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Modeling of residual stresses in structural stainless steel sections

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Abstract

The influence of residual stresses on structural members is to cause premature yielding and loss of stiffness, often leading to deterioration of load carrying capacity. Knowledge of their magnitude and distribution is therefore important for both structural design and finite element simulations, and hence extensive studies have been performed on structural carbon steel components. With greater emphasis now being placed on durability and reducing consumption of resources, the use of stainless steel in construction is growing, heralding the need for a more precise understanding of its structural response. Stainless steel exhibits differing physical and thermal properties from carbon steel, both of which influence the formation of residual stresses, and it cannot simply be assumed that residual stress models for carbon steel are also appropriate for stainless steel. This paper examines all existing data on residual stresses in stainless steel sections, including that generated from a recent experimental program carried out at Imperial College London and summarized herein. The collated residual stress data have been used to develop models for predicting the magnitude and distribution of residual stresses in press braked, cold rolled, hot rolled and fabricated stainless steel structural sections.

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Introduction

Stresses that exist within a component or structural member in its unloaded state are termed residual stresses. These stresses are self-equilibrating and are typically induced in structural components through plastic deformation and differential cooling during manufacture. The general influence of residual stresses on structural members is to cause premature yielding and loss of stiffness, which can significantly deteriorate load carrying capacity.

The magnitude and distribution of residual stresses in structural sections is greatly dependant on the production process. In hot rolled sections and welded sections, residual stresses are primarily induced through uneven cooling, whilst for cold formed sections, residual stresses are induced principally through plastic deformation. Plastic deformation may occur during the coiling, uncoiling and leveling of the sheet material, during cutting operations and during forming of the section (whether press braked or cold rolled). Press braking is a section forming process where corners are formed in sheet material between a tool and a die, whereas cold rolling is a continuous process where sections are produced directly from coiled material that is uncoiled and fed through a series of shaping rollers.

For hot rolled and fabricated (welded) sections, only axial (membrane) residual stresses have been observed to be of significant magnitude. However, in the case of cold formed sections significant curvatures have been observed in sectioned material indicating the presence of through-thickness bending residual stresses, and measured strains are commonly considered as two components. The first is the membrane component, either compressive or tensile, which occurs uniformly throughout the thickness of the section. The second is the bending component which is often modeled, for thin material, as linearly varying through the thickness of the section (Weng and Peköz, 1990). Both components of residual stresses are shown diagrammatically in Fig. 1 where ε_m and σ_m indicate membrane strains and stresses, ε_b and σ_b indicate bending strains and stresses (assumed to vary linearly through the material thickness), and when considered together, the combined residual stress is denoted as σ_{rc}. However, the through thickness variation in thick welded carbon steel plates has been shown in tests to be non linear (Brozzetti et al., 1971), and similar findings have been reported following analytical modeling of the production of cold formed sections (Quach et al., 2006 and Ingvarsson, 1975). A consequence of the presence of a non linear residual stress distribution is that stresses will not be fully nullified as a result of sectioning (and the release of a linear through thickness stress distribution). It follows that if the through thickness residual stress distribution is non linear, a third component of residual stress must be present in the material post sectioning, which has no resultant axial residual stress and is in moment equilibrium. This component, described by Key and Hancock (1993), is termed the layering residual stress. Therefore, in general, although the released bending moment (upon sectioning) can be evaluated from the change in surface strains (or curvature) of a strip, the original residual stress magnitudes can only be approximated by first assuming the way in which the stresses were distributed.

Extensive research into the effect of residual stresses has been carried out for carbon steel sections. For example, the influence of residual stresses on the behavior of fabricated carbon steel sections has been discussed by Huber and Beedle (1954), Fukumoto and Itoh (1981) and Chernenko and Kennedy (1991), whilst hot rolled sections have been discussed by Nethercot

(1974), Fukumoto and Itoh (1980) and Madugula et al. (1997). A summary of the formation and influence of residual stresses in hot rolled and fabricated sections has been reported by Lay and Ward (1969). Residual stresses in both press braked and cold rolled sections have been discussed by Weng and Peköz (1990) and Schafer and Peköz (1998). Residual stresses in cold rolled sections have been investigated by Chen and Ross (1977) and Kato and Aoki (1978), and in press braked sections by Weng and White (1990). The effect of residual stresses on the behavior of structural stainless steel members has received less scrutiny, though Coetzee et al. (1990) have considered their influence on cold formed stainless steel sections and Bredenkamp and van den Berg (1992) on welded stainless steel I sections.

Literature Review

This section provides a summary of existing residual stress studies, including experimental data, analytical and numerical investigations, and proposed models for the prediction of the magnitude and distribution of residual stresses in sheet material and cold formed, fabricated and hot rolled sections. Studies incorporating residual stress measurements in structural stainless steel sections are also introduced. The collated residual stress data are used to propose models for predicting the magnitude and distribution of residual stresses in press braked, cold rolled, fabricated and hot rolled stainless steel structural sections.

Residual stresses in sheet materials

Cold formed sections, both press braked sections and cold rolled, are produced from sheet material. Sheet material can be formed either solely by hot rolling to produce hot band or by hot rolling and subsequently cold rolling to produce thinner material. The cold rolled sheet material is generally coiled for easy storage and transportation; the sheet material may be annealed before coiling. Prior to section forming, the coiled material is uncoiled and leveled.

Wang et al. (2002) employed neutron diffraction to investigate residual stresses in thin cold rolled stainless steel sheet and to determine the influence of annealing the material. Measurements revealed highly directional intergranular residual stresses after the rolling process. Annealing to 500°C was found to significantly reduce this degree of alignment.

Quach et al. (2004) carried out an analytical model study, validated against a finite element study, to predict the residual stresses induced by the coiling, uncoiling and leveling of carbon steel material; an extension to this study was carried out by Quach (2005) for stainless steel sheet material. It was assumed that annealing occurred prior to coiling and therefore there were no residual stresses present in the sheet material before this coiling began. It was found, using the von Mises yield criteria and the Prandtl-Reuss plastic flow rule, that the created through thickness variation of residual stresses is non linear and that longitudinal residual stresses up to 25% greater than the original material yield strength may result. Residual stresses greater than the yield strength of the uncoiled material can be attributed to strain hardening of the outer fibers of the material during coiling, uncoiling and leveling, resulting in enhanced material strength in these locations. In addition, longitudinal stresses greater than the uniaxial yield stress are possible with the von Mises yield criterion in the presence of simultaneous transverse stresses. Residual stresses caused by the coiling processes are dependant on the curvature of coiling, which in turn is dependant on the thickness of the material, the inner diameter of the coil and the position from which the sheet material is taken from the coil. A range of inner coil diameters (200 to 700 mm) were considered in the study and it was proposed that this range could account for the variation of residual stresses observed along the lengths of cold rolled sections and between nominally similar sections.

Residual stresses in press braked sections

Press braking is one of the simplest section forming processes, where flat sheet material is placed between a tool and die and folded along the length of the member. Due to physical limitations of the press braking machine, large curvatures in the sheet material caused by coiling and leveling must be removed prior to forming. Elastic spring back in formed material requires the section to be over bent to achieve the desired fold angle. Spring back means that some elastic recovery occurs after production, altering the residual stresses remaining in the component. Residual stress data from stainless steel press braked sections have been reported by Cruise and Gardner (in press) with corresponding material strength data in Cruise (2007). A total of eight press braked angle sections of varying thickness and varying corner radius were investigated. The results are examined herein and form the basis for the proposed residual stress models. Coetzee et al. (1990) investigated the influence of residual stresses on the structural behavior of stainless steel press braked lipped channel sections.

The remainder of this sub-section presents experimental data and predictive residual stress models for press braked carbon steel sections. An experimental and analytical study of press braked sections was carried out by Ingvarsson (1975), where the experimental results revealed high corner bending residual stresses of approximately $0.5\sigma_y$ (determined on the assumption of a linearly varying through thickness stress distribution). The existence of non linear, through thickness, longitudinal residual stresses in both press braked and cold rolled carbon steel sections was attributed to the transverse strains associated with the corner forming process in conjunction with the Poisson effect. Weng and Peköz (1990) observed combined bending and membrane residual stresses in press braked sections in the range of 0.25-0.70σ_y (where σ_y is the material yield strength), of which the bending residual stresses represented a considerable proportion. Relatively uniform combined residual stresses were reported along the section faces, with increased values in the corner regions. The membrane residual stresses in the corner regions were reported to be low, showing that the increase in residual stresses in the corners was primarily due to an increase in bending residual stresses, related to the high localized plastic deformation. Based on a number of experimental studies of residual stresses in press braked carbon steel sections, Schafer and Peköz (1998) proposed the predictive model of Fig. 2. The model contained only bending residual stresses since the membrane residual stresses were found to be of low magnitude (generally less than $0.06\sigma_y$).

Quach et al. (2006) used finite element modeling to superimpose the residual stresses caused by cold forming of structural sections onto those obtained by modeling the coiling, uncoiling and levelling of the sheet material previously presented by Quach et al. (2004). The results were validated against an experimental study carried out by Weng and White (1990). The findings were similar to those of Ingvarsson (1975), predicting non linear through thickness residual stress distributions. Residual stresses obtained in the corner regions of the sections were found to be greater than the uniaxial yield strength of the material.

Residual stresses in cold rolled sections

Cold rolled hollow sections represent the most widely used structural stainless steel product. Their forming process initiates with uncoiling and leveling of the sheet material followed by cold rolling through a series of shaped rollers to produce square, rectangular and circular sections (SHS, RHS and CHS). The most common section forming route for SHS and RHS involves firstly forming into a circular tube, followed by seam welding and finally reforming into a box section.

Residual stress measurements in cold rolled stainless steel box sections (SHS and RHS) have been reported by the Centre for Advanced Structural Engineering (1990), Clarin (2003), Young and Lui (2005) and Cruise and Gardner (in press). The Centre for Advanced Structural Engineering (1990) took residual stress measurements of two grade 304 stainless steel hollow sections – one CHS and one SHS. As for the press braked sections, the membrane residual stress in the cold rolled CHS and SHS were found to be negligible compared to the bending stresses, and both residual stress components were higher in the SHS than in the CHS. Similarly large bending residual stresses were reported in a high strength stainless steel cold rolled box section by Young and Lui (2005). Clarin (2003) presented residual stress measurements from a cold formed stainless steel RHS produced from cold worked sheet material (grade 301 LN). These experimental results again revealed the presence of large bending residual stresses (0.3-0.9$\sigma_{0.2}$), and lower membrane residual stresses (less than 0.25$\sigma_{0.2}$).

The remainder of this sub-section reviews previous residual stress studies on cold rolled carbon steel sections. Schafer and Peköz (1998) proposed a model (Fig. 3) for the prediction of bending residual stresses in cold rolled carbon steel channel sections. Higher bending residual stresses were proposed for the web than for the flanges, supported by the experimental data of Weng and Peköz (1990). Membrane residual stresses were reported to be less than 0.08σ_y, with the highest values in the corner regions of the sections (Schafer and Peköz, 1998). Based on the results of Weng and Peköz (1990) and their own experimental data from two sizes of cold rolled lipped channels, Abdel-Rahman and Sivakumaran (1997) proposed that the bending residual stresses in all flat regions could be modeled as 0.18σ_y (despite an observed variation with face width) and those of the corner regions could be approximated as 0.40σ_y.

Residual stresses in fabricated sections

Fabricated sections are built up by the welding together of plate material. Typically, only membrane residual stresses are considered in welded sections, since the bending residual stresses are generally negligible. It may be observed from existing measurements that membrane residual stresses measured in welded I sections are significantly larger than those in cold formed sections. The membrane residual stresses depend upon the manner in which the plate material is cut and the welding techniques employed. Cutting options include flame, laser or saw cutting. Saw cutting may induce work hardening, whilst the flame and laser cutting can cause differential heating and cooling, leaving plate edges in residual tension. The welding process itself causes temperature gradients around the heat affected zone (HAZ) with hotter material at the weld being left in residual tension, whilst the slower cooling surrounding material is left in residual compression, as detailed by Lay and Ward (1969).

Stainless steel possesses different physical and thermal properties to carbon steel, both of which influence the formation of residual stresses. The stress-strain behavior of stainless steel is fundamentally different from that of carbon steel, being of a rounded nature with no sharply defined yield point (Gardner, 2005). Austenitic stainless steel has a coefficient of thermal expansion of approximately 17×10^{-6}/ ºC compared to 12×10^{-6}/ ºC for carbon steel, and a room temperature thermal conductivity of 16.2 W/m ºC compared to 52 W/m ºC for carbon steel. The lower thermal conductivity tends to lead to higher thermal gradients in stainless steel, whilst the higher thermal expansion results in greater thermal stress and distortions. There have been two studies on fabricated stainless steel I beams (Lagerqvist and Olsson, 2001; Bredenkamp et al., 1992), though no predictive models have been proposed. Lagerqvist and Olsson (2001) examined residual stresses in austenitic (grade 304) and duplex (austenitic-ferritic) stainless steel welded I sections, whilst Bredenkamp et al. (1992) sectioned four I beams fabricated from guillotined plates of ferritic stainless steel. The residual stress patterns for the ferritic sections were found to be similar to those shown in Fig. 4(a) for carbon steel – this would be expected since ferritic stainless steels possess physical and thermal properties that are more comparable to those of carbon steel. The magnitude of the residual stresses was observed to increase with the thickness of material; this is attributed to the greater heat input required to form welds in thick material.

Experience gained from residual stress studies of welded carbon steel sections are summarized below. Membrane residual stress models for both mill cut and flame cut fabricated carbon steel I sections were reviewed in detail by Chernenko and Kennedy (1991) and indicative distributions of those discussed are shown in Fig. 4(a) and 4(b). Fig. 5 shows the weld induced residual stress model proposed in the Swedish design code BSK 99 (1999). In this model, t_f and t_w are the thicknesses of the flanges and web respectively, and the magnitude of the compressive stress σ_c is defined to achieve equilibrium in the section. Fukumoto and Itoh (1981) compared residual stresses in fabricated and hot rolled carbon steel I beams and observed that there was more variation in the residual stresses measured in welded sections than in hot rolled I sections. The membrane residual stress magnitudes in the weld region were close to the yield strength of the material, whilst the compressive residual stresses in the web were approximately 0.4-0.6σ_y; lower residual stresses were observed in the flanges. Dwight and Moxham (1969) and Masubuchi (1980) have also proposed predictive models for weld induced residual stresses in carbon steel sections. Dwight and Moxham (1969) proposed that the membrane residual stresses in the weld and heat affected zone (HAZ) can be considered to be equal to the yield strength of the material, where the width ηt of the HAZ either side of the weld could be approximated from Eq. (1).

$$\eta t = \frac{CA}{\sigma_y \sum t} \qquad (1)$$

in which t is the material thickness, Σt is the sum of the thicknesses of material to be welded, A is the cross sectional area of the added weld material and C is a constant defined by experimental data.

Masubuchi (1980) proposed that membrane residual stresses can be modeled as a function of distance y from the weld, as given by Eq. (2).

$$\sigma_x(y) = \sigma_{max}\left(1 - \left(\frac{y}{p}\right)^2\right) e^{-\frac{1}{2}\left(\frac{y}{p}\right)^2} \qquad (2)$$

where σ_{max} is the maximum tensile residual stress measured at the weld, which is commonly taken as the yield strength of the material, y is the distance from the weld and p is the width of the tension zone created by the weld.

Residual stresses in hot rolled sections

Hot rolled structural stainless steel sections are relatively uncommon. However, such sections have been introduced in South Africa, as described by Laubscher and van der Merwe (2003). As for fabricated sections, bending residual stresses in hot-rolled sections are generally low, so typically only membrane residual stresses are examined. Residual stresses in hot rolled sections are attributed to differential cooling due to variation in thickness around the sections, as well as any straightening process that might be employed once the section has cooled. The formation of residual stresses in hot rolled sections has been described in detail by Lay and

Ward (1969). Residual stress data for three hot rolled stainless steel angle sections have been presented by Cruise and Gardner (in press), where both membrane and bending residual stresses were of low magnitude, generally less than $0.2\sigma_{0.2}$.

Residual stresses in hot rolled carbon steel I sections have been examined by Chernenko and Kennedy (1991), and as summarized by Nethercot (1974), a number of other researchers. These studies have resulted in the proposal of predictive models, which vary in complexity and differ in their predictions for the magnitude and distribution of residual stresses. Madugula et al. (1997) carried out residual stress measurements on 42 hot rolled carbon steel angles, but the results showed considerable variation and as a result no predictive models were proposed. Variations in residual stresses in hot rolled sections are generally attributed to differences in the hot rolling and straightening processes.

Summary of experimental study

An experimental study to quantify the residual stresses in austenitic grade 1.4301 stainless steel sections from three different production routes has been carried out. The testing program, described fully by Cruise and Gardner (in press), employed the sectioning technique to map the residual stress distributions in three hot rolled angles, eight press braked angles and seven cold rolled box sections, with a total of over 900 residual strain readings taken. Tensile coupon tests were performed on each of the released strips to provide material stress-strain data, against which the residual stress magnitudes could be compared (Cruise, 2007).

In 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 revealed 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 typically ranged between about 30% and 70% of the material 0.2% proof stress.

Proposed predictive models

Introduction

The experimental data obtained by sectioning from the current experimental program, described in detail by Cruise and Gardner (in press), have been combined with existing data to propose or modify membrane and bending residual stress models for four different types of stainless steel sections - press braked, cold rolled, hot rolled and fabricated. Throughout this section of the paper, the bending σ_b and membrane σ_m residual stresses released from the sectioned material have been normalized by the material strength (taken as the 0.2% proof stress $\sigma_{0.2}$ obtained by performing tensile coupon tests on the corresponding sectioned material) and the position x in the section face has been normalized by the width of the section face b. To identify the specimens, the following reference system has been adopted: PB for press braked, CR for cold rolled, HR for hot rolled and F for fabricated followed by the two cross section dimensions and the thickness t, and finally the internal corner radii r_i, if specified, in brackets. For fabricated sections the thicknesses of both the web and flange are indicated sequentially.

For the evaluation of bending residual stresses magnitudes on the basis of surface strain measurements, a through thickness stress distribution must be assumed. In the present study, as discussed in more detail by Cruise and Gardner (in press), two possible initial stress distributions were considered – linearly varying through the thickness, as commonly assumed for cold formed carbon steel sections (Weng and Peköz, 1990; Schafer and Peköz, 1998), and a rectangular stress block distribution, which is more representative of the distributions obtained experimentally (in thick plates) by (Weng and White, 1990), and analytically and numerically in cold formed sections by Ingvarsson (1975) and Quach et al., (2006). Clearly, however, the actual stress distribution will deviate from both of these idealisations and will vary from section to section. 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. In this study, bending residual stresses in the hot rolled sections were calculated on the basis of a linearly varying through thickness distribution. For cold formed sections however (both press braked and cold rolled), bending residual stresses were calculated on the assumption of rectangular stress blocks, a distribution associated with the large plastic bending deformations that occur during the production process.

Press braked angles

All available residual stress data for stainless steel press braked sections (Cruise and Gardner, in press) have been analyzed. The normalized bending and membrane residual stresses obtained are shown in Figs 6 and 7. The eight angles tested were of dimensions 50 mm by 50 mm and of varying corner radii and thickness. Based on the 200 readings that were taken, the overall mean residual stress values for the flat faces and corners, together with the mean ± 1.64 standard deviations (representing the 95th percentile values based on a normal distribution, referred to herein as characteristic values) are indicated in Figs 6 and 7. Table 1 summarizes the numerical values of the normalized membrane and bending residual stresses from each individual tested press braked section, separating the residual stress values taken from the flat faces of press braked sections and those taken from the corners of the sections.

Both membrane and bending residual stresses may be seen to be low compared to the material 0.2% proof strength. The results of Table 1 also show that the sum of the mean normalized membrane residual stresses of the flat and corner regions is approximately zero, suggesting that the requirement for longitudinal equilibrium is approximately met (given that the individual strips are each of similar area and similar 0.2% proof stresses). Since no clear pattern of membrane residual stresses emerges from Fig. 6, it is proposed firstly to determine representative values of the stresses – chosen as the mean and 95th percentile (characteristic value) of their absolute values – and secondly to apply them in a suitably detrimental (self-equilibrating) distribution. Both mean and characteristic (95th percentile) values of residual stresses are presented to allow choice of which to implement depending on the type and purpose of the analysis being performed.

Mean values of the absolute membrane residual stresses were found to be 0.06$\sigma_{0.2}$ for the flat faces and 0.03$\sigma_{0.2}$ for the corner regions, while characteristic values were determined as 0.14 $\sigma_{0.2}$ for the flat faces and 0.11$\sigma_{0.2}$ for the corners. The most detrimental pattern of membrane residual stresses will depend upon the type of loading and the proportions of the structural member. However, in general, an appropriately severe self-equilibrating distribution would comprise compression towards the tips of outstand flanges (unstiffened elements) and central portions of internal parts (stiffened elements) and tension over the remainder of the section.

The normalized bending stresses in the flat faces are also low, and exhibit no clear pattern. The mean and characteristic values of the absolute bending residual stresses for the flat faces were obtained as 0.06$\sigma_{0.2}$ and 0.15$\sigma_{0.2}$, respectively. Since no clear pattern emerges from the measurements, the bending residual stresses may be applied as either tension or compression at the outer surface, the choice of which would be expected to have little influence on the structural response. In the corner regions of the press braked angle sections, where highly localized plastic deformation is known to occur during the forming process, higher bending residual stresses of consistent sign (i.e. tension at the outer surface of the sections, as shown in Fig. 7), were found. The mean and characteristic bending residual stresses in the corner regions were found to be 0.24$\sigma_{0.2}$ and 0.36$\sigma_{0.2}$, respectively. Owing to the consistent sign of the bending residual stresses in the corner regions, it is proposed that these are modeled as tension at the outer surface.

Fig. 8 shows how the magnitudes of the bending residual stresses in the press braked sections varies with the material 0.2% proof strength. The graph generally shows higher bending residual stresses with increasing material strength, indicating that their presence is linked with plastic deformation and cold work. The recommendations for bending residual stresses in the corner regions are similar in magnitude to those made by Schafer and Peköz (1998) for press braked carbon steel lipped channels. Based on characteristic values and assuming a through thickness rectangular stress block distribution, the proposed bending residual stress pattern for press braked sections is shown in Fig. 9.

Cold rolled boxes

All available experimental residual stress data from cold rolled stainless steel box sections (the Centre for Advanced Structural Engineering, 1990; Clarin, 2003; Young and Lui, 2005; Cruise and Gardner, in press) have been collated, and are shown in Figs. 10 and 11 and separate mean values are identified in Table 2 for the flat faces and corner regions of the sections.

Similar to the press braked sections, no particular distribution of membrane residual stresses emerges from Fig. 10 and the mean of the data sets is again close to zero. Hence, mean and characteristic values of the absolute normalized membrane residual stresses have been obtained as representative magnitudes. Mean values of the absolute membrane residual stresses were found to be $0.13\sigma_{0.2}$ for the flat faces and $0.12\sigma_{0.2}$ for the corner regions, while characteristic values were determined as $0.37\sigma_{0.2}$ for the flat faces and $0.24\sigma_{0.2}$ for the corners.

The normalized bending residual stresses in the cold rolled box sections show a consistent tendency of tension at the outer surface of the section. The mean of the normalized bending residual stresses is very high in the flat regions of the section ($0.47\sigma_{0.2}$) and generally lower in the corner regions ($0.26\sigma_{0.2}$), though the material strength in the corner region is higher. Characteristic values for the flat and corner regions were found to be $0.63\sigma_{0.2}$ and $0.37\sigma_{0.2}$ respectively. A similar pattern was observed by Schafer and Peköz (1998) where the bending residual stresses in the webs of cold rolled carbon steel channels were greater than those in the corners, though Abdel-Rahman and Sivakumaran (1997) reported the reverse. The magnitudes for bending residual stresses in the corner regions are slightly higher than those predicted for carbon steel sections by Schafer and Peköz (1998) and Abdel-Rahman and Sivakumaran (1997).

Fig. 12 shows how the bending residual stresses in the cold rolled sections vary with the material 0.2% proof strength. The graph shows a strong trend, more so than for the press braked sections (Fig. 8), with bending residual stresses increasing with material strength where the higher material strength is associated with greater plastic deformation. This finding was predicted analytically by Ingvarsson (1979) for carbon steel sections.

A simple model for bending residual stresses based on characteristic values (mean + 1.64 standard deviations) and assuming a rectangular stress block distribution is given in Fig. 13. Since no clear pattern of membrane residual stresses emerges from the test data for cold rolled box sections, it is proposed, as for press-braked sections, to apply the determined magnitudes (mean or characteristic) in a suitably severe self-equilibrating distribution, as recommended for press braked sections.

Hot rolled sections

The majority of residual stress models developed for hot rolled sections have been for I sections. However, no data for hot rolled stainless steel I sections are available, and data only exists for hot rolled stainless steel angles (Cruise and Gardner, in press). The residual stress patterns for the webs and flanges of I sections tend to describe a region close to the web-to-flange junction in high residual tension, with the remainder of the section in residual compression. This pattern exists due to the differential cooling around the section following hot rolling arising from the variation in thickness (or surface area to volume ratio). The cooling rate at the web-to-flange junction is slower than surrounding regions due to its higher surface area to volume ratio.

The residual stress data for three stainless steel hot rolled angles (Cruise and Gardner, in press) are plotted in Figs 14 and 15 and tabulated in Table 3. Both the membrane and bending residual stresses may be seen to be of relatively low magnitude.

The membrane residual stress values from the flat regions of the hot rolled stainless steel angle sections are of comparable magnitude and similar scatter to those presented for carbon steel sections by Madugula et al. (1997). Given the variation of patterns observed between sections, a simple model for bending residual stresses assuming a linear through thickness variation based on either mean on characteristic values of the absolute measured stresses is proposed. The mean bending residual stresses in the flat and corner regions were found to be $0.11\sigma_{0.2}$ and $0.29\sigma_{0.2}$, respectively, while the characteristic values (shown in Fig. 16) were determined $0.21\sigma_{0.2}$ and $0.45\sigma_{0.2}$ for the flats and corners. Since the data do not indicate a consistent sign for these stresses, as was observed for cold rolled sections with tension at the outer surface, the bending residual stresses in hot rolled sections can be modeled with either a tensile or compressive stresses on the outer surface of the section (with minimal anticipated differences in results). As for press braked and cold rolled sections, the membrane residual stresses in the investigated hot rolled sections show no consistent trend (see Fig. 14). Again, the mean and characteristic values of the absolute membrane residual stresses have been obtained – mean values for the flat regions and the corners were $0.05\sigma_{0.2}$ and $0.07\sigma_{0.2}$, respectively and characteristic values for the same locations were $0.12\sigma_{0.2}$ and $0.13\sigma_{0.2}$ respectively. It is proposed that these be distributed as outlined for press braked sections to achieve a suitably detrimental response – for angle sections, this would generally be compression at the flange tips (and self-equilibrating tension elsewhere), which would in fact be the expected distribution in these sections since the flange tips represent the most rapidly cooling regions.

Fabricated sections

Residual stress data for fabricated stainless steel I sections have been reported by Lagerqvist and Olsson (2001) and Bredenkamp et al. (1992). In the case of Bredenkamp et al. (1992) numerical data has been extracted from published graphs for four ferritic (grade 409) I sections: F 140×70×4.5×3.5, F 300×160×10×6, F 250×140×8×6 and F 180×90×6×4.5. Lagerqvist and Olsson (2001) analyzed two I sections - F 120×300×12×4.01 (austenitic grade 304) and F 50×50×13×3.99 (austenitic-ferritic grade S32205). The residual stress data are shown in Table 4.

The membrane residual stresses shown in Figs 17, 18, 21 and 22 exhibit the anticipated pattern of tensile residual stresses in the weld region, and equilibrating compressive residual stresses, of lower magnitude, in the other parts of the section. Bending residual stresses (calculated assuming a linear through thickness distribution) may also be observed in Figs 19 and 20. The distributions suggest that the asymmetry at the web-to-flange joint (the weld being on one side of the flange only) has created a tensile residual stress on the internal face of the flange and an opposing compressive stress on inner face for the surrounding material. This phenomenon has been observed and discussed in detail by Weisman (1976).

Comparing the membrane residual stresses in Figs 17, 18, 21 and 22 with the BSK 99 (1999) model (which varies between sections due to its dependence on the material and geometric properties), generally shows reasonable agreement. However, it may be observed that the tensile residual stresses in the web of the austenitic section are of larger magnitude than the model and have a larger region of influence for both the austenitic and austenitic-ferritic sections. This may be attributed to the higher thermal expansion of the material. For the ferritic sections, the tensile peaks in the weld regions may be seen to be significantly lower than the material yield strength.

For austenitic and austenitic-ferritic stainless steel sections it is proposed to modify the model given in the Swedish design code BSK 99 (1999) by increasing the magnitude of the tensile regions to $1.3\sigma_{0.2}$ and increasing the regions of tension in the web to $3t_w$ as shown in Fig. 23. For ferritic sections, given the similarity in micro-structure with carbon steel and the acceptable agreement with the BSK 99 model shown in Fig 5, it is proposed to adopt the existing model.

Conclusions

Stainless steel exhibits differing physical and thermal properties from carbon steel, both of which influence the formation of residual stresses, and it cannot simply be assumed that residual stress models for carbon steel are also appropriate for stainless steel. This paper examines all existing data on residual stresses in stainless steel sections, including that generated from a recent experimental program carried out at Imperial College London and summarized herein. The collated residual stress data have been used to develop models for predicting the magnitude and distribution of residual stresses in press braked, cold rolled, hot rolled and fabricated stainless steel structural sections.

The two types of cold formed sections (press braked and cold rolled) generally show low membrane residual stresses, but high bending residual stresses. These bending residual stresses are principally associated with the plastic deformation that occurs in section production, which also causes significant cold working. Based on characteristic values of residual stress magnitudes (mean + 1.64 standard deviations) observed in press braked stainless steel angles, it is proposed that membrane residual stress magnitudes may be taken as $0.14\sigma_{0.2}$ in the flat regions and $0.11\sigma_{0.2}$ in the corner regions and bending residual stresses may be taken $0.15\sigma_{0.2}$ in the flat regions and $0.36\sigma_{0.2}$ in the corner regions, based on a rectangular stress block distribution. For cold rolled sections, residual stresses were found to be greater. Again based on characteristic values, the magnitude of membrane residual stresses can be taken as $0.37\sigma_{0.2}$ in the flat region and $0.24\sigma_{0.2}$ in the corner regions. Bending residual stresses may be taken as $0.63\sigma_{0.2}$ in the flat regions and $0.37\sigma_{0.2}$ in the corner regions, based on a characteristic rectangular stress block distribution.

For the stainless steel hot rolled angles, both the membrane and bending residual stresses were of relatively low magnitude. The membrane residual stress values from the flat regions of the stainless steel angle sections were found to be of comparable magnitude and similar scatter to existing carbon steel data. Simple predictive models for the hot rolled sections were proposed, but the limited data set and relatively high scatter dictates a degree of uncertainty. For the fabricated stainless steel sections, residual stress results from the ferritic sections were similar to those predicted by BSK 99 model for carbon steel; this would be anticipated due to the similar micro-structure, and it was proposed simply to adopt the existing model unchanged. Fabricated austenitic and austenitic-ferritic sections showed higher thermally induced residual stresses in the weld regions, as well as larger areas of influence than in residual stress models developed for carbon steel; this is principally due to the higher rate of thermal expansion and has been reflected by appropriate modification to the existing BSK 99 model.

The proposed residual stresses patterns (based on either mean or characteristic values) may be incorporated in structural models (such as finite element models) to allow for their influence on structural response. Although of lower magnitude, the membrane residual stresses would be expected to have a stronger effect on the structural response than the bending residual stresses. In fact, the influence of bending residual stresses will be inherently present in the stress-strain behaviour of material extracted from structural sections (provided coupons were not straightened by plastic bending prior to testing) and would therefore not generally have to be explicitly re-introduced into numerical models.

Acknowledgements

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Notation

The following symbols are used in this paper:

A = Cross sectional area of weld material;

b = The face width of sections;

C = Constant defined by experimental data for defining the width of the heat affected zone;

p = Width of the tension zone in weld;

r_i = Internal radius of section corners;

t = Thickness of sections;

t_f = Thickness of flange for fabricated sections;

t_w = Thickness of web for fabricated sections;

x = Position in section face;

y = Distance from the weld;

ε_b = Bending residual strain;

ε_m = Membrane residual strain;

ηt = Width of HAZ either side of weld;

Σt = Sum of the thickness of material welded;

σ_b = Bending residual stress;

σ_c = Compressive stress for fabricated I sections;

σ_m = Membrane residual stress;

σ_{max} = Maximum tensile membrane residual stress measured at the weld;

σ_{rc} = Combined bending and membrane residual stress;

σ_x = Membrane residual stress in the weld region at location y;

σ_y = Material yield stress for carbon steel;

$\sigma_{0.2}$ = Stress at 0.2% plastic strain. Taken as the equivalent yield stress for stainless steel;

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

Fig. 2. Predictive model for bending residual stresses in press braked carbon steel sections proposed by Schafer and Peköz (1998)

Fig. 3. Predictive model for bending residual stresses in cold rolled carbon steel sections proposed by Schafer and Peköz (1998)

Fig. 4. Two indicative residual stress distributions for welded I sections (Chernenko and Kennedy, 1991)

Fig. 5. Model of membrane stresses in a welded carbon steel I sections presented in the Swedish design rules BSK 99 (1999)

Fig. 6. Normalised membrane residual stresses in press braked angles

Fig. 7. Normalised bending residual stresses in press braked angles (assuming a rectangular block through thickness distribution)

Fig. 8. The magnitude of bending residual stresses at the outer surface of the section against material strength in press braked angles

Fig. 9. Proposed bending residual stresses model for press braked sections (assuming a rectangular block through thickness distribution)

Fig. 10. Normalised membrane residual stresses in cold rolled boxes

Fig. 11. Normalised bending residual stresses in cold rolled boxes (assuming a rectangular block through thickness distribution)

Fig. 12. Bending residual stresses at the outer surface of the section plotted against material strength for cold rolled boxes

Fig. 13. Proposed bending residual stress model for cold rolled boxes (assuming a rectangular block through thickness distribution)

Fig. 14. Normalised membrane residual stresses in hot rolled angles

Fig. 15. Normalised bending residual stresses in hot rolled angles (assuming a linear through thickness variation)

Fig. 16. Proposed bending residual stresses model for hot rolled angles (assuming a linear through thickness variation)

Fig. 17. Normalised membrane residual stresses in the flanges of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (Positive values indicate tensile membrane residual stresses)

Fig. 18. Normalised membrane residual stresses in the webs of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (Positive values indicate tensile membrane residual stresses)

Fig. 19. Normalised bending residual stresses in the flanges of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (assuming a linear variation through thickness)

Fig. 20. Normalised bending residual stresses in the webs of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (assuming a linear variation through thickness)

Fig. 21. Normalised membrane residual stresses in the flanges of ferritic fabricated sections tested by Bredenkamp et al. (1992), (Positive values indicate tensile membrane residual stresses)

Fig. 22. Normalised membrane residual stresses in the webs in ferritic fabricated sections tested by Bredenkamp et al. (1992) (Positive values indicates tensile membrane residual stresses)

Fig. 23. Proposed membrane residual stress model for austenitic and austenitic-ferritic stainless steel fabricated I sections (Positive values indicates tensile membrane residual stresses)

Table 1. Weighted mean normalised membrane and bending residual stresses in press braked angles

Table 2. Weighted mean normalised membrane and bending residual stresses in cold rolled boxes

Table 3. Weighted mean normalised membrane and bending residual stresses in hot rolled angles

Table 4. Weighted mean normalised membrane and bending residual stresses in fabricated I sections

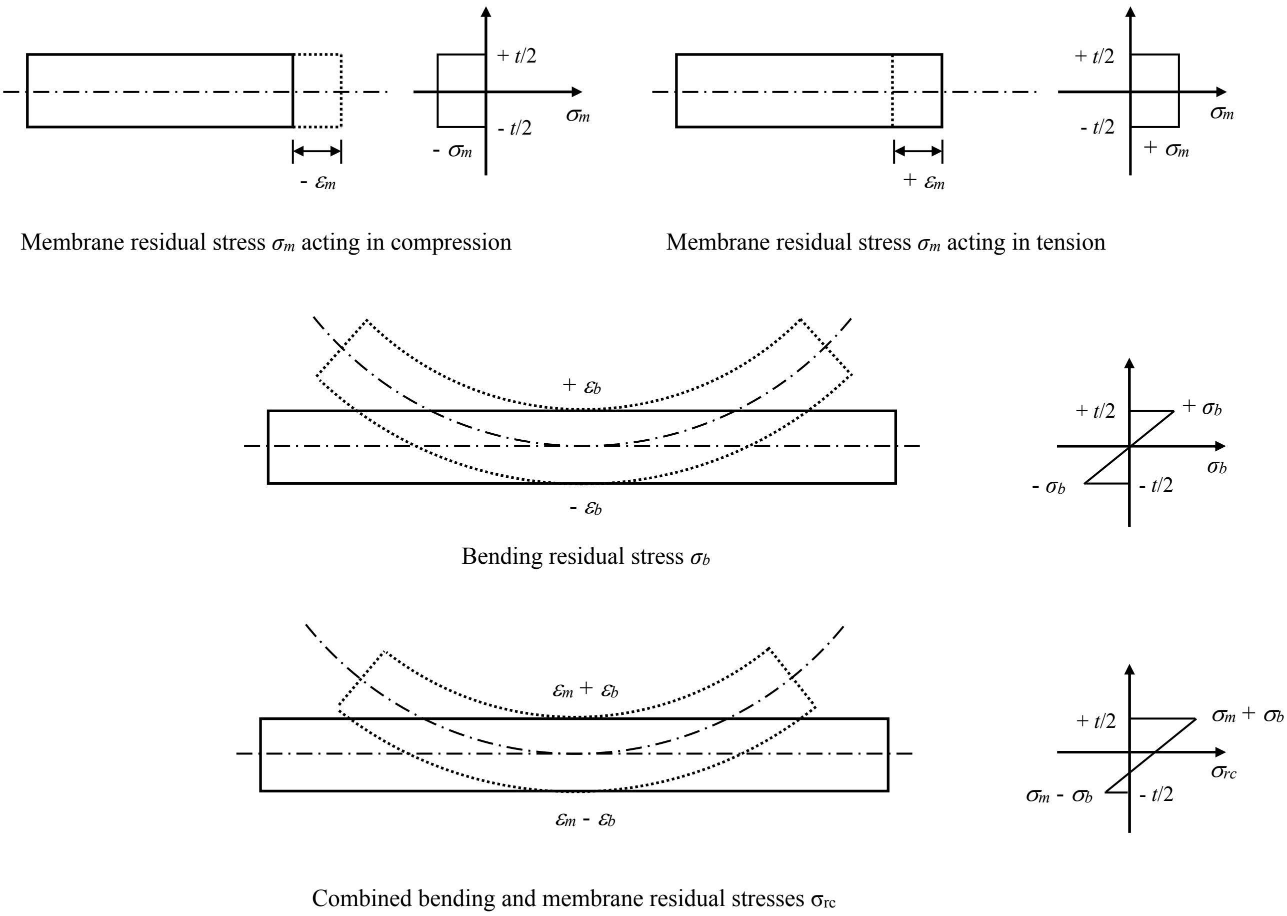


Fig. 1. Modelling of residual stresses with a membrane and bending stress component

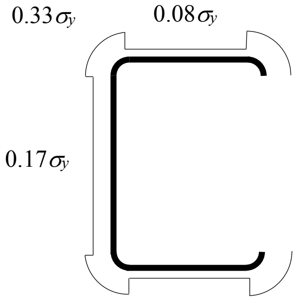


Fig. 2. Predictive model for bending residual stresses in press braked carbon steel sections proposed by Schafer and Peköz (1998)

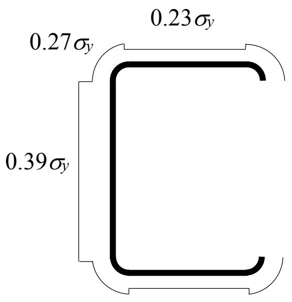
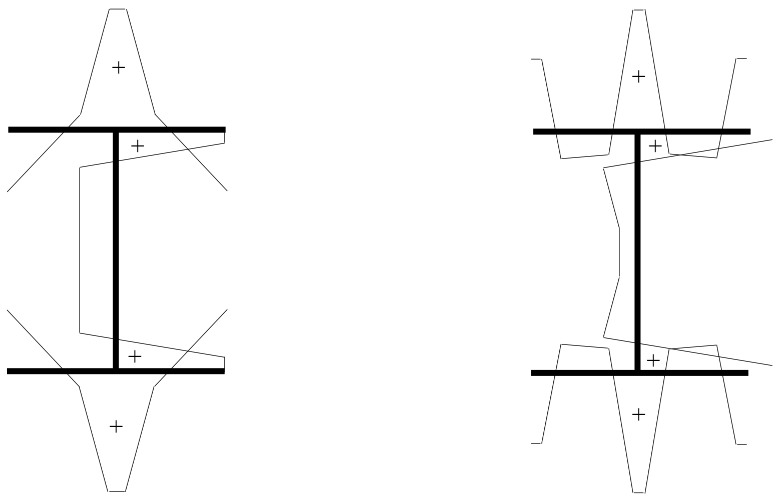


Fig. 3. Predictive model for bending residual stresses in cold rolled carbon steel sections proposed by Schafer and Peköz (1998)



(a) Welded and mill cut plates (b) Welded and oxygen cut plates

Fig. 4. Two indicative residual stress distributions for welded I sections (Chernenko and Kennedy, 1991)

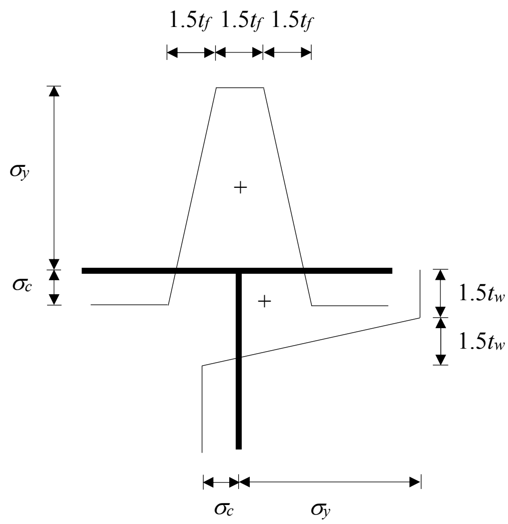


Fig. 5. Model of membrane stresses in a welded carbon steel I sections presented in the Swedish design rules BSK 99 (1999)

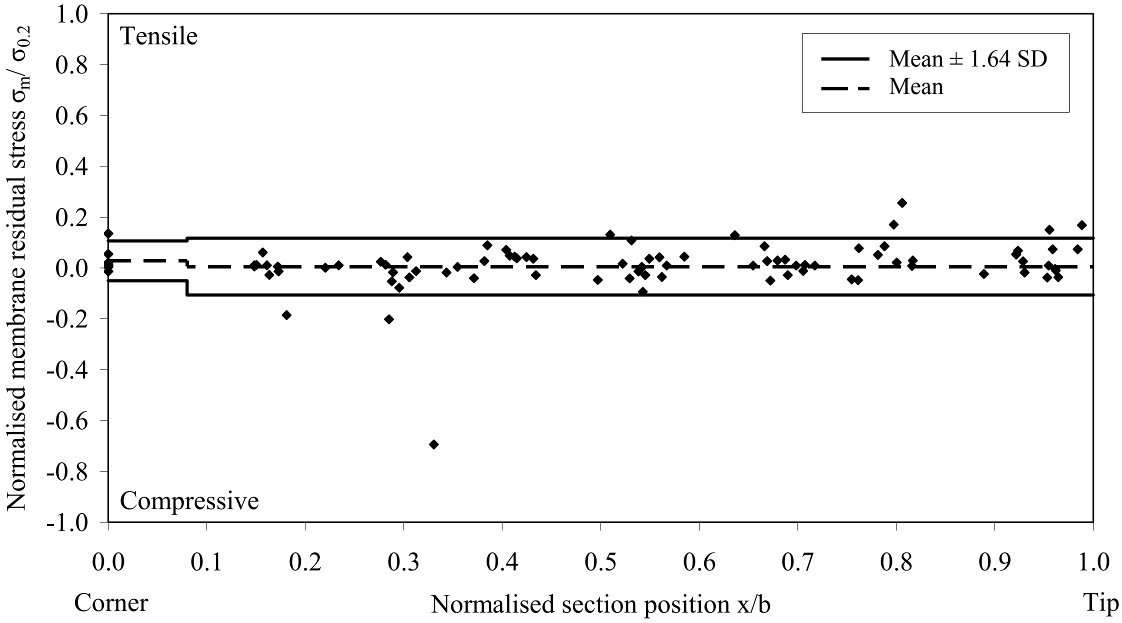


Fig. 6. Normalised membrane residual stresses in press braked angles

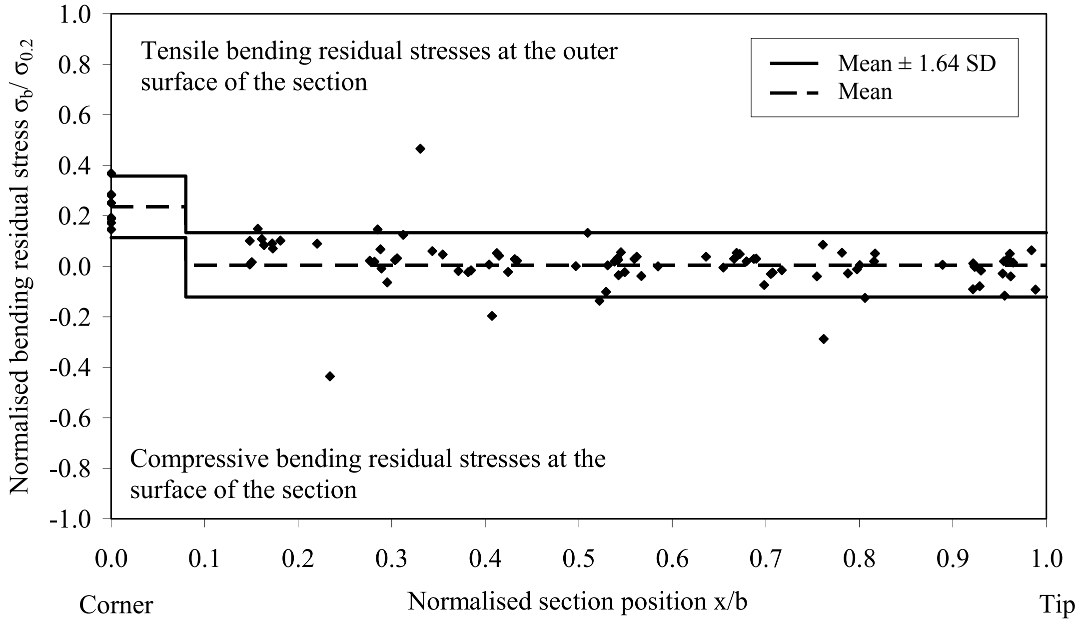


Fig. 7. Normalised bending residual stresses in press braked angles (assuming a rectangular block through thickness distribution)

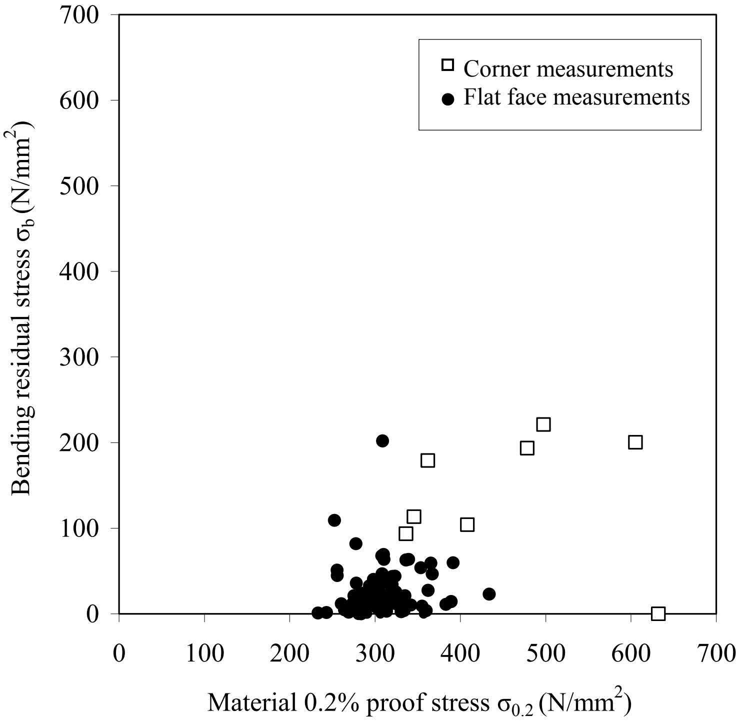


Fig. 8. The magnitude of bending residual stresses at the outer surface of the section against material strength in press braked angles

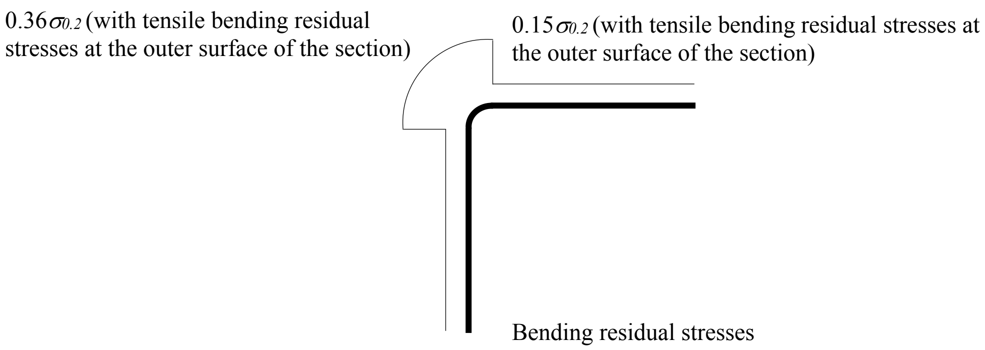


Fig. 9. Proposed bending residual stresses model for press braked sections (assuming a rectangular block through thickness distribution)

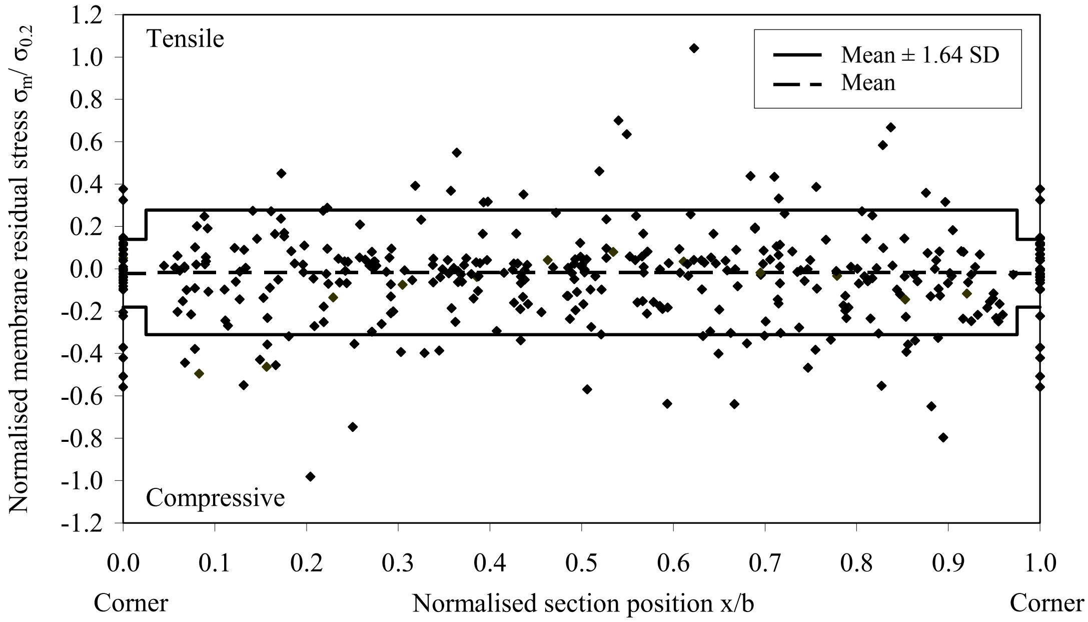


Fig. 10. Normalised membrane residual stresses in cold rolled boxes

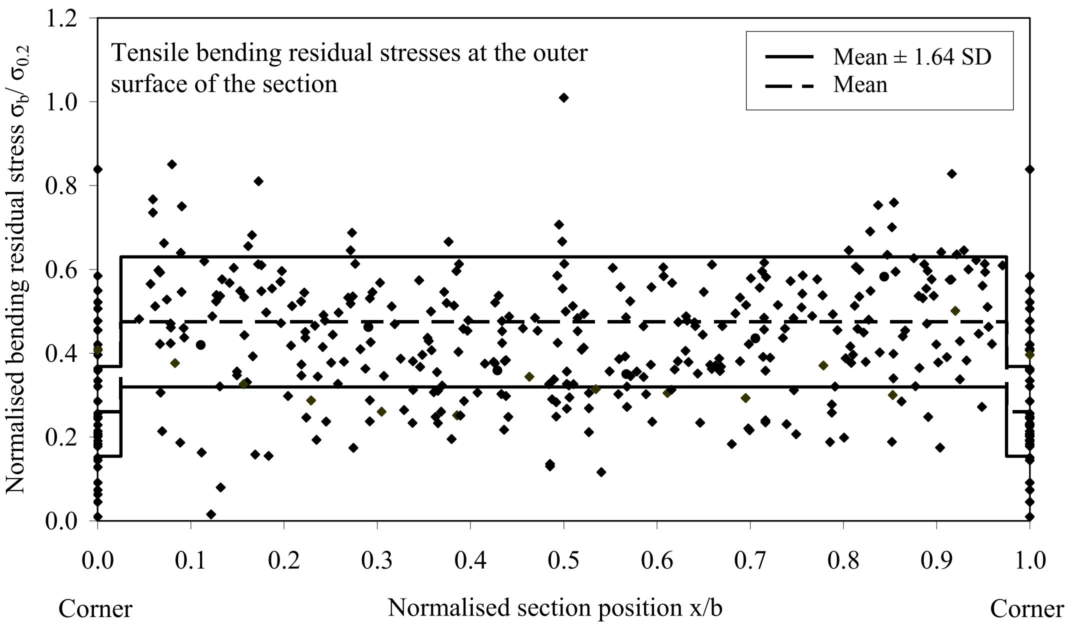


Fig. 11. Normalised bending residual stresses in cold rolled boxes (assuming a rectangular block through thickness distribution)

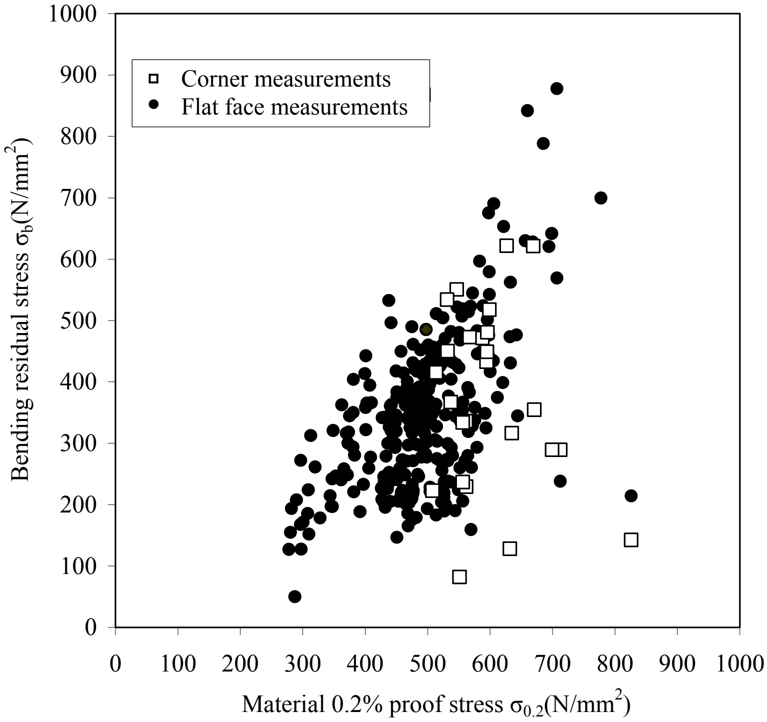


Fig. 12. Bending residual stresses at the outer surface of the section plotted against material strength for cold rolled boxes

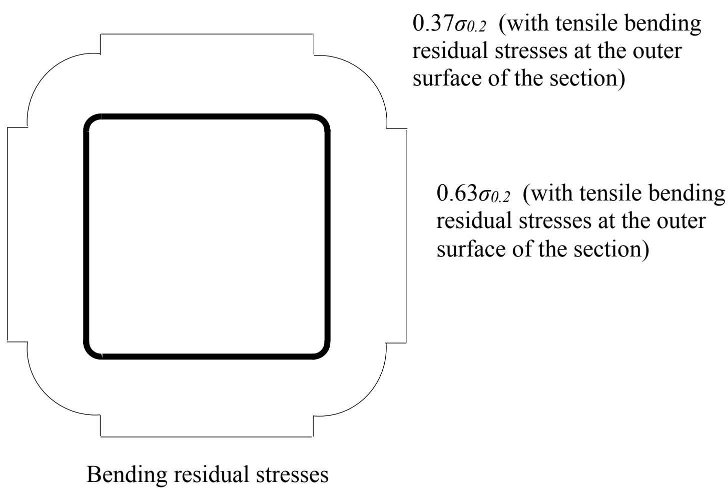


Fig. 13. Proposed bending residual stress model for cold rolled boxes (assuming a rectangular block through thickness distribution)

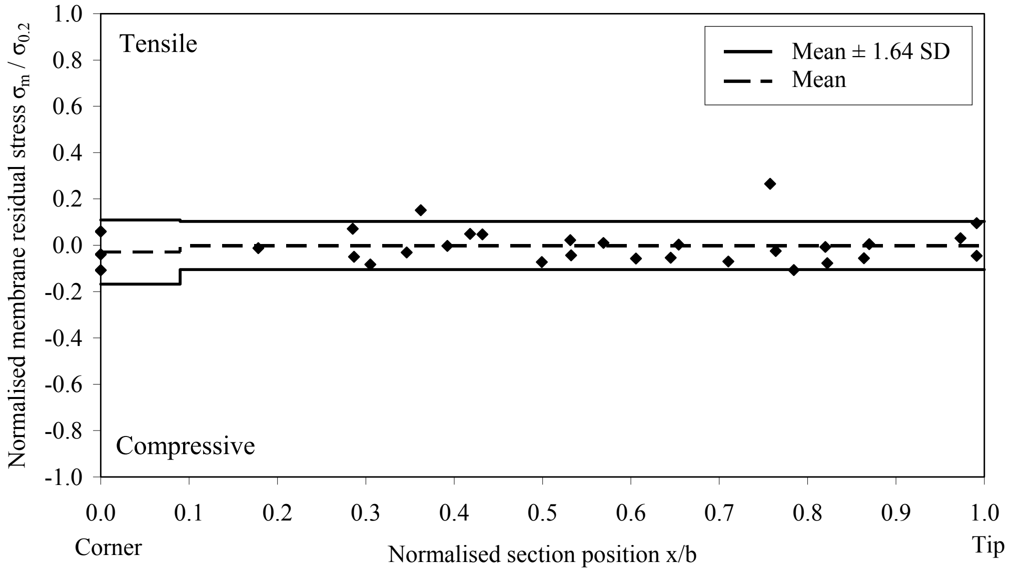


Fig. 14. Normalised membrane residual stresses in hot rolled angles

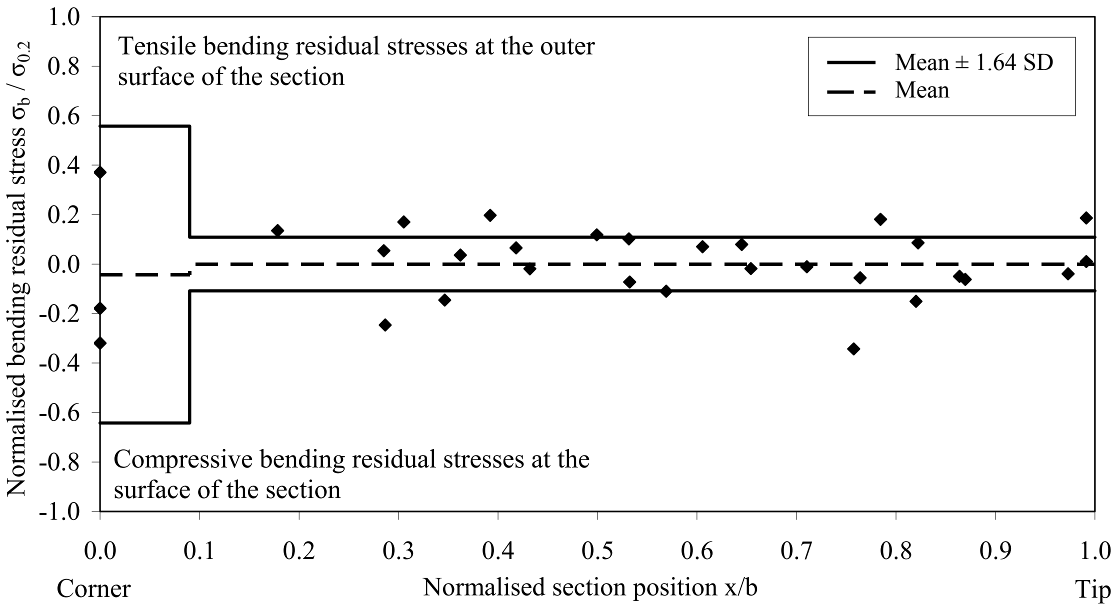


Fig. 15. Normalised bending residual stresses in hot rolled angles (assuming a linear through thickness variation)

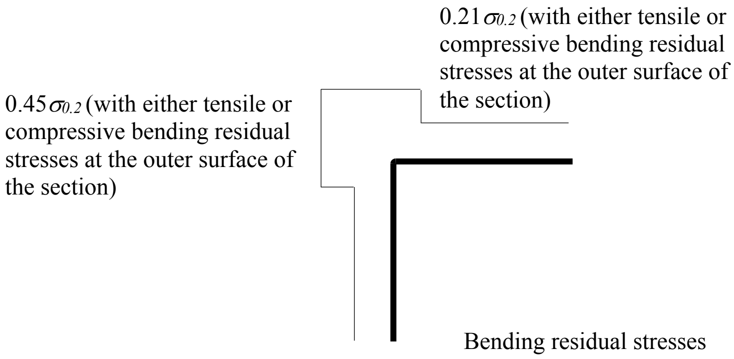


Fig. 16. Proposed bending residual stresses model for hot rolled angles (assuming a linear through thickness variation)

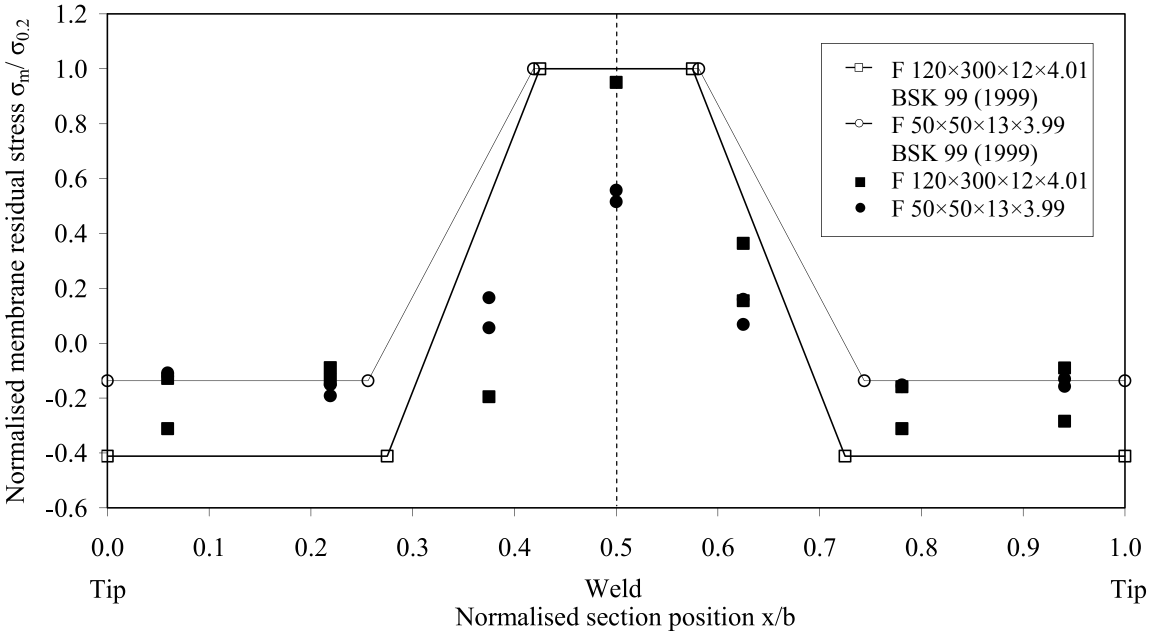


Fig. 17. Normalised membrane residual stresses in the flanges of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (Positive values indicate tensile membrane residual stresses)

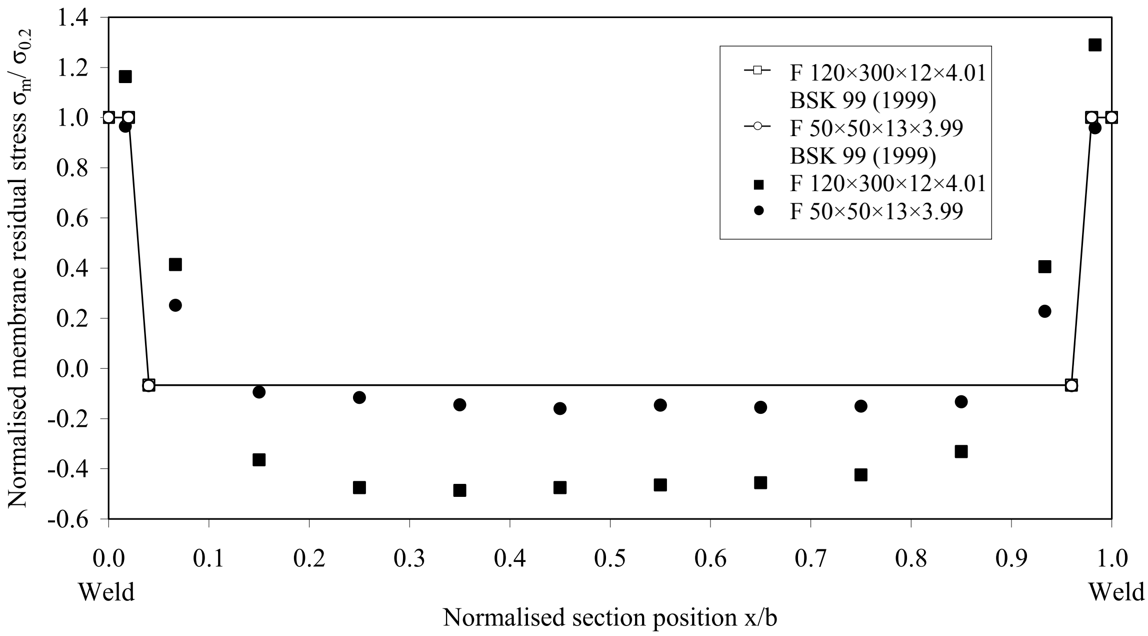


Fig. 18. Normalised membrane residual stresses in the webs of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (Positive values indicate tensile membrane residual stresses)

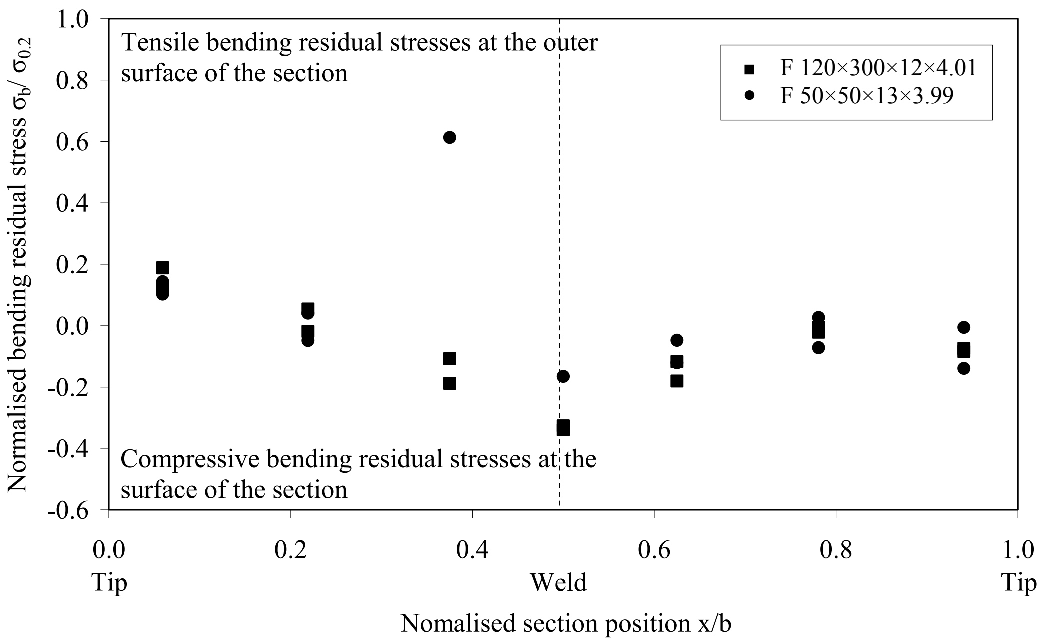


Fig. 19. Normalised bending residual stresses in the flanges of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (assuming a linear variation through thickness)

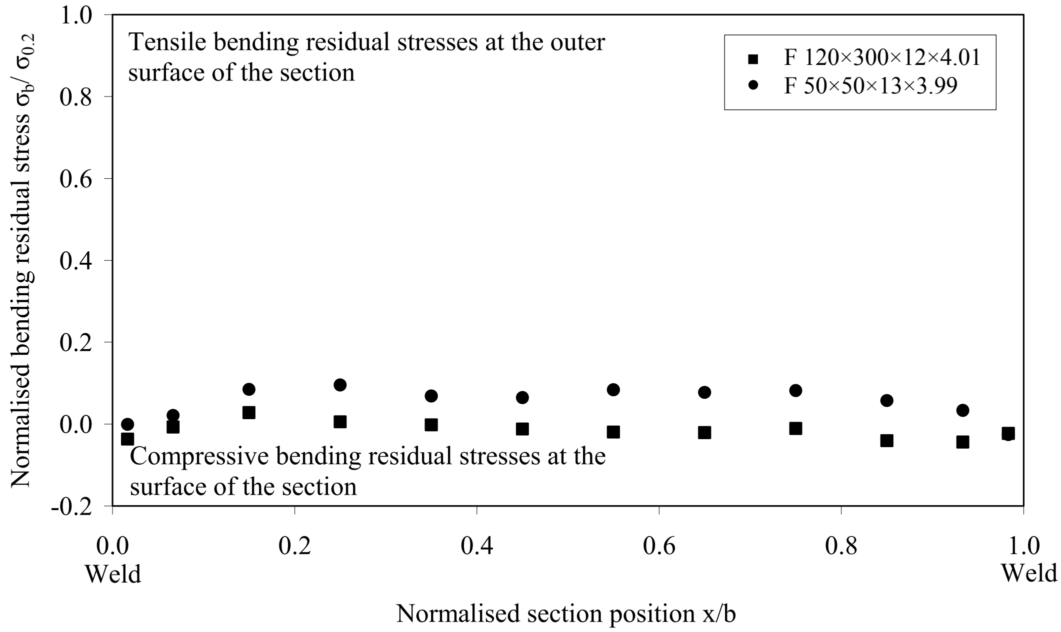


Fig. 20. Normalised bending residual stresses in the webs of austenitic and austenitic-ferritic fabricated sections tested by Lagerqvist and Olsson (2001) (assuming a linear variation through thickness)

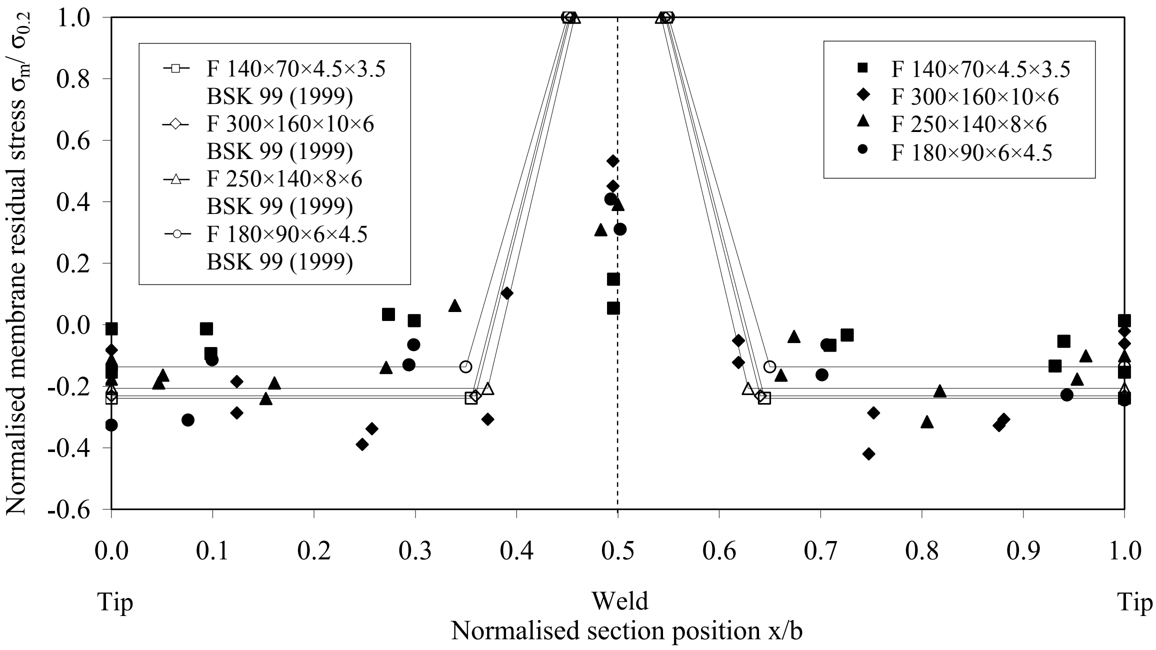


Fig. 21. Normalised membrane residual stresses in the flanges of ferritic fabricated sections tested by Bredenkamp et al. (1992), (Positive values indicate tensile membrane residual stresses)

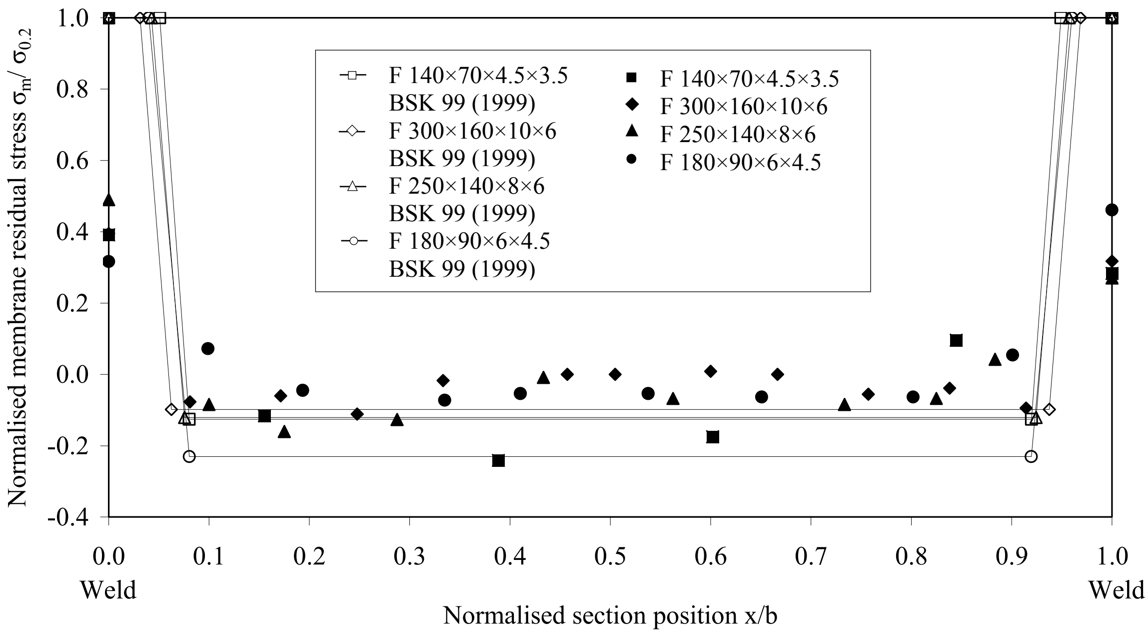


Fig. 22. Normalised membrane residual stresses in the webs in ferritic fabricated sections tested by Bredenkamp et al. (1992) (Positive values indicates tensile membrane residual stresses)

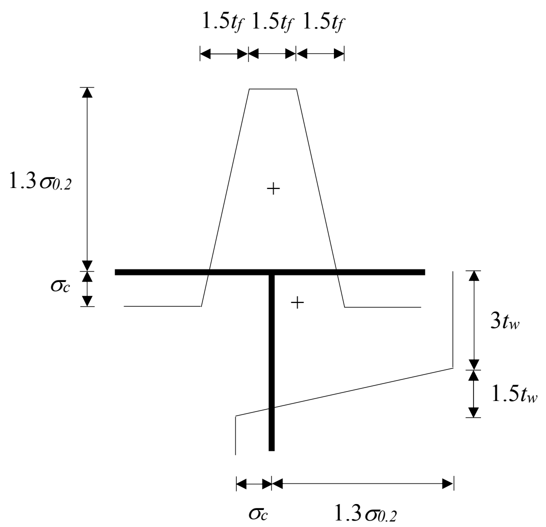


Fig. 23. Proposed membrane residual stress model for austenitic and austenitic-ferritic stainless steel fabricated I sections (Positive values indicates tensile membrane residual stresses)

Table 1. Weighted mean normalised membrane and bending residual stresses in press braked angles

	Flat faces				Corner regions			
	$\sigma_m/\sigma_{0.2}$		$\sigma_b/\sigma_{0.2}$		$\sigma_m/\sigma_{0.2}$		$\sigma_b/\sigma_{0.2}$	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
PB 50×50×2 (r_i=3.2)	0.08	0.07	0.01	0.10	-	-	-	-
PB 50×50×2 (r_i=3.5)	0.01	0.03	0.01	0.04	-	-	-	-
PB 50×50×2 (r_i=4.5)	0.01	0.03	0.04	0.02	-	-	-	-
PB 50×50×2 (r_i=7.5)	0.01	0.03	-0.05	0.14	-	-	-	-
PB 50×50×3 (r_i=3.2)	0.02	0.06	0.02	0.05	-	-	-	-
PB 50×50×4 (r_i=3.5)	-0.01	0.06	-0.02	0.06	-	-	-	-
PB 50×50×5 (r_i=3.5)	-0.01	0.02	0.01	0.06	-	-	-	-
PB 50×50×5 (r_i=4.5)	-0.06	0.23	0.04	0.16	-	-	-	-
Mean	0.02	0.07	0.01	0.08	0.03	0.05	0.24	0.07

Table 2. Weighted mean normalised membrane and bending residual stresses in cold rolled boxes

	Flats faces				Corner regions			
	$\sigma_m/\sigma_{0.2}$		$\sigma_b/\sigma_{0.2}$		$\sigma_m/\sigma_{0.2}$		$\sigma_b/\sigma_{0.2}$	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
CR 120×80×3[a]	0.11	0.17	0.40	0.06	0.01	0.10	0.20	0.02
CR 200×110×4[b]	-0.05	0.12	0.24	0.10	0.05	0.10	0.09	0.07
CR 200×110×4[b]	0.00	0.11	0.19	0.06	0.02	0.03	0.05	0.06
CR 80×80×3[c]	0.01	-	1.01	-	0.01	-	0.06	-
CR 100×50×2[d]	-0.13	0.19	0.52	0.13	-0.41	0.11	0.32	0.09
CR 100×100×2[d]	-0.18	0.28	0.45	0.11	-0.09	0.32	0.22	0.07
CR 100×50×3[d]	-0.15	0.19	0.53	0.07	-0.03	0.06	0.43	0.03
CR 100×100×3[d]	-0.10	0.15	0.33	0.08	0.15	0.10	0.51	0.18
CR 100×50×4[d]	0.15	0.20	0.54	0.14	0.12	0.02	0.21	0.07
CR 100×100×4[d]	0.13	0.17	0.58	0.07	-0.01	0.11	0.54	0.03
CR 150×150×4[d]	0.04	0.22	0.43	0.14	-0.06	0.02	0.24	0.04
Mean	-0.01	0.18	0.47	0.09	-0.02	0.10	0.26	0.07

[a] Clarin (2003)
[b] Young and Lui (2005)
[c] The Centre for Advanced Structural Engineering (1990)
[d] Cruise and Gardner (in press)

Table 3. Weighted mean normalised membrane and bending residual stresses in hot rolled angles

	Flat faces				Corner regions			
	$\sigma_m / \sigma_{0.2}$		$\sigma_b / \sigma_{0.2}$		$\sigma_m / \sigma_{0.2}$		$\sigma_b / \sigma_{0.2}$	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
HR 50×50×3	0.00	0.08	0.05	0.12	-	-	-	-
HR 50×50×5	0.02	0.07	0.03	0.13	-	-	-	-
HR 50×50×10	-0.02	0.04	-0.08	0.07	-	-	-	-
Mean	0.00	0.06	0.00	0.11	-0.03	0.08	-0.04	0.36

Table 4. Weighted mean normalised membrane and bending residual stresses in fabricated I sections

	Flat faces			
	$\sigma_m / \sigma_{0.2}$		$\sigma_b / \sigma_{0.2}$	
	Mean	Stdev	Mean	Stdev
F 120×300×12×4.01	-0.09	0.34	0.01	0.16
F 50×50×13×3.99	0.00	0.25	-0.03	0.14
F 140×70×4.5×3.5	-0.01	0.15	-	-
F 300×160×10×6	-0.06	0.23	-	-
F 250×140×8×6	-0.05	0.19	-	-
F 180×90×6×4.5	-0.04	0.22	-	-
Mean	-0.04	0.23	-0.01	0.15