

Residual stress analysis of structural stainless steel sections

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Abstract

The magnitude and distribution of residual stresses in structural carbon steel sections have been thoroughly investigated. However, few residual stress measurements have been made on structural stainless steel sections. Stainless steel has differing material stress-strain characteristics and thermal properties to carbon steel, both of which influence the formation of residual stresses. This suggests that established carbon steel residual stress models may not be appropriate for stainless steel. With increased use of stainless steel in load bearing applications, it is important to establish the residual stresses that exist within structural members. An experimental program to quantify the residual stresses in stainless steel sections from three different production routes has therefore been carried out. Comprehensive residual stress distributions have been obtained for three hot rolled angles, eight press braked angles and seven cold rolled box sections, with a total of over 800 readings taken. This paper presents the experimental techniques implemented and the residual stress distributions obtained as well as discussing the assumptions commonly made regarding through thickness residual stress variations. In the hot rolled and press braked sections, residual stresses were typically found to be below 20% of the material 0.2% proof stress, though for the cold rolled box sections, whilst membrane residual stresses were relatively low, bending residual stresses were found to be between 40% and 70% of the material 0.2% proof stress.

Keywords: plastic deformation, residual stresses, sectioning method, stainless steel, structures, thermal properties

1. Introduction

Stresses that exist in structural sections in their unloaded state are termed residual stresses; these have been extensively quantified for carbon steel sections. The formation of residual stresses occurs primarily during the section production process and is associated with differential cooling and non-uniform plastic deformation. The general influence of residual stresses on structural members is to cause premature yielding, leading to a loss of stiffness and a reduction in load-carrying capacity. Studies of residual stresses in fabricated carbon steel sections have been presented in [1, 2, 3], whilst those in hot rolled sections have been discussed in [4, 5, 6]. A summary of the influence of residual stresses on both hot rolled and fabricated sections has been prepared by Lay and Ward [7]. Residual stresses in cold formed sections generally, have been examined by Weng and Peköz [8] and Schafer and Peköz [9]. More particularly, residual stresses in cold rolled sections have been investigated by Chen and Ross [10] and Kato and Aoki [11] and in press braked sections by Weng and White [12]. The rigour with which these stresses have been quantified for carbon steel sections from different production routes reflects their potential influence on structural performance.

With increased interest in the use of stainless steel in construction [13] it is important to quantify the residual stresses that exist within structural members. It cannot simply be assumed that residual stresses in stainless steel sections are of the same magnitude or distribution as those in carbon steel sections, due to the different physical and thermal properties that stainless steel exhibits. Differences include higher thermal expansion and lower thermal conductivity than carbon steel, and a rounded stress-strain curve with significant strain hardening.

The experimental program described in this paper was carried out at Imperial College London, where the sectioning technique was employed to quantify the longitudinal residual stress distributions in a range of structural stainless steel sections. Three hot rolled angles, eight press braked angles and seven cold rolled box sections were examined. Measurements were taken with electrical strain gauges and, for one section, with a mechanical strain gauge; an appraisal of the applicability of both of these techniques is made herein. Tensile coupon tests were performed on the released strips of material to obtain the corresponding material stress-strain relationship.

Following a survey of existing residual stress data from carbon steel and stainless steel sections, together with proposed models for the prediction of residual stresses in carbon steel structural sections, the data presented herein have been combined with existing data and used to develop residual stress models specifically for stainless steel sections [14].

1.1 Experimental techniques

There are three recognised types of residual stress that equilibrate over different scales. Type I residual stresses act and equilibrate over the macro scale. It is the type I stresses which, when present along the length of a member, have the greatest effect on the structural behaviour. Types II and III residual stresses act over the micro-scale and are related to more local stress disturbances caused between and within the metal grain structure. Further detail on these distinctions and the origin of residual stresses are given in [15].

Techniques to measure type I residual stresses may be classified as either destructive or non-destructive. Non-destructive methods include X-ray, neutron or electron diffraction, ultrasonic methods and magnetic methods. Destructive methods rely on the measurement of deformations due to the release of residual stresses upon removal of material from the specimen. Sectioning is the principal destructive technique used to measure residual stresses in structural members. This method has been used extensively to analyse residual stresses in structural carbon steel [16], aluminium [17] and stainless steel [18, 19] sections and is adopted in this study. A comprehensive description of the different techniques and their potential for measuring residual stresses has been presented in [20].

1.2 Modelling residual stresses

For the purposes of structural design, residual stresses which occur along the length of the member are the most influential on structural behaviour. Therefore, although significant residual stresses can exist in other directions, particularly in the circumferential direction [10], longitudinal strains on the internal and external surfaces of the section are most commonly measured and converted into stresses.

In general, the strips of material released by the sectioning process may exhibit both axial deformation and curvature, corresponding to membrane and bending (through thickness) residual stresses, respectively. Membrane residual stresses σ_m generally dominate in hot rolled

and fabricated sections whereas bending residual stresses σ_b are generally dominant in cold formed sections. These two residual stress components are illustrated in Fig. 1, where the bending stresses are assumed to be linearly varying through the thickness. From this assumption it follows that the combined membrane and bending residual stress pattern σ_{rc} is always a linear relationship [9]. For thick plates, where it is possible to measure residual stresses at incremental depths through the material thickness, this assumption has been shown to be inaccurate [12, 21]. For thinner material it is physically difficult to measure these through thickness changes, though analytical and finite element studies have also predicted a non-linear through thickness variation of residual stresses [22, 23].

1.3 Production routes

Due to the sensitivity of stainless steel to plastic deformation and thermal effects, the section production route has an important influence on the final residual stress distribution. Sections from three principal production routes have been considered in this experimental program - hot rolled angles, press braked angles and cold rolled box sections.

Residual stress patterns in hot rolled sections are normally associated with differential cooling rates due to variation in material thickness. The faster cooling regions of the section, such as the flange tips are left in residual compression and the thicker, slower cooling regions, such as the corners are left in residual tension. Techniques used to straighten the cooled sections may also modify the residual stress patterns and cold work the material.

Residual stress patterns in cold formed sections (press braked and cold rolled sections) are linked primarily to plastic deformation which can occur during sheet production and in the processes used to form the sheet material into sections. Sheet material used for cold forming can be either hot rolled or cold reduced, the latter causing substantial plastic deformation. Sheet material is subsequently rolled onto a coil for storage and transportation, after which the material is uncoiled and levelled for further processing. The processes of coiling and uncoiling the sheet material induces additional plastic deformation altering the through thickness residual stress distribution [24]. The two cold forming techniques (press braking and cold rolling) cause differing levels of plastic deformation and allow for different amounts of elastic spring back resulting in different residual stress patterns. In addition residual stresses in cold rolled hollow sections may be influenced by the seam weld used to close the formed sheet material into a tube.

1.4 Material properties

Unlike structural carbon steel, which displays a clearly defined linear elastic region, a flat plastic plateau and a moderate degree of strain hardening, stainless steel exhibits a rounded stress-strain curve with considerable strain hardening. In the absence of a sharply defined yield point, the 0.2% proof stress $\sigma_{0.2}$ is generally adopted, whilst the limit of proportionality is generally defined as the stress at 0.01% plastic strain $\sigma_{0.01}$, as shown in Fig. 2. To represent the rounded stress-strain response of stainless steel, the Ramberg-Osgood model is commonly adopted. The development of this model for stainless steel stress-strain behaviour, from its origins in 1943 to the more recently adopted two-stage versions, is given in the following references [25, 26, 27, 28, 29, 30, 31].

In addition to the fundamental differences in the form of the stress-strain response between stainless steel and carbon steel, there is also variation in thermal properties, including specific heat, thermal conductivity and thermal expansion [13, 32], all of which will influence the formation of residual stresses. The specific heat of stainless steel is approximately 500 J/kgK as compared to carbon steel which has a value of approximately 600J/kgK. The lower the specific heat of a material, the more rapidly it tends to heat up. For temperatures below about 1000°C, the thermal conductivity of stainless steel is lower than that of carbon steel; at low temperatures the difference is significant, whilst above about 700°C, the difference is small. The coefficient of thermal expansion of stainless steel is up to approximately 50% larger than that of carbon steel, which may result in greater distortion of material during heat input and larger residual stresses.

2. Experimental Program

An experimental program was carried out at Imperial College London to quantify the distributions of residual stresses in three different types of structural stainless steel sections: hot rolled angles, press braked angles and cold rolled box sections using the sectioning technique. All sections were manufactured from austenitic stainless steel (Grade 1.4301).

2.1 Specimen preparation

The specimens were set out as shown in Fig. 3, with sufficient material either side of the central portions to ensure a representative initial residual stress distribution. The first central portion A was divided into a series of strips as shown in Figs 13, 17, and 26 for the three types of cross section.

The strains released during the cutting process were generally measured using electrical strain gauges, though mechanical curvature measurements were also made, and for one section, a mechanical strain gauge was also employed. Initial readings prior to the sectioning process and final readings after sectioning were taken for all released strips. Sectioning was performed on an automated milling machine as shown in Fig. 4. A set of released strips from a cold rolled box section are shown in Fig. 5.

2.2 Mechanical strain readings

For the first cold rolled box section, released residual strains were measured by mechanical means, following the procedure recommended in [33]. Initial and final membrane strains were measured using a mechanical strain gauge (or Whitemore gauge) (Fig. 6a), whilst bending strains were measured with a curvature dial (Fig. 6b). For both initial and final readings a mean value was determined from three readings. To locate the Whitemore gauge on the specimens, pairs of pellets with pre-drilled gauge holes were adhered to the surface; this was done as an alternative to drilling holes into the specimen as proposed in [34].

2.2.1 Bending residual stresses

Bending residual stresses σ_b were initially determined by assuming a linearly varying through thickness stress distribution, by means of Eq. (1). A rectangular stress block distribution will also be considered.

$$\sigma_b = \frac{Ey}{R_{i-f}} \quad (1)$$

where E is the Young's modulus, R_{i-f} is the change in radius of curvature and y is the distance from the neutral axis, taken as $t/2$ (where t is the material thickness) to determine the surface stresses. The asymmetry of the corner strips meant that the inner and outer surface stresses

were not equal. The change in radius of curvature R_{i-f} of the strips was calculated from Eq. (2). It was assumed that the curvature was constant along the length of the strips (which was confirmed with curvature dial measurements).

$$R_{i-f} = \frac{(S_f - S_i)}{2} + \frac{N^2}{8(S_f - S_i)} \quad (2)$$

where N is the length over which the deflection is measured ($N = 100$ mm), S_i is the initial deflection of the strip and S_f is the final deflection of strip (see Fig. 6b).

2.2.2 Membrane residual stresses

The calculation of the membrane residual stress is more complex, as the measurements made by the Whittemore gauge must be corrected to remove the effects of strip curvature caused by the existence of bending residual stresses. Expressions to calculate membrane residual stresses from Whittemore gauge and curvature dial measurements have been proposed by Galambos [33] and Sherman [34]. Both [33, 34] approximate the curvature of the released strips as parabolic, though this is found herein to be inappropriate in the presence of large bending residual stresses, which are particularly prominent in cold rolled sections. An alternative circular approximation is therefore proposed, whereby the released strip is assumed to be a circular arc and the Whittemore gauge length (measured between gauge points at A and B in Fig. 7) is assumed to be a chord of length D . The relationship between angle of curvature θ and chord length D , is expressed in Eq. (3) and illustrated in Fig. 7.

$$\sin \theta = \frac{D}{2R} \quad (3)$$

where R is the radius of curvature measured from the centre of curvature to the surface of the gauge hole pellets.

There are three corrections required to convert the measurements taken from the Whittemore gauge and curvature dial to membrane residual stresses acting along the neutral axis of the strip [34]. In the context of the circular approximation, these are described in the following sub-sections.

2.2.2.1 The gauge hole correction

The Whittemore gauge has two conical points to enable it to be positioned in the gauge holes on the strip. Owing to the curvature of the strips, the centreline of each of the conical points does not pass through the centreline of the gauge hole, but is offset by a distance Δ . Assuming that the conical point remains in complete contact with the outer circumference of the gauge hole and that the strip is of constant curvature, the offset Δ can be determined by simple 2-dimensional geometrical rules applied to Fig. 8 and expressed in Eq. (4),

$$\Delta = \left(\frac{g}{2} \right) \sin \theta \tan \phi \quad (4)$$

where g is the diameter of the gauge hole, θ is the angle of curvature, and ϕ is half the internal angle of the conical point. The new gauge length D_c can be used to calculate a revised angle of curvature θ_c from Eq. (4).

2.2.2.2 The surface to neutral axis correction

Calculations so far have employed the radius of curvature R of the released strips from the centre of curvature to the surface of the gauge hole pellets. In order to remove the influence of bending residual stresses from the membrane stress calculation, the radius of curvature of the strips measured to the neutral axis R_n is required. For a strip of rectangular cross section, this simply requires the addition or subtraction of $(t/2 + p)$ where t is the strip thickness and p is the pellet thickness from the radius of curvature R measured to the surface of the pellets. The corresponding chord length D_n can be obtained using Eq. (3).

2.2.2.3 The chord to arc correction

The final correction is to convert the chord length D_n into the arc length L . Using the radius of curvature of the strips measured to the neutral axis R_n and the revised angle of curvature θ_c , the length along the arc can be calculated using Eq. (5).

$$L = R_n \theta_c \quad (5)$$

By performing this process for both the initial and final state of the strips, the initial and final arc lengths L_i and L_f may be determined, and hence the membrane residual strain ϵ_m may be

calculated through Eq. (6). Assuming an elastic material response, the residual stress may then be calculated by means of the Young's modulus.

$$\varepsilon_m = \frac{L_i - L_f}{L_i} \quad (6)$$

2.2.3 Discussion of Corrections

The corrections proposed by Galambos [33] and Sherman [34] were developed principally to remove the effects of strip curvature (due to bending residual stresses) during the calculation of membrane residual stresses in hot rolled sections. In such sections, bending residual stresses are low and hence the approximations made [33, 34] (including representation of the curved strips as a parabola and small angle assumptions) induce only minimal errors. However, for cold formed sections, bending residual stresses are far more significant, and adoption of the Galambos or Sherman approximations leads to calculated membrane residual stresses displaying large discrepancies from those determined using the circular approximation described above. Deviation in calculated membrane residual stresses using the Galambos and Sherman approximations from the circular approximation is indicated in Fig. 9 for a strip of thickness 4 mm; the results show that as the radius of curvature reduces, the deviation increases. It is later demonstrated, by comparison of residual stresses determined by mechanical means with those determined by electrical strain gauges, that the circular approximation remains accurate, even in the presence of the high curvatures associated with cold formed sections.

2.3 Electrical strain readings

Electrical strain gauges were selected in preference to the mechanical strain gauge for the residual strain measurements of the remaining 17 cross sections (Fig. 10). Curvature dial readings were still taken to verify the results of the electrical strain gauges. To account for any temperature effects on the measured resistance the strain box was zeroed against a high precision resistor with a temperature variation coefficient very close to that of the strain gauges. Different techniques were used to determine residual stresses in the angles and box sections due to the difficulties of affixing strain gauges to the inner surfaces of the box sections, as described in the following sub-sections.

2.3.1 Angle sections

Strain gauges were adhered to both the inner and outer surfaces of the hot rolled and press braked angle sections and readings were taken prior to ($\epsilon_{i,in}$ and $\epsilon_{i,out}$) and after ($\epsilon_{f,in}$ and $\epsilon_{f,out}$) sectioning. On the assumption that the residual strain distribution can be modelled as linearly varying through the material thickness, Eqs (7) and (8) may be used to calculate membrane and bending residual strains respectively, where a positive value indicates a tensile residual strain and a negative value indicates a compressive residual strain.

$$\epsilon_m = -\left(\frac{(\epsilon_{f,out} - \epsilon_{i,out}) + (\epsilon_{f,in} - \epsilon_{i,in})}{2}\right) \quad (7)$$

$$\epsilon_b = \pm\left(\frac{(\epsilon_{f,out} - \epsilon_{i,out}) - (\epsilon_{f,in} - \epsilon_{i,in})}{2}\right) \quad (8)$$

2.3.2 Box sections

Due to physical constraints, it was not possible to mount strain gauges on the inner surface of the cold rolled box sections; strain gauges were therefore only mounted on the outer surface prior to sectioning. A different procedure was therefore developed to establish residual stresses, whereby the second set of strain gauges was attached to the inner surface of the strips after sectioning and the strips were returned to a flat configuration on a mill plate using two clamps at each end of the strips, which were gradually adjusted. Bending residual stresses determined from the electrical strain gauges by this means were compared with values obtained from the curvature dial; Fig. 11 shows excellent correlation between the two approaches, suggesting that the circular approximation described earlier is a reasonable one to employ. The membrane residual strains were obtained by subtracting the bending strains from total strain readings taken on the outer strain gauges. Fig. 12 illustrates the procedure adopted, and Eqs (10) and (11) express the membrane residual strains and bending residual strains in terms of the measured strains. The letter ‘b’ in the strain subscripts indicate measurements that were taken when both the inner and outer strain gauges were attached (see Fig. 12).

$$\epsilon_m = -(\epsilon_{f,out} - \epsilon_{i,out}) - (\epsilon_{bf,out} - \epsilon_{bi,out}) \quad (10)$$

$$\epsilon_b = \pm\left(\frac{(\epsilon_{bf,out} - \epsilon_{bi,out}) - (\epsilon_{bf,in} - \epsilon_{bi,in})}{2}\right) \quad (11)$$

3. Results

3.1 Introduction

Residual stresses have been analysed in a total of 18 stainless steel cross sections. The results are presented and analysed in this section. Throughout this section, a specimen reference system is adopted, which firstly gives the production route: PB for press braked, CR for cold rolled and HR for hot rolled, followed by the two cross sectional dimensions and the thickness t , and finally the internal corner radii r_i , if specified, is given in brackets.

Graphical results for all tested sections are presented in Figs 14 to 16 (for the hot rolled sections), Figs 18 to 25 (for the press braked sections) and Figs 27 to 33 (for the cold rolled sections). Tabulated results for three sections: one hot rolled angle (HR 50×50×3), one press braked angle (PB 50×50×2 ($r_i = 4.5$)) and one cold rolled rectangular hollow section (CR 100×50×4) are also given in Tables 1-3. The full set of residual stresses are available in [35].

In order to evaluate the magnitude of the bending residual stresses, the initial through thickness stress distribution needs to be assumed (in the absence of measurements). In this study, bending residual stresses in the hot rolled sections were calculated on the basis of a linearly varying through thickness distribution, as commonly assumed for both hot rolled and cold formed carbon steel sections [8, 9]. A rectangular stress block distribution was assumed for cold formed sections (both press braked and cold rolled) which is more representative of the through thickness distribution associated with the large plastic bending deformations that occur during production, which have been obtained experimentally for thick plates by [12], and analytically and numerically for cold formed sections by [22] and [23]. For a rectangular cross section (as is the case for all the flat strips considered herein), surface bending residual stresses calculated on the basis of a linearly varying through thickness stress distribution will be some 50% higher than those calculated on the basis of rectangular stress blocks – this follows from the fact that rectangular sections have a shape factor of 1.5 in bending.

3.2 Hot rolled sections

The residual stress results for the three hot rolled angles are presented in Figs 14, 15 and 16. Table 1 presents the numerical data from sectioned strips obtained at different locations around the cross section for specimen HR 50×50×3. The location of the strips within the cross section

is given in Fig. 13. For the hot rolled stainless steel angles, bending residual stresses were calculated on the assumption of a linearly varying through thickness distribution. Both the bending and membrane residual stresses may be seen to be relatively low. The results show that membrane residual stresses were typically below 10% of the material 0.2% proof stress, whilst bending residual stresses were of slightly higher magnitude, though typically below 20% of the material 0.2% proof stress.

3.3 Press braked sections

Figures 18 to 25 show the complete set of bending and membrane residual stress values for the eight stainless steel press braked sections. The bending residual stresses are calculated assuming a rectangular stress block through thickness distribution. Table 2 presents the numerical data from sectioned strips obtained at different locations around the press braked section PB 50×50×2 ($r_t = 4.5$). The location of the strips within this cross section is shown in Fig. 17. The membrane and bending residual stresses for the unformed flat regions of the press braked sections are generally low, typically below 10% of the material 0.2% proof strength. In the corner regions, however, where large plastic deformation occurs, higher bending residual stresses may be seen. The corner bending residual stresses typically reach about 30% of the corner material 0.2% proof strength, which itself will have been enhanced beyond the strength of the flat material due to cold work during production.

3.4 Cold rolled sections

The residual stress maps for the seven cold rolled stainless steel box sections are shown in Figs 27 to 33. The numerical data and setting out diagram for the cold rolled section CR 100×50×4 are given in Table 3 and Fig. 26 respectively. The results calculated on the assumption of a rectangular stress block distribution reveal slightly higher membrane residual stresses than those observed in the hot rolled and press braked sections, and considerably higher bending residual stresses. The calculated bending residual stresses typically range between about 30% and 70% of the material 0.2% proof stress. The results are discussed further in the following section.

3.5 Discussion

The residual stresses observed in both the hot rolled and press braked stainless steel angles are generally of relatively low magnitude as discussed in section 3.2 and 3.3 respectively. For the

cold rolled stainless steel box sections, the observed residual stresses are high, particularly the bending residual stresses. The calculated bending residual stresses for all seven box sections have been normalised by the material 0.01% proof stress (the approximate elastic limit) and the 0.2% proof stress (the equivalent yield stress) of the released strips tested in tension and plotted in Figs 34 and 35, respectively. The results show that whilst the residual stresses are generally below the material 0.2% proof stress, the 0.01% proof stress is often exceeded, implying that the residual stresses may be inelastic. If this were to be the case, calculation of the residual stresses from the measured residual strains on the assumption of elastic material behaviour would overestimate their magnitude. The residual stresses are, however, believed to be largely elastic, on the basis that the released strips exhibited the same residual strains upon deforming them back to their initial (flat) configuration and subsequently re-releasing.

Two explanations for the appearance of residual stresses greater than the material 0.01% proof stress, but still remaining elastic, are offered. The first relates to the strain hardening of the sheet material during the coiling and uncoiling process where the outer fibres of the sheet receive the greatest cold work. This results in material stratification through the thickness with higher strength material at the extreme fibres, from where the greatest contributions to residual curvature emanate. Calculated residual stresses have simply been normalised by the average material strength of the strip obtained from a tensile coupon test. A detailed through thickness strength distribution has not been measured directly, but indicative results from hardness tests support this assertion. The second explanation relates to the presence of transverse residual stresses, in addition to the measured longitudinal residual stresses. According to the von Mises yield criterion, if the residual stress condition is purely uniaxial, stresses are limited to the yield stress in order to remain elastic. However with a two-dimensional stress system, the plane stress condition predicts that a maximum longitudinal stress of $2/\sqrt{3} \sigma_y$ can be obtained in the presence of transverse stress before yielding occurs [36].

4. Conclusions

Comprehensive residual stress distributions have been obtained for a total of eighteen stainless steel structural sections from three different production routes. Three hot rolled angles, eight press braked angles and seven cold rolled box sections were analysed using the sectioning method, with a total of over 800 readings taken.

The principal means of determining residual stresses was through the use of electrical strain gauges, though a mechanical (Whittemore) gauge and curvature dial was also employed. The calculation of the membrane residual stresses based on measurements made by the Whittemore gauge must be corrected to remove the effects of strip curvature caused by the existence of bending residual stresses. Existing methods developed for hot rolled sections, where bending residual stresses are low, assume strip curvature to be parabolic and make small angle approximations. When applied to cold formed sections, where bending residual stresses are high, large discrepancies from the circular approximation recommended herein were observed.

For the hot rolled sections, the results showed that membrane residual stresses were typically below 10% of the material 0.2% proof stress, whilst bending residual stresses were of slightly higher magnitude, though typically below about 20% of the material 0.2% proof stress. For the press braked sections, the membrane and bending residual stresses in the unformed flat regions were generally low, typically below 10% of the material 0.2% proof strength. In the corner regions, however, where large plastic deformation occurs, higher bending residual stresses were observed. The corner bending residual stresses typically reached about 30% of the corner material 0.2% proof strength, which itself has been enhanced beyond the strength of the flat material due to cold work during production. For the cold rolled sections, the results reveal slightly higher membrane residual stresses than those observed in the hot rolled and press braked sections, and considerably higher bending residual stresses. The bending residual stresses that were measured typically ranged between about 30% and 70% of the material 0.2% proof stress.

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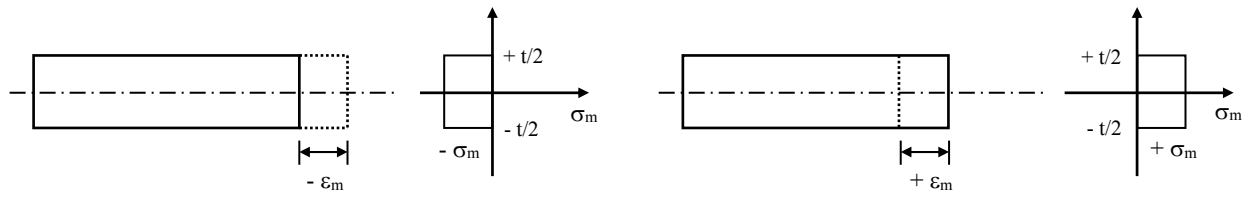
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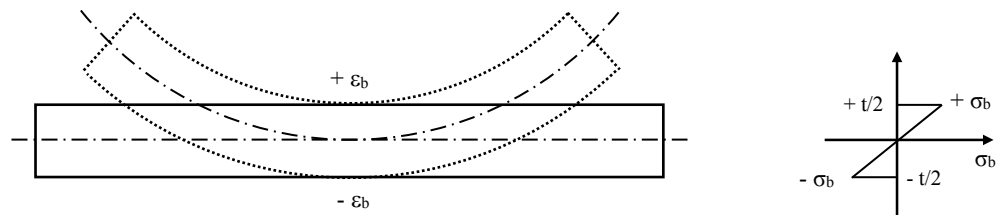
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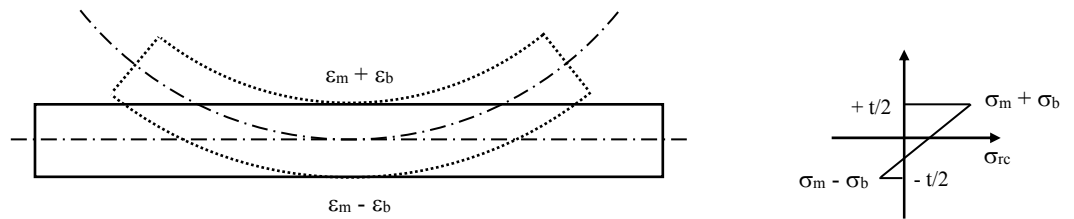


Membrane residual stress σ_m acting in compression

Membrane residual stress σ_m acting in tension



Bending residual stress σ_b



Combined bending and membrane residual stresses σ_{rc}

Fig. 1: Modelling of residual stresses with a membrane and bending stress components

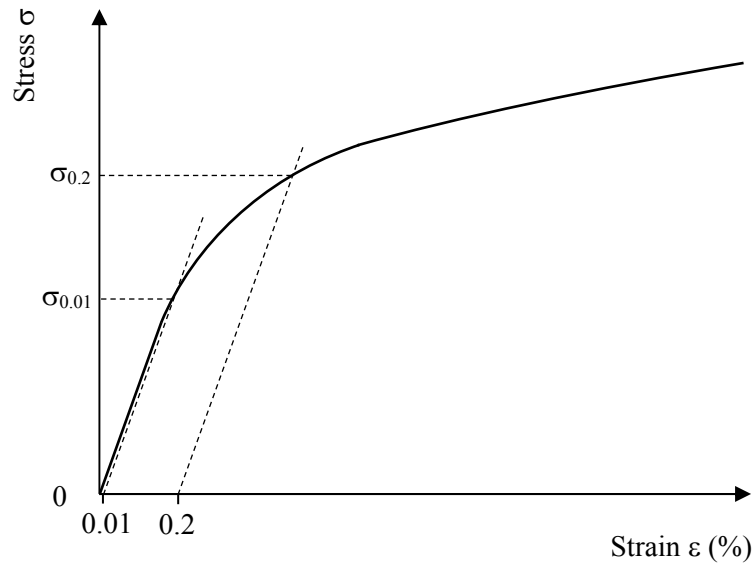


Fig. 2: Stainless steel material stress-strain behaviour

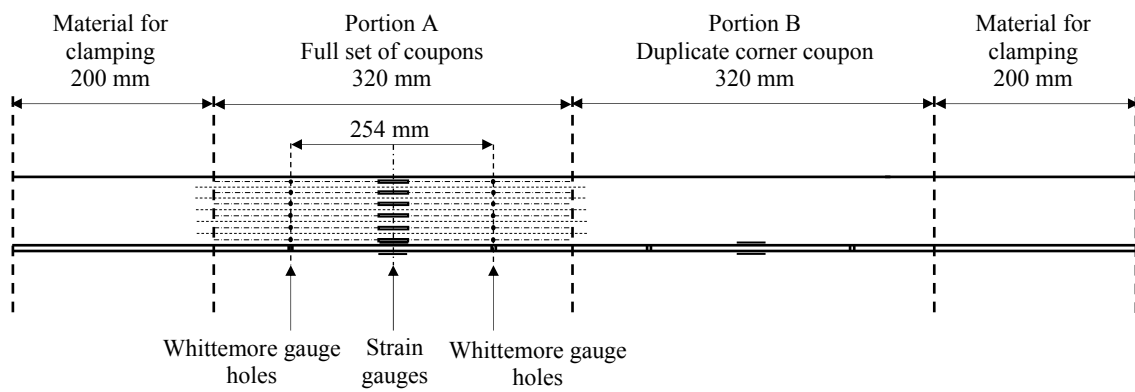


Fig. 3: Specimen setting out (angle section)

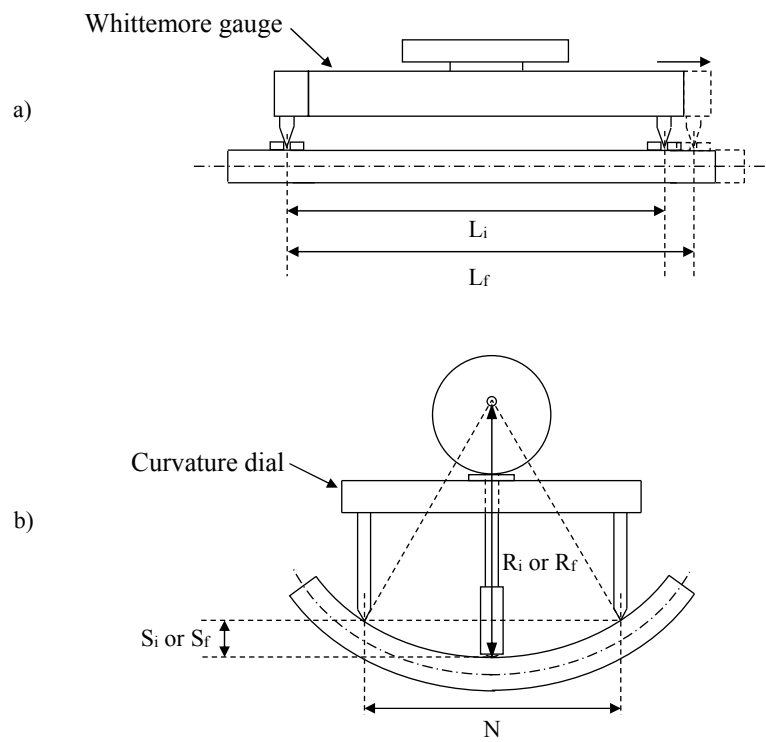


Fig. 6: The geometrical deformation measured by a) Whittemore gauge and b) Curvature dial

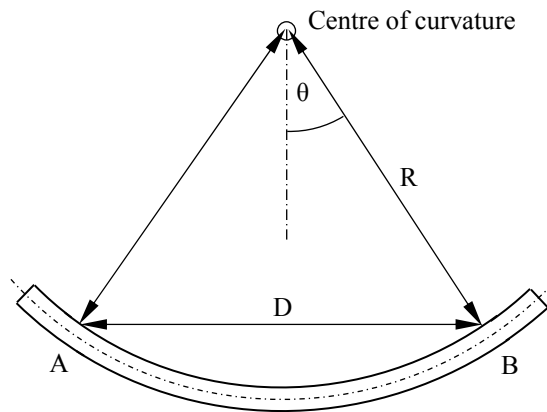


Fig. 7: Definition of angle of curvature θ

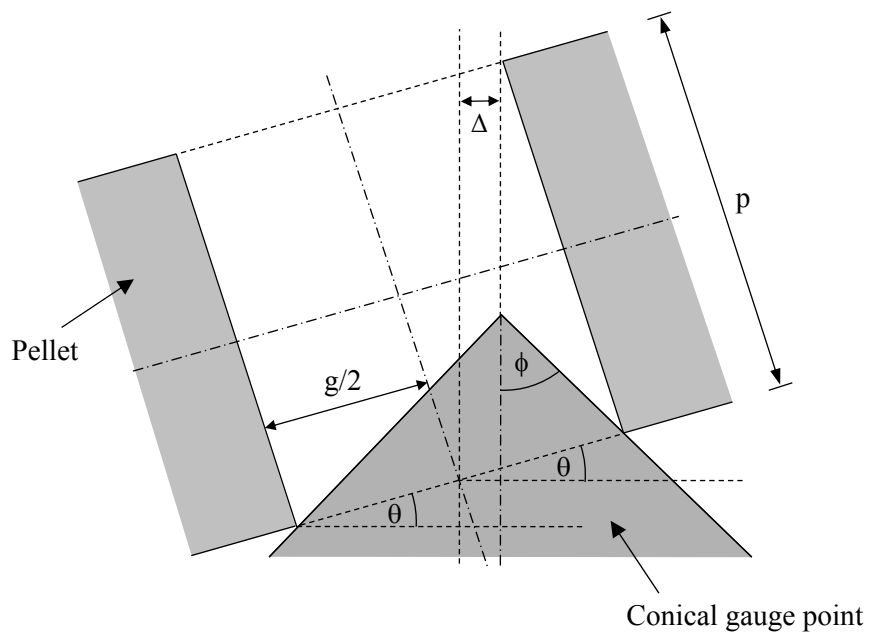


Fig. 8: The gauge hole correction

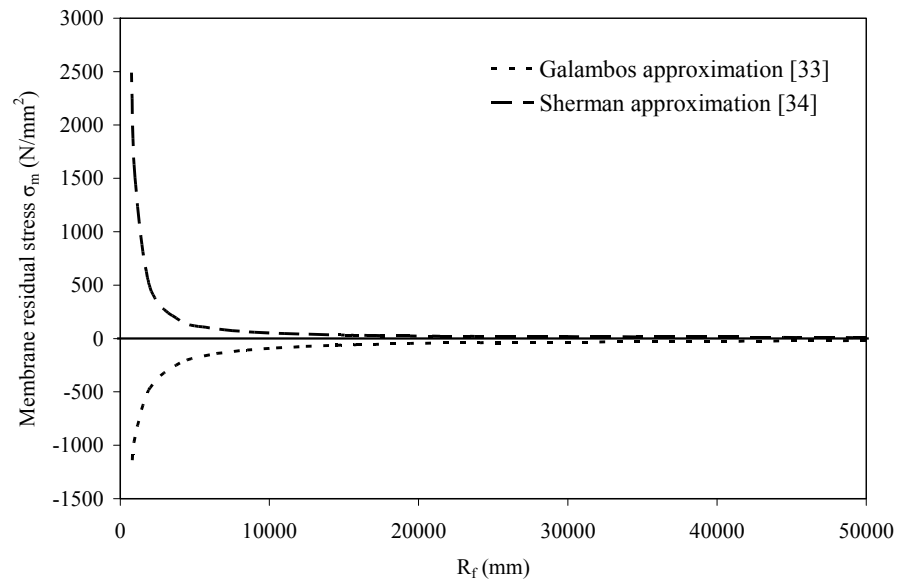


Fig. 9: Deviation of calculated membrane residual stresses σ_m of [33, 34] from the circular approximation for varying radius of curvature R_f

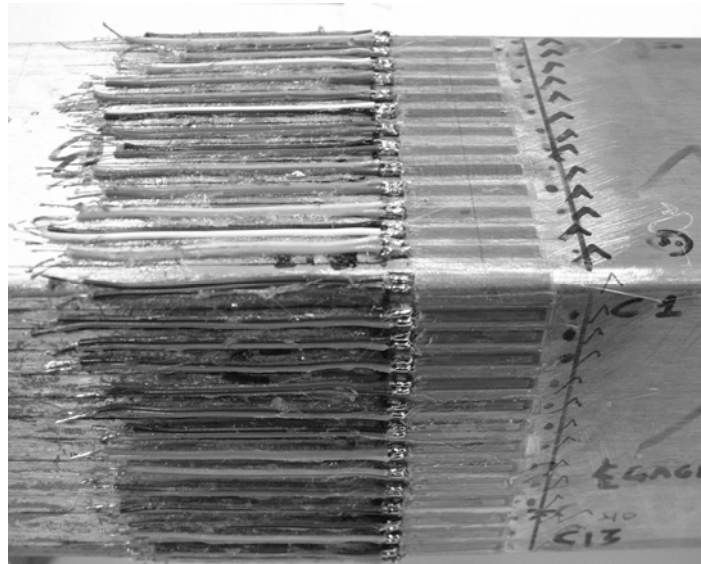


Fig. 10: Strain gauges affixed to cold rolled box specimen prior to sectioning

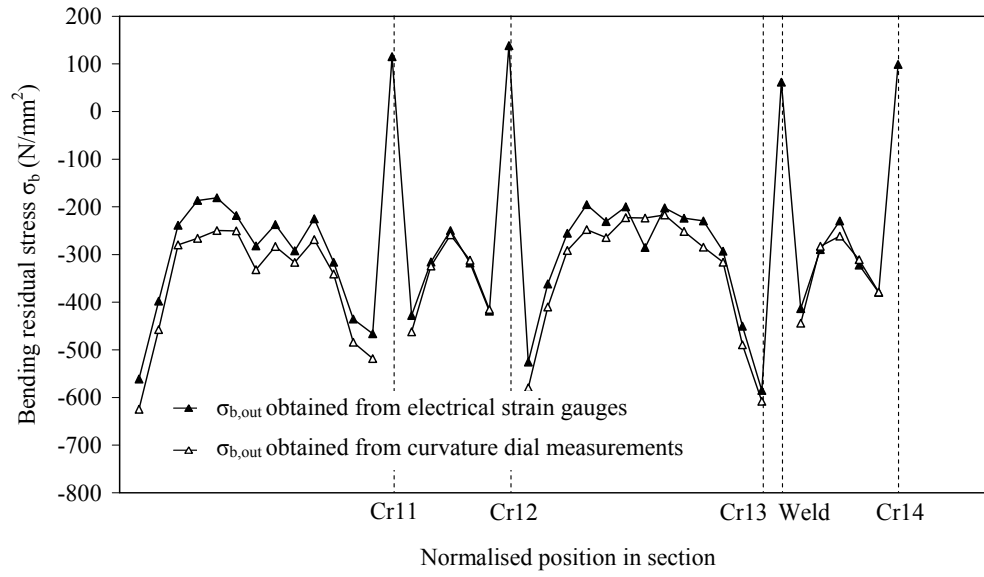


Fig. 11: Correlation between bending residual stress σ_b from mechanical and electrical strain gauges (CR 100 $\times$ 50 $\times$ 4). (No curvature dial readings were taken for the corner strips)

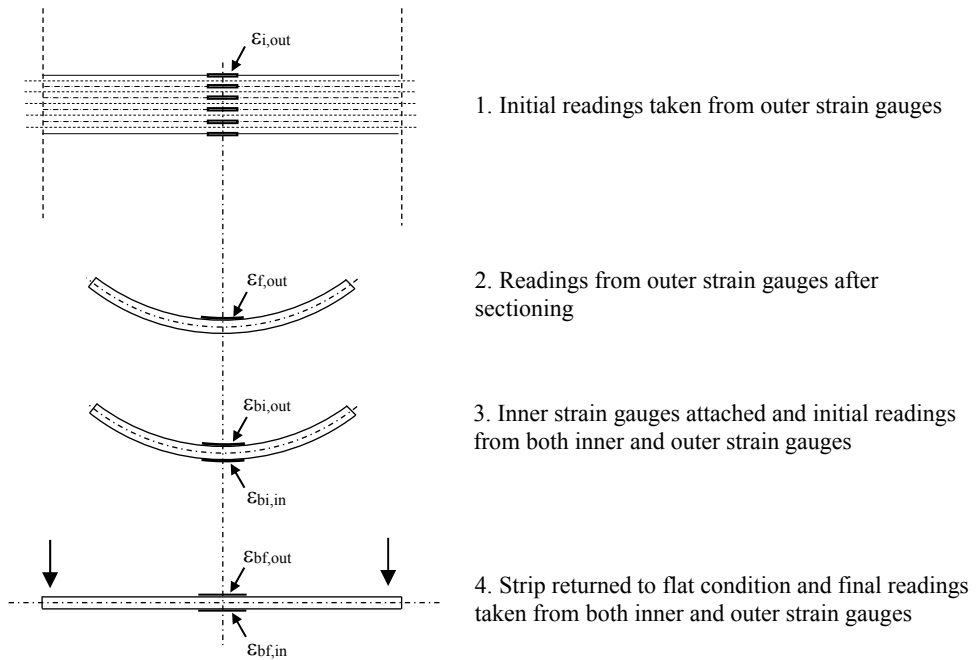


Fig. 12: Residual strain measurements for cold rolled box sections

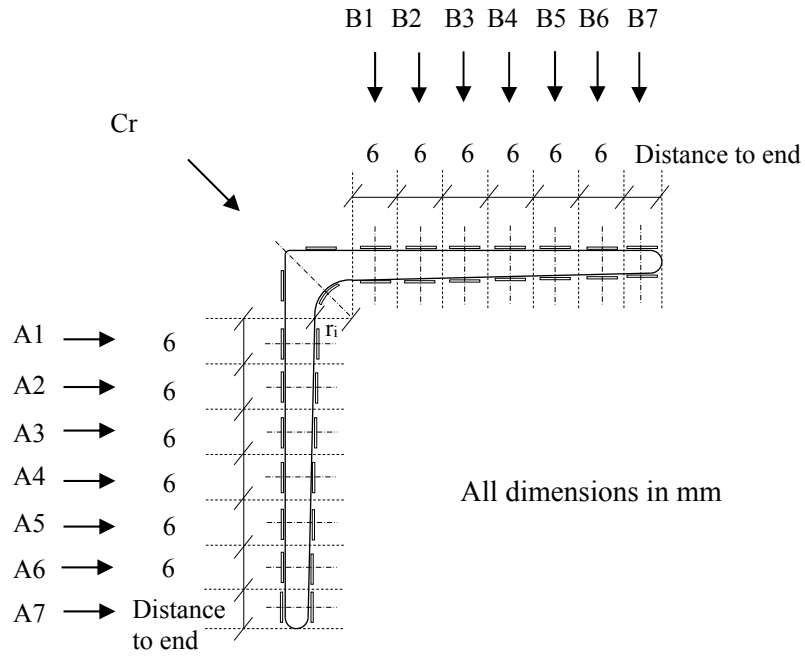


Fig. 13: Setting out of hot rolled section HR 50×50×3 ($r_1=5$)

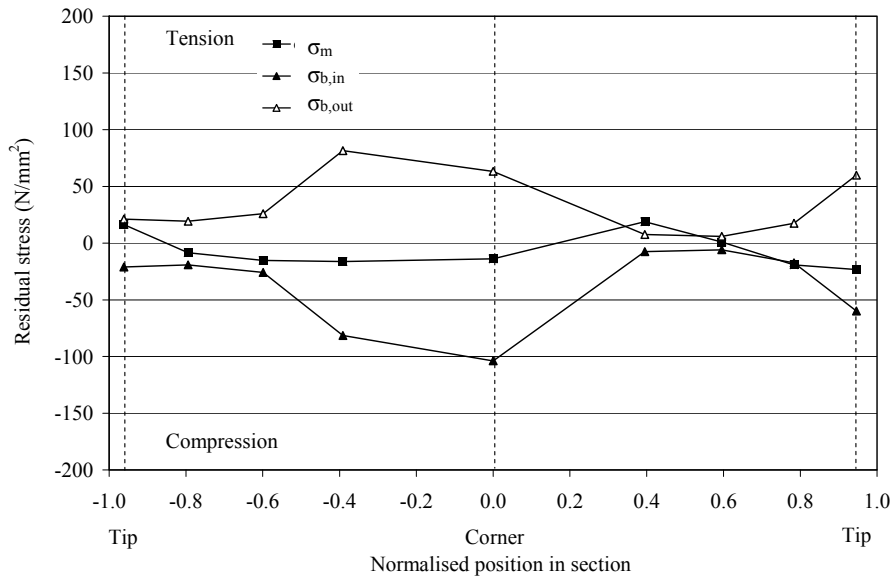


Fig. 14: Membrane and bending residual stress distributions around HR 50×50×3. (Average material 0.2% proof strength from the flat regions was 362 N/mm². Material 0.2% proof strength from the corner strip was 289 N/mm²)

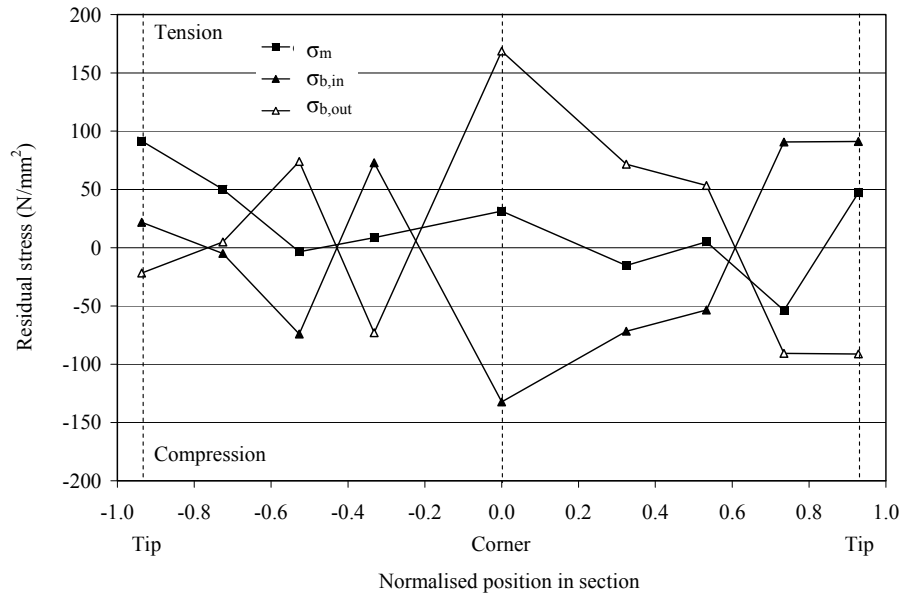


Fig. 15: Membrane and bending stresses distributions around HR 50×50×5. (Average material 0.2% proof strength from the flat regions was 510 N/mm². Material 0.2% proof strength from the corner strip was 528 N/mm²)

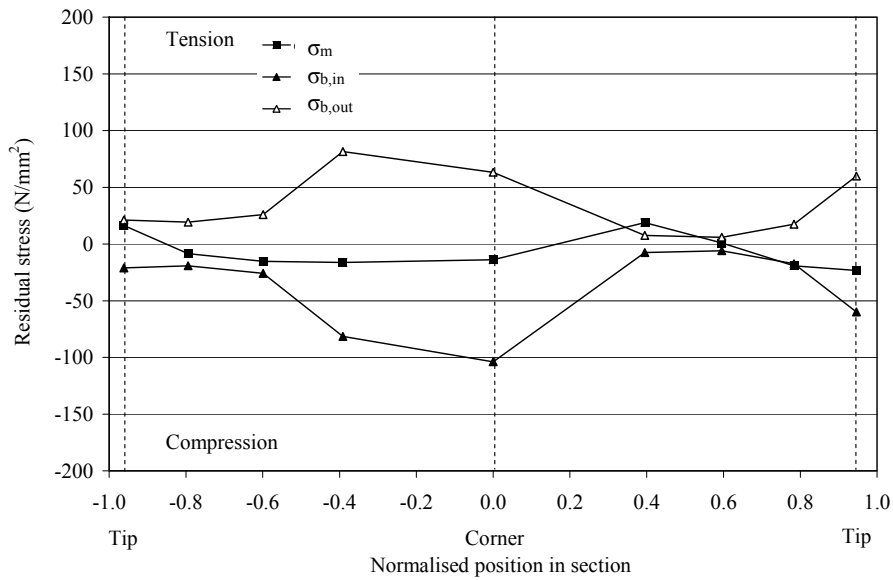


Fig. 16: Membrane and bending stresses distributions around HR 50×50×10. (Average material 0.2% proof strength from the flat regions was 396 N/mm². Material 0.2% proof strength from the corner strip was 353 N/mm²)

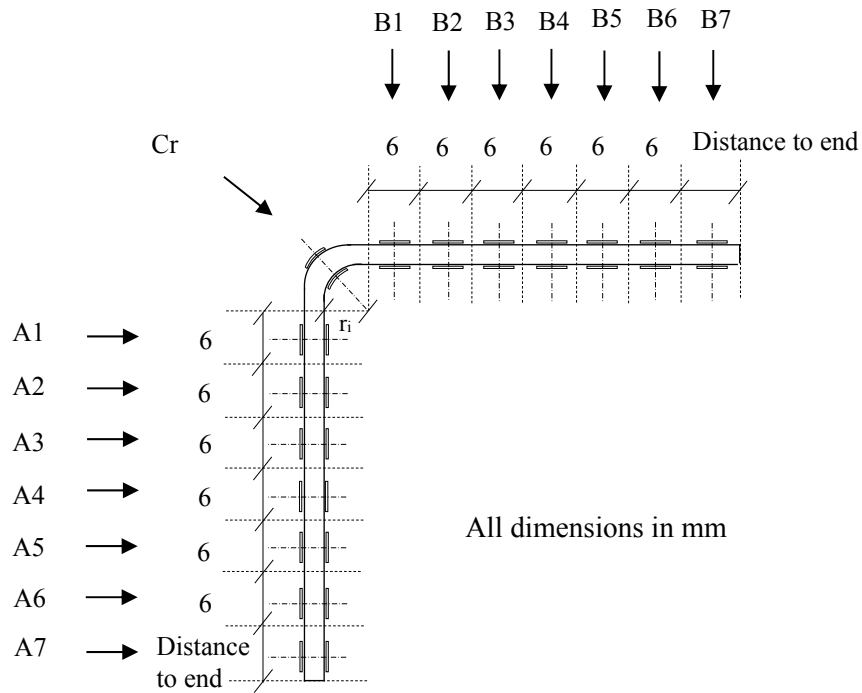


Fig. 17: Setting out of press braked section PB 50×50×2 ($r_1=4.5$)

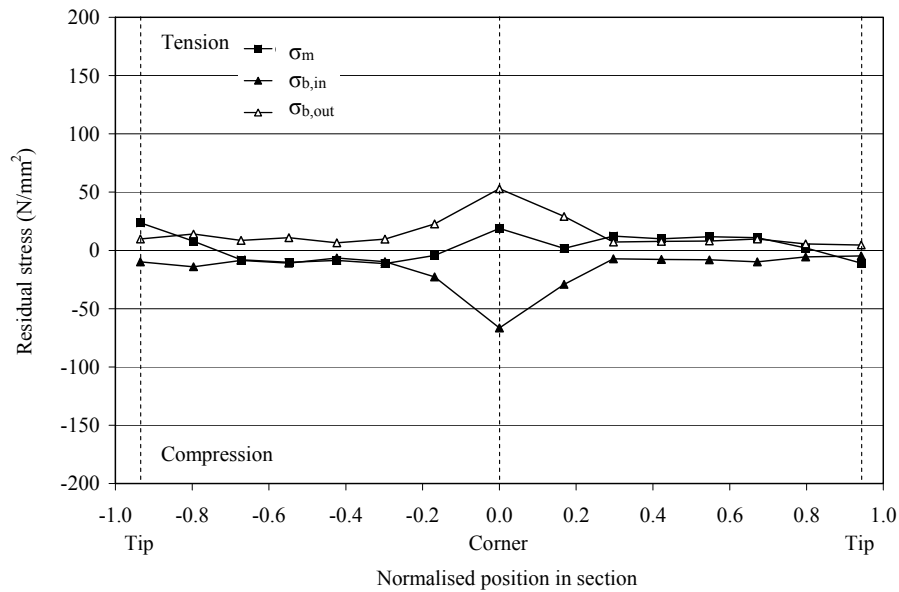


Fig. 18: Membrane and bending stresses distributions around PB 50×50×2 ($r_1=3.2$). (Average material 0.2% proof strength from the flat regions was 289 N/mm². Material 0.2% proof strength from the corner strip was 362 N/mm²)

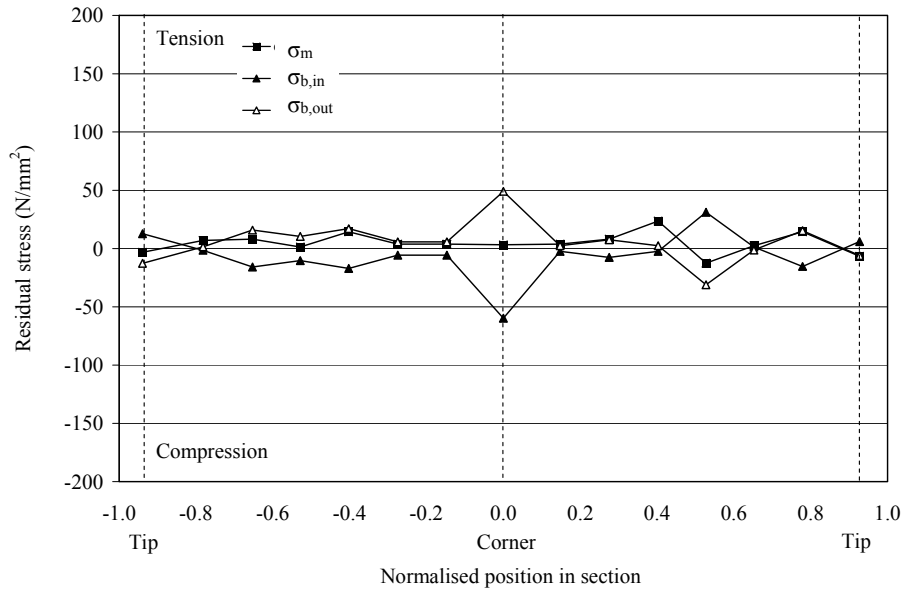


Fig. 19: Membrane and bending stresses distributions around PB 50×50×2 ($r_i=3.5$). (Average material 0.2% proof strength from the flat regions was 320 N/mm². Material 0.2% proof strength from the corner strip was 408 N/mm²)

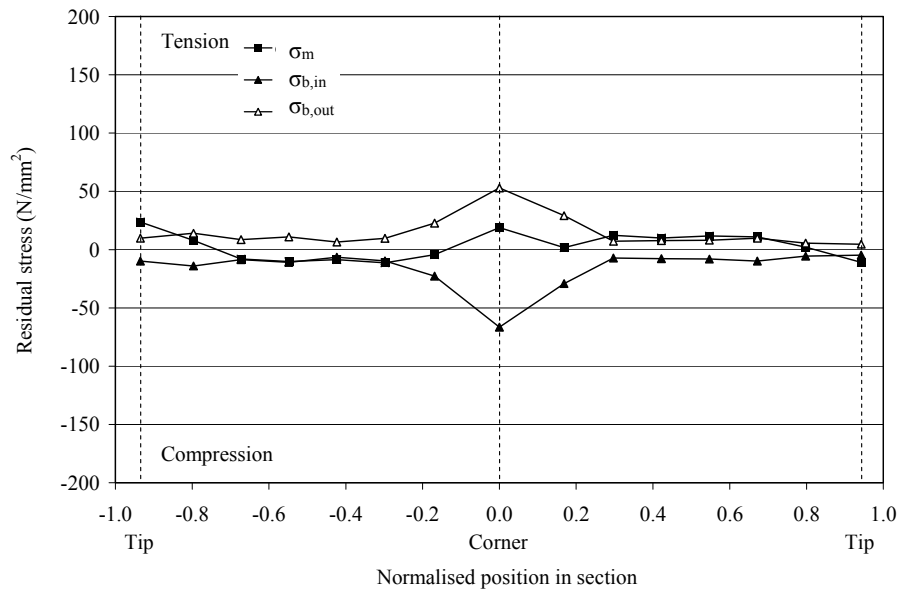


Fig. 20: Membrane and bending stresses distributions around PB 50×50×2 ($r_i=4.5$) (Average material 0.2% proof strength from the flat regions was 298 N/mm². Material 0.2% proof strength from the corner strip was 346 N/mm²)

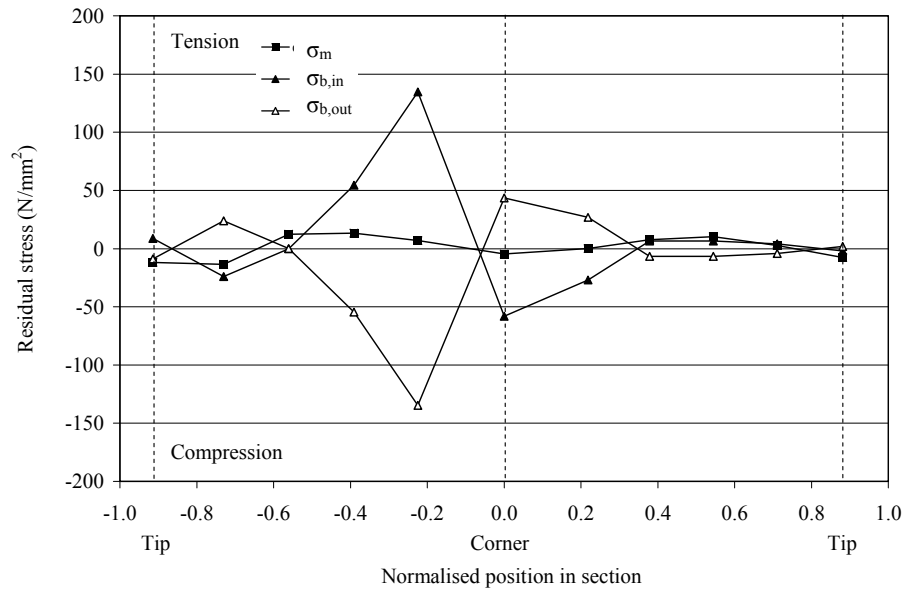


Fig. 21: Membrane and bending stresses distributions around PB 50×50×2 ($r_1=7.5$) (Average material 0.2% proof strength from the flat regions was 292 N/mm². Material 0.2% proof strength from the corner strip was 336 N/mm²)

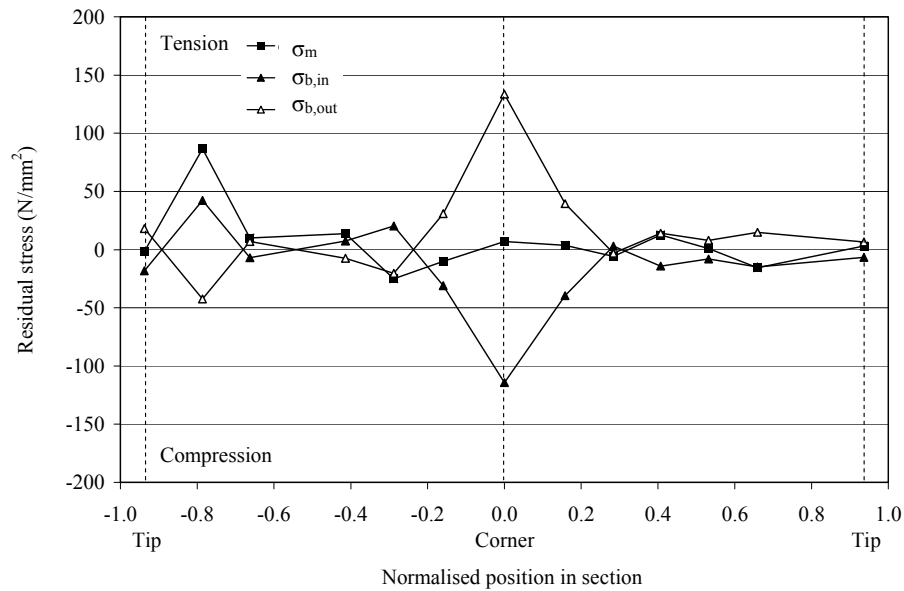


Fig. 22: Membrane and bending stresses distributions around PB 50×50×3 ($r_1=3.2$) (Average material 0.2% proof strength from the flat regions was 333 N/mm². Material 0.2% proof strength from the corner strip was 605 N/mm²)

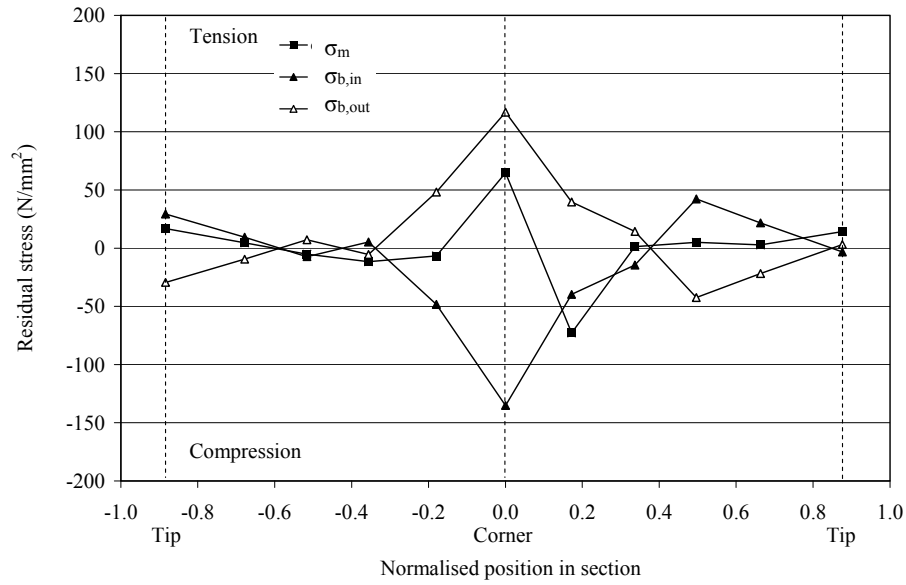


Fig. 23: Membrane and bending stresses distributions around PB 50×50×4 ($r_i=3.5$) (Average material 0.2% proof strength from the flat regions was 328 N/mm². Material 0.2% proof strength from the corner strip was 479 N/mm²)

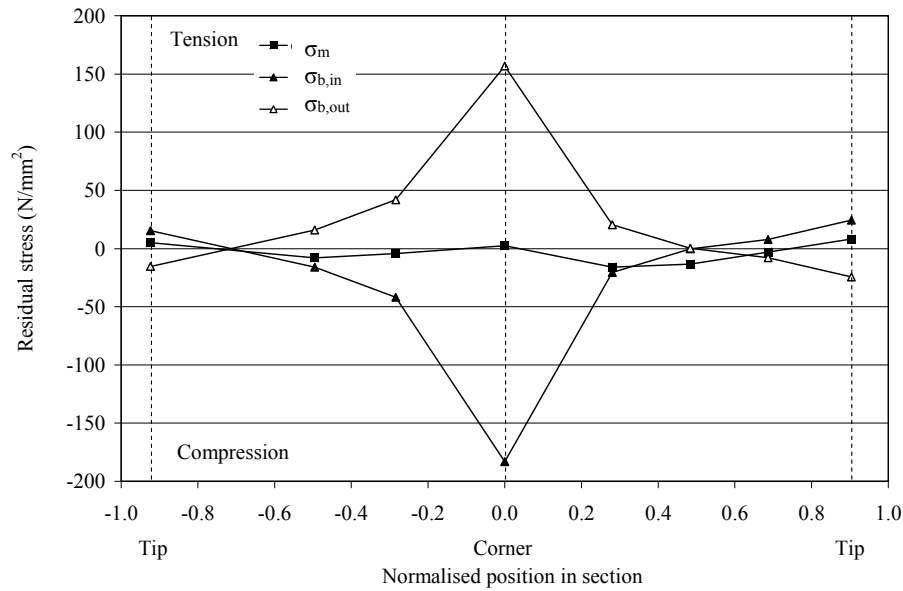


Fig. 24: Membrane and bending stresses distributions around PB 50×50×5 ($r_i=3.5$) (Average material 0.2% proof strength from the flat regions was 314 N/mm². Material 0.2% proof strength from the corner strip was 497 N/mm²)

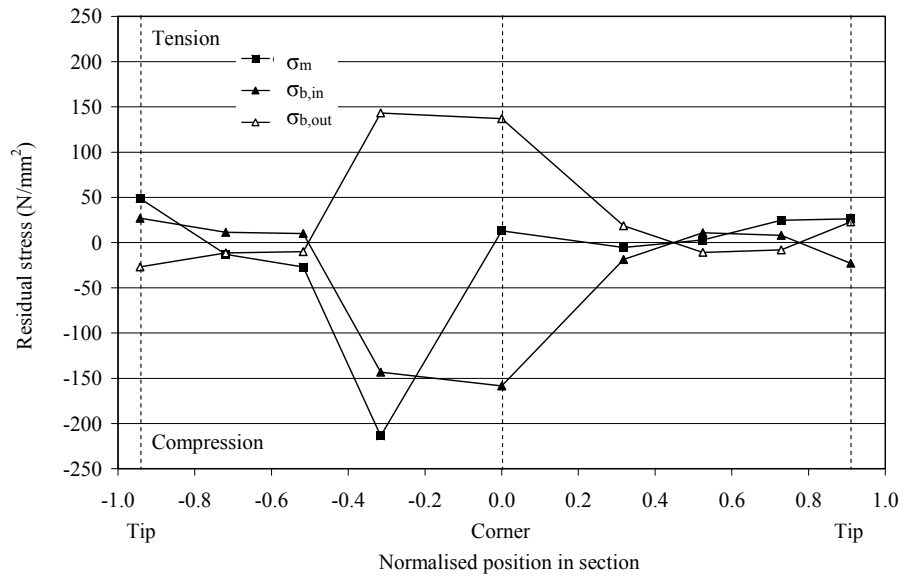


Fig. 25: Membrane and bending stresses distributions around PB 50×50×5 ($r_t=4.5$) (Average material 0.2% proof strength from the flat regions was 302 N/mm². Material 0.2% proof strength from the corner strip was 632 N/mm²)

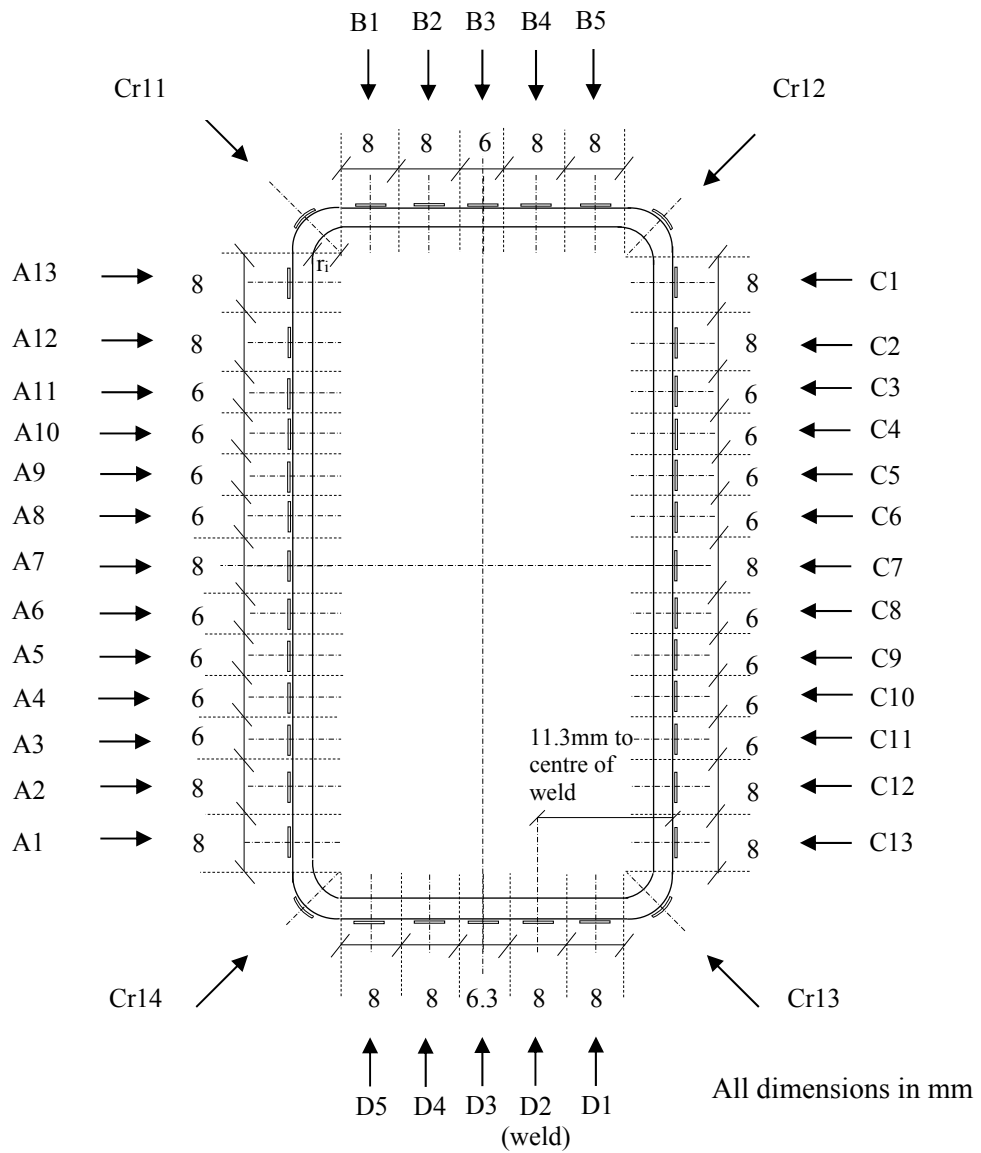


Fig. 26: Setting out of cold rolled section CR 100×50×4 ($r_1 = 2$)

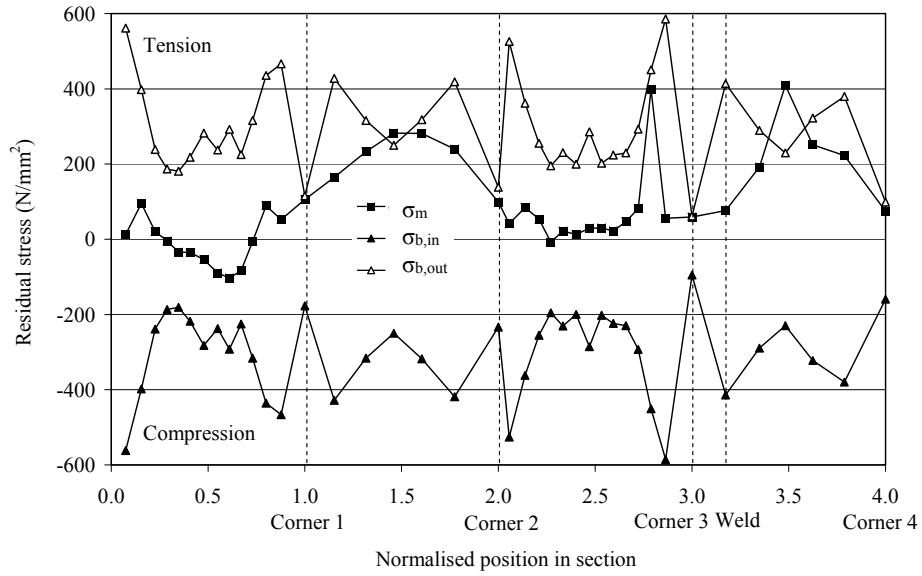


Fig. 27: Membrane and bending stresses distributions around CR 100×50×2 (Average material 0.2% proof strength from the flat regions was 488 N/mm². Average material 0.2% proof strength from the corner strips was 615 N/mm²)

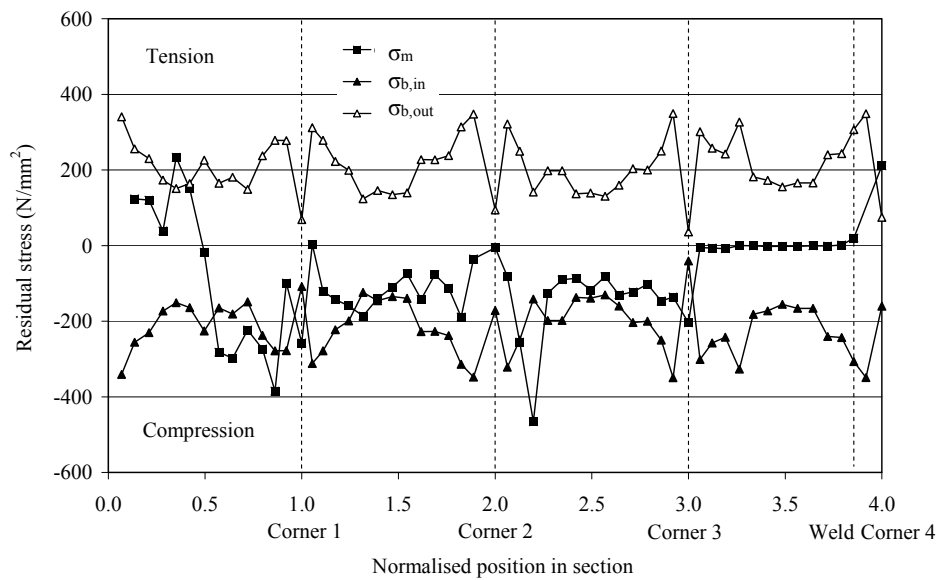


Fig. 28: Membrane and bending stresses distributions around CR 100×100×2 (Average material 0.2% proof strength from the flat regions was 481 N/mm². Average material 0.2% proof strength from the corner strips was 573 N/mm²)

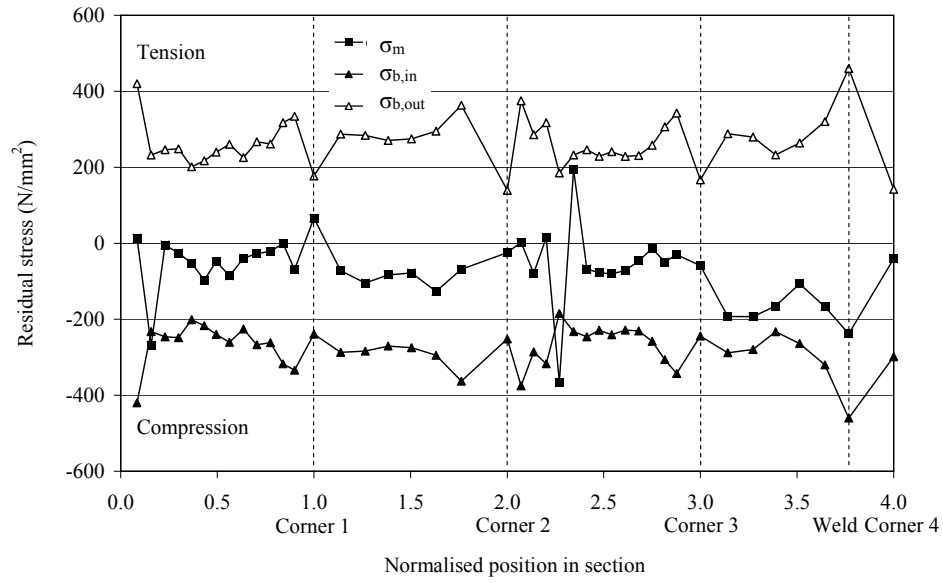


Fig. 29: Membrane and bending stresses distributions around CR 100×50×3 (Average material 0.2% proof strength from the flat regions was 521 N/mm². Average material 0.2% proof strength from the corner strips was 602 N/mm²)

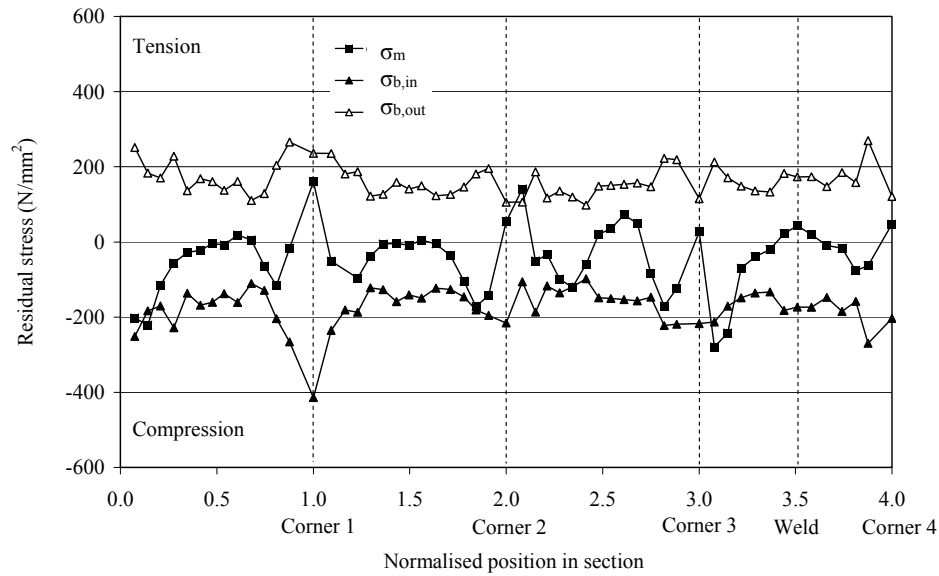


Fig. 30: Membrane and bending stresses distributions around CR 100×100×3 (Average material 0.2% proof strength from the flat regions was 506 N/mm². Average material 0.2% proof strength from the corner strips was 534 N/mm²)

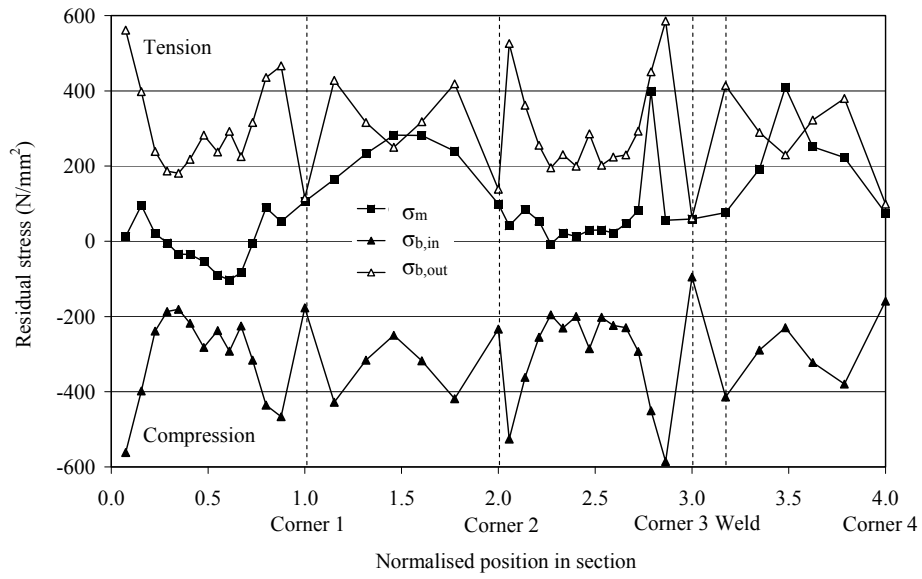


Fig. 31: Membrane and bending stresses distributions around CR 100×50×4 (Average material 0.2% proof strength from the flat regions was 599 N/mm². Average material 0.2% proof strength from the corner strips was 624 N/mm²)

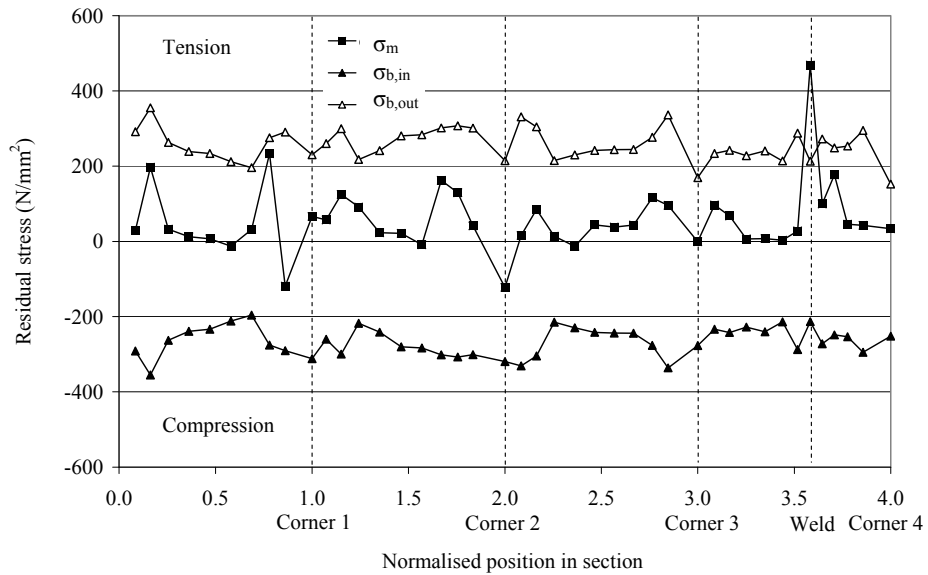


Fig. 32: Membrane and bending stresses distributions around CR 100×100×4 (Average material 0.2% proof strength from the flat regions was 452 N/mm². Average material 0.2% proof strength from the corner strips was 536 N/mm²)

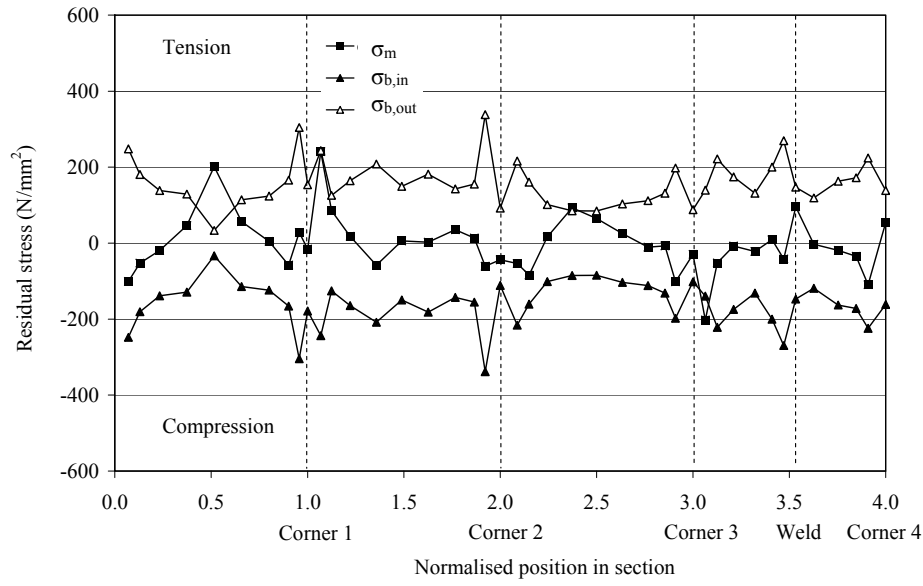


Fig. 33: Membrane and bending stresses distributions around CR 150×150×4 (Average material 0.2% proof strength from the flat regions was 362 N/mm². Average material 0.2% proof strength from the corner strips was 550 N/mm²)

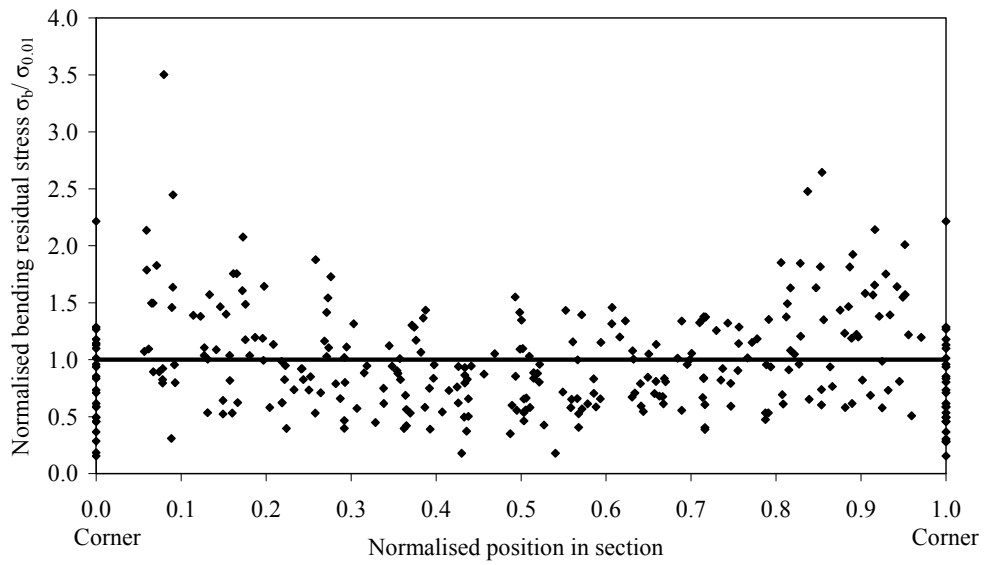


Fig. 34: Bending residual stresses σ_b from cold rolled box sections normalised by material 0.01% proof strength $\sigma_{0.2}$

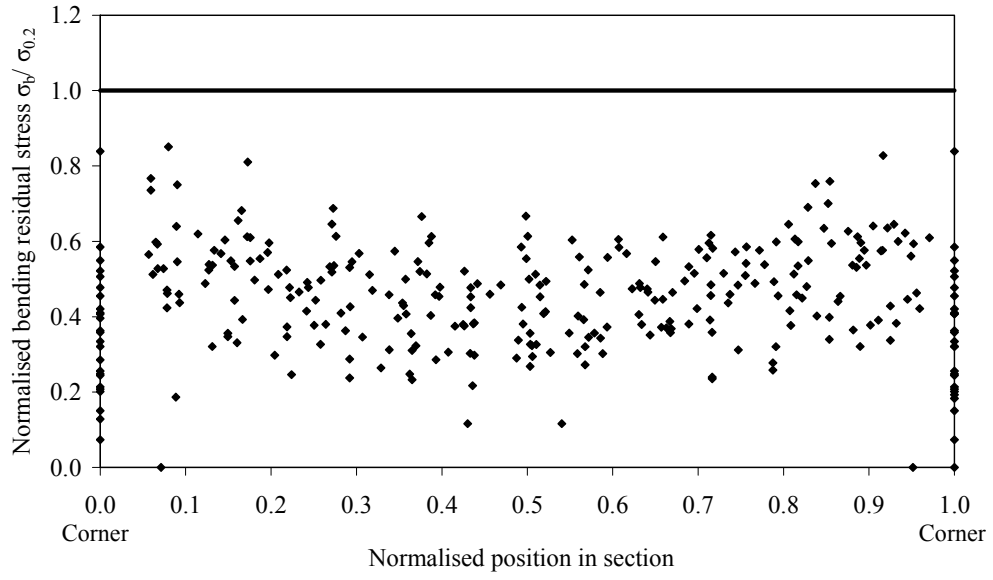


Fig. 35: Bending residual stresses σ_b from cold rolled box sections normalised by material 0.2% proof strength $\sigma_{0.2}$

Table 1: Residual stress values for HR 50×50×3 ($r_i=5.0$)

HR 50×50×3	Section position (mm)	Width (mm)	σ_m (N/mm ²)	σ_b (N/mm ²)	σ_{rc} (N/mm ²)	$\sigma_m/\sigma_{0.2}$	$\sigma_b/\sigma_{0.2}$	$\sigma_{rc}/\sigma_{0.2}$
A7	38.5	3.36	-32	-36	68	-0.08	-0.09	0.16
A6	33.2	3.36	-27	4	31	-0.07	0.01	0.08
A5	28.3	3.44	-21	-26	47	-0.06	-0.07	0.13
A4	23.3	3.51	-26	-42	68	-0.07	-0.12	0.19
A3	18.3	3.52	-1	-67	68	0.00	-0.20	0.20
A2	13.3	3.50	24	-18	42	0.07	-0.05	0.13
A1	8.3	3.49	-5	-50	55	-0.01	-0.14	0.15
Cr	0.0		-31	-107	138	-0.11	-0.37	0.48
B1	8.4	3.56	-29	-60	89	-0.08	-0.17	0.25
B2	13.4	3.60	17	-22	39	0.05	-0.07	0.12
B3	18.5	3.62	7	-34	41	0.02	-0.10	0.12
B4	23.7	3.60	-19	-28	46	-0.05	-0.08	0.13
B5	28.7	3.54	92	119	211	0.27	0.34	0.61
B6	33.8	3.56	2	22	23	0.00	0.06	0.07
B7	39.2	3.58	-20	-4	24	-0.05	-0.01	0.06

Table 2: Residual stress distribution for PB 50×50×2 ($r_i=4.5$)

PB 50×50×2 ($r_i=4.5$)	Section position (mm)	Width (mm)	σ_m (N/mm ²)	σ_b (N/mm ²)	σ_{rc} (N/mm ²)	$\sigma_m/\sigma_{0.2}$	$\sigma_b/\sigma_{0.2}$	$\sigma_{rc}/\sigma_{0.2}$
A7	46.8	5.46	24	-10	34	0.07	-0.03	0.10
A6	39.8	4.63	8	-14	22	0.03	-0.04	0.08
A5	33.6	4.76	-8	-9	17	-0.03	-0.03	0.06
A4	27.4	4.71	-10	-11	21	-0.04	-0.03	0.07
A3	21.2	4.76	-9	-7	15	-0.03	-0.02	0.05
A2	14.9	4.76	-11	-10	21	-0.04	-0.03	0.07
A1	8.4	5.19	-4	-23	27	-0.01	-0.07	0.08
Cr	0.0	1.96	19	-67	85	0.05	-0.21	0.25
B1	8.4	5.15	2	-29	31	0.01	-0.09	0.10
B2	14.8	4.70	12	-7	20	0.04	-0.02	0.07
B3	21.1	4.79	10	-8	18	0.04	-0.02	0.07
B4	27.4	4.72	12	-8	20	0.04	-0.03	0.07
B5	33.6	4.76	11	-10	21	0.03	-0.03	0.06
B6	39.9	4.82	2	-6	8	0.01	-0.02	0.03
B7	47.1	5.95	-11	-5	16	-0.04	-0.01	0.05

Table 3: Residual stress distribution for CR 100×50×4 ($r_i=2$)

CR 100×50×4	Section position (mm)	Width (mm)	σ_m (N/mm ²)	σ_b (N/mm ²)	σ_{rc} (N/mm ²)	$\sigma_m/\sigma_{0.2}$	$\sigma_b/\sigma_{0.2}$	$\sigma_{rc}/\sigma_{0.2}$
A1	7.8	7.11	13	-561	574	0.02	-0.85	0.87
A2	16.3	6.60	96	-398	493	0.16	-0.68	0.85
A3	23.9	5.27	21	-239	259	0.04	-0.41	0.45
A4	30.6	4.63	-4	-187	191	-0.01	-0.35	0.35
A5	37.0	4.73	-34	-181	215	-0.06	-0.32	0.38
A6	43.5	4.93	-35	-218	253	-0.07	-0.42	0.49
A7	51.1	6.92	-54	-282	336	-0.10	-0.51	0.61
A8	58.7	4.89	-90	-237	327	-0.18	-0.46	0.64
A9	65.3	4.88	-103	-292	395	-0.19	-0.55	0.74
A10	71.8	4.69	-83	-225	308	-0.14	-0.39	0.54
A11	78.3	4.91	-6	-316	322	-0.01	-0.54	0.55
A12	85.8	6.66	89	-436	525	0.14	-0.70	0.84
A13	94.0	6.36	53	-466	519	0.07	-0.60	0.67
Cr11	0.0		106	-177	282	0.15	-0.25	0.40
B1	7.9	7.34	165	-428	593	0.24	-0.61	0.85
B2	16.6	6.64	233	-316	548	0.37	-0.50	0.87
B3	24.2	5.27	282	-250	532	0.46	-0.41	0.87
B4	32.0	6.92	281	-318	599	0.44	-0.49	0.93
B5	41.0	7.61	240	-419	658	0.36	-0.63	0.99
Cr12	0.0		100	-234	333	0.14	-0.33	0.48
C1	5.9	6.85	42	-526	567	0.06	-0.77	0.83
C2	14.5	7.07	84	-362	446	0.14	-0.60	0.74
C3	22.2	4.99	54	-255	309	0.09	-0.45	0.54
C4	28.8	4.76	-8	-195	203	-0.01	-0.36	0.38
C5	35.6	5.41	22	-231	253	0.04	-0.44	0.48
C6	42.9	5.80	13	-200	213	0.02	-0.38	0.40
C7	50.3	5.50	30	-285	315	0.06	-0.55	0.61
C8	57.1	4.73	30	-202	232	0.06	-0.39	0.45
C9	63.7	5.05	22	-224	246	0.04	-0.41	0.45
C10	70.6	5.38	47	-229	276	0.09	-0.42	0.51
C11	77.5	5.00	82	-293	375	0.14	-0.49	0.63
C12	84.6	5.93	399	-450	849	0.67	-0.75	1.42
C13	92.6	6.61	56	-585	641	0.08	-0.83	0.91
Cr13	0.0		59	-95	154	0.09	-0.15	0.24
D1 (weld)	8.9	9.48	76	-414	490	0.11	-0.60	0.71
D2	18.2	5.69	192	-290	481	0.32	-0.48	0.80
D3	25.4	5.22	410	-230	639	0.64	-0.36	0.99
D4	33.0	6.53	251	-322	574	0.43	-0.56	0.99
D5	41.6	7.46	223	-380	603	0.32	-0.54	0.85
Cr14	0.0		75	-159	234	0.09	-0.19	0.28