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Influence of Residual Stresses on the Global Buckling Resistance of Cellular and Castellated Members

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Abstract
Cellular and castellated steel members are usually made starting from a hot-rolled I-section member, of which the web is thermally cut according to a certain pattern. Subsequently, the obtained halves are welded together. Thus, a member with a larger depth and with circular or hexagonal web openings placed regularly along its length is obtained.

In the past, it has been shown for hot-rolled I-section members that residual stresses have a considerable detrimental influence on the global buckling resistance, which is mainly governed by the compressive residual stresses in the flanges. While it was expected that similar effects play a role for cellular and castellated members, it was yet unknown to which extent the residual stresses in these members would be modified by the fabrication procedure. As a result, it was difficult to correctly predict the buckling resistance of cellular or castellated members using numerical simulations.

As part of a more extensive research about the global buckling resistance of cellular and castellated members, the authors have measured the residual stresses in a number of castellated and cellular member specimens. The results of these measurements are summarized in this paper and the influence of different modified residual stress patterns on the weak-axis flexural buckling and lateral torsional buckling resistances is determined. Based on these results, a residual stress pattern valid for castellated and cellular members will be proposed. It will be shown that the fabrication procedure has a considerable effect on the original residual stresses, which will influence the buckling resistance detrimentally.

1. Introduction

Cellular and castellated members are usually made by thermally cutting the web of a hot-rolled I-section member, called the parent section, according to a certain pattern. Subsequently, the obtained halves are shifted and welded together again. Thus, a member with a larger depth and with circular or hexagonal web openings placed regularly along its length is obtained. The main advantage of these members is their increased bending resistance about the strong axis, when

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compared with the original parent section, resulting in a more economic material behaviour. Another advantage is the possibility to guide service ducts through the openings in the castellated or cellular beams instead of underneath them, which decreases the total necessary floor-to-floor height in a building. Lastly, the lighter appearance of these members is also appreciated out of aesthetic considerations. Cellular and castellated members are mostly used as beams, columns and beam-columns (Fig. 1).

Figure 1. Cellular beam applications.

The failure behaviour of cellular and castellated members will differ from the behaviour of plain-webbed members, because of the different geometry and because of the modification of imperfections during the production process. With regard to global buckling failure modes such as lateral-torsional buckling or flexural-buckling, it is expected that mainly the modified geometry and the modified residual stress pattern will influence the global buckling resistance. Nevertheless, the global buckling behaviour of these members will remain similar on a qualitative level. In this paper, only the effect of the modification of the residual stress pattern will be considered. In (Sonck 2014a) a more extensive analysis is provided, which also includes the modified geometry.

For plain-webbed I-section members, the influence of residual stresses on the global buckling resistance was thoroughly examined during the last century. At the initiative of the Column Research Council, a measuring campaign, supplemented with numerical and experimental investigations, was started to investigate residual stresses and their effect on the flexural buckling resistance of columns (Beedle 1957), (Beedle 1960). Later, the effect was also examined for lateral-torsional buckling failure (Galambos 1963). It was found that the residual stresses have a considerable detrimental influence on both the flexural and lateral-torsional buckling resistance. This detrimental effect was caused by the compressive residual stresses at the flange tips Compared with the influence of these residual stresses, the influence of the web residual stresses on the global buckling resistance was negligible (Beedle 1957), (Beedle 1960), (Galambos 1963). A more detailed literature overview is provided in (Sonck 2014a).

For cellular and castellated members, it was yet unknown to which extent the residual stresses would be modified during the fabrication procedure, and accordingly, what their effect on the buckling resistance would be. As part of a more extensive research about the global buckling resistance of cellular and castellated members in (Sonck 2014a), the authors have measured the residual stresses in a number of castellated and cellular member specimens. As illustrated in (Sonck 2013), (Sonck 2014a) and (Sonck 2014b), the residual stress pattern of cellular and castellated members is altered during the fabrication process. This is caused by thermal effects during the cutting and welding, as well as by a rearrangement of the residual stresses to comply with the normal equilibrium constraint. In these works, it was shown that the compressive residual stresses in the flanges increase. Similarly as would be the case for plain-webbed I-section members, this is expected to have a detrimental effect on the global buckling resistance.

In this work, the results of the residual stress measurements is summarized, and the influence of different modified residual stress patterns on the global buckling resistance is determined numerically. Based on these results, a residual stress pattern valid for castellated and cellular members will be proposed. It will be demonstrated that the fabrication procedure has a considerable effect on the original residual stresses, which will influence the buckling resistance detrimentally.

The sign convention in this work will be such that compressive stresses are negative and tensile stresses positive.

2. Residual stresses

In this section, the results of the earlier executed residual stress measurements will be given, and it will be explained how these measurements are used to propose a residual stress pattern for the flanges of castellated and cellular members. This pattern will be used in a numerical investigation of the lateral-torsional and weak-axis flexural buckling behaviour of these members, as described in Sections 3 and 4. The residual stresses in the web varied considerably along the length of the members, which made it less straightforward to propose a simple residual stress pattern for the web.

In the numerical parametric study, both the original and modified residual stress pattern in the flanges will be considered, with different residual stress patterns along the web. This way, the effect of the modification and the effect of the residual stresses in the web can be determined numerically. To separate the effect of the web openings from that of the residual stresses, only plain-webbed members with different web heights will be considered.

2.1 Results of measurements

In previous work by the authors, the residual stresses were measured in a number of castellated and cellular beam sections, as well as in their parent sections. This study has already been discussed partially at a previous Annual Stability Conference (Sonck 2013), but meanwhile it is has been described fully in (Sonck 2014a) and (Sonck 2014b). Since the cellular member specimens used in this study were made following a non-standard production method, only the results for the (normally produced) castellated members will be concisely discussed below. It is expected that the residual stress measurements will be similar for cellular members made according to a standard production protocol.

The residual stresses were measured using the sectioning method, in which the relaxation strains were measured using electrical strain gauges. The specimens were all made from IPE160 parent sections with steel grade S275, of which the nominal yield stress is 275 MPa. Measurements were executed in the parent sections and in the castellated members. In the castellated members, the stresses were measured at the web post (between two openings) and at the tee section (at the centre of an opening).

In Fig. 2a, the measured residual stresses in the parent section are given. In Fig. 2b, the obtained residual stresses are compared with the residual stress patterns proposed by (Young 1975) and (ECCS 1984). It can be seen that the flange stresses agree well with those proposed by the ECCS, while the residual stresses in the web lie between both patterns.

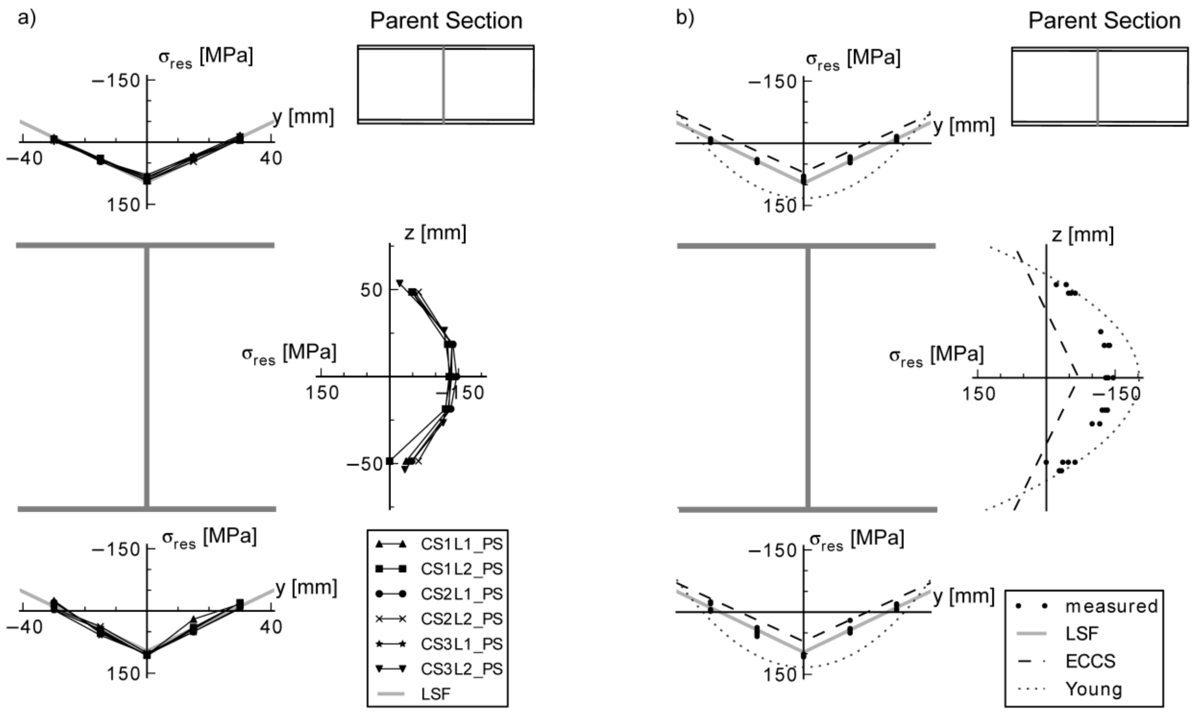

Figure 2. (a) Measured residual stresses in the IPE160 parent section. (b) Comparison of measured stresses with results from literature (b). Reprinted from (Sonck 2014b), with permission from Elsevier.

The residual stresses measured in the castellated members are depicted in Fig. 3. At the locations of the cuts and the weld in the web, high tensile residual stresses are present. This causes an increase in compressive stresses in the flanges. The least-square fits (LSF) of the measured residual stresses in the flanges and in the castellated member specimens are given in Fig. 4a. It can be seen that the compressive flange stresses at both the tee section and web post increase during the production process. Based on these residual stress patterns, it is proposed to use a constant triangular residual stress pattern with a tensile stress of 50 MPa at the web-flange intersection and a compressive residual stress of -100 MPa at the flange tips (Fig 4b) for the flanges of the tested specimens. The exact pattern of the residual stresses in the web will not be considered, since it is known that the flange stresses are most important for the global buckling load (Beedle 1957), (Beedle 1960), (Galambos 1963). This will be confirmed later on in this paper.

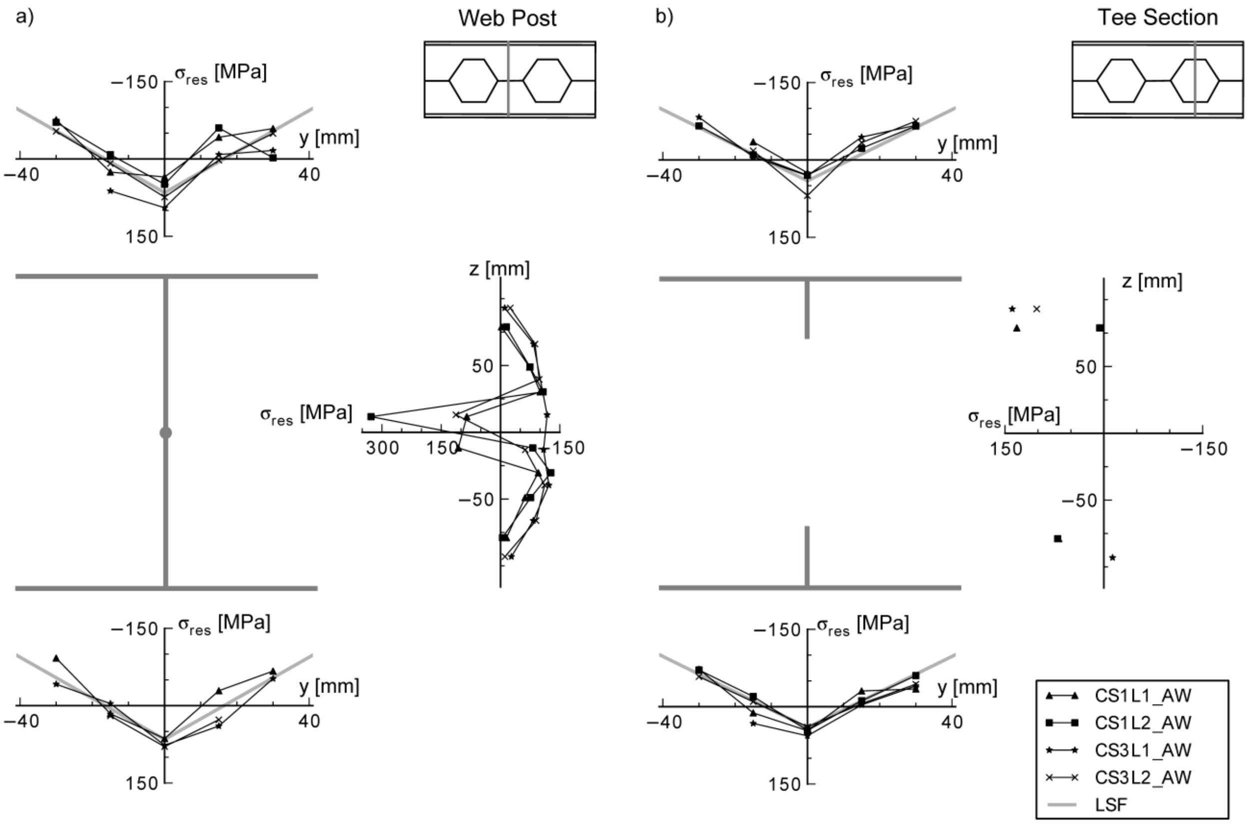

Figure 3. Measured residual stresses in the completed castellated member specimens. Reprinted from (Sonck 2014b), with permission from Elsevier.

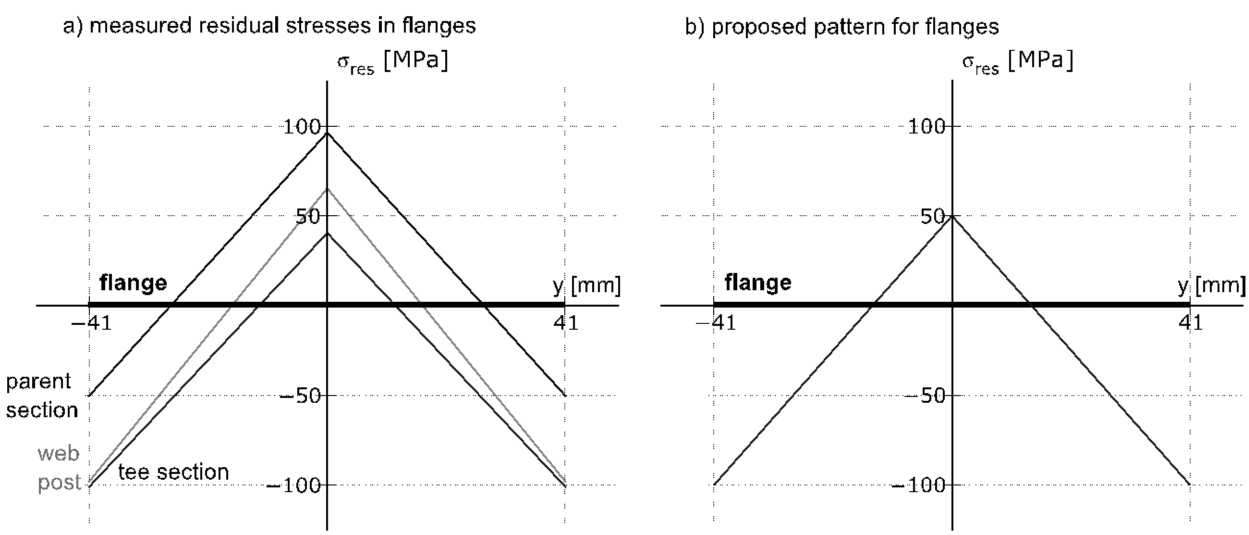

Figure 4. (a) Evolution of the residual stresses in the flanges during the production process for the castellated member geometries. The stresses in the completed members are given between the openings (web post) and at the opening location (tee section). (b) proposed residual stress pattern for the flanges of the specimens.

2.2 Considered residual stress patterns

All considered specimens for the executed residual stress measurements were made from one group of IPE160 parent sections. This section is a relatively light section compared to the heavier cross-sections of which castellated and cellular members are usually made. Consequently, it should be checked whether the proposed residual stress pattern for the flanges could also be valid for these heavier sections. This was done using an analytical approximation of the separate effects of the residual stress rearrangement due to normal equilibrium and of the effects of thermal cutting and welding. The latter effect was based on (ECCS 1976), where approximations were given for the size of the tensile zone surrounding a cut or weld, in which the residual stress is equal to the yield stress. Additionally, the effect of different yield stress values f_y was considered. Overall, the residual stress variations had the same order of magnitude for the tested geometries as for the considered heavier geometries (which coincide with those given in Table 1). Additionally, it was demonstrated that the effect of the yield stress was small, because the tensile zone size was inversely proportional to the yield stress. More details about this study can be found in (Sonck 2014a).

Based on the results obtained using the analytical approximation as described above, it was decided to extrapolate the results for the residual flange stresses from Fig. 4b to a wider array of cross-sections. During this extrapolation and during the preceding analytical study, the effect of the height-to-width ratio h/b on the residual stress magnitude in the cross-section was taken into account by considering the pattern σ_{res1} from Fig. 5 as residual stress pattern for the parent section, as proposed in (ECCS 1984). Using this pattern as a basic pattern for the IPE160 specimens (for which h/b>1.2), a stress decrease of 20 MPa and 30 MPa is obtained, the former for the flange-web intersection and the latter at the flange tips. Thus, for sections with a value of h/b ≤1.2, the resulting residual stress value at the flange-web intersection is 100 MPa and -150 MPa at the flange tips.

A parametric study, as described in the next section, will be executed to study the effect of different residual stress patterns on the weak axis flexural buckling and lateral-torsional buckling resistance. For each considered geometry, four different residual stress patterns will be considered, as depicted in Fig. 5. Pattern σ_{res1} is the residual stress pattern proposed in (ECCS 1984). The second pattern (σ_{res2}) is identical to the first pattern in the flanges, but has zero residual stresses in the web. Thus, the influence of the web residual stresses on the global buckling resistance can be determined. The residual stresses in the flanges of the last two patterns are identical and based on the residual stress measurements for castellated sections. In pattern σ_{res3}, the compressive resultant force in the flanges is balanced by a uniform tensile stress over the web. In the last pattern (σ_{res4}), the flange residual stresses are now balanced by a smaller zone in the web with tensile stresses equal to the yield stress f_y of the considered members in the parametric study (235 MPa, see Section 3). The height h_{tee} over which these high tensile stresses are introduced is taken as small as possible, and is calculated according to Eq. 1, in which b is the flange width, t_f the flange thickness and t_w the web thickness.

$$h_{tee} = \frac{25 \cdot b \cdot t_f}{235 \cdot t_w} \tag{1}$$

By considering these four patterns, the influence of the residual stresses in the web can be estimated, as well as the influence of the change in residual stress pattern due to the production process of castellated and cellular members. As already mentioned above, the value of h/b determines the magnitude of the residual stresses for each considered pattern. It should be emphasized that, while the proposed residual stress patterns in the flanges of cellular and castellated members have been partially validated by analytical approximations, they remain preliminary. Indeed, it would still be very useful to do some further residual stress measurements on heavier castellated and cellular member specimens to confirm the proposed residual stress pattern in the flanges.

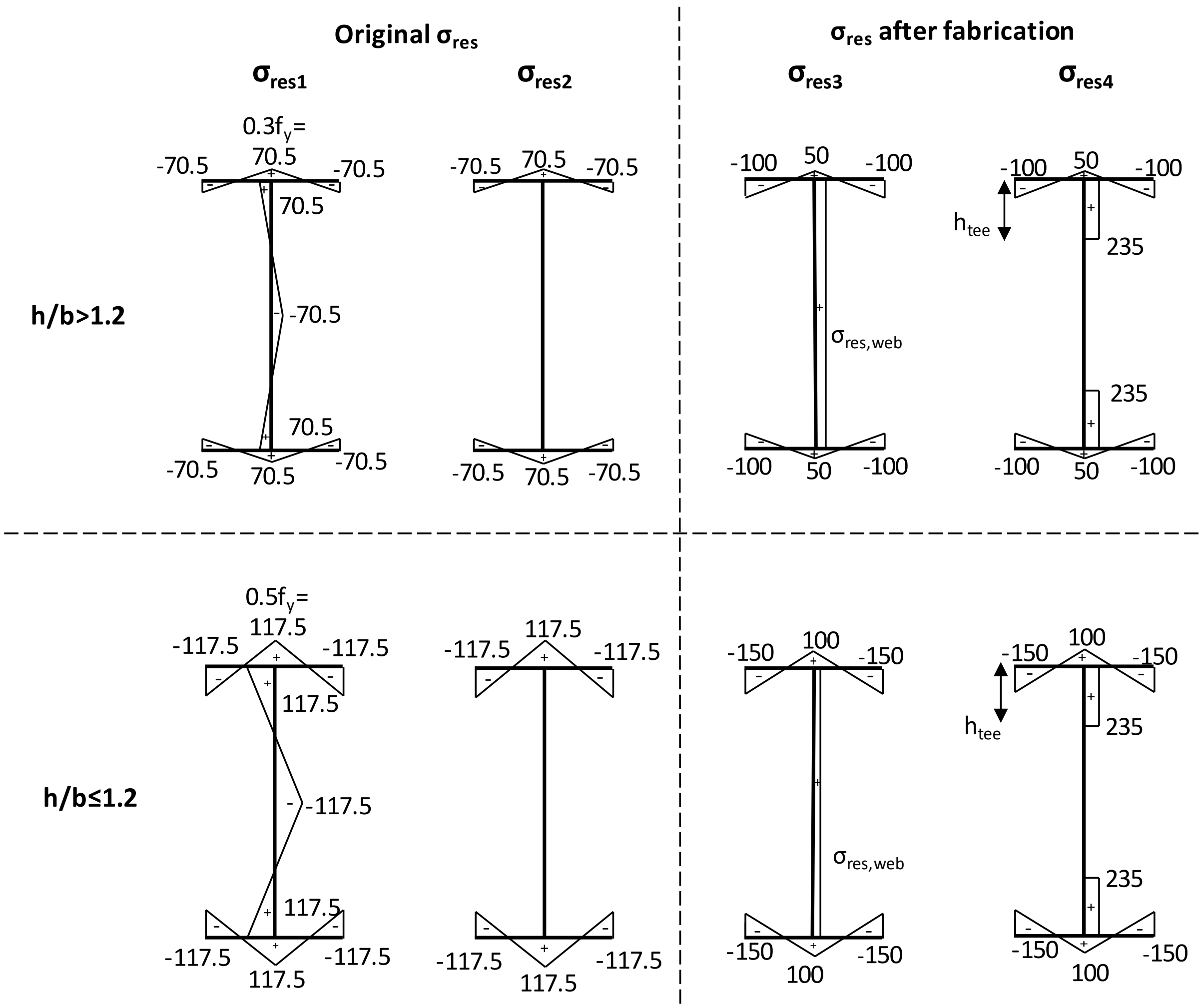

Figure 5: Considered residual stress patterns (stresses in MPa).

3. Parametric study and numerical model

In this section, the parametric study and the numerical model used for this study will be described.

3.1 Parametric study

In the parametric study, the effect of the four different residual stress patterns given in Fig. 5 on the global buckling behaviour was determined, more specifically for the weak-axis flexural and lateral-torsional buckling behaviour. Thus, the global buckling resistance was determined for a simply supported member loaded by a constant bending moment and a member loaded by an axial force.

Only plain-webbed members were modelled, to be able to consider all residual stress patterns from Fig. 5 and to separate the influence of the web openings from that of the residual stresses. As parent sections, the geometries given in Table 1 were used. The examined cross-section geometries had the same flange width b, flange thickness t_f and web thickness t_w as those given in Table 1. As total height H, both values of H=h and H=1.5h were considered, the latter based on the typical height increase of a castellated or cellular member compared to its parent section. This resulted in 12 different cross-sections.

Table 1. Considered parent cross-section geometries

	Total height h (m)	Flange width b (m)	Flange thickness t_f (m)	Web thickness t_w (m)
IPE300	0.300	0.150	0.0107	0.0071
IPE600	0.600	0.220	0.0190	0.0120
HEA320	0.310	0.300	0.0155	0.0090
HEA650	0.640	0.300	0.0260	0.0135
HEM320	0.359	0.309	0.0400	0.0210
HEM650	0.668	0.305	0.0400	0.0210

For each cross-section, 5 different values of the length were used, so that the corresponding values of the slenderness $\bar{\lambda}$ and $\bar{\lambda}_{LT}$ were equal to 0.6; 0.8; 1; 1.2 or 1.4, taking into account a minimum length L of 5H. The flexural buckling slenderness $\bar{\lambda}$ can be determined using Eq. 2, and Eq. 3 was used for the lateral-torsional buckling slenderness $\bar{\lambda}_{LT}$. In these equations, N_{cr} is the critical buckling load, N_{pl} the plastic load of the cross-section, M_{cr} the critical lateral-torsional buckling load and M_{pl} the plastic moment of the cross-section. It is expected that the influence of the residual stresses on the global buckling resistance is the largest for values of the slenderness around 1. For large slenderness values, the failure will be elastic buckling, and for small values of the slenderness, the failure will be governed by plastic yielding.

$$\bar{\lambda} = \sqrt{\frac{N_{pl}}{N_{cr}}} \qquad (2)$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{M_{pl}}{M_{cr}}} \qquad (3)$$

The yield stress of all considered members was 235 MPa, because this is the lowest value of the yield stress which is generally used in structural steel members in Europe. Furthermore, the effects of the residual stresses are more pronounced for lower values of the yield stress. Thus, a safe estimation of the effect of the residual stresses can be made.

For each of the two load cases, six parent sections, four different residual stress patterns, five slenderness values and two heights were considered. This resulted in a total number of 240 different geometries for each load case.

3.2 Numerical model

The numerical model used for the parametric study was constructed in Abaqus (Dassault Systèmes 2014). The member was modelled using quadratic shell elements with reduced integration (S8R) for the flanges and the web, disregarding the fillet between the flanges and the web. The modelled members were simply supported by fork-supports at their ends, which prevented torsional rotation but allowed warping. The members were loaded by a constant bending moment or a central compressive force, which were both applied using shell edge loads on the edges of the web and the flanges at the ends of the member. Kinematic coupling constraints prevented local cross-sectional deformations at the beam ends.

The global buckling resistance was determined by performing a geometrically nonlinear analysis with geometric imperfections, residual stresses and elastic-plastic material behaviour. This was done using the modified Riks method. The considered material, of steel grade S235, was perfectly elastic-plastic with a modulus of elasticity E of 210 GPa, a yield stress f_y of 235 MPa and a Poisson's ratio ν of 0.3. As geometric imperfection, a sideways half-sine wave with amplitude L/1000 was introduced in the system, L being the member length. The residual stresses, according to Fig. 5, were introduced using a user subroutine. For each analysis, the load-displacement curve could be drawn, of which the maximum was considered as the failure load N_{abq} or the failure moment M_{abq}.

4. Results and discussion

4.1 General

The results for some beams will not be included in this paper, as they did not fail by lateral-torsional buckling, because the load-deflection diagram kept increasing past the critical buckling moment. According to (Trahair 1993), this is caused by the stabilizing effects of the pre-buckling deflections for long beams. Additionally, for some shorter members the analysis failed to converge before the maximum in the load-displacement diagram was reached. They are also not included below.

4.2 Effect of distribution of residual stresses in the web

In this part, results will be compared for residual stress patterns σ_{res1} and $\sigma_{res2,}$ as well as σ_{res3} and σ_{res4}. For each pair, the flange residual stresses remain identical, but the residual stress pattern in the web differs.

4.2.1 Original parent section (σ_{res1} and σ_{res2})

In Fig. 6, the results obtained for patterns σ_{res1} and σ_{res2} are compared. The pattern σ_{res1} corresponded with the original residual stresses in the parent section. In pattern σ_{res2} the flange stresses are identical, but the stresses in the web are zero. For both the cases of compression and bending, the influence of the removal of the web residual stresses remains small for all considered cross-sections.

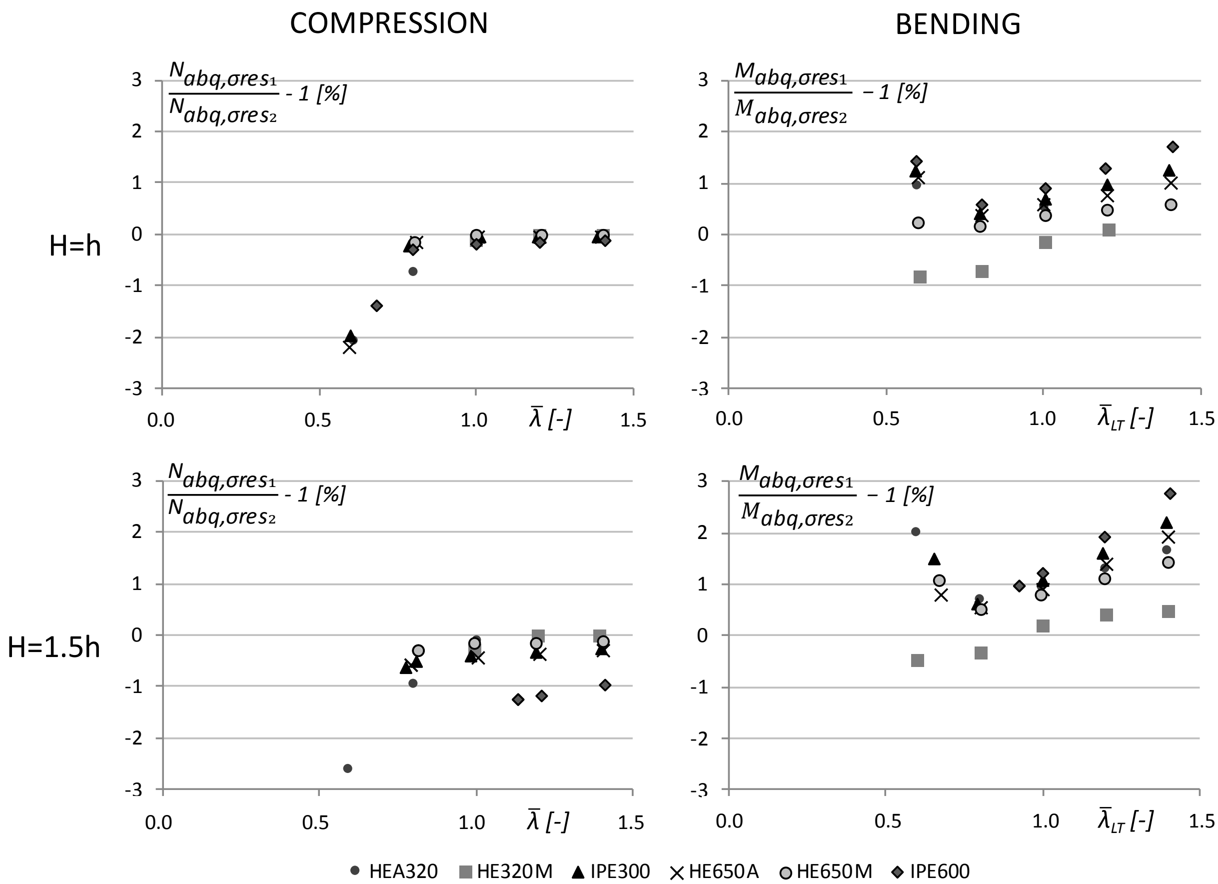

Figure 6: Comparison of obtained results for residual stress patterns σ_{res1} and σ_{res2}.

4.2.2 Cellular/castellated members (σ_{res3} and σ_{res4})

In Fig. 7, the results obtained for patterns σ_{res3} and σ_{res4} are compared. These two residual stress patterns are based on the measured residual stresses in a group of castellated members, as described in Section 2. For these patterns, the residual stresses in the flanges remained identical, but the residual stresses in the web differed. In pattern σ_{res3}, the equilibrating tensile residual stresses are distributed along the full web height. In pattern σ_{res4}, the equilibrating tensile stresses are present in a small area of the web close to the flanges, which corresponds with the measured values at the tee section.

Again, the effect of the residual stress pattern in the web remained limited. Nevertheless, pattern σ_{res4} would be easier to introduce in the numerical model of a member with web openings, since it can be taken constant along the length of the member. Consequently, it was decided to use, in a first approximation, pattern σ_{res4} in the numerical simulations of the global buckling behaviour of cellular and castellated members.

4.3 Influence of production pattern on residual stresses

The influence of the production process can be estimated by comparing the global buckling resistances obtained using the residual stress pattern σ_{res1} for the parent section with the resistances obtained by using a suitable residual stress pattern for cellular and castellated members. Based on the reasoning above, it was decided to use pattern σ_{res4} for the latter. Both resistance values are compared in Fig. 8. For all geometries, the production process has a detrimental influence on the global buckling resistance, as expected. For the compression load case, the detrimental influence varies between 5 and 12%, while for the bending load case the detrimental influence varies between 1.5 and 12%.

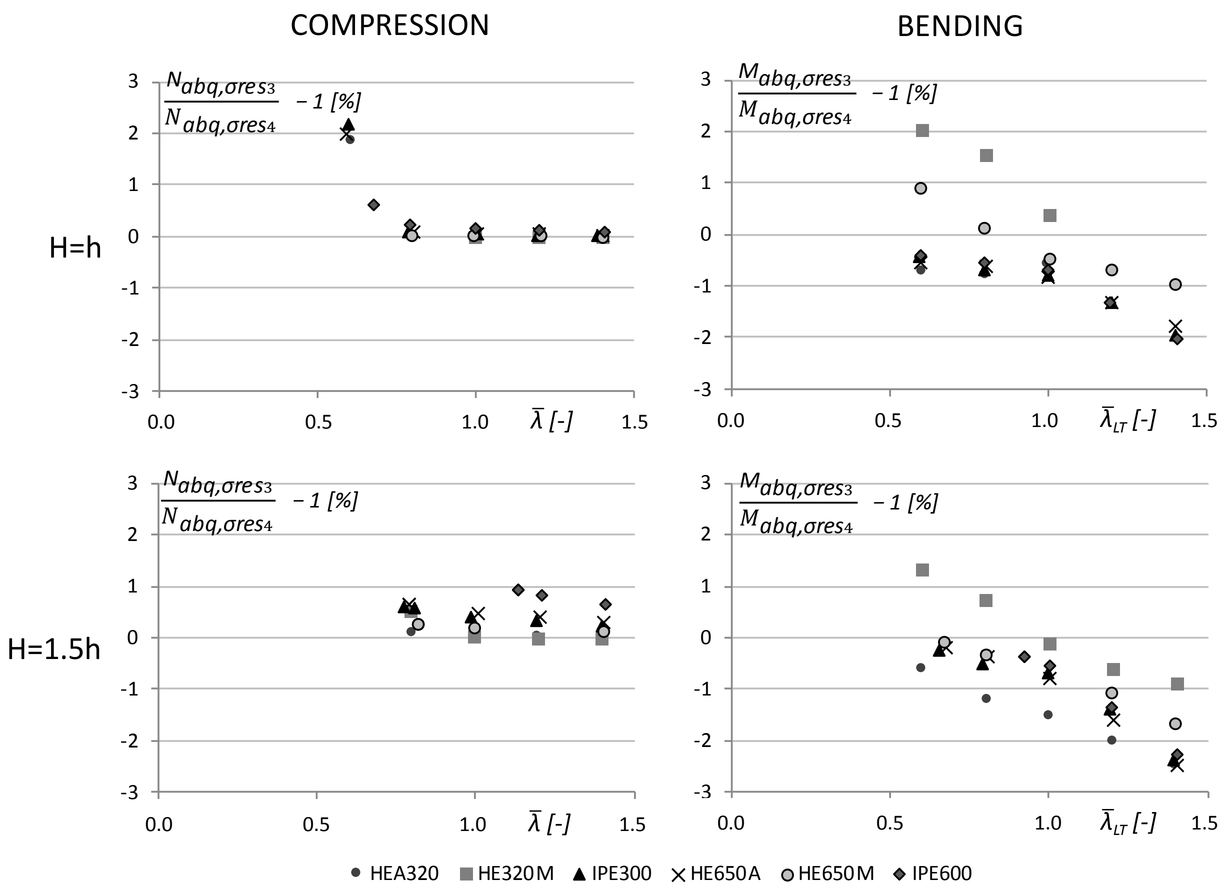

Figure 7: Comparison of obtained results for residual stress patterns σ_{res3} and σ_{res4}.

The effect of the production process can also be considered by comparing the obtained resistance values with the buckling curves currently used in the European standard Eurocode 3 (CEN 2005). Depending on the cross-section's dimensions and the load case, a certain buckling curve is prescribed, which indicates how much the buckling resistance is influenced detrimentally by imperfections such as geometric imperfections and residual stresses. These curves are drawn in Figs. 9 and 10: buckling curve *a* (the highest) represents a small imperfection influence and a relatively high buckling resistance, while buckling curve *d* (the lowest) corresponds with large detrimental imperfection influences and a low buckling resistance. On the horizontal axis, the slenderness is drawn, which is a function of the critical buckling load and the plastic resistance according to Eqs. 2 and 3. On the vertical axis, the reduction factor χ is given (Eq. 4), which is the ratio between the buckling resistance (N_{Rd} or M_{Rd}) and the plastic resistance (N_{pl} or M_{pl}). The obtained numerical resistance values are transformed into values of χ_{abq} following Eq. 5.

$$\chi = \frac{N_{Rd}}{N_{pl}} \ or \ \frac{M_{Rd}}{M_{pl}} \tag{4}$$

$$\chi_{abq} = \frac{N_{abq}}{N_{pl}} \; or \; \frac{M_{abq}}{M_{pl}} \tag{5}$$

In Fig. 9, the comparison is made for the weak-axis flexural buckling results. In this figure, the values of the reduction factor $\chi_{abq,\sigma res1}$ obtained using the original residual stress pattern σ_{res1} can be compared with the reduction factors $\chi_{abq,\sigma res4}$ obtained using the pattern σ_{res4} for castellated and cellular members. It can be seen that the effect of the residual stress modification results in reduction factors that lie approximately one buckling curve lower. In Fig. 10, the same comparison is made for the lateral-torsional buckling resistance, for which similar conclusions can be drawn.

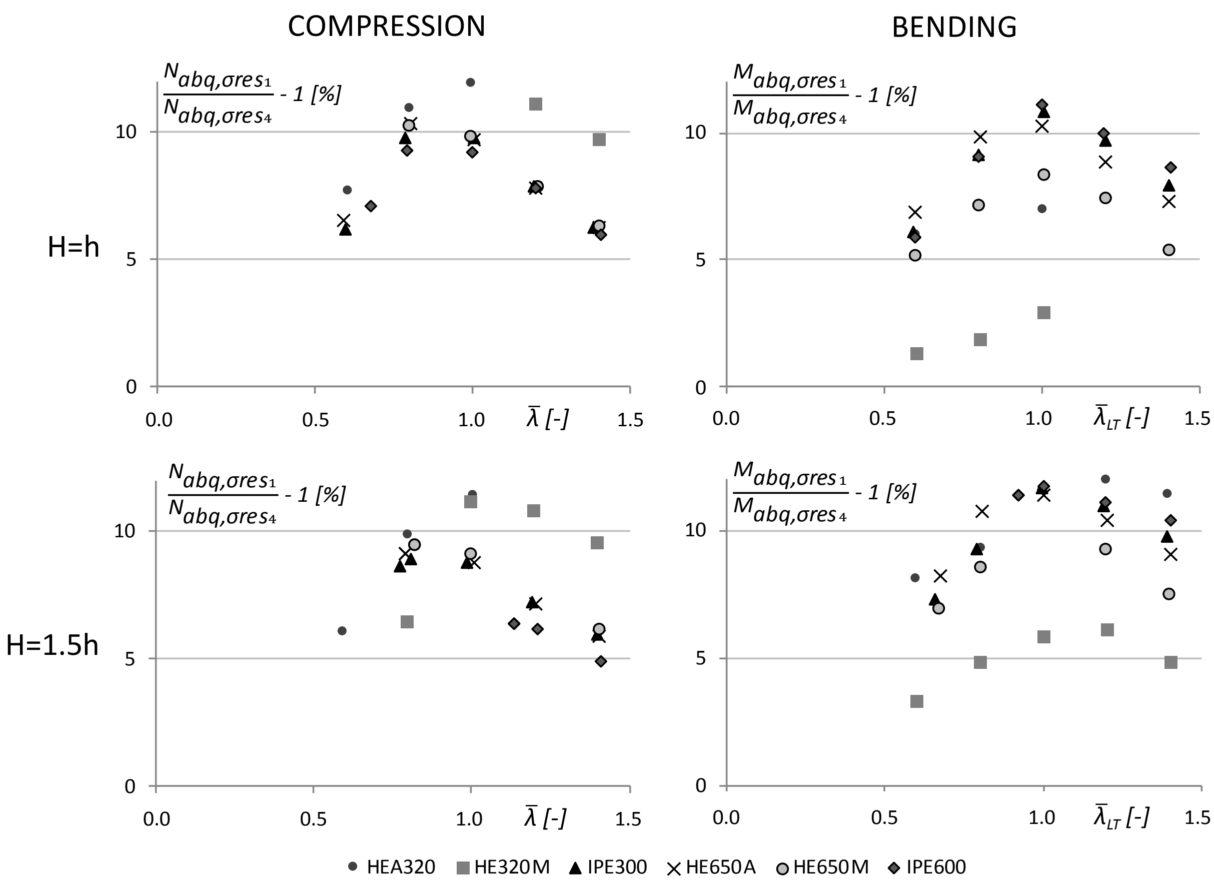

Figure 8: Comparison of obtained results for residual stress patterns σ_{res1} and σ_{res4}.

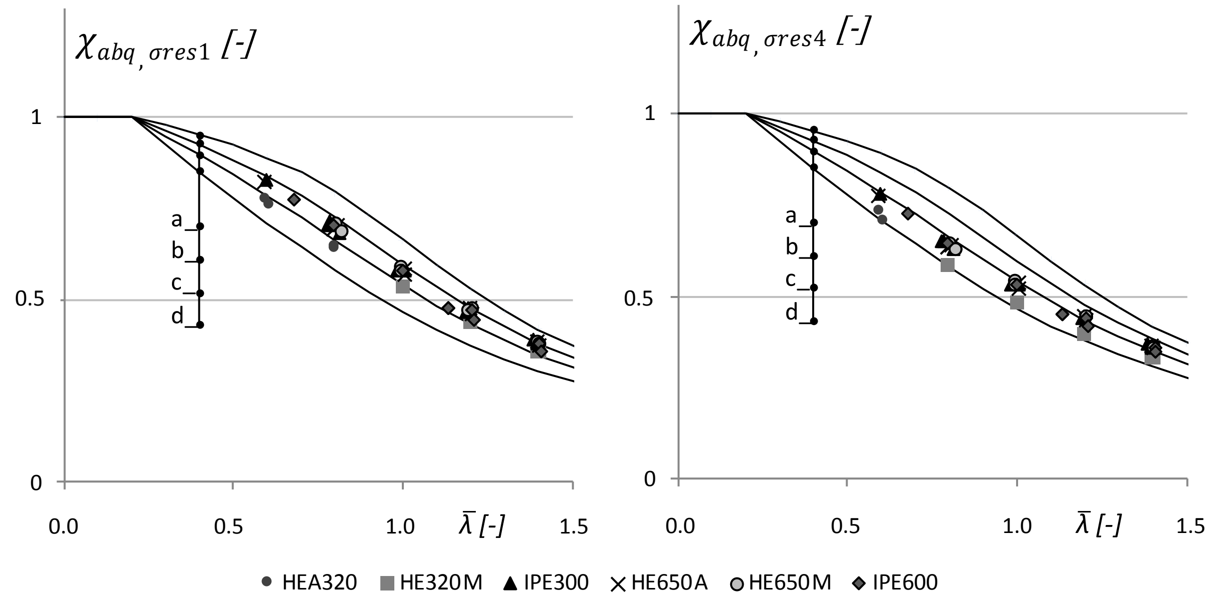

Figure 9: Effect of production process for weak-axis flexural buckling: comparison of results obtained using σ_{res1} and σ_{res4} with the buckling curves.

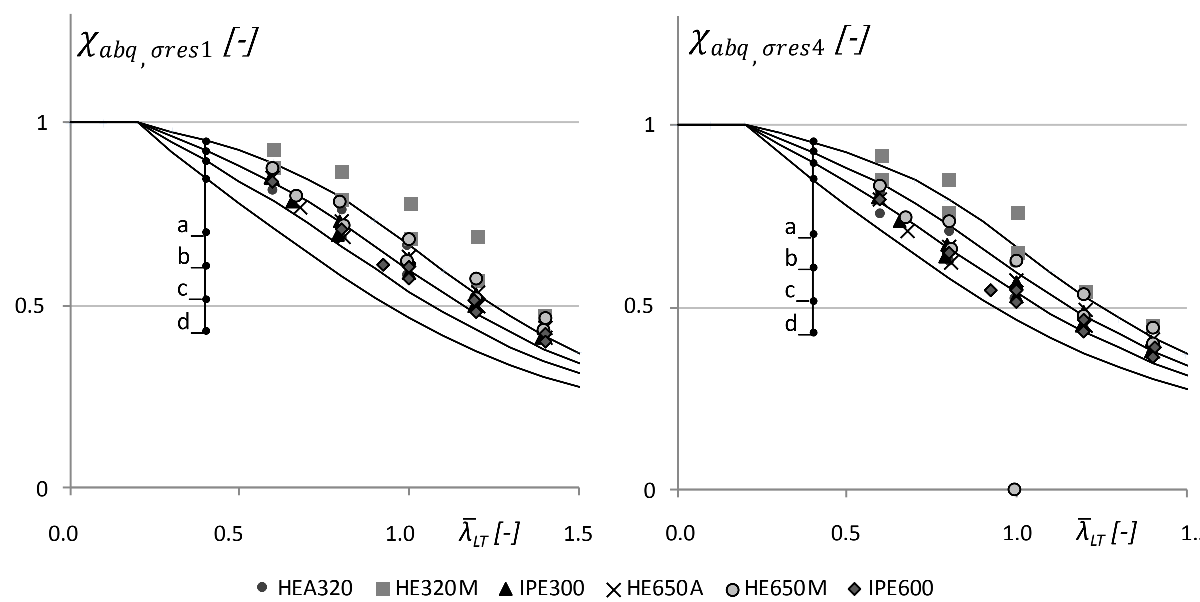

Figure 10: Effect of production process for lateral-torsional buckling: comparison of results obtained using σ_{res1} and σ_{res4} with the buckling curves.

5. Conclusions

In this paper, the influence of typical residual stress patterns of cellular and castellated members on the strong-axis flexural buckling and lateral-torsional buckling resistance was examined numerically. The considered residual stress patterns are based on commonly used patterns for the parent sections and on the measured residual stresses in a group of castellated members during a measurement campaign. The effect of the variation of the residual stresses in the web was studied by considering different patterns for these residual stresses.

It was found that the effect of the residual stress pattern in the web was generally negligible, which corresponds with the notion that the compressive residual flange stresses have a dominant (detrimental) effect on the global buckling resistance. Additionally, the increase in compressive residual flange stresses during the production process of castellated and cellular members causes a non-negligible reduction of the global buckling resistance of these members.

It was proposed to use residual stress pattern σ_{res4}, which corresponds with the measured residual stress pattern at the tee section as a constant pattern over the full length of the member. However, it would be useful to additionally measure the residual stresses in members made from heavier parent sections, as well as parent sections with higher initial residual stresses. In this respect, it is recommended to perform a residual stress measurement at the tee section and at the web post of each tested cellular and castellated member, so that a database of residual stress measurements for cellular and castellated members can be composed.

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