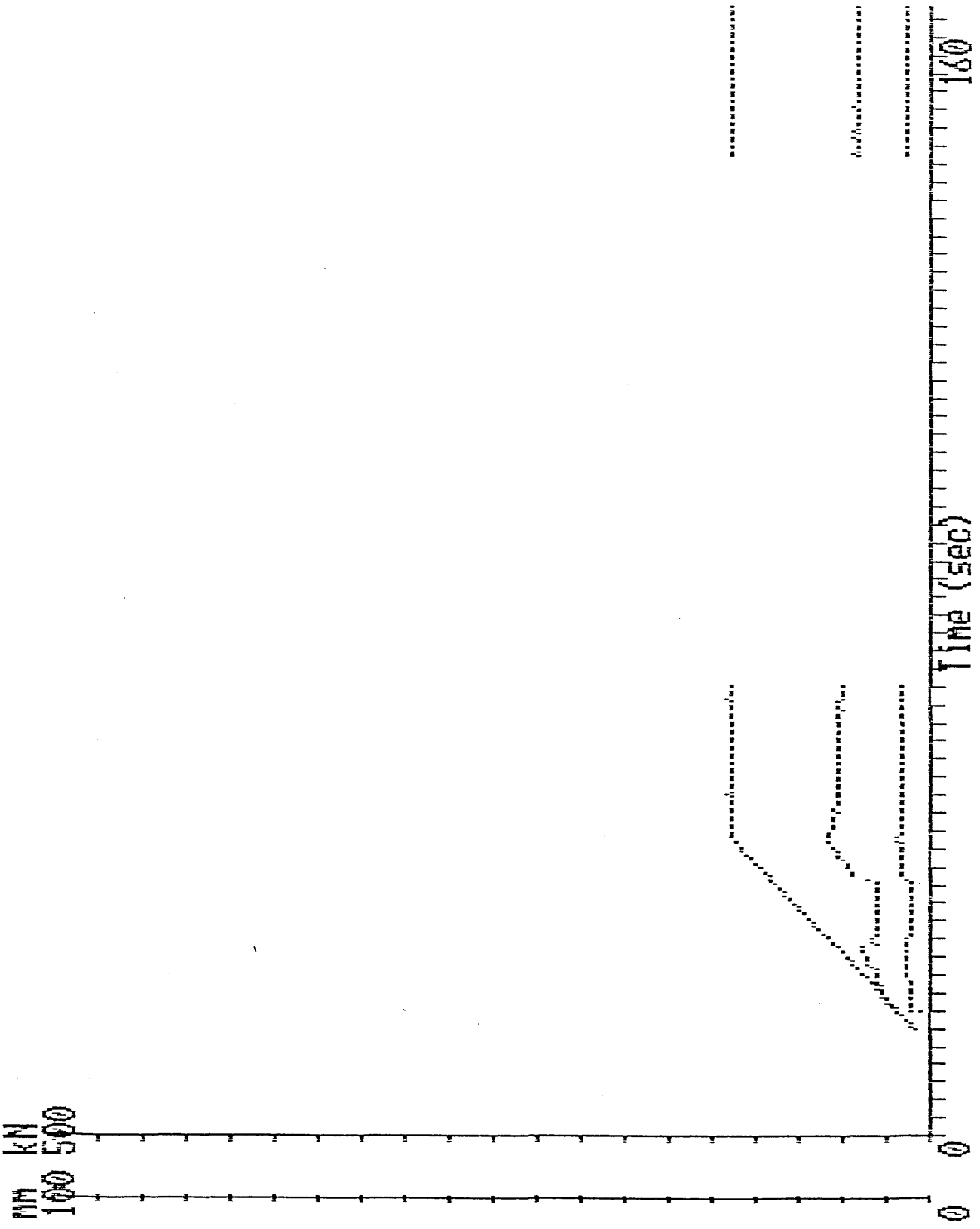


Fig.A5.4. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.5.

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RESULTS - SPECIMEN No.6

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The results of this test are stored in the file B:06-01-06.DAT

The values at maximum load are :-

Load at Top Load Cell = 95.68433 (kN)

Load at Bottom Load Cell = 31.1001 (kN)

Displacement = 44.75923 (mm)

Time Elasped = 95.79 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	5.5540	0.1900	0.0000	0.0000	5.5540	0.5600
0.0000	0.0000	5.5540	0.9400	0.0000	0.0000	5.5540	1.3300
0.0000	0.0000	5.5540	1.7100	0.0000	0.0000	5.5540	2.1000
0.0000	0.0000	5.5540	2.4900	0.0000	0.0000	5.5540	2.8800
0.0000	0.0000	5.5540	3.2600	0.0000	0.0000	5.5540	3.6500
0.0000	0.0000	5.5540	4.0400	0.0000	0.0000	5.5540	4.4300
0.0000	0.0000	5.5540	4.8200	0.0000	0.0000	5.5540	5.2000
0.0000	0.0000	5.6518	5.5900	0.0000	0.0000	5.9451	5.9800
0.0000	0.0000	6.1407	6.3700	0.0000	0.0000	6.5317	6.7600
0.0000	0.0000	6.7273	7.1400	0.0000	0.0000	6.8250	7.5300
0.0000	0.0000	7.4116	7.9200	0.0000	0.0000	7.6072	8.3100
0.0000	0.0000	7.9983	8.7000	0.0000	0.0000	8.3893	9.0800
0.0000	0.0000	8.5849	9.4700	0.0000	0.0000	8.9759	9.8600
0.0000	0.0000	9.2692	10.2500	0.0000	0.0000	9.6603	10.6400
0.0000	0.0000	9.8559	11.0300	0.0000	0.0000	10.2469	11.4200
0.0000	0.0000	10.5402	11.8100	0.0000	0.0000	10.9313	12.2000
0.0000	0.0000	11.1268	12.5900	0.0000	0.0000	11.5179	12.9800
0.0000	0.0000	11.8112	13.3700	0.0000	0.0000	12.1045	13.7600
0.0000	0.0000	12.4956	14.1500	0.0000	0.0000	12.7889	14.5400
0.0000	0.0000	13.0822	14.9300	0.0000	0.0000	13.3755	15.3200
0.0000	0.0000	13.6688	15.7100	0.0000	0.0000	14.0599	16.1000
0.0000	0.0000	14.3532	16.4900	0.0000	0.0000	14.7443	16.8800
0.0000	0.0000	15.0376	17.2700	0.0000	0.0000	15.2331	17.6600
0.0000	0.0000	15.6242	18.0500	0.0000	0.0000	15.9175	18.4400
7.4468	7.5001	16.0153	18.8300	21.0217	12.6626	16.2108	19.2200
24.4155	14.1376	16.6019	19.6100	24.4155	14.1376	16.7974	20.0000
26.1125	14.8751	17.1885	20.3900	26.1125	14.8751	17.3840	20.7800
27.8093	14.8751	17.6773	21.1600	29.5061	15.6125	18.0684	21.5500
31.2031	16.3501	18.3617	21.9400	31.2031	15.6125	18.6550	22.3300
31.2031	16.3501	18.8506	22.7200	31.2031	16.3501	19.2416	23.1000
31.2031	16.3501	19.5349	23.4900	32.8999	16.3501	19.8282	23.8800
32.8999	16.3501	20.2193	24.2700	32.8999	16.3501	20.5126	24.6600
32.8999	17.0875	20.7082	25.0400	32.8999	17.0875	21.0992	25.4300
32.8999	17.0875	21.2948	25.8200	32.8999	17.0875	21.5881	26.2000
34.5969	17.0875	21.9792	26.5900	36.2937	17.8251	22.1747	26.9800
36.2937	17.8251	22.5658	27.3700	37.9905	17.8251	22.8591	27.7600
37.9905	18.5626	23.0546	28.1400	39.6875	19.3000	23.5435	28.5300
41.3843	19.3000	23.7390	28.9200	43.0813	19.3000	24.0323	29.3100

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
43.0813	20.0376	24.3256	29.7000	44.7781	20.0376	24.7167	30.0800
44.7781	20.0376	25.0100	30.4700	44.7781	20.7750	25.3033	30.8600
46.4749	20.7750	25.4988	31.2500	46.4749	20.7750	25.8899	31.6400
48.1719	20.7750	26.0854	32.0200	48.1719	20.7750	26.3787	32.4100
49.8687	21.5126	26.7698	32.8000	51.5657	21.5126	27.0631	33.1900
51.5657	22.2501	27.3564	33.5700	53.2625	22.2501	27.6497	33.9600
53.2625	22.2501	27.8453	34.3500	51.5657	21.5126	28.3341	34.7400
39.6875	17.8251	28.7252	35.1200	46.4749	20.0376	28.8230	35.5100
51.5657	21.5126	29.2140	35.9000	44.7781	19.3000	29.4096	36.2900
51.5657	21.5126	29.8006	36.6800	44.7781	20.0376	30.0939	37.0600
39.6875	17.8251	30.2895	37.4500	48.1719	20.7750	30.6806	37.8400
44.7781	19.3000	30.9739	38.2300	39.6875	17.8251	31.2672	38.6100
48.1719	20.7750	31.6582	39.0000	46.4749	20.0376	31.8538	39.3900
44.7781	19.3000	32.1471	39.7800	41.3843	18.5626	32.5382	40.1600
41.3843	19.3000	32.7337	40.5500	49.8687	21.5126	33.0270	40.9400
49.8687	20.7750	33.4181	41.3200	49.8687	20.7750	33.6136	41.7100
49.8687	21.5126	33.9069	42.1000	49.8687	20.7750	34.2980	42.4800
51.5657	21.5126	34.5913	42.8700	43.0813	19.3000	34.7868	43.2500
44.7781	19.3000	35.1779	43.6400	46.4749	19.3000	35.5690	44.0300
48.1719	20.7750	35.7645	44.4100	49.8687	20.7750	35.9601	44.8000
60.0500	24.4625	36.3511	45.1800	61.7468	24.4625	36.5467	45.5700
60.0500	24.4625	36.5467	45.9600	60.0500	23.7251	36.6444	46.3400
60.0500	23.7251	36.6444	46.7300	58.3530	23.7251	36.5467	47.1200
60.0500	23.7251	36.5467	47.5000	58.3530	23.7251	36.6444	47.8900
58.3530	23.7251	36.6444	48.2700	58.3530	23.7251	36.5467	48.6600
58.3530	23.7251	36.5467	49.0500	58.3530	23.7251	36.6444	49.4300
58.3530	23.7251	36.5467	49.8200	58.3530	23.7251	36.6444	50.2000
58.3530	23.7251	36.6444	50.5900	58.3530	23.7251	36.4489	50.9800
58.3530	23.7251	36.5467	51.3600	58.3530	23.7251	36.5467	51.7500
56.6563	23.7251	36.6444	52.1300	56.6563	23.7251	36.6444	52.5200
56.6563	23.7251	36.5467	52.9100	56.6563	22.9875	36.6444	53.2900
56.6563	22.9875	36.6444	53.6800	56.6563	23.7251	36.5467	54.0600
56.6563	22.9875	36.5467	54.4500	56.6563	22.9875	36.6444	54.8400
56.6563	22.9875	36.5467	55.2200	56.6563	22.9875	36.5467	55.6100
56.6563	22.9875	36.6444	55.9900	56.6563	22.9875	36.6444	56.3800
54.9592	22.9875	36.5467	56.7700	56.6563	22.9875	36.5467	57.1500
54.9592	22.9875	36.6444	57.5400	54.9592	22.9875	36.7422	57.9300
54.9592	22.9875	36.5467	58.3100	54.9592	22.9875	36.6444	58.7000
54.9592	22.9875	36.6444	59.0800	54.9592	22.9875	36.5467	59.4700
54.9592	22.9875	36.6444	59.8600	54.9592	22.9875	36.7422	60.2400
54.9592	22.9875	36.5467	60.6300	54.9592	22.9875	36.5467	61.0100
53.2625	22.9875	36.6444	61.4100	54.9592	22.9875	36.6444	61.8000
54.9592	22.9875	36.5467	62.1900	54.9592	22.2501	36.6444	62.5800
54.9592	22.2501	36.6444	62.9800	54.9592	22.2501	36.5467	63.3700
54.9592	22.2501	36.6444	63.7600	54.9592	22.2501	36.5467	64.1600
53.2625	22.2501	36.6444	64.5500	53.2625	22.2501	36.6444	64.9400
53.2625	22.2501	36.5467	65.3300	53.2625	22.2501	36.6444	65.7300
53.2625	22.2501	36.6444	66.1200	53.2625	22.2501	36.5467	66.5100
53.2625	22.2501	36.6444	66.9100	53.2625	22.2501	36.5467	67.3000
53.2625	22.2501	36.5467	67.6900	53.2625	22.2501	36.6444	68.0800
53.2625	22.2501	36.5467	68.4700	53.2625	22.2501	36.5467	68.8700
53.2625	22.2501	36.5467	69.2600	53.2625	22.2501	36.6444	69.6500
53.2625	22.2501	36.6444	70.0400	53.2625	22.2501	36.5467	70.4400
53.2625	22.2501	36.5467	70.8400	53.2625	22.2501	36.6444	71.2300
53.2625	22.2501	36.6444	71.6300	56.6563	22.9875	36.5467	72.0200
56.6563	22.9875	36.6444	72.4200	58.3530	23.7251	36.7422	72.8100

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
58.3530	23.7251	36.7422	73.2100	60.0500	23.7251	36.7422	73.6000
60.0500	24.4625	36.7422	74.0000	61.7468	24.4625	36.8400	74.3900
61.7468	24.4625	36.9377	74.7900	63.4436	24.4625	36.9377	75.1900
63.4436	25.2001	36.9377	75.5800	63.4436	25.2001	37.1333	75.9800
65.1406	25.2001	37.2310	76.3700	65.1406	25.2001	37.3288	76.7700
65.1406	25.2001	37.1333	77.1600	65.1406	25.2001	37.4266	77.5600
65.1406	25.2001	37.6221	77.9600	65.1406	25.2001	37.6221	78.3500
66.8374	25.2001	37.6221	78.7500	66.8374	25.9376	37.8177	79.1400
66.8374	25.9376	37.9154	79.5400	66.8374	25.9376	38.1110	79.9400
66.8374	25.9376	38.1110	80.3300	66.8374	25.9376	38.2087	80.7300
68.5344	25.9376	38.4043	81.1200	68.5344	25.9376	38.5998	81.5200
68.5344	25.9376	38.6976	81.9200	68.5344	25.9376	38.7953	82.3100
68.5344	26.6750	38.8931	82.7100	70.2312	26.6750	39.0887	83.1100
70.2312	26.6750	39.2842	83.5000	70.2312	26.6750	39.4797	83.9000
71.9280	26.6750	39.5775	84.3000	71.9280	27.4126	39.6753	84.6900
71.9280	27.4126	39.9686	85.0900	71.9280	27.4126	40.2619	85.4800
73.6250	27.4126	40.3597	85.8800	73.6250	27.4126	40.4574	86.2800
73.6250	27.4126	40.5552	86.6700	75.3218	28.1500	40.8485	87.0700
75.3218	28.1500	41.1418	87.4700	77.0188	28.1500	41.3373	87.8600
77.0188	28.1500	41.4351	88.2600	77.0188	28.1500	41.5329	88.6600
78.7156	28.8876	41.8262	89.0500	78.7156	28.8876	42.0217	89.4500
80.4124	28.8876	42.2173	89.8500	80.4124	28.8876	42.3150	90.2400
80.4124	28.8876	42.4128	90.6400	82.1094	29.6251	42.7061	91.0300
82.1094	29.6251	42.9016	91.4300	83.8062	29.6251	43.0972	91.8300
85.5032	29.6251	43.1949	92.2200	85.5032	29.6251	43.2927	92.6200
85.5032	30.3625	43.4882	93.0200	87.2000	30.3625	43.7815	93.4100
88.8967	31.1001	43.9771	93.8100	90.5938	31.1001	44.0748	94.2000
90.5938	31.1001	44.2704	94.6000	92.2905	31.1001	44.4659	94.9900
92.2905	31.1001	44.6615	95.3900	95.6843	31.1001	44.7592	95.7900
92.2905	31.1001	44.7592	96.1800	90.5938	31.1001	44.8570	96.5800
90.5938	31.1001	44.9548	96.9700	90.5938	31.1001	44.8570	97.3700
88.8967	31.1001	44.7592	97.7700	88.8967	31.1001	44.8570	98.1600
88.8967	30.3625	44.9548	98.5600	87.2000	30.3625	44.9548	98.9500
87.2000	30.3625	44.9548	99.3500	87.2000	30.3625	44.8570	99.7500
87.2000	30.3625	44.9548	100.1400	85.5032	30.3625	44.9548	100.5400
87.2000	30.3625	44.9548	100.9300	85.5032	30.3625	44.8570	101.3300
85.5032	30.3625	44.8570	101.7300	85.5032	30.3625	44.9548	102.1200
85.5032	29.6251	44.9548	102.5200	85.5032	30.3625	44.8570	102.9100
83.8062	29.6251	44.8570	103.3100	83.8062	29.6251	44.9548	103.7100
83.8062	29.6251	44.9548	104.1000	83.8062	29.6251	44.8570	104.5000
83.8062	29.6251	44.8570	104.8900	83.8062	29.6251	44.9548	105.2900
83.8062	29.6251	44.9548	105.6800	83.8062	29.6251	44.8570	106.0800
82.1094	29.6251	44.8570	106.4800	82.1094	29.6251	44.8570	106.8700
82.1094	29.6251	45.0525	107.2700	82.1094	28.8876	44.9548	107.6600
82.1094	29.6251	44.8570	108.0600	82.1094	28.8876	44.9548	108.4600
80.4124	28.8876	44.9548	108.8500	80.4124	28.8876	44.9548	109.2500
80.4124	28.8876	44.8570	109.6400	80.4124	28.8876	44.9548	110.0400
80.4124	28.8876	44.9548	110.4300	80.4124	28.8876	44.9548	110.8300
80.4124	28.8876	44.8570	111.2300	78.7156	28.8876	44.8570	111.6200
78.7156	28.8876	44.9548	112.0200	78.7156	28.8876	44.9548	112.4100
78.7156	28.8876	44.8570	112.8100	78.7156	28.8876	44.8570	113.2000
78.7156	28.8876	44.9548	113.6000	78.7156	28.1500	44.9548	114.0000
78.7156	28.1500	45.0525	114.3900	78.7156	28.8876	44.8570	114.7900
78.7156	28.8876	44.9548	115.1800	77.0188	28.1500	45.0525	115.5800
77.0188	28.1500	44.9548	115.9700	77.0188	28.1500	44.9548	116.3700
77.0188	28.1500	44.8570	116.7700	77.0188	28.1500	44.9548	117.1600

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
77.0188	28.1500	45.0525	117.5600	77.0188	28.1500	44.9548	117.9600
77.0188	28.1500	44.8570	118.3500	77.0188	28.1500	44.8570	118.7500
77.0188	28.1500	45.0525	119.1400	77.0188	28.1500	45.0525	119.5400
77.0188	28.1500	44.9548	119.9400	75.3218	28.1500	44.9548	120.3200
75.3218	28.1500	44.8570	120.7100	75.3218	28.1500	44.9548	121.1000
75.3218	28.1500	44.8570	121.4900	75.3218	28.1500	44.9548	121.8900
75.3218	28.1500	44.9548	122.2800	75.3218	28.1500	44.9548	122.6800
75.3218	28.1500	44.9548	123.0700	75.3218	28.1500	45.0525	123.4600
75.3218	28.1500	44.8570	123.8600	75.3218	28.1500	44.9548	124.2500
75.3218	27.4126	44.9548	124.6500	75.3218	27.4126	44.8570	125.0400
75.3218	27.4126	44.9548	125.4300	75.3218	27.4126	44.9548	125.8300
73.6250	27.4126	44.8570	126.2200	73.6250	27.4126	44.9548	126.6100
75.3218	27.4126	44.9548	127.0100	73.6250	27.4126	44.9548	127.4000
73.6250	27.4126	45.0525	127.7900	73.6250	27.4126	44.9548	128.1900
73.6250	27.4126	44.9548	128.5800	73.6250	27.4126	45.0525	128.9700
73.6250	27.4126	44.8570	129.3700	73.6250	27.4126	44.9548	129.7600
73.6250	27.4126	45.0525	130.1500	73.6250	27.4126	44.9548	130.5500
73.6250	27.4126	44.9548	130.9500	73.6250	27.4126	44.9548	131.3400
73.6250	27.4126	44.9548	131.7400	73.6250	27.4126	44.9548	132.1400
73.6250	27.4126	44.9548	132.5300	73.6250	27.4126	44.8570	132.9300
73.6250	27.4126	44.8570	133.3300	73.6250	27.4126	44.9548	133.7200
73.6250	27.4126	45.0525	134.3200	73.6250	27.4126	44.9548	134.7100
71.9280	27.4126	44.8570	135.1100	71.9280	27.4126	44.9548	135.5100
73.6250	27.4126	45.0525	135.9000	73.6250	27.4126	44.9548	136.3000
71.9280	27.4126	44.9548	136.7000	71.9280	27.4126	44.8570	137.0900
71.9280	27.4126	44.9548	137.4900	71.9280	27.4126	45.0525	137.8900
71.9280	27.4126	44.9548	138.2800	71.9280	27.4126	44.9548	138.6800
71.9280	27.4126	44.9548	139.0800	71.9280	27.4126	44.9548	139.4700
71.9280	26.6750	45.0525	139.8700	71.9280	26.6750	45.0525	140.2600
71.9280	27.4126	44.9548	140.6600	71.9280	27.4126	44.8570	141.0600
71.9280	27.4126	44.9548	141.4500	71.9280	26.6750	45.0525	141.8500
71.9280	26.6750	44.9548	142.2400	71.9280	27.4126	44.9548	142.6400
71.9280	27.4126	44.9548	143.0400	71.9280	26.6750	45.0525	143.4300
71.9280	26.6750	45.0525	143.8300	71.9280	26.6750	44.9548	144.2300
71.9280	26.6750	44.9548	144.6200	66.8374	25.9376	45.0525	219.8800

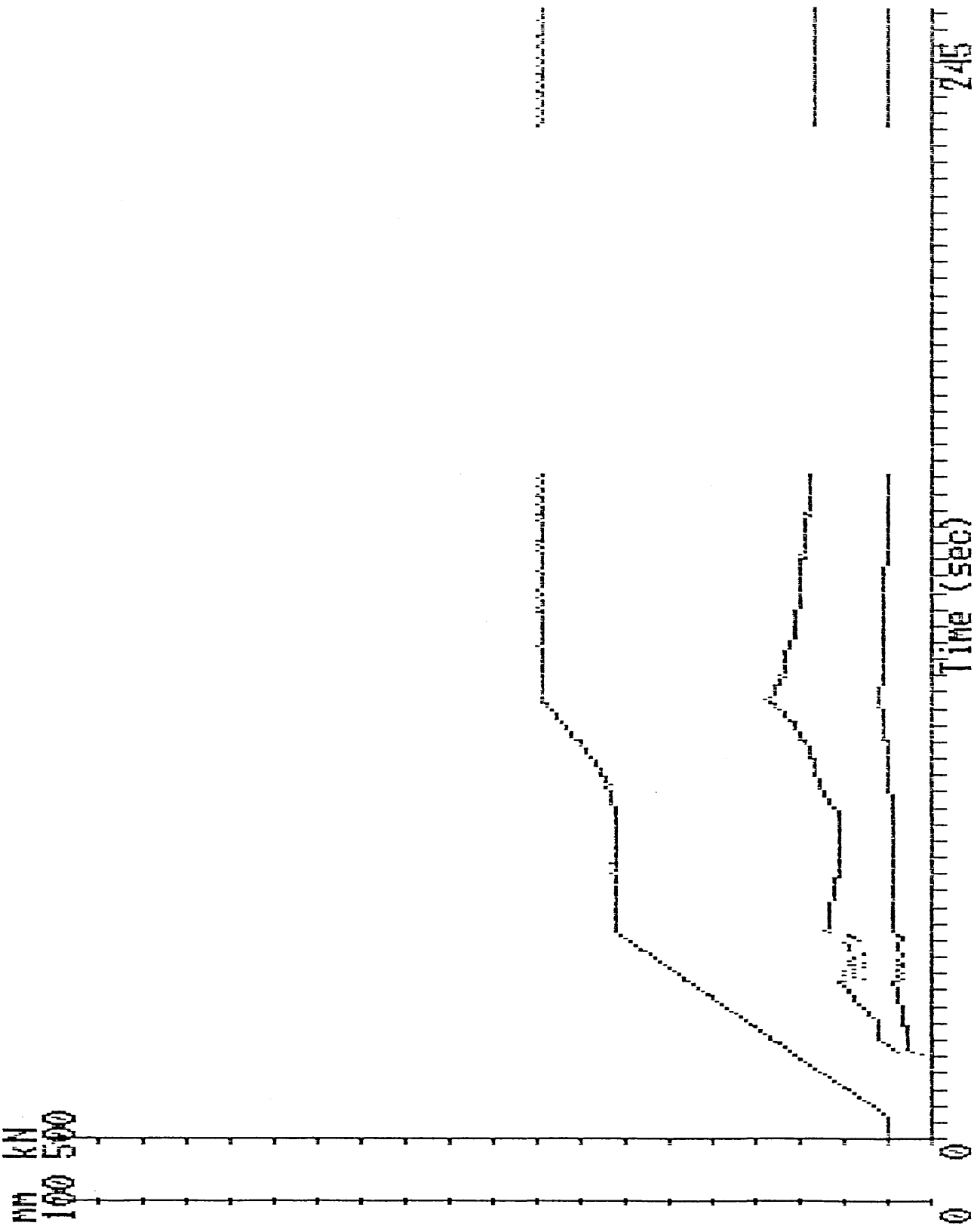


Fig.A5.5. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.6.

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RESULTS - SPECIMEN No.7

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The results of this test are stored in the file B:08-01-07.DAT

The values at maximum load are :-

Load at Top Load Cell = 60.05005 (kN)

Load at Bottom Load Cell = 22.25012 (kN)

Displacement = 27.45419 (mm)

Time Elasped = 44.64 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.3300	0.0000	0.0000	0.0000	7.7200
0.0000	0.0000	0.0000	8.1100	0.0000	0.0000	0.0000	8.5000
0.0000	0.0000	0.0000	8.8900	0.0000	0.0000	0.0000	9.2700
0.0000	0.0000	0.0000	9.6600	0.0000	0.0000	0.0000	10.0500
0.0000	0.0000	0.0000	10.4400	0.0000	0.0000	0.0000	10.8300
0.0000	0.0000	0.0000	11.2200	0.0000	0.0000	1.7411	11.6100
0.0000	0.0000	1.9366	12.0100	0.0000	0.0000	2.3277	12.4000
0.0000	0.0000	2.5232	12.7900	0.0000	0.0000	2.9143	13.1800
0.0000	0.0000	3.2076	13.5700	0.0000	0.0000	3.5009	13.9600
0.0000	0.0000	3.8920	14.3500	0.0000	0.0000	4.1853	14.7400
0.0000	0.0000	4.4786	15.1300	0.0000	0.0000	4.6741	15.5200
0.0000	0.0000	5.0652	15.9100	0.0000	0.0000	5.2607	16.3000
0.0000	0.0000	5.7496	16.6900	0.0000	0.0000	6.0429	17.0800
0.0000	0.0000	6.3362	17.4700	0.0000	0.0000	6.6295	17.8600
0.0000	0.0000	7.0206	18.2500	0.0000	0.0000	7.3139	18.6400
0.0000	0.0000	7.6072	19.0300	0.0000	0.0000	7.9983	19.4300
0.0000	0.0000	8.2916	19.8200	0.0000	0.0000	8.5849	20.2100
0.0000	0.0000	8.8782	20.5900	0.0000	0.0000	9.2692	20.9800
0.0000	0.0000	9.4648	21.3700	0.0000	0.0000	9.8559	21.7600
0.0000	0.0000	10.1492	22.1500	0.0000	0.0000	10.4425	22.5400
0.0000	0.0000	10.8335	22.9300	0.0000	0.0000	11.0291	23.3100
0.0000	0.0000	11.4202	23.7000	0.0000	0.0000	11.7135	24.0900
0.0000	0.0000	12.0068	24.4800	0.0000	0.0000	12.3978	24.8700
0.0000	0.0000	12.5934	25.2600	0.0000	0.0000	12.9845	25.6500
0.0000	0.0000	13.2778	26.0300	0.0000	0.0000	13.5711	26.4200
0.0000	0.0000	13.8644	26.8100	0.0000	0.0000	14.1577	27.2000
0.0000	0.0000	14.5488	27.5900	0.0000	0.0000	14.8421	27.9800
0.0000	0.0000	15.2331	28.3700	0.0000	0.0000	15.4287	28.7600
0.0000	0.0000	15.7220	29.1400	0.0000	0.0000	16.2108	29.5300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
1.0376	1.6001	16.3086	29.9200	17.6282	9.7125	16.5041	30.3100
26.1125	11.9250	16.6997	30.7000	26.1125	11.9250	16.8952	31.0800
26.1125	11.9250	17.3840	31.4700	27.8093	12.6626	17.5796	31.8600
27.8093	12.6626	17.8729	32.2500	29.5061	12.6626	18.2639	32.6400
29.5061	12.6626	18.4595	33.0200	29.5061	13.4000	18.8506	33.4100
31.2031	13.4000	19.1439	33.8000	31.2031	14.1376	19.3394	34.1800
32.8999	14.1376	19.7305	34.5700	32.8999	14.1376	20.0238	34.9600
32.8999	14.1376	20.3171	35.3500	32.8999	14.1376	20.7082	35.7400
34.5969	14.8751	20.9037	36.1200	36.2937	14.8751	21.1970	36.5100
36.2937	15.6125	21.5881	36.9000	37.9905	16.3501	21.7836	37.2900
39.6875	16.3501	22.1747	37.6800	39.6875	16.3501	22.4680	38.0600
41.3843	17.0875	22.6635	38.4500	43.0813	17.0875	23.0546	38.8400
44.7781	17.8251	23.2502	39.2300	46.4749	18.5626	23.6412	39.6100
48.1719	18.5626	23.9345	40.0000	49.8687	19.3000	24.1301	40.3900
51.5657	19.3000	24.5211	40.7700	51.5657	20.0376	24.8144	41.1600
53.2625	20.0376	25.0100	41.5500	53.2625	20.0376	25.4011	41.9300
53.2625	20.0376	25.6944	42.3200	54.9592	20.7750	25.8899	42.7100
56.6563	20.7750	26.1832	43.0900	56.6563	20.7750	26.5743	43.4800
58.3530	21.5126	26.7698	43.8600	58.3530	21.5126	27.0631	44.2500
60.0500	22.2501	27.4542	44.6400	60.0500	22.2501	27.6497	45.0200
51.5657	19.3000	27.9430	45.4100	48.1719	19.3000	28.4319	45.8000
53.2625	20.0376	28.7252	46.1800	48.1719	18.5626	28.9207	46.5700
51.5657	20.0376	29.2140	46.9500	51.5657	19.3000	29.6051	47.3400
48.1719	18.5626	29.8006	47.7300	43.0813	17.0875	30.0939	48.1100
53.2625	19.3000	30.4850	48.5000	44.7781	17.8251	30.5828	48.8900
44.7781	17.0875	30.6806	49.2700	46.4749	17.8251	30.6806	49.6600
44.7781	17.8251	30.7783	50.0400	44.7781	17.8251	30.6806	50.4300
44.7781	17.8251	30.7783	50.8200	44.7781	17.8251	30.6806	51.2000
44.7781	17.8251	30.6806	51.5900	44.7781	17.0875	30.6806	51.9700
44.7781	17.0875	30.7783	52.3600	46.4749	17.8251	30.6806	52.7500
44.7781	17.0875	30.6806	53.1300	44.7781	17.0875	30.7783	53.5200
46.4749	17.8251	30.5828	53.9100	46.4749	17.0875	30.6806	54.2900
44.7781	17.0875	30.7783	54.6800	44.7781	17.8251	30.7783	55.0700
44.7781	17.8251	30.6806	55.4500	44.7781	17.0875	30.6806	55.8400
44.7781	17.8251	30.7783	56.2200	44.7781	17.8251	30.6806	56.6100
44.7781	17.0875	30.6806	57.0000	44.7781	17.0875	30.7783	57.3800
44.7781	17.8251	30.6806	57.7700	44.7781	17.0875	30.6806	58.1600
44.7781	17.0875	30.7783	58.5400	44.7781	17.8251	30.6806	58.9300
44.7781	17.0875	30.6806	59.3200	44.7781	17.0875	30.7783	59.7000
44.7781	17.8251	30.6806	60.0900	44.7781	17.8251	30.6806	60.4700
44.7781	17.0875	30.7783	60.8600	44.7781	17.0875	30.6806	61.2500
44.7781	17.0875	30.7783	61.6500	44.7781	17.0875	30.7783	62.0400
44.7781	17.0875	30.6806	62.4300	44.7781	17.0875	30.6806	62.8300
44.7781	17.0875	30.6806	63.2200	44.7781	17.0875	30.6806	63.6100
44.7781	17.0875	30.6806	64.0100	44.7781	17.0875	30.6806	64.4000
44.7781	17.0875	30.6806	64.7900	44.7781	17.0875	30.7783	65.1800
44.7781	17.0875	30.6806	65.5800	44.7781	17.0875	30.7783	65.9700
44.7781	17.0875	30.6806	66.3600	44.7781	17.0875	30.6806	66.7600
44.7781	17.0875	30.7783	67.1500	44.7781	17.0875	30.6806	67.5400
44.7781	17.0875	30.6806	67.9300	44.7781	17.0875	30.7783	68.3300
44.7781	17.0875	30.6806	68.7200	44.7781	17.0875	30.6806	69.1100
44.7781	17.0875	30.6806	69.5000	44.7781	17.0875	30.6806	69.9000
44.7781	17.0875	30.6806	70.2900	43.0813	17.0875	30.7783	70.6900
44.7781	17.0875	30.6806	71.0800	44.7781	17.0875	30.6806	71.4800
44.7781	17.0875	30.7783	71.8800	44.7781	17.0875	30.7783	72.2700
44.7781	17.0875	30.7783	72.6700	43.0813	17.0875	30.6806	73.0600

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
44.7781	17.0875	30.6806	73.4600	44.7781	17.0875	30.6806	73.8600
44.7781	17.0875	30.7783	74.2500	43.0813	17.0875	30.6806	74.6500
43.0813	17.0875	30.6806	75.0400	43.0813	17.0875	30.6806	75.4400
43.0813	17.0875	30.7783	75.8300	43.0813	17.0875	30.6806	76.2300
43.0813	17.0875	30.6806	76.6300	43.0813	17.0875	30.6806	77.0200
43.0813	17.0875	30.6806	77.4200	43.0813	17.0875	30.7783	77.8100
43.0813	17.0875	30.6806	78.2100	43.0813	17.0875	30.6806	78.6000
43.0813	17.0875	30.8761	79.0000	43.0813	17.0875	30.7783	79.3900
43.0813	17.0875	30.6806	79.7900	43.0813	17.0875	30.6806	80.1900
43.0813	17.0875	30.6806	80.5800	43.0813	17.0875	30.6806	80.9800
43.0813	17.0875	30.7783	81.3800	43.0813	16.3501	30.7783	81.7800
43.0813	16.3501	30.6806	82.1700	39.6875	15.6125	30.7783	157.0800
39.6875	15.6125	30.6806	157.4800	39.6875	15.6125	30.6806	157.8800
39.6875	15.6125	30.6806	158.2700	39.6875	15.6125	30.6806	158.6700
39.6875	15.6125	30.7783	159.0600	37.9905	15.6125	30.7783	159.4600
39.6875	15.6125	30.6806	159.8600	37.9905	15.6125	30.6806	160.2500
39.6875	15.6125	30.6806	160.6500	37.9905	15.6125	30.7783	161.0500
39.6875	15.6125	30.7783	161.4400	37.9905	15.6125	30.6806	161.8400
39.6875	15.6125	30.5828	162.2300	37.9905	15.6125	30.6806	162.6300
37.9905	15.6125	30.7783	163.0300	39.6875	15.6125	30.7783	163.4200
37.9905	15.6125	30.6806	163.8200	37.9905	15.6125	30.7783	164.2200
39.6875	15.6125	30.6806	164.6100	37.9905	15.6125	30.6806	165.0100
39.6875	15.6125	30.6806	165.4000	39.6875	15.6125	30.6806	165.8000
39.6875	15.6125	30.6806	166.2000	39.6875	15.6125	30.6806	166.5900
37.9905	15.6125	30.6806	166.9900	37.9905	15.6125	30.7783	167.3900
39.6875	15.6125	30.7783	167.7800	39.6875	15.6125	30.6806	168.1800
37.9905	15.6125	30.6806	168.5700	37.9905	15.6125	30.7783	168.9700
37.9905	15.6125	30.7783	169.3700	37.9905	15.6125	30.7783	169.7600
37.9905	15.6125	30.6806	170.1600	39.6875	15.6125	30.6806	170.5600
37.9905	15.6125	30.7783	170.9500	37.9905	15.6125	30.7783	171.3500
37.9905	15.6125	30.7783	171.7500	37.9905	15.6125	30.6806	172.1400
37.9905	15.6125	30.7783	172.5400	39.6875	15.6125	30.6806	172.9300
37.9905	15.6125	30.6806	173.3300	39.6875	15.6125	30.6806	173.7300
37.9905	15.6125	30.6806	174.1200	37.9905	15.6125	30.6806	174.5200
37.9905	15.6125	30.6806	174.9200	37.9905	15.6125	30.7783	175.3100
37.9905	15.6125	30.7783	175.7100	39.6875	15.6125	30.6806	176.1000
39.6875	15.6125	30.6806	176.5000	37.9905	15.6125	30.6806	176.9000
37.9905	15.6125	30.6806	177.2900	37.9905	14.8751	30.7783	177.6900

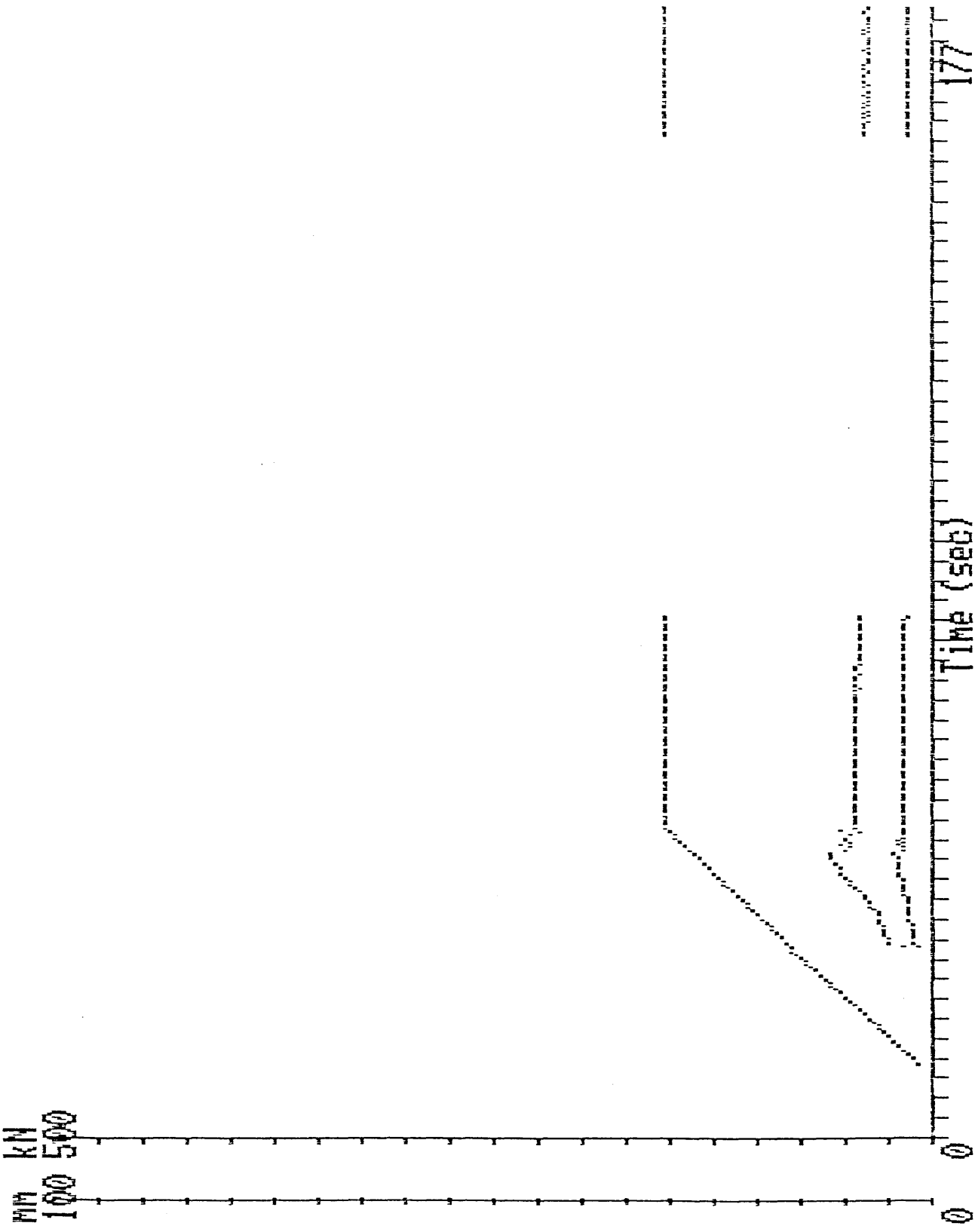


Fig.A5.6. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.7.

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RESULTS - SPECIMEN No.8

****

The results of this test are stored in the file B:08-01-08.DAT

The values at maximum load are :-

Load at Top Load Cell = 136.4094 (kN)

Load at Bottom Load Cell = 50.27502 (kN)

Displacement = 46.61684 (mm)

Time Elasped = 68.5 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5400
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4800	0.0000	0.0000	0.0000	9.8700
0.0000	0.0000	1.7411	10.2600	0.0000	0.0000	2.0344	10.6500
0.0000	0.0000	2.4254	11.0400	0.0000	0.0000	2.6210	11.4300
0.0000	0.0000	3.0121	11.8200	0.0000	0.0000	3.3054	12.2100
0.0000	0.0000	3.6964	12.6000	0.0000	0.0000	3.9897	12.9900
0.0000	0.0000	4.2831	13.3800	0.0000	0.0000	4.5764	13.7700
0.0000	0.0000	4.9674	14.1600	0.0000	0.0000	5.1630	14.5500
0.0000	0.0000	5.5540	14.9400	0.0000	0.0000	5.8474	15.3300
0.0000	0.0000	6.1407	15.7200	0.0000	0.0000	6.4340	16.1100
0.0000	0.0000	6.8250	16.5000	0.0000	0.0000	7.1183	16.8900
0.0000	0.0000	7.4116	17.2900	0.0000	0.0000	7.8027	17.6800
0.0000	0.0000	8.0960	18.0700	0.0000	0.0000	8.3893	18.4600
0.0000	0.0000	8.6826	18.8500	0.0000	0.0000	8.9759	19.2400
0.0000	0.0000	9.3670	19.6300	0.0000	0.0000	9.6603	20.0200
0.0000	0.0000	9.9536	20.4100	0.0000	0.0000	10.2469	20.7900
0.0000	0.0000	10.6380	21.1800	0.0000	0.0000	10.8335	21.5700
0.0000	0.0000	11.2246	21.9600	0.0000	0.0000	11.5179	22.3500
0.0000	0.0000	11.9090	22.7400	0.0000	0.0000	12.1045	23.1200
0.0000	0.0000	12.3978	23.5100	0.0000	0.0000	12.7889	23.9000
0.0000	0.0000	13.0822	24.2900	0.0000	0.0000	13.4733	24.6800
0.0000	0.0000	13.7666	25.0700	0.0000	0.0000	14.0599	25.4600
0.0000	0.0000	14.3532	25.8400	0.0000	0.0000	14.5488	26.2300
0.0000	0.0000	15.1354	26.6200	0.0000	0.0000	15.2331	27.0100
0.0000	0.0000	15.6242	27.4000	0.0000	0.0000	15.9175	27.7900
0.0000	0.0000	16.2108	28.1800	0.0000	0.0000	16.6019	28.5600
4.4314	0.8625	16.7974	28.9500	10.8406	10.4501	16.9930	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
12.5374	11.1876	17.2863	29.7300	10.8406	10.4501	17.4818	30.1200
10.8406	10.4501	17.9706	30.5000	10.8406	9.7125	18.1662	30.8900
10.8406	9.7125	18.4595	31.2800	10.8406	9.7125	18.8506	31.6600
9.1438	9.7125	19.0461	32.0500	9.1438	8.9751	19.4372	32.4400
9.1438	8.9751	19.8282	32.8200	9.1438	8.9751	20.0238	33.2100
9.1438	8.9751	20.3171	33.6000	9.1438	8.2375	20.7082	33.9800
9.1438	8.2375	21.0015	34.3700	7.4468	8.2375	21.1970	34.7600
7.4468	7.5001	21.5881	35.1400	7.4468	7.5001	21.8814	35.5300
7.4468	7.5001	22.1747	35.9200	7.4468	7.5001	22.5658	36.3000
7.4468	7.5001	22.8591	36.6900	7.4468	6.7626	23.0546	37.0800
5.7500	6.7626	23.4457	37.4600	5.7500	6.0250	23.8368	37.8500
7.4468	7.5001	23.9345	38.2400	19.3250	17.8251	24.3256	38.6200
22.7188	20.7750	24.6189	39.0100	24.4155	21.5126	24.8144	39.4000
24.4155	22.2501	25.2055	39.7900	26.1125	23.7251	25.4988	40.1700
27.8093	25.2001	25.6944	40.5600	27.8093	25.2001	25.9877	40.9500
27.8093	25.9376	26.3787	41.3400	29.5061	25.9376	26.5743	41.7200
29.5061	25.9376	26.9653	42.1100	29.5061	25.9376	27.3564	42.4900
29.5061	26.6750	27.5520	42.8800	29.5061	26.6750	27.8453	43.2700
29.5061	26.6750	28.1386	43.6600	31.2031	27.4126	28.5296	44.0400
31.2031	28.1500	28.7252	44.4300	31.2031	28.8876	29.1163	44.8100
32.8999	30.3625	29.4096	45.2000	32.8999	31.1001	29.6051	45.5900
34.5969	31.1001	29.9962	45.9700	36.2937	32.5751	30.2895	46.3600
36.2937	33.3126	30.4850	46.7500	37.9905	33.3126	30.7783	47.1300
37.9905	34.0500	31.1694	47.5200	39.6875	34.7876	31.3649	47.9100
39.6875	35.5250	31.7560	48.2900	39.6875	35.5250	32.0493	48.6800
41.3843	36.2626	32.3426	49.0700	43.0813	37.0001	32.5382	49.4500
43.0813	37.0001	33.0270	49.8400	44.7781	37.0001	33.2225	50.2200
44.7781	37.7375	33.4181	50.6100	46.4749	37.7375	33.8092	51.0000
49.8687	37.7375	34.1025	51.3800	49.8687	37.7375	34.3958	51.7700
51.5657	37.7375	34.6891	52.1600	53.2625	37.7375	35.0801	52.5400
54.9592	37.7375	35.2757	52.9300	56.6563	38.4751	35.5690	53.3200
56.6563	37.7375	35.9601	53.7000	58.3530	37.7375	36.2534	54.0900
60.0500	37.7375	36.4489	54.4700	61.7468	37.7375	36.7422	54.8600
63.4436	37.7375	37.1333	55.2500	65.1406	37.7375	37.3288	55.6300
65.1406	37.7375	37.6221	56.0200	66.8374	37.7375	38.0132	56.4000
68.5344	37.7375	38.2087	56.7900	68.5344	37.7375	38.5020	57.1800
70.2312	37.7375	38.8931	57.5600	70.2312	37.7375	39.1864	57.9500
71.9280	37.7375	39.2842	58.3400	73.6250	37.7375	39.6753	58.7200
73.6250	37.7375	40.0663	59.1100	75.3218	37.7375	40.2619	59.4900
75.3218	37.7375	40.4574	59.8800	77.0188	37.7375	40.8485	60.2600
78.7156	37.0001	41.2396	60.6500	78.7156	37.7375	41.3373	61.0400
80.4124	37.7375	41.8262	61.4300	82.1094	38.4751	42.0217	61.8200
83.8062	38.4751	42.3150	62.2200	85.5032	38.4751	42.6083	62.6100
87.2000	39.2125	42.8039	63.0000	88.8967	39.9501	43.1949	63.3900
92.2905	39.9501	43.4882	63.7900	93.9875	40.6876	43.6838	64.1800
95.6843	40.6876	44.0748	64.5700	99.0781	41.4250	44.2704	64.9700
102.4719	42.1626	44.6615	65.3600	105.8655	42.9000	44.9548	65.7500
109.2593	44.3751	45.1503	66.1400	112.6531	45.1125	45.5414	66.5400
117.7437	45.8501	45.7369	66.9300	122.8342	47.3251	45.9324	67.3200
127.9250	48.8000	46.3235	67.7100	134.7124	49.5376	46.4213	68.1000
136.4094	50.2750	46.6168	68.5000	133.0156	49.5376	46.7146	68.8900
131.3186	49.5376	46.8124	69.2800	129.6218	48.8000	46.8124	69.6700
127.9250	48.8000	46.7146	70.0600	127.9250	48.8000	46.7146	70.4600
126.2280	48.8000	46.8124	70.8600	126.2280	48.8000	46.8124	71.2500
126.2280	48.8000	46.7146	71.6500	124.5313	48.8000	46.8124	72.0400
124.5313	48.0626	46.8124	72.4400	124.5313	48.0626	46.8124	72.8300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
122.8342	48.0626	46.7146	73.2300	122.8342	48.0626	46.7146	73.6200
122.8342	48.0626	46.8124	74.0200	122.8342	48.0626	46.8124	74.4100
122.8342	48.0626	46.7146	74.8100	122.8342	48.0626	46.7146	75.2000
121.1375	48.0626	46.8124	75.6000	121.1375	47.3251	46.8124	75.9900
121.1375	47.3251	46.8124	76.3900	121.1375	48.0626	46.7146	76.7800
119.4407	47.3251	46.8124	77.1800	119.4407	47.3251	46.9101	77.5700
119.4407	47.3251	46.8124	77.9700	119.4407	47.3251	46.7146	78.3600
119.4407	47.3251	46.8124	78.7600	119.4407	47.3251	46.9101	79.1500
119.4407	47.3251	46.8124	79.5500	119.4407	47.3251	46.7146	79.9500
119.4407	47.3251	46.8124	80.3400	119.4407	47.3251	46.8124	80.7400
119.4407	47.3251	46.8124	81.1300	119.4407	47.3251	46.8124	81.5300
117.7437	47.3251	46.7146	81.9200	117.7437	47.3251	46.8124	82.3200
117.7437	46.5875	46.9101	82.7200	117.7437	46.5875	46.8124	83.1100
116.0469	46.5875	46.8124	83.5100	117.7437	46.5875	46.7146	83.9100
117.7437	46.5875	46.8124	84.3000	117.7437	46.5875	46.8124	84.7000
116.0469	46.5875	46.9101	85.0900	116.0469	46.5875	46.8124	85.4900
116.0469	46.5875	46.7146	85.8900	116.0469	46.5875	46.8124	86.2800
116.0469	46.5875	46.8124	86.6800	116.0469	46.5875	46.9101	87.0700
116.0469	46.5875	46.8124	87.4700	116.0469	46.5875	46.7146	87.8600
116.0469	46.5875	46.8124	88.2600	116.0469	46.5875	46.9101	88.6600
116.0469	46.5875	46.9101	89.0500	116.0469	46.5875	46.8124	89.4500
114.3499	46.5875	46.7146	89.8400	114.3499	46.5875	46.8124	90.2400
114.3499	45.8501	46.9101	90.6400	116.0469	46.5875	46.9101	91.0300
114.3499	46.5875	46.8124	91.4300	114.3499	46.5875	46.7146	91.8200
114.3499	46.5875	46.8124	92.2200	114.3499	45.8501	46.9101	92.6100
114.3499	45.8501	46.8124	93.0100	114.3499	46.5875	46.8124	93.4100
114.3499	46.5875	46.8124	93.8000	114.3499	45.8501	46.9101	94.1900
114.3499	45.8501	46.9101	94.5900	114.3499	45.8501	46.8124	94.9900
114.3499	46.5875	46.7146	95.3800	114.3499	46.5875	46.7146	95.7800
114.3499	45.8501	46.9101	96.1700	114.3499	45.8501	46.8124	96.5700
112.6531	45.8501	46.7146	96.9600	114.3499	45.8501	46.8124	97.3600
114.3499	45.8501	46.9101	97.7600	114.3499	45.8501	46.8124	98.1500
112.6531	45.8501	46.8124	98.5500	112.6531	45.8501	46.8124	98.9400
114.3499	45.8501	46.8124	99.3400	112.6531	45.8501	46.9101	99.7300
112.6531	45.8501	46.7146	100.1300	114.3499	45.8501	46.7146	100.5200
112.6531	45.8501	46.8124	100.9200	112.6531	45.8501	46.9101	101.3100
112.6531	45.8501	46.8124	101.7100	112.6531	45.8501	46.7146	102.1000
112.6531	45.8501	46.8124	102.5000	112.6531	45.8501	46.9101	102.9000
112.6531	45.8501	46.9101	103.2900	112.6531	45.8501	46.7146	103.6900
112.6531	45.8501	46.8124	104.0800	112.6531	45.8501	46.9101	104.4800
112.6531	45.8501	46.9101	104.8700	112.6531	45.8501	46.5191	105.2700
112.6531	45.8501	46.7146	105.6600	112.6531	45.8501	46.8124	106.0600
112.6531	45.8501	46.9101	106.4500	112.6531	45.8501	46.8124	106.8500
112.6531	45.8501	46.7146	107.2400	112.6531	45.8501	46.9101	107.6400
112.6531	45.8501	46.9101	108.0400	112.6531	45.8501	46.8124	108.4300
112.6531	45.8501	46.7146	108.8300	112.6531	45.8501	46.7146	109.2200
110.9563	45.8501	46.9101	109.6200	112.6531	45.8501	46.9101	110.0100
112.6531	45.8501	46.8124	110.4100	110.9563	45.8501	46.7146	110.8000
110.9563	45.8501	46.8124	111.2000	110.9563	45.8501	46.9101	111.5900
110.9563	45.8501	46.9101	111.9900	112.6531	45.8501	46.7146	112.3900
110.9563	45.8501	46.7146	112.7800	110.9563	45.8501	46.9101	113.1800
110.9563	45.8501	46.9101	113.5700	110.9563	45.8501	46.8124	113.9700
110.9563	45.8501	46.7146	114.3600	110.9563	45.8501	46.8124	114.7600
110.9563	45.1125	46.9101	115.1500	110.9563	45.8501	46.8124	115.5500
110.9563	45.8501	46.7146	115.9500	110.9563	45.8501	46.8124	116.3400
110.9563	45.8501	46.9101	116.7400	110.9563	45.8501	46.8124	117.1300

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec)	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
110.9563	45.8501	46.8124	117.5300	107.5625	44.3751	46.9101	192.8100
107.5625	44.3751	46.9101	193.2000	107.5625	44.3751	46.8124	193.6000
105.8655	44.3751	46.8124	194.0000	105.8655	45.1125	46.7146	194.3900
107.5625	45.1125	46.8124	194.7900	107.5625	44.3751	46.8124	195.1900
105.8655	44.3751	46.9101	195.5800	107.5625	44.3751	46.9101	195.9800
107.5625	44.3751	46.8124	196.3800	107.5625	44.3751	46.8124	196.7700
107.5625	45.1125	46.8124	197.1700	107.5625	44.3751	46.8124	197.5600
107.5625	44.3751	46.9101	197.9600	107.5625	44.3751	46.9101	198.3600
107.5625	44.3751	46.9101	198.7500	107.5625	44.3751	46.8124	199.1500
107.5625	45.1125	46.7146	199.5400	107.5625	45.1125	46.7146	199.9400
107.5625	45.1125	46.8124	200.3400	107.5625	44.3751	46.9101	200.7300
107.5625	44.3751	46.8124	201.1300	107.5625	44.3751	46.8124	201.5200
105.8655	45.1125	46.7146	201.9200	107.5625	44.3751	46.7146	202.3200
105.8655	45.1125	46.8124	202.7100	107.5625	44.3751	46.9101	203.1100
107.5625	44.3751	46.9101	203.5000	107.5625	44.3751	46.8124	203.9000
105.8655	44.3751	46.7146	204.3000	105.8655	45.1125	46.8124	204.6900
105.8655	44.3751	46.8124	205.0900	107.5625	44.3751	46.9101	205.4800
105.8655	44.3751	46.9101	205.8800	107.5625	44.3751	46.8124	206.2800
107.5625	44.3751	46.8124	206.6700	105.8655	44.3751	46.8124	207.0700
105.8655	45.1125	46.8124	207.4600	105.8655	44.3751	46.9101	207.8600
105.8655	44.3751	46.9101	208.2600	107.5625	44.3751	46.9101	208.6500
107.5625	44.3751	46.8124	209.0500	107.5625	45.1125	46.7146	209.4400
105.8655	45.1125	46.8124	209.8400	105.8655	45.1125	46.8124	210.2400
105.8655	44.3751	46.8124	210.6300	107.5625	44.3751	46.9101	211.0300
107.5625	45.1125	46.8124	211.4200	105.8655	45.1125	46.7146	211.8200
105.8655	44.3751	46.8124	212.2200	105.8655	45.1125	46.8124	212.6100
107.5625	44.3751	46.9101	213.0100	105.8655	44.3751	46.9101	213.4000
105.8655	44.3751	46.8124	213.8000	107.5625	45.1125	46.8124	214.1900
105.8655	44.3751	46.7146	214.5900	107.5625	45.1125	46.7146	214.9900
105.8655	44.3751	46.9101	215.3800	105.8655	44.3751	46.9101	215.7800
105.8655	44.3751	46.9101	216.1700	105.8655	45.1125	46.8124	216.5700
105.8655	44.3751	46.8124	216.9700	105.8655	45.1125	46.8124	217.3600
105.8655	44.3751	46.8124	217.7600	105.8655	44.3751	46.9101	218.1500
105.8655	44.3751	46.8124	218.5500	71.9280	26.6750	44.9548	144.2300

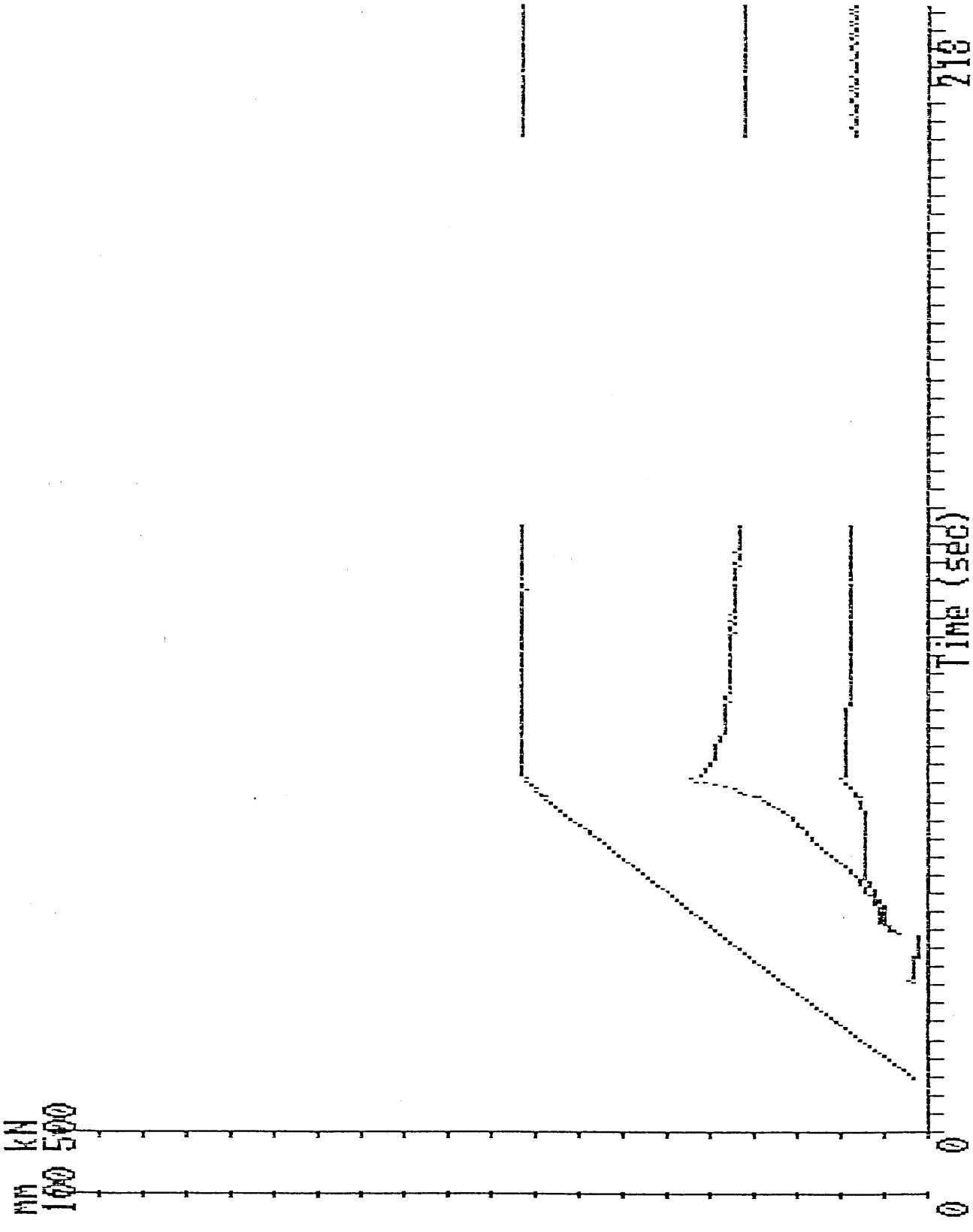


Fig.A5.7. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.8.

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RESULTS - SPECIMEN No.9

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The results of this test are stored in the file B:08-01-09.DAT

The values at maximum load are :-

Load at Top Load Cell = 63.4436 (kN)

Load at Bottom Load Cell = 38.4751 (kN)

Displacement = 33.71138 (mm)

Time Elasped = 47.48 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4800	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8100	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	1.6433	6.3700	0.0000	0.0000	1.8388	6.7600
0.0000	0.0000	2.2299	7.1400	0.0000	0.0000	2.5232	7.5300
0.0000	0.0000	2.8165	7.9200	0.0000	0.0000	3.1098	8.3100
0.0000	0.0000	3.5009	8.7000	0.0000	0.0000	3.7942	9.0800
0.0000	0.0000	4.0875	9.4700	0.0000	0.0000	4.4786	9.8600
0.0000	0.0000	4.6741	10.2500	0.0000	0.0000	4.9674	10.6400
0.0000	0.0000	5.3585	11.0300	0.0000	0.0000	5.6518	11.4200
0.0000	0.0000	5.9451	11.8100	0.0000	0.0000	6.2384	12.2000
0.0000	0.0000	6.6295	12.5900	0.0000	0.0000	6.9228	12.9800
0.0000	0.0000	7.2161	13.3800	0.0000	0.0000	7.5094	13.7700
0.0000	0.0000	7.8027	14.1600	0.0000	0.0000	8.1938	14.5500
0.0000	0.0000	8.4871	14.9400	0.0000	0.0000	8.7804	15.3300
0.0000	0.0000	9.1715	15.7200	0.0000	0.0000	9.4648	16.1100
0.0000	0.0000	9.7581	16.5000	0.0000	0.0000	9.9536	16.8900
0.0000	0.0000	10.4425	17.2800	0.0000	0.0000	10.6380	17.6700
0.0000	0.0000	11.0291	18.0600	0.0000	0.0000	11.1268	18.4500
0.0000	0.0000	11.5179	18.8400	0.0000	0.0000	11.9090	19.2300
0.0000	0.0000	12.2023	19.6200	0.0000	0.0000	12.5934	20.0100
0.0000	0.0000	12.8867	20.4000	0.0000	0.0000	13.2778	20.7900
0.0000	0.0000	13.4733	21.1700	0.0000	0.0000	13.8644	21.5600
0.0000	0.0000	14.1577	21.9500	0.0000	0.0000	14.4510	22.3400
0.0000	0.0000	14.7443	22.7300	0.0000	0.0000	15.0376	23.1200
0.0000	0.0000	15.4287	23.5100	0.0000	0.0000	15.7220	23.9000
0.0000	0.0000	15.9175	24.2800	0.0000	0.0000	16.4063	24.6700
0.0000	0.0000	16.6997	25.0600	4.0530	7.5001	16.7974	25.4500
4.0530	8.2375	17.0907	25.8300	4.0530	8.2375	17.2863	26.2200
4.0530	8.2375	17.6773	26.6100	2.3562	7.5001	17.9706	26.9900
4.0530	8.2375	18.2639	27.3800	2.3562	7.5001	18.5573	27.7700
2.3562	7.5001	18.9483	28.1500	2.3562	7.5001	19.1439	28.5400
2.3562	7.5001	19.5349	28.9200	2.3562	7.5001	19.8282	29.3100

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.6594	7.5001	20.1216	29.6900	2.3562	6.7626	20.4149	30.0800
0.6594	6.7626	20.7082	30.4600	2.3562	6.7626	21.0015	30.8500
0.6594	6.0250	21.2948	31.2300	0.6594	6.0250	21.7836	31.6200
0.6594	6.0250	21.8814	32.0100	0.6594	6.0250	22.2725	32.3900
0.6594	5.2876	22.5658	32.7800	1.0376	5.2876	22.7613	33.1600
1.0376	5.2876	23.2502	33.5500	1.0376	4.5500	23.4457	33.9400
1.0376	4.5500	23.8368	34.3300	1.0376	4.5500	24.1301	34.7100
9.1438	13.4000	24.3256	35.1000	14.2344	18.5626	24.6189	35.4900
14.2344	20.0376	24.9122	35.8700	14.2344	20.7750	25.2055	36.2600
14.2344	20.7750	25.5966	36.6500	17.6282	22.2501	25.7921	37.0400
17.6282	23.7251	26.1832	37.4200	17.6282	23.7251	26.3787	37.8100
19.3250	24.4625	26.6720	38.2000	21.0217	26.6750	26.9653	38.5900
22.7188	28.1500	27.2587	38.9700	24.4155	30.3625	27.5520	39.3600
27.8093	31.8375	27.8453	39.7500	27.8093	33.3126	28.2363	40.1400
29.5061	35.5250	28.4319	40.5200	31.2031	37.0001	28.7252	40.9100
32.8999	38.4751	29.0185	41.3000	32.8999	35.5250	29.3118	41.6800
34.5969	37.0001	29.7029	42.0700	36.2937	37.7375	29.8984	42.4600
37.9905	37.7375	30.1917	42.8400	39.6875	38.4751	30.5828	43.2300
41.3843	38.4751	30.7783	43.6200	43.0813	38.4751	31.1694	44.0000
46.4749	38.4751	31.3649	44.3900	48.1719	38.4751	31.5605	44.7800
51.5657	38.4751	32.0493	45.1600	53.2625	38.4751	32.2449	45.5500
54.9592	38.4751	32.5382	45.9300	56.6563	38.4751	32.9292	46.3200
60.0500	38.4751	33.0270	46.7100	61.7468	38.4751	33.4181	47.0900
63.4436	38.4751	33.7114	47.4800	61.7468	37.0001	33.6136	47.8600
61.7468	37.0001	33.7114	48.2500	61.7468	37.0001	33.7114	48.6400
61.7468	36.2626	33.7114	49.0200	60.0500	36.2626	33.8092	49.4100
60.0500	36.2626	33.7114	49.8000	60.0500	36.2626	33.7114	50.1800
60.0500	36.2626	33.8092	50.5700	60.0500	36.2626	33.7114	50.9500
60.0500	36.2626	33.8092	51.3400	60.0500	36.2626	33.7114	51.7300
60.0500	36.2626	33.7114	52.1100	60.0500	36.2626	33.8092	52.5000
60.0500	36.2626	33.6136	52.8800	60.0500	36.2626	33.7114	53.2700
60.0500	36.2626	33.8092	53.6600	60.0500	36.2626	33.7114	54.0400
60.0500	36.2626	33.8092	54.4300	60.0500	36.2626	33.8092	54.8200
60.0500	35.5250	33.7114	55.2000	60.0500	35.5250	33.8092	55.5900
60.0500	35.5250	33.6136	55.9700	60.0500	35.5250	33.7114	56.3600
60.0500	35.5250	33.7114	56.7500	60.0500	35.5250	33.6136	57.1300
58.3530	35.5250	33.7114	57.5200	58.3530	35.5250	33.7114	57.9100
58.3530	35.5250	33.7114	58.2900	60.0500	35.5250	33.8092	58.6800
58.3530	35.5250	33.7114	59.0700	60.0500	35.5250	33.7114	59.4500
58.3530	35.5250	33.7114	59.8400	58.3530	35.5250	33.6136	60.2200
58.3530	35.5250	33.8092	60.6100	58.3530	35.5250	33.7114	61.0000
58.3530	35.5250	33.8092	61.3900	58.3530	35.5250	33.7114	61.7800
58.3530	35.5250	33.7114	62.1800	58.3530	35.5250	33.8092	62.5700
58.3530	35.5250	33.7114	62.9600	58.3530	35.5250	33.7114	63.3600
58.3530	35.5250	33.7114	63.7500	58.3530	35.5250	33.8092	64.1400
58.3530	35.5250	33.7114	64.5400	58.3530	35.5250	33.7114	64.9300
58.3530	35.5250	33.8092	65.3200	58.3530	35.5250	33.8092	65.7200
58.3530	35.5250	33.7114	66.1100	58.3530	35.5250	33.7114	66.5000
58.3530	35.5250	33.7114	66.8900	58.3530	35.5250	33.7114	67.2900
58.3530	35.5250	33.7114	67.6800	51.5657	33.3126	33.6136	142.5800
51.5657	32.5751	33.7114	142.9800	51.5657	32.5751	33.7114	143.3700
51.5657	32.5751	33.8092	143.7700	51.5657	32.5751	33.8092	144.1600
51.5657	32.5751	33.7114	144.5600	51.5657	32.5751	33.6136	144.9500
51.5657	32.5751	33.7114	145.3500	51.5657	32.5751	33.7114	145.7500
51.5657	32.5751	33.8092	146.1400	51.5657	32.5751	33.7114	146.5400
51.5657	32.5751	33.7114	146.9300	51.5657	32.5751	33.6136	147.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
51.5657	32.5751	33.7114	147.7200	51.5657	32.5751	33.8092	148.1200
51.5657	32.5751	33.8092	148.5100	51.5657	32.5751	33.7114	148.9100
51.5657	32.5751	33.7114	149.3000	51.5657	32.5751	33.7114	149.7000
51.5657	32.5751	33.7114	150.0900	51.5657	32.5751	33.8092	150.4900
51.5657	32.5751	33.8092	150.8800	51.5657	32.5751	33.9069	151.2800
51.5657	32.5751	33.7114	151.6700	51.5657	32.5751	33.7114	152.0700
51.5657	32.5751	33.7114	152.4600	51.5657	32.5751	33.7114	152.8600
51.5657	32.5751	33.8092	153.2500	51.5657	32.5751	33.7114	153.6500
51.5657	32.5751	33.7114	154.0400	51.5657	32.5751	33.7114	154.4400
49.8687	32.5751	33.7114	154.8300	51.5657	32.5751	33.8092	155.2300
49.8687	32.5751	33.8092	155.6300	49.8687	32.5751	33.8092	156.0200
51.5657	32.5751	33.7114	156.4200	49.8687	32.5751	33.7114	156.8200
49.8687	32.5751	33.7114	157.2100	49.8687	32.5751	33.7114	157.6100
49.8687	32.5751	33.8092	158.0000	49.8687	31.8375	33.8092	158.4000
51.5657	32.5751	33.8092	158.7900	49.8687	32.5751	33.7114	159.1900
49.8687	32.5751	33.7114	159.5900	49.8687	32.5751	33.7114	159.9800
49.8687	32.5751	33.7114	160.3800	51.5657	32.5751	33.9069	160.7700
49.8687	31.8375	33.8092	161.1700	49.8687	32.5751	33.8092	161.5700
49.8687	32.5751	33.7114	161.9600	49.8687	32.5751	33.7114	162.3600
49.8687	32.5751	33.7114	162.7500	49.8687	32.5751	33.7114	163.1500
49.8687	32.5751	33.6136	163.5400	49.8687	31.8375	33.8092	163.9400
49.8687	31.8375	33.8092	164.3400	49.8687	31.8375	33.8092	164.7300

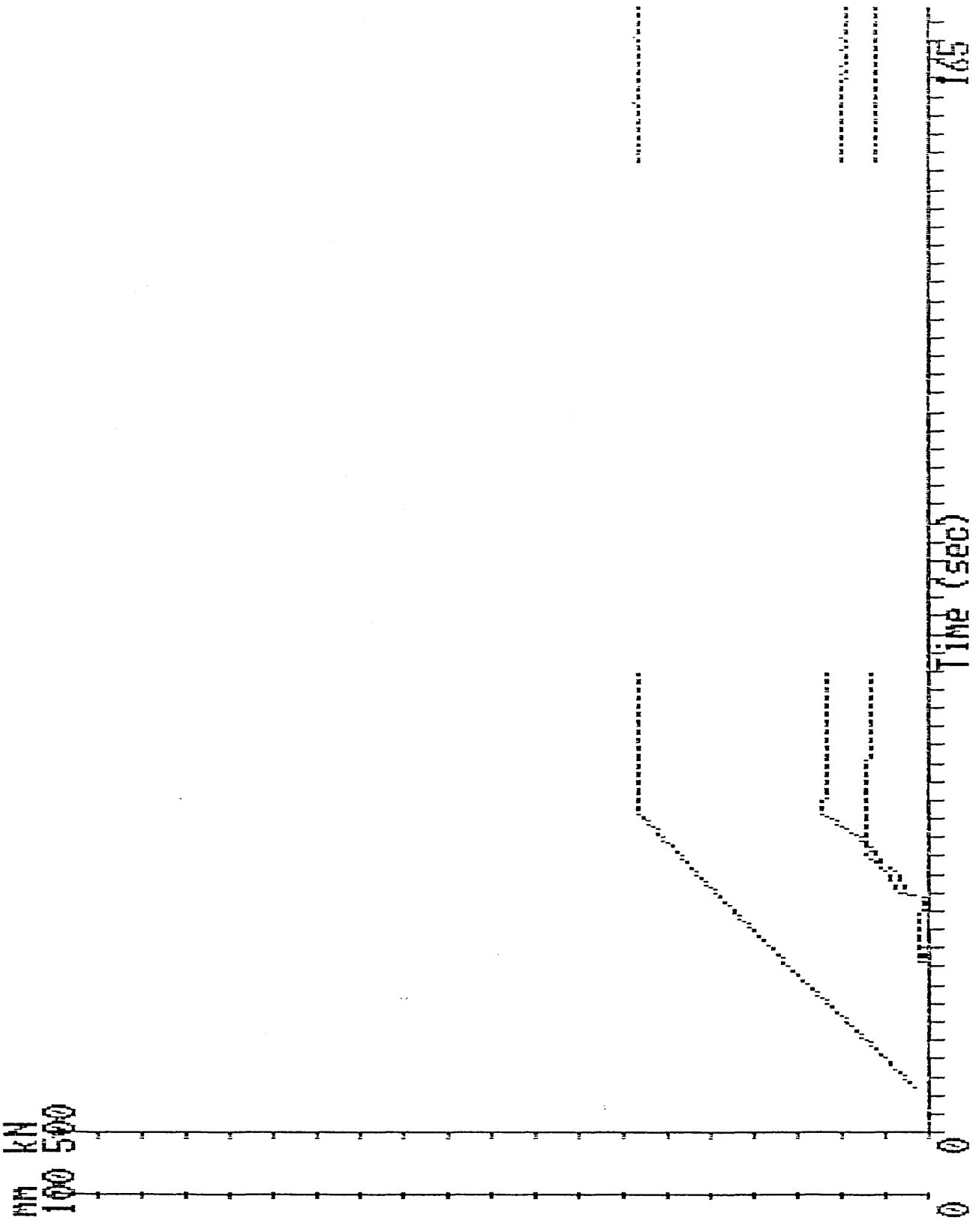


Fig.A5.8. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.9.

****

RESULTS - SPECIMEN No.10

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The results of this test are stored in the file B:08-01-10.DAT

The values at maximum load are :-

Load at Top Load Cell = 88.89673 (kN)

Load at Bottom Load Cell = 39.95007 (kN)

Displacement = 35.96007 (mm)

Time Elasped = 54.07 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0800
0.0000	0.0000	1.7411	9.4700	0.0000	0.0000	1.9366	9.8600
0.0000	0.0000	2.2299	10.2500	0.0000	0.0000	2.5232	10.6400
0.0000	0.0000	2.9143	11.0300	0.0000	0.0000	3.3054	11.4200
0.0000	0.0000	3.5987	11.8200	0.0000	0.0000	3.8920	12.2000
0.0000	0.0000	4.1853	12.6000	0.0000	0.0000	4.4786	12.9900
0.0000	0.0000	4.6741	13.3800	0.0000	0.0000	5.1630	13.7700
0.0000	0.0000	5.3585	14.1600	0.0000	0.0000	5.7496	14.5500
0.0000	0.0000	6.0429	14.9400	0.0000	0.0000	6.3362	15.3300
0.0000	0.0000	6.6295	15.7200	0.0000	0.0000	7.0206	16.1100
0.0000	0.0000	7.3139	16.5000	0.0000	0.0000	7.6072	16.8900
0.0000	0.0000	7.9005	17.2800	0.0000	0.0000	8.1938	17.6700
0.0000	0.0000	8.5849	18.0600	0.0000	0.0000	8.7804	18.4500
0.0000	0.0000	9.1715	18.8400	0.0000	0.0000	9.4648	19.2300
0.0000	0.0000	9.7581	19.6200	0.0000	0.0000	10.1492	20.0100
0.0000	0.0000	10.3447	20.4000	0.0000	0.0000	10.7358	20.7900
0.0000	0.0000	11.1268	21.1800	0.0000	0.0000	11.3224	21.5700
0.0000	0.0000	11.7135	21.9600	0.0000	0.0000	11.9090	22.3500
0.0000	0.0000	12.3001	22.7300	0.0000	0.0000	12.5934	23.1200
0.0000	0.0000	12.8867	23.5100	0.0000	0.0000	13.1800	23.9000
0.0000	0.0000	13.5711	24.2900	0.0000	0.0000	13.7666	24.6800
0.0000	0.0000	14.1577	25.0600	0.0000	0.0000	14.4510	25.4500
0.0000	0.0000	14.7443	25.8400	0.0000	0.0000	15.0376	26.2300
0.0000	0.0000	15.4287	26.6200	0.0000	0.0000	15.6242	27.0100
0.0000	0.0000	16.0153	27.4000	0.0000	0.0000	16.3086	27.7800
0.0000	0.0000	16.5041	28.1700	0.0000	0.0000	16.8952	28.5600
0.0000	0.0000	17.1885	28.9500	0.0000	0.0000	17.4818	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
7.4468	9.7125	17.6773	29.7300	4.0530	8.2375	17.9706	30.1100
5.7500	8.2375	18.1662	30.5000	4.0530	7.5001	18.5573	30.8900
4.0530	7.5001	18.8506	31.2700	4.0530	7.5001	19.1439	31.6600
4.0530	7.5001	19.4372	32.0500	4.0530	7.5001	19.8282	32.4300
4.0530	7.5001	20.0238	32.8200	4.0530	7.5001	20.3171	33.2000
4.0530	7.5001	20.7082	33.5900	4.0530	7.5001	20.9037	33.9800
4.0530	6.7626	21.1970	34.3700	4.0530	6.7626	21.5881	34.7500
4.0530	6.7626	21.9792	35.1400	2.3562	6.0250	22.1747	35.5200
2.3562	6.0250	22.4680	35.9100	2.3562	6.0250	22.8591	36.3000
2.3562	6.0250	23.1524	36.6800	2.3562	6.0250	23.3479	37.0700
2.3562	6.0250	23.7390	37.4500	9.1438	11.1876	24.0323	37.8400
17.6282	20.0376	24.2278	38.2300	19.3250	21.5126	24.4234	38.6100
19.3250	21.5126	24.8144	39.0000	19.3250	21.5126	25.1078	39.3900
21.0217	22.9875	25.3033	39.7800	22.7188	24.4625	25.6944	40.1600
22.7188	24.4625	25.9877	40.5500	24.4155	25.2001	26.1832	40.9300
24.4155	25.2001	26.5743	41.3200	24.4155	25.9376	26.9653	41.7100
26.1125	27.4126	27.0631	42.0900	27.8093	28.1500	27.4542	42.4800
29.5061	29.6251	27.8453	42.8700	31.2031	31.8375	27.9430	43.2500
32.8999	33.3126	28.2363	43.6400	32.8999	34.7876	28.7252	44.0300
34.5969	36.2626	28.9207	44.4100	36.2937	37.7375	29.1163	44.8000
37.9905	39.2125	29.5073	45.1900	37.9905	39.2125	29.8006	45.5700
41.3843	37.7375	29.9962	45.9600	43.0813	38.4751	30.2895	46.3500
44.7781	39.2125	30.6806	46.7300	46.4749	39.2125	30.8761	47.1200
48.1719	39.2125	31.1694	47.5100	49.8687	39.2125	31.4627	47.8900
51.5657	39.2125	31.8538	48.2800	53.2625	39.2125	32.0493	48.6600
56.6563	39.2125	32.3426	49.0500	58.3530	39.2125	32.7337	49.4400
61.7468	39.9501	32.9292	49.8200	63.4436	39.2125	33.1248	50.2100
65.1406	39.2125	33.5159	50.5900	68.5344	39.2125	33.8092	50.9800
71.9280	39.9501	34.0047	51.3700	73.6250	39.2125	34.2002	51.7500
77.0188	39.2125	34.6891	52.1400	77.0188	38.4751	34.8846	52.5300
80.4124	39.2125	35.1779	52.9100	83.8062	39.2125	35.4712	53.3000
85.5032	39.2125	35.8623	53.6800	88.8967	39.9501	35.9601	54.0700
87.2000	39.2125	36.1556	54.4600	83.8062	38.4751	36.2534	54.8400
83.8062	37.7375	36.3511	55.2300	82.1094	37.7375	36.1556	55.6200
82.1094	37.7375	36.1556	56.0000	80.4124	37.0001	36.2534	56.3900
80.4124	37.0001	36.2534	56.7700	80.4124	37.0001	36.1556	57.1600
78.7156	37.0001	36.2534	57.5500	78.7156	37.0001	36.2534	57.9300
78.7156	37.0001	36.2534	58.3200	78.7156	37.0001	36.1556	58.7100
78.7156	36.2626	36.2534	59.0900	77.0188	36.2626	36.2534	59.4800
77.0188	36.2626	36.1556	59.8600	77.0188	36.2626	36.2534	60.2500
77.0188	36.2626	36.2534	60.6400	77.0188	36.2626	36.2534	61.0200
77.0188	36.2626	36.2534	61.4100	77.0188	36.2626	36.1556	61.8100
77.0188	36.2626	36.3511	62.2000	75.3218	35.5250	36.2534	62.5900
75.3218	36.2626	36.1556	62.9900	75.3218	35.5250	36.3511	63.3800
75.3218	35.5250	36.2534	63.7700	75.3218	35.5250	36.2534	64.1700
75.3218	35.5250	36.2534	64.5600	75.3218	35.5250	36.1556	64.9500
73.6250	35.5250	36.2534	65.3400	73.6250	35.5250	36.2534	65.7400
73.6250	35.5250	36.2534	66.1300	73.6250	35.5250	36.3511	66.5200
73.6250	35.5250	36.1556	66.9200	73.6250	35.5250	36.2534	67.3100
73.6250	35.5250	36.1556	67.7000	73.6250	35.5250	36.2534	68.0900
73.6250	35.5250	36.2534	68.4900	73.6250	35.5250	36.1556	68.8800
73.6250	35.5250	36.2534	69.2700	73.6250	35.5250	36.1556	69.6600
73.6250	35.5250	36.2534	70.0600	73.6250	34.7876	36.2534	70.4500
73.6250	34.7876	36.3511	70.8500	73.6250	34.7876	36.1556	71.2400
73.6250	34.7876	36.2534	71.6400	71.9280	34.7876	36.2534	72.0400
71.9280	34.7876	36.2534	72.4300	71.9280	34.7876	36.1556	72.8300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
71.9280	34.7876	36.2534	73.2200	71.9280	34.7876	36.3511	73.6200
71.9280	34.7876	36.2534	74.0100	71.9280	34.7876	36.1556	74.4100
71.9280	34.7876	36.2534	74.8100	71.9280	34.7876	36.3511	75.2000
71.9280	34.7876	36.2534	75.6000	71.9280	34.7876	36.1556	75.9900
71.9280	34.7876	36.3511	76.3900	71.9280	34.0500	36.3511	76.7800
71.9280	34.7876	36.2534	77.1800	71.9280	34.7876	36.1556	77.5800
71.9280	34.7876	36.2534	77.9700	71.9280	34.7876	36.2534	78.3700
70.2312	34.0500	36.2534	78.7600	71.9280	34.7876	36.1556	79.1600
71.9280	34.0500	36.2534	79.5500	70.2312	34.0500	36.2534	79.9500
71.9280	34.0500	36.2534	80.3500	70.2312	34.7876	36.1556	80.7400
70.2312	34.0500	36.2534	81.1400	70.2312	34.0500	36.2534	81.5400
70.2312	34.0500	36.2534	81.9300	70.2312	34.0500	36.2534	82.3300
70.2312	34.0500	36.1556	82.7300	70.2312	34.0500	36.2534	83.1200
70.2312	34.0500	36.3511	83.5200	70.2312	34.0500	36.2534	83.9200
70.2312	34.0500	36.2534	84.3100	70.2312	34.0500	36.1556	84.7100
70.2312	34.0500	36.2534	85.1100	70.2312	34.0500	36.3511	85.5000
70.2312	34.0500	36.2534	85.9000	70.2312	34.0500	36.1556	86.3000
70.2312	34.0500	36.1556	86.6900	70.2312	34.0500	36.2534	87.0900
70.2312	34.0500	36.2534	87.4800	70.2312	34.0500	36.3511	87.8800
70.2312	34.0500	36.1556	88.2800	70.2312	34.0500	36.2534	88.6700
70.2312	33.3126	36.2534	89.0700	70.2312	34.0500	36.3511	89.4700
70.2312	34.0500	36.2534	89.8600	70.2312	34.0500	36.1556	90.2600
68.5344	34.0500	36.2534	90.6600	68.5344	33.3126	36.2534	91.0500
68.5344	34.0500	36.2534	91.4500	68.5344	34.0500	36.2534	91.8400
68.5344	34.0500	36.2534	92.2400	68.5344	33.3126	36.2534	92.6400
68.5344	34.0500	36.3511	93.0300	68.5344	33.3126	36.2534	93.4300
68.5344	34.0500	36.1556	93.8300	68.5344	34.0500	36.2534	94.2200
68.5344	33.3126	36.3511	94.6200	68.5344	33.3126	36.2534	95.0100
68.5344	34.0500	36.1556	95.4100	68.5344	33.3126	36.2534	95.8100
68.5344	33.3126	36.2534	96.2000	68.5344	33.3126	36.2534	96.6000
68.5344	33.3126	36.1556	96.9900	68.5344	33.3126	36.1556	97.3900
68.5344	33.3126	36.2534	97.7900	68.5344	33.3126	36.2534	98.1800
68.5344	33.3126	36.2534	98.5800	68.5344	33.3126	36.0578	98.9700
68.5344	33.3126	36.2534	99.3700	66.8374	33.3126	36.3511	99.7700
68.5344	33.3126	36.2534	100.1600	68.5344	33.3126	36.1556	100.5600
66.8374	33.3126	36.1556	100.9500	66.8374	33.3126	36.2534	101.3500
66.8374	33.3126	36.3511	101.7500	66.8374	33.3126	36.1556	102.1400
66.8374	33.3126	36.2534	102.5400	66.8374	33.3126	36.2534	102.9300
66.8374	32.5751	36.3511	103.3300	66.8374	33.3126	36.2534	103.7300
66.8374	33.3126	36.1556	104.1200	66.8374	33.3126	36.1556	104.5200
66.8374	33.3126	36.2534	104.9100	66.8374	33.3126	36.3511	105.3100
66.8374	33.3126	36.2534	105.7100	66.8374	33.3126	36.1556	106.1000
60.0500	30.3625	36.2534	181.0700	60.0500	30.3625	36.1556	181.4600
60.0500	30.3625	36.3511	181.8600	60.0500	30.3625	36.2534	182.2500
60.0500	30.3625	36.1556	182.6500	60.0500	30.3625	36.3511	183.0400
60.0500	30.3625	36.2534	183.4300	60.0500	30.3625	36.1556	183.8300
60.0500	30.3625	36.2534	184.2200	60.0500	30.3625	36.3511	184.6100
60.0500	31.1001	36.2534	185.0100	60.0500	30.3625	36.2534	185.4000
60.0500	30.3625	36.3511	185.7900	60.0500	30.3625	36.2534	186.1900
60.0500	30.3625	36.2534	186.5800	60.0500	30.3625	36.3511	186.9700
60.0500	30.3625	36.1556	187.3700	60.0500	30.3625	36.2534	187.7600
60.0500	30.3625	36.3511	188.1500	60.0500	30.3625	36.1556	188.5500
60.0500	30.3625	36.2534	188.9400	60.0500	30.3625	36.2534	189.3400
60.0500	30.3625	36.1556	189.7300	60.0500	30.3625	36.2534	190.1200
60.0500	30.3625	36.2534	190.5200	60.0500	30.3625	36.2534	190.9200
60.0500	30.3625	36.3511	191.3100	60.0500	30.3625	36.2534	191.7100

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
58.3530	30.3625	36.2534	192.1100	58.3530	30.3625	36.2534	192.5000
60.0500	30.3625	36.2534	192.9000	58.3530	30.3625	36.3511	193.3000
60.0500	30.3625	36.2534	193.6900	60.0500	30.3625	36.1556	194.0900
60.0500	30.3625	36.1556	194.4900	60.0500	30.3625	36.3511	194.8800
60.0500	30.3625	36.2534	195.2800	60.0500	30.3625	36.2534	195.6800
60.0500	30.3625	36.2534	196.0700	58.3530	30.3625	36.2534	196.4700
58.3530	30.3625	36.2534	196.8700	58.3530	30.3625	36.1556	197.2600
58.3530	30.3625	36.3511	197.6600	60.0500	30.3625	36.3511	198.0600
58.3530	30.3625	36.2534	198.4500	58.3530	30.3625	36.2534	198.8500
58.3530	30.3625	36.1556	199.2500	58.3530	30.3625	36.2534	199.6400
58.3530	29.6251	36.3511	200.0400	58.3530	30.3625	36.3511	200.4400
58.3530	30.3625	36.2534	200.8300	58.3530	30.3625	36.2534	201.2300
58.3530	30.3625	36.2534	201.6200	60.0500	30.3625	36.3511	202.0200
58.3530	30.3625	36.3511	202.4200	58.3530	30.3625	36.2534	202.8100
58.3530	30.3625	36.1556	203.2100	58.3530	30.3625	36.2534	203.6100
58.3530	30.3625	36.2534	204.0000	58.3530	30.3625	36.3511	204.4000
58.3530	30.3625	36.1556	204.7900	58.3530	30.3625	36.1556	205.1900
58.3530	30.3625	36.2534	205.5900	58.3530	30.3625	36.2534	205.9800
58.3530	29.6251	36.2534	206.3800	58.3530	29.6251	36.2534	206.7800

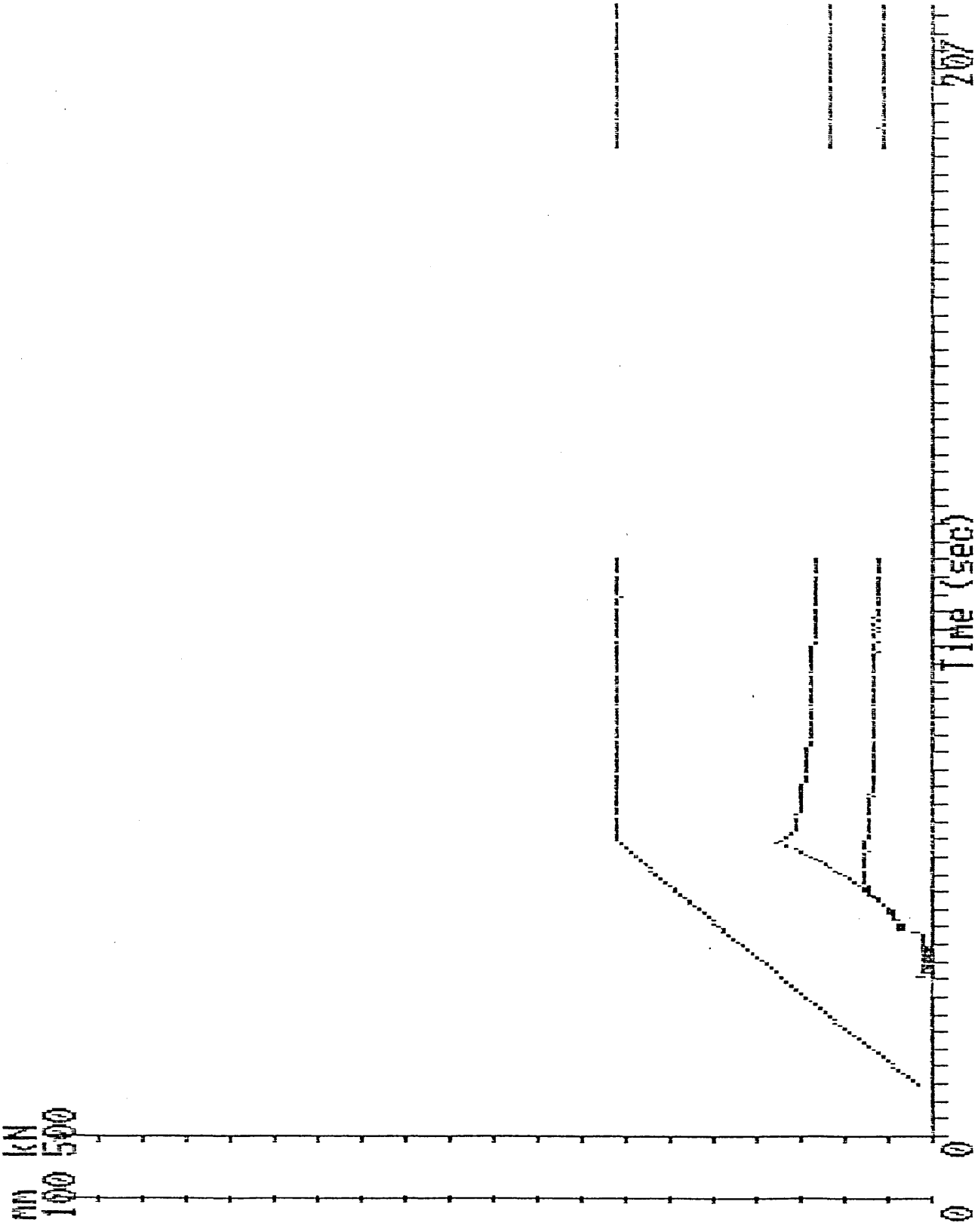


Fig.A5.9. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.10.

****

RESULTS - SPECIMEN No.11

****

The results of this test are stored in the file B:08-01-11.DAT

The values at maximum load are :-

Load at Top Load Cell = 51.56567 (kN)

Load at Bottom Load Cell = 36.26257 (kN)

Displacement = 32.04932 (mm)

Time Elasped = 51.35 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9300	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.0900
0.0000	0.0000	0.0000	2.4800	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4200
0.0000	0.0000	0.0000	4.8100	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0800
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	0.0000	9.8600
0.0000	0.0000	0.0000	10.2500	0.0000	0.0000	0.0000	10.6400
0.0000	0.0000	0.0000	11.0300	0.0000	0.0000	0.0000	11.4200
0.0000	0.0000	0.0000	11.8100	0.0000	0.0000	1.8388	12.2000
0.0000	0.0000	2.1321	12.5900	0.0000	0.0000	2.4254	12.9800
0.0000	0.0000	2.7188	13.3800	0.0000	0.0000	3.1098	13.7700
0.0000	0.0000	3.4031	14.1600	0.0000	0.0000	3.6964	14.5500
0.0000	0.0000	3.9897	14.9400	0.0000	0.0000	4.3808	15.3300
0.0000	0.0000	4.5764	15.7200	0.0000	0.0000	4.9674	16.1100
0.0000	0.0000	5.2607	16.5000	0.0000	0.0000	5.6518	16.8900
0.0000	0.0000	5.8474	17.2800	0.0000	0.0000	6.2384	17.6700
0.0000	0.0000	6.5317	18.0600	0.0000	0.0000	6.8250	18.4500
0.0000	0.0000	7.0206	18.8400	0.0000	0.0000	7.3139	19.2300
0.0000	0.0000	7.5094	19.6200	0.0000	0.0000	7.9005	20.0100
0.0000	0.0000	8.1938	20.4000	0.0000	0.0000	8.4871	20.7900
0.0000	0.0000	8.7804	21.1800	0.0000	0.0000	8.9759	21.5700
0.0000	0.0000	9.4648	21.9600	0.0000	0.0000	9.6603	22.3500
0.0000	0.0000	10.0514	22.7300	0.0000	0.0000	10.4425	23.1200
0.0000	0.0000	10.5402	23.5100	0.0000	0.0000	10.9313	23.9000
0.0000	0.0000	11.2246	24.2900	0.0000	0.0000	11.6157	24.6800
0.0000	0.0000	11.9090	25.0600	0.0000	0.0000	12.1045	25.4500
0.0000	0.0000	12.4956	25.8400	0.0000	0.0000	12.7889	26.2300
0.0000	0.0000	13.0822	26.6200	0.0000	0.0000	13.4733	27.0100
0.0000	0.0000	13.6688	27.4000	0.0000	0.0000	14.0599	27.7800
0.0000	0.0000	14.2554	28.1700	0.0000	0.0000	14.7443	28.5600
0.0000	0.0000	14.9398	28.9500	0.0000	0.0000	15.2331	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	15.6242	29.7300	0.0000	0.0000	15.8197	30.1100
0.0000	0.0000	16.2108	30.5000	2.3562	6.7626	16.4063	30.8900
2.3562	7.5001	16.6019	31.2800	2.3562	7.5001	16.8952	31.6600
2.3562	6.7626	17.2863	32.0500	2.3562	7.5001	17.5796	32.4300
2.3562	7.5001	17.7751	32.8200	2.3562	6.7626	18.0684	33.2000
2.3562	6.7626	18.4595	33.5900	2.3562	6.7626	18.7528	33.9700
2.3562	6.7626	18.9483	34.3600	2.3562	6.7626	19.3394	34.7500
2.3562	6.0250	19.6327	35.1300	2.3562	6.0250	20.0238	35.5200
0.6594	6.0250	20.2193	35.9000	0.6594	6.0250	20.5126	36.2900
0.6594	6.0250	20.9037	36.6700	0.6594	6.0250	21.1970	37.0600
0.6594	5.2876	21.3925	37.4400	0.6594	5.2876	21.7836	37.8300
0.6594	4.5500	22.0769	38.2100	0.6594	5.2876	22.3702	38.6000
0.0376	4.5500	22.6635	38.9900	0.0376	4.5500	23.0546	39.3700
0.0376	4.5500	23.3479	39.7600	0.0376	4.5500	23.5435	40.1500
5.7500	8.9751	23.8368	40.5300	14.2344	17.8251	24.1301	40.9200
15.9312	19.3000	24.4234	41.3000	15.9312	20.0376	24.6189	41.6900
17.6282	20.7750	25.0100	42.0700	17.6282	20.7750	25.4011	42.4600
17.6282	21.5126	25.4988	42.8500	17.6282	21.5126	25.7921	43.2300
19.3250	22.9875	26.1832	43.6200	21.0217	23.7251	26.3787	44.0000
21.0217	24.4625	26.6720	44.3900	22.7188	25.2001	27.0631	44.7800
24.4155	25.9376	27.3564	45.1600	24.4155	26.6750	27.5520	45.5500
24.4155	27.4126	27.9430	45.9400	26.1125	28.1500	28.2363	46.3200
26.1125	29.6251	28.5296	46.7100	27.8093	31.1001	28.7252	47.1000
29.5061	32.5751	29.1163	47.4800	31.2031	34.0500	29.4096	47.8700
32.8999	35.5250	29.6051	48.2600	32.8999	37.0001	29.9962	48.6400
36.2937	36.2626	30.2895	49.0300	39.6875	36.2626	30.4850	49.4200
41.3843	37.0001	30.7783	49.8000	44.7781	36.2626	31.1694	50.1900
46.4749	37.0001	31.2672	50.5700	48.1719	37.0001	31.6582	50.9600
51.5657	36.2626	32.0493	51.3500	49.8687	35.5250	32.1471	51.7300
49.8687	35.5250	32.0493	52.1200	48.1719	34.7876	31.9516	52.5100
48.1719	34.7876	32.1471	52.8900	48.1719	34.7876	32.1471	53.2800
48.1719	34.7876	32.0493	53.6600	48.1719	34.0500	32.1471	54.0500
46.4749	34.0500	32.1471	54.4400	46.4749	34.0500	32.0493	54.8200
48.1719	34.0500	31.9516	55.2100	46.4749	34.0500	32.1471	55.6000
46.4749	34.0500	32.1471	55.9800	46.4749	34.0500	32.0493	56.3700
46.4749	34.0500	32.1471	56.7600	46.4749	34.0500	32.0493	57.1400
46.4749	34.0500	32.0493	57.5300	46.4749	34.0500	32.0493	57.9100
46.4749	33.3126	32.1471	58.3000	46.4749	34.0500	32.0493	58.6900
46.4749	34.0500	32.0493	59.0700	46.4749	33.3126	32.1471	59.4600
46.4749	34.0500	32.1471	59.8500	46.4749	33.3126	32.0493	60.2300
44.7781	33.3126	32.0493	60.6200	46.4749	33.3126	32.1471	61.0100
44.7781	33.3126	32.0493	61.4000	46.4749	33.3126	32.0493	61.7900
44.7781	33.3126	32.1471	62.1900	44.7781	33.3126	32.0493	62.5800
44.7781	33.3126	32.1471	62.9700	44.7781	33.3126	32.1471	63.3700
44.7781	33.3126	32.0493	63.7600	44.7781	33.3126	32.1471	64.1500
44.7781	33.3126	32.0493	64.5400	44.7781	33.3126	32.0493	64.9400
44.7781	32.5751	32.1471	65.3300	44.7781	33.3126	32.0493	65.7200
44.7781	32.5751	32.1471	66.1200	44.7781	32.5751	32.0493	66.5100
44.7781	33.3126	32.1471	66.9000	44.7781	32.5751	32.1471	67.3000
44.7781	33.3126	32.0493	67.6900	44.7781	32.5751	32.1471	68.0800
44.7781	32.5751	32.0493	68.4700	44.7781	32.5751	32.1471	68.8700
44.7781	32.5751	32.1471	69.2600	44.7781	32.5751	32.0493	69.6500
44.7781	32.5751	32.1471	70.0400	44.7781	32.5751	32.1471	70.4400
44.7781	32.5751	32.0493	70.8400	44.7781	32.5751	32.0493	71.2300
44.7781	32.5751	32.1471	71.6300	44.7781	32.5751	32.1471	72.0200
43.0813	32.5751	32.0493	72.4200	43.0813	32.5751	32.0493	72.8200

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
43.0813	32.5751	32.1471	73.2100	43.0813	32.5751	32.1471	73.6100
43.0813	32.5751	32.0493	74.0000	43.0813	32.5751	32.0493	74.4000
43.0813	32.5751	32.1471	74.7900	43.0813	32.5751	32.1471	75.1900
43.0813	32.5751	32.0493	75.5800	43.0813	32.5751	32.0493	75.9800
43.0813	31.8375	32.1471	76.3800	43.0813	32.5751	32.1471	76.7700
43.0813	32.5751	32.0493	77.1700	43.0813	31.8375	32.0493	77.5600
43.0813	31.8375	32.1471	77.9600	43.0813	31.8375	32.0493	78.3500
43.0813	32.5751	32.0493	78.7500	43.0813	31.8375	32.1471	79.1400
43.0813	31.8375	32.1471	79.5400	43.0813	31.8375	31.9516	79.9400
43.0813	32.5751	32.0493	80.3400	43.0813	31.8375	32.0493	80.7300
43.0813	31.8375	32.1471	81.1300	43.0813	31.8375	32.1471	81.5200
43.0813	31.1001	32.0493	81.9200	43.0813	31.8375	32.1471	82.3200
43.0813	31.8375	32.0493	82.7100	43.0813	31.1001	32.1471	83.1100
43.0813	31.1001	32.1471	83.5100	43.0813	31.8375	32.0493	83.9000
43.0813	31.1001	32.0493	84.3000	43.0813	31.8375	32.1471	84.7000
43.0813	31.1001	32.1471	85.0900	43.0813	31.1001	32.1471	85.4900
41.3843	31.8375	32.0493	85.8900	43.0813	31.1001	32.0493	86.2800
41.3843	31.1001	32.1471	86.6800	41.3843	31.1001	32.1471	87.0800
43.0813	31.1001	32.1471	87.4700	43.0813	31.1001	32.0493	87.8700
41.3843	31.1001	32.0493	88.2700	41.3843	31.1001	32.1471	88.6600
41.3843	31.1001	32.1471	89.0600	41.3843	31.1001	32.0493	89.4600
41.3843	31.1001	32.0493	89.8500	41.3843	31.1001	32.1471	90.2500
41.3843	31.1001	32.1471	90.6500	41.3843	31.1001	32.1471	91.0400
41.3843	31.1001	32.0493	91.4400	41.3843	31.1001	32.0493	91.8400
41.3843	31.1001	32.1471	92.2300	41.3843	31.1001	32.1471	92.6300
41.3843	31.1001	32.1471	93.0200	41.3843	31.1001	32.0493	93.4200
41.3843	31.1001	32.1471	93.8200	41.3843	31.1001	32.1471	94.2100
41.3843	31.1001	32.1471	94.6100	41.3843	31.1001	32.0493	95.0000
41.3843	31.1001	32.0493	95.4000	41.3843	31.1001	32.1471	95.8000
36.2937	28.8876	32.1471	171.0800	36.2937	28.1500	32.1471	171.4700
36.2937	28.8876	32.1471	171.8700	36.2937	28.8876	32.1471	172.2700
36.2937	28.1500	32.1471	172.6600	36.2937	28.1500	32.1471	173.0600
36.2937	28.8876	32.1471	173.4600	36.2937	28.8876	32.0493	173.8500
36.2937	28.8876	32.1471	174.2500	36.2937	28.8876	32.1471	174.6400
36.2937	28.1500	32.0493	175.0400	36.2937	28.8876	32.0493	175.4400
36.2937	28.8876	32.0493	175.8300	36.2937	28.1500	32.1471	176.2300
36.2937	28.8876	32.1471	176.6300	36.2937	28.1500	32.0493	177.0200
36.2937	28.1500	32.0493	177.4200	36.2937	28.8876	32.1471	177.8100
36.2937	28.1500	32.1471	178.2100	36.2937	28.1500	32.1471	178.6100
36.2937	28.8876	32.0493	179.0000	36.2937	28.1500	32.0493	179.4000
36.2937	28.1500	32.1471	179.8000	36.2937	28.1500	32.0493	180.1800
36.2937	28.1500	32.1471	180.5700	36.2937	28.1500	32.1471	180.9600
36.2937	28.1500	32.1471	181.3500	36.2937	28.1500	32.0493	181.7500
36.2937	28.1500	32.1471	182.1400	36.2937	28.1500	32.1471	182.5400
36.2937	28.8876	31.9516	182.9300	36.2937	28.1500	32.1471	183.3200
36.2937	28.1500	32.1471	183.7200	36.2937	28.1500	32.0493	184.1100
36.2937	28.1500	32.1471	184.5100	36.2937	28.1500	32.2449	184.9000
36.2937	28.1500	32.0493	185.3000	36.2937	28.1500	32.0493	185.6900
36.2937	28.1500	32.1471	186.0800	36.2937	28.1500	32.0493	186.4800
34.5969	28.1500	32.0493	186.8700	36.2937	28.1500	32.1471	187.2600
34.5969	28.1500	32.0493	187.6600	34.5969	28.1500	32.0493	188.0500
36.2937	28.1500	32.1471	188.4500	34.5969	28.1500	32.0493	188.8400
36.2937	28.1500	32.0493	189.2300	36.2937	28.1500	32.1471	189.6300
36.2937	28.1500	32.0493	190.0200	36.2937	28.1500	32.0493	190.4200
34.5969	28.1500	32.1471	190.8200	34.5969	28.1500	32.1471	191.2100
34.5969	28.1500	32.1471	191.6100	36.2937	28.1500	32.1471	192.0100

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
34.5969	28.1500	32.0493	192.4000	34.5969	28.1500	32.0493	192.8000
34.5969	28.1500	32.1471	193.2000	34.5969	28.1500	32.1471	193.5900
36.2937	28.1500	32.1471	193.9900	36.2937	28.1500	32.0493	194.3900
34.5969	28.1500	32.1471	194.7900	34.5969	28.1500	32.0493	195.1800
34.5969	28.1500	32.1471	195.5800	34.5969	28.1500	32.1471	195.9800
34.5969	28.1500	32.1471	196.3800	34.5969	28.1500	32.1471	196.7700
34.5969	28.1500	32.1471	197.1700	34.5969	28.1500	32.0493	197.5700
34.5969	28.1500	32.1471	197.9600	34.5969	28.1500	32.2449	198.3600
34.5969	28.1500	32.1471	198.7600	34.5969	28.1500	32.0493	199.1500
34.5969	28.1500	32.0493	199.5500	14.2344	15.6125	32.0493	199.9500
2.3562	6.0250	32.0493	200.3400	2.7344	1.6001	31.8538	200.7400
0.0000	0.0000	31.7560	201.1300	0.0000	0.0000	31.7560	201.5300
0.0000	0.0000	31.8538	201.9300	0.0000	0.0000	31.7560	202.3300
0.0000	0.0000	31.6582	202.7200	0.0000	0.0000	31.4627	203.1200
0.0000	0.0000	31.4627	203.5200	0.0000	0.0000	31.3649	203.9100
0.0000	0.0000	31.3649	204.3100	0.0000	0.0000	31.3649	204.7100
0.0000	0.0000	31.1694	205.1000	0.0000	0.0000	31.0716	205.5000
0.0000	0.0000	31.0716	205.9000	0.0000	0.0000	30.9739	206.2900
0.0000	0.0000	30.9739	206.6900	0.0000	0.0000	30.8761	207.0900
0.0000	0.0000	30.5828	207.4800	0.0000	0.0000	29.6051	207.8800
0.0000	0.0000	27.7475	208.2800	0.0000	0.0000	25.4988	208.6800
0.0000	0.0000	22.7613	209.0700	0.0000	0.0000	19.7305	209.4700
0.0000	0.0000	16.6997	209.8700	0.0000	0.0000	13.6688	210.2600
0.0000	0.0000	10.7358	210.6600	0.0000	0.0000	7.7049	211.0600
0.0000	0.0000	4.6741	211.4600	0.0000	0.0000	1.8388	211.8500
0.0000	0.0000	0.0000	212.2500	0.0000	0.0000	0.0000	212.6500
0.0000	0.0000	0.0000	213.0400	0.0000	0.0000	0.0000	213.4400
0.0000	0.0000	0.0000	213.8400	0.0000	0.0000	0.0000	214.2400
0.0000	0.0000	0.0000	214.6300	0.0000	0.0000	0.0000	215.0300
0.0000	0.0000	0.0000	215.4300	0.0000	0.0000	0.0000	215.8300
0.0000	0.0000	0.0000	216.2200	0.0000	0.0000	0.0000	216.6200
0.0000	0.0000	0.0000	217.0200	0.0000	0.0000	0.0000	217.4200
0.0000	0.0000	0.0000	217.8100	0.0000	0.0000	0.0000	218.2100
0.0000	0.0000	0.0000	218.6100	0.0000	0.0000	0.0000	219.0100
0.0000	0.0000	0.0000	219.4000	0.0000	0.0000	0.0000	219.8000
0.0000	0.0000	0.0000	220.2000	0.0000	0.0000	0.0000	220.5900
0.0000	0.0000	0.0000	220.9900	0.0000	0.0000	0.0000	221.3900
0.0000	0.0000	0.0000	221.7900	0.0000	0.0000	0.0000	222.1800
0.0000	0.0000	0.0000	222.5800	0.0000	0.0000	0.0000	222.9800
0.0000	0.0000	0.0000	223.3800	0.0000	0.0000	0.0000	223.7700
0.0000	0.0000	0.0000	224.1700	0.0000	0.0000	0.0000	224.5700
0.0000	0.0000	0.0000	224.9600	0.0000	0.0000	0.0000	225.3600
0.0000	0.0000	0.0000	225.7600	0.0000	0.0000	0.0000	226.1600
0.0000	0.0000	0.0000	226.5500	0.0000	0.0000	0.0000	226.9500
0.0000	0.0000	0.0000	227.3500	0.0000	0.0000	0.0000	227.7500
0.0000	0.0000	0.0000	228.1400	0.0000	0.0000	0.0000	228.5400
0.0000	0.0000	0.0000	228.9400	0.0000	0.0000	0.0000	229.3300
0.0000	0.0000	0.0000	229.7300	0.0000	0.0000	0.0000	230.1300

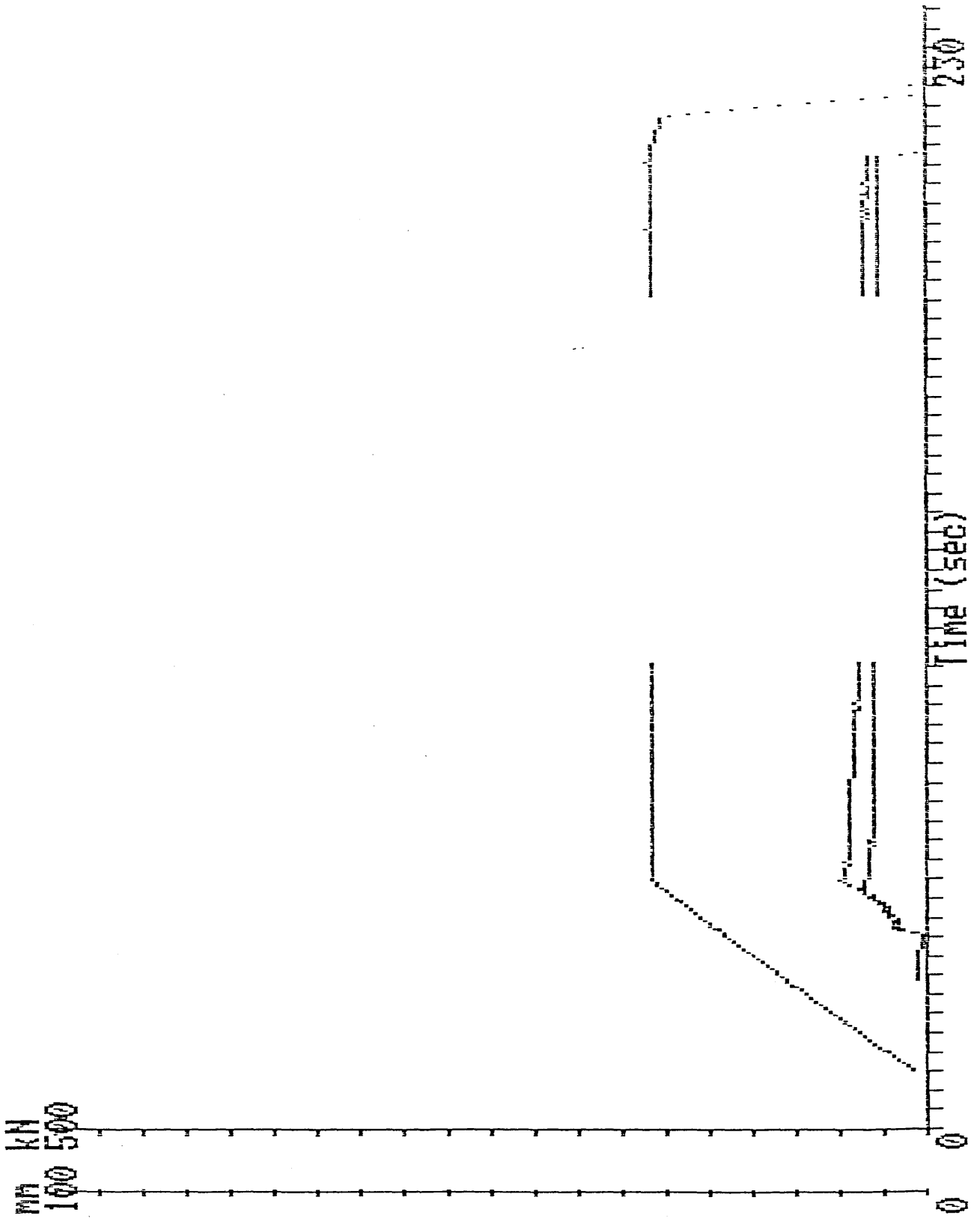


Fig.A5.10. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.11.

****

RESULTS - SPECIMEN No.12

****

The results of this test are stored in the file B:09-01-12.DAT

The values at maximum load are :-

Load at Top Load Cell = 77.0188 (kN)

Load at Bottom Load Cell = 25.20007 (kN)

Displacement = 27.84528 (mm)

Time Elasped = 44.41 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5700
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0500	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.6000	0.0000	0.0000	0.0000	5.9900
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5400
0.0000	0.0000	0.0000	7.9300	0.0000	0.0000	0.0000	8.3200
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
2.3562	3.0751	1.5455	9.4800	7.4468	4.5500	1.7411	9.8700
7.4468	4.5500	2.0344	10.2500	7.4468	4.5500	2.3277	10.6400
5.7500	4.5500	2.6210	11.0300	5.7500	4.5500	3.0121	11.4200
7.4468	4.5500	3.3054	11.8100	5.7500	4.5500	3.5987	12.2000
7.4468	4.5500	3.8920	12.5900	5.7500	4.5500	4.1853	12.9800
5.7500	4.5500	4.4786	13.3700	5.7500	4.5500	4.7719	13.7600
5.7500	4.5500	5.0652	14.1400	5.7500	4.5500	5.3585	14.5300
5.7500	4.5500	5.7496	14.9200	5.7500	4.5500	5.9451	15.3100
7.4468	4.5500	6.3362	15.7000	5.7500	4.5500	6.6295	16.0900
5.7500	4.5500	6.9228	16.4800	7.4468	4.5500	7.2161	16.8700
5.7500	4.5500	7.5094	17.2600	7.4468	4.5500	7.9005	17.6400
5.7500	4.5500	8.0960	18.0300	12.5374	6.7626	8.4871	18.4200
19.3250	9.7125	8.6826	18.8100	22.7188	10.4501	8.9759	19.2000
24.4155	11.1876	9.1715	19.5900	24.4155	11.1876	9.5625	19.9800
26.1125	11.9250	9.8559	20.3700	26.1125	11.9250	10.1492	20.7600
26.1125	11.9250	10.4425	21.1500	26.1125	11.9250	10.7358	21.5300
27.8093	12.6626	11.1268	21.9200	29.5061	12.6626	11.3224	22.3100
29.5061	12.6626	11.7135	22.7000	29.5061	12.6626	11.9090	23.0900
31.2031	13.4000	12.3001	23.4800	31.2031	13.4000	12.4956	23.8600
31.2031	13.4000	12.7889	24.2500	31.2031	13.4000	13.1800	24.6400
31.2031	13.4000	13.3755	25.0300	31.2031	13.4000	13.7666	25.4200
32.8999	14.1376	13.9621	25.8100	32.8999	14.1376	14.2554	26.1900
32.8999	14.1376	14.6465	26.5800	34.5969	14.8751	14.9398	26.9700
34.5969	14.8751	15.3309	27.3600	36.2937	14.8751	15.4287	27.7500
36.2937	14.8751	15.8197	28.1400	37.9905	15.6125	16.1130	28.5200
39.6875	15.6125	16.4063	28.9100	39.6875	15.6125	16.6997	29.3000

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
39.6875	16.3501	16.9930	29.6900	41.3843	16.3501	17.2863	30.0800
43.0813	17.0875	17.4818	30.4700	43.0813	17.0875	17.8729	30.8500
44.7781	17.0875	18.1662	31.2400	44.7781	17.8251	18.4595	31.6300
46.4749	17.8251	18.7528	32.0200	46.4749	18.5626	19.0461	32.4000
48.1719	18.5626	19.3394	32.7900	49.8687	18.5626	19.6327	33.1800
49.8687	18.5626	19.8282	33.5700	49.8687	19.3000	20.2193	33.9600
51.5657	19.3000	20.4149	34.3400	53.2625	19.3000	20.8059	34.7300
53.2625	20.0376	21.0992	35.1200	54.9592	20.0376	21.2948	35.5100
54.9592	20.0376	21.6859	35.9000	56.6563	20.7750	21.8814	36.2800
56.6563	20.7750	22.1747	36.6700	46.4749	18.5626	22.5658	37.0600
58.3530	20.7750	22.7613	37.4500	60.0500	20.7750	23.1524	37.8300
60.0500	21.5126	23.3479	38.2200	61.7468	21.5126	23.6412	38.6100
61.7468	21.5126	24.0323	39.0000	63.4436	22.2501	24.2278	39.3800
65.1406	22.2501	24.5211	39.7700	65.1406	22.9875	24.9122	40.1600
66.8374	22.9875	25.1078	40.5400	68.5344	22.9875	25.3033	40.9300
68.5344	23.7251	25.6944	41.3200	70.2312	23.7251	25.8899	41.7000
70.2312	23.7251	26.1832	42.0900	71.9280	23.7251	26.5743	42.4800
73.6250	24.4625	26.7698	42.8600	73.6250	24.4625	27.0631	43.2500
75.3218	24.4625	27.4542	43.6300	75.3218	25.2001	27.6497	44.0200
77.0188	25.2001	27.8453	44.4100	71.9280	24.4625	28.0408	44.7900
71.9280	24.4625	27.9430	45.1800	70.2312	23.7251	27.9430	45.5700
70.2312	23.7251	27.9430	45.9500	70.2312	23.7251	27.9430	46.3400
70.2312	23.7251	27.8453	46.7200	70.2312	23.7251	27.9430	47.1100
68.5344	23.7251	28.0408	47.5000	68.5344	23.7251	27.9430	47.8800
68.5344	23.7251	27.9430	48.2700	68.5344	22.9875	28.0408	48.6600
68.5344	23.7251	27.9430	49.0400	66.8374	22.9875	27.9430	49.4300
66.8374	22.9875	28.0408	49.8100	66.8374	23.7251	27.9430	50.2000
66.8374	22.9875	27.9430	50.5900	66.8374	22.9875	28.0408	50.9700
65.1406	22.9875	27.9430	51.3600	65.1406	22.9875	27.9430	51.7500
65.1406	22.9875	28.0408	52.1300	65.1406	22.9875	28.0408	52.5200
65.1406	22.9875	27.9430	52.9000	65.1406	22.9875	28.0408	53.2900
65.1406	22.9875	27.9430	53.6800	63.4436	22.9875	27.9430	54.0600
63.4436	22.2501	27.9430	54.4500	63.4436	22.2501	28.0408	54.8300
63.4436	22.2501	27.9430	55.2200	63.4436	22.2501	27.9430	55.6100
63.4436	22.2501	28.0408	55.9900	63.4436	22.2501	27.9430	56.3800
63.4436	22.2501	27.9430	56.7700	61.7468	22.2501	28.0408	57.1500
61.7468	22.2501	27.9430	57.5400	61.7468	22.2501	27.9430	57.9300
61.7468	22.2501	28.0408	58.3100	61.7468	22.2501	27.9430	58.7000
61.7468	22.2501	27.9430	59.0800	61.7468	22.2501	28.0408	59.4700
60.0500	22.2501	27.9430	59.8600	61.7468	22.2501	27.9430	60.2400
60.0500	22.2501	28.0408	60.6300	60.0500	22.2501	28.0408	61.0200
60.0500	22.2501	28.0408	61.4100	60.0500	22.2501	27.9430	61.8000
60.0500	21.5126	28.0408	62.1900	60.0500	21.5126	28.0408	62.5900
60.0500	21.5126	27.9430	62.9800	60.0500	21.5126	27.9430	63.3800
60.0500	21.5126	28.0408	63.7700	60.0500	21.5126	28.0408	64.1600
60.0500	22.2501	27.9430	64.5500	58.3530	21.5126	28.0408	64.9500
58.3530	21.5126	27.9430	65.3400	58.3530	21.5126	28.0408	65.7300
58.3530	21.5126	28.0408	66.1300	58.3530	21.5126	27.9430	66.5200
58.3530	21.5126	28.0408	66.9100	58.3530	21.5126	28.0408	67.3100
58.3530	21.5126	27.9430	67.7000	58.3530	21.5126	28.0408	68.0900
58.3530	21.5126	28.0408	68.4800	58.3530	21.5126	27.9430	68.8800
58.3530	21.5126	28.0408	69.2700	58.3530	21.5126	27.9430	69.6600
56.6563	21.5126	27.9430	70.0600	56.6563	21.5126	28.0408	70.4500
56.6563	21.5126	28.0408	70.8500	56.6563	20.7750	27.9430	71.2400
56.6563	21.5126	27.9430	71.6400	56.6563	21.5126	27.9430	72.0400
56.6563	20.7750	28.0408	72.4300	56.6563	20.7750	28.0408	72.8300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
39.6875	16.3501	16.9930	29.6900	41.3843	16.3501	17.2863	30.0800
43.0813	17.0875	17.4818	30.4700	43.0813	17.0875	17.8729	30.8500
44.7781	17.0875	18.1662	31.2400	44.7781	17.8251	18.4595	31.6300
46.4749	17.8251	18.7528	32.0200	46.4749	18.5626	19.0461	32.4000
48.1719	18.5626	19.3394	32.7900	49.8687	18.5626	19.6327	33.1800
49.8687	18.5626	19.8282	33.5700	49.8687	19.3000	20.2193	33.9600
51.5657	19.3000	20.4149	34.3400	53.2625	19.3000	20.8059	34.7300
53.2625	20.0376	21.0992	35.1200	54.9592	20.0376	21.2948	35.5100
54.9592	20.0376	21.6859	35.9000	56.6563	20.7750	21.8814	36.2800
56.6563	20.7750	22.1747	36.6700	46.4749	18.5626	22.5658	37.0600
58.3530	20.7750	22.7613	37.4500	60.0500	20.7750	23.1524	37.8300
60.0500	21.5126	23.3479	38.2200	61.7468	21.5126	23.6412	38.6100
61.7468	21.5126	24.0323	39.0000	63.4436	22.2501	24.2278	39.3800
65.1406	22.2501	24.5211	39.7700	65.1406	22.9875	24.9122	40.1600
66.8374	22.9875	25.1078	40.5400	68.5344	22.9875	25.3033	40.9300
68.5344	23.7251	25.6944	41.3200	70.2312	23.7251	25.8899	41.7000
70.2312	23.7251	26.1832	42.0900	71.9280	23.7251	26.5743	42.4800
73.6250	24.4625	26.7698	42.8600	73.6250	24.4625	27.0631	43.2500
75.3218	24.4625	27.4542	43.6300	75.3218	25.2001	27.6497	44.0200
77.0188	25.2001	27.8453	44.4100	71.9280	24.4625	28.0408	44.7900
71.9280	24.4625	27.9430	45.1800	70.2312	23.7251	27.9430	45.5700
70.2312	23.7251	27.9430	45.9500	70.2312	23.7251	27.9430	46.3400
70.2312	23.7251	27.8453	46.7200	70.2312	23.7251	27.9430	47.1100
68.5344	23.7251	28.0408	47.5000	68.5344	23.7251	27.9430	47.8800
68.5344	23.7251	27.9430	48.2700	68.5344	22.9875	28.0408	48.6600
68.5344	23.7251	27.9430	49.0400	66.8374	22.9875	27.9430	49.4300
66.8374	22.9875	28.0408	49.8100	66.8374	23.7251	27.9430	50.2000
66.8374	22.9875	27.9430	50.5900	66.8374	22.9875	28.0408	50.9700
65.1406	22.9875	27.9430	51.3600	65.1406	22.9875	27.9430	51.7500
65.1406	22.9875	28.0408	52.1300	65.1406	22.9875	28.0408	52.5200
65.1406	22.9875	27.9430	52.9000	65.1406	22.9875	28.0408	53.2900
65.1406	22.9875	27.9430	53.6800	63.4436	22.9875	27.9430	54.0600
63.4436	22.2501	27.9430	54.4500	63.4436	22.2501	28.0408	54.8300
63.4436	22.2501	27.9430	55.2200	63.4436	22.2501	27.9430	55.6100
63.4436	22.2501	28.0408	55.9900	63.4436	22.2501	27.9430	56.3800
63.4436	22.2501	27.9430	56.7700	61.7468	22.2501	28.0408	57.1500
61.7468	22.2501	27.9430	57.5400	61.7468	22.2501	27.9430	57.9300
61.7468	22.2501	28.0408	58.3100	61.7468	22.2501	27.9430	58.7000
61.7468	22.2501	27.9430	59.0800	61.7468	22.2501	28.0408	59.4700
60.0500	22.2501	27.9430	59.8600	61.7468	22.2501	27.9430	60.2400
60.0500	22.2501	28.0408	60.6300	60.0500	22.2501	28.0408	61.0200
60.0500	22.2501	28.0408	61.4100	60.0500	22.2501	27.9430	61.8000
60.0500	21.5126	28.0408	62.1900	60.0500	21.5126	28.0408	62.5900
60.0500	21.5126	27.9430	62.9800	60.0500	21.5126	27.9430	63.3800
60.0500	21.5126	28.0408	63.7700	60.0500	21.5126	28.0408	64.1600
60.0500	22.2501	27.9430	64.5500	58.3530	21.5126	28.0408	64.9500
58.3530	21.5126	27.9430	65.3400	58.3530	21.5126	28.0408	65.7300
58.3530	21.5126	28.0408	66.1300	58.3530	21.5126	27.9430	66.5200
58.3530	21.5126	28.0408	66.9100	58.3530	21.5126	28.0408	67.3100
58.3530	21.5126	27.9430	67.7000	58.3530	21.5126	28.0408	68.0900
58.3530	21.5126	28.0408	68.4800	58.3530	21.5126	27.9430	68.8800
58.3530	21.5126	28.0408	69.2700	58.3530	21.5126	27.9430	69.6600
56.6563	21.5126	27.9430	70.0600	56.6563	21.5126	28.0408	70.4500
56.6563	21.5126	28.0408	70.8500	56.6563	20.7750	27.9430	71.2400
56.6563	21.5126	27.9430	71.6400	56.6563	21.5126	27.9430	72.0400
56.6563	20.7750	28.0408	72.4300	56.6563	20.7750	28.0408	72.8300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
56.6563	20.7750	28.0408	73.2200	56.6563	20.7750	28.0408	73.6200
56.6563	20.7750	27.9430	74.0200	56.6563	20.7750	27.9430	74.4100
56.6563	20.7750	28.0408	74.8100	56.6563	20.7750	28.0408	75.2000
56.6563	20.7750	28.0408	75.6000	54.9592	20.7750	27.8453	76.0000
54.9592	20.7750	28.0408	76.3900	54.9592	20.7750	28.0408	76.7900
56.6563	20.7750	28.0408	77.1800	54.9592	20.7750	27.9430	77.5800
54.9592	20.7750	27.9430	77.9700	54.9592	20.7750	28.0408	78.3700
54.9592	20.0376	28.0408	78.7700	54.9592	20.7750	28.0408	79.1600
54.9592	20.7750	27.9430	79.5600	54.9592	20.7750	27.9430	79.9500
54.9592	20.7750	27.9430	80.3500	54.9592	20.7750	28.0408	80.7500
54.9592	20.7750	28.0408	81.1400	54.9592	20.7750	28.0408	81.5400
54.9592	20.7750	27.9430	81.9400	54.9592	20.7750	27.9430	82.3400
54.9592	20.7750	27.9430	82.7300	54.9592	20.7750	28.0408	83.1300
53.2625	20.7750	28.0408	83.5200	54.9592	20.7750	28.0408	83.9200
54.9592	20.7750	28.0408	84.3200	54.9592	20.0376	28.0408	84.7100
53.2625	20.0376	27.9430	85.1100	53.2625	20.7750	28.0408	85.5100
53.2625	20.0376	28.0408	85.9000	53.2625	20.0376	28.0408	86.3000
53.2625	20.0376	28.0408	86.7000	53.2625	20.0376	27.9430	87.0900
53.2625	20.0376	27.9430	87.4900	53.2625	20.0376	28.0408	87.8900
53.2625	20.0376	28.0408	88.2800	53.2625	20.0376	28.0408	88.6800
53.2625	20.0376	28.0408	89.0800	53.2625	20.0376	27.9430	89.4700
53.2625	20.0376	27.9430	89.8700	53.2625	20.0376	28.0408	90.2700
53.2625	20.0376	28.0408	90.6600	53.2625	20.0376	28.0408	91.0600
53.2625	20.0376	28.0408	91.4600	53.2625	20.0376	28.0408	91.8500
46.4749	18.5626	28.0408	166.7600	46.4749	18.5626	28.0408	167.1500
46.4749	18.5626	28.0408	167.5500	46.4749	18.5626	28.0408	167.9400
46.4749	18.5626	28.0408	168.3400	46.4749	18.5626	28.0408	168.7400
46.4749	18.5626	28.0408	169.1300	46.4749	18.5626	28.0408	169.5300
46.4749	18.5626	28.0408	169.9200	46.4749	18.5626	28.1386	170.3200
46.4749	18.5626	28.0408	170.7200	46.4749	18.5626	28.0408	171.1100
46.4749	18.5626	28.0408	171.5100	46.4749	18.5626	28.0408	171.9000
46.4749	18.5626	28.0408	172.3000	46.4749	18.5626	28.0408	172.7000
46.4749	18.5626	28.0408	173.0900	46.4749	18.5626	27.9430	173.4900
46.4749	18.5626	28.0408	173.8900	46.4749	18.5626	28.1386	174.2800
46.4749	18.5626	28.0408	174.6800	46.4749	18.5626	28.0408	175.0700
46.4749	18.5626	27.9430	175.4700	46.4749	18.5626	27.9430	175.8700
46.4749	18.5626	28.0408	176.2600	46.4749	18.5626	28.1386	176.6600
46.4749	18.5626	28.0408	177.0600	46.4749	18.5626	28.0408	177.4500
46.4749	18.5626	27.9430	177.8500	46.4749	18.5626	28.0408	178.2400
46.4749	18.5626	28.0408	178.6400	46.4749	18.5626	28.0408	179.0400
46.4749	18.5626	28.0408	179.4300	17.6282	8.9751	27.9430	1 79.8300
4.0530	3.8126	27.8453	180.2200	1.0376	0.8625	27.7475	180.6000
0.0000	0.0000	27.6497	180.9900	0.0000	0.0000	27.5520	181.3800
0.0000	0.0000	27.5520	181.7800	0.0000	0.0000	27.3564	182.1700
0.0000	0.0000	27.3564	182.5600	0.0000	0.0000	27.3564	182.9600
0.0000	0.0000	27.3564	183.3500	0.0000	0.0000	27.2587	183.7500
0.0000	0.0000	27.0631	184.1400	0.0000	0.0000	27.0631	184.5400
0.0000	0.0000	27.0631	184.9300	0.0000	0.0000	26.8676	185.3300
0.0000	0.0000	25.3033	185.7200	0.0000	0.0000	22.6635	186.1100
0.0000	0.0000	19.7305	186.5100	0.0000	0.0000	16.6019	186.9000
0.0000	0.0000	13.5711	187.3000	0.0000	0.0000	10.6380	187.6900
0.0000	0.0000	7.6072	188.0900	0.0000	0.0000	4.6741	188.4800
0.0000	0.0000	1.7411	188.8800	0.0000	0.0000	0.0000	189.2700
0.0000	0.0000	0.0000	189.6600	0.0000	0.0000	0.0000	190.0600
0.0000	0.0000	0.0000	190.4600	0.0000	0.0000	0.0000	190.8600
0.0000	0.0000	0.0000	191.2500	0.0000	0.0000	0.0000	191.6500

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	192.0500	0.0000	0.0000	0.0000	192.4500
0.0000	0.0000	0.0000	192.8500	0.0000	0.0000	0.0000	193.2400
0.0000	0.0000	0.0000	193.6400	0.0000	0.0000	0.0000	194.0400
0.0000	0.0000	0.0000	194.4400	0.0000	0.0000	0.0000	194.8300
0.0000	0.0000	0.0000	195.2300	0.0000	0.0000	0.0000	195.6300
0.0000	0.0000	0.0000	196.0300	0.0000	0.0000	0.0000	196.4300
0.0000	0.0000	0.0000	196.8200	0.0000	0.0000	0.0000	197.2200
0.0000	0.0000	0.0000	197.6200	0.0000	0.0000	0.0000	198.0200
0.0000	0.0000	0.0000	198.4100	0.0000	0.0000	0.0000	198.8100
0.0000	0.0000	0.0000	199.2100	0.0000	0.0000	0.0000	199.6100
0.0000	0.0000	0.0000	200.0100	0.0000	0.0000	0.0000	200.4000
0.0000	0.0000	0.0000	200.8000	0.0000	0.0000	0.0000	201.2000
0.0000	0.0000	0.0000	201.5900	0.0000	0.0000	0.0000	201.9900
0.0000	0.0000	0.0000	202.3900	0.0000	0.0000	0.0000	202.7900
0.0000	0.0000	0.0000	203.1900	0.0000	0.0000	0.0000	203.5800
0.0000	0.0000	0.0000	203.9800	0.0000	0.0000	0.0000	204.3800
0.0000	0.0000	0.0000	204.7800	0.0000	0.0000	0.0000	205.1700

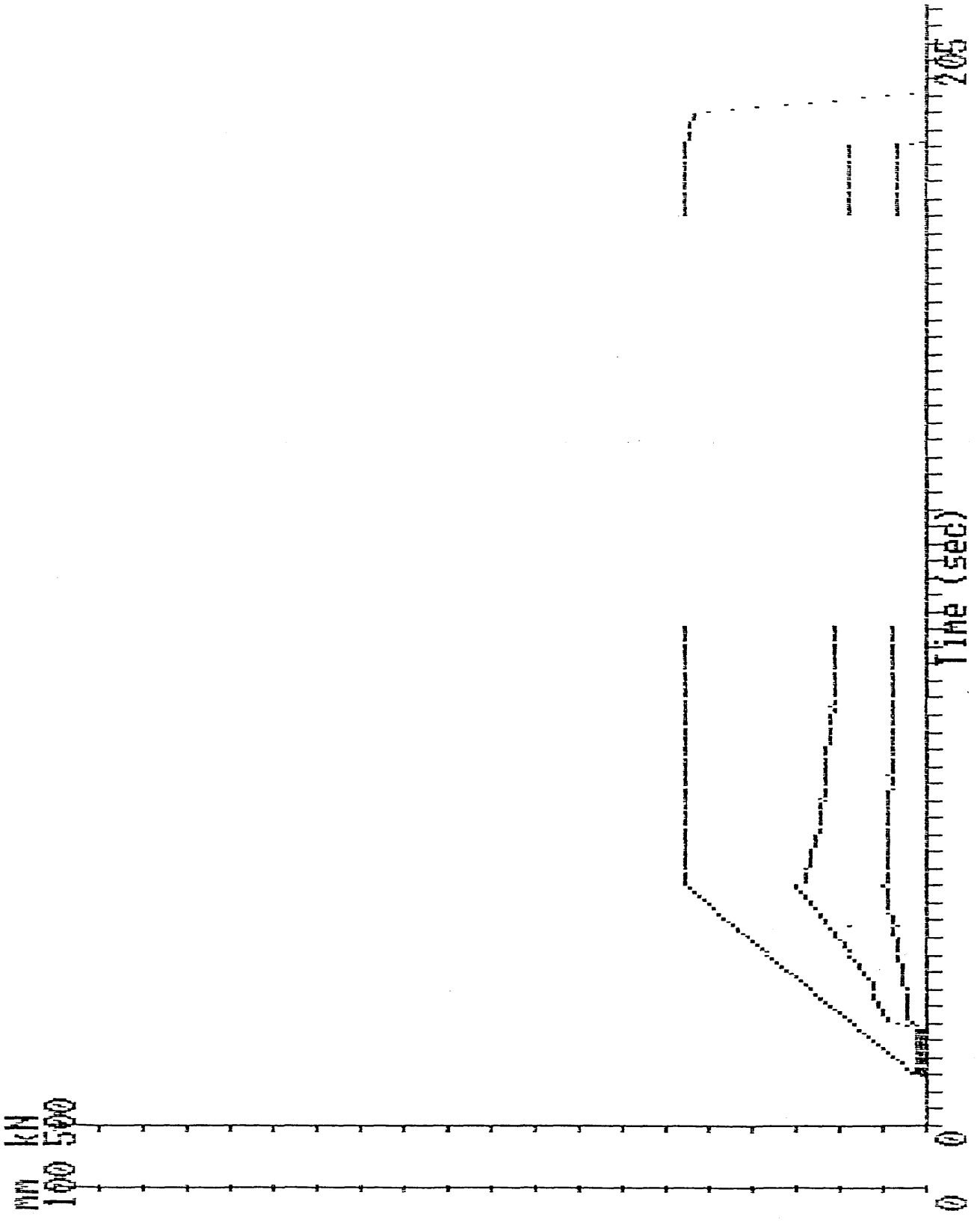


Fig.A5.11. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.12.

****

RESULTS - SPECIMEN No.13

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The results of this test are stored in the file B:09-01-13.DAT

The values at maximum load are :-

Load at Top Load Cell = 70.2312 (kN)

Load at Bottom Load Cell = 21.51257 (kN)

Displacement = 19.43718 (mm)

Time Elasped = 31.26 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	1.7411	7.9200	0.0000	0.0000	1.9366	8.3100
0.0000	0.0000	2.3277	8.7000	0.0000	0.0000	2.6210	9.0800
0.0000	0.0000	2.9143	9.4700	0.0000	0.0000	3.3054	9.8600
1.0376	1.6001	3.5009	10.2500	15.9312	11.9250	3.6964	10.6400
29.5061	17.0875	3.8920	11.0300	31.2031	17.8251	4.1853	11.4200
31.2031	17.8251	4.4786	11.8100	31.2031	17.8251	4.7719	12.2000
31.2031	17.8251	5.0652	12.5900	31.2031	17.8251	5.4563	12.9800
32.8999	17.8251	5.6518	13.3700	32.8999	18.5626	5.9451	13.7600
32.8999	18.5626	6.2384	14.1500	32.8999	18.5626	6.6295	14.5400
32.8999	18.5626	6.9228	14.9300	32.8999	18.5626	7.2161	15.3200
32.8999	18.5626	7.5094	15.7100	32.8999	18.5626	7.9005	16.1000
32.8999	18.5626	8.0960	16.4900	32.8999	18.5626	8.3893	16.8800
36.2937	19.3000	8.7804	17.2700	37.9905	20.0376	9.0737	17.6600
39.6875	20.0376	9.3670	18.0500	41.3843	20.0376	9.6603	18.4400
41.3843	20.0376	9.9536	18.8300	43.0813	20.7750	10.2469	19.2200
44.7781	20.7750	10.5402	19.6100	44.7781	20.7750	10.8335	20.0000
46.4749	20.7750	11.1268	20.3900	46.4749	20.7750	11.4202	20.7800
48.1719	20.7750	11.7135	21.1700	48.1719	20.7750	12.1045	21.5600
49.8687	20.7750	12.3001	21.9400	49.8687	20.7750	12.6911	22.3300
51.5657	20.7750	12.8867	22.7200	51.5657	20.7750	13.1800	23.1100
51.5657	20.7750	13.5711	23.5000	53.2625	20.7750	13.7666	23.8800
53.2625	20.7750	14.1577	24.2700	54.9592	20.7750	14.4510	24.6600
54.9592	20.7750	14.7443	25.0500	56.6563	21.5126	15.0376	25.4400
56.6563	21.5126	15.2331	25.8300	58.3530	21.5126	15.6242	26.2100
60.0500	21.5126	15.8197	26.6000	60.0500	21.5126	16.2108	26.9900
61.7468	21.5126	16.5041	27.3800	63.4436	20.7750	16.7974	27.7700
63.4436	21.5126	17.1885	28.1500	63.4436	21.5126	17.2863	28.5400
65.1406	21.5126	17.6773	28.9300	65.1406	21.5126	17.9706	29.3200

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
66.8374	21.5126	18.2639	29.7100	66.8374	21.5126	18.5573	30.1000
68.5344	21.5126	18.8506	30.4800	68.5344	21.5126	19.3394	30.8700
70.2312	21.5126	19.4372	31.2600	68.5344	20.7750	19.5349	31.6500
68.5344	20.7750	19.4372	32.0400	68.5344	20.7750	19.4372	32.4200
68.5344	20.7750	19.6327	32.8100	66.8374	20.7750	19.4372	33.2000
66.8374	20.7750	19.5349	33.5900	66.8374	20.7750	19.5349	33.9800
66.8374	20.7750	19.5349	34.3600	66.8374	20.7750	19.5349	34.7500
66.8374	20.7750	19.4372	35.1400	66.8374	20.0376	19.5349	35.5300
66.8374	20.7750	19.6327	35.9100	66.8374	20.7750	19.5349	36.3000
66.8374	20.0376	19.5349	36.6900	66.8374	20.7750	19.4372	37.0800
66.8374	20.0376	19.5349	37.4700	65.1406	20.0376	19.5349	37.8500
65.1406	20.0376	19.4372	38.2400	65.1406	20.0376	19.5349	38.6300
65.1406	20.0376	19.5349	39.0200	65.1406	20.0376	19.5349	39.4000
65.1406	20.0376	19.5349	39.7900	65.1406	20.0376	19.5349	40.1800
65.1406	20.0376	19.5349	40.5600	65.1406	20.0376	19.5349	40.9500
65.1406	20.0376	19.4372	41.3400	65.1406	20.0376	19.5349	41.7200
63.4436	20.0376	19.6327	42.1100	63.4436	20.0376	19.5349	42.5000
63.4436	20.0376	19.5349	42.8800	63.4436	19.3000	19.5349	43.2700
63.4436	20.0376	19.5349	43.6600	63.4436	20.0376	19.5349	44.0400
63.4436	19.3000	19.5349	44.4300	61.7468	20.0376	19.5349	44.8200
63.4436	19.3000	19.5349	45.2000	63.4436	19.3000	19.5349	45.5900
63.4436	19.3000	19.5349	45.9700	61.7468	19.3000	19.5349	46.3600
63.4436	19.3000	19.5349	46.7500	61.7468	19.3000	19.5349	47.1300
61.7468	19.3000	19.5349	47.5200	61.7468	19.3000	19.5349	47.9100
61.7468	19.3000	19.5349	48.2900	61.7468	19.3000	19.4372	48.6800
61.7468	19.3000	19.5349	49.0600	61.7468	19.3000	19.5349	49.4500
61.7468	19.3000	19.5349	49.8400	61.7468	19.3000	19.6327	50.2200
60.0500	19.3000	19.5349	50.6100	60.0500	19.3000	19.5349	51.0000
60.0500	19.3000	19.5349	51.3800	60.0500	18.5626	19.5349	51.7700
60.0500	19.3000	19.5349	52.1500	60.0500	19.3000	19.5349	52.5400
60.0500	19.3000	19.5349	52.9300	60.0500	19.3000	19.5349	53.3100
60.0500	19.3000	19.5349	53.7000	60.0500	19.3000	19.6327	54.0900
60.0500	19.3000	19.5349	54.4700	60.0500	19.3000	19.5349	54.8600
60.0500	18.5626	19.5349	55.2500	60.0500	19.3000	19.5349	55.6300
60.0500	18.5626	19.5349	56.0200	60.0500	18.5626	19.5349	56.4000
60.0500	19.3000	19.5349	56.7900	58.3530	18.5626	19.5349	57.1800
58.3530	18.5626	19.5349	57.5600	58.3530	18.5626	19.5349	57.9500
58.3530	18.5626	19.5349	58.3400	58.3530	18.5626	19.5349	58.7200
58.3530	18.5626	19.5349	59.1100	58.3530	18.5626	19.5349	59.5000
58.3530	18.5626	19.5349	59.8800	58.3530	18.5626	19.5349	60.2700
58.3530	18.5626	19.5349	60.6600	58.3530	18.5626	19.5349	61.0400
58.3530	18.5626	19.5349	61.4400	58.3530	18.5626	19.5349	61.8300
58.3530	18.5626	19.5349	62.2200	53.2625	16.3501	19.5349	62.6200
58.3530	18.5626	19.5349	63.0100	56.6563	18.5626	19.5349	63.4000
58.3530	18.5626	19.5349	63.8000	58.3530	18.5626	19.6327	64.1900
58.3530	18.5626	19.5349	64.5800	58.3530	18.5626	19.5349	64.9700
58.3530	18.5626	19.6327	65.3700	56.6563	18.5626	19.5349	65.7600
58.3530	18.5626	19.5349	66.1500	56.6563	18.5626	19.5349	66.5400
56.6563	18.5626	19.7305	66.9400	56.6563	18.5626	19.5349	67.3300
56.6563	17.8251	19.5349	67.7200	56.6563	18.5626	19.5349	68.1200
56.6563	18.5626	19.5349	68.5100	56.6563	18.5626	19.5349	68.9000
56.6563	18.5626	19.5349	69.2900	56.6563	17.8251	19.5349	69.6900
56.6563	17.8251	19.5349	70.0800	56.6563	17.8251	19.5349	70.4800
56.6563	17.8251	19.5349	70.8700	56.6563	17.8251	19.5349	71.2700
56.6563	17.8251	19.5349	71.6600	56.6563	17.8251	19.5349	72.0600
56.6563	17.8251	19.5349	72.4600	56.6563	17.8251	19.5349	72.8500

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
56.6563	17.8251	19.5349	73.2500	56.6563	17.8251	19.6327	73.6400
56.6563	17.8251	19.5349	74.0400	51.5657	17.0875	19.5349	149.0000
51.5657	17.0875	19.5349	149.4000	51.5657	17.0875	19.5349	149.7900
51.5657	17.0875	19.5349	150.1900	51.5657	17.0875	19.5349	150.5800
51.5657	17.0875	19.5349	150.9800	51.5657	17.0875	19.5349	151.3700
51.5657	17.0875	19.6327	151.7700	51.5657	17.0875	19.5349	152.1600
51.5657	17.0875	19.5349	152.5600	51.5657	17.0875	19.5349	152.9600
51.5657	17.0875	19.6327	153.3500	51.5657	17.0875	19.5349	153.7500
51.5657	17.0875	19.5349	154.1400	51.5657	17.0875	19.5349	154.5400
51.5657	17.0875	19.5349	154.9300	51.5657	17.0875	19.6327	155.3300
51.5657	17.0875	19.5349	155.7300	51.5657	17.0875	19.5349	156.1200
51.5657	17.0875	19.5349	156.5200	51.5657	17.0875	19.5349	156.9200
51.5657	17.0875	19.6327	157.3100	51.5657	17.0875	19.6327	157.7100
51.5657	17.0875	19.5349	158.1000	51.5657	17.0875	19.5349	158.5000
51.5657	17.0875	19.5349	158.9000	51.5657	16.3501	19.6327	159.2900
51.5657	17.0875	19.6327	159.6900	51.5657	17.0875	19.5349	160.0900
51.5657	17.0875	19.5349	160.4800	51.5657	17.0875	19.5349	160.8800
51.5657	16.3501	19.5349	161.2700	51.5657	17.0875	19.5349	161.6700
51.5657	17.0875	19.5349	162.0700	51.5657	17.0875	19.5349	162.4600
51.5657	17.0875	19.5349	162.8600	51.5657	17.0875	19.6327	163.2500
51.5657	17.0875	19.5349	163.6500	51.5657	17.0875	19.5349	164.0500
51.5657	17.0875	19.5349	164.4400	51.5657	16.3501	19.6327	164.8400
51.5657	17.0875	19.6327	165.2300	51.5657	17.0875	19.5349	165.6300
51.5657	17.0875	19.5349	166.0300	51.5657	17.0875	19.5349	166.4200
51.5657	16.3501	19.6327	166.8200	51.5657	17.0875	19.5349	167.2100
51.5657	17.0875	19.5349	167.6100	51.5657	17.0875	19.5349	168.0100
51.5657	17.0875	19.5349	168.4000	9.1438	4.5500	19.4372	168.8000
0.0000	0.0000	18.8506	169.1900	0.0000	0.0000	16.8952	169.5900
0.0000	0.0000	14.0599	169.9900	0.0000	0.0000	11.1268	170.3900
0.0000	0.0000	8.2916	170.7800	0.0000	0.0000	5.3585	171.1800
0.0000	0.0000	2.4254	171.5800	0.0000	0.0000	0.0000	171.9800
0.0000	0.0000	0.0000	172.3700	0.0000	0.0000	0.0000	172.7700
0.0000	0.0000	0.0000	173.1700	0.0000	0.0000	0.0000	173.5700
0.0000	0.0000	0.0000	173.9600	0.0000	0.0000	0.0000	174.3600
0.0000	0.0000	0.0000	174.7600	0.0000	0.0000	0.0000	175.1600
0.0000	0.0000	0.0000	175.5600	0.0000	0.0000	0.0000	175.9500
0.0000	0.0000	0.0000	176.3500	0.0000	0.0000	0.0000	176.7500
0.0000	0.0000	0.0000	177.1500	0.0000	0.0000	0.0000	177.5400
0.0000	0.0000	0.0000	177.9400	0.0000	0.0000	0.0000	178.3400
0.0000	0.0000	0.0000	178.7400	0.0000	0.0000	0.0000	179.1400
0.0000	0.0000	0.0000	179.5300	0.0000	0.0000	0.0000	179.9300
0.0000	0.0000	0.0000	180.3200	0.0000	0.0000	0.0000	180.7100
0.0000	0.0000	0.0000	181.1000	0.0000	0.0000	0.0000	181.5000
0.0000	0.0000	0.0000	181.8900	0.0000	0.0000	0.0000	182.2900
0.0000	0.0000	0.0000	182.6800	0.0000	0.0000	0.0000	183.0800
0.0000	0.0000	0.0000	183.4700	0.0000	0.0000	0.0000	183.8700

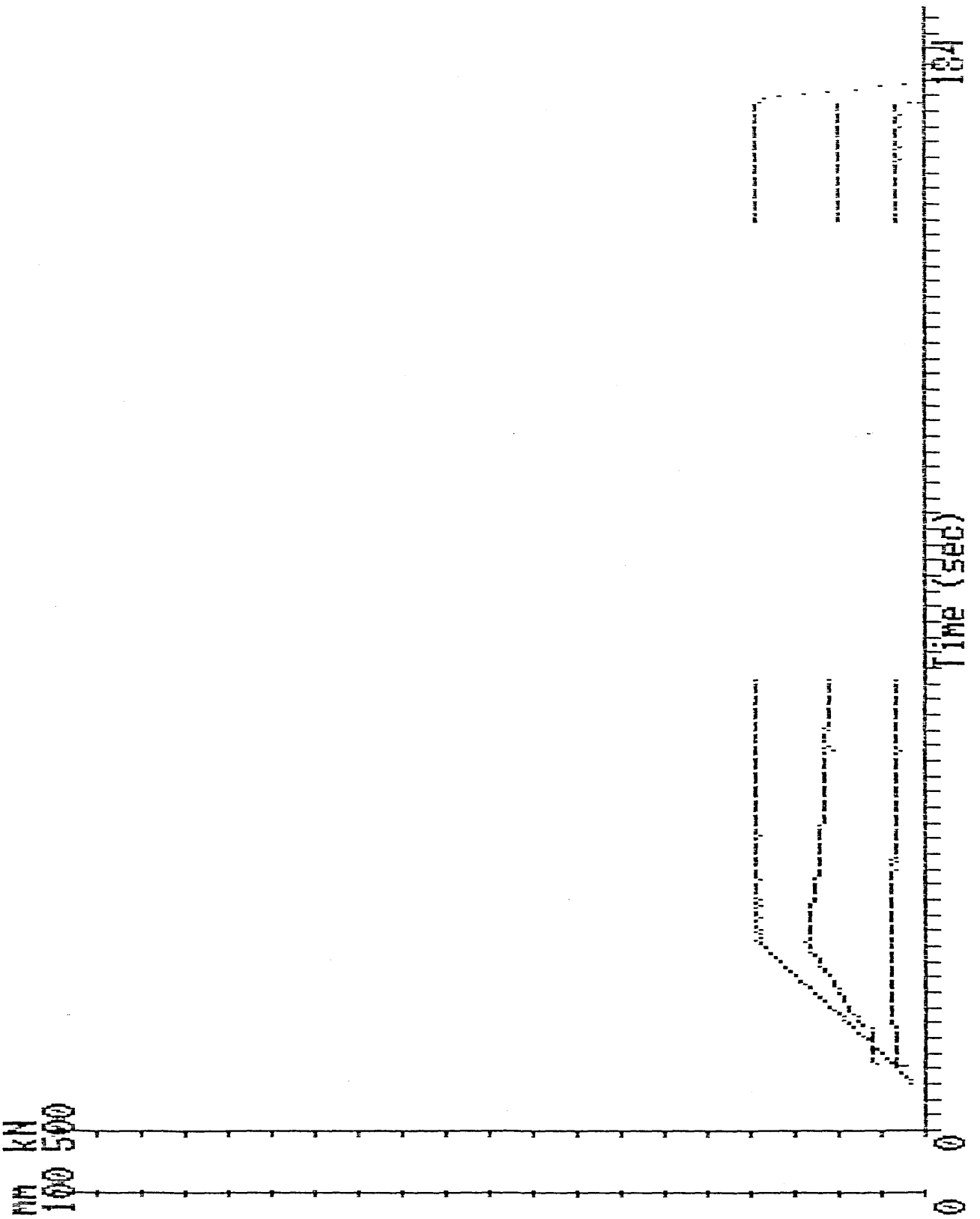


Fig.A5.12. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.13.

****

RESULTS - SPECIMEN No.14

****

The results of this test are stored in the file B:09-01-14.DAT

The values at maximum load are :-

Load at Top Load Cell = 48.17188 (kN)

Load at Bottom Load Cell = 20.77502 (kN)

Displacement = 12.59337 (mm)

Time Elasped = 25.06 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9300	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.0900
0.0000	0.0000	0.0000	2.4800	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4200
0.0000	0.0000	0.0000	4.8100	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0800
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	0.0000	9.8600
0.0000	0.0000	0.0000	10.2500	0.0000	0.0000	1.7411	10.6400
0.0000	0.0000	2.0344	11.0300	0.0000	0.0000	2.4254	11.4200
0.0000	0.0000	2.6210	11.8100	0.0000	0.0000	3.0121	12.2000
0.0000	0.0000	3.3054	12.5900	0.0000	0.0000	3.5987	12.9800
9.1438	8.2375	3.6964	13.3700	21.0217	11.9250	3.9897	13.7600
22.7188	12.6626	4.2831	14.1500	24.4155	13.4000	4.5764	14.5400
24.4155	13.4000	4.7719	14.9300	26.1125	13.4000	5.1630	15.3300
26.1125	14.1376	5.3585	15.7200	26.1125	14.1376	5.7496	16.1000
26.1125	14.1376	6.0429	16.4900	27.8093	14.8751	6.3362	16.8900
29.5061	14.8751	6.6295	17.2800	29.5061	14.8751	6.9228	17.6700
29.5061	15.6125	7.2161	18.0600	31.2031	15.6125	7.5094	18.4500
31.2031	15.6125	7.9005	18.8400	31.2031	15.6125	8.1938	19.2300
32.8999	15.6125	8.4871	19.6200	32.8999	16.3501	8.7804	20.0100
32.8999	16.3501	9.0737	20.4000	34.5969	17.0875	9.3670	20.7900
36.2937	17.0875	9.6603	21.1700	36.2937	17.0875	10.0514	21.5600
37.9905	17.8251	10.1492	21.9500	37.9905	17.8251	10.5402	22.3400
39.6875	18.5626	10.9313	22.7300	41.3843	19.3000	11.1268	23.1100
43.0813	19.3000	11.6157	23.5000	44.7781	20.0376	11.8112	23.8900
44.7781	20.0376	12.0068	24.2800	46.4749	20.0376	12.3978	24.6700
48.1719	20.7750	12.5934	25.0600	48.1719	20.7750	12.8867	25.4400
32.8999	15.6125	13.3755	25.8300	41.3843	17.8251	13.5711	26.2200
36.2937	16.3501	13.8644	26.6100	34.5969	16.3501	14.2554	27.0000
34.5969	15.6125	14.4510	27.3900	34.5969	15.6125	15.1354	27.7700
37.9905	17.0875	14.8421	28.1600	39.6875	17.0875	14.7443	28.5500
37.9905	17.0875	14.8421	28.9400	39.6875	17.0875	14.8421	29.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
37.9905	17.0875	14.8421	29.7200	37.9905	17.0875	14.8421	30.1000
37.9905	17.0875	14.8421	30.4900	37.9905	17.0875	14.8421	30.8800
37.9905	17.0875	14.8421	31.2700	37.9905	17.0875	14.8421	31.6600
37.9905	17.0875	14.8421	32.0400	37.9905	17.0875	14.8421	32.4300
37.9905	17.0875	14.8421	32.8200	37.9905	17.0875	14.8421	33.2100
37.9905	17.0875	14.8421	33.6000	37.9905	17.0875	14.8421	33.9800
37.9905	17.0875	14.8421	34.3700	37.9905	17.0875	14.8421	34.7600
37.9905	17.0875	14.8421	35.1500	37.9905	17.0875	14.8421	35.5400
37.9905	17.0875	14.8421	35.9200	37.9905	17.0875	14.8421	36.3100
37.9905	17.0875	14.8421	36.7000	37.9905	17.0875	14.8421	37.0900
37.9905	17.0875	14.8421	37.4800	37.9905	17.0875	14.7443	37.8700
37.9905	17.0875	14.8421	38.2500	37.9905	17.0875	14.8421	38.6400
37.9905	17.0875	14.8421	39.0300	37.9905	17.0875	14.8421	39.4200
37.9905	17.0875	14.8421	39.8100	37.9905	17.0875	14.8421	40.1900
36.2937	17.0875	14.7443	40.5800	37.9905	17.0875	14.8421	40.9700
37.9905	17.0875	14.8421	41.3500	36.2937	17.0875	14.8421	41.7400
37.9905	17.0875	14.8421	42.1300	37.9905	17.0875	14.8421	42.5100
37.9905	17.0875	14.8421	42.9000	36.2937	17.0875	14.8421	43.2900
36.2937	17.0875	14.8421	43.6700	36.2937	16.3501	14.8421	44.0600
37.9905	17.0875	14.8421	44.4500	36.2937	16.3501	14.8421	44.8300
36.2937	16.3501	14.8421	45.2200	36.2937	17.0875	14.5488	45.6100
36.2937	17.0875	14.8421	45.9900	36.2937	17.0875	14.8421	46.3800
36.2937	17.0875	14.8421	46.7700	36.2937	17.0875	14.8421	47.1500
36.2937	17.0875	14.8421	47.5400	36.2937	16.3501	14.8421	47.9300
36.2937	16.3501	14.8421	48.3200	36.2937	16.3501	14.8421	48.7000
36.2937	16.3501	14.8421	49.0900	36.2937	16.3501	14.8421	49.4800
36.2937	17.0875	14.8421	49.8600	36.2937	17.0875	14.8421	50.2500
36.2937	16.3501	14.9398	50.6400	36.2937	17.0875	14.8421	51.0200
36.2937	16.3501	14.8421	51.4100	36.2937	16.3501	14.9398	51.8000
36.2937	16.3501	14.8421	52.1800	36.2937	16.3501	14.8421	52.5700
36.2937	16.3501	14.8421	52.9600	36.2937	16.3501	14.8421	53.3400
36.2937	16.3501	14.8421	53.7300	36.2937	16.3501	14.8421	54.1200
36.2937	16.3501	14.8421	54.5000	36.2937	16.3501	14.8421	54.8900
36.2937	16.3501	14.8421	55.2800	36.2937	16.3501	14.8421	55.6700
36.2937	16.3501	14.8421	56.0500	36.2937	16.3501	14.8421	56.4400
36.2937	16.3501	14.8421	56.8300	36.2937	16.3501	14.8421	57.2100
36.2937	16.3501	14.8421	57.6000	36.2937	16.3501	14.9398	57.9900
36.2937	16.3501	14.8421	58.3700	36.2937	16.3501	14.8421	58.7600
36.2937	16.3501	14.9398	59.1500	36.2937	16.3501	14.8421	59.5300
36.2937	16.3501	14.8421	59.9200	36.2937	16.3501	14.8421	60.3100
36.2937	16.3501	14.8421	60.7000	36.2937	16.3501	14.8421	61.0800
36.2937	16.3501	14.9398	61.4800	36.2937	16.3501	14.8421	61.8700
32.8999	14.8751	14.8421	136.7900	32.8999	14.8751	14.9398	137.1800
32.8999	14.8751	14.8421	137.5800	32.8999	14.8751	14.7443	137.9800
32.8999	14.8751	14.8421	138.3700	32.8999	14.8751	14.9398	138.7700
32.8999	14.8751	14.8421	139.1600	32.8999	14.8751	14.8421	139.5600
32.8999	14.8751	14.8421	139.9600	32.8999	14.8751	14.9398	140.3500
32.8999	14.8751	14.8421	140.7500	32.8999	14.8751	14.8421	141.1400
32.8999	14.8751	14.8421	141.5400	32.8999	14.8751	14.8421	141.9300
32.8999	14.8751	14.8421	142.3300	32.8999	14.8751	14.8421	142.7300
32.8999	14.8751	14.9398	143.1200	32.8999	14.8751	14.8421	143.5200
32.8999	14.8751	14.8421	143.9100	32.8999	15.6125	14.8421	144.3100
32.8999	14.8751	14.9398	144.7000	32.8999	14.8751	14.8421	145.1000
32.8999	14.8751	14.8421	145.4900	32.8999	15.6125	14.8421	145.8900
32.8999	14.8751	14.8421	146.2800	32.8999	14.8751	14.8421	146.6800
32.8999	14.8751	14.8421	147.0800	32.8999	14.8751	14.8421	147.4700

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
32.8999	14.8751	14.8421	147.8700	32.8999	14.8751	14.8421	148.2600
32.8999	14.8751	14.8421	148.6600	32.8999	14.8751	14.9398	149.0500
32.8999	14.8751	14.8421	149.4500	32.8999	14.8751	14.8421	149.8400
32.8999	14.8751	14.8421	150.2400	32.8999	14.8751	14.8421	150.6400
32.8999	14.8751	14.6465	151.0300	32.8999	14.8751	14.7443	151.4300
32.8999	14.8751	14.8421	151.8200	32.8999	14.8751	14.8421	152.2200
32.8999	14.8751	14.8421	152.6100	32.8999	14.8751	14.8421	153.0100
32.8999	14.8751	14.8421	153.4000	32.8999	14.8751	14.8421	153.8000
32.8999	14.8751	14.8421	154.1900	32.8999	14.8751	14.8421	154.5900
32.8999	14.8751	14.8421	154.9900	32.8999	14.8751	14.8421	155.3800
32.8999	14.8751	14.8421	155.7800	32.8999	14.8751	14.7443	156.1800
32.8999	14.8751	14.8421	156.5700	31.2031	14.8751	14.8421	156.9700
31.2031	14.8751	14.9398	157.3700	32.8999	14.8751	14.8421	157.7600
32.8999	14.8751	14.8421	158.1600	32.8999	14.8751	14.8421	158.5600
32.8999	14.8751	14.8421	158.9500	32.8999	14.8751	14.8421	159.3500

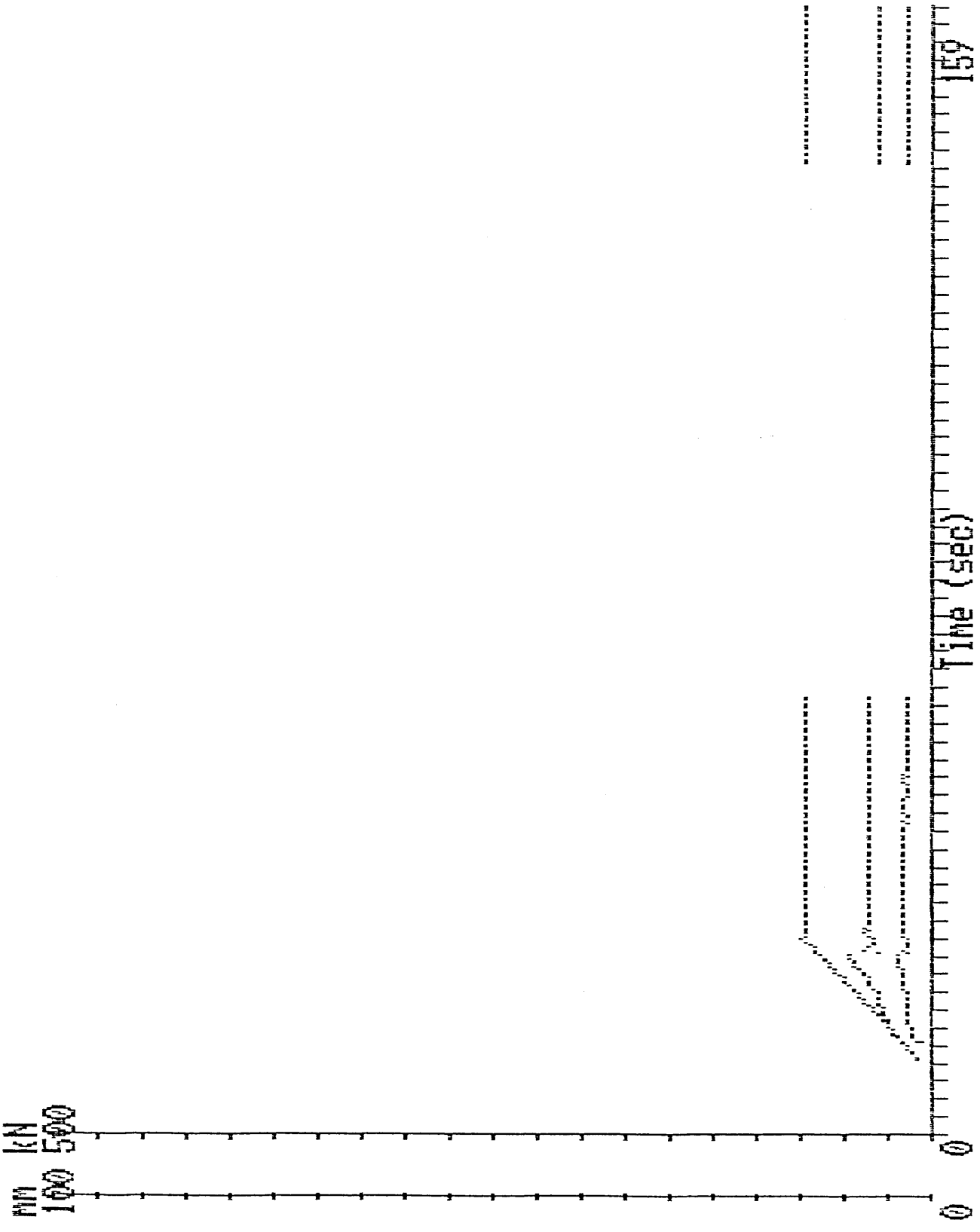


Fig.A5.13. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.14.

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RESULTS - SPECIMEN No.15

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The results of this test are stored in the file B:09-01-15.DAT

The values at maximum load are :-

Load at Top Load Cell = 70.2312 (kN)

Load at Bottom Load Cell = 20.77502 (kN)

Displacement = 11.909 (mm)

Time Elasped = 23.89 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	1.7411	9.8600
0.0000	0.0000	1.9366	10.2500	0.0000	0.0000	2.3277	10.6400
0.0000	0.0000	2.6210	11.0400	0.0000	0.0000	3.0121	11.4300
0.0000	0.0000	3.3054	11.8200	0.0000	0.0000	3.5987	12.2100
2.3562	3.0751	3.6964	12.6000	21.0217	10.4501	3.8920	12.9800
26.1125	11.1876	4.1853	13.3800	26.1125	11.1876	4.4786	13.7700
26.1125	11.1876	4.6741	14.1600	26.1125	11.1876	5.1630	14.5500
27.8093	11.9250	5.3585	14.9400	27.8093	12.6626	5.6518	15.3300
31.2031	12.6626	5.9451	15.7200	31.2031	13.4000	6.2384	16.1100
32.8999	14.1376	6.4340	16.5000	32.8999	14.1376	6.8250	16.8900
34.5969	14.8751	7.0206	17.2800	36.2937	15.6125	7.4116	17.6700
37.9905	16.3501	7.6072	18.0600	41.3843	16.3501	7.9983	18.4500
43.0813	17.8251	8.2916	18.8400	44.7781	17.8251	8.5849	19.2300
46.4749	18.5626	8.7804	19.6200	49.8687	18.5626	9.2692	20.0100
53.2625	19.3000	9.3670	20.4000	54.9592	19.3000	9.7581	20.7900
56.6563	20.0376	9.9536	21.1700	58.3530	20.0376	10.1492	21.5600
60.0500	20.0376	10.5402	21.9500	61.7468	20.0376	10.7358	22.3400
63.4436	20.0376	11.1268	22.7300	65.1406	20.0376	11.4202	23.1100
66.8374	20.7750	11.6157	23.5000	70.2312	20.7750	11.9090	23.8900
66.8374	20.0376	12.0068	24.2800	66.8374	20.0376	12.1045	24.6700
65.1406	19.3000	12.1045	25.0500	65.1406	20.0376	12.0068	25.4400
65.1406	19.3000	12.1045	25.8300	65.1406	19.3000	12.0068	26.2200
65.1406	19.3000	12.0068	26.6100	65.1406	19.3000	12.1045	27.0000
65.1406	19.3000	12.0068	27.3800	65.1406	19.3000	12.1045	27.7700
65.1406	19.3000	12.1045	28.1600	65.1406	19.3000	12.0068	28.5500
63.4436	19.3000	12.1045	28.9400	63.4436	19.3000	12.0068	29.3200

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
63.4436	19.3000	12.1045	29.7100	63.4436	19.3000	12.1045	30.1000
63.4436	19.3000	12.0068	30.4900	63.4436	19.3000	12.1045	30.8800
63.4436	19.3000	12.0068	31.2600	63.4436	19.3000	12.0068	31.6500
63.4436	18.5626	12.1045	32.0400	63.4436	19.3000	12.0068	32.4300
63.4436	19.3000	12.1045	32.8200	63.4436	19.3000	12.1045	33.2000
63.4436	18.5626	12.0068	33.5900	63.4436	19.3000	12.1045	33.9800
63.4436	19.3000	12.1045	34.3700	63.4436	19.3000	12.0068	34.7600
63.4436	18.5626	12.1045	35.1400	61.7468	19.3000	12.0068	35.5300
61.7468	18.5626	12.0068	35.9200	63.4436	18.5626	12.1045	36.3100
61.7468	18.5626	12.0068	36.7000	63.4436	18.5626	12.1045	37.0800
61.7468	18.5626	12.1045	37.4700	61.7468	18.5626	12.0068	37.8600
61.7468	18.5626	12.1045	38.2500	61.7468	19.3000	12.1045	38.6300
61.7468	19.3000	12.0068	39.0200	61.7468	18.5626	12.1045	39.4100
61.7468	18.5626	12.0068	39.8000	61.7468	18.5626	12.0068	40.1800
61.7468	18.5626	12.1045	40.5700	61.7468	18.5626	12.1045	40.9600
61.7468	18.5626	12.0068	41.3400	61.7468	18.5626	12.1045	41.7300
61.7468	18.5626	12.1045	42.1200	61.7468	18.5626	12.0068	42.5000
61.7468	18.5626	12.1045	42.8900	61.7468	18.5626	12.1045	43.2700
61.7468	18.5626	12.0068	43.6600	61.7468	18.5626	12.1045	44.0500
61.7468	18.5626	12.1045	44.4300	61.7468	18.5626	12.1045	44.8200
61.7468	18.5626	12.0068	45.2100	61.7468	18.5626	12.1045	45.5900
61.7468	18.5626	12.1045	45.9800	61.7468	18.5626	12.0068	46.3700
60.0500	18.5626	12.1045	46.7500	61.7468	18.5626	12.1045	47.1400
60.0500	18.5626	12.0068	47.5300	60.0500	18.5626	12.1045	47.9100
61.7468	18.5626	12.0068	48.3000	60.0500	18.5626	12.0068	48.6900
60.0500	18.5626	12.0068	49.0700	60.0500	18.5626	12.1045	49.4600
60.0500	18.5626	12.1045	49.8500	60.0500	18.5626	12.0068	50.2300
60.0500	18.5626	12.1045	50.6200	60.0500	18.5626	12.1045	51.0100
60.0500	18.5626	12.0068	51.3900	60.0500	18.5626	12.1045	51.7800
60.0500	18.5626	12.1045	52.1600	60.0500	18.5626	12.0068	52.5500
60.0500	18.5626	12.1045	52.9400	60.0500	18.5626	12.1045	53.3200
60.0500	18.5626	12.0068	53.7100	60.0500	18.5626	12.0068	54.1000
60.0500	18.5626	12.1045	54.4800	60.0500	18.5626	12.1045	54.8700
60.0500	18.5626	12.0068	55.2600	60.0500	18.5626	12.1045	55.6400
60.0500	18.5626	12.1045	56.0300	60.0500	18.5626	12.0068	56.4200
60.0500	17.8251	12.1045	56.8000	60.0500	18.5626	12.1045	57.1900
60.0500	18.5626	12.0068	57.5800	60.0500	17.8251	12.0068	57.9600
60.0500	18.5626	12.1045	58.3500	60.0500	18.5626	12.0068	58.7400
60.0500	17.8251	12.0068	59.1200	60.0500	17.8251	12.1045	59.5100
60.0500	18.5626	12.1045	59.9000	60.0500	18.5626	12.0068	60.2800
60.0500	18.5626	12.1045	60.6700	60.0500	17.8251	12.1045	61.0600
60.0500	17.8251	12.1045	61.4500	60.0500	18.5626	12.1045	61.8400
60.0500	18.5626	12.1045	62.2400	58.3530	17.8251	12.1045	62.6300
60.0500	18.5626	12.0068	63.0200	60.0500	17.8251	12.1045	63.4200
58.3530	18.5626	12.1045	63.8100	58.3530	17.8251	12.0068	64.2000
60.0500	17.8251	12.1045	64.6000	56.6563	17.0875	12.1045	139.8700
56.6563	17.0875	12.1045	140.2700	54.9592	17.0875	12.0068	140.6600
56.6563	17.0875	12.1045	141.0600	56.6563	17.0875	12.1045	141.4500
56.6563	17.8251	12.1045	141.8500	56.6563	17.0875	12.1045	142.2400
56.6563	17.0875	12.1045	142.6400	54.9592	17.0875	12.1045	143.0400
56.6563	17.0875	12.0068	143.4300	54.9592	17.0875	12.1045	143.8300
54.9592	17.0875	12.1045	144.2200	54.9592	17.0875	12.1045	144.6200
56.6563	17.0875	12.0068	145.0100	54.9592	17.0875	12.1045	145.4100
54.9592	17.0875	12.1045	145.8000	54.9592	17.0875	12.0068	146.2000
54.9592	17.0875	12.0068	146.5900	54.9592	17.0875	12.1045	146.9900
54.9592	17.0875	12.1045	147.3800	56.6563	17.0875	12.0068	147.7800

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
56.6563	17.0875	12.1045	148.1700	56.6563	17.0875	12.1045	148.5700
54.9592	17.0875	12.0068	148.9600	54.9592	17.0875	12.0068	149.3600
54.9592	17.0875	12.1045	149.7500	56.6563	17.0875	12.1045	150.1500
54.9592	17.0875	12.0068	150.5400	54.9592	17.0875	12.1045	150.9400
56.6563	17.0875	12.2023	151.3400	54.9592	17.0875	12.1045	151.7300
54.9592	17.0875	12.0068	152.1300	54.9592	17.0875	12.1045	152.5200
54.9592	17.0875	12.1045	152.9200	54.9592	17.0875	12.0068	153.3100
54.9592	17.0875	12.0068	153.7100	54.9592	17.0875	12.1045	154.1000
54.9592	17.0875	12.1045	154.5000	54.9592	17.0875	12.0068	154.8900
54.9592	17.0875	12.0068	155.2900	54.9592	17.0875	12.1045	155.6900
54.9592	17.0875	12.1045	156.0800	54.9592	17.0875	12.0068	156.4800
54.9592	17.0875	12.0068	156.8700	54.9592	17.0875	12.1045	157.2700
54.9592	17.0875	12.0068	157.6700	54.9592	17.0875	12.1045	158.0600
54.9592	17.0875	12.1045	158.4600	54.9592	17.0875	12.1045	158.8600
54.9592	17.0875	12.1045	159.2500	54.9592	17.0875	12.1045	159.6500
54.9592	17.0875	12.0068	160.0400	54.9592	17.0875	12.1045	160.4400
54.9592	17.0875	12.1045	160.8400	54.9592	17.0875	12.1045	161.2300
54.9592	17.0875	12.1045	161.6300	54.9592	17.0875	12.0068	162.0200
54.9592	17.0875	12.1045	162.4200	54.9592	17.0875	12.1045	162.8200
0.0000	0.0000	11.6157	163.2100	0.0000	0.0000	10.1492	163.6100
0.0000	0.0000	7.4116	164.0100	0.0000	0.0000	4.5764	164.4000
0.0000	0.0000	1.8388	164.8000	0.0000	0.0000	0.0000	165.2000
0.0000	0.0000	0.0000	165.6000	0.0000	0.0000	0.0000	165.9900
0.0000	0.0000	0.0000	166.3900	0.0000	0.0000	0.0000	166.7900
0.0000	0.0000	0.0000	167.1900	0.0000	0.0000	0.0000	167.5800
0.0000	0.0000	0.0000	167.9800	0.0000	0.0000	0.0000	168.3800
0.0000	0.0000	0.0000	168.7800	0.0000	0.0000	0.0000	169.1700
0.0000	0.0000	0.0000	169.5700	0.0000	0.0000	0.0000	169.9700
0.0000	0.0000	0.0000	170.3700	0.0000	0.0000	0.0000	170.7700
0.0000	0.0000	0.0000	171.1600	0.0000	0.0000	0.0000	171.5600
0.0000	0.0000	0.0000	171.9600	0.0000	0.0000	0.0000	172.3600
0.0000	0.0000	0.0000	172.7500	0.0000	0.0000	0.0000	173.1500
0.0000	0.0000	0.0000	173.5500	0.0000	0.0000	0.0000	173.9500
0.0000	0.0000	0.0000	174.3400	0.0000	0.0000	0.0000	174.7400
0.0000	0.0000	0.0000	175.1400	0.0000	0.0000	0.0000	175.5400
0.0000	0.0000	0.0000	175.9400	0.0000	0.0000	0.0000	176.3300
0.0000	0.0000	0.0000	176.7300	0.0000	0.0000	0.0000	177.1300
0.0000	0.0000	0.0000	177.5300	0.0000	0.0000	0.0000	177.9200
0.0000	0.0000	0.0000	178.3200	0.0000	0.0000	0.0000	178.7200
0.0000	0.0000	0.0000	179.1200	0.0000	0.0000	0.0000	179.1400

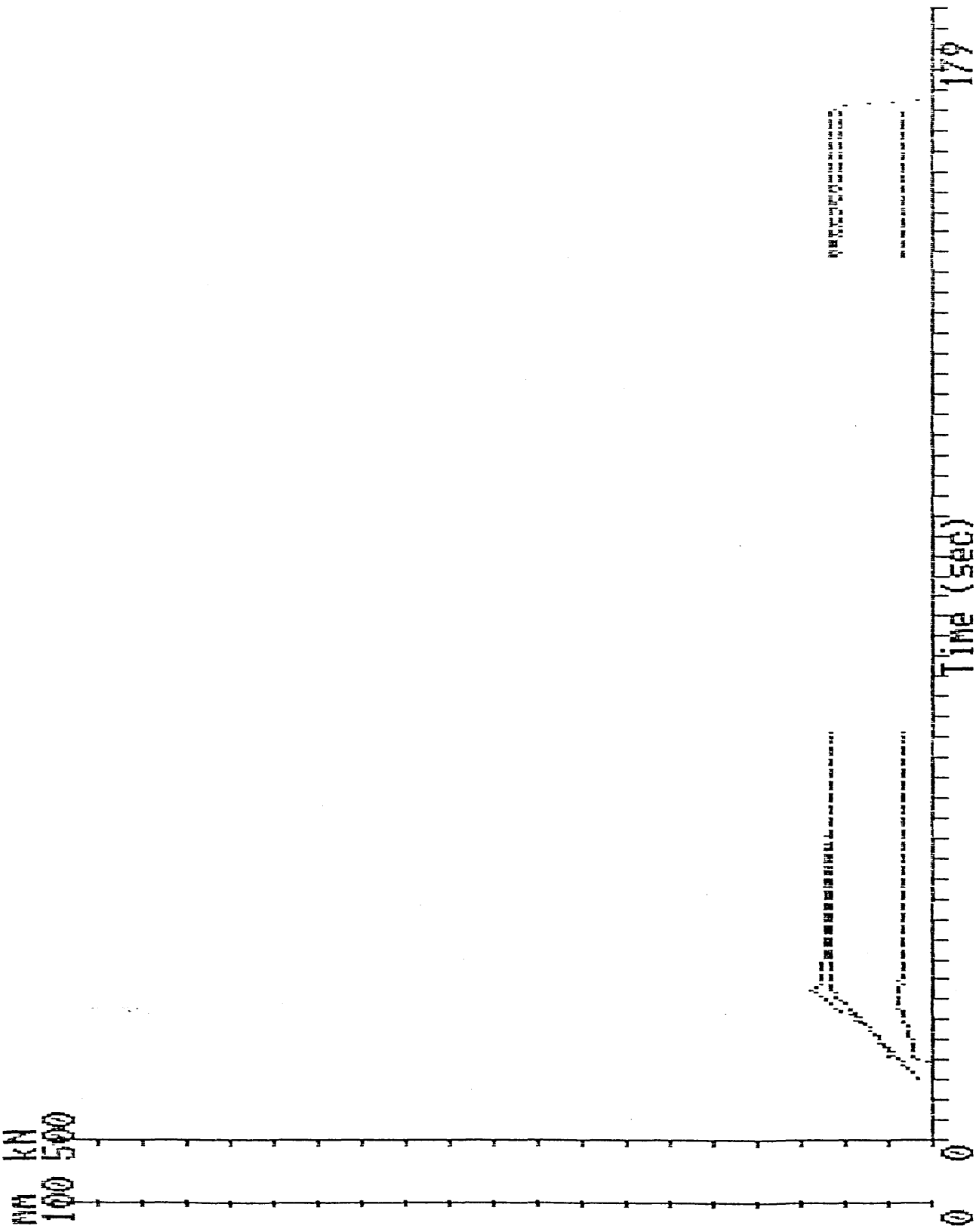


Fig.A5.14. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.15.

****

RESULTS - SPECIMEN No.16

****

The results of this test are stored in the file B:09-01-16.DAT

The values at maximum load are :-

Load at Top Load Cell = 92.29053 (kN)

Load at Bottom Load Cell = 20.0376 (kN)

Displacement = 12.59337 (mm)

Time Elasped = 24.67 (sec)

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5700
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.6000	0.0000	0.0000	0.0000	5.9900
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5400
0.0000	0.0000	0.0000	7.9300	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4800	0.0000	0.0000	1.8388	9.8700
0.0000	0.0000	2.0344	10.2600	0.0000	0.0000	2.4254	10.6500
0.0000	0.0000	2.7188	11.0400	0.0000	0.0000	2.9143	11.4300
0.0000	0.0000	3.3054	11.8200	9.1438	8.9751	3.5009	12.2100
21.0217	15.6125	3.6964	12.6000	21.0217	15.6125	3.9897	12.9900
22.7188	16.3501	4.2831	13.3800	22.7188	16.3501	4.5764	13.7700
22.7188	16.3501	4.8697	14.1600	24.4155	16.3501	5.1630	14.5500
24.4155	17.0875	5.4563	14.9400	26.1125	17.0875	5.7496	15.3300
27.8093	17.8251	6.0429	15.7200	29.5061	18.5626	6.3362	16.1100
29.5061	18.5626	6.6295	16.5000	32.8999	18.5626	7.0206	16.8900
34.5969	19.3000	7.2161	17.2800	37.9905	19.3000	7.5094	17.6700
41.3843	19.3000	7.8027	18.0600	44.7781	19.3000	8.0960	18.4500
48.1719	19.3000	8.3893	18.8400	51.5657	19.3000	8.6826	19.2300
53.2625	19.3000	9.0737	19.6200	56.6563	19.3000	9.2692	20.0100
60.0500	19.3000	9.5625	20.4000	63.4436	20.0376	9.8559	20.7900
66.8374	20.0376	10.1492	21.1800	70.2312	20.0376	10.4425	21.5600
73.6250	20.0376	10.6380	21.9500	77.0188	19.3000	10.9313	22.3400
78.7156	20.0376	11.2246	22.7300	80.4124	19.3000	11.5179	23.1200
83.8062	20.0376	11.8112	23.5100	87.2000	20.0376	12.1045	23.8900
90.5938	19.3000	12.3978	24.2800	92.2905	20.0376	12.5934	24.6700
88.8967	19.3000	12.5934	25.0600	88.8967	18.5626	12.6911	25.4400
87.2000	18.5626	12.3978	25.8300	87.2000	18.5626	12.6911	26.2200
87.2000	18.5626	12.5934	26.6100	87.2000	18.5626	12.5934	27.0000
87.2000	18.5626	12.6911	27.3800	85.5032	18.5626	12.5934	27.7700
85.5032	18.5626	12.6911	28.1600	85.5032	18.5626	12.5934	28.5500
85.5032	18.5626	12.5934	28.9400	85.5032	18.5626	12.5934	29.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
85.5032	18.5626	12.5934	29.7100	85.5032	18.5626	12.6911	30.1000
85.5032	18.5626	12.6911	30.4900	85.5032	18.5626	12.5934	30.8800
83.8062	17.8251	12.6911	31.2600	83.8062	17.8251	12.5934	31.6500
83.8062	17.8251	12.5934	32.0400	83.8062	17.8251	12.6911	32.4300
83.8062	17.8251	12.5934	32.8200	83.8062	17.8251	12.5934	33.2000
83.8062	18.5626	12.6911	33.5900	83.8062	17.8251	12.5934	33.9800
83.8062	17.8251	12.6911	34.3700	83.8062	17.8251	12.5934	34.7600
83.8062	17.8251	12.5934	35.1400	83.8062	17.8251	12.6911	35.5300
83.8062	17.8251	12.5934	35.9200	82.1094	17.8251	12.6911	36.3100
83.8062	17.8251	12.5934	36.6900	82.1094	18.5626	12.5934	37.0800
82.1094	17.8251	12.6911	37.4700	82.1094	17.8251	12.6911	37.8600
82.1094	17.8251	12.5934	38.2400	82.1094	17.8251	12.6911	38.6300
82.1094	17.8251	12.5934	39.0200	82.1094	17.8251	12.5934	39.4100
82.1094	17.8251	12.6911	39.8000	82.1094	17.8251	12.5934	40.1800
82.1094	17.8251	12.6911	40.5700	82.1094	17.8251	12.3001	40.9600
82.1094	17.8251	12.5934	41.3400	82.1094	17.8251	12.6911	41.7300
82.1094	17.8251	12.5934	42.1100	82.1094	17.8251	12.5934	42.5000
82.1094	17.8251	12.5934	42.8900	82.1094	17.8251	12.6911	43.2800
82.1094	17.8251	12.6911	43.6600	80.4124	17.8251	12.5934	44.0500
82.1094	17.8251	12.6911	44.4300	82.1094	17.8251	12.6911	44.8200
80.4124	17.8251	12.5934	45.2100	80.4124	17.8251	12.5934	45.5900
82.1094	17.8251	12.6911	45.9800	80.4124	17.8251	12.5934	46.3700
80.4124	17.8251	12.6911	46.7500	80.4124	17.8251	12.6911	47.1400
80.4124	17.8251	12.6911	47.5300	80.4124	17.8251	12.5934	47.9100
80.4124	17.8251	12.6911	48.3000	80.4124	17.8251	12.6911	48.6900
80.4124	17.8251	12.5934	49.0700	80.4124	17.8251	12.6911	49.4600
80.4124	17.8251	12.6911	49.8400	80.4124	17.8251	12.5934	50.2300
80.4124	17.8251	12.5934	50.6200	80.4124	17.0875	12.4956	51.0000
80.4124	17.8251	12.5934	51.3900	80.4124	17.8251	12.5934	51.7800
80.4124	17.8251	12.6911	52.1600	80.4124	17.8251	12.6911	52.5500
80.4124	17.8251	12.5934	52.9300	80.4124	17.8251	12.6911	53.3200
80.4124	17.8251	12.5934	53.7100	80.4124	17.8251	12.5934	54.0900
80.4124	17.8251	12.6911	54.4800	80.4124	17.0875	12.6911	54.8700
80.4124	17.8251	12.5934	55.2500	80.4124	17.8251	12.5934	55.6400
78.7156	17.0875	12.6911	56.0300	80.4124	17.8251	12.6911	56.4100
80.4124	17.8251	12.5934	56.8000	80.4124	17.8251	12.6911	57.1900
80.4124	17.8251	12.6911	57.5700	78.7156	17.0875	12.5934	57.9600
73.6250	17.0875	12.6911	132.8600	73.6250	16.3501	12.6911	133.2500
75.3218	16.3501	12.6911	133.6500	73.6250	16.3501	12.5934	134.0400
73.6250	16.3501	12.6911	134.4400	73.6250	16.3501	12.6911	134.8300
75.3218	16.3501	12.5934	135.2300	73.6250	16.3501	12.3978	135.6300
73.6250	16.3501	12.6911	136.0200	73.6250	16.3501	12.6911	136.4200
73.6250	16.3501	12.5934	136.8100	73.6250	17.0875	12.5934	137.2100
73.6250	16.3501	12.6911	137.6000	75.3218	17.0875	12.6911	138.0000
73.6250	16.3501	12.5934	138.3900	73.6250	17.0875	12.5934	138.7900
73.6250	16.3501	12.6911	139.1800	73.6250	16.3501	12.6911	139.5800
73.6250	16.3501	12.6911	139.9800	75.3218	16.3501	12.5934	140.3700
73.6250	17.0875	12.6911	140.7700	73.6250	16.3501	12.6911	141.1600
73.6250	16.3501	12.5934	141.5600	73.6250	16.3501	12.5934	141.9500
73.6250	16.3501	12.6911	142.3500	73.6250	16.3501	12.6911	142.7400
73.6250	16.3501	12.5934	143.1400	73.6250	16.3501	12.5934	143.5300
73.6250	16.3501	12.6911	143.9300	73.6250	16.3501	12.6911	144.3300
73.6250	16.3501	12.6911	144.7200	73.6250	16.3501	12.5934	145.1200
73.6250	16.3501	12.6911	145.5100	73.6250	16.3501	12.6911	145.9100
73.6250	16.3501	12.6911	146.3000	73.6250	16.3501	12.5934	146.7000
73.6250	16.3501	12.6911	147.0900	73.6250	16.3501	12.6911	147.4900

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
73.6250	16.3501	12.5934	147.8800	73.6250	16.3501	12.5934	148.2800
73.6250	16.3501	12.6911	148.6800	73.6250	16.3501	12.6911	149.0700
73.6250	16.3501	12.5934	149.4700	73.6250	16.3501	12.6911	149.8600
73.6250	16.3501	12.6911	150.2600	73.6250	16.3501	12.6911	150.6500
73.6250	17.0875	12.5934	151.0500	73.6250	17.0875	12.5934	151.4400
73.6250	16.3501	12.6911	151.8400	73.6250	16.3501	12.6911	152.2300
73.6250	17.0875	12.5934	152.6300	73.6250	16.3501	12.6911	153.0200
73.6250	16.3501	12.6911	153.4200	73.6250	16.3501	13.2778	153.8100
73.6250	16.3501	12.5934	154.2100	73.6250	17.0875	12.6911	154.6100
73.6250	16.3501	12.6911	155.0000	73.6250	16.3501	12.6911	155.4000
73.6250	16.3501	12.5934	155.7900	73.6250	16.3501	12.5934	156.1900
73.6250	16.3501	12.6911	156.5900	73.6250	16.3501	12.6911	156.9800
73.6250	16.3501	12.6911	157.3800	73.6250	16.3501	12.5934	157.7800
73.6250	16.3501	12.6911	158.1700	73.6250	16.3501	12.6911	158.5700
73.6250	16.3501	12.6911	158.9600	73.6250	16.3501	12.6911	159.3600
73.6250	16.3501	12.5934	159.7600	73.6250	16.3501	12.6911	160.1500
73.6250	16.3501	12.6911	160.5500	73.6250	16.3501	12.6911	160.9400
73.6250	16.3501	12.6911	161.3400	73.6250	16.3501	12.5934	161.7400
73.6250	16.3501	12.5934	162.1300	73.6250	16.3501	12.6911	162.5300
73.6250	16.3501	12.6911	162.9300	73.6250	16.3501	12.6911	163.3200
73.6250	16.3501	12.5934	163.7200	73.6250	16.3501	12.6911	164.1200
73.6250	16.3501	12.6911	164.5100	73.6250	16.3501	12.6911	164.9100
73.6250	16.3501	12.6911	165.3100	73.6250	17.0875	12.5934	165.7000
73.6250	16.3501	12.5934	166.1000	73.6250	16.3501	12.6911	166.4900
73.6250	16.3501	12.6911	166.8900	73.6250	16.3501	12.5934	167.2900
73.6250	16.3501	12.6911	167.6800	73.6250	16.3501	12.5934	168.0800
73.6250	16.3501	12.6911	168.4800	73.6250	16.3501	12.6911	168.8700
73.6250	16.3501	12.6911	169.2700	73.6250	16.3501	12.5934	169.6600
73.6250	16.3501	12.6911	170.0600	0.0000	0.0000	12.0068	170.4500
0.0000	0.0000	9.9536	170.8500	0.0000	0.0000	7.1183	171.2500
0.0000	0.0000	4.2831	171.6500	0.0000	0.0000	0.0000	172.0400
0.0000	0.0000	0.0000	172.4400	0.0000	0.0000	0.0000	172.8400
0.0000	0.0000	0.0000	173.2400	0.0000	0.0000	0.0000	173.6400
0.0000	0.0000	0.0000	174.0300	0.0000	0.0000	0.0000	174.4300
0.0000	0.0000	0.0000	174.8300	0.0000	0.0000	0.0000	175.2300
0.0000	0.0000	0.0000	175.6300	0.0000	0.0000	0.0000	176.0200
0.0000	0.0000	0.0000	176.4200	0.0000	0.0000	0.0000	176.8200
0.0000	0.0000	0.0000	177.2200	0.0000	0.0000	1.6433	177.6100
0.0000	0.0000	0.0000	178.0100	0.0000	0.0000	0.0000	178.4100
0.0000	0.0000	0.0000	178.8100	0.0000	0.0000	0.0000	179.2100
0.0000	0.0000	0.0000	179.6000	0.0000	0.0000	0.0000	120.0000
0.0000	0.0000	0.0000	180.3900	0.0000	0.0000	0.0000	180.7800
0.0000	0.0000	0.0000	181.1700	0.0000	0.0000	0.0000	181.5700
0.0000	0.0000	0.0000	181.9600	0.0000	0.0000	0.0000	182.3600
0.0000	0.0000	0.0000	182.7600	0.0000	0.0000	0.0000	183.1500
0.0000	0.0000	0.0000	183.5500	0.0000	0.0000	0.0000	183.9400
0.0000	0.0000	0.0000	184.3400	0.0000	0.0000	0.0000	184.7400
0.0000	0.0000	0.0000	185.1300	0.0000	0.0000	0.0000	185.5300
0.0000	0.0000	0.0000	185.9200	0.0000	0.0000	0.0000	186.3200
0.0000	0.0000	0.0000	186.7100	0.0000	0.0000	0.0000	187.1100
0.0000	0.0000	0.0000	187.5000	0.0000	0.0000	0.0000	187.9000
0.0000	0.0000	0.0000	188.2900	0.0000	0.0000	0.0000	188.6900
0.0000	0.0000	0.0000	189.0800	0.0000	0.0000	0.0000	189.4800
0.0000	0.0000	0.0000	189.8700	0.0000	0.0000	0.0000	190.2700
0.0000	0.0000	0.0000	190.6700	0.0000	0.0000	0.0000	191.0700
0.0000	0.0000	0.0000	191.4700	0.0000	0.0000	0.0000	191.8700

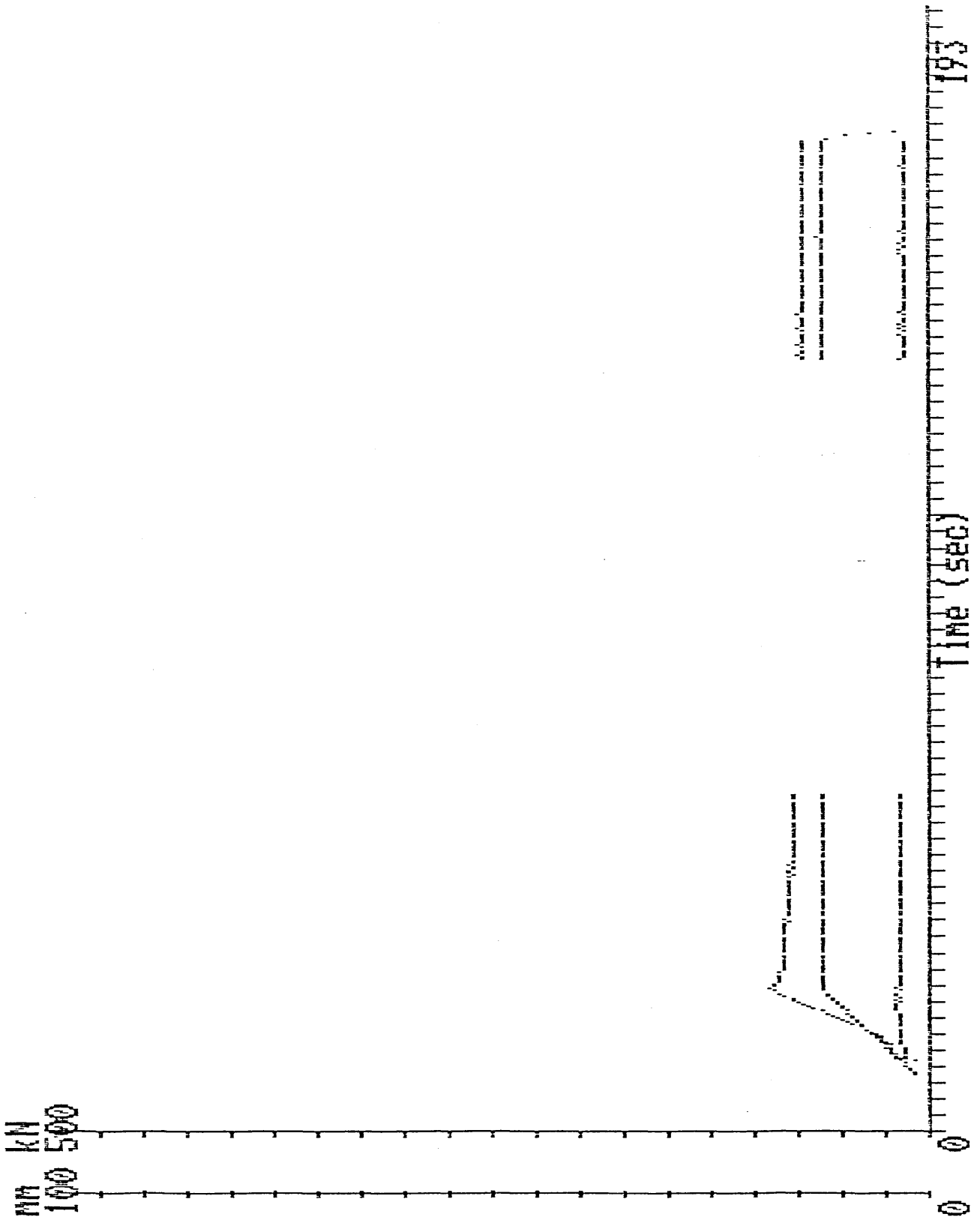


Fig.A5.15. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.16.

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RESULTS - SPECIMEN No.17

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The results of this test are stored in the file B:09-01-17.DAT

The values at maximum load are :-

Load at Top Load Cell = 58.35303 (kN)

Load at Bottom Load Cell = 17.82507 (kN)

Displacement = 9.85585 (mm)

Time Elasped = 26.22 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0800
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	0.0000	9.8600
0.0000	0.0000	0.0000	10.2500	0.0000	0.0000	0.0000	10.6400
0.0000	0.0000	0.0000	11.0300	0.0000	0.0000	0.0000	11.4200
0.0000	0.0000	0.0000	11.8100	0.0000	0.0000	0.0000	12.2000
0.0000	0.0000	0.0000	12.5900	0.0000	0.0000	0.0000	12.9900
0.0000	0.0000	0.0000	13.3800	0.0000	0.0000	0.0000	13.7700
0.0000	0.0000	0.0000	14.1600	0.0000	0.0000	0.0000	14.5500
0.0000	0.0000	0.0000	14.9400	0.0000	0.0000	1.7411	15.3300
0.0000	0.0000	2.0344	15.7200	0.0000	0.0000	2.3277	16.1100
0.0000	0.0000	2.6210	16.5000	0.0000	0.0000	3.0121	16.8900
0.0000	0.0000	3.2076	17.2800	0.0000	0.0000	3.5987	17.6700
2.3562	3.0751	3.7942	18.0600	17.6282	8.2375	4.0875	18.4500
26.1125	8.9751	4.2831	18.8400	27.8093	9.7125	4.5764	19.2300
27.8093	9.7125	4.7719	19.6200	29.5061	10.4501	5.1630	20.0100
31.2031	11.1876	5.4563	20.4000	32.8999	11.1876	5.6518	20.7900
32.8999	11.1876	6.0429	21.1700	34.5969	11.9250	6.2384	21.5600
36.2937	11.9250	6.8250	21.9500	37.9905	12.6626	6.9228	22.3400
39.6875	13.4000	7.2161	22.7300	41.3843	13.4000	7.5094	23.1200
43.0813	14.1376	7.7049	23.5100	44.7781	14.8751	8.0960	23.9000
46.4749	14.8751	8.3893	24.2800	48.1719	15.6125	8.5849	24.6700
49.8687	16.3501	8.8782	25.0600	53.2625	17.0875	9.1715	25.4500
54.9592	17.0875	9.5625	25.8400	58.3530	17.8251	9.8559	26.2200
56.6563	17.8251	9.7581	26.6100	56.6563	17.0875	9.8559	27.0000
56.6563	17.0875	9.8559	27.3900	56.6563	17.0875	9.9536	27.7800
56.6563	17.0875	9.8559	28.1600	56.6563	17.0875	9.7581	28.5500
56.6563	17.0875	9.8559	28.9400	56.6563	17.0875	9.8559	29.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
54.9592	17.0875	9.8559	29.7200	54.9592	17.0875	9.8559	30.1000
56.6563	17.0875	9.8559	30.4900	54.9592	17.0875	9.8559	30.8800
56.6563	17.0875	9.9536	31.2700	54.9592	16.3501	9.8559	31.6600
54.9592	17.0875	9.8559	32.0400	54.9592	17.0875	9.7581	32.4300
54.9592	17.0875	9.8559	32.8200	54.9592	17.0875	9.8559	33.2100
54.9592	17.0875	9.8559	33.5900	54.9592	16.3501	9.8559	33.9800
54.9592	17.0875	9.8559	34.3700	54.9592	17.0875	9.8559	34.7600
54.9592	16.3501	9.8559	35.1400	54.9592	16.3501	9.7581	35.5300
54.9592	16.3501	9.8559	35.9200	54.9592	17.0875	9.8559	36.3100
54.9592	17.0875	9.8559	36.7000	54.9592	16.3501	9.8559	37.0800
54.9592	17.0875	9.8559	37.4700	54.9592	16.3501	9.8559	37.8600
54.9592	16.3501	9.8559	38.2500	54.9592	16.3501	9.7581	38.6300
54.9592	16.3501	9.8559	39.0200	54.9592	16.3501	9.8559	39.4100
54.9592	16.3501	9.8559	39.8000	54.9592	16.3501	9.8559	40.1800
54.9592	17.0875	9.8559	40.5700	54.9592	17.0875	9.7581	40.9600
54.9592	16.3501	9.8559	41.3400	54.9592	17.0875	9.8559	41.7300
54.9592	17.0875	9.7581	42.1200	54.9592	16.3501	9.8559	42.5000
53.2625	16.3501	9.8559	42.8900	54.9592	16.3501	9.8559	43.2800
54.9592	16.3501	9.9536	43.6600	54.9592	16.3501	9.7581	44.0500
54.9592	16.3501	9.7581	44.4400	53.2625	16.3501	9.8559	44.8200
54.9592	16.3501	9.8559	45.2100	54.9592	16.3501	9.8559	45.5900
54.9592	16.3501	9.8559	45.9800	54.9592	16.3501	9.8559	46.3700
53.2625	16.3501	9.8559	46.7500	53.2625	16.3501	9.7581	47.1400
53.2625	16.3501	9.8559	47.5300	54.9592	16.3501	9.8559	47.9100
54.9592	16.3501	9.7581	48.3000	53.2625	16.3501	9.8559	48.6900
53.2625	16.3501	9.8559	49.0700	54.9592	16.3501	9.7581	49.4600
53.2625	16.3501	9.8559	49.8400	53.2625	16.3501	9.8559	50.2300
53.2625	16.3501	9.7581	50.6200	54.9592	16.3501	9.8559	51.0000
53.2625	16.3501	9.8559	51.3900	53.2625	16.3501	9.7581	51.7800
54.9592	16.3501	9.8559	52.1600	53.2625	16.3501	9.8559	52.5500
53.2625	16.3501	9.8559	52.9300	53.2625	16.3501	9.8559	53.3200
53.2625	16.3501	9.8559	53.7100	53.2625	16.3501	9.8559	54.0900
53.2625	16.3501	9.7581	54.4800	53.2625	16.3501	9.8559	54.8700
53.2625	16.3501	9.7581	55.2500	53.2625	16.3501	9.7581	55.6400
53.2625	16.3501	9.8559	56.0300	53.2625	16.3501	9.8559	56.4100
53.2625	16.3501	9.8559	56.8000	53.2625	16.3501	9.8559	57.1900
53.2625	16.3501	9.8559	57.5700	53.2625	16.3501	9.7581	57.9600
53.2625	16.3501	9.8559	58.3500	53.2625	16.3501	9.8559	58.7300
53.2625	16.3501	9.7581	59.1200	53.2625	16.3501	9.8559	59.5100
53.2625	16.3501	9.8559	59.8900	53.2625	16.3501	9.8559	60.2800
53.2625	16.3501	9.8559	60.6600	53.2625	16.3501	9.8559	61.0500
53.2625	16.3501	9.8559	61.4500	53.2625	16.3501	9.9536	61.8400
53.2625	16.3501	9.8559	62.2400	51.5657	15.6125	9.8559	137.5100
51.5657	15.6125	9.9536	137.9000	51.5657	16.3501	9.7581	138.3000
51.5657	15.6125	9.8559	138.7000	51.5657	15.6125	9.8559	139.0900
51.5657	15.6125	9.8559	139.4900	51.5657	15.6125	9.7581	139.8800
51.5657	15.6125	9.8559	140.2800	51.5657	15.6125	9.8559	140.6700
51.5657	15.6125	9.8559	141.0700	51.5657	15.6125	9.7581	141.4600
51.5657	15.6125	9.8559	141.8600	51.5657	15.6125	9.8559	142.2500
51.5657	15.6125	9.8559	142.6500	51.5657	15.6125	9.7581	143.0400
51.5657	15.6125	9.8559	143.4400	51.5657	15.6125	9.8559	143.8300
51.5657	15.6125	9.8559	144.2300	51.5657	15.6125	9.7581	144.6200
51.5657	15.6125	9.7581	145.0200	51.5657	15.6125	9.9536	145.4100
51.5657	15.6125	9.8559	145.8100	51.5657	15.6125	9.7581	146.2100
51.5657	15.6125	9.7581	146.6000	51.5657	15.6125	9.8559	147.0000
51.5657	15.6125	9.8559	147.3900	51.5657	16.3501	9.7581	147.7900

51.5657	15.6125	9.8559	148.1800	51.5657	15.6125	9.8559	148.5800
51.5657	15.6125	9.8559	148.9700	51.5657	15.6125	9.8559	149.3700
51.5657	15.6125	9.7581	149.7600	51.5657	15.6125	9.8559	150.1600
51.5657	15.6125	9.8559	150.5500	51.5657	15.6125	9.7581	150.9500
51.5657	15.6125	9.8559	151.3500	51.5657	15.6125	9.8559	151.7400
51.5657	15.6125	9.8559	152.1400	51.5657	15.6125	9.8559	152.5300
51.5657	15.6125	9.7581	152.9300	51.5657	15.6125	9.8559	153.3200
51.5657	15.6125	9.8559	153.7200	51.5657	15.6125	9.8559	154.1100
51.5657	15.6125	9.8559	154.5100	51.5657	15.6125	9.8559	154.9000
51.5657	15.6125	9.8559	155.3000	51.5657	15.6125	9.8559	155.7000
51.5657	15.6125	9.8559	156.0900	51.5657	15.6125	9.7581	156.4900
51.5657	15.6125	9.7581	156.8900	51.5657	15.6125	9.8559	157.2800
51.5657	15.6125	9.9536	157.6800	51.5657	15.6125	9.8559	158.0800
51.5657	15.6125	9.7581	158.4700	51.5657	15.6125	9.8559	158.8700
51.5657	15.6125	9.8559	159.2700	51.5657	15.6125	9.8559	159.6600
51.5657	15.6125	9.8559	160.0600	51.5657	15.6125	9.8559	160.4500
51.5657	15.6125	9.7581	160.8500	51.5657	15.6125	9.8559	161.2500
51.5657	15.6125	9.8559	161.6400	51.5657	15.6125	9.8559	162.0400
51.5657	15.6125	9.8559	162.4400	51.5657	15.6125	9.8559	162.8300
51.5657	15.6125	9.8559	163.2300	51.5657	15.6125	9.8559	163.6200
49.8687	15.6125	9.8559	164.0200	17.6282	4.5500	9.6603	164.4200
2.3562	0.0000	9.4648	164.8100	0.0000	0.0000	9.4648	165.2100
0.0000	0.0000	9.4648	165.6000	0.0000	0.0000	9.3670	166.0000
0.0000	0.0000	9.2692	166.4000	0.0000	0.0000	9.1715	166.8000
0.0000	0.0000	9.0737	167.1900	0.0000	0.0000	9.0737	167.5900
0.0000	0.0000	8.9759	167.9900	0.0000	0.0000	8.9759	168.3900
0.0000	0.0000	8.8782	168.7800	0.0000	0.0000	8.6826	169.1800
0.0000	0.0000	8.6826	169.5800	0.0000	0.0000	8.5849	169.9800
0.0000	0.0000	8.5849	170.3700	0.0000	0.0000	8.4871	170.7700
0.0000	0.0000	8.4871	171.1700	0.0000	0.0000	8.3893	171.5700
0.0000	0.0000	8.2916	171.9600	0.0000	0.0000	8.1938	172.3600
0.0000	0.0000	7.9983	172.7600	0.0000	0.0000	7.7049	173.1600
0.0000	0.0000	7.6072	173.5600	0.0000	0.0000	7.4116	173.9500
0.0000	0.0000	7.2161	174.3500	0.0000	0.0000	7.1183	174.7500
0.0000	0.0000	6.8250	175.1500	0.0000	0.0000	5.9451	175.5400
0.0000	0.0000	5.0652	175.9400	0.0000	0.0000	4.0875	176.3400
0.0000	0.0000	3.3054	176.7400	0.0000	0.0000	2.3277	177.1400
0.0000	0.0000	0.0000	177.5300	0.0000	0.0000	0.0000	177.9300
0.0000	0.0000	0.0000	178.3300	0.0000	0.0000	0.0000	178.7300
0.0000	0.0000	0.0000	179.1200	0.0000	0.0000	0.0000	179.5200
0.0000	0.0000	0.0000	179.9200	0.0000	0.0000	0.0000	180.3100
0.0000	0.0000	0.0000	180.7000	0.0000	0.0000	0.0000	181.0900
0.0000	0.0000	0.0000	181.4900	0.0000	0.0000	0.0000	181.8800
0.0000	0.0000	0.0000	182.2800	0.0000	0.0000	0.0000	182.6800
0.0000	0.0000	0.0000	183.0700	0.0000	0.0000	0.0000	183.4700
0.0000	0.0000	0.0000	183.8600	0.0000	0.0000	0.0000	184.2600
0.0000	0.0000	0.0000	184.6500	0.0000	0.0000	0.0000	185.0500
0.0000	0.0000	0.0000	185.4400	0.0000	0.0000	0.0000	185.8400
0.0000	0.0000	0.0000	186.2400	0.0000	0.0000	0.0000	186.6300
0.0000	0.0000	0.0000	187.0300	0.0000	0.0000	0.0000	187.4200
0.0000	0.0000	0.0000	187.8200	0.0000	0.0000	0.0000	188.2100
0.0000	0.0000	0.0000	188.6100	0.0000	0.0000	0.0000	189.0000
0.0000	0.0000	0.0000	189.4000	0.0000	0.0000	0.0000	189.7900
0.0000	0.0000	0.0000	190.1900	0.0000	0.0000	0.0000	190.5900
0.0000	0.0000	0.0000	190.9900	0.0000	0.0000	0.0000	191.3900
0.0000	0.0000	0.0000	191.7900	0.0000	0.0000	0.0000	192.1800
0.0000	0.0000	0.0000	192.5800	0.0000	0.0000	0.0000	192.9800
0.0000	0.0000	0.0000	193.3800	0.0000	0.0000	0.0000	193.7800
0.0000	0.0000	0.0000	194.1800	0.0000	0.0000	0.0000	194.5800

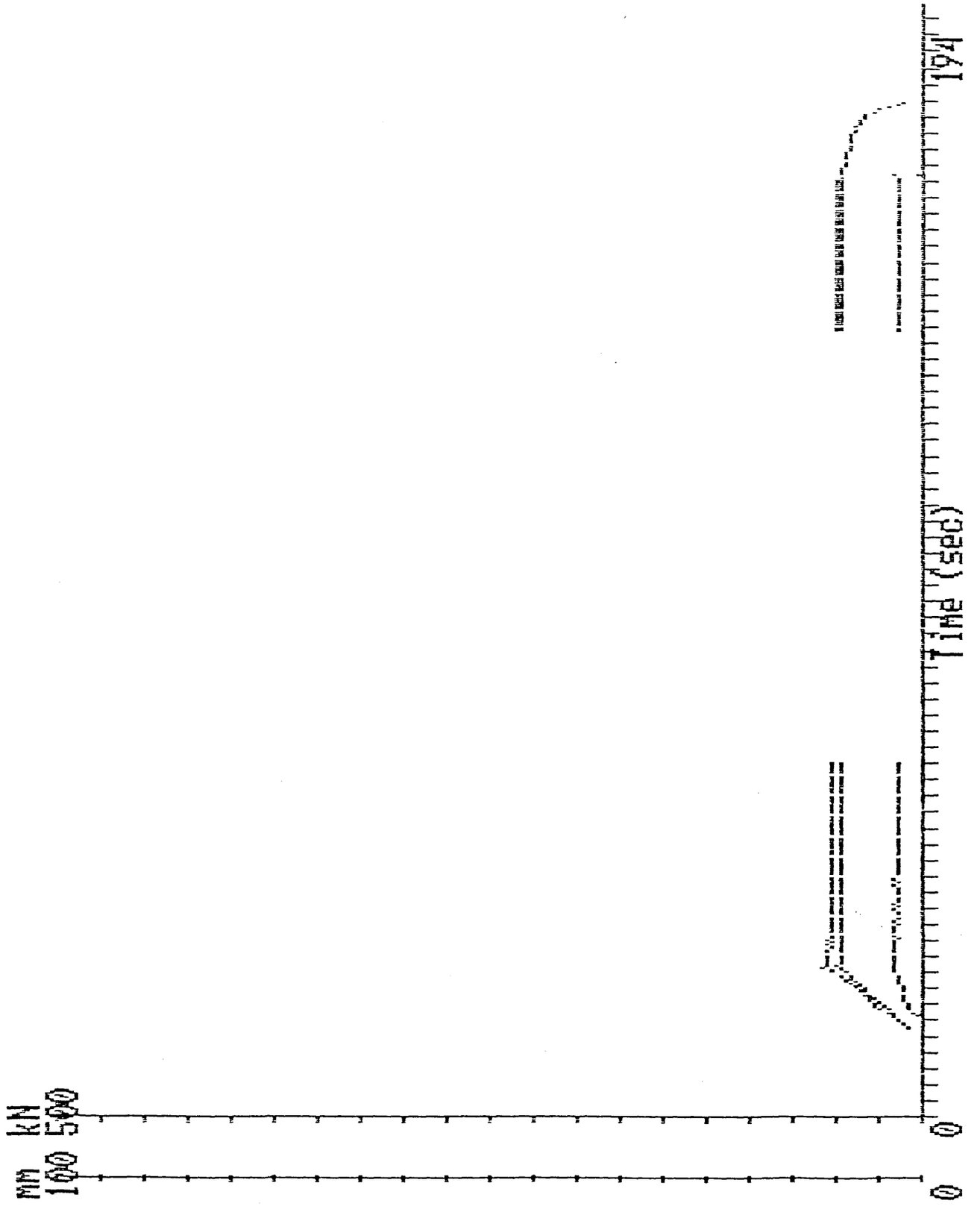


Fig.A5.16. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.17.

****

RESULTS - SPECIMEN No.18

****

The results of this test are stored in the file B:09-01-18.DAT

The values at maximum load are :-

Load at Top Load Cell = 100.7749 (kN)

Load at Bottom Load Cell = 20.77502 (kN)

Displacement = 38.20874 (mm)

Time Elasped = 57.97 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1800	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9300	0.0000	0.0000	0.0000	1.3200
0.0000	0.0000	0.0000	1.7100	0.0000	0.0000	0.0000	2.0900
0.0000	0.0000	0.0000	2.4800	0.0000	0.0000	0.0000	2.8700
0.0000	0.0000	0.0000	3.2600	0.0000	0.0000	0.0000	3.6500
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4200
0.0000	0.0000	0.0000	4.8100	0.0000	0.0000	0.0000	5.2000
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1400	0.0000	0.0000	0.0000	7.5300
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0800
0.0000	0.0000	0.0000	9.4700	0.0000	0.0000	0.0000	9.8600
0.0000	0.0000	0.0000	10.2500	0.0000	0.0000	1.7411	10.6400
0.0000	0.0000	2.0344	11.0300	0.0000	0.0000	2.3277	11.4200
0.0000	0.0000	2.7188	11.8100	0.0000	0.0000	2.9143	12.2000
0.0000	0.0000	3.4031	12.5900	0.0000	0.0000	3.5987	12.9800
0.0000	0.0000	3.8920	13.3800	0.0000	0.0000	4.2831	13.7700
0.0000	0.0000	4.4786	14.1600	0.0000	0.0000	4.8697	14.5500
0.0000	0.0000	5.1630	14.9400	0.0000	0.0000	5.5540	15.3300
0.0000	0.0000	5.7496	15.7200	0.0000	0.0000	6.1407	16.1100
0.0000	0.0000	6.4340	16.5000	0.0000	0.0000	6.7273	16.8900
0.0000	0.0000	7.0206	17.2800	0.0000	0.0000	7.3139	17.6700
0.0000	0.0000	7.6072	18.0600	0.0000	0.0000	7.9983	18.4500
0.0000	0.0000	8.3893	18.8400	0.0000	0.0000	8.5849	19.2300
0.0000	0.0000	8.9759	19.6200	0.0000	0.0000	9.2692	20.0100
0.0000	0.0000	9.6603	20.4000	0.0000	0.0000	9.8559	20.7900
0.0000	0.0000	10.2469	21.1800	0.0000	0.0000	10.4425	21.5700
0.0000	0.0000	10.9313	21.9500	0.0000	0.0000	11.1268	22.3400
0.0000	0.0000	11.5179	22.7300	0.0000	0.0000	11.7135	23.1200
0.0000	0.0000	12.1045	23.5100	0.0000	0.0000	12.3978	23.9000
0.0000	0.0000	12.6911	24.2900	0.0000	0.0000	13.0822	24.6700
0.0000	0.0000	13.2778	25.0600	0.0000	0.0000	13.7666	25.4500
0.0000	0.0000	13.8644	25.8400	0.0000	0.0000	14.2554	26.2300
0.0000	0.0000	14.5488	26.6200	0.0000	0.0000	14.9398	27.0000
0.0000	0.0000	15.1354	27.3900	0.0000	0.0000	15.5264	27.7800
0.0000	0.0000	15.8197	28.1700	0.0000	0.0000	16.1130	28.5600
0.0000	0.0000	16.5041	28.9500	0.0000	0.0000	16.6997	29.3300

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	17.0907	29.7200	0.0000	0.0000	17.2863	30.1100
0.0000	0.0000	17.6773	30.5000	0.0000	0.0000	17.9706	30.8900
0.0000	0.0000	18.3617	31.2800	0.0000	0.0000	18.5573	31.6700
0.0000	0.0000	18.9483	32.0500	0.0000	0.0000	19.2416	32.4400
0.6594	2.3375	19.4372	32.8300	15.9312	6.7626	19.7305	33.2100
21.0217	8.9751	19.9260	33.6000	22.7188	9.7125	20.2193	33.9900
24.4155	10.4501	20.5126	34.3800	24.4155	10.4501	20.7082	34.7600
24.4155	10.4501	21.0992	35.1500	26.1125	10.4501	21.2948	35.5400
24.4155	10.4501	21.6859	35.9300	26.1125	11.1876	21.9792	36.3100
26.1125	11.1876	22.2725	36.7000	27.8093	11.1876	22.6635	37.0900
27.8093	11.9250	22.8591	37.4800	27.8093	11.9250	23.2502	37.8700
27.8093	11.9250	23.4457	38.2500	27.8093	11.9250	23.8368	38.6400
29.5061	11.9250	24.1301	39.0300	29.5061	11.9250	24.4234	39.4200
29.5061	11.9250	24.7167	39.8100	29.5061	12.6626	24.7167	40.1900
31.2031	12.6626	25.3033	40.5800	31.2031	13.4000	25.5966	40.9700
31.2031	13.4000	25.8899	41.3500	31.2031	13.4000	26.2810	41.7400
32.8999	14.1376	26.4765	42.1300	32.8999	14.1376	26.6720	42.5100
32.8999	14.1376	27.0631	42.9000	34.5969	14.8751	27.3564	43.2900
34.5969	14.8751	27.6497	43.6700	36.2937	14.8751	28.1386	44.0600
36.2937	15.6125	28.2363	44.4400	37.9905	15.6125	28.5296	44.8300
37.9905	15.6125	28.9207	45.2200	39.6875	16.3501	29.1163	45.6000
39.6875	16.3501	29.5073	45.9900	41.3843	16.3501	29.8006	46.3800
41.3843	17.0875	29.9962	46.7600	43.0813	17.0875	30.3873	47.1500
43.0813	17.8251	30.6806	47.5400	44.7781	17.8251	30.8761	47.9200
46.4749	17.8251	31.2672	48.3100	46.4749	17.8251	31.4627	48.7000
48.1719	18.5626	31.7560	49.0800	49.8687	18.5626	32.1471	49.4700
51.5657	19.3000	32.3426	49.8500	53.2625	19.3000	32.6359	50.2400
54.9592	19.3000	33.0270	50.6300	54.9592	19.3000	33.2225	51.0100
56.6563	20.0376	33.5159	51.4000	58.3530	19.3000	33.9069	51.7900
60.0500	20.0376	34.0047	52.1700	60.0500	20.0376	34.3958	52.5600
61.7468	20.0376	34.7868	52.9400	63.4436	20.7750	34.9824	53.3300
65.1406	20.0376	35.3734	53.7200	66.8374	20.7750	35.5690	54.1000
68.5344	20.7750	35.7645	54.4900	71.9280	20.7750	36.1556	54.8800
73.6250	20.7750	36.3511	55.2600	77.0188	20.7750	36.6444	55.6500
80.4124	20.7750	37.0355	56.0300	83.8062	20.7750	37.2310	56.4200
87.2000	20.7750	37.4266	56.8100	90.5938	20.0376	37.8177	57.1900
93.9875	20.7750	38.1110	57.5800	100.7749	20.7750	38.2087	57.9700
99.0781	19.3000	38.5020	58.3500	87.2000	17.8251	38.5020	58.7400
85.5032	17.8251	38.4043	59.1200	83.8062	17.0875	38.5998	59.5100
83.8062	17.0875	38.5020	59.9000	83.8062	17.0875	38.5020	60.2800
83.8062	17.0875	38.5998	60.6700	82.1094	17.0875	38.5020	61.0600
82.1094	16.3501	38.5998	61.4500	82.1094	16.3501	38.5020	61.8400
82.1094	16.3501	38.5020	62.2300	80.4124	16.3501	38.5998	62.6300
80.4124	16.3501	38.5998	63.0200	80.4124	16.3501	38.5020	63.4100
80.4124	16.3501	38.5998	63.8100	78.7156	16.3501	38.5020	64.2000
78.7156	16.3501	38.5020	64.5900	78.7156	16.3501	38.5998	64.9800
78.7156	16.3501	38.5998	65.3800	78.7156	16.3501	38.5020	65.7700
77.0188	16.3501	38.5998	66.1600	77.0188	16.3501	38.5998	66.5600
77.0188	16.3501	38.5020	66.9500	77.0188	16.3501	38.5998	67.3400
77.0188	15.6125	38.5998	67.7300	77.0188	15.6125	38.5020	68.1300
77.0188	15.6125	38.5998	68.5200	77.0188	15.6125	38.5998	68.9100
75.3218	15.6125	38.5020	69.3000	75.3218	15.6125	38.5998	69.7000
75.3218	15.6125	38.5998	70.0900	75.3218	15.6125	38.5020	70.4800
75.3218	15.6125	38.5020	70.8800	73.6250	15.6125	38.5998	71.2800
73.6250	15.6125	38.5998	71.6700	73.6250	15.6125	38.5998	72.0700
73.6250	15.6125	38.5020	72.4600	73.6250	15.6125	38.5020	72.8600

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
73.6250	15.6125	38.5020	73.2500	73.6250	15.6125	38.5998	73.6500
73.6250	15.6125	38.5998	74.0400	73.6250	14.8751	38.5998	74.4400
73.6250	15.6125	38.5020	74.8400	71.9280	15.6125	38.5020	75.2300
71.9280	14.8751	38.5998	75.6300	73.6250	14.8751	38.5998	76.0200
71.9280	14.8751	38.5998	76.4200	71.9280	14.8751	38.5020	76.8100
71.9280	14.8751	38.5998	77.2100	71.9280	14.8751	38.5998	77.6000
71.9280	14.8751	38.5998	78.0000	71.9280	14.8751	38.5998	78.3900
71.9280	14.8751	38.5020	78.7900	71.9280	14.8751	38.5998	79.1800
71.9280	14.8751	38.5998	79.5800	71.9280	14.8751	38.5998	79.9800
71.9280	14.8751	38.5998	80.3700	71.9280	14.8751	38.5998	80.7700
70.2312	14.8751	38.5020	81.1600	70.2312	14.8751	38.5020	81.5600
70.2312	14.8751	38.5998	81.9600	70.2312	14.8751	38.5998	82.3500
70.2312	14.8751	38.5998	82.7500	70.2312	14.8751	38.5998	83.1500
70.2312	14.8751	38.5020	83.5400	70.2312	14.8751	38.5998	83.9400
70.2312	14.8751	38.5020	84.3400	70.2312	14.8751	38.5998	84.7300
70.2312	14.8751	38.6976	85.1300	70.2312	14.8751	38.5998	85.5200
70.2312	14.1376	38.5998	85.9200	70.2312	14.8751	38.5020	86.3200
70.2312	14.8751	38.5020	86.7100	70.2312	14.8751	38.5998	87.1100
70.2312	14.1376	38.5998	87.5100	68.5344	14.8751	38.5998	87.9000
70.2312	14.1376	38.5998	88.3000	70.2312	14.8751	38.5020	88.7000
70.2312	14.8751	38.5020	89.0900	70.2312	14.8751	38.5020	89.4900
68.5344	14.8751	38.5998	89.8800	70.2312	14.1376	38.5998	90.2800
68.5344	14.1376	38.5998	90.6800	70.2312	14.1376	39.1864	91.0700
68.5344	14.1376	38.5020	91.4700	68.5344	14.8751	38.5020	91.8700
68.5344	14.8751	38.5998	92.2600	68.5344	14.1376	38.5998	92.6600
68.5344	14.1376	38.5998	93.0500	68.5344	14.1376	38.5998	93.4500
68.5344	14.8751	38.5020	93.8400	68.5344	14.1376	38.5998	94.2400
68.5344	14.8751	38.5998	94.6400	68.5344	14.1376	38.5998	95.0300
68.5344	14.1376	38.5998	95.4300	68.5344	14.1376	38.5998	95.8200
68.5344	14.1376	38.5020	96.2200	68.5344	14.1376	38.5998	96.6100
68.5344	14.1376	38.5998	97.0100	68.5344	14.1376	38.6976	97.4100
68.5344	14.1376	38.5998	97.8000	68.5344	14.1376	38.5020	98.2000
68.5344	14.1376	38.5998	98.5900	68.5344	14.1376	38.5998	98.9900
68.5344	14.1376	38.5998	99.3900	68.5344	14.1376	38.5998	99.7800
68.5344	14.1376	38.5020	100.1800	68.5344	14.1376	38.5020	100.5700
68.5344	14.1376	38.5998	100.9700	68.5344	14.1376	38.5998	101.3600
66.8374	14.1376	38.5998	101.7600	66.8374	14.1376	38.5020	102.1500
68.5344	14.1376	38.5020	102.5500	68.5344	14.1376	38.5998	102.9500
68.5344	14.1376	38.5998	103.3400	66.8374	13.4000	38.5998	103.7400
66.8374	14.1376	38.5998	104.1300	66.8374	14.1376	38.5020	104.5300
66.8374	14.1376	38.5998	104.9200	66.8374	14.1376	38.5998	105.3200
66.8374	14.1376	38.6976	105.7200	66.8374	14.1376	38.5020	106.1100
66.8374	14.1376	38.5998	106.5100	66.8374	14.1376	38.5998	106.9000
66.8374	14.1376	38.5998	107.3000	66.8374	14.1376	38.5998	107.6900
66.8374	14.1376	38.5998	108.0900	66.8374	14.1376	38.5020	108.4800
66.8374	14.1376	38.5998	108.8800	66.8374	14.1376	38.5998	109.2800
66.8374	14.1376	38.5998	109.6700	66.8374	14.1376	38.5998	110.0700
66.8374	14.1376	38.5020	110.4600	66.8374	14.1376	38.5998	110.8600
66.8374	14.1376	38.5998	111.2500	66.8374	14.1376	38.5998	111.6500
66.8374	14.1376	38.5998	112.0400	66.8374	14.1376	38.5020	112.4400
66.8374	14.1376	38.5998	112.8400	66.8374	14.1376	38.6976	113.2300
66.8374	14.1376	38.5998	113.6300	66.8374	14.1376	38.5998	114.0200
66.8374	14.1376	38.5020	114.4200	66.8374	14.1376	38.5998	114.8100
66.8374	14.1376	38.5998	115.2100	66.8374	14.1376	38.6976	115.6000
66.8374	14.1376	38.5998	116.0000	63.4436	13.4000	38.5020	190.9700
63.4436	13.4000	38.5020	191.3700	63.4436	13.4000	38.5998	191.7600

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
63.4436	13.4000	38.5998	192.1600	63.4436	13.4000	38.5998	192.5600
63.4436	13.4000	38.5998	192.9500	63.4436	13.4000	38.5998	193.3500
63.4436	13.4000	38.5020	193.7500	63.4436	13.4000	38.5020	194.1400
63.4436	13.4000	38.5998	194.5400	63.4436	13.4000	38.5998	194.9400
63.4436	13.4000	38.5998	195.3400	63.4436	13.4000	38.5998	195.7300
63.4436	13.4000	38.5020	196.1300	63.4436	13.4000	38.5998	196.5200
63.4436	13.4000	38.5020	196.9200	63.4436	13.4000	38.5020	197.3200
63.4436	13.4000	38.5020	197.7100	63.4436	13.4000	38.5998	198.1100
63.4436	13.4000	38.6976	198.5100	63.4436	13.4000	38.5998	198.9000
63.4436	13.4000	38.5998	199.3000	63.4436	13.4000	38.5020	199.7000
63.4436	13.4000	38.5020	200.0900	63.4436	13.4000	38.5998	200.4900
63.4436	13.4000	38.5998	200.8900	63.4436	13.4000	38.5998	201.2800
63.4436	13.4000	38.5998	201.6800	63.4436	13.4000	38.5020	202.0700
63.4436	13.4000	38.5020	202.4700	63.4436	13.4000	38.5998	202.8700
63.4436	13.4000	38.5998	203.2600	63.4436	12.6626	38.6976	203.6600
63.4436	13.4000	38.6976	204.0600	63.4436	13.4000	38.5998	204.4500
63.4436	13.4000	38.5020	204.8500	63.4436	13.4000	38.5020	205.2400
63.4436	13.4000	38.5998	205.6400	63.4436	13.4000	38.5998	206.0400
63.4436	13.4000	38.5998	206.4300	63.4436	13.4000	38.6976	206.8300
63.4436	12.6626	38.5998	207.2300	63.4436	13.4000	38.5020	207.6200
63.4436	13.4000	38.5020	208.0200	63.4436	13.4000	38.5998	208.4200
63.4436	13.4000	38.5998	208.8100	63.4436	13.4000	38.5998	209.2100
63.4436	13.4000	38.5998	209.6000	63.4436	13.4000	38.5998	210.0000
63.4436	13.4000	38.5020	210.4000	63.4436	13.4000	38.5020	210.7900
63.4436	13.4000	38.5998	211.1900	63.4436	13.4000	38.7953	211.5900
63.4436	13.4000	38.6976	211.9800	63.4436	13.4000	38.5998	212.3800
63.4436	13.4000	38.5020	212.7700	63.4436	13.4000	38.5020	213.1700
63.4436	13.4000	38.5998	213.5700	63.4436	13.4000	38.5998	213.9600
63.4436	13.4000	38.6976	214.3600	31.2031	6.0250	38.4043	214.7600
0.0000	0.0000	37.9154	215.1500	0.0000	0.0000	37.3288	215.5500
0.0000	0.0000	36.5467	215.9400	0.0000	0.0000	35.5690	216.3400
0.0000	0.0000	34.4935	216.7400	0.0000	0.0000	33.3203	217.1400
0.0000	0.0000	32.1471	217.5300	0.0000	0.0000	30.9739	217.9300
0.0000	0.0000	29.8006	218.3300	0.0000	0.0000	28.5296	218.7300
0.0000	0.0000	27.3564	219.1200	0.0000	0.0000	26.1832	219.5200
0.0000	0.0000	25.0100	219.9200	0.0000	0.0000	23.8368	220.3200
0.0000	0.0000	22.6635	220.7200	0.0000	0.0000	21.5881	221.1100
0.0000	0.0000	20.4149	221.5100	0.0000	0.0000	19.2416	221.9100
0.0000	0.0000	18.0684	222.3000	0.0000	0.0000	16.8952	222.7000
0.0000	0.0000	15.7220	223.1000	0.0000	0.0000	14.5488	223.5000
0.0000	0.0000	13.3755	223.8900	0.0000	0.0000	12.3001	224.2900
0.0000	0.0000	11.1268	224.6900	0.0000	0.0000	10.1492	225.0900
0.0000	0.0000	8.8782	225.4800	0.0000	0.0000	7.5094	225.8800
0.0000	0.0000	6.2384	226.2800	0.0000	0.0000	4.8697	226.6800
0.0000	0.0000	3.6964	227.0700	0.0000	0.0000	2.3277	227.4700
0.0000	0.0000	0.0000	227.8700	0.0000	0.0000	0.0000	228.2700
0.0000	0.0000	0.0000	228.6700	0.0000	0.0000	0.0000	229.0600
0.0000	0.0000	0.0000	229.4600	0.0000	0.0000	0.0000	229.8600
0.0000	0.0000	0.0000	230.2600	0.0000	0.0000	0.0000	230.6600
0.0000	0.0000	0.0000	231.0500	0.0000	0.0000	0.0000	231.4500
0.0000	0.0000	0.0000	231.8500	0.0000	0.0000	0.0000	232.2500
0.0000	0.0000	0.0000	232.6500	0.0000	0.0000	0.0000	233.0400
0.0000	0.0000	0.0000	233.4400	0.0000	0.0000	0.0000	233.8400
0.0000	0.0000	0.0000	234.2400	0.0000	0.0000	0.0000	234.6400
0.0000	0.0000	0.0000	235.0300	0.0000	0.0000	0.0000	235.4300
0.0000	0.0000	0.0000	235.8300	0.0000	0.0000	0.0000	236.2300

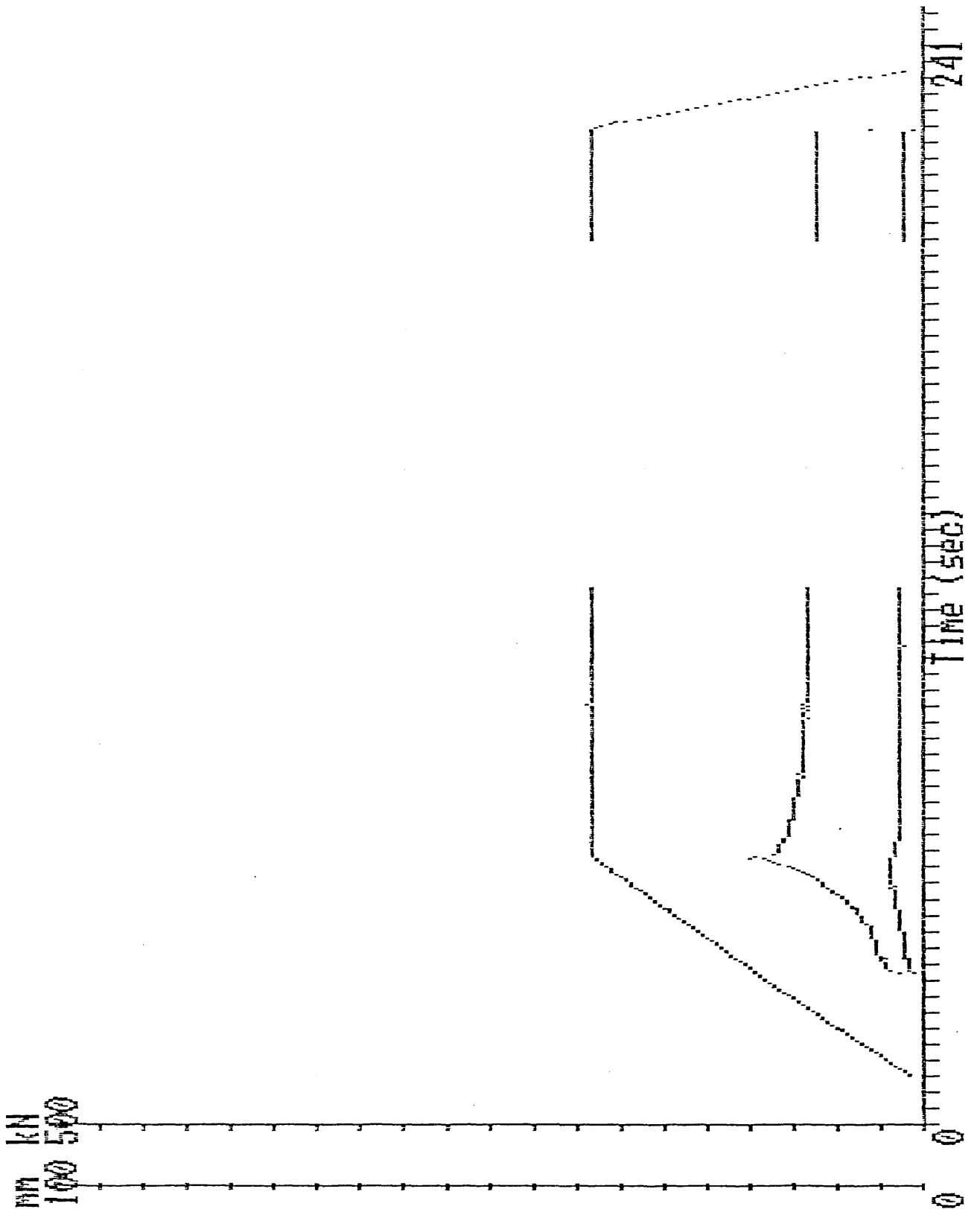


Fig.A5.17. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.18.

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RESULTS - SPECIMEN No.19

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The results of this test are stored in the file B:09-01-19.DAT

The values at maximum load are :-

Load at Top Load Cell = 54.95923 (kN)

Load at Bottom Load Cell = 20.77502 (kN)

Displacement = 36.25337 (mm)

Time Elasped = 56.43 (sec)

* T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	0.0000	0.1900	0.0000	0.0000	0.0000	0.5600
0.0000	0.0000	0.0000	0.9400	0.0000	0.0000	0.0000	1.3300
0.0000	0.0000	0.0000	1.7200	0.0000	0.0000	0.0000	2.1000
0.0000	0.0000	0.0000	2.4900	0.0000	0.0000	0.0000	2.8800
0.0000	0.0000	0.0000	3.2700	0.0000	0.0000	0.0000	3.6600
0.0000	0.0000	0.0000	4.0400	0.0000	0.0000	0.0000	4.4300
0.0000	0.0000	0.0000	4.8200	0.0000	0.0000	0.0000	5.2100
0.0000	0.0000	0.0000	5.5900	0.0000	0.0000	0.0000	5.9800
0.0000	0.0000	0.0000	6.3700	0.0000	0.0000	0.0000	6.7600
0.0000	0.0000	0.0000	7.1500	0.0000	0.0000	0.0000	7.5400
0.0000	0.0000	0.0000	7.9200	0.0000	0.0000	0.0000	8.3100
0.0000	0.0000	0.0000	8.7000	0.0000	0.0000	0.0000	9.0900
0.0000	0.0000	0.0000	9.4800	0.0000	0.0000	0.0000	9.8700
0.0000	0.0000	0.0000	10.2600	0.0000	0.0000	0.0000	10.6500
0.0000	0.0000	0.0000	11.0400	0.0000	0.0000	1.6433	11.4300
0.0000	0.0000	1.8388	11.8200	0.0000	0.0000	2.1321	12.2100
0.0000	0.0000	2.4254	12.6000	0.0000	0.0000	2.7188	12.9900
0.0000	0.0000	3.0121	13.3800	0.0000	0.0000	3.4031	13.7700
0.0000	0.0000	3.6964	14.1600	0.0000	0.0000	3.9897	14.5500
0.0000	0.0000	4.2831	14.9400	0.0000	0.0000	4.5764	15.3300
0.0000	0.0000	4.9674	15.7300	0.0000	0.0000	5.2607	16.1100
0.0000	0.0000	5.5540	16.5100	0.0000	0.0000	5.8474	16.9000
0.0000	0.0000	6.2384	17.2900	0.0000	0.0000	6.6295	17.6800
0.0000	0.0000	6.8250	18.0700	0.0000	0.0000	7.0206	18.4600
0.0000	0.0000	7.5094	18.8500	0.0000	0.0000	7.6072	19.2400
0.0000	0.0000	8.0960	19.6300	0.0000	0.0000	8.2916	20.0200
0.0000	0.0000	8.6826	20.4100	0.0000	0.0000	8.9759	20.8000
0.0000	0.0000	9.2692	21.1800	0.0000	0.0000	9.6603	21.5700
0.0000	0.0000	9.8559	21.9600	0.0000	0.0000	10.2469	22.3500
0.0000	0.0000	10.4425	22.7400	0.0000	0.0000	10.9313	23.1300
0.0000	0.0000	11.1268	23.5100	0.0000	0.0000	11.4202	23.9000
0.0000	0.0000	11.8112	24.2900	0.0000	0.0000	12.0068	24.6800
0.0000	0.0000	12.4956	25.0700	0.0000	0.0000	12.6911	25.4600
0.0000	0.0000	12.9845	25.8500	0.0000	0.0000	13.2778	26.2300
0.0000	0.0000	13.5711	26.6200	0.0000	0.0000	13.8644	27.0100
0.0000	0.0000	14.1577	27.4000	0.0000	0.0000	14.5488	27.7900
0.0000	0.0000	14.8421	28.1800	0.0000	0.0000	15.2331	28.5700
0.0000	0.0000	15.5264	28.9600	0.0000	0.0000	15.8197	29.3400

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
0.0000	0.0000	16.1130	29.7300	0.0000	0.0000	16.3086	30.1200
0.0000	0.0000	16.7974	30.5100	0.0000	0.0000	16.9930	30.9000
0.0000	0.0000	17.2863	31.2900	0.0000	0.0000	17.6773	31.6800
0.0000	0.0000	17.8729	32.0600	0.0000	0.0000	18.3617	32.4500
0.0000	0.0000	18.5573	32.8400	0.0000	0.0000	18.8506	33.2300
0.6594	1.6001	19.0461	33.6200	12.5374	8.9751	19.1439	34.0000
17.6282	10.4501	19.4372	34.3900	17.6282	10.4501	19.8282	34.7800
19.3250	11.1876	20.0238	35.1600	19.3250	10.4501	20.3171	35.5500
19.3250	11.1876	20.7082	35.9400	19.3250	11.1876	20.9037	36.3200
19.3250	11.1876	21.2948	36.7100	19.3250	11.1876	21.4903	37.1000
19.3250	11.9250	21.7836	37.4900	21.0217	11.9250	22.1747	37.8700
21.0217	11.9250	22.4680	38.2600	21.0217	11.9250	22.6635	38.6500
21.0217	11.9250	23.0546	39.0400	21.0217	11.9250	23.2502	39.4200
21.0217	11.9250	23.6412	39.8100	21.0217	11.9250	23.9345	40.2000
21.0217	11.9250	24.1301	40.5800	22.7188	11.9250	24.5211	40.9700
22.7188	11.9250	24.9122	41.3600	22.7188	11.9250	25.1078	41.7400
22.7188	11.9250	25.4011	42.1300	22.7188	12.6626	25.7921	42.5200
22.7188	12.6626	25.9877	42.9000	24.4155	12.6626	26.2810	43.2900
24.4155	12.6626	26.4765	43.6800	24.4155	13.4000	26.8676	44.0600
26.1125	13.4000	27.1609	44.4500	26.1125	13.4000	27.5520	44.8400
26.1125	14.1376	27.8453	45.2200	26.1125	14.1376	28.0408	45.6100
27.8093	14.1376	28.4319	46.0000	27.8093	14.8751	28.7252	46.3800
29.5061	14.8751	28.9207	46.7700	29.5061	14.8751	29.3118	47.1500
29.5061	14.8751	29.6051	47.5400	31.2031	15.6125	29.8006	47.9300
31.2031	15.6125	30.0939	48.3200	32.8999	15.6125	30.5828	48.7000
32.8999	16.3501	30.6806	49.0900	32.8999	16.3501	30.9739	49.4700
32.8999	16.3501	31.3649	49.8600	34.5969	17.0875	31.6582	50.2500
36.2937	17.0875	31.8538	50.6300	37.9905	17.8251	32.2449	51.0200
37.9905	17.8251	32.5382	51.4100	39.6875	17.8251	32.6359	51.7900
39.6875	18.5626	33.0270	52.1800	41.3843	19.3000	33.3203	52.5700
43.0813	19.3000	33.6136	52.9500	43.0813	19.3000	34.0047	53.3400
44.7781	19.3000	34.2980	53.7300	46.4749	20.0376	34.3958	54.1100
46.4749	20.0376	34.7868	54.5000	48.1719	20.0376	35.1779	54.8900
49.8687	20.0376	35.2757	55.2700	51.5657	20.7750	35.5690	55.6600
53.2625	20.7750	35.9601	56.0400	54.9592	20.7750	36.2534	56.4300
51.5657	20.0376	36.1556	56.8200	49.8687	19.3000	36.2534	57.2000
48.1719	19.3000	36.3511	57.5900	48.1719	19.3000	36.2534	57.9700
46.4749	18.5626	36.2534	58.3600	46.4749	18.5626	36.2534	58.7500
46.4749	18.5626	36.2534	59.1300	46.4749	18.5626	36.1556	59.5200
46.4749	18.5626	36.3511	59.9100	46.4749	18.5626	36.3511	60.2900
44.7781	18.5626	36.2534	60.6800	44.7781	17.8251	36.2534	61.0700
44.7781	18.5626	36.2534	61.4600	44.7781	17.8251	36.3511	61.8500
44.7781	17.8251	36.2534	62.2500	44.7781	17.8251	36.2534	62.6400
44.7781	17.8251	36.3511	63.0300	43.0813	17.8251	36.2534	63.4300
44.7781	17.8251	36.2534	63.8200	43.0813	17.8251	36.3511	64.2100
43.0813	17.8251	36.1556	64.6000	43.0813	17.8251	36.2534	65.0000
43.0813	17.8251	36.3511	65.3900	43.0813	17.8251	36.2534	65.7800
43.0813	17.8251	36.3511	66.1700	43.0813	17.8251	36.2534	66.5700
43.0813	17.8251	36.2534	66.9600	41.3843	17.0875	36.3511	67.3500
43.0813	17.0875	36.2534	67.7400	41.3843	17.0875	36.3511	68.1400
41.3843	17.0875	36.3511	68.5300	41.3843	17.0875	36.2534	68.9200
41.3843	17.0875	36.3511	69.3200	41.3843	17.0875	36.3511	69.7100
41.3843	17.0875	36.2534	70.1000	41.3843	17.0875	36.3511	70.5000
41.3843	17.0875	36.3511	70.8900	41.3843	17.0875	36.3511	71.2900
41.3843	16.3501	36.2534	71.6900	39.6875	16.3501	36.2534	72.0800
39.6875	17.0875	36.3511	72.4800	39.6875	16.3501	36.3511	72.8700

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
39.6875	16.3501	36.4489	73.2700	39.6875	16.3501	36.2534	73.6700
39.6875	16.3501	36.2534	74.0600	39.6875	16.3501	36.3511	74.4600
39.6875	16.3501	36.3511	74.8500	39.6875	16.3501	36.2534	75.2500
39.6875	16.3501	36.2534	75.6400	37.9905	16.3501	36.3511	76.0400
39.6875	16.3501	36.3511	76.4400	39.6875	16.3501	36.3511	76.8300
37.9905	16.3501	36.2534	77.2300	37.9905	16.3501	36.2534	77.6200
37.9905	15.6125	36.3511	78.0200	37.9905	16.3501	36.3511	78.4100
37.9905	16.3501	36.2534	78.8100	37.9905	16.3501	36.2534	79.2000
37.9905	15.6125	36.3511	79.6000	37.9905	15.6125	36.3511	80.0000
37.9905	15.6125	36.3511	80.3900	37.9905	15.6125	36.2534	80.7900
37.9905	15.6125	36.2534	81.1900	37.9905	15.6125	36.3511	81.5800
37.9905	15.6125	36.3511	81.9800	37.9905	15.6125	36.4489	82.3800
36.2937	15.6125	36.3511	82.7700	37.9905	15.6125	36.2534	83.1700
37.9905	15.6125	36.2534	83.5700	36.2937	15.6125	36.2534	83.9600
36.2937	15.6125	36.3511	84.3600	36.2937	15.6125	36.3511	84.7600
36.2937	15.6125	36.3511	85.1500	36.2937	15.6125	36.2534	85.5500
36.2937	15.6125	36.2534	85.9500	36.2937	15.6125	36.3511	86.3400
36.2937	15.6125	36.3511	86.7400	36.2937	15.6125	36.3511	87.1400
36.2937	15.6125	36.3511	87.5300	36.2937	15.6125	36.2534	87.9300
36.2937	14.8751	36.2534	88.3300	36.2937	14.8751	36.2534	88.7200
36.2937	14.8751	36.3511	89.1200	36.2937	14.8751	36.3511	89.5200
36.2937	14.8751	36.3511	89.9100	34.5969	14.8751	36.2534	90.3100
36.2937	14.8751	36.2534	90.7100	36.2937	14.8751	36.3511	91.1000
34.5969	14.8751	36.2534	91.5000	34.5969	14.8751	36.3511	91.9000
34.5969	14.8751	36.3511	92.2900	34.5969	14.8751	36.2534	92.6900
34.5969	14.8751	36.3511	93.0800	34.5969	14.8751	36.3511	93.4800
34.5969	14.8751	36.3511	93.8800	34.5969	14.8751	36.2534	94.2700
34.5969	14.8751	36.2534	94.6700	34.5969	14.8751	36.3511	95.0600
34.5969	14.8751	36.3511	95.4600	32.8999	14.8751	36.4489	95.8600
34.5969	14.8751	36.2534	96.2500	32.8999	14.8751	36.2534	96.6500
32.8999	14.8751	36.3511	97.0500	34.5969	14.8751	36.3511	97.4400
32.8999	14.8751	36.3511	97.8400	34.5969	14.8751	36.2534	98.2300
32.8999	14.8751	36.2534	98.6300	32.8999	14.8751	36.3511	99.0300
32.8999	14.1376	36.3511	99.4200	32.8999	14.1376	36.3511	99.8200
32.8999	14.8751	36.2534	100.2100	32.8999	14.1376	36.3511	100.6100
32.8999	14.1376	36.4489	101.0000	32.8999	14.1376	36.4489	101.4000
32.8999	14.1376	36.2534	101.8000	32.8999	14.8751	36.3511	102.1900
32.8999	14.1376	36.3511	102.5900	32.8999	14.1376	36.3511	102.9800
32.8999	14.1376	36.3511	103.3800	32.8999	14.1376	36.2534	103.7800
32.8999	14.1376	36.3511	104.1700	32.8999	14.1376	36.4489	104.5700
32.8999	14.1376	36.4489	104.9600	32.8999	14.1376	36.3511	105.3600
32.8999	14.1376	36.2534	105.7600	32.8999	14.1376	36.3511	106.1500
32.8999	14.1376	36.3511	106.5500	32.8999	14.1376	36.3511	106.9400
32.8999	14.1376	36.2534	107.3400	32.8999	14.1376	36.2534	107.7400
32.8999	14.1376	36.3511	108.1300	32.8999	14.1376	36.3511	108.5300
32.8999	14.1376	36.3511	108.9200	32.8999	14.1376	36.2534	109.3200
27.8093	12.6626	36.3511	184.3900	27.8093	12.6626	36.2534	184.7800
27.8093	12.6626	36.3511	185.1800	27.8093	12.6626	36.3511	185.5700
29.5061	12.6626	36.3511	185.9700	27.8093	12.6626	36.3511	186.3600
29.5061	12.6626	36.4489	186.7500	27.8093	12.6626	36.3511	187.1500
27.8093	12.6626	36.3511	187.5400	27.8093	12.6626	36.3511	187.9300
27.8093	12.6626	36.3511	188.3300	27.8093	12.6626	36.2534	188.7200
27.8093	12.6626	36.4489	189.1100	29.5061	12.6626	36.3511	189.5100
29.5061	12.6626	36.2534	189.9000	27.8093	12.6626	36.3511	190.3000
27.8093	11.9250	36.4489	190.7000	27.8093	11.9250	36.3511	191.0900
27.8093	12.6626	36.3511	191.4900	27.8093	12.6626	36.2534	191.8900

* T.L.C. * (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) **	** T.L.C. (kN)	B.L.C. (kN)	DISPLACEMENT (mm)	TIME (sec) *
27.8093	12.6626	36.3511	192.2800	27.8093	12.6626	36.2534	192.6800
27.8093	12.6626	36.3511	193.0800	27.8093	12.6626	36.3511	193.4700
27.8093	12.6626	36.3511	193.8700	27.8093	11.9250	36.3511	194.2700
27.8093	12.6626	36.2534	194.6700	27.8093	12.6626	36.3511	195.0600
27.8093	12.6626	36.3511	195.4600	27.8093	11.9250	36.4489	195.8600
27.8093	12.6626	36.3511	196.2500	27.8093	11.9250	36.3511	196.6500
27.8093	12.6626	36.3511	197.0500	27.8093	12.6626	36.2534	197.4400
27.8093	12.6626	36.4489	197.8400	27.8093	12.6626	36.3511	198.2400
27.8093	11.9250	36.4489	198.6300	27.8093	12.6626	36.3511	199.0300
27.8093	12.6626	36.2534	199.4300	27.8093	12.6626	36.3511	199.8200
27.8093	11.9250	36.4489	200.2200	27.8093	11.9250	36.3511	200.6200
27.8093	11.9250	36.3511	201.0100	27.8093	11.9250	36.3511	201.4100
27.8093	12.6626	36.3511	201.8100	27.8093	11.9250	36.3511	202.2000
27.8093	11.9250	36.4489	202.6000	27.8093	11.9250	36.3511	203.0000
27.8093	12.6626	36.2534	203.3900	27.8093	12.6626	36.2534	203.7900
27.8093	12.6626	36.3511	204.1800	27.8093	12.6626	36.3511	204.5800
27.8093	11.9250	36.3511	204.9800	27.8093	12.6626	36.3511	205.3700
27.8093	12.6626	36.3511	205.7700	27.8093	12.6626	36.4489	206.1700
27.8093	11.9250	36.3511	206.5600	27.8093	11.9250	36.3511	206.9600
27.8093	11.9250	36.3511	207.3600	27.8093	12.6626	36.3511	207.7500
27.8093	12.6626	36.3511	208.1500	27.8093	12.6626	36.3511	208.5500
27.8093	11.9250	36.4489	208.9400	27.8093	11.9250	36.3511	209.3400
27.8093	11.9250	36.3511	209.7400	27.8093	12.6626	36.3511	210.1300
27.8093	12.6626	36.3511	210.5300	27.8093	11.9250	36.3511	210.9300
27.8093	12.6626	36.3511	211.3200	27.8093	11.9250	36.3511	211.7200
27.8093	12.6626	36.2534	212.1100	27.8093	12.6626	36.2534	212.5100
27.8093	12.6626	36.3511	212.9100	27.8093	11.9250	36.2534	213.3000
27.8093	11.9250	36.3511	213.7000	27.8093	11.9250	36.3511	214.1000
27.8093	11.9250	36.3511	214.4900	27.8093	11.9250	36.2534	214.8900
27.8093	11.9250	36.4489	215.2900	27.8093	11.9250	36.3511	215.6800
27.8093	11.9250	36.3511	216.0800	27.8093	12.6626	36.2534	216.4800
27.8093	11.9250	36.3511	216.8700	27.8093	11.9250	36.3511	217.2700
27.8093	11.9250	36.3511	217.6700	27.8093	11.9250	36.3511	218.0600
27.8093	12.6626	36.2534	218.4600	27.8093	12.6626	36.3511	218.8500
27.8093	11.9250	36.3511	219.2500	1.0376	0.1251	36.2534	219.6500
0.0000	0.0000	35.6667	220.0400	0.0000	0.0000	34.3958	220.4400
0.0000	0.0000	32.5382	220.8400	0.0000	0.0000	30.6806	221.2300
0.0000	0.0000	28.7252	221.6300	0.0000	0.0000	26.5743	222.0300
0.0000	0.0000	24.6189	222.4200	0.0000	0.0000	22.7613	222.8200
0.0000	0.0000	20.8059	223.2200	0.0000	0.0000	18.8506	223.6100
0.0000	0.0000	16.8952	224.0100	0.0000	0.0000	14.8421	224.4100
0.0000	0.0000	12.8867	224.8000	0.0000	0.0000	10.9313	225.2000
0.0000	0.0000	9.0737	225.6000	0.0000	0.0000	7.1183	226.0000
0.0000	0.0000	5.2607	226.3900	0.0000	0.0000	3.4031	226.7900
0.0000	0.0000	0.0000	227.1900	0.0000	0.0000	0.0000	227.5800
0.0000	0.0000	0.0000	227.9800	0.0000	0.0000	0.0000	228.3800
0.0000	0.0000	0.0000	228.7800	0.0000	0.0000	0.0000	229.1700
0.0000	0.0000	0.0000	229.5700	0.0000	0.0000	0.0000	229.9700
0.0000	0.0000	0.0000	230.3700	0.0000	0.0000	0.0000	230.7600
0.0000	0.0000	0.0000	231.1600	0.0000	0.0000	0.0000	231.5600
0.0000	0.0000	0.0000	231.9600	0.0000	0.0000	0.0000	232.3500
0.0000	0.0000	0.0000	232.7500	0.0000	0.0000	0.0000	233.1500
0.0000	0.0000	0.0000	233.5400	0.0000	0.0000	0.0000	233.9400
0.0000	0.0000	0.0000	234.3400	0.0000	0.0000	0.0000	234.7400
0.0000	0.0000	0.0000	235.1300	0.0000	0.0000	0.0000	235.5300
0.0000	0.0000	0.0000	235.9300	0.0000	0.0000	0.0000	236.3300

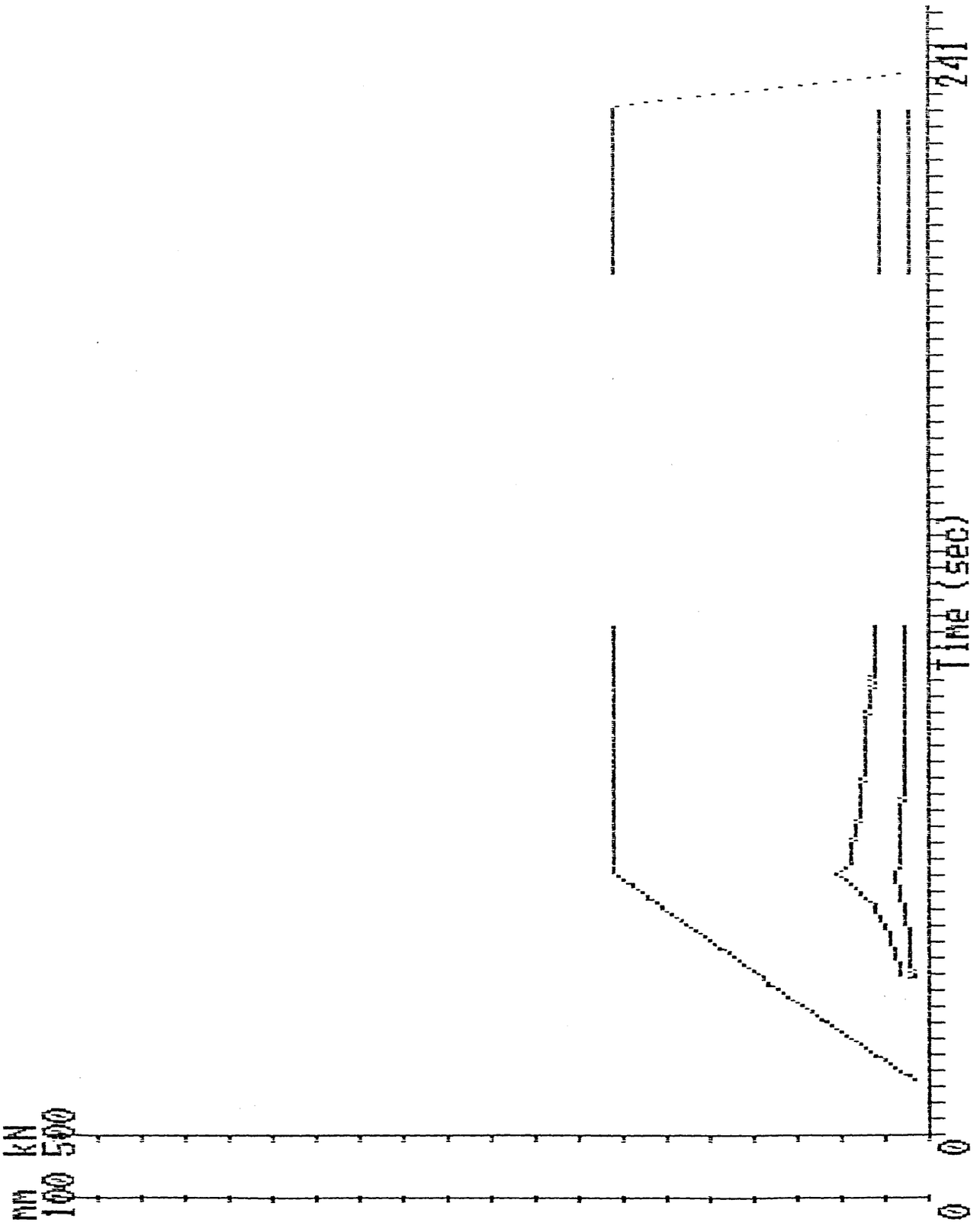


Fig.A5.18. Load on the Top Load Cell, Load on the Bottom Load Cell and Displacement versus Time for Specimen No.19.

ERRATA

1. Page 6 - 7th line from the bottom reads:"7.2. ..." should read:"7.1. ..."

2. Page 24 - 2nd line from the bottom reads:"The incompressibility constraint can be removed by introducing ..." should read:"The incompressibility constraint can be enforced by introducing ..."

3. Page 25 - 16th line from the top reads:"... - developed in 1979 [10]" should read:"... - developed in 1979 [74,75]".

4. Page 28 - Eqn.(2.6) reads:"...$\mathbf{d\{\delta\}}$ - ..." should read "...$\mathbf{d\{\sigma\}}$ - ...".

5. Page 29 - Eqn.(2.12) reads:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E]\ \mathbf{dV})$..." should read:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E][\mathbf{B}]\ \mathbf{dV})$...".

6. Page 29 - line after Eqn.(2.12) reads:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E]\ \mathbf{dV})$..." should read:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E][\mathbf{B}]\ \mathbf{dV})$...".

7. Page 29 - third unnumbered equation from the top reads:"... = $-\int [\mathbf{B}]^t$ ..." should read:"... = $+\int [\mathbf{B}]^t$ ...".

8. Page 29 - Eqn.(2.13) reads:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E]\ \mathbf{dV})$..." should read:"...$(\int [\mathbf{B}]^t[\mathbf{D}^E][\mathbf{B}]\ \mathbf{dV})$...".

9. Page 32 - beneath Eqn.(2.20) the expression should be added:
" where:
$$s = \frac{2}{3}\bar{\sigma}^2\left(1 + \frac{H'}{3G}\right)".$$

10. Page 33 - Fig.2.2 on 'F' axis reads:"$F_C\ F_B\ F_A$" should read:"$F_A\ F_B\ F_C$".

11. Page 37 - line before Eqn.(2.29) reads:"... above $\mathbf{d\{\varepsilon\}}$ = ..." should read:"... above $\mathbf{d\{\varepsilon^p\}}$ = ...".

12. Page 38 - Equation before Eqn.(2.33) reads:"... $\mathbf{d\{\delta\}\{dp\}}$" should read:"... $\mathbf{d\{\delta\}}$ - $\mathbf{\{dp\}}$".

13. Page 40 - first unnumbered equation reads:"... $\{\alpha_0\ \beta_0\ \alpha_1\ \beta_1\ \alpha_2\ \beta_2\}^t$" should read: "... $\{a_0\ b_0\ a_1\ b_1\ a_2\ b_2\}^t$".

14. Page 41 equation before Eqn.(2.41)
reads: "$[\mathbf{d}] = \begin{bmatrix} \frac{\partial u}{\partial x} & 0 \\ 0 & \frac{\partial u}{\partial y} \\ \frac{\partial u}{\partial y} & \frac{\partial u}{\partial x} \end{bmatrix}$" should read: "$[\mathbf{d}] = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}$".

15. Page 43 - lines 8 & 9 from the top everywhere where reads:"... nine ..." should read:"...four...".

16. Page 44 - Eqn.(2.44)
reads:"$\begin{bmatrix} \dots\ \mathbf{n}_5 & \mathbf{0} \\ \dots\ \mathbf{0} & \mathbf{n}_5 \end{bmatrix}$" should read:"$\begin{bmatrix} \dots\ \mathbf{n}_4 & \mathbf{0} \\ \dots\ \mathbf{0} & \mathbf{n}_4 \end{bmatrix}$".

17. Pages 47 to 49 - Eqns.(3.3) to (3.14) reads:"... σ^y ..." should read:"... σ_y ...".

18. Page 49 - line after Eqn.(3.14) reads:"... Eqn.(A2.15), ..." should read:"... Eqn.(A2.16), ...".

19. Page 51 - 4th line from the bottom reads:"extremum principle [46] the functional (3.1) takes the absolute minimum value for then" should read:"extremum principle [46] the functional (3.15) takes the absolute minimum value for the"

20. Page 55 - Eqn.(3.34) reads:"**... dS (3.34)**" should read:"**... dS = 0 (3.34)**"

21. Page 59 - Eqn.(3.54) reads:" ... $\mathbf{d\xi d\eta dxdy}$" should read:" ... $\mathbf{d\xi d\eta t}$" and after the same equation should read " where: **t** - element thickness".

22. Page 60 - 5th line from the bottom reads: "..., thus equation (3.60) ..." should read: "..., thus equation (3.61) ..."