Experiments on Stainless Steel Hollow Sections - Part 1: Material and Cross Sectional Behaviour

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Abstract

Basic material properties and cross-sectional data (stress-strain curves and load-end shortening curves) are presented for square, rectangular and circular hollow section specimens in Grade 1.4301 stainless steel. The material tests cover flat material in tension and in compression as well as corner material in tension. Modifications to the Ramberg-Osgood representation are suggested to ensure a close fit to both tensile and compressive behaviour over the full range of strains of interest. Results, including full load-end shortening curves, for a total of 37 stub column tests have been presented. The results have been used to develop an explicit relationship between cross-sectional slenderness and cross-sectional deformation capacity, which forms the basis for a proposed new design approach for stainless steel structures.

Introduction

Design procedures for stainless steel structural members have, until now, generally followed those for carbon steel rather closely. An obvious attraction of this approach is that designers are not required to master a new set of procedures when working with a material that they are unlikely to be using frequently. However, stainless steel is expensive and not to recognise its particular properties is, of course, likely to mean that the results will be less-cost effective than would be the case if a more accurate and more appropriate set of procedures were used.

One particular feature of stainless steel that differs from carbon steels is the form of its basic material stress-strain curve. Conventional steel design places heavy reliance on the fact that it is normally appropriate to represent the material stress-strain behaviour as a bi-linear relationship. Although studies of the behaviour of stainless steel are less

numerous, sufficient exist to demonstrate that the material possesses a rounded stress-strain curve, with no sharp yield point.

Compared with carbon steel or even aluminium alloys, test data on stainless steel components are rather limited. Given the importance attached to the use of good quality laboratory results in calibrating design guidance, this limitation potentially hinders attempts to improve the design procedures for stainless steel. In an attempt to correct this situation a comprehensive study has recently been undertaken [1, 2]. This has included: measurements of basic material properties, stub column tests and experiments on columns and beams; the experimental work has been complemented by a parallel numerical study [3]. All tests have been on square, rectangular or circular hollow sections (SHS, RHS, CHS) in Grade 1.4301 material in the “as-rolled” condition. For the SHS and RHS specimens full details of chemical composition and basic coil properties were available from the suppliers [1].

This paper describes the stub column tests, together with the associated material property tests. It also explains how a modified version of the well-known Ramberg-Osgood formula may be used to represent the stress-strain response of flat material in tension or in compression and the somewhat different behaviour of the corner regions. The main purpose of the stub column tests was the provision of relationships between applied load and deformation capacity in the form of load-end shortening curves. These were then used to develop an explicit relationship between deformation capacity and cross-sectional slenderness, including an allowance for restraint to the most critical plate element from the surrounding components. It is this relationship that forms the core of the new design approach [4]. The column and beam tests form the subject of the second part of this paper [5].

Material Property Tests

In addition to the total of 54 basic tensile coupon tests – conducted in accordance with ASTM S370-87a [6] using an Amsler 350 kN hydraulic testing machine – measurements have also been made of compressive stress-strain properties (56 coupon tests) and the tensile properties of the corner regions (5 coupon tests). Early work by Johnson and

Winter [7] has shown that some differences between behaviour in tension and in compression may be expected for stainless steel; very little compression data are available. Although no detailed studies of the properties of the corner regions of roll-formed stainless steel members are known, evidence from carbon steel [8] suggests that extensive strain hardening will cause substantial increases in strength as compared with the basic flat material; five corner specimens were therefore included in the present programme. For basic flat material coupons were taken from each face of the SHS and RHS members. No basic material tests were conducted for the CHS members since data were available from a previous investigation by Chryssanthopoulos and Kiymaz [9]

Tensile coupons were machined as parallel sided 320 x 30 mm (or in the case of the smaller cross-sections 320 x 20 mm). Drilled and reamed holes 20 mm from each end were provided to accommodate the pins in the jaws of the testing machine. It was observed that as machining progressed, release of through-thickness residual stresses caused some curving of the specimens. However, no attempt was made to straighten them prior to tensile testing.

Each specimen was provided with a pair of linear electrical post-yield strain gauges, capable of reaching 20% strain. Readings were taken at 4 second intervals of pressure, strain, displacement and input voltage using the DATASCAN data acquisition equipment and logged using the DALITE computer package. Tests normally lasted for some 45 minutes.

It is clearly necessary when testing thin coupons in compression to provide a system of lateral support so as to prevent premature failure by minor axis buckling. Some form of jig arrangement - sufficiently tight to prevent buckling but with room to allow unrestrained expansion due to Poisson's ratio effects – is normally employed. Jigs have previously been devised by Rockey and Jenkins [10] and by Rasmussen and Hancock [11]; that used for the present tests was an adaptation of these two designs.

Figure 1 shows the jig. Its 70 mm height allowed the 72 x 16 mm coupons to protrude sufficiently beyond the ends to permit compressive loads corresponding to 2% strain to be applied. The 1 mm protrusion on either side of the central region allowed 2 strain gauges to be attached at mid height to the specimen's edges as illustrated in Figure 2.

Trials indicated that providing the contact surfaces of the jig and specimen were smeared with lubricating paste prior to testing, frictional effects were negligible.

The jig was placed in a 10 T Amsler hydraulic testing machine, with load being measured using a 10 T load cell. Data acquisition was as for the tensile tests, with readings being taken at 2 second intervals. Small adjustments made under alignment loads, together with careful machining of the specimens so as to ensure parallel ends, meant that concentric loading conditions were achieved. Tests normally occupied some 30 minutes and were continued up to 2% compressive strain.

Corner specimens were tested in pairs, gripped symmetrically at the ends around steel bars that had the same radius as the internal corner radii of the test specimens. Each pair of specimens was removed from the same corner of the cross-section and, as ultimate failure normally occurred simultaneously for both coupons, the aim of achieving similar material properties was felt to have been achieved. The arrangement permitted strain gauges to be attached to the inner and outer radii of the corner test pieces. Similar loading rates to those employed for the tests on the flat tensile specimens were used; the data acquisition arrangements were the same as those employed for the other two series.

Typical stress-strain curves for flat material in tension are shown up to 1% strain in Figure 3. These exhibit an initial elastic part, yielding in the form of a rounded knee and significant strain-hardening. Higher yield strengths were consistently observed on faces 1 and 4 (welded and opposite faces) than faces 2 and 3 (see Figure 4). It should be noted that the weld always appeared on one of the two narrower faces of the cross-section for the RHS specimens. Essentially similar stress-strain behaviour was observed for each of the 54 tensile specimens.

The full set of results is presented in Table 1 in the form of weighted average properties. Results for the tensile coupons are designated TF. The average 0.2% proof stress $\sigma_{0.2}$ is 430 N/mm² and the average ultimate tensile strength is 700 N/mm². These compare with the minimum specified values for sheet/plate and strip given in BS EN 10088 Part 2: 1995 [12] of 230 N/mm² and between 520 N/mm² and 720 N/mm² respectively. Since design is at present [13] based on the use of the minimum specified proof strength, there

is clearly significant potential for greater efficiency if more representative material strengths can be utilised in structural calculations.

Typical compressive stress-strain curves for flat material are given as Figure 5. These are generally very similar to the corresponding tensile curves. Table 1 lists weighted average properties under the description CF. The essential differences between the shapes of typical tensile and compressive curves for flat material are shown in Figure 6. Taking the mean of all 16 pairs of curves:

- Young's modulus was 1% higher in compression than in tension.
- 0.2% proof stress was 5% lower in compression than in tension.
- 1% proof stress was 4% higher in compression than in tension.

Thus the compressive curve was more rounded than its tensile equivalent. This finding is in general accordance with the limited compressive data available from other studies on stainless steel.

Properties for the corner regions given in Table 1 (signified by TC) show 0.2% proof strengths, on average, some 50% higher than for the equivalent flat specimens – although the variation over 5 results is between 4% and 93%. Working with cold-formed carbon steel sections, Karren [8] has previously suggested that since the corner regions typically make up between 5% and 30% of the total cross-sectional area, the influence of their enhanced strength should be allowed for in structural calculations. With the greater degree of strain hardening that stainless steel exhibits, this suggestion becomes even more pertinent.

Description of stress-strain behaviour

Stainless steel exhibits a rounded stress-strain curve, with the degree of roundedness varying from grade to grade. The austenitic grades demonstrate the greatest non-linearity and strain hardening and it is also these grades that are most frequently used in

structural applications. The most commonly used expression to describe non-linear material stress-strain behaviour is that proposed by Ramberg and Osgood [14], and modified by Hill [15].

$$\varepsilon = \frac{\sigma}{E_0} + 0.002 \left(\frac{\sigma}{\sigma_{0.2}} \right)^n \quad (1)$$

where σ and ε are engineering stress and strain, respectively, E_0 is the material Young's modulus, $\sigma_{0.2}$ is the material 0.2% proof stress and n is a strain hardening exponent.

Numerous previous studies have shown that the basic Ramberg-Osgood formulation (Equation 1) gives excellent agreement with stainless steel experimental stress-strain data up to $\sigma_{0.2}$. At higher strains however, the model generally over estimates the stress corresponding to a given level of strain [16].

A number of recent proposals to improve modelling accuracy at higher strains was reviewed by Gardner [1]. It was concluded that a compound (2-stage) Ramberg-Osgood stress-strain curve devised by Mirambell and Real [17] provided the best agreement with observed behaviour. Mirambell & Real's proposal was to use the basic Ramberg-Osgood expression, given by Equation 1, up to the 0.2% proof stress, and a modified Ramberg-Osgood expression, given by Equation 2, between the 0.2% proof stress and the ultimate stress of the material.

$$\varepsilon = \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} + \varepsilon_{pu} \left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}} \right)^{n'_{0.2,u}} + \varepsilon_{t0.2} \quad (\sigma \geq \sigma_{0.2}) \quad (2)$$

where σ_u is the ultimate material strength, ε_{pu} is the plastic strain at ultimate strength, $\varepsilon_{t0.2}$ is the total strain at the 0.2% proof stress, $n'_{0.2,u}$ is a strain hardening exponent that can be determined from the ultimate strength and another intermediate point, and $E_{0.2}$ is the stiffness at the 0.2% proof stress. Rasmussen [18] investigated the application of the 2-stage model to stainless steel stress-strain data in greater depth and developed expressions for the additional extended Ramberg-Osgood parameters in terms of the basic Ramberg-Osgood parameters.

It is worth noting that the curve defined by Equation 2 produces a slight inconsistency in that it does not pass through the point of σ_u at ε_{tu} , (where ε_{tu} is the total strain at ultimate stress). However, due to the high ductility of stainless steels, the errors incurred are negligible. For mathematical consistency Equation 2 would be replaced by Equation 3.

$$\varepsilon = \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} + \left(\varepsilon_{tu} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}} - \varepsilon_{t0.2} \right) \left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}} \right)^{n'_{0.2,u}} + \varepsilon_{t0.2} \quad (\sigma \geq \sigma_{0.2}) \quad (3)$$

Use of the ultimate stress, σ_u in the second phase of the Mirambell and Real model (between $\sigma_{0.2}$ and σ_u) has two drawbacks. Firstly, since the strain at σ_u is far higher than those strains concurrent with general structural response, greater deviation between measured and modelled material behaviour results than if a lower strain was used. Secondly, and more importantly, the model is not applicable to compressive stress-strain behaviour, since there is no ultimate stress in compression, due to the absence of the necking phenomenon.

It is therefore proposed to use the 1% proof stress in place of the ultimate stress, leading to Equation 4. Equation 1 continues to apply for stresses up to $\sigma_{0.2}$.

$$\varepsilon = \frac{(\sigma - \sigma_{0.2})}{E_{0.2}} + \left(0.008 - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}} \right) \left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}} \right)^{n'_{0.2,1.0}} + \varepsilon_{t0.2} \quad (\sigma \geq \sigma_{0.2}) \quad (4)$$

where $n'_{0.2, 1.0}$ is a strain hardening coefficient representing a curve that passes through $\sigma_{0.2}$ and $\sigma_{1.0}$.

Equation 4 was found to give excellent agreement with experimental stress-strain data, both in compression and tension, up to strains of approximately 10%, and was therefore adopted as the material model used in all associated numerical analyses described in [3] and in a new proposed design method for stainless steel structures presented in [4].

Corner material properties

The stress-strain properties of the corner regions in cold-formed stainless steel cross-sections differ from the properties of the flat regions due to the material's response to deformation. Owing to the very pronounced degree of strain hardening that stainless steel exhibits, the cold-worked corner regions of cold-formed stainless steel SHS and RHS have 0.2% proof strengths commonly between 20% and 100% higher than the 0.2% proof strengths of the flat regions. This is accompanied by a corresponding loss in ductility.

Following an extensive study into the corner properties of cold-formed carbon steel cross-sections, Karren [8] proposed methods for predicting corner strengths based on a number of base material and geometric variables. Abdel-Rahman & Sivakumaran [19] stated that the Karren model can only be used to predict the yield strength in the curved corner portions of cross-sections, and it is not valid for the areas immediately adjacent to the corners (which also showed strength enhancements). The Karren model was revised by multiplying the increase in yield strength in the corner regions by a factor of 0.6, and applying this increased yield strength to a region extending to $0.5\pi r_i$, where r_i is the internal corner radius, beyond the curved corner portions of cross-sections. Based largely upon the research carried out by Karren [8], Van den Berg & Van der Merwe [20] calibrated an expression to predict the corner mechanical properties of cold-formed (press-braked) stainless steel material. Tensile corner coupons were prepared by bending strips of the virgin material to different internal corner radii. A study was carried out to determine whether these formulations could be applied to the prediction of the corner material strength in cold-formed stainless steel SHS and RHS. However, agreement between predicted and experimental results was poor and attempts to re-calibrate the expression led to an improved mean prediction, but a large scatter remained. It should be noted that the predictions were based on the average properties of material cut from the flat faces of the cross-sections, rather than virgin properties. Virgin material properties of the flat sheet (prior to fabrication into SHS and RHS) were not known to a high degree of certainty.

Table 2 displays the results from six tests conducted on flat and corner material cut from cold-formed stainless steel SHS and RHS. One of the tests was performed by

Rasmussen and Hancock [11] on material from a stainless steel Grade 1.4306 roll-formed SHS. The remaining five tests were conducted as part of the current investigation, where all material was Grade 1.4301. It should be noted that the six cross-sections were not fabricated by direct bending from a flat sheet, but instead by a roll-forming process that involved first forming the material into a circular hollow section (CHS), and then shaping it into an SHS or RHS.

Unlike the fabrication method of directly bending flat sheet to form the SHS or RHS, which produces essentially unchanged properties in the flat regions, with large strength enhancements at the corners, the method of first forming a CHS, and then shaping into an SHS or RHS appears to produce moderate strength enhancements in the flat regions, and greater enhancements in the corners, (beyond the strengths of the direct fabrication method.

Following further analysis of the available test data in Table 2, it was found that the 0.2% proof strength of the corner material, $\sigma_{0.2,c}$ could be accurately described as a fixed percentage of the ultimate strength of the flat material, σ_u . It is therefore proposed that $\sigma_{0.2,c}$ be evaluated through Equation 5.

$$\sigma_{0.2,c} = 0.85 \sigma_u \quad (5)$$

Explanation of the expression is as follows: Corner material is work hardened to strains between about 10% and 20%. This region of the stress-strain curve is relatively flat, so the stress is not sensitive to the exact level of applied strain. Between 10% and 20% strain, the stress is approximately 85% of the ultimate material strength.

Despite its simplicity, Equation 5 provides excellent agreement with the test results in Table 2. The mean test $\sigma_{0.2,c}$ is predicted exactly, with a standard deviation of 2%. Equation 5 was therefore used for generating the corner material properties in the FE models described in [3].

Stub Column Tests

All stub column tests were conducted according to the general recommendations of the Structural Stability Research Council [21]. In all, some 37 tests were carried out: 17 on SHS specimens, 16 on RHS and 4 on CHS. All specimens had aspect ratios of between 0.5 and 1.0 and had their ends milled flat and square. Initial adjustments in the 300 T Amsler hydraulic testing machine using the corner strain readings (see Figure 7 for the arrangements of strain gauges on the specimens) ensured concentric loading. Figure 8 shows a general view of the test set up.

Prior to testing, each face of each SHS and RHS specimen was examined using an arrangement comprising a dial gauge fitted to the head of a milling machine with the specimen clamped to the base so that the initial profile of the face could be mapped. Expressions for predicting the magnitude of local geometric imperfections were developed and reported in [3]. A rather less comprehensive approach was used for the CHS specimens.

End shortening readings were obtained by combining the strain data with the three sets of displacement transducer readings using the procedure recommended by the University of Sydney [22]. This permits the effects of the end platen deformation to be removed, thereby enabling true specimen end shortening to be extracted. A full set of load-end shortening curves is given as Figure 9. These demonstrate good consistency between repeat tests on similar specimens and show how deformation capacity is dependent on geometry. Table 3 lists the geometric properties of the specimens, their maximum test loads and the end shortenings corresponding to the maximum test loads.

The Eurocode design method

Eurocode 3: Part 1.4 (for structural stainless steel design) uses the conventional approach to the classification of plate elements in cross-sections, basing the class on the plate slenderness (b/t), the material properties ($\sigma_{0.2}$ and E_0), the edge support conditions and the form of the applied stress field. For class 4 cross-sections it allows for loss of effectiveness due to premature local buckling through the effective width

concept. Much of this approach is similar to that used for carbon steel (Eurocode 3: Part 1.1) and implicitly relies on the existence and use of a sharply defined material yield point.

Comparisons of all available SHS, RHS and CHS stub column test results (a total of 48 specimens; 37 from the current study, 3 specimens tested by Rasmussen and Hancock [11], 3 specimens tested by Talja [23] and 3 specimens tested by Talja and Salmi [24]) were made with predicted results from Eurocode 3 Part 1.4. For the comparisons, measured geometric and material properties were used and all partial factors were set to unity. The comparison revealed (see [1] for full details) that the Eurocode prediction was conservative on average by over 20%.

The obvious conclusion from this comparison is that the Eurocode 3 Part 1.4 approach does not adequately reflect the important physical features of the subject. Much of this can be attributed to the overly simplistic (bi-linear) material model, which is implicit with the conventional classification system. Thus an alternative approach that better recognises the particular features of stainless steel has been developed. The basis of the approach is set out below and is described fully as part of a complete design treatment in [4].

Basis for an improved design approach

This section summarises how the stub column test results have been used to derive an explicit relationship between element slenderness and cross-section deformation capacity, and how this is subsequently used to determine cross-sectional resistances.

Cross-section deformation capacity is defined herein as the strain at ultimate load, ϵ_{LB} (local buckling strain) determined directly from the stub column load-end shortening curves, as shown in Figure 10, by dividing the end shortening at ultimate load, δ_u by the stub column length, L .

SHS and RHS

The raw SHS and RHS stub column test results from the current study (given in Tables 3a and 3b) and from all existing studies (given in Table 4a) have been manipulated and assembled in Table 5a and Table 5b, and plotted in Figure 11. Figure 11 relates the normalised local buckling strain ($=\varepsilon_{LB}/\varepsilon_0$), where ε_0 is the elastic strain at the material compressive 0.2% proof stress, to the cross-section slenderness, β . The slenderness β is defined for SHS and RHS elements as:

$$\beta = (b/t)\sqrt{\sigma_{0.2}/E_0} \quad (6)$$

where b is the plate width measured between the centrelines of the adjoining plates, (i.e. (D-t) or (B-t), where t is the material thickness) and $\sigma_{0.2}$ and E_0 are based on material stress-strain behaviour in compression. The value of β for the most slender plate in the cross-section is used as the basic measure of slenderness. The elastic critical buckling curve for a simply-supported plate element in pure compression (with the buckling coefficient, k set equal to 4.0, and Poisson's ratio taken as 0.3) is also shown in Figure 11.

From Figure 11 it can be seen that all bar one test result lie above the elastic critical buckling curve. Deviation of the test results from the elastic critical buckling curve is due to several effects including inelastic material behaviour, geometric imperfections, residual stresses, and post buckling response.

For slender cross-sections, where β is greater than about 1.6, it was observed that the deformation capacity at ultimate load, δ_u becomes increasingly dominated by post-buckling response. Figure 12 compares the load-deformation behaviour of stub columns with slender and non-slender cross-sections.

For the non-slender case, deviation from the material σ - ε curve occurs approximately at ultimate load where there is the onset of local buckling. Therefore, using ε_2 in conjunction with the material stress-strain curve, the predicted design strength, $\sigma_{2, \text{pred}}$ is close to the actual strength of the stub column, $\sigma_{2, \text{actual}}$. However, for the slender case (where β is greater than about 1.6), local buckling occurs in the elastic range, and

deviation from the stress-strain curve may be followed by considerable post-buckling deformation. Therefore, using ε_0 would result in an over-prediction of the actual stub column strength by the proposed design method. Thus, for cross-sections where β is greater than 1.6, deformation capacity is redefined at an empirically-derived proportion of the ultimate load. The linear reduction given in Equation 7 was derived from the test results.

$$\varphi = -0.0833\beta + 1.133 \quad \text{for } \beta > 1.6 \quad (7)$$

where φ is the proportion of ultimate load at which deformation capacity is defined.

Revised values of ε_{LB} and $\varepsilon_{LB}/\varepsilon_0$ for cross-sections where $\beta > 1.6$ are given in Table 6.

To describe the local buckling behaviour of aluminium plate elements, Faella et al [25], from a basis of elastic critical buckling, proposed an expression of the general form given in Equation 8. The constants C_1 , C_2 , and C_3 were determined from a regression analysis of experimental points.

$$\frac{\varepsilon_{LB}}{\varepsilon_0} = \frac{C_1}{\beta^{C_2 + C_3\beta}} \quad (8)$$

The right hand side of the Equation 8 was multiplied by χ^{C_4} by Faella et al [25], where χ is the ratio of slenderness of the least slender element to that of the most slender element in the cross-section, (i.e. for a RHS of constant thickness and material properties, the aspect ratio of the cross-section), and C_4 was another constant that was determined experimentally to account for the greater edge restraint that the two longer faces of an RHS cross-section receive from the two shorter ones. With increasing cross-section aspect ratio there is clearly an increasing level of restraint.

A regression analysis of the results from Table 5a, Table 5b and Table 6 (for the revised values for cross-sections where $\beta > 1.6$) yielded $C_1 = 7.07$, $C_2 = 2.13$ and $C_3 = 0.21$ for SHS. The experimental results indicated that the increased deformation capacity for the two longer faces of RHS was less significant for sections with lower cross-section slenderness. To reflect this behaviour, it was therefore decided to multiply the right

hand side of Equation 8 by $\chi^{C_4\beta^{0.5}}$, where the constant $C_4 = -0.30$ was determined based on the experimental results for RHS with aspect ratios of 0.67 and 0.50. Substituting the derived constants into Equation 8 and including the modification factor for RHS therefore yields Equation 9.

$$\frac{\varepsilon_{LB}}{\varepsilon_0} = \frac{7.07}{\beta^{2.13+0.21\beta}} \chi^{-0.30\beta^{0.5}} \quad (9)$$

The resulting curves are plotted in Figure 13 for $\chi = 1.0$ (SHS), $\chi = 0.67$ and $\chi = 0.50$. It is worth noting that although the effect of the increased edge restraint for the RHS appears to be relatively small, it can lead to increases in cross-section compressive resistance of up to 10%.

CHS

The relationship between CHS cross-section slenderness and deformation capacity is derived in a similar way to the SHS and RHS, by looking initially at the elastic critical buckling of a perfect, uniformly compressed cylinder. For CHS, the slenderness β is defined as:

$$\beta = (R/t)(\sigma_{0.2}/E_0) \quad (10)$$

where R is the radius of the CHS, measured to the centreline of the wall thickness, (i.e. $R = (D_0 - t)/2$, where D_0 is the outside diameter of the cross-section). The value of β will be used as the measure of cross-section slenderness. The parameters $\sigma_{0.2}$ and E_0 are based on material stress-strain behaviour in compression. In the absence of compressive stress-strain data, stub column values are to be adopted instead.

The raw CHS stub column test results from the current study (given in Table 3c) and from all other studies (given in Table 4b) have been manipulated and assembled in Table 5c, and plotted in Figure 14. Results from finite element simulations of the tests (from a parallel numerical modelling study described in [3]) have also been plotted in Figure 14. Figure 14 shows a graph of normalised local buckling strain ($=\varepsilon_{LB}/\varepsilon_0$), where ε_0 is the elastic strain at the material compressive 0.2% proof stress (or stub column 0.2% proof stress in the absence of compressive stress-strain data), versus cross-

section slenderness, β . The elastic critical buckling curve for a perfect cylinder in pure compression (with Poisson's ratio taken as 0.3) has been added to Figure 14.

Figure 14 shows that, unlike for the results for SHS and RHS, the CHS stub column results lie significantly below the elastic critical buckling curve, indicating a higher sensitivity to imperfections.

The general expression given in Equation 8 (and used to generate the SHS and RHS stub column curves) also forms the basis for the generation of the CHS mean design curve. However, since CHS are axis-symmetric, no modification to the right hand side of the expression is necessary. A regression analysis of experimentally and numerically generated results yielded the constants $C_1 = 0.116$, $C_2 = 1.21$ and $C_3 = 1.69$. Substituting the derived constants into Equation 8 results in Equation 11.

$$\frac{\varepsilon_{LB}}{\varepsilon_0} = \frac{0.116}{\beta^{1.21+1.69\beta}} \quad (11)$$

Figure 15 shows the experimentally and numerically generated CHS stub column results and the normalised local buckling curve defined by Equation 11. For comparison, the regression curve for the CHS test results alone is also shown in Figure 15.

Cross-section resistance

With knowledge of the deformation capacity of the cross-section (determined from the cross-section slenderness, β), its ultimate compressive resistance may hence be determined with reference to the material stress-strain curve. The compressive resistance is therefore given by the stress, σ_{LB} corresponding to the ε_{LB} multiplied by the gross cross-sectional area. The material stress-strain curve is defined by means of the compound Ramberg-Osgood expression (described above), though for design purposes, values may be tabulated so direct use of the material model is avoided. Full details of the design method are described in [4].

The cross-section compression strength of a total of 48 stub columns (20 SHS, 18 RHS and 10 CHS) of various classifications (1-4) was predicted using Eurocode 3 Part 1.4 and the proposed design method. A graphical illustration of the results is shown in

Figure 16. The results show that the proposed method gives a better prediction of strength for all classes of cross-section. As expected, the Eurocode predictions are increasingly conservative for stockier sections (as neglect of strain hardening becomes progressively more influential).

Conclusions

Results from 54 tensile coupon tests and 56 compressive coupon tests on material cut from finished cold-formed stainless steel tubular members have been presented. The concept of a 2-stage Ramberg-Osgood expression has been used to allow accurate modelling of observed stress-strain behaviour in both tension and compression.

Further tensile coupons tests were conducted on material cut from the heavily cold-worked corner regions of five cross-sections. A simple yet accurate model for the prediction of corner material properties based on those of the flat material has been proposed.

Results, including full load-end shortening curves, for a total of 37 stub column tests (17 SHS, 16 RHS and 4 CHS) have been presented. The results have been used to develop an explicit relationship between cross-sectional slenderness and cross-sectional deformation capacity, which forms the basis for a proposed new design approach for stainless steel structures. For cross-section resistance in compression, the proposed method offers a benefit of around 20% over the Eurocode approach and a reduction in scatter of the prediction; safe side design strengths are maintained.

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Figure 1: General view of compressive coupon bracing jig

Figure 2: Compressive coupon test piece

Figure 3: Typical stress-strain curves for flat material in tension

Figure 4: Labelling convention for faces of cross-sections

Figure 5: Typical stress-strain curves for flat material in compression

Figure 6: Comparison between average stress-strain behaviour in tension and compression

Figure 7: Location of strain gauges on SHS and RHS specimens

Figure 8: General view of SHS and RHS test set-up

(a) SHS 80x80x4

(b) SHS 80x80x4 - Annealed

(c) SHS 100x100x2

(d) SHS 100x100x3

(e) SHS 100x100x4

(f) SHS 100x100x6

(g) SHS 100x100x8

(h) SHS 150x150x4

(i) RHS 60x40x4

(j) RHS 100x50x2

(k) RHS 100x50x3

(l) RHS 100x50x4

(m) RHS 100x50x6

(n) RHS 120x80x3

(o) RHS 120x80x6

(p) RHS 150x100x4

(q) CHS 103x1.5

(r) CHS 153x1.5

Figure 9: Load- end shortening curves from stub column tests

Figure 10: Determination of cross-section deformation capacity

Figure 11: Normalised local buckling strain versus cross-section slenderness

Figure 12: Behaviour of stub columns with slender and non-slender cross-sections

Figure 13: SHS and RHS cross-section deformation capacity versus cross-section slenderness

Figure 14: CHS stub column test results and FE simulations of test results

Figure 15: CHS deformation capacity versus cross-section slenderness

Figure 16: Comparison between Eurocode 3 Part 1.4 and proposed design method

Table 1: Weighted average measured material properties for SHS and RHS coupons

Coupons	E_0 (N/mm ²)	$\sigma_{0.2}$ (N/mm ²)	$\sigma_{1.0}$ (N/mm ²)	σ_u (N/mm ²)	ε_{pu} (%)	Modified R-O coefficients		
						n	$n'_{0.2,u}$	$n'_{0.2,1.0}$
SHS 80×80×4- TF	186600	457	525	706	0.43	5.0	3.2	3.5
SHS 80×80×4- TC	215000	594	723	820	0.30	4.5	6.0	4.5
SHS 80×80×4- CF	203200	416	544	-	-	3.5	-	3.1
SHS 80×80×4- A- TF	-	-	-	-	-	-	-	-
SHS 80×80×4- A- TC	-	-	-	-	-	-	-	-
SHS 80×80×4- A- CF	206300	261	316	-	-	11.5	-	1.5
SHS 100×100×2- TF	201300	382	424	675	0.56	6.6	2.3	2.8
SHS 100×100×2- TC	197400	587	745	820	0.18	3.5	6.0	5.0
SHS 100×100×2- CF	207100	370	446	-	-	4.7	-	2.4
SHS 100×100×3- TF	195800	388	433	691	0.57	5.6	2.4	3.2
SHS 100×100×3- TC	-	-	-	-	-	-	-	-
SHS 100×100×3- CF	208800	379	468	-	-	3.8	-	2.6

Table 1 (continued): Weighted average measured material properties for SHS and RHS coupons

Coupons	E_0 (N/mm ²)	$\sigma_{0.2}$ (N/mm ²)	$\sigma_{1.0}$ (N/mm ²)	σ_u (N/mm ²)	ε_{pu} (%)	Modified R-O coefficients		
						n	$n'_{0.2,u}$	$n'_{0.2,1.0}$
SHS 100×100×4- TF	191300	465	519	713	0.45	5.7	2.9	3.7
SHS 100×100×4- TC	-	-	-	-	-	-	-	-
SHS 100×100×4- CF	203400	437	563	-	-	3.9	-	2.9
SHS 100×100×6- TF	198400	501	571	715	0.39	5.2	3.7	3.9
SHS 100×100×6- TC	-	-	-	-	-	-	-	-
SHS 100×100×6- CF	197900	473	590	-	-	4.4	-	2.6
SHS 100×100×8- TF	202400	328	378	653	0.52	6.4	2.2	2.6
SHS 100×100×8- TC	-	-	-	-	-	-	-	-
SHS 100×100×8- CF	205200	330	392	-	-	6.4	-	2.1
SHS 150×150×4- TF	206000	314	358	659	0.54	6.8	2.2	2.2
SHS 150×150×4- TC	194000	563	649	844	0.20	5.2	2.9	3.5
SHS 150×150×4- CF	195400	294	366	-	-	4.5	-	2.3

Table 1 (continued): Weighted average measured material properties for SHS and RHS coupons

Coupons	E_0	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	ε_{pu}	Modified R-O coefficients		
	(N/mm ²)	(N/mm ²)	(N/mm ²)	(N/mm ²)	(%)	n	n' _{0.2,u}	n' _{0.2,1.0}
RHS 60×40×4- TF	192800	489	591	705	0.40	3.9	5.1	4.6
RHS 60×40×4- TC	-	-	-	-	-	-	-	-
RHS 60×40×4- CF	193100	469	617	-	-	3.6	-	3.0
RHS 120×80×3- TF	209300	419	488	739	0.54	4.1	2.9	3.6
RHS 120×80×3- TC	-	-	-	-	-	-	-	-
RHS 120×80×3- CF	197300	429	536	-	-	4.2	-	2.9
RHS 120×80×6- TF	194500	509	572	714	0.40	5.3	3.5	3.6
RHS 120×80×6- TC	-	-	-	-	-	-	-	-
RHS 120×80×6- CF	192300	466	591	-	-	4.4	-	2.8
RHS 150×100×4- TF	205800	297	345	663	0.62	8.0	2.3	2.4
RHS 150×100×4- TC	191700	572	690	809	0.20	4.6	4.8	4.0
RHS 150×100×4- CF	200300	319	386	-	-	4.7	-	2.0

Table 1 (continued): Weighted average measured material properties for SHS and RHS coupons

Coupons	E_0	$\sigma_{0.2}$	$\sigma_{1.0}$	σ_u	ε_{pu}	Modified R-O coefficients		
	(N/mm ²)	(N/mm ²)	(N/mm ²)	(N/mm ²)	(%)	n	n' _{0.2,u}	n' _{0.2,1.0}
RHS 100×50×2- TF	208000	403	443	707	0.57	6.9	2.2	2.6
RHS 100×50×2- TC	-	-	-	-	-	-	-	-
RHS 100×50×2- CF	205900	370	442	-	-	5.2	-	2.4
RHS 100×50×3- TF	203600	479	563	716	0.48	4.2	4.1	4.2
RHS 100×50×3- TC	-	-	-	-	-	-	-	-
RHS 100×50×3- CF	200900	455	572	-	-	4.1	-	3.0
RHS 100×50×4- TF	208000	471	530	702	0.45	5.2	3.2	3.5
RHS 100×50×4- TC	-	-	-	-	-	-	-	-
RHS 100×50×4- CF	203900	439	562	-	-	3.8	-	3.3
RHS 100×50×6- TF	187200	605	686	754	0.36	5.7	6.0	4.5
RHS 100×50×6- TC	197700	631	773	802	0.18	3.5	10.0	6.0
RHS 100×50×6- CF	206300	494	649	-	-	4.0	-	3.2

Key: TF - Tension Flat
TC - Tension Corner
CF - Compression Flat

Table 2: Results from tensile tests conducted on flat and corner regions of cold-formed SHS and RHS

Section size	r_1 / t	Flat tensile properties		Corner tensile properties			Corner/ flat values			
		$\sigma_{0.2}$ (N/mm ²)	σ_u (N/mm ²)	$\sigma_{0.2,c}$ (N/mm ²)	$\sigma_{1.0,c}$ (N/mm ²)	$\sigma_{u,c}$ (N/mm ²)	$\sigma_{0.2,c} / \sigma_{0.2}$	$\sigma_{0.2,c} / \sigma_u$	$\sigma_{1.0,c} / \sigma_u$	$\sigma_{u,c} / \sigma_u$
SHS 80×80×3 ¹	0.84	408	695	580	-	805	1.42	0.83	-	1.16
SHS 80×80×4 ²	1.18	457	706	594	723	820	1.30	0.84	1.02	1.16
SHS 100×100×2 ²	0.68	382	675	587	745	820	1.54	0.87	1.10	1.21
SHS 150×150×4 ²	1.57	314	659	563	649	844	1.79	0.85	0.98	1.28
RHS 100×50×6 ²	0.93	605	754	631	773	802	1.04	0.84	1.03	1.06
RHS 150×100×4 ²	1.46	297	663	572	690	809	1.93	0.86	1.04	1.22
Mean:							1.50	0.85	1.04	1.18

Notes: ¹ Tests conducted by Rasmussen and Hancock (1993)

² Tests conducted as part of current study

Table 3a: Measured dimensions and a summary of test results for SHS stub columns

Specimen identification	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Length, L (mm)	Int. corner rad., r_1 (mm)	Area, A (mm ²)	Ultimate load, F_u (kN)	End shortening at ultimate load, δ_u (mm)
SHS 80×80×4- SC1	79.8	79.9	3.68	400.2	4.6	1080	727	7.4
SHS 80×80×4- SC2	80.1	80.1	3.82	399.9	4.4	1124	714	7.2
SHS 80×80×4- SC3	80.1	79.9	3.83	399.4	4.4	1125	711	7.7
SHS 80×80×4- ASC1	79.5	79.7	3.77	400.4	4.1	1105	309	8.6
SHS 80×80×4- ASC2	79.7	79.6	3.68	399.8	4.4	1080	335	7.1
SHS 100×100×2- SC1	100.2	100.0	1.91	400.5	1.3	743	197	1.1
SHS 100×100×2- SC2	99.9	100.0	1.91	400.2	1.3	739	187	0.9
SHS 100×100×3- SC1	100.1	100.3	2.87	400.0	1.5	1101	489	2.2
SHS 100×100×3- SC2	100.1	100.1	2.84	399.8	1.5	1089	496	2.3
SHS 100×100×4- SC1	99.8	99.9	3.84	399.8	4.5	1431	779	4.0
SHS 100×100×4- SC2	99.7	99.8	3.83	400.4	4.5	1426	774	4.0
SHS 100×100×6- SC1	100.1	100.1	5.94	399.8	5.8	2147	1513	13.4
SHS 100×100×6- SC2	100.2	100.1	5.92	399.6	5.8	2153	1507	13.5
SHS 100×100×8- SC1	100.3	100.7	7.97	399.1	8.0	2785	1630	29.0
SHS 100×100×8- SC2	100.1	100.7	7.97	400.0	8.0	2781	1797	38.2
SHS 150×150×4- SC1	150.4	149.9	3.79	449.9	5.8	2167	726	1.7
SHS 150×150×4- SC2	150.2	150.0	3.74	450.7	6.0	2139	713	1.6

Table 3b: Measured dimensions and a summary of test results for RHS stub columns

Specimen identification	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Length, L (mm)	Int. corner rad., r_i (mm)	Area, A (mm ²)	Ultimate load, F_u (kN)	End shortening at ultimate load, δ_u (mm)
RHS 60×40×4- SC1	60.0	40.0	3.83	180.3	2.9	675	492	6.7
RHS 60×40×4- SC2	60.0	40.0	3.82	179.6	2.9	675	497	6.7
RHS 120×80×3- SC1	120.1	80.2	2.93	359.9	4.6	1109	452	1.6
RHS 120×80×3- SC2	120.0	80.2	2.91	360.0	4.6	1100	447	1.6
RHS 120×80×6- SC1	119.9	80.4	5.85	360.1	7.0	2107	1459	7.8
RHS 120×80×6- SC2	120.0	80.3	5.85	360.1	7.0	2108	1465	7.9
RHS 150×100×4- SC1	149.9	99.9	3.82	450.4	5.6	1799	660	2.5
RHS 150×100×4- SC2	149.9	99.9	3.83	450.0	5.6	1805	659	2.3
RHS 100×50×2- SC1	99.8	49.8	1.85	300.6	2.3	529	182	1.2
RHS 100×50×2- SC2	99.8	50.0	1.84	299.8	2.3	529	181	1.3
RHS 100×50×3- SC1	100.1	50.1	2.89	299.9	3.1	811	407	1.8
RHS 100×50×3- SC2	100.1	50.0	2.89	300.0	3.1	811	415	1.8
RHS 100×50×4- SC1	99.7	49.9	3.73	300.4	3.6	1026	626	3.5
RHS 100×50×4- SC2	99.8	49.8	3.68	300.6	3.6	1014	627	3.7
RHS 100×50×6- SC1	100.1	50.1	5.95	300.0	5.6	1558	1217	9.3
RHS 100×50×6- SC2	100.0	50.1	5.96	300.1	5.5	1559	1217	9.8

Table 3c: Measured dimensions and a summary of test results for CHS stub columns

Specimen identification	Outer diameter, D_o (mm)	Thickness, t (mm)	Length, L (mm)	Area, A (mm ²)	Ultimate load, F_u (kN)	End shortening at ultimate load, δ_u (mm)
CHS 103x1.5- SC1	103.2	1.50	506.8	480	214	4.1
CHS 103x1.5- SC2	103.1	1.50	507.2	477	217	4.2
CHS 153x1.5- SC1	153.1	1.43	757.7	683	287	3.3
CHS 153x1.5- SC2	153.4	1.45	757.6	690	286	3.9

Table 4a: Measured dimensions and a summary of test results for SHS and RHS stub columns from other test programmes

Specimen identification	Depth, D (mm)	Breadth, B (mm)	Thickness, t (mm)	Length, L (mm)	Internal corner radius, r_i (mm)	Area, A (mm ²)	Ultimate load, F_u (kN)	End shortening at ultimate load, δ_u (mm)
SHS 80×80×3- SC1 (RH)	80.4	80.4	3.00	300	5.5	908	485	2.0
SHS 80×80×3- SC2 (RH)	79.7	79.7	3.00	298	5.5	900	471	2.2
SHS 60×60×5- SC1 (TS)	59.6	59.8	4.77	399	3.5	999	801	9.4
RHS 150×100×3- SC1 (TS)	150.7	100.5	2.89	1048	3.0	1397	372	3.7
RHS 150×100×6- SC1 (TS)	150.5	100.7	5.77	1049	5.5	2683	1292	12.0

Key: (RH) – Tested by Rasmussen and Hancock (1993)
(TS) – Tested by Talja and Salmi (1995)

Table 4b: Measured dimensions and a summary of test results for CHS stub columns from other test programmes

Specimen identification	Outer diameter, D_o (mm)	Thickness, t (mm)	Length, L (mm)	Area, A (mm ²)	Ultimate load, F_u (kN)	End shortening at ultimate load, δ_u (mm)
CHS 101.6×2.85- SC1 (RH)	101.5	2.96	350	916	426	5.7
CHS 101.6×2.85- SC2 (RH)	101.5	2.96	350	916	425	6.0
CHS 101.6×2.85- SC3 (RH)	102.1	2.77	350	864	391	3.9
CHS 140×2- SC (T)	139.4	1.97	499	851	278	4.5
CHS 140×3- SC (T)	139.4	2.87	498	1231	468	6.0
CHS 140×4- SC (T)	138.7	3.99	499	1689	665	12.8

Key: (RH) – Tested by Rasmussen and Hancock (1993)
(T) – Tested by Talja (1997)

Table 5a: Cross-section slenderness and deformation capacity for SHS stub columns

Specimen identification	$\beta_{\square} = b/t(\sigma_{0.2}/E_0)^{0.5}$	$\varepsilon_0 = \sigma_{0.2}/E_0$	ε_{LB}	$\varepsilon_{LB}/\varepsilon_0$
SHS 60×60×5- SC ¹	0.57	0.0025	0.0236	9.50
SHS 80×80×3- SC1 ¹	1.19	0.0021	0.0068	3.21
SHS 80×80×3- SC2 ¹	1.18	0.0021	0.0073	3.45
SHS 80×80×4- SC1	1.02	0.0024	0.0184	7.52
SHS 80×80×4- SC2	0.99	0.0024	0.0180	7.33
SHS 80×80×4- SC3	0.98	0.0024	0.0193	7.86
SHS 80×80×4- ASC1	0.71	0.0013	0.0214	16.90
SHS 80×80×4- ASC2	0.73	0.0013	0.0179	14.12
SHS 100×100×2- SC1	2.17	0.0018	0.0027 ²	1.50 ²
SHS 100×100×2- SC2	2.18	0.0018	0.0022 ²	1.26 ²
SHS 100×100×3- SC1	1.45	0.0018	0.0056	3.09
SHS 100×100×3- SC2	1.46	0.0018	0.0057	3.14
SHS 100×100×4- SC1	1.16	0.0021	0.0100	4.67
SHS 100×100×4- SC2	1.16	0.0021	0.0100	4.65
SHS 100×100×6- SC1	0.78	0.0024	0.0335	14.00
SHS 100×100×6- SC2	0.77	0.0024	0.0337	14.11
SHS 100×100×8- SC1	0.46	0.0016	0.0726	45.14
SHS 100×100×8- SC2	0.46	0.0016	0.0954	59.31
SHS 150×150×4- SC1	1.50	0.0015	0.0037	2.48
SHS 150×150×4- SC2	1.52	0.0015	0.0036	2.37

Notes: ¹ Results obtained from other test programmes

² Peaks of load-end shortening curves dominated by post buckling effects
(revised values for ε_{LB} presented in Table 6)

Table 5b: Cross-section slenderness and deformation capacity for RHS stub columns

Specimen identification	$\beta_{\square} = b/t(\sigma_{0.2}/E_0)^{0.5}$	$\varepsilon_0 = \sigma_{0.2}/E_0$	ε_{LB}	$\varepsilon_{LB}/\varepsilon_0$
RHS 60×40×4- SC1	0.72	0.0024	0.0370	15.25
RHS 60×40×4- SC2	0.72	0.0024	0.0371	15.29
RHS 120×80×3- SC1	1.86	0.0022	0.0045 ²	2.06 ²
RHS 120×80×3- SC2	1.88	0.0022	0.0044 ²	2.03 ²
RHS 120×80×6- SC1	0.96	0.0024	0.0218	8.98
RHS 120×80×6- SC2	0.96	0.0024	0.0218	9.00
RHS 150×100×3- SC ¹	1.98	0.0015	0.0035 ¹	2.37 ¹
RHS 150×100×4- SC1	1.53	0.0016	0.0055	3.43
RHS 150×100×4- SC2	1.52	0.0016	0.0051	3.20
RHS 150×100×6- SC ¹	0.96	0.0015	0.0114	7.77
RHS 100×50×2- SC1	2.25	0.0018	0.0040 ²	2.22 ²
RHS 100×50×2- SC2	2.25	0.0018	0.0042 ²	2.32 ²
RHS 100×50×3- SC1	1.60	0.0023	0.0060	2.66
RHS 100×50×3- SC2	1.60	0.0023	0.0059	2.62
RHS 100×50×4- SC1	1.19	0.0022	0.0116	5.38
RHS 100×50×4- SC2	1.21	0.0022	0.0124	5.76
RHS 100×50×6- SC1	0.77	0.0024	0.0309	12.92
RHS 100×50×6- SC2	0.77	0.0024	0.0327	13.64

Notes: ¹ Results obtained from other test programmes

² Peaks of load-end shortening curves dominated by post buckling effects
(revised values for ε_{LB} presented in Table 6)

Table 5c: Cross-section slenderness and deformation capacity for CHS stub columns

Specimen identification	$\beta_{\square} = (R/t)(\sigma_{0.2}/E_0)$	$\varepsilon_0 = \sigma_{0.2}/E_0$	ε_{LB}	$\varepsilon_{LB}/\varepsilon_0$
CHS 103×1.5- SC1 ²	0.060	0.0018	0.008	4.53
CHS 103×1.5- SC2 ²	0.061	0.0018	0.008	4.64
CHS 101.6×2.85- SC1 ¹	0.032	0.0019	0.016	8.44
CHS 101.6×2.85- SC2 ¹	0.032	0.0019	0.017	8.88
CHS 101.6×2.85- SC3 ¹	0.035	0.0019	0.011	5.77
CHS 140×2- SC1,2	0.051	0.0015	0.009	6.13
CHS 140×3- SC1,2	0.039	0.0017	0.012	7.30
CHS 140×4- SC1,2	0.026	0.0016	0.026	16.35
CHS 153×1.5- SC1 ²	0.106	0.0020	0.004	2.18
CHS 153×1.5- SC2 ²	0.105	0.0020	0.005	2.58

Notes: ¹ Results obtained from other test programmes

² No material coupon tests conducted in compression. Values based on stub column curves.

Table 6: Cross-section slenderness and revised deformation capacity for SHS and RHS stub columns with $\beta_{\square} > 1.6$

Specimen identification	$\beta_{\square} = b/t(\sigma_{0.2}/E_0)^{0.5}$	$\varepsilon_0 = \sigma_{0.2}/E_0$	φ	ε_{LB}	$\varepsilon_{LB}/\varepsilon_0$
SHS 100×100×2- SC1	2.17	0.0018	0.95	0.0017	0.94
SHS 100×100×2- SC2	2.18	0.0018	0.95	0.0016	0.92
RHS 120×80×3- SC1	1.86	0.0022	0.98	0.0038	3.43
RHS 120×80×3- SC2	1.88	0.0022	0.98	0.0038	3.20
RHS 150×100×3- SC1 ¹	1.98	0.0015	0.97	0.0027	1.84
RHS 100×50×2- SC1	2.25	0.0018	0.95	0.0025	1.39
RHS 100×50×2- SC2	2.25	0.0018	0.95	0.0025	1.38

Note: ¹Results obtained from other test programmes