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MECHANICAL PROPERTIES OF STAINLESS STEEL LIPPED CHANNELS.

by

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SUMMARY

This paper describes and discusses the results obtained from a series of tensile tests performed on cold formed stainless steel Type 304 members of lipped channel cross-section. Standard tensile tests on coupons cut from the webs of the sections were carried out, as were full section tensile tests. Ramberg-Osgood type curves based on the procedure suggested in the ASCE design code were fitted to the stress-strain results and these are compared with the experimental results and Ramberg-Osgood type curves derived on an alternative basis.

INTRODUCTION

The mechanical properties of stainless steels are significantly different from those of carbon steel. Stainless steels can display anisotropy and non-linear stress-strain behaviour, and often have low proportional limits and a pronounced response to cold working. The material properties of various stainless steels have been thoroughly investigated since the 1960s, by a number of investigators, e.g (1), (2), (3), (4). It has been generally concluded that the stress-strain behaviour of stainless steels can be best described by the Ramberg-Osgood model (5), and a modified form of the Ramberg-Osgood equation is used in design specifications.

The main design specification for stainless steels is the ASCE specification (6) and in Europe Eurocode 3, Part 1.4 (7) has been recently developed for the design of stainless steel members. The two codes use different approaches when dealing with the mechanical properties of the material . The ASCE code employs the modified form of the Ramberg-Osgood model used to describe the stress-strain behaviour of a material, whereas the Eurocode relies for most purposes on the specification of a linear stress-strain law, with the yield strength taken as the 0.2% proof stress. In a companion paper (8) a comparison of the Eurocode and ASCE code predictions for lipped channel columns is illustrated, and the simpler Eurocode analysis has been found to give reasonable estimates of concentrically loaded column strength without taking account of the non-linearity of the stress-strain curve. As part of this investigation a series of tensile tests were carried out on coupons cut from the stainless steel sections, and on full sections, and the stress-strain characteristics are examined in this paper.

MECHANICAL PROPERTIES OF COLD FORMED STAINLESS STEEL LIPPED CHANNEL MEMBERS

In the formation of a profiled section, the cold working occurs in localised areas, with the material at the bends being strain hardened. Therefore the properties of the material vary throughout the cross-section where at the formed bends, higher yield and tensile strengths exist.

The stress-strain behaviour of stainless steel members is complex when full cross-section tensile tests are performed on cold formed members, with the introduction of regions of high yield and tensile strength at formed corners. The level of increase is dependent on the ratio of corner radius to material thickness (r/t). The cold formed lipped channels under investigation have cross-sections with small web, flange and lip dimensions and are considered to be thick and hence four corner bends are formed with small r/t ratios (<1). These four corners will have an effect on the stress-strain response of the material obtained from a full section test, which could then be compared to that obtained for virgin material from a standard tensile test.

The ASCE design specification adopts the modified form of the Ramberg-Osgood formula (5) given by equation (1). It is a three-parameter equation for expressing the relationship between the stress and strain for stresses up to a value slightly greater than the yield strength of the material.

$$\varepsilon = \frac{\sigma}{E} + K\left(\frac{\sigma}{E}\right)^{n} \qquad (1)$$

where ε = unit strain
σ = unit stress (N/mm^2)
E = modulus of elasticity (N/mm^2)

K and n are constants for a given curve, which are evaluated through two secant yield strength values for slopes of 0.7E and 0.85E. Equation (1) was modified by Hill (9). Instead of using secant yield strengths, K and n can be evaluated in terms of two yield strength values:

1. σ_1 at an offset ε_1
2. σ_2 at an offset ε_2

The equation of the deviation of the curve from the initial modulus can be written:

$$d = K\left(\frac{\sigma}{E}\right)^n \tag{2}$$

From which:

$$\ln d = \ln K + n\ln\left(\frac{\sigma}{E}\right) \tag{3}$$

Substituting σ_1 and d_1, and σ_2 and d_2 into the equation gives two simultaneous equations in K and n, which when solved for n gives:

$$n = \frac{\ln\left(\frac{d_2}{d_1}\right)}{\ln\left(\frac{\sigma_2}{\sigma_1}\right)} \tag{4}$$

From equation (2), K can be expressed:

$$K = \frac{d_2}{\left(\frac{\sigma_2}{E}\right)^n} \qquad \text{or} \qquad K = \frac{d_1}{\left(\frac{\sigma_1}{E}\right)^n} \tag{5}$$

Substituting equation (5) into equation (1) gives the equation for the stress-strain curve:

$$\varepsilon = \frac{\sigma}{E} + d_2\left(\frac{\sigma}{\sigma_2}\right)^n \qquad \text{or} \qquad \varepsilon = \frac{\sigma}{E} + d_1\left(\frac{\sigma}{\sigma_1}\right)^n \tag{6}$$

Using the most common offset (d_2) of 0.002 for the yield stress (σ_2) and assuming that the modulus of elasticity E, is equal to the initial value Eo, equation (6) becomes:

$$\varepsilon = \frac{\sigma}{E_o} + 0.002\left(\frac{\sigma}{\sigma_y}\right)^n \tag{7}$$

The ASCE design code makes use of the modified Ramberg-Osgood formula (equation 7), and the three points on the stress-strain curve are defined as:

1. the origin;
2. the point of 0.2% proof stress;
3. another offset strength (e.g. 0.01%).

If the above points are substituted into equation (6) then the only unknown, n, can be evaluated. The term n is referred to in the ASCE design code as the plasticity factor. The accuracy of the above method is largely based on how well the analytical equation fits the stress-strain relationship of the material. The code lists for particular grades of stainless steel, tables of yield stress, tangent modulus and plasticity factors that can be used in the above calculations.

The results obtained for the stress-strain relationship from both virgin material and full section tensile tests will be used for comparison with the results obtained from the above ASCE Ramberg-Osgood approach and by a trial and error 'best fit' method using the experimental stress-strain curves. These will then be examined in the far post-yield range, and modifications suggested to improve the accuracy of the Ramberg-Osgood formula at large strains.

EXPERIMENTAL INVESTIGATION

Figure 1 shows a typical cross-section of the cold formed stainless steel lipped channel member under investigation. The member is commercially available and was supplied in two different sizes of cross-section with the details given in Table 1. In order to determine the material properties of the sections, tensile tests were set-up where the applied load and gauge specimen elongation were recorded continuously until fracture of the specimen occurred. The measured load and elongation were normalised to give a stress-strain relationship. Due to the anisotropy of stainless steel, a full analysis of the material properties would require tensile tests in the longitudinal and transverse directions, as well as compression tests in the same directions. Indeed, provision is made in the ASCE design code to enable use to be made of them in specific applications. However, compression tests were not carried out as there would be difficulty in establishing the true material properties of the material due to likely buckling effects. Also, transverse direction tensile tests could not be carried out because of the limitations in the geometry of the sections. Hence tensile testing was limited to the longitudinal direction.

All tensile tests were carried out in accordance with BSEN10002-1 (10). Standard tensile tests were performed to ascertain the material properties of the stainless steel for the 2 different thicknesses. Coupons were cut from the webs of the columns and tested to obtain the 0.2% proof stress and the modulus of elasticity.

Tensile tests were also performed on full sections to include the effects of the cold formed corners and from these tests the 0.2% proof stress and the initial modulus of elasticity were determined.

For the standard coupons, a total of three thin (THN) specimens and six thick (THK) specimens were tested and the average results were noted. For the full section tests, two THN and two THK specimens were tested and again, the average results were noted. It should be mentioned here that the thick sections have wider webs than the thin sections, and in the graphs reference is often made to “W” sections (which are THK specimens) and “T” sections (THN specimens).

RESULTS

All results obtained from tensile tests to establish virgin material and full cross-section mechanical properties are shown in Table 2.

The results obtained from the standard coupon tensile tests on the column web material showed that the 0.2% proof stress varied from 475 N/mm^2 to 487.5 N/mm^2 for the THN section with the average being 480 N/mm^2. The modulus of elasticity was found to be 174 kN/mm^2. For THK section material, the 0.2% proof stress varied from 446.79 N/mm^2 to 483.8 N/mm^2 with the average being 460 N/mm^2, and the modulus of elasticity was evaluated as 180 kN/mm^2.

From the full section tensile tests, the 0.2% proof stress for the THN sections ranged from 518 N/mm^2 to 522 N/mm^2 with the average being 520 N/mm^2, The modulus of elasticity was calculated to be 174 kN/mm^2. For the THK sections, the 0.2% proof stress varied from 536.5 N/mm^2 to 543.5 N/mm^2 with the average being 540 N/mm^2, and the modulus of elasticity obtained from the tests was 180 kN/mm^2.

The results obtained for the plasticity factors n from the ASCE design code, i.e. the modified form of the Ramberg-Osgood equation given by equation (7) above, are shown in Table 3. Also shown in Table 3 are the plasticity factors obtained from comparative plots and a trial and error (‘best fit’) process using the stress-strain curves obtained from the tensile tests.

Figures 2 and 3 show graphs of stress v. strain for the THN and THK standard coupon tensile tests respectively, comparing the curves obtained from experiments with those obtained using the plasticity factors from ASCE and from the ‘best fit’ procedure. Figures 4 and 5 show graphs of stress v. strain for the THN and THK full section tensile tests respectively, comparing the curves obtained from experiments with those obtained using the plasticity factors from ASCE and from the 'best fit' procedure.

OBSERVATIONS

The curves shown in Figure 2 for standard coupon THN material show a very good correlation between the experimental results and the results obtained by using the 'best fit' method where n = 6.22. The ASCE design code where n = 3.80, overestimates the stress in the material beyond a strain value of approximately 0.005. A very similar comparison can be made for the THK material as shown in Figure 3 where the n = 7.5 from the 'best fit' method and n = 4.66 from ASCE.

The curves shown in Figure 4 for THN full sections show an improved correlation between the experimental results and the results obtained by using the 'best fit' method where n = 6.65. The ASCE design code where n = 5.02, overestimates the stress in the material beyond a strain value of approximately 0.007, but the overestimation is less than that for the standard coupon results. For the THK full sections, Figure 5 shows that the experimental and 'best fit' where n= 6.00 curves are almost identical, but the ASCE, where n = 3.62, overestimates the stress beyond a strain value of 0.006, and the overestimation is more significant in this case.

The main reason for the discrepancies between the ASCE and the 'best fit' curves is in the method used to generate the curves. The ASCE curve has to pass through 3 points: the origin, 0.2% proof stress and 0.01% offset stress. The 'best fit' method did not use the 0.01% offset stress point, but did use a point in the plastic behaviour range, higher up the curve providing a much better correlation to the experimental curve, particularly at strains greater than 0.005. The method suggested by the ASCE code ensures accurate assessment of the stress-strain behaviour at stresses up to, and slightly beyond the 0.2% proof stress. For larger stresses and strains the curve thus obtained can become inaccurate. The curves obtained by the "best fit" method sacrifice accuracy at low strains to achieve agreement with experiment at higher strains. For any given strain a law can be generated that gives the precise result for that strain, and for the 0.2% proof strain, but the accuracy at other strain values is not guaranteed.

Figures 4 and 5 show that for the tensile tests carried out on the full sections, that the cold forming process increased the strength of both the THN and THK material quite considerably. The modulus of elasticity remained the same value as for those obtained from the standard coupon tests, but the yield strength was increased by 8.3% and 17.4% for the THN and THK lipped channel sections respectively. Interestingly, this meant that the THK sections had a higher yield strength (540 N/mm^2) than the THN sections (520 N/mm^2) which was in contrast with the results obtained from the standard coupon tests. A number of factors can be attributed to this effect including the amount of cold working in the material, e.g. roll pressure and corner radii, and also the properties of the stainless steel. However, it is more likely that the main factor in this case was that the thicker material required more cold work to be carried out during manufacture to produce channels with such very small r/t ratios.

STRESS - STRAIN BEHAVIOUR FAR BEYOND YIELD

The results shown indicate that if the modified Ramberg-Osgood curve is derived with the 0.2% proof stress and 0.01% offset stress, very accurate approximations to the experimental stress-strain curves are obtained at strains up to and slightly beyond the 0.2% proof strain (which occurs at a total strain of approximately 0.5%) and thereafter inaccuracies arise. The "best fit" approach used here could be used to get accurate results at any specific strain value beyond yield, but only at the expense of accuracy in the pre-yield range, which is not at all desirable.

With the ready availability of finite element packages suited to dealing with non-linear material behaviour, there is no reason not to have as accurate a specification of the material stress-strain behaviour as possible. The Ramberg-Osgood curve as presently used is limited in accuracy to curves which follow a combination of linear and single power laws. As has been seen the materials examined here only seem to follow such laws with a fairly substantial degree of approximation. The use of the 0.2% proof stress and the 0.01% offset stress results in relatively low nonlinearity indices "n" which give accurate results at low strains, while curve fitting at higher strain values results in higher "n" values. Figure 6, drawn for a test in which the material failed at a strain just below 2.5% (specimen W2) shows these curves (labelled "ASCE" and "Best Fit") become inaccurate at high strains. The realisation that larger values of the index "n" are required for accuracy at large strains suggests that if n is allowed to vary as the strain increases then an accurate portrayal of the stress-strain relationship at all strains could be derived.

To examine this hypothesis a simple trial and error approach was used to fit such a curve to the test data, and this is reproduced in Figure 6. The equation of this curve is:-

$$\varepsilon = \frac{\sigma}{E_o} + 0.002\left(\frac{\sigma}{\sigma_1}\right)^{\left(4 + 2.5\left(\frac{\sigma}{\sigma_1}\right)^6\right)} \qquad (8)$$

As may be observed this curve is extremely close to the experimental stress strain curve at all stages of loading.

Specimen W3 strained to approximately 7% before failing, and this was felt to be a good test of the hypothesis. Figure 7 shows the experimental curve, the curves fitted using the Ramberg-Osgood laws and a trial and error modified curve of the form:-

$$\varepsilon = \frac{\sigma}{E_o} + 0.002\left(\frac{\sigma}{\sigma_1}\right)^{\left(2.5+4\left(\frac{\sigma}{\sigma_1}\right)^4\right)} \qquad (9)$$

As may be observed this curve is an excellent approximation to the experimental curve over the complete range, while the Ramberg-Osgood curves only follow the initial experimental curves with accuracy.

CONCLUSIONS

The main conclusion from the investigation is that the material properties of stainless steel can be accurately modelled in the range up to and just beyond yield using the ASCE design code recommendations, but an improvement can be obtained by using the 'best fit' method described in the paper. This is true not only for standard coupon material properties, but also significantly, for full section material properties where increased yield strength is largely ignored in structural design. The investigation of stainless steel lipped channel sections has shown that an improvement in material properties is gained from the cold forming process for stainless steel members even with very small r/t ratios.

An accurate approximation to the stress-strain behaviour of stainless steels far beyond the yield strain can be obtained by considering that the nonlinearity index "n" varies as the strain varies.

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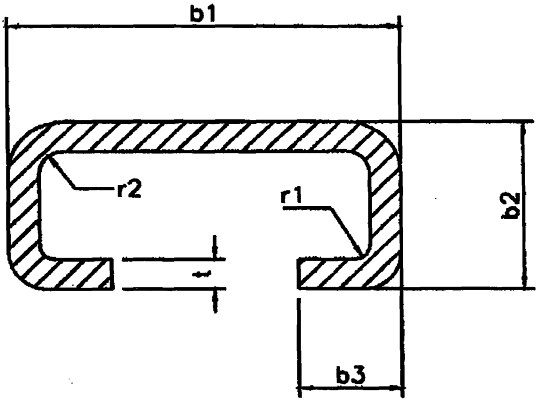

Figure 1: Typical Lipped Channel Cross-Section

Table 1.
Average Dimensions of Lipped Channel Cross-Sections

Section Ref:	Web, b_1 (mm)	Flange, b_2 (mm)	Lip, b_3 (mm)	Thickness, t (mm)	Radius, r_1 (mm)	Radius, r_2 (mm)
THN (T)	28.00	14.88	7.45	2.43	1.10	1.10
THK (W)	38.00	17.19	9.99	3.05	0.735	2.255

Table 2.
Tensile Test Results: Virgin Material and Full Section Mechanical Properties

Material Ref:	**Thickness t (mm)**	**Average Virgin 0.2% P.S. (N/mm^2)**	**Average Virgin UTS (N/mm^2)**	**Average Full Section 0.2% P.S. (N/mm^2)**	**Average Full Section UTS (N/mm^2)**
THN (T)	2.43	480	553	520	689
THK (W)	3.05	460	541	540	744

Table 3.
Plasticity Factors

Tensile Test	**n (Best Fit)**	**n (ASCE)**
Coupon – THN (T)	6.22	3.80
Coupon – THK (W)	7.50	4.66
Full Section – THN (T)	6.65	5.02
Full Section – THK (W)	6.00	3.62

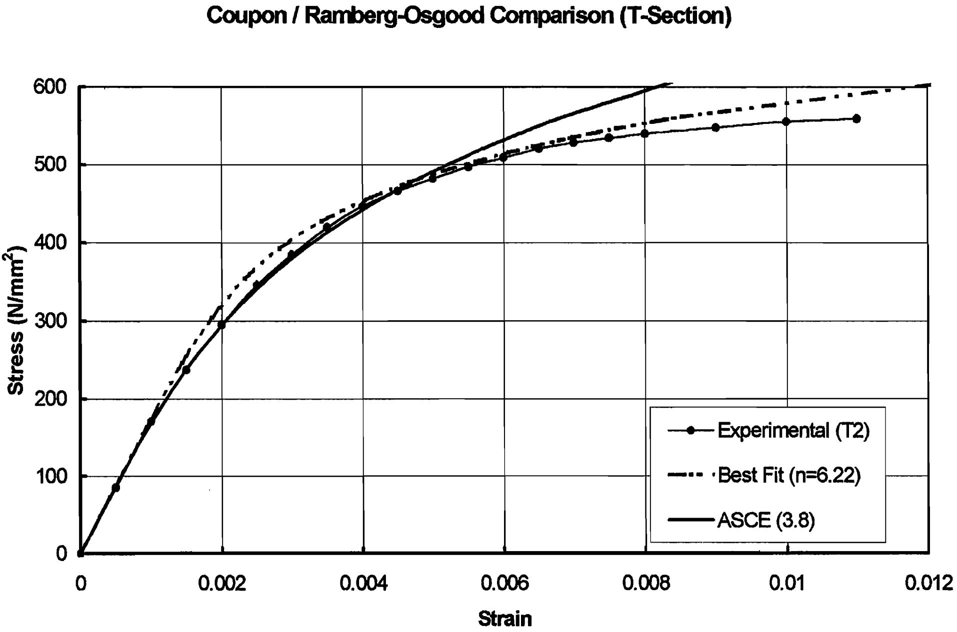

Figure 2

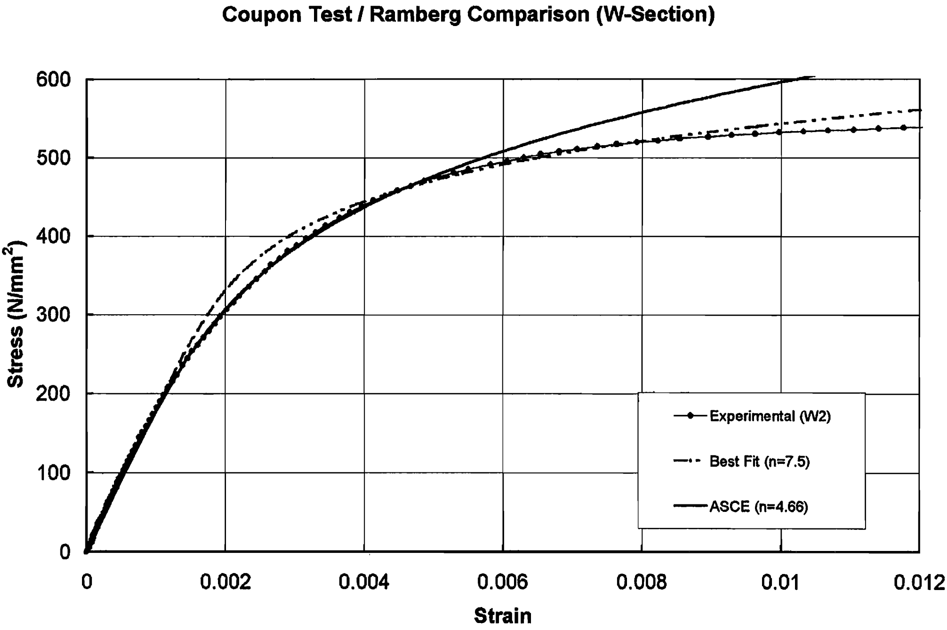

Figure 3

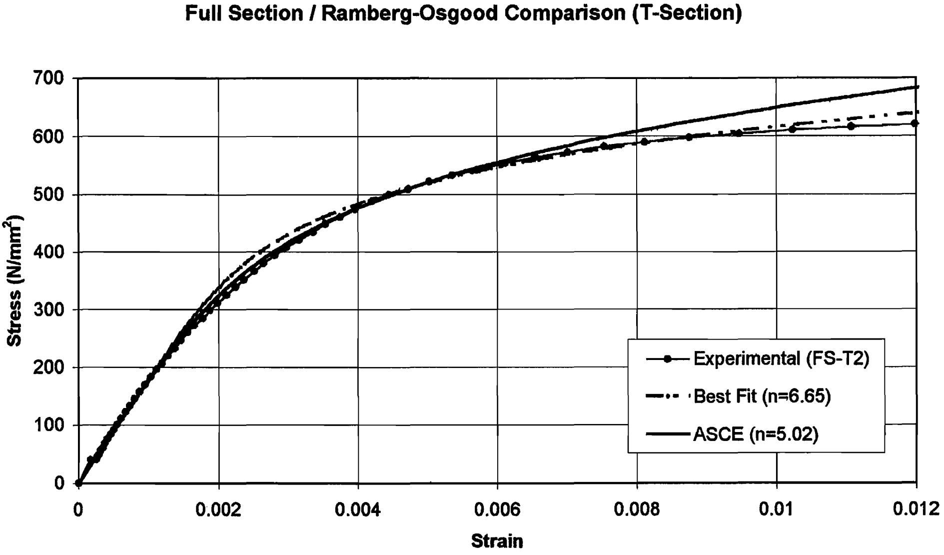

Figure 4

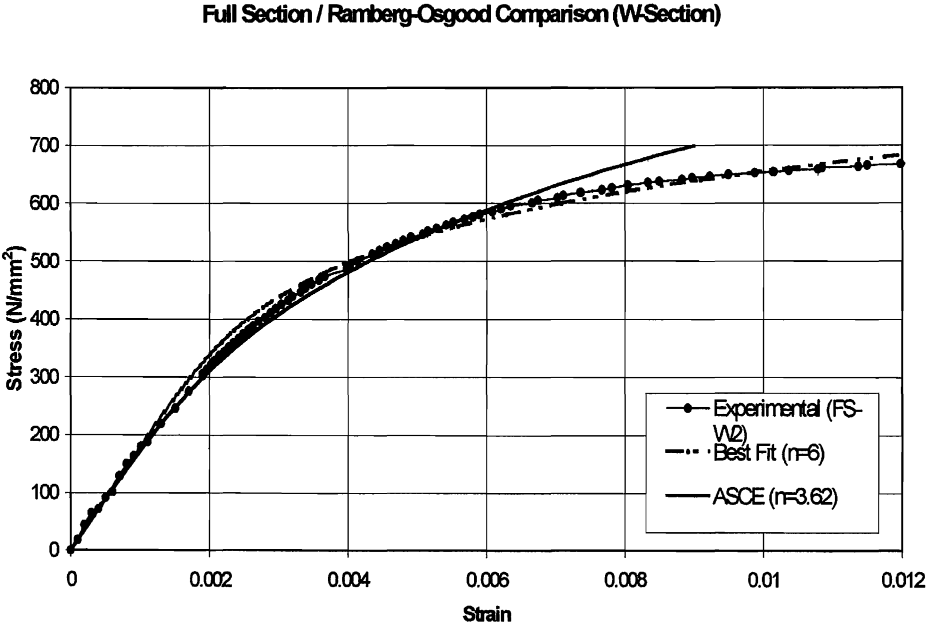

Figure 5

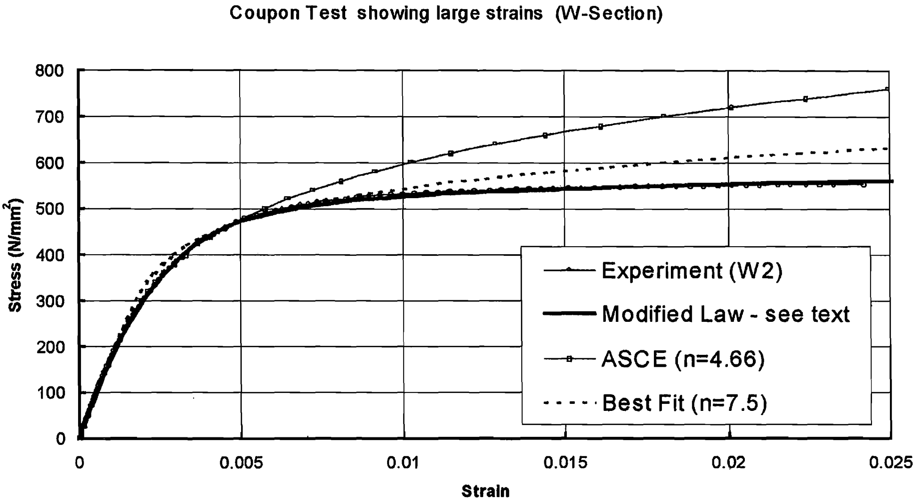

Figure 6

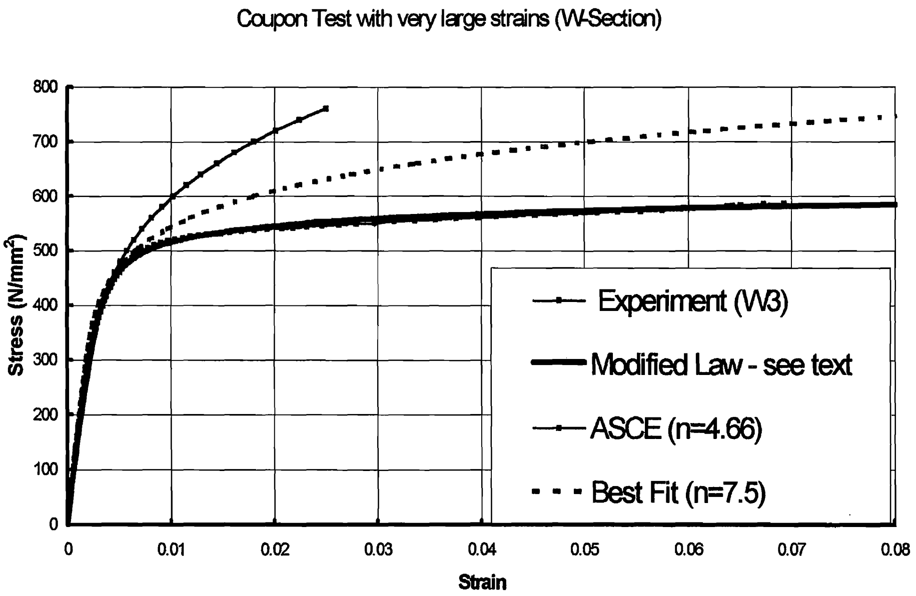

Figure 7