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DOI:
10.1016/j.jcsr.2013.06.009

Document status and date:
Published: 01/01/2013

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)


ELSEVIER
JOURNAL OF CONSTRUCTIONAL STEEL RESEARCH

Journal of Constructional Steel Research 89 (2013) 63–74

Contents lists available at SciVerse ScienceDirect

Journal of Constructional Steel Research

Experimental investigation on residual stresses in heavy wide flange QST steel sections

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ARTICLE INFO

Article history:
Received 23 February 2013
Accepted 23 June 2013
Available online xxxx

Keywords:
Residual stress measurements
Heavy wide flange sections
Quenched and self-tempered steel
Residual stress model

ABSTRACT

This paper presents the experimental results of residual stress measurements conducted on heavy wide flange quenched and self-tempered (QST) steel sections which have been developed by ArcelorMittal under the proprietary name HISTAR (HIgh-STrength ARcelorMittal). These sections are often applied in high-rise buildings, trusses or offshore structures and combine high strength with good toughness and weldability. The experiments are part of a larger study to arrive at buckling curves for these members as they are currently not provided by the European code. Two different sections with flange thicknesses greater than 100 mm are investigated and two types are examined: the stocky HD and more slender HL type. The sectioning method is adopted for measuring the residual stresses. It is found that both types display compressive residual stresses at the flange tips and the web and tensile residual stresses at the web-to-flange junctions. In absolute sense the residual stresses are greater in the HL type. From the experimental results a residual stress model is derived which can serve as the initial stress state of a heavy HISTAR section in non-linear finite element analyses.

1. Introduction

1.1. Background

Modern day construction shows a trend towards high-strength steels for structures. High-strength is a term commonly used for steels which have a nominal yield stress greater than 430 N/mm^2; ECCS [1]. These steels have greater resistance to the acting loads compared to their equivalents made from mild steel. Whereas in the 1990s a shift took place from (European) grade S235 to S355 mild steel, the latter grade is now already being superseded by high-strength grade S460 or higher.

Together with the shift towards higher grade steels there is an ongoing world-wide competition in designing and constructing the tallest buildings, placing a premium on heavy steel sections (sections with a flange thicker than 40 mm) with high strength and good weldability. Although the earliest skyscrapers in the United States were built with mild steel heavy steel sections (also known as jumbo sections), nowadays there is an increasing supply in high-strength heavy sections.

However, due to the limits of the rolling forces in conventional rolling methods increasing quantities of alloying elements are necessary to get the required strength for heavy sections, which is detrimental to their toughness and weldability.

In order to overcome these difficulties, a combined thermo-mechanical process of quenching and self-tempering (QST) was developed by ArcelorMittal to produce heavy sections which combine high strength, good weldability and good toughness at low temperature, Bjorhovde [2].

In the QST process, the sections are intensely cooled around the entire surface after the last pass of the hot-rolling process. Cooling is stopped before the inner core of the sections is affected. As the temperature equalizes in the section, the outer layers are tempered by the heat flow from the core to the surface. The QST process can be regarded as an extension of thermo-mechanical treatment and is therefore classified as a thermo-mechanically controlled process. With this process it is possible to manufacture even the heaviest steel wide flange sections in high-strength steels.

Under the proprietary name of HISTAR (HIgh-STrength ARcelorMittal) heavy wide flange QST sections are produced by ArcelorMittal in different steel grades which have an improved minimum guaranteed yield stress for thick products compared to other high-strength steel grades such as S460M or S500M. For heavy sections this means that a smaller reduction in yield stress has to be applied. Heavy sections for general construction applications are made with the QST process in two high-strength steel grades: HISTAR 460 and HISTAR 460 L.

These steel grades sections are predominantly used for high-rise structures and wide-span trusses. Flexural buckling is often the

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http://dx.doi.org/10.1016/j.jcsr.2013.06.009

decisive failure mode as the member is subjected to large compressive forces. The relative resistance χ of compression members failing by flexural buckling can be determined using their relative slenderness $\bar{\lambda}$ in combination with the buckling curves from Eurocode3, EN 1993-1-1 [3], see Fig. 1. The European standard offers five different buckling curves: a_0, a, b, c, d, where each curve represents the flexural buckling resistance for columns made from different cross-sections, depending on the steel grade and buckling direction (weak-axis or strong-axis).

The assignment of columns to one of the five curves depends on their height-to-width ratio (h/b), flange thickness (t_f), steel grade and direction of buckling (Table 1). This classification reflects the dependence of residual stresses on the section geometry and steel grade and their influence on the elastic–plastic buckling response, ECCS [1]. Column sections failing by weak axis buckling (z–z) belong to less favorable buckling curves in comparison to the same section failing by strong axis buckling (y–y). The experimental and numerical work which formed the basis for this assignment procedure is presented in more detail in the subsequent sections.

Currently heavy wide flange HISTAR 460 sections with flange thickness greater than 100 mm and h/b values smaller than 1.2 are assigned to buckling curve "c" according to Eurocode3, EN 1993-1-1 [3]. For heavy HISTAR 460 sections possessing flanges thicker than 100 mm and with h/b-values greater than 1.2 no buckling curves are specified. It seems to be most logic to adopt the same curve for these sections to maintain consistency with HISTAR 460 sections with $h/b < 1.2$ and $t_f > 100$ mm. The selected buckling curve is probably on the conservative side.

1.2. Motivation for research

In order to arrive at a more realistic buckling curve for heavy wide flange HISTAR 460 sections with $h/b > 1.2$ and $t_f > 100$ mm a research project was initiated by ArcelorMittal, Long Products, Research & Development in Luxembourg and carried out by Eindhoven University of Technology in the Netherlands. Its primary goal is to arrive at realistic buckling curves for heavy HISTAR 460 sections with flange thickness greater than 100 mm based on residual stress measurements and finite element analyses. Residual stresses are measured in two heavy HISTAR 460 sections from which a residual stress model is derived. This model can then subsequently serve as the initial stress state for non-linear finite element analyses to simulate flexural buckling. The present paper describes the residual stress measurements as performed on heavy

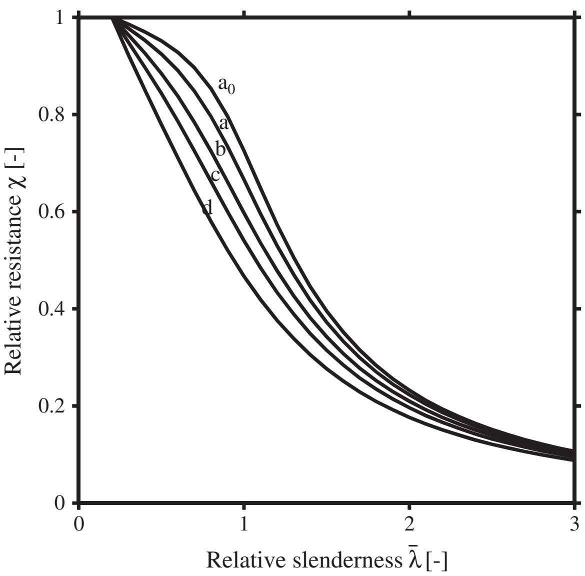
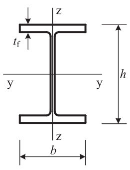


Fig. 1. Buckling curves according to EN 1993-1-1.

Table 1
Buckling curve classification according to Eurocode3, EN 1993-1-1.

Cross-section	Limits	Buckling about axis	Buckling curve	
			S 235 / S 275 / S 355 / S 420	S460
Rolled I-sections 	$h/b > 1.2$	y–y	a	a_0
	$t_f \le 40$ mm	z–z	b	a_0
	40 mm $< t_f \le 100$ mm	y–y	b	a
		z–z	c	a
	$h/b \le 1.2$	y–y	b	a
	$t_f \le 100$ mm	z–z	c	a
	$t_f > 100$ mm	y–y	d	c
		z–z	d	c

HISTAR 460 sections and proposes a residual stress model. To the knowledge of the authors, thus far no residual stress measurements have been performed on heavy sections with flanges thicker than 100 mm made from high-strength steel.

1.3. Earlier residual stress measurements

Depending on the nature of manufacturing (e.g. hot-rolling, welding or cold-forming) a residual stress distribution is present in a steel member. Residual stresses can be in compression or tension. The residual stresses are such that the resulting forces are in equilibrium since no external loads are acting on the member. Compressive residual stresses can have detrimental effect on the stability of columns failing by flexural buckling. These residual stresses cause premature yielding at specific locations in a column under compression which leads to a rapid deterioration of the stiffness and hence early elastic–plastic buckling failure.

The effect of residual stresses on buckling curve classification is largely reflected by the ratio between the extreme (compressive) residual stress values and the yield stress (also known as normalized residual stress) and the direction of buckling. The flexural buckling resistance of columns with greater normalized residual stresses is represented by less favorable buckling curves compared to sections with lower normalized residual stresses.

In hot-rolled steels, residual stresses are largely formed due to non-uniform cooling of the member after hot-rolling. The residual stress distribution is significantly influenced by the section geometry as this determines the cooling rate. Wide flange sections with small h/b-values possess residual stress distributions different from sections with great h/b-values. Also the thickness of the flange affects the residual stress distribution. For high-strength steels the normalized residual stresses are significantly smaller than their mild-steel counterparts. These geometrical and material properties determine to a large extent the magnitude and distribution of residual stresses and, as a consequence, the elastic–plastic buckling response of hot-rolled steel sections. As such, the section geometry, material properties and buckling direction form the salient parameters for selecting the appropriate buckling curve (Table 1).

1.3.1. Heavy steel shapes in mild steels

Mild steel heavy sections have already been applied in steel structures for several decades. A survey was conducted by Bjorhovde and Tall [4] and showed the widespread application of rolled and welded heavy sections in the construction industry. In the early 1950s and 1960s extensive residual stress measurements have been conducted at Lehigh University in Bethlehem, Pennsylvania, United States, on welded and hot-rolled mild steel heavy steel sections.

Fujita [5] conducted residual stress measurements on a broad range of wide flange sections. The experimental plan included a heavy rolled 14WF426 section made from steel grade ASTM A7 with a yield stress f_y of 227 N/mm^2 (33 ksi). Tensile residual stresses (σ_{res}) were observed in the web and web-to-flange junction. The flange tips were under large compressive residual stresses where values of more than 137 N/mm^2 (20 ksi) were recorded. The normalized residual stress (σ_{res}/f_y) at the flange tip was approximately 0.60.

Brozetti et al. [6] selected a hot-rolled member 14WF730 made from ASTM A36 steel with a nominal yield stress of 248 N/mm^2 (36 ksi) for residual stress measurements. Extreme values for tensile and compressive residual stresses were around 86 N/mm^2 (12.5 ksi) and 124 N/mm^2 (18 ksi), respectively. In addition through-thickness residual stress measurements were performed which showed a variation between plus and minus 28 N/mm^2 (4 ksi) across the thickness of the flanges. The flange tips displayed compressive residual stresses whereas the web and web-to-flange junctions were under tensile residual stresses. The measured residual stresses were significantly smaller than those reported by Fujita [5]. This is reflected by a normalized residual stress at the flange tips which was in the order of 0.35 for the section tested by Brozetti et al. [6].

The experimental results of Fujita [5] were used to define the initial stress state of sections in non-linear analyses to arrive at buckling curves for heavy rolled shapes made from mild steel, ECCS [1]. From the computations it was suggested that mild steel heavy rolled shapes failing by weak-axis or strong-axis buckling should be designed according to buckling curve “d”. The EN 1993-1-1 (Table 1) states that mild steel heavy wide flange sections with $h/b > 1.2$ are to be designed according to buckling curve “c” when failing by weak-axis buckling (z–z) and buckling curve “b” for strong-axis buckling (y–y). For heavy sections made from mild steel with $h/b \leq 1.2$ and $t_f \leq 100$ mm weak-axis buckling and strong-axis buckling resistance are best represented by the buckling curves “c” and “b”, respectively. Sections with $t_f > 100$ mm are assigned to buckling curve “d”, irrespective of the buckling direction.

1.3.2. High-strength steels

Belgian and British buckling tests showed that the resistance of high-strength steel columns failing by weak-axis buckling can be represented by buckling curve “b”; ECCS [1]. Buckling curve “a” was assigned to high-strength steel columns buckling about the strong-axis in ECCS [1]. Residual stress measurements were not reported and an assumption was made about their distribution and magnitude in high-strength steel columns. A value of 0.3 was used to define the normalized compressive residual stresses at the flange tips.

Residual stress measurements were conducted by Bernard [7] on HE 400 and IPE 400 sections made from high-strength steel (S460) in addition to buckling tests and stub column tests to arrive at buckling curve expressions for members with h/b-values greater than 1.2. Extreme compressive residual stress values were recorded at the flange tips and centre of the web. Based on the experimental results and supplementary computer simulations it was stated that buckling curve “a_0” or “a” should be assigned to hot-rolled I-sections made from high-strength steel with a ratio of $h/b > 1.2$.

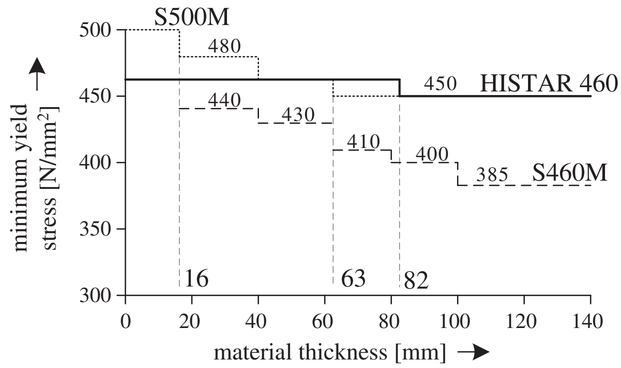


Fig. 2. Decrease of yield stress of HISTAR 460, S460 and S500 with increasing material thickness.

Boeraeve [8] measured residual stresses in a HE 280A, HE 400B and W12 × 12 × 336 made from S460 steel. The latter possesses a flange thickness of 74 mm and can be classified as a heavy section. In the W12 × 12 × 336 maximum compressive residual stresses of 116 N/mm^2 were observed at the flange tips and at the center of the web, rendering a normalized residual stress of 0.25. The web-to-flange junction displayed tensile residual stresses.

According to EN 1993-1-1, high-strength heavy wide flange sections can be designed using buckling curve “a” when failing by weak-axis or strong axis buckling, irrespective of their h/b-ratio. However, this buckling curve is only valid for heavy sections with flange thickness up to 100 mm. For heavy steel sections with $h/b > 1.2$ and which have a flange thickness greater than 100 mm no buckling curve is specified (Table 1). High-strength heavy steel sections for which the height-to-width ratio is smaller than 1.2 and which have a flange thickness greater than 100 mm were assigned to buckling curve “c”.

1.4. Scope and aims

When observing the residual stress measurements which lead to the buckling curve classification of heavy rolled shapes, it is obvious that considerable differences are present between different heavy section types and steel grades. This is reflected by the buckling curves assigned to the heavy rolled shapes which cover almost the entire range from “a” to “d” (Table 1).

Residual stresses have been measured on large heavy rolled sections made from mild steel and on a single heavy rolled shape made from high-strength steel. The flange thickness of the latter was 74 mm. No residual stress measurements have been made on heavy sections made from HISTAR steel which possess thicker flanges. As the heavy HISTAR sections differ considerably in geometry, strength properties and manufacturing method, it cannot be assumed that the magnitude and distribution of the residual stress distribution for these sections is identical to those of mild steel heavy sections or heavy high-strength sections with thinner flanges for which residual

Table 2
Heavy rolled section offered by ArcelorMittal with $h/b > 1.2$ and $t_f > 100$ mm.

Section name (European)	Section name (American — Imperial)	Weight per m [kg]	h [mm]	b [mm]	t_w [mm]	t_f [mm]	h/b [–]
HD 400 × 900	W14 × 16 × 605	900	531	442	65.9	106	1.20
HD 400 × 990	W14 × 16 × 665	990	550	448	71.9	115	1.23
HD 400 × 1086	W14 × 16 × 730	1086	569	454	78	125	1.25
HD 400 × 1202	W14 × 16 × 808	1202	580	471	95	130	1.23
HD 400 × 1299	W14 × 16 × 873	1299	600	476	100	140	1.26
HL 920 × 1194	W36 × 16.5 × 802	1194	1081	457	60.5	109	2.37
HL 920 × 1269	W36 × 16.5 × 853	1269	1093	461	64	115.1	2.37
HL 920 × 1377	W36 × 16.5 × 925	1377	1093	473	76.7	115.1	2.31

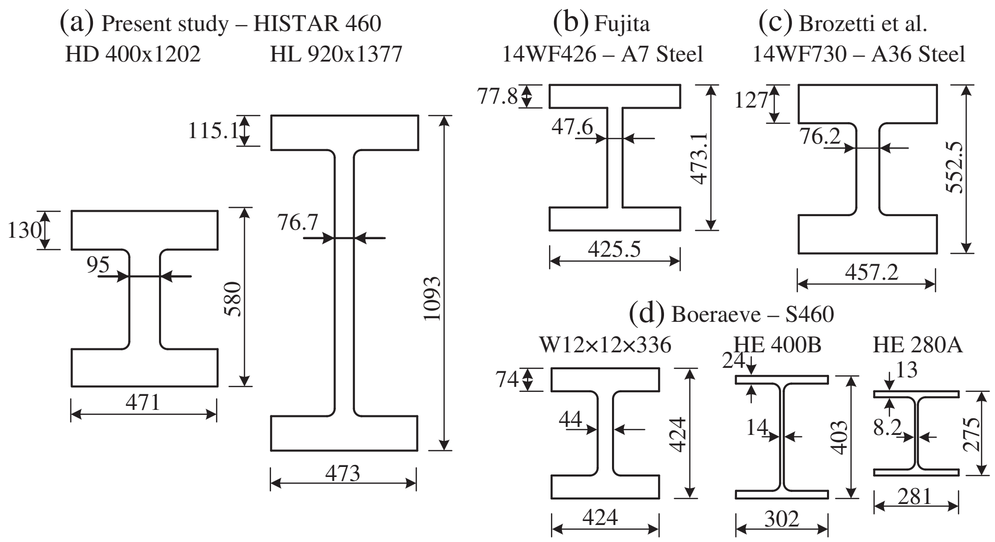


Fig. 3. Rolled shapes with nominal section dimensions in mm.

stress distributions are known. Hence, using existing residual stress models to define the initial stress state for heavy rolled HISTAR sections can lead to conservative or unconservative buckling curves.

The present paper presents residual stress measurements in heavy wide flange sections made from HISTAR 460 steel, possessing flanges thicker than 100 mm and *h*/*b* values greater than 1.2. The sectioning method is used to obtain the residual stresses. The experimental results are converted to residual stress models, which can be used to define the initial stress state for heavy HISTAR sections in non-linear finite element analyses.

2. Experiments

2.1. Experimental plan

Currently, a total of 8 heavy wide flange sections manufactured by ArcelorMittal are not covered by the buckling curves due to the absence of residual stress measurements (Table 2). These sections can be classified as a HD-type or HL-type, where the first has a *h*/*b*-value of around 1.23, and the latter a *h*/*b*-value of about 2.35. All heavy sections can be delivered in conventional steel grades, in high-strength steel grades S460M and S460 ML (according to EN 10025-4) as well as in HISTAR 460 and HISTAR 460 L (according to ETA-10/0156). High strength steel S500M is expected to be included in the next issue of EN10025-4 and will then also be available.

For heavy sections made from steel grade HISTAR 460 only a minimum reduction in yield stress has to be applied to account for material thickness effects, whereas greater reductions must be taken into account for identical sections made from other steel grades. An illustrative comparison between the minimum yield stress for HISTAR 460, S500M and S460M is shown in Fig. 2.

From both section types two members were selected: HD 400 ×1202 and HL 920 × 1377 made from steel grade HISTAR 460 (denoted in bold in Table 2). The cross-sections of the selected specimens are shown in Fig. 3 in addition to heavy steel sections and high-strength sections selected for earlier residual stress measurements.

For each section type two specimens were manufactured (Fig. 4). Two residual stress measurements were conducted on one specimen, whilst one residual stress measurement was performed on the other specimen. Hence for each section type three residual stress measurements were

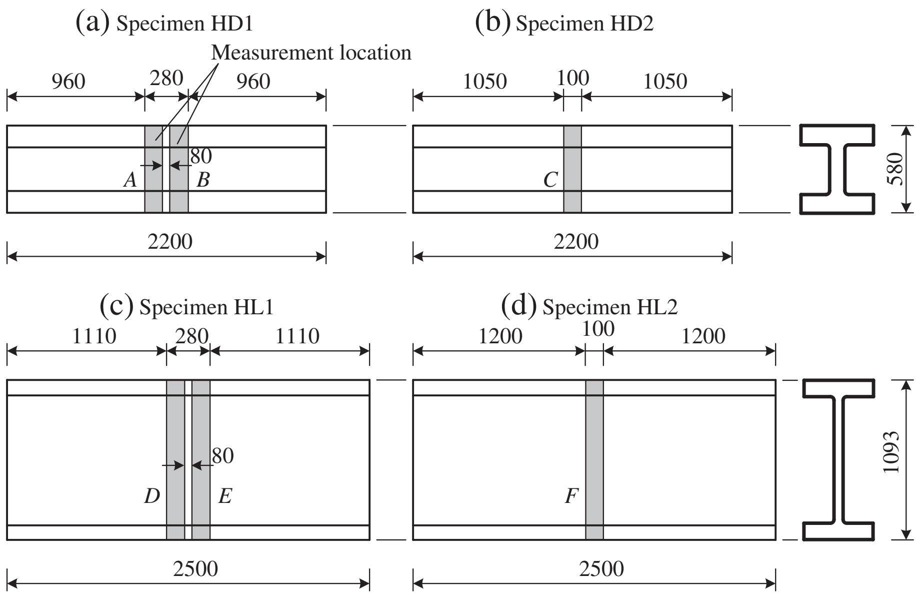


Fig. 4. Position of measurement areas.

Table 3
Mechanical properties HD 400 × 1202.

Coupon	Yield stress [N/mm^2]	Tensile stress [N/mm^2]	Elongation at fracture [%]
1	545	670	20.7
2	529	666	18.0
3	495	665	19.1
4	558	669	16.7

Table 4
Mechanical properties HL 920 × 1377.

Coupon	Yield stress [N/mm^2]	Tensile stress [N/mm^2]	Elongation at fracture [%]
1	461	597	20.4
2	464	601	19.1

performed: for the HD 400 × 1202 section, measurements A, B and C and for the HL 920 × 1377 section, measurements D, E, and F.

The test areas were placed a distance of at least 2 times the section width from the ends to prevent end effects. This complies with location recommendations by Tebedge et al. [9]. Only longitudinal residual stresses were measured as they are considered to have primary influence on the load carrying resistance of heavy HISTAR columns.

2.2. Material properties

The material used is HISTAR 460 with a nominal yield stress of $f_y = 460$ N/mm^2. However, for the sections used here, with flange thicknesses exceeding 82 mm, the nominal yield stress reduces to $f_y = 450$ N/mm^2.

Coupons were removed from the HD 400 × 1202 and HL 920 × 1377 sections and tested in a tensile test setup at the plant of ArcelorMittal to examine the mechanical properties. The yield stress, tensile stress and elongation at fracture for the HD 400 × 1202 and HL 920 × 1377 are listed in Tables 3 and 4.

The nominal yield stress of 450 N/mm^2 has been used hereafter for e.g. normalization of residual stress values.

2.3. Measurement procedure

The sectioning method with a mechanical extensometer was used to measure residual stresses. A change in strain (representative for the residual stresses in the section) is measured by recording the length of a steel strip before and after saw-cutting. From the difference in length before and after saw-cutting the residual stresses can be computed as follows:

$$\sigma_{res} = -\varepsilon E = \left(\frac{L_b - L_a}{L_a}\right)E \qquad (1)$$

where:

E is the Young's modulus for which a value of 200 000 N/mm^2 was used
L_b is the distance measured after saw-cutting
L_a is the distance measured before saw-cutting.

Compressive and tensile residual stresses are denoted negative and positive, respectively. The negative sign in Eq. (1) is included as an elongation indicates the presence of compressive residual stresses and vice versa. Eq. (1) is based on the assumption that the length changes are entirely elastic, Tebedge et al. [9].

The sectioning method is largely identical to procedures used by Brozetti et al. [6] and others on heavy steel shapes, with the exception that in the present study a DEMEC extensometer was used instead of a Whittemore gauge. Both devices are capable of measuring length (changes) with high accuracy, necessary to arrive at proper strain values. The exception lies in the preparation: the Whittemore gauge

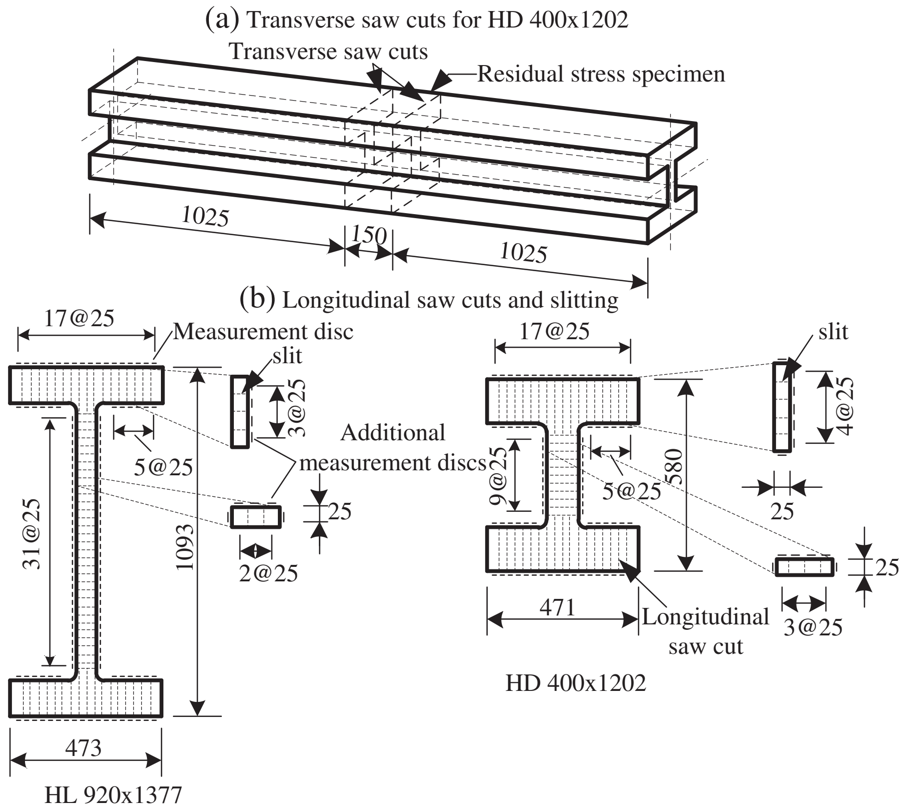
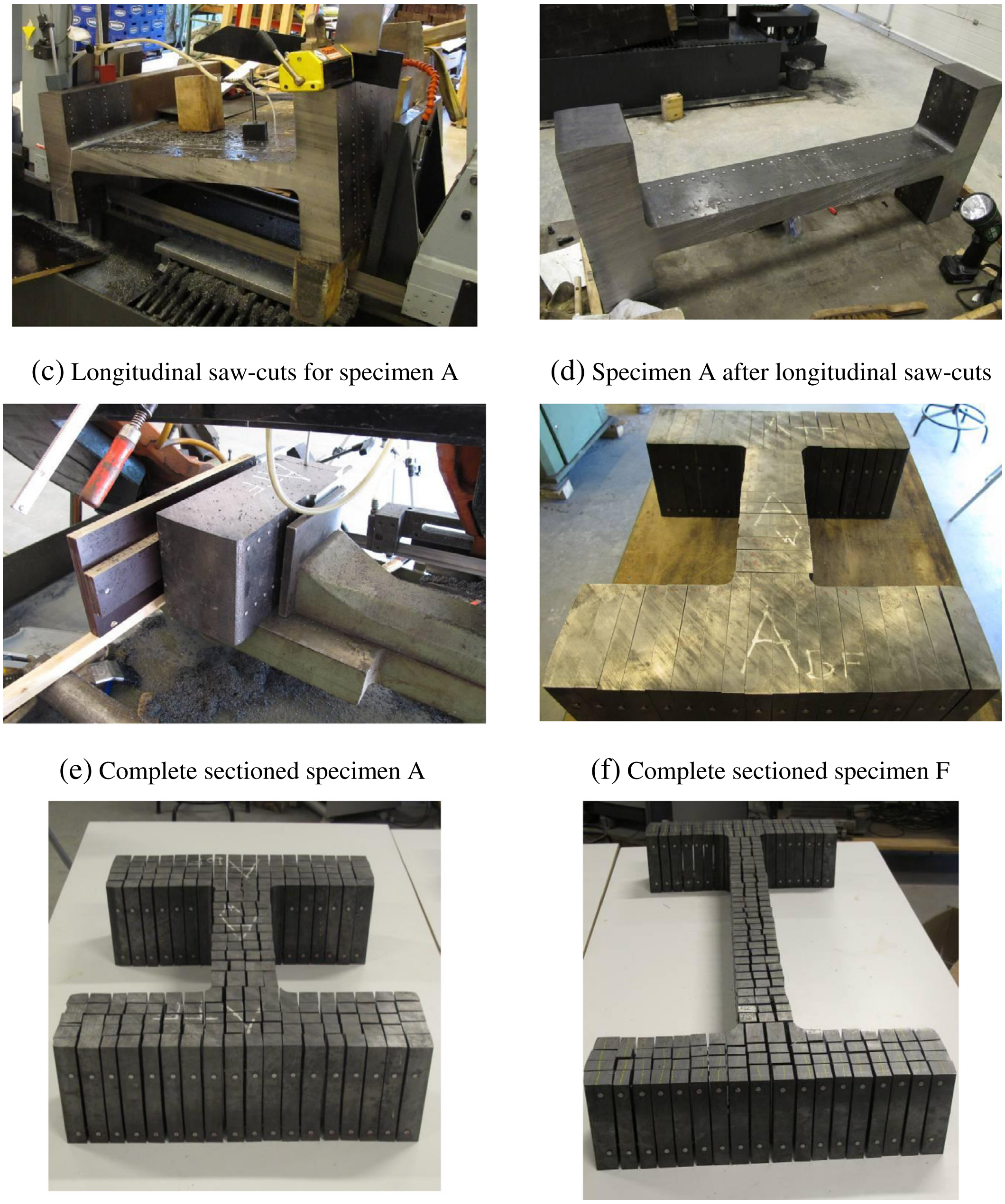


Fig. 5. Saw-cutting steps in sectioning method.

requires gage holes to be punched into the surface with a drill bit whilst the DEMEC extensometer relies on gluing discs onto the surface. These discs with a diameter of 6.3 mm contain a small conical hole in the centre which matches with the gauge points of the DEMEC extensometer. The accuracy of the DEMEC extensometer is 0.8 μm, or ±1.6 N/mm^2, based on a nominal gauge length of 100 mm and Young's modulus of 200 000 N/mm^2. The accuracy of the Whittemore gauge is 0.2 ksi (1.4 N/mm^2), Tebedge et al. [9].

The accuracy was assessed by performing residual stress measurement on an IPE 240 made from steel grade S235 using the DEMEC extensometer and electrical strain gauges. Both measurements produced similar residual stress distributions, confirming the working accuracy of the DEMEC extensometer. The results of the accuracy investigation are presented in Appendix A. For the present study a mechanical extensometer was selected in preference to electrical strain gauges due to the duration of and handling procedures involved in the saw-cutting process. As electrical strain gauges need to be connected to a measuring device or data collector during the entire measurement procedure, employing them would pose restrictions on the specimen handling and lengthen the process of the experimental program considerably.

Measuring discs were laid out around the specimen. The nominal transverse distance between two discs was 25 mm (Fig. 5b). The longitudinal distance was 100 mm which complies with the working distance of the DEMEC extensometer. Prior to sawing the longitudinal distance between the discs was measured. In the first step, the specimen was transversely cut, at a distance sufficiently away from the discs in order to avoid damaging these (Figs. 5a and 6a–b). In the second step, the resulting block of 150 mm length was longitudinally cut into smaller pieces of approximately 25 mm (Figs. 5b and 6c–d). The



(a) Transverse saw-cut for specimen E

(b) Specimen E after transverse saw-cuts

(c) Longitudinal saw-cuts for specimen A

(d) Specimen A after longitudinal saw-cuts

(e) Complete sectioned specimen A

(f) Complete sectioned specimen F

Fig. 6. Saw-cutting operations.

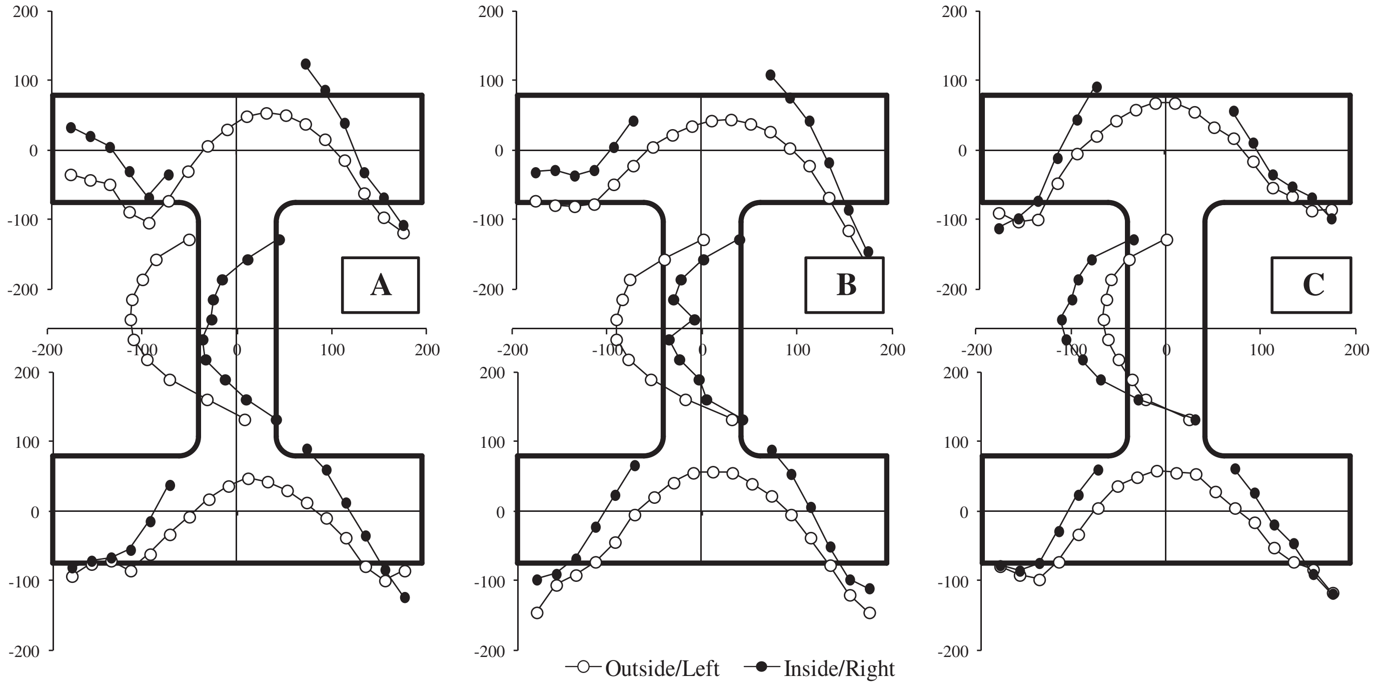


Fig. 7. Residual stress distribution in HD 400 × 1202.

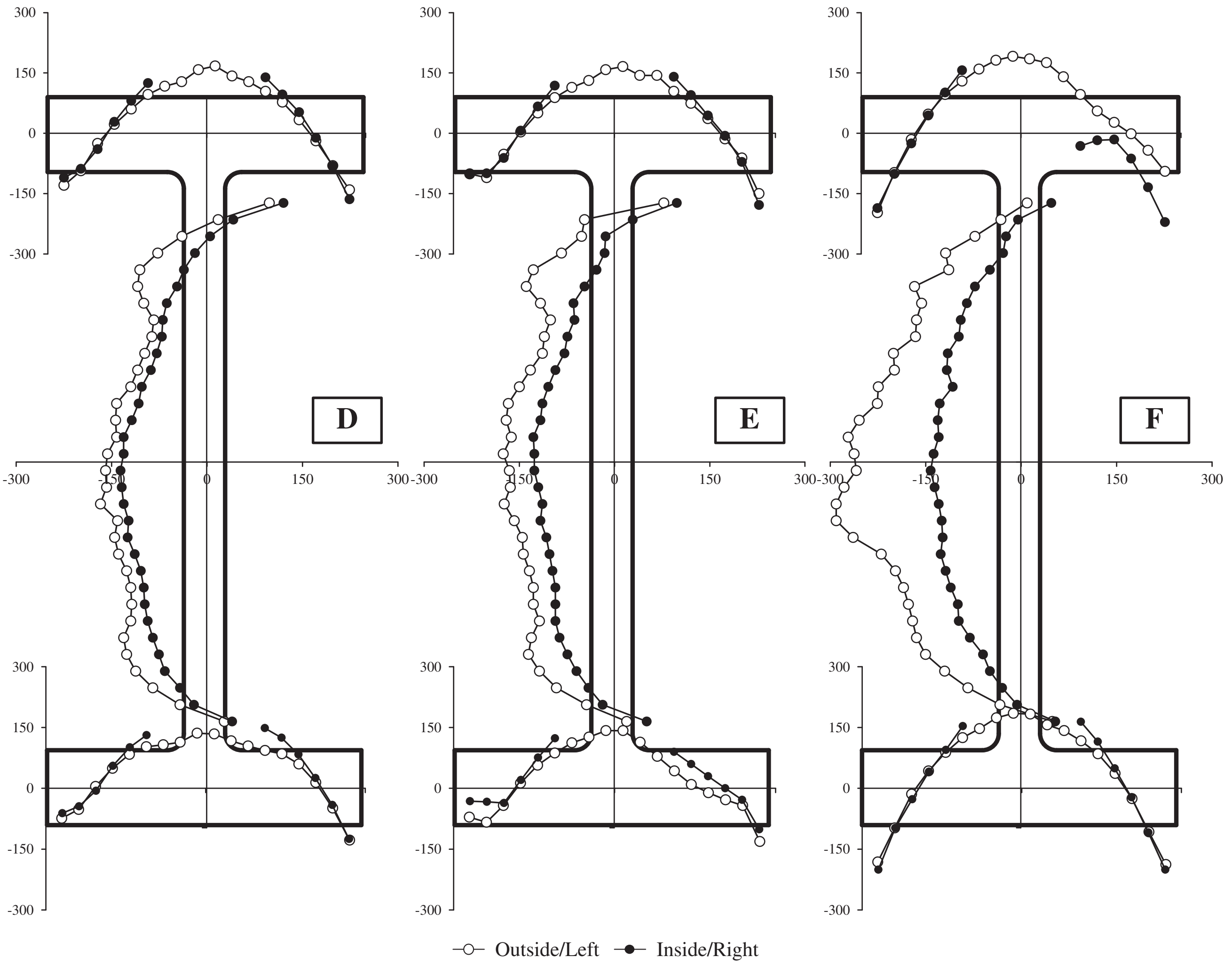


Fig. 8. Residual stress distribution in HL 920 × 1377.

first two steps only give residual stress values for the surface of the specimen (surface measurements). For wide flange sections possessing thin flanges and web, surface measurements will often suffice for making an educated guess concerning the through-thickness residual stress distribution. The surface readings from either side of the flange or web are used to construct a linear residual stress gradient across the thickness. However, for heavy sections the assumption that the residual stresses are distributed linearly is often questioned as it can be expected that these vary significantly through the thickness, Alpsten and Tall [10]. Therefore through-thickness measurements for one HD and one HL residual stress specimen were performed, which is labeled as the third step in the sectioning method. Additional measuring discs were adhered to one side of the steel strips and the distance between the discs was measured. Readings were only taken from one side of the steel strips as it was assumed that bending residual stresses would be negligible across the strip. Subsequently, the steel strips were slit across the thickness into slices (Fig. 5b). The recorded residual stresses from the third step are superimposed upon the residual stress gradient from sectioning step two. During the saw-cutting operations fluid coolant was supplied to prevent the band saw from overheating. Prior to each saw-cut operation the temperature of the specimen was recorded to relate the measured length change to the release of residual stresses and prevent erroneous readings due to temperature change.

A total of 80 and 124 surface measurements were taken from each measurement location for the HD 400 × 1202 and HL 920 × 1377, respectively (Fig. 5b). In addition, 220 through-thickness readings were obtained from the HD 400 × 1202 section (Fig. 6e). For the HL 920 × 1377 240 readings for the through-thickness residual stresses were made (Fig. 6f).

In the presentation of the results a distinction is made between the surface measurements and through-thickness measurements. For the first only the first and second step of the sectioning method are used. The complete sectioning method has been executed to get through-thickness measurements.

3. Results

3.1. Surface measurements

3.1.1. Residual stresses in HD 400 × 1202

Fig. 7 shows the measured residual stresses in the HD 400 × 1202 section. For all three measurements, the residual stress at the flange tips and the centre of the web are largely in compression. The web-to-flange junction and the portion of the web outside the centre display tensile residual stresses. The extreme values are found at the flange tips (compression) and web-to-flange junction (tension). It can be seen that specimen A has an asymmetric residual stress distribution in the top flange with respect to its minor axis. This is caused by straightening operations in the steel mill. Straightening operations are often performed on steel sections after hot-rolling to meet the straightness requirements. The member is bent around the weak-axis through application of point loads along the length, a method known as gag straightening, Lay and Ward [11] and Alpsten [12].

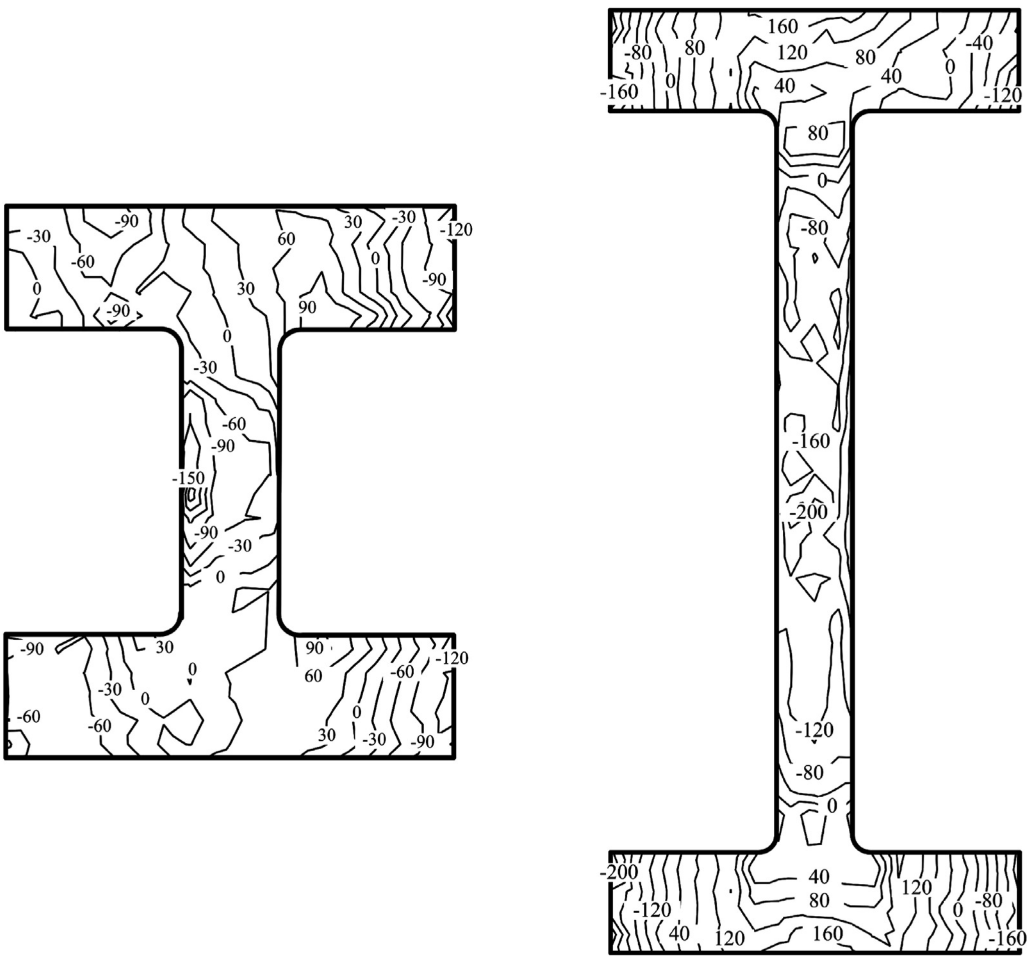


Fig. 9. Residual stresses in specimen A (left) and specimen F (right) after complete sectioning.

Gag straightening causes local plastic deformations in the vicinity of the load application. As a consequence the residual stress pattern due to non-uniform cooling is altered to a certain degree at the locations where point loads are applied. It is most likely that the measurement area of specimen A was close to one of these locations.

When comparing the present results with earlier measurements on sections with similar geometry it can be seen that the absolute value of residual stresses in the flanges for the HD sections have strong correlation with experimental results reported by Brozetti et al. [6]. In the present study compressive residual stresses are found in the web, whereas earlier measurements by Brozetti et al. showed tensile residual stresses. The experimental findings in this paper show better agreement with the residual stress measured on a heavy high-strength steel section by Boeraeve [8]. The extreme values for compressive residual stresses in the flange tips are significantly smaller than those measured by Fujita [5].

3.1.2. Residual stresses in HL 920 × 1377

The residual stress distribution of the HL 920 × 1377 members are shown in Fig. 8. The residual stresses are largely symmetrical with respect to both axes. It is likely that the investigated locations are not affected by gag straightening operations. The flange tips and centre region of the web display compressive residual stresses. Tensile residual stresses are found at the web-to-flange junction and at the portions in the web furthest away from the centre of the web. Extreme compressive values of approximately −220 N/mm^2 are found at the flange tips, whereas extreme tensile residual stresses of 191 N/mm^2 were recorded at the web-to-flange junction. Surface measurements taken from the outside of the flange and inside of the flange follow each other closely. The compressive residual stresses in specimen F are more extreme compared to specimen D or E. This is caused by the greater tensile residual stresses in the same specimen, which are balanced by high compressive stresses to maintain internal equilibrium.

3.2. Through-thickness residual stresses

The results of the through-thickness measurements are superimposed upon the linear stress gradient across the thickness constructed from residual stress values from the surface measurements. The resulting patterns are shown in Fig. 9 for specimen A and specimen F. As can be seen from the contour lines, there are steep stress gradients near the flange tips. There are no steep gradients parallel to the flange width or web height, indicating that the through-thickness measurements show little deviation from a linear gradient constructed from the surface values. In the subsequent section, a residual stress model is developed based on surface measurements.

4. Residual stress model

A residual stress model is proposed, representing a simplified distribution deduced from the experimental results. This residual stress model can serve as an initial stress state for non-linear finite element analyses. The derived model is representative for cross-sections with similar dimensions and made with identical production methods.

From the experimental results it was found that specimens with high tensile residual stresses at the web-to-flange junction also displayed high compressive stresses in the web. When constructing a net force from the surface values, a resultant tensile force was found in the flanges and a compressive force in the web. The magnitude and distribution of residual stresses in the flanges and web are interrelated which emanates from the condition of internal equilibrium. The measured values show a gradual transition between compression and tension residual stresses over the width of the flanges and height of the web. Through thickness residual stress values differed little from surface values.

Based on these observations, a parabolic stress pattern together with four individual residual stress values at specific locations is proposed to define the residual stress model. The pattern is assumed constant over the thickness of the web and flanges. This model is partly based on an earlier model suggested by Young [13] for medium-size hot-rolled wide flange sections. Parabolic residual stress models have been used earlier in the buckling curve derivation for wide flange sections in ECCS [1]. The parabolic shapes in the proposed model are symmetric with respect to the minor and major axis thereby meeting internal equilibrium requirements for bending about both axes. The residual stress value at the flange tips (σ_{frc}), at the centre of the flange (σ_{frt}) and at the top and bottom of the web (σ_{wrt}) were chosen such that good agreement between the experimental values and the model was obtained. The residual stress values are expressed as a fraction of the nominal yield stress of 450 N/mm^2, thereby taking into account the yield stress reduction due to the thickness of the flange for HISTAR 460 steel. The residual stress value at the centre of the flange is equal to the residual stress value at the top or bottom of the web. The parabolic residual stress equations are as follows:

$$\sigma_{res;flange} = \frac{4(\sigma_{frc}-\sigma_{frt})}{b^2} y^2 + \sigma_{frt} \quad \text{where}: -{}^{b}\!/_{2} \le y \le {}^{b}\!/_{2} \qquad (2)$$

$$\sigma_{res;web} = \frac{4(\sigma_{wrt}-\sigma_{wrc})}{h_w^2} z^2 \quad \text{where}: -{}^{h_w}\!/_{2} \le z \le {}^{h_w}\!/_{2} \qquad (3)$$

where y is the flange axis according to Fig. 10a, z is the web axis, h_w is the height of the web ($h - 2t_f$), and σ_{wrc} is the residual stress value at the centre of the web. This stress value is calculated from the balance of normal force in the section. By integrating Eqs. (2) and (3) over the

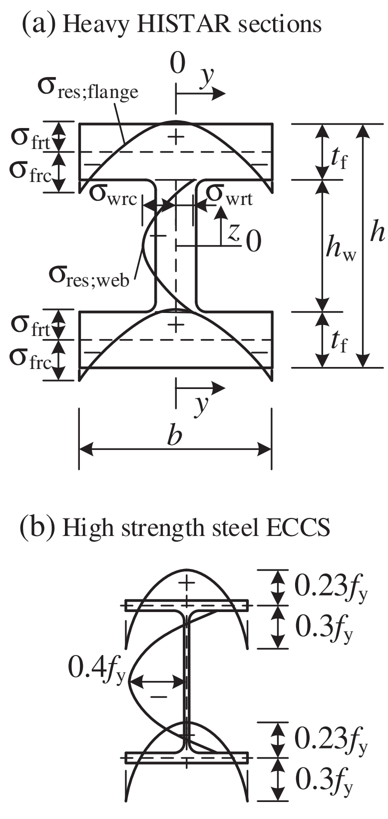


Fig. 10. Residual stress models.

Table 5
Normalized residual stress values for model.

Section	σ_{frt}	σ_{frc}	σ_{wrt}	σ_{wrc} (Eq. (9))
HD 400 × 1202	$0.18f_y$	$-0.30f_y$	$0.18f_y$	$-0.21f_y$
HL 920 × 1377	$0.40f_y$	$-0.50f_y$	$0.40f_y$	$-0.44f_y$

area of the flanges and web, respectively, and ignoring the area of the fillets the net normal force for both components can be computed.

$$N_w = 2t_w \int_0^{h_w/2} \left(\frac{4(\sigma_{wrt} - \sigma_{wrc})}{h_w^2} z^2 + \sigma_{wrc} \right) dz = 2t_w \left[\frac{4(\sigma_{wrt} - \sigma_{wrc})}{3h_w^2} z^3 + \sigma_{wrc} z \right]_0^{h_w/2} \quad (4)$$

$$N_{fl} = 4t_f \int_0^{b/2} \left(\frac{4(\sigma_{frc} - \sigma_{frt})}{b^2} y^2 + \sigma_{frt} \right) dy = 4t_{fl} \left[\frac{4(\sigma_{frc} - \sigma_{frt})}{3b^2} y^3 + \sigma_{frt} y \right]_0^{b/2} \quad (5)$$

where N_w is the net force for the web and N_{fl} is the net force for both flanges.

Further refining Eqs. (4) and (5) yields:

$$N_w = {}^1\!/_3 (\sigma_{wrt} + 2\sigma_{wrc}) t_w h_w \quad (6)$$

$$N_{fl} = {}^2\!/_3 (\sigma_{frc} + 2\sigma_{frt}) t_f b. \quad (7)$$

Adding both components and equating the resulting term to zero gives an expression for σ_{wrc} for which the normal force for the entire section is zero:

$$N_w + N_{fl} = 0 \quad (8)$$

$$\sigma_{wrc} = -\frac{\sigma_{wrt}}{2} - (\sigma_{frc} + 2\sigma_{frt}) \frac{A_f}{A_w} \quad (9)$$

where:

A_f is the area of the flange: $b \times t_f$.
A_w is the area of the web: $h_w \times t_w$.

The residual stress values are shown in Table 5 for the two sections tested. In view of earlier residual stress models proposed for high-strength hot-rolled sections it can be seen that compressive residual stress at the flange tips for HD sections is similar to that of the ECCS

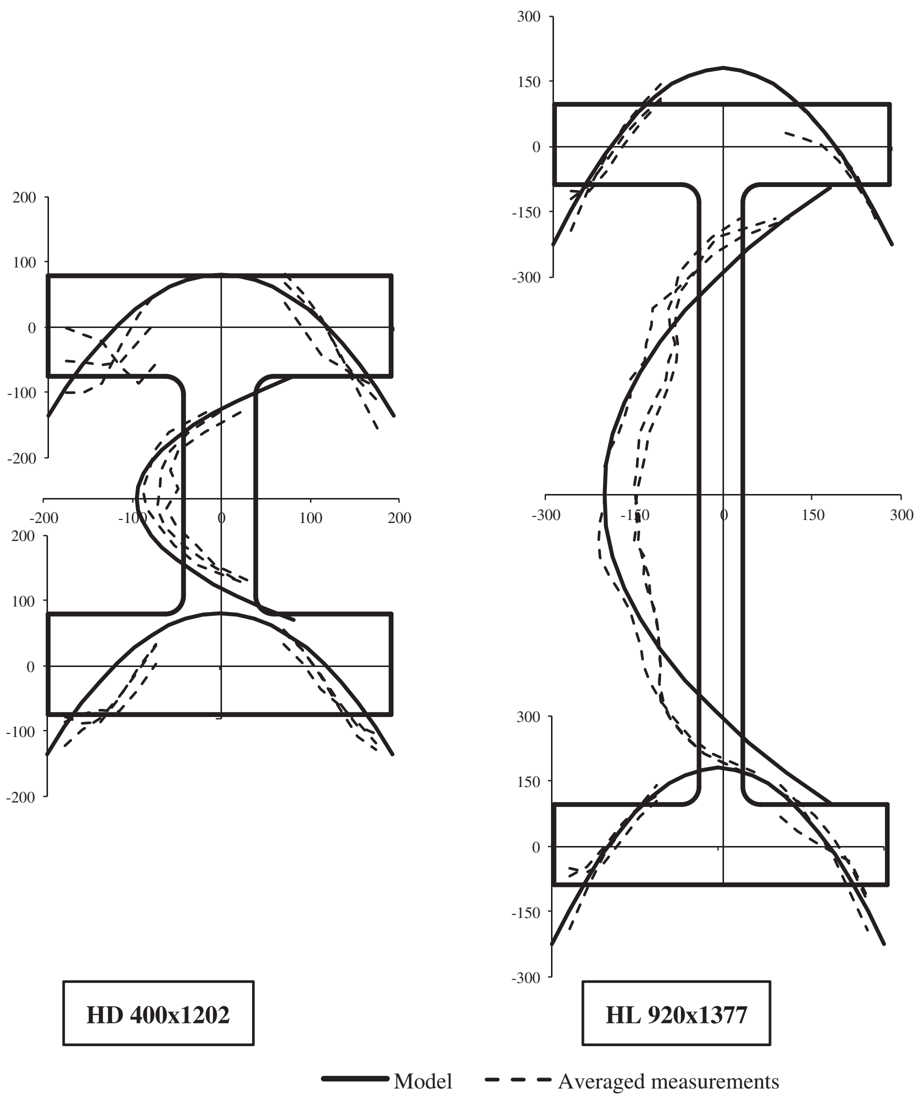


Fig. 11. Comparison between residual stress model and averaged experimental results.

(Fig. 10b). However, the model for HL sections has greater normalized residual stresses at the flange tips.

5. Discussion

5.1. Accuracy residual stress model

A qualitative comparison between the proposed residual stress model and the averaged experimental results is presented in Fig. 11. The surface readings from either side of the flange or web have been used to compute the average residual stress distribution. The residual stress model follows the experimental results quite closely for both section types. Greater discrepancies can be found at the flange tips of the HD 400 × 1202 where the residual stresses are formed by a combination of hot-rolling and straightening.

5.2. Effect of residual stress model

The influence of the residual stress model on the elastic–plastic flexural buckling resistance is largely reflected by the normalized residual stresses at the flange tips. Columns having smaller normalized compressive residual stresses at the flange tips can sustain greater elastic–plastic buckling loads compared to equivalent columns with greater normalized compressive residual stresses. This is especially the case for columns with a relative slenderness between about 0.7 and 2.0 and failing by weak-axis buckling.

These trends are mirrored in the derivation of buckling curves in ECCS [1]; medium-size hot-rolled sections made from mild steel with compressive residual stresses of $0.5f_y$ were assigned to buckling curve “c” for the weak axis buckling case. The elastic–plastic buckling response of hot-rolled sections failing by strong-axis buckling with compressive residual stresses of $0.3f_y$ was best represented by buckling curve “a”.

When extending these conclusions to the present study it can be expected that the residual stresses will have the greatest effect on HL sections failing by weak-axis buckling. The influence of residual stresses will be the smallest for HD sections failing by strong-axis buckling.

6. Conclusions

This paper presented the results of residual stress measurements conducted on heavy quenched and self-tempered (QST) sections made from high-strength steel which combine high strength with good toughness and weldability. These sections are manufactured by ArcelorMittal under the proprietary name HISTAR (HIgh-STrength ARcelorMittal). The residual stress measurements are part of a larger study on buckling curves for these sections as they are currently not covered by the European code.

Two different sections with flange thicknesses greater than 100 mm and height-to-width ratios greater than 1.2 were investigated. A stockier type of section (HD) and a more slender type (HL) were investigated. The investigated sections were a HD 400 × 1202 section and a HL 920 × 1377 section made of HISTAR 460. The sectioning

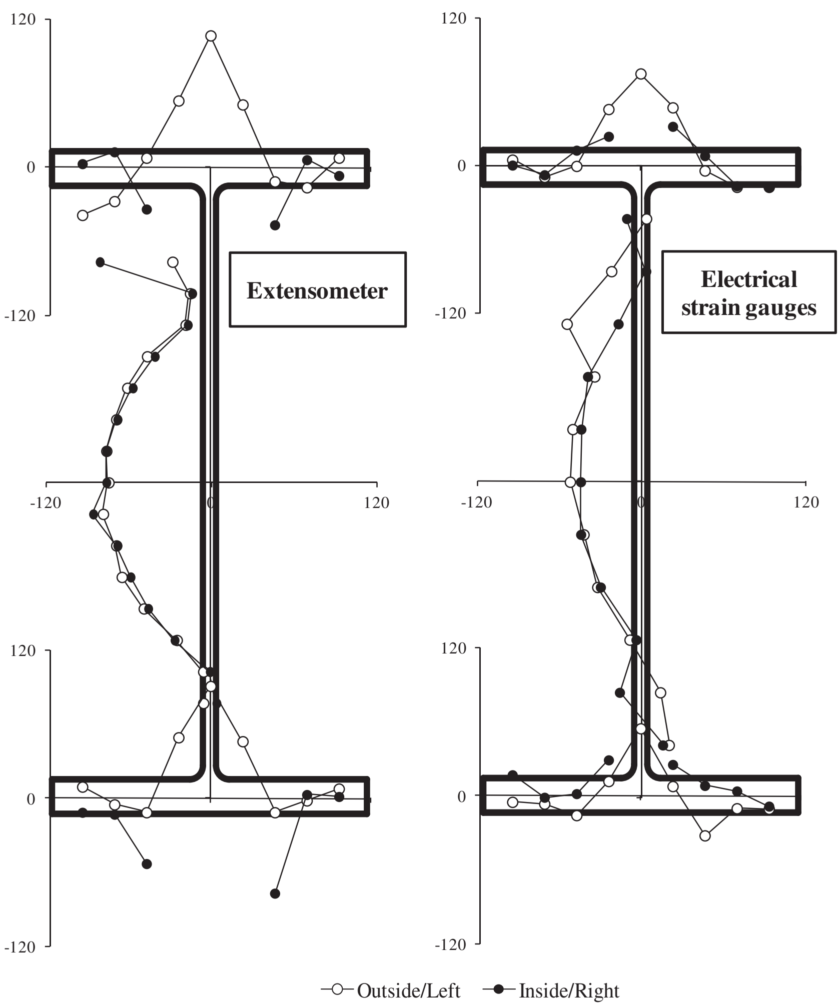


Fig. 12. Comparison of residual stresses from extensomter and electrical strain gauges for IPE 240.

method together with a mechanical gauge was used to measure residual stresses. From the experimental results it was found that the flange tips and the centre of the web displayed compressive residual stresses. Tensile residual stresses were observed in the web and flange near the web-to-flange junction. The extreme values of residual stresses were greater in the HL type compared to the HD type.

A residual stress model was proposed for both section types based on the experimental results. This model can serve as the initial stress state for non-linear finite element analyses to compute e.g. the ultimate flexural buckling resistance of columns. The residual stress model was featured by a parabolic shape in the flanges and the web. The stress values in the model were chosen such that the internal equilibrium requirements were met. The residual stress model is applicable to heavy wide flange sections with similar dimensions and produced with identical methods as those investigated in the paper.

As the compressive residual stresses in the flange tips of HL sections are greater than in HD sections it is expected that the effect of residual stresses on the elastic–plastic bucking response will be less profound for the latter.

Acknowledgments

All residual stress measurements were conducted at the Pieter van Musschenbroek Laboratory at Eindhoven University of Technology, Department of the Built Environment. The authors would like to express their sincere gratitude to T.J. van de Loo, M.P.F. Canters, A.W. van Alen and H.L.M. Wijen for arranging the test-setup and performing the saw-cutting operations.

Appendix A

In order to get insight into the accuracy of the DEMEC extensometer, residual stresses were measured using the extensometer and electrical strain gauges. A medium-size hot-rolled section IPE240 made from steel grade S235 was selected for the investigation. It is known from earlier experiments on measuring residual stresses that electrical strain gauges are able to provide accurate strain readings with the sectioning method. The results are shown in Fig. 12 for both measurement techniques.

It can be seen that the residual stresses using the extensometer are largely similar to those obtained with electrical strain gauges. In view of the scatter of residual stresses along the length of a hot-rolled beam it is therefore concluded that the DEMEC extensometer is able to provide accurate residual stress values and can be used for the heavy wide flange HISTAR sections.

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