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Study of residual stresses in I-section members and cellular members

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Abstract
Cellular or castellated members are steel I-section members with evenly spaced circular or hexagonal web openings. Most of the cellular members used nowadays are made starting from a hot-rolled I-section member, called the parent section. In the production process, the latter member is cut into two halves according to a certain pattern. Cellular members are produced by shifting these halves and welding them together again. Compared to their parent sections, these members have a more optimal material use in strong-axis bending.
Residual stresses are present in both the parent sections and the cellular members. For plain-webbed I-section beams, such as the parent sections, it has been shown that these residual stresses can have a considerable adverse influence on the buckling failure behaviour of the members. It is expected that this will also be the case for cellular or castellated members. However, it is still unknown how the production process of these members will affect the already present residual stresses in the parent sections. This is currently being investigated by the authors in a larger research project about the global buckling failure of cellular members.
This paper presents the authors' experimental research concerning the residual stresses in cellular or castellated members and their parent sections. An overview is given of the results of residual stress measurements in 4 parent sections and 12 cellular members sections, after which these results are compared with literature. This way, an indication can be given of the influence of the production process on the residual stresses and the global buckling behaviour of cellular or castellated members.

1. Introduction

Residual stresses are internal stresses which can exist in a member which is not subjected to external loads. Hence, they are always in internal static equilibrium. Residual stresses can be induced in steel members through two processes during the manufacturing process. Firstly, residual stresses can have a thermal origin, due to uneven cooling and the corresponding differential plastic deformation in the member, originating in the variability of the yield stress with temperature. Secondly, residual stresses can be of mechanical nature, when they are formed because of cold-deformation of the member. An example of the first kind are the residual stresses due to a welding process in a plate (Fig. 1). After welding, the locally heated part of the plate

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will cool last. Upon cooling, it will undergo a thermal contraction, which will be restrained by the cooler and thus stiffer parts of the plate surrounding it. Hence, the region in close vicinity to the weld will be in residual tension, and the other regions of the plate will balance this tension by being in compression. Most of the time, the regions which cool last will be in residual tension, while the others are in compression. An example of the second kind is the loading of a member by its plastic moment M_{pl}, after which it is unloaded elastically (Fig. 2).

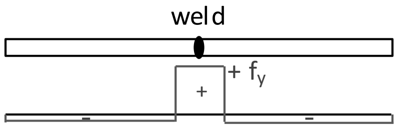

Figure 1. Schematized thermal residual stresses in a welded plate

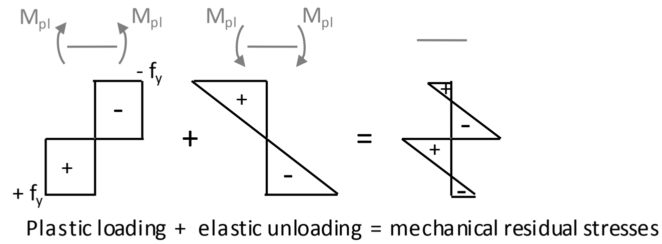

Figure 2. Mechanical residual stresses due to loading of a beam up to the plastic moment M_{pl} and elastic unloading

Residual stresses in hot-rolled I-section members are generated during the cooling process of the beams after having passed through the rolling mill. The flange tips will cool first, entailing a decrease of the yield stress in these parts. The locations where the flange meets the web will cool last. Upon cooling, there will be a thermal contraction at these locations, which will be restrained by the already cooled flange tips. As a result, the flange tips will be in compression and the flange-web intersection will be in tension. Depending on the cross-sectional geometry, initial temperature, material properties and cooling conditions, the residual stresses in the flanges and especially the web vary (Huber, 1956). If the web can cool quickly, there will also be residual compressive stresses in the web center. However, if this is not the case, it is possible that the full web is in residual tension.

After the cooling of the beams, their straightness is measured and they will be cold-straightened if necessary. The incidence of this procedure during production is noticeable by the presence of “yield lines” occurring on the flanges in the finished beam (Fig. 3). These lines are rust lines in the mill scale, inclined at an angle of 45° relative to the length-direction of the beam (Lay, 1969) The straightening procedure will modify the residual stresses once again. As a result, there is a great variability in possible residual stress patterns. However, some standard residual stress patterns were proposed (eg. Fig. 8), taking into account some of the most common production processes and most detrimental residual stress patterns. The effect of cold-straightening was not included, because it was shown that this process has an advantageous effect on the residual stress pattern (cf. infra).

Mostly, residual stresses reduce the ultimate strength of a member, by increasing its flexibility, hence reducing the buckling strength. For I-section members of intermediate slenderness, the compressive stresses at the flange tips have a detrimental effect on the stability of the member, both in compression and bending.

Cellular or castellated members are made from parent sections with an I-cross-section through a cutting, shifting and rewelding process (Fig. 4). This way, an I-section beam with regularly spaced round or hexagonal web openings along its length comes into existence. Both in the cutting and welding processes, heat is induced in the member. Because of these additional processes required, additional variations and uncertainties are induced in the residual stress problem. Hence, it is still unknown how the production process of the cellular members will affect the already present residual stresses in the parent sections. However, it is possible that the resulting residual stress pattern in cellular members is more disadvantageous for the member instability than the original residual stress pattern. This is currently being investigated by the authors in a larger research project where the influence of the production process and openings of cellular members on their global buckling failure is being investigated experimentally and numerically.

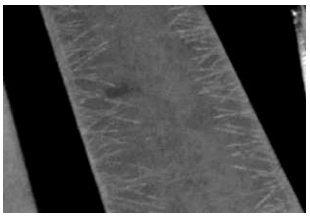

Figure 3. Yield lines in the flanges of tested members

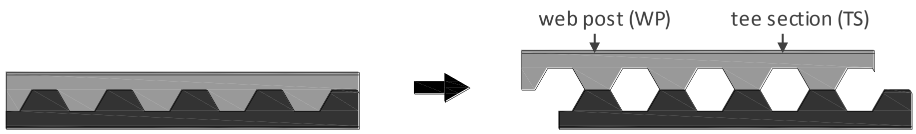

Figure 4. Fabrication of a castellated member starting from a plain-webbed parent section

In this paper, the executed experimental study of the residual stresses in cellular members and their parent section members will be described. An overview of the measurements made in 4 parent sections and at 12 different locations in cellular and castellated members will be given. Subsequently, the results for the parent sections will be compared with known results for I-section members residual stresses from literature. Finally, the effect of the production process on the residual stresses in cellular members will be considered, as well as their effect on member instability. This way, a first estimate of the effect of the production process on cellular member instability can be made.

In the next paragraph an overview will be given of existing research about residual stresses in hot-rolled I-section members. The possible measurement techniques will be reviewed and a short overview of existing results for I-section and cellular members will be given. Subsequently, the experimental procedures and the production of the specimens will be described. Next, an overview of the results of the residual stress measurements will be given, after which these results will be compared with the earlier results to confirm their validity. Finally, an estimate will be made of the effect of the present residual stresses on the buckling behavior of castellated members.

In the remainder of this paper, positive stresses will indicate tensile stresses, while negative stresses will be compressive, unless explicitly stated otherwise.

2. Existing Research

This section covers the research concerning residual stresses done in the past by various authors. Firstly, the possible experimental techniques to measure residual stresses will be discussed. Subsequently, an overview will be given of residual stress measurement results for hot-rolled I-sections. Finally, some preliminary research about residual stresses in cellular members, done at the Laboratory for Research on Structural Models (LMO) will be discussed.

2.1 Residual stress measurement techniques

Before beginning with the experimental study, several residual stress measurement techniques were considered. These techniques can be divided into two subgroups: destructive and non-destructive ones. A good overview of the possible techniques is given in (Withers, 2008) and (Tebedge, 1971). The destructive methods can also be described as relaxation methods, in which the strain up to relaxation is measured instead of a direct measurement of the residual stress. For this (partial) relaxation a disturbance of the residual stress pattern is necessary by removal of material from the specimen. The non-destructive methods are physical methods, in which a physical parameter related to the stress in the material is measured, such as (among others) the conductivity, magnetic properties and the diffraction in the material. Factors in choosing the appropriate measurement method were the relatively large required penetration depth (5-15 mm) and spatial resolution (5-10 mm).

In order to save material and to facilitate the examination of a large number of cellular members, it was first verified whether we could use non-destructive techniques. However, taking into account the required penetration depth and the feasibility and cost of the measurements, none of the non-destructive methods were found suitable.

For the destructive methods, three methods suited the required penetration depth: the contour method, the deep hole drilling method and the sectioning method. In the contour method, the specimen is cut into two at the location where the residual stresses need to be measured. Subsequently, the deformations of the cut surfaces are measured. Using a finite element procedure, the stresses necessary to regain a flat surface are calculated, thus obtaining the residual stresses (Prime, 2001). For this method, very precise cutting and measurement techniques are required.

In the deep-hole drilling method, the drilling of a hole in a stress field results in the elastic deformations in its vicinity. Measuring the strains around the opening (e.g. with an electrical strain gage rosette) allows for the calculation of residual stresses around the opening.

The sectioning method is the oldest of all residual stress measurement methods. In this method, the beam is cut into different longitudinal sections by a series of transverse and longitudinal cuts (Fig. 5). By measuring the strain difference before and after the cut, the longitudinal stress in each section can be calculated. This method is used most often for residual stress measurement in steel members (cf. §2.2). The last method was chosen to perform the measurements because of the longstanding experience of our laboratory with this method, as well as its straightforwardness and proven suitability for the longitudinal residual stress measurement in steel members.

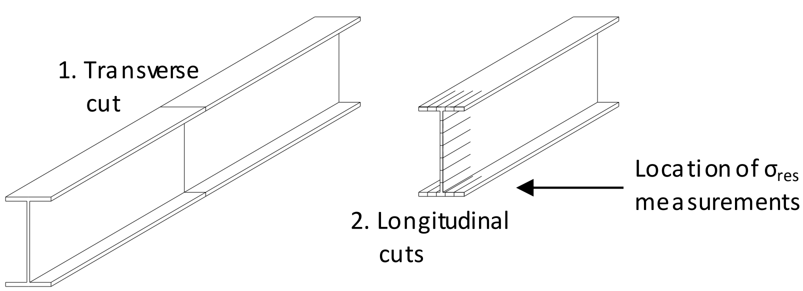

Figure 5. Overview of the cutting during the sectioning method

2.2 Residual stresses in hot-rolled I-section members

In 1946, the Column Research Council (the former SSRC) recommended that the effect of residual stresses on the strength of compression members should be studied (Beedle, 1951), because experiments had shown that, for certain conditions, residual stresses could have a detrimental effect on the strength of these members. On account of this recommendation, research at Lehigh started on the influence of residual stresses on the column strength of hot-rolled I-section members. The results of this research are summarized in(Beedle 1960). More details can be found in (Huber, 1953), (Huber, 1954), (Huber, 1956) and (Beedle, 1957). The most important results of this research will be summarized in the following paragraphs.

It was found that the thermal residual stresses along the flange varied parabolically, with compressive stresses at the edges and tensile stress at the center. The sign of the stresses in the web depended on the cross-sectional dimensions. The variation of the thermal residual stresses was small along one member. While the variation in residual stresses in material from one ingot was still relatively small, there were larger variations for members from different lots. The largest variations occurred for the webs, while the compressive flange tip stresses were relatively constant. Little variation of the flange stresses in thickness direction was found, provided that the thickness of the flanges was small. Additionally, it was demonstrated that the thermal residual stresses due to the hot-rolling process were independent of the yield strength of the steel.

The majority of the measured residual stresses were thermal residual stresses, but some measurements were also done on cold-straightened sections. It was found that there was a good qualitative agreement between the stresses in these sections and the theoretical cold-straightening residual stress distributions. Furthermore, it was shown that the thermal residual stress pattern was conservative, the cold-bending residual stresses being not more critical than the thermal residual stresses. Later, it was confirmed by other researchers that the stresses in cold-straightened sections were lower, hence diminishing the effect of the residual stresses on column instability (Jez-Gala 1962), (Lay, 1969), (Frey, 1969) and (Alpsten, 1975).

Through theoretical analysis, which was confirmed with experiments, it was shown that the residual stresses could have a considerable detrimental influence on the buckling strength of columns, their influence being more pronounced for weak-axis buckling. The reduction in column strength is larger if the compressed region of the flanges is bigger.

In Table 1, an overview is given of the extreme values of the measured thermal residual stresses, in which a distinction was made between beams and columns on the basis of their height-to-width ratio h/b (Beedle, 1960). It can be seen that the compressive flange edge stresses are larger for columns than for beams. This is caused by the faster cooling of the flange edges for the beam type sections. For the beams, the web will be relatively higher and it will cool quicker, resulting in compressive stresses in both web centers and flange tips, which will result in lower flange tip compressive stresses.

In the above research, the sectioning method was used to determine the residual stresses. For the majority of the experiments, measurements of the strain were done mechanically with a Whittemore strain gage over a gage length with a magnitude of about 10" or 25 cm. However, in some experiments, smaller strain gages were used. In (Huber, 1956), a 1" length electrical strain gage was used to determine the residual strain. It was found that there was no substantial difference with the 10” mechanical gage length measurements.

Table 1: Thermal residual stresses obtained during study in (Beedle, 1960)

σ_{res} in Mpa[1]	Flange Edge			Flange Center			Web Center		
	max	avg	min	max	avg	min	max	avg	min
columns (h/b≤1.5)	-53	-88	-129	114	32	-28	125	55	-107
beams (h/b>1.5)	-28	-52	-74	167	104	57	-61	-150	-283

1. Values converted from ksi to MPa.

Up to here, all mentioned research examined the influence of residual stresses on column buckling. However, in (Galambos, 1963) the detrimental influence of residual stresses on the lateral-torsional buckling behaviour of I-section beams is illustrated as well. By not taking into account the effect of residual stresses on the loss of stifness of the beam, results that are up to 30% unsafe could be obtained.

Results of four Belgian residual stress measurements are given in (Mas, 1966). There, it was seen that the residual stresses in more compact cross-sections with a thicker web and flanges were less severe, because of the slower cooling of the cross-section after hot-rolling. In (Lay, 1969), a very good overview is given of the knowledge up to then about residual stresses and their effect on column buckling. The results of residual stress measurements executed in Italy are given in (Daddi, 1971). Because of the straightening process, there was a large variation in possible residual stress patterns. Here, it was proposed to base the residual stress patterns on the envelope of possible residual stresses in the flanges, and to calculate the residual stress in the web based on equilibrium conditions.

In (Young, 1975), results of residual stress measurements on British non-cold-straightened and cold-straightened hot-rolled members are given. Based on these measurements and on available measurements from literature, Young proposed a residual stress model for all I-shapes, for which the amplitudes could be calculated based on the ratio of the web area to the total flange area A_W/A_F (Fig. 6). Also shown in this figure is the residual stress pattern that was then utilized for American sections. The main difference between both patterns are the stresses in the web, which was due to the different cooling conditions in British and American rolling mills: in British rolling mills, the webs could cool quicker since the sections were spaced apart more than in American mills.

In (Alpsten, 1975), the effect of straightening by rotorizing was studied extensively for Swedish hot-rolled members. It was found that the roller-straightening procedure redistributed the unfavorable thermal residual stresses and increased the yield strength. Because of this, an increase in column strength of up to 20% could be obtained from a suitable rotorizing procedure. Because of the important economic benefits, Alpsten suggested to take this advantageous effect into account by optimizing this procedure and using adapted column curves.

However, in the Manual on Stability of steel Structures from the ECCS (European Convention for Constructional Steelwork), the column buckling curves were calculated by taking into account only the thermal residual stresses, thus neglecting the advantageous (but more difficult to predict) effect of the straightening operations (ECCS 1976). A distinction was made between sections with a height-to-width ratio h/b ≤1.2 and h/b>1.2, with corresponding residual stress magnitudes of 0.5*235MPa and 0.3*235MPa. In (ECCS 1984), the residual stress patterns for hot-rolled sections are repeated (Fig. 7). These patterns are nowadays predominantly used as the residual stress pattern valid for hot-rolled beams in numerical simulations.

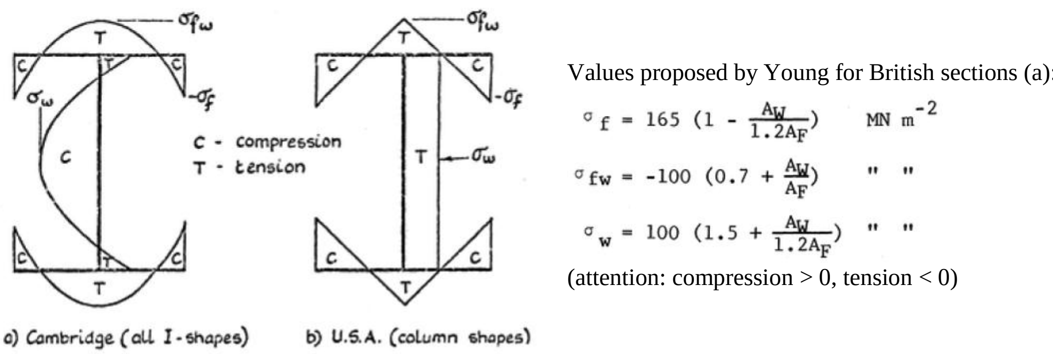

Figure 6. Residual stress distribution proposed by Young for British sections (a) and existing residual stress pattern used for American sections (b). Extracted from (Young, 1975)

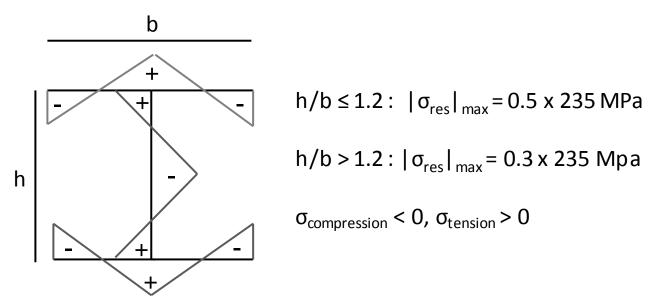

Figure 7. The ECCS residual stress pattern for hot-rolled members.

A more recent measurement of residual stresses was made in (Spoorenberg, 2010). Here, electrical strain gages were used. The results of these measurements are quite typical and the effect of the cold-straightening of the beams was noticeable in most measurements.

2.3 Residual stresses in cellular members

Cellular members are made from I-section members through a thermal cutting and welding process. Both processes will modify the residual stresses present in the parent section, because of the necessary rearranging of the residual stresses due to equilibrium requirements and the local heat induced during the cutting and welding process. The cutting process is usually a thermal cutting process, such as an oxyfuel or plasma cutting process, while the welding process is usually a semiautomatic gas metal arc welding process. The focus in this paper will be on the oxyfuel cutting process and the Metal Active Gas (MAG) welding process, since these were used during the production of the tested specimens.

The heat distribution during the welding and cutting process was studied mathematically in (Rosenthal, 1941). Due to the welding, the deposited molten weld metal will heat the surrounding base material and the welded plate. According to Rosenthal, for the same welding conditions, the heat affected zone will be larger in thin plates than in thick plates. The width of the plate only has an effect on the general rise in temperature after welding, and not the behavior in the proximity of the weld.

In (Nagaraja Rao, 1960), the residual stresses in plates due to welding are studied. The most important influence factors are the geometry of the plate, the welding type, welding speed and cooling rate. It was found that the residual stresses at the weld are very high tensile stresses (close to the yield strength of the weld, which can be higher than the yield strength of the bulk material) and that the stresses in the other parts of the plate balanced these tensile stresses (e.g. Fig. 1). For thin plates (i.e. with a thickness smaller than 0.5") the residual stress distribution in thickness direction was found to be uniform. Furthermore, the effect of multiple weld passes was studied: it was shown that the variation of residual stresses in welded plates between successive passes was low. Hence, the first weld pass caused the major portion of the residual stress.

In (Beedle, 1960), the effect of residual stresses in built-up I-section members on the column buckling strength was described. It was shown that very high tensile stresses were present in the surroundings of the welds (at the ends of the web plate), which were countered by compressive stresses in the remainder of the section. A typical residual stress distribution is shown in Fig. 8. The tensile stresses will be close to the yield point. The buckling strength of these members in compression was appreciably lower than for hot-rolled members, because of the large zone with compressive stresses in the flanges.

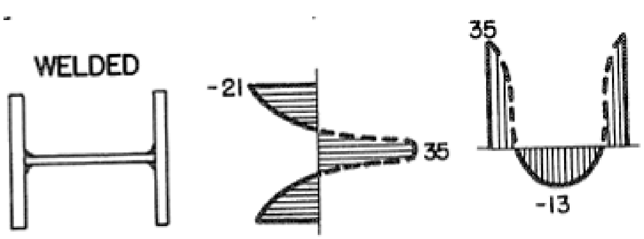

Figure 8: typical residual stress shape for built-up I-sections. stresses are given in ksi (1 ksi≈6.9 MPa). Extracted from (Beedle, 1960)

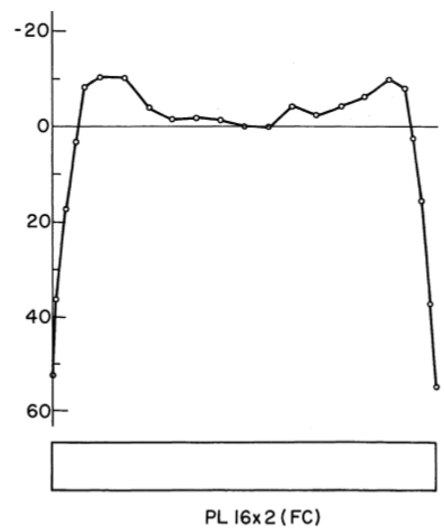

Figure 9: residual stresses in flame-cut thick plate (thickness 2"). Stresses in ksi (1 ksi≈6.9 MPa). Extracted from (Alpsten, 1969)

The heat distribution of welded plates is further studied in (Tall, 1961) and (Nagaraja Rao, 1963). The former was a theoretical study, in which the thermal residual stress formation due to welding was studied, while the latter comprises residual stress measurements in welded shapes. In the latter study, the effect of edge preparations such as flame-cutting was studied. It was shown that these edge preparations have little influence on the final residual stresses in welded shape, since the effects of the welding operation are dominant.

In (Alpsten,69), the results of the Lehigh University study about residual stresses in heavy welded shapes and thick welded plates are summarized. It is concluded that the major influence on the residual stresses is the geometry of the welded plates and cross-sections. Furthermore, the residual stresses in these shapes tend to decrease with increasing member size, because the relative heat input will be smaller. Measurements of residual stresses in thick flame-cut plates are also given: the tensile residual stresses are very high at the flanges, and are balanced with compressive residual stresses near the center (Fig. 9). In (Lay, 69) residual stresses due to gas-cutting are mentioned, as well as the presence of tensile residual stresses at the cut, similar as for a welded edge plate. However, no quantitative data are given. Very limited data was found on the formation of residual stresses during the thermal cutting process in thinner plates.

Similar as for welded plates and fabricate I-sections, it is to be expected that the local heat input during both the cutting and welding process will have some influence on the residual stresses of castellated and cellular members. These production processes can have an additional detrimental influence on the residual stresses, e.g. if the welding in the center of the web increases the compressive residual stresses in the web.

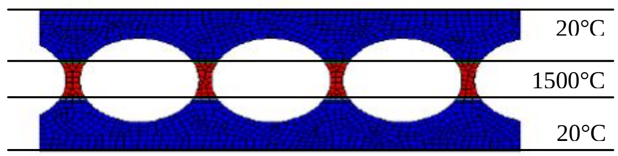

Figure 10. Heated zone in the web between two openings. Extracted from (Boey, 2011)

A preliminary study of the effect of the production process of cellular members on their residual stresses was done at the LMO (Boey, 2011), by means of a numerical study for 16 different cellular member geometries with steel grade S235. The effect of the heat input due to the cutting process was neglected in this study, while the welding process was studied by simplified simulations in Abaqus. The heat input during this processes was simulated by defining a heated zone (with a temperature of 1500°C) at the location of the weld (Fig. 10). In a thermal analysis, the temperature variation in the member was found, which was imported in a mechanical analysis with temperature dependent material properties. The height of the heated zone between the openings in the web was taken equal to half the height of the opening. In the mechanical simulations, the residual stress patterns in the parent sections were based on Fig. 7. The results of the simulations showed that the compressive stresses at the flange tips in the area above the openings could increase because of the production process. In the area between the flanges, the magnitude of the flange tip compressive stresses decreased. Taking into account the most detrimental residual stress patterns that could be derived from the results, the magnitude of the compressive residual stresses could increase with 50 MPa, which has an adverse effect on the member stability. It should be emphasized that these results are very preliminary, and that they should be confirmed by further numerical and experimental research.

3. Experimental work

In this part an overview will be given of the tested specimens and their production method, as well as the used measurement method, which is the sectioning method. Due to practical constraints, only a limited number of specimens could be studied experimentally. The results of this experimental study will be used to validate a finite element model, which will be used in a much wider parametric study.

3.1 Parent sections and material

The two cellular and two castellated members were constructed from IPE160 parent sections, of which the nominal dimensions are given in Fig. 11. The steel has a steel grade S275 with a characteristic yield stress of 275 MPa. The nominal Young's modulus used in the calculations is 210 GPa. Tensile tests to determine the actual modulus of elasticity and yield stress are in progress. According to (Simões da Silva, 2009), the mean yield stress for the S275 steel grade and the thickness t≤16 mm is 327.07 MPa, while the standard deviation of the yield stress is 18.63 MPa.

In total, four different IPE160 beams of 12 m length were used for the parent sections. Yield lines, presumably from cold straightening were present in the beams' flanges (Fig. 3). The distribution of the yield lines in the flanges was uniform along the length of the members, so it was expected that the effect of cold straightening would also be uniform along the members' length.

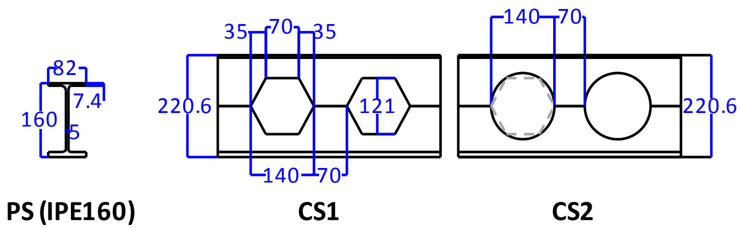

Figure 11. Dimensions of the parent section PS, CS1 and CS2 (in mm)

3.2 Fabrication of the cellular members and specimens

The castellated and cellular beams were fabricated at Huys NV, Venlo (Holland). Before the production of the castellated and cellular beams started, a piece of 1 m long was cut from each beam, in order to have specimens for the residual stress measurements on the parent sections.

From two of the IPE160 beams, castellated beams were made (CS1 in Fig. 11), and from the other two beams, cellular beams were made (CS2 in Fig. 11). The cellular beams were made starting from castellated beams by cutting circular openings around the original hexagonal openings in the castellated beam (Fig. 12). This production procedure is one of the possible production procedures of cellular members. However, more often used is the procedure in which cellular members are constructed directly from the parent section, by using a modified cutting pattern. It is expected that the effect on the resulting residual stress pattern of the latter procedure and the production procedure of castellated beams with regular hexagonal openings is similar.

For the production of the two cellular members, the same original castellated member geometry was used as for the two castellated members. As a result, the production at Huys NV started with the cutting of all four IPE160 parent section webs according to a pattern corresponding with a castellated beam with regular hexagonal openings (CS1 in Fig. 11). The cutting process was an oxyfuel cutting process with an oxygen-acetylene mixture as fuel gas.

Figure 12. Production process. Left: cutting of the castellated beams. Middle: welding of the castellated beam. Right: cutting of the round openings for the cellular beams

After the cutting of the hexagonal pattern in the web, the obtained beam halves were shifted and welded together. The welding process was a semiautomatic MAG welding process, in which the shielding gas was a mixture of 85% Argon and 15% CO_2. The weld joint type was a but joint existing of two weld passes, one for each side of the web. For one of the castellated members, a section was left unwelded, so that the influence of the cutting process alone on the residual stresses could be measured (CS1L1_AC in Fig. 13).

After the welding, the two castellated beams (CS1L1 and CS1L2) were completed. However, the two cellular members (CS2L1 and CS2L2) still had to be constructed starting from the remaining two castellated beams. In the web of the latter beams, circular openings were cut around the original regular hexagonal openings using the same oxyfuel cutting process described above. For each web opening, the cutting procedure had to be restarted: the web material had to be heated until ignition temperature (1200 K according to (Powell, 2009)), after which the oxidation of the steel started and the cut was made. Because of this, there was a larger heat input in this process than in the cutting process used for the original cutting of the castellated web. After the cutting of the round openings in the two castellated members, the two cellular members were completed as well.

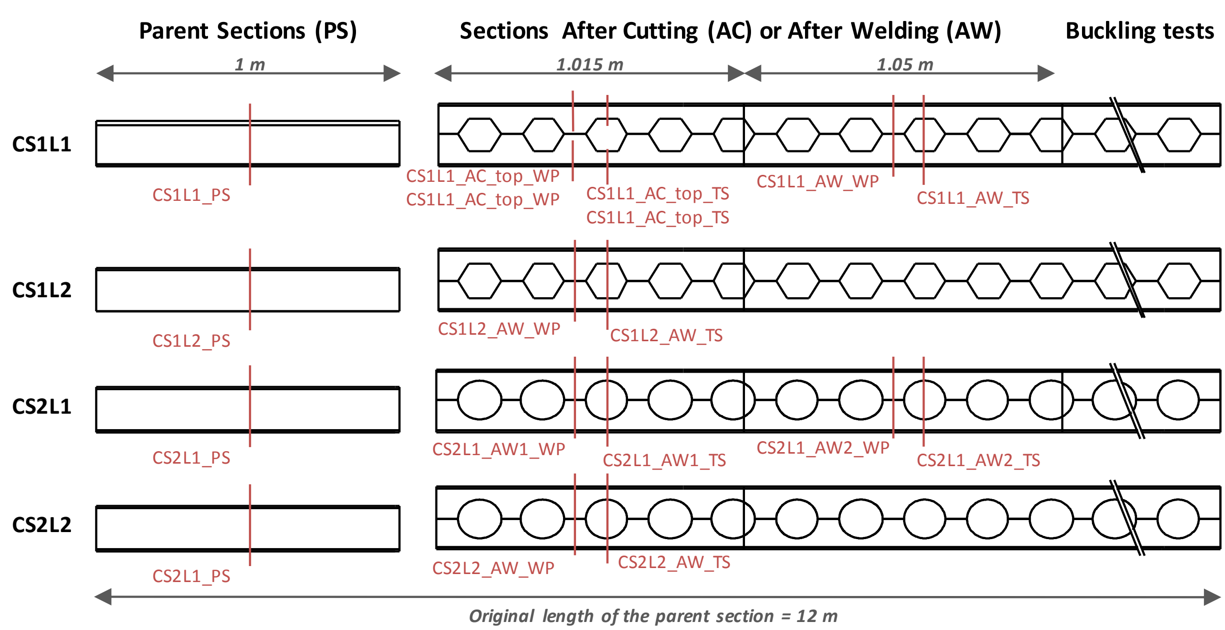

Figure 13. Residual stress specimens. The location of the strain measurements is shown in red and the cuts between the different specimens are shown in black.

After completion, the four completed castellated and cellular members where cut into shorter (length ca. 1 m) and longer (length 3.3-6.3 m) sections, the former to be used for the residual stress measurements and the latter to be used for flexural and lateral-torsional buckling tests. The sections destined for the residual stress measurements were located at the same end as the original parent beam sections (Fig. 13). In each parent section specimen, the residual stresses were only measured at one location: in the middle of the beam. In each cellular or castellated member specimen, residual stress measurements were done simultaneously at two locations, at the cross-section between the openings (the web post WP) and at the cross-section at the center of an opening (the tee section TS). The length of the specimens was chosen so that the distance between the locations of measurement and the length of the beam was at least twice the height of the beam. This way edge effects, which could disturb the residual stress patterns, are avoided.

3.3 Residual stress measurement by the sectioning method

As mentioned in section 2.1, the sectioning method was chosen because of its straightforwardness for longitudinal residual stress measurement. As a result, this method has been used primarily for the residual stress measurement in I-section beams. The sectioning method is a relaxation method, where the strain is measured in a longitudinal segment before and after its relaxation. The relaxation of each segment is accomplished by sectioning the member: first the member is cut in transverse direction, after which longitudinal cuts are made to separate all segments (Fig. 5). The residual stress σ_{res} was calculated from the measured residual strain ε_{meas} by Eq. 1. This formula was derived under the assumption of an elastic behavior of the specimen during the test and the assumption that the transverse residual stresses could be neglected. Furthermore, it was assumed that the induced thermal stresses due to the cutting process are negligible. If the segment undergoes a contraction (ε_{meas} <0), this means that residual tensile stresses (σ_{res} >0) were present in the segment and vice versa.

$$\sigma_{res} = -E.\varepsilon_{meas} \quad (1)$$

For the cellular and castellated members, the residual stress was expected to be different in cross-sections at the web post and at the tee section, and to vary between these two patterns. As a result, a relatively small gage length was necessary to measure the residual stresses at these two locations. Consequently, electrical strain gages, with a linear pattern and a gage length of 3.18 mm were used to measure the residual strains. By using electrical strain gages, a complete overview of the variation of residual strains during the complete sectioning procedure was obtained.

The electrical strain gages were adhesively bonded to the surface where the strain has to be measured, so that the strain at the surface is the strain in the strain gage. The strain gage consists of plastic backing on which a metal foil pattern is mounted. The relative electrical resistance of the strain gage changes linearly with the strain in the strain gage, so by measuring the resistance change of the strain gage, the strain can be determined. The resistance change is measured by connecting the strain gage to a Wheatstone bridge, thus transforming the relative resistance change in voltage change which can be measured.

For each of the parent sections, 15 strain gages were used for the residual stress measurement: five strain gages for the web and five for each flange. These strain gages were divided over the width of the flange and the height of the web and their location can be seen schematically in Figures 14-17. All measurements were done on the outside flanges and on the right side of the web. The order in which the longitudinal cuts were made was predetermined for all specimens and was as symmetrical as possible. During the cuts, a cutting fluid was used to limit the local heating of the specimens. The strain gages were protected from the cutting oil with a protective coating.

The cutting process was executed with an electrical band saw, combined with a handsaw for some of the transverse cuts. During this process, the measured strains were recorded and monitored continuously, to make sure that there was no damaging or malfunctioning of the electrical strain gages because of the multiple manipulations of the specimen. However, some of the strain gages got permanently damaged during the test: of the total of 240 used strain gages, 21 were found faulty due to damage during the measuring process. The measured strains in these gages (if any) were not included in the final results.

4. Results and discussion

4.1 Results of the residual stress measurements

The results of the residual stress measurements are given in Figures 14-17, in which the measured values of the residual stresses are depicted, together with least-square fit (LSF) curves for the results in the web and the flanges. The curves were obtained by mirroring all results about the horizontal and vertical symmetry axes and using a least square algorithm with a quadratic function for the web and the flanges, supplemented with a linear curve for the flanges.
The extreme compressive (<0) and tensile (>0) residual stresses are given in Table 2, for both flanges and web. For the flanges, the extreme values of the LSF curves are given as well. For the web, the extreme values of the LSF curves are only given for the parent sections. The number of measurements in Table 2 includes the strain gages which were later found to be faulty. However, the values at these strain gages are not included in the results nor in the figures.

4.2 Discussion and comparison with existing results

The measured residual stress in the parent sections (Fig.14) is consistent with the earlier measurements from literature and with the residual stress pattern proposed by Young (Fig. 6 with σ_w=-202 MPa; σ_w=133 MPa; σ_f=-78 MPa) and the ECCS (Fig. 7 with h/b=1.95). Additionally, the measured stresses are very similar for the four tested parent sections. While yield lines were noticeable in the flanges of the specimens, no influence of cold-straightening of the beams was observed. The measured stresses lie very closely together, suggesting that all parent sections came from the same batch.

The influence of the oxyfuel cutting of the parent sections on the residual stresses is depicted in Fig. 15. The influence of the thermal cutting on the flange stresses is rather limited. In the web, some influence of the cutting process can be noticed: the stresses at the center of the web increase. However, no definitive conclusions can be drawn, considering the limited number of measurements and the variability of the residual stresses in the web. Further measurements will be needed to study the effect of the cutting process experimentally.

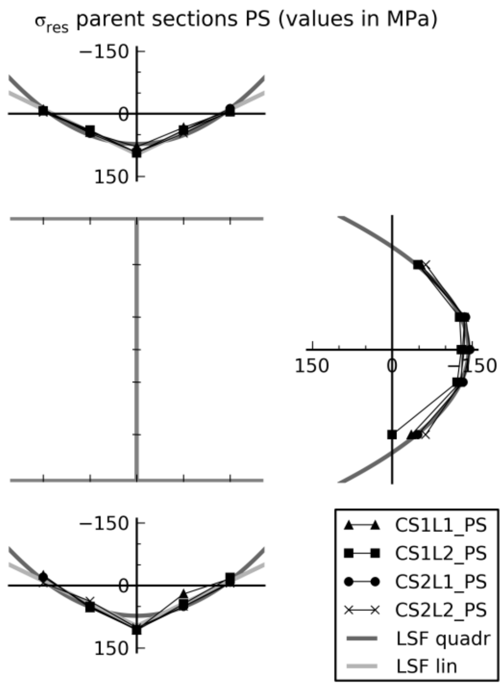

Figure 14. Residual stresses in the parent sections with different least square fits (LSF)

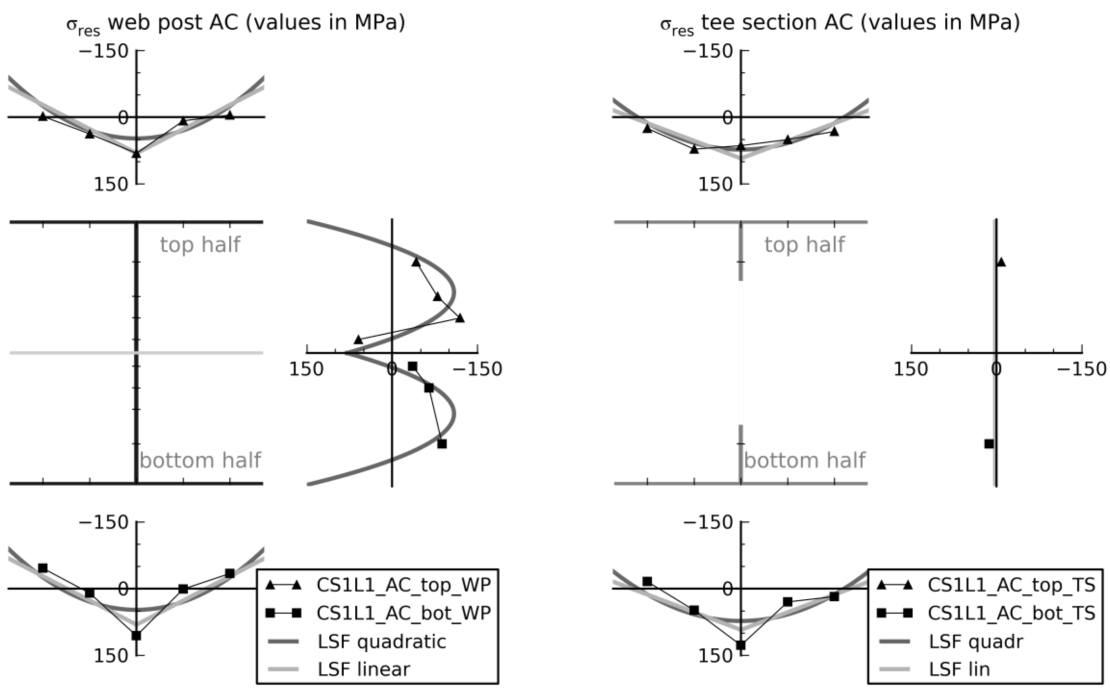

Figure 15. Residual stresses in the cellular member CS1 after cutting (AC) and before welding, with different least square fits (LSF)

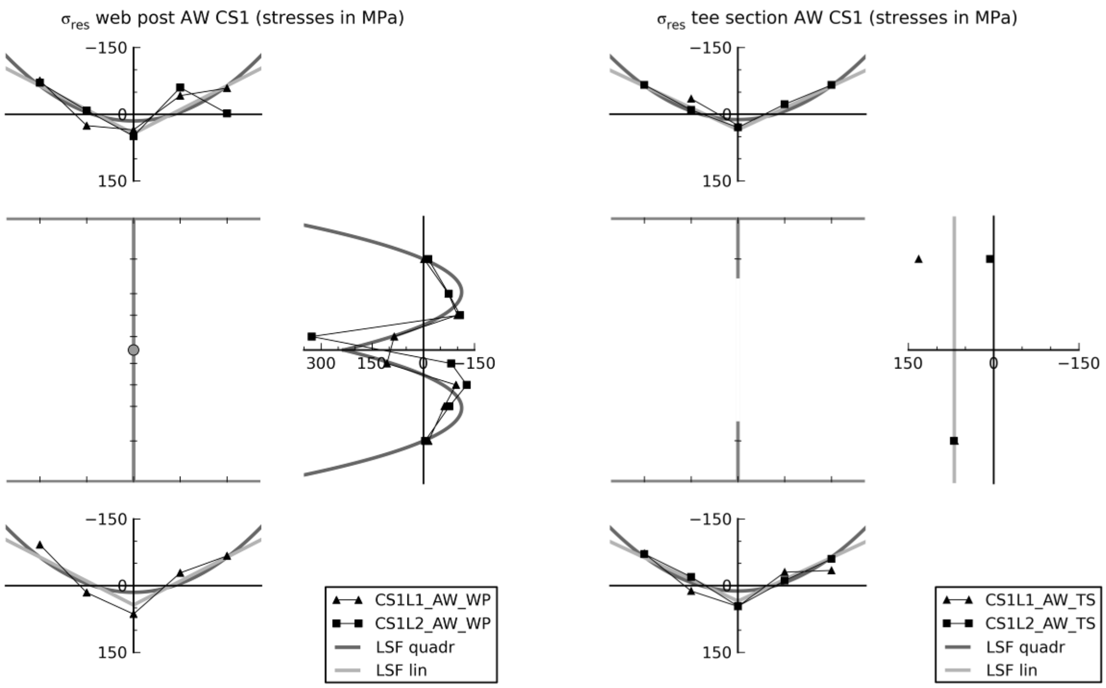

Figure 16. Residual stresses in the castellated member specimens CS1, after welding (AW), with different least square fits (LSF)

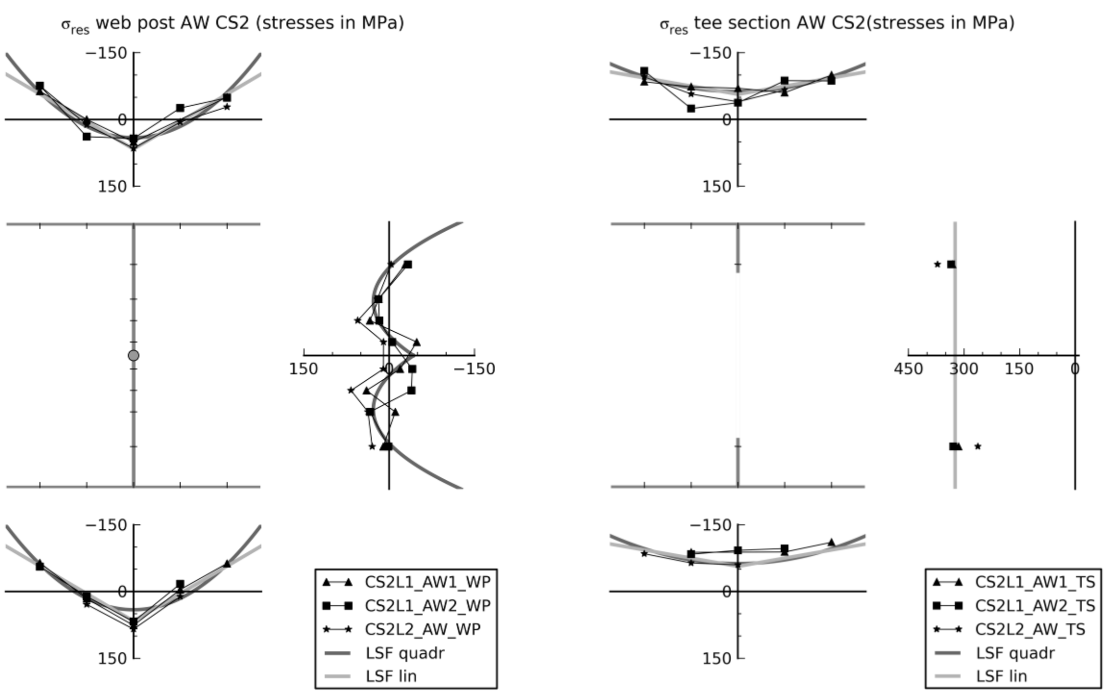

Figure 17. Residual stresses in the cellular member specimens CS2, after welding (AW), with different least square fits (LSF)

Table 2: Residual stress measurement results

Parent sections (PS)		# meas.[1]	measured values		quadratic LSF		linear LSF	
			$\sigma_{res,min}$	$\sigma_{res,max}$	$\sigma_{res,\ quadr\ LSF,\ min}$	$\sigma_{res,\ quadr\ LSF,\ max}$	$\sigma_{res,\ lin\ LSF,\ min}$	$\sigma_{res,\ lin\ LSF,\ max}$
	flange	8x5	-25	107	-87	72	-51	97
	web	4x5	-146	0	-143	98	-	-

Sections after cutting (AC)		# meas.[1]	measured values		quadratic LSF		linear LSF	
			$\sigma_{res,min}$	$\sigma_{res,max}$	$\sigma_{res,\ quadr\ LSF,\ min}$	$\sigma_{res,\ quadr\ LSF,\ max}$	$\sigma_{res,\ lin\ LSF,\ min}$	$\sigma_{res,\ lin\ LSF,\ max}$
CS1 AC, TS	flange	2x5	-16	127	-39	73	-16	93
	web	1x2	-8	13	-	-	-	-
CS1 AC, WP	flange	2x5	-46	106	-89	48	-68	81
	web	1x8	-119	59	-	-	-	-

Sections after welding (AW)		# meas.[1]	measured values		quadratic LSF		linear LSF	
			$\sigma_{res,min}$	$\sigma_{res,max}$	$\sigma_{res,\ quadr\ LSF,\ min}$	$\sigma_{res,\ quadr\ LSF,\ max}$	$\sigma_{res,\ lin\ LSF,\ min}$	$\sigma_{res,\ lin\ LSF,\ max}$
CS1 AW, TS	flange	4x5	-73	47	-131	12	-99	35
	web	2x2	6	132	-	-	-	-
CS2 AW, TS	flange	6x5	-111	-25	-125	-63	-107	-57
	web	3x2	262	371	-	-	-	-
CS1 AW, WP	flange	4x5	-92	64	-133	15	-104	43
	web	2x8	-127	328	-	-	-	-
CS2 AW, WP	flange	6x5	-76	85	-150	41	-102	66
	web	3x8	-48	67	-	-	-	-

1. Including the faulty strain gages

The effect of the welding process on the stresses in the castellated sections CS1 is noticeable: both at the web post and at the tee section, a decrease of the residual stresses between 40 MPa and 70 MPa is visible (Fig. 16). This net increase of compressive stresses is balanced by an increase of the tensile stresses in the web. In the web post, the influence of the welding process is visible, with high tensile residual stresses, close to the nominal yield stress of the steel in some cases. The increase of compressive stresses in both the web post and tee section flanges does not fully comply with the earlier numerical research. Since the amount of experiments was rather limited and the numerical research was quite rough, more measurements and more refined numerical research will be necessary to draw any definitive conclusions.

The additional effect of the cutting of the round openings can be seen in Fig. 17 for CS2. At the tee section, the extra heat input due to the cutting can be seen. In the web, the tensile stresses become very high (larger than the yield stress), which is balanced by large compressive forces in the flange. The flange stresses at the web post have also shifted more towards the compressive side and at the center of the web post, the residual stresses are mostly in compression. At first sight, it is theoretically impossible that the calculated residual stress is higher than the yield stress. However, the real yield stress of the steel has to be taken into account. Currently, tensile tests still have to be executed, but it is known (cf. section 3.1) that the mean yield stress of the used steel is 327.07 MPa, while the standard deviation of the yield stress is 18.63 MPa. Taking this into account, it is possible that the yield stress of the web goes up to 371 MPa. Nevertheless, tensile tests will be executed to ascertain this.

The results for CS1 and CS2 indicate an increase of the compressive stresses in the flanges because of the welding process. For CS2, this is paired with the added detrimental effect of the cutting of the circular openings. Earlier research has shown that these stresses are the most detrimental for the global buckling failure load. As a result, it is expected that the effect of the residual stresses on the failure load of castellated or cellular members is more detrimental than it is for regular I-section members. The magnitude of this influence has to be determined by further research.

A limited influence of the roller-straightening operation is visible in some flanges of the CS1 and CS2 specimens (Figures 15-17), where the residual stresses are slightly asymmetric (eg. in the top flange of CS2L1_AW2_TS, Fig. 17). Since it is expected that the straightening operation reduces the initial residual stresses in the parent sections, the residual stresses could be even more detrimental for the stability if the parent section was not roller-straightened.

5. Further work

All strain measurements done for CS1 will be repeated for a supplementary castellated member cross-section, so that a higher number of tested specimens is obtained, as well as a larger variation in tested geometry. No further residual stress measurements will happen on cellular member geometries of the CS2-production procedure, because it is believed that the used production procedure does not agree with the commonly used production procedure, which could result in unrealistic and uneconomic compressive residual stresses in the flanges. It is believed that the more commonly used cellular member production procedure should give results which are close to the results for the castellated beams. However, this will be checked using finite element simulations.

The obtained results shall be used to validate finite element simulations in which the variation of the thermal residual stresses during the production procedure is studied. Using the validated finite element model, a parametric study will be conducted, based on the results of which a conservative residual stress pattern will be formulated. The obtained residual stress patterns will be used in the larger study of the failure behavior of cellular members and cellular columns, of which the presented study is only a small part.

6. Conclusions

Residual stresses are present both in castellated or cellular members, as in their parent sections. For the parent sections, which are hot-rolled I-section beams, it had been shown that the residual stresses have a detrimental influence on the global buckling behavior of the members. This influence, caused by the presence of compressive residual stresses at the flange tips, becomes larger with increasing magnitude of the flange compressive stresses. However, it was not fully known how the production process of the cellular and castellated members influenced the present residual stresses, an whether it had a detrimental influence on the buckling behavior.

In this paper, the executed study of the residual stresses in castellated and cellular members and their parent sections is described. The study consisted of a literature review of residual stresses in hot-rolled I-sections and their measurement methods, as well as an experimental study with measurements in four parent sections, six castellated member sections and six cellular member sections. For the castellated member, the influence of the cutting and the welding procedures in the production process were considered separately.

The measured residual stresses in the parent sections complied well with what was found in literature. The study showed no major influence of the cutting procedure, but further experimental and numerical research will be necessary to confirm this, given the limited number of tested specimen. However, the influence of the welding operation was quite large, with an increase of the flange compressive stresses. Because of this, the effect of the production procedure on the residual stresses will be detrimental for the global buckling stability. Hence, a further study of these effects is necessary, both experimental as numerical.

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References

Alpsten, G. , Tall, L. (1969). "Residual stresses in heavy welded shapes." *Fritz Laboratory Reports.* Paper 334.

Alpsten, G. A. (1975). Residual Stresses, “Yield Stress and Column Strength of Hot-Rolled and Roller-Straightened Steel Shapes.” *Proceedings IABSE Colloquium: On Column Strength*, Paris. 39-59.

Beedle, L. S. (1951), "Proposal ‘Pilot program on the influence of residual stress on column strength.’" *Fritz Laboratory Reports.* Paper 1501.

Beedle, L. S., Huber, A. W. (1957), "Residual stress and the compressive properties of steel - a summary report." *Fritz Laboratory Reports.* Paper 46.

Beedle, L. S., Tall, L. (1960). “Basic column strength.” *Journal of the Structural Division*, 86(7), 139–173.

Boey, T. (2011). “Numeriek onderzoek naar residuele spanningen in cellulaire elementen en hun invloed op de bezwijklast.” *Master thesis*, Universiteit Gent (in Dutch).

Daddi, I., Mazzolani, F. M. (1971). “Determinazione sperimentale delle imperfezioni strutturali nei profilati di acciaio.” *Costruzioni Metalliche*, 5, 3–23 (in Italian).

ECCS-Committee 8 Stability (1976). “Manual on Stability of Steel Structures.”, ECCS.

ECCS-TC8 Structural Stability. (1984). “Ultimate Limit State Calculations of Sway Frames with Rigid Joints.” ECCS, Brussels.

Frey, F. (1971). “Calcul au flambement des barres industrieles.“ *Bulletin Technique de la Suisse Romande*, 11, 239–258 (in French).

Galambos, T. V. (1963). “Inelastic lateral buckling of beams.” *Journal of the Structural Division ASCE*, 89(236).

Huber, A. W., Beedle, L. S. (1953). “Residual Stress and the Compressive Strength of Steel - Final Report.” *Fritz Laboratory Reports*. No. 220A.9.

Huber, A. W., Beedle, L. S. (1954), "Residual stress and the compressive strength of steel.” *Welding Journal, res. Supl.*, 33 (12), p. 589-614.

Huber, A. W. (1956). "Residual stresses in wide flange beams and columns.” *Fritz Laboratory Reports,* No. 220A.25.

Jez-Gala, C. (1962). “Residual stresses in rolled I-sections”. *Proceedings of the institution of civil engineers (ICE)*, 23(3), 361–378.

Lay, M. G., Ward, R. (1969). “Residual stresses in steel sections”. *Journal of the Australian Institute of Steel Construction*, 3(3), 2–21.

Mas, E., Massonnet, C. E. (1966). “Part prise par la belgique dans les recherches experimentales de la convention europeenne des associations de la construction metallique sur le flambement centriques des barres en acier doux.”. *Acier-stahl-steel*, 9, 393–400 (in French).

Nagaraja Rao, N. R., Tall, L. (1960). “Residual stresses in welded plates.” *Fritz Laboratory Reports,* No. 249.7.

Nagaraja Rao, N. R., Estuar, F. R., Tall, L. (1963). Residual stresses in welded shapes.” *Fritz Laboratory Reports,* No. 249.18.

Powell, J., Petring, D., Kumar, R. V, Al-Mashikhi, S. O., Kaplan, a F. H., Voisey, K. T. (2009). "Laser–oxygen cutting of mild steel: the thermodynamics of the oxidation reaction". *Journal of Physics D: Applied Physics*, 42(1).

Prime, M. B. (2001). "Cross-sectional mapping of residual stresses by measuring the surface contour after a cut". *Journal of Engineering Materials and Technology*, 23 (2), 162-168.

Rosenthal, D. (1941). "Mathematical Theory of Heat Distribution During Welding and Cutting". *Welding Journal, res. Supl.*, 20(5), 220–234.

Simões da Silva, L., Rebelo, C., Nethercot, D. A., Marques, L., Simões, R., Vila Real, P. M. M. (2009). "Statistical evaluation of the lateral–torsional buckling resistance of steel I-beams, Part 2: Variability of steel properties." *Journal of Constructional Steel Research*, 65(4), 832–849.

Spoorenberg, R. C., Snijder, H. H.,Hoenderkamp, J. C. D. (2010). "Experimental investigation of residual stresses in roller bent wide flange steel sections." *Journal of Constructional Steel Research*, 66(6), 737–747.

Tall, L. (1961). Residual stresses in welded plates. A theoretical study." *Fritz Laboratory Reports,* No. 249.11

Tebedge, N., Alpsten, G. A., & Tall, L. (1971). Measurement of residual stresses. A study of methods." *Fritz Laboratory Reports,* No. 337.8.

Withers, P. J., Turski, M., Edwards, L., Bouchard, P. J., Buttle, D. J. (2008). "Recent advances in residual stress measurement." *International Journal of Pressure Vessels and Piping*, 85(3), 118–127.

Young, B. W. (1975). "Residual stresses in hot rolled members." *Proceedings IABSE Colloquium: On Column Strength*, Paris, 25-38.