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Experimental investigation of residual stresses in steel cellular and castellated members

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HIGHLIGHTS

- Cellular or castellated members are fabricated from hot-rolled parent sections.
- Residual stresses lower the global buckling resistance of the parent sections.
- The production process influence was determined by measuring the residual stress.
- During the production process, the residual stresses become more detrimental.

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ABSTRACT

The global buckling resistance of hot-rolled steel I-section members is adversely influenced by the presence of residual stresses. It is expected that thermal effects during the production of cellular and castellated members will influence the already present stresses in the hot-rolled parent sections, but it is yet unknown to what extent. In this paper, the experimental investigation of the residual stresses in these members is described, and it is shown that the production process increases the already present compressive flange stresses, which will be detrimental for their buckling resistance. This effect will be even more pronounced for deviating production procedures.

1. Introduction

Cellular or castellated members are I-section members with circular or hexagonal web openings regularly spaced along the length of the member. Usually, they are manufactured starting from steel hot-rolled I-section members of which the web is thermally cut according to a certain pattern, after which the obtained halves are shifted and rewelded (Fig. 1). Variations in the cutting pattern and the properties of the top and bottom halves of the beam result in a large variety of final member geometries, in which tapered beams, different web opening shapes or asymmetric beams are possible.

The main advantage of cellular or castellated members compared to normal I-section members is their increased strong-axis bending resistance. Furthermore, service ducts can be guided through the web openings instead of under the member, thus diminishing the necessary total story height. Additionally, they can also be used out of aesthetic considerations because of their lighter appearance. The members are mainly used for applications in which they are loaded in bending, both in steel and steel–concrete construction. However, they are also increasingly used for columns and beam-columns, where the column is subjected to both bending and compression.

Clearly the presence of the web openings will influence the failure behaviour of cellular or castellated members [1]. For instance, new localized failure modes can arise, such as Vierendeel bending around the web openings or local buckling of the web surrounding the openings. Specific rules for these failure modes are currently being developed and optimized [2–8]. However, the already existing failure modes for I-section members will also be modified, because of the change in geometry and the influence of the production process on imperfections such as geometric imperfections and residual stresses. Examples of this are the global instability failure modes for members loaded in compression and/or bending, such as

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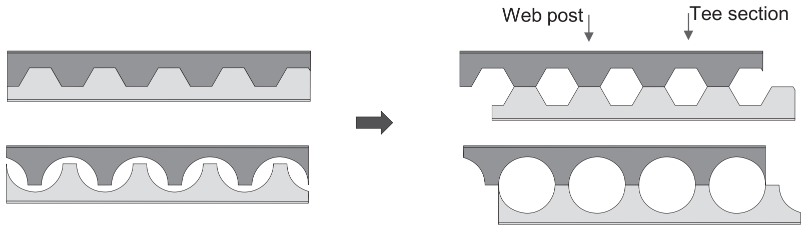

Fig. 1. Standard fabrication method of castellated and cellular members starting from a plain-webbed parent section.

flexural buckling or lateral–torsional buckling. Unfortunately, the existing research for these global instability modes is incomplete, conflicting or lacking altogether [9–11]. An important aspect of the global instability behaviour of cellular and castellated members that has not been investigated yet is the influence of residual stresses.

Residual stresses are internal stresses which can exist in a member not subjected to external loads. Hence, residual stresses are always in static equilibrium. In hot-rolled I-section members, thermal residual stresses originate during the cooling after the hot-rolling process because of the non-uniform cooling and corresponding thermal contraction, coupled with a temperature-dependent yield stress. Typically, the flange tips will be in compression and the flange centres in tension, while the sign and variation of the residual stresses in the web varies depending on the cooling parameters and cross-section geometry [12–17]. Examples of typical thermal residual stress shapes are shown in Fig. 2 [17,18]. If the straightness of the beams after cooling is not sufficient, the beams will undergo a cold-straightening process which redistributes the residual stresses in the flanges [19,20]. As a result, the possible residual stress patterns in I-section members are very diverse.

The influence of residual stresses on the global buckling failure of I-section members without web openings has been studied extensively for the cases of flexural buckling [14,15] and lateral–torsional buckling [21], which are the most important global failure modes for I-section members. It was shown that the residual stresses have a detrimental effect on the global buckling resistance of the I-section members, caused by the compressive residual stresses at the flange tips. Due to these stresses, the onset of yielding will occur quicker at the flange tips, increasing the members' flexibility and reducing the corresponding buckling resistance. Furthermore, it was shown that the redistribution of the flange stresses due to cold-straightening is always advantageous for the failure load [16,19,20,22]. Therefore, it was decided not to take this into account in the proposed standard residual stress patterns and to consider only the more detrimental thermal residual stress pattern in finite element calculations to determine the buckling resistance. Likewise, only non-straightened members were used in the flexural buckling experiments to determine the buckling resistance of columns [23].

During the cutting and welding processes in the production of cellular or castellated members, heat is introduced at the cutting and welding locations, which will influence the already present residual stresses. At the locally heated zone, very high tensile residual stresses (up to the material's yield stress) will be present, balanced by compressive (and possibly also tensile) stresses farther away from the location of heat introduction [15,19,23–28]. Typical schematized residual stress distributions for plates cut at one side and plates welded in their middle are depicted in Fig. 3. As a result, it is very well possible that the production process increases the magnitude of the compressive residual stresses in the flanges, hence decreasing the global buckling failure load. Nevertheless, the change in residual stresses of cellular and castellated members during their production process has not been investigated yet and it is currently not known how significant the possible detrimental effect on the members' stability will be.

In this paper, the effect of the production process of cellular and castellated beams on the residual stresses is investigated by measuring the residual stresses in a series of castellated and cellular members. Measurements were done both for the parent sections and the resulting castellated and cellular members. By comparing the measured stresses before, during, and after production, the effect of the production procedure could be studied. In this paper, tensile stresses will be taken as positive stresses and compressive stresses as negative.

2. Residual stress measurement method and specimens

In this section, an overview will be given of the used measurement method and the specimens in which the residual stresses were measured. All measurements were done at the Laboratory for Research on Structural Models (LMO, Ghent University).

2.1. Measurement method

The residual stresses were measured using the sectioning method, which is a destructive relaxation method. The longitudinal residual stresses in each segment can be calculated using the strain difference before and after the relaxation of each segment. The relaxation of each segment is accomplished by the sectioning of the member. First, the member is cut transversally at the location of measurement, after which a series of longitudinal cuts is made to separate all segments in which the strains are measured

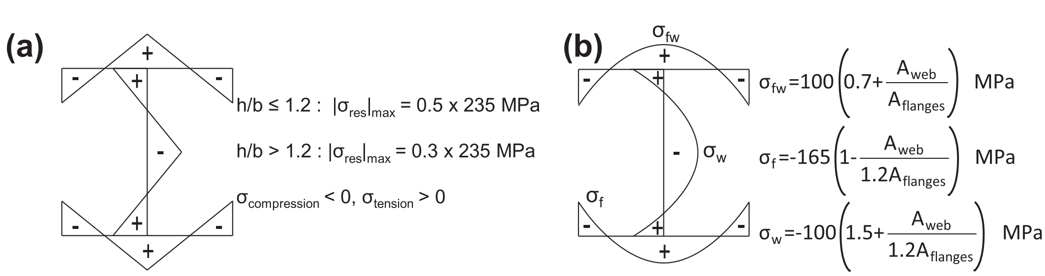

Fig. 2. Residual stress pattern in hot-rolled I-section members: (a) according to ECCS [18]; (b) according to Young [17].