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Weak-axis flexural buckling of cellular and castellated columns

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ABSTRACT

Cellular and castellated members are usually produced by performing cutting and rewelding operations on a hot-rolled I-section member. As illustrated in previous work, these operations will influence the residual stresses present in the members in a manner which is detrimental for the flexural buckling resistance. Up to now, this has not been considered in the limited amount of literature concerning the flexural buckling resistance of these members.

In this paper, the weak-axis flexural buckling resistance is examined, taking into account the influence of the modified residual stress pattern and the modified geometry of cellular and castellated members. Therefore, the critical buckling load and the buckling resistance of simply supported cellular and castellated members were investigated numerically. In the numerical model, a modified residual stress pattern was introduced, based on earlier measurements. As the amount of measurements was relatively limited, the results of these simulations should be considered as preliminary results, in attendance of a confirmation of the utilized residual stress pattern. The results of the simulations illustrate the detrimental influence of the expected residual stress pattern modification on the buckling resistance. By comparing the results with the European buckling curves, preliminary best fit curves could be selected. This comparison was executed with a 2T approach, in which all cross-sectional properties are calculated for the 2T section at the centre of the opening.

1. Introduction

Castellated and cellular members are I-section members with large hexagonal or circular openings in their web. These members are commonly made by cutting the web of a hot-rolled I-section member (the parent section) according to a pattern corresponding with the desired openings shapes, after which both obtained halves are shifted and welded together again (Fig. 1). The part of the member between two openings is referred to as the web post, while the section at the opening is called the tee section. Since the main advantage of these members is their optimal material use in strong-axis bending, they are predominantly used for applications in which they are loaded in this manner. However, cellular and castellated members are also applied for cases in which they are loaded by a combination of a bending moment and a compressive force or even for cases where only a compressive force is present. After all, apart from the increased strong axis bending capacity, they also have the advantage of their ability to pass service ducts through their web openings and their lighter appearance.

Columns loaded in compression can fail by global flexural buckling (FB) about the weak axis or about the strong axis, depending on the boundary conditions. It is expected that the flexural buckling resistance of castellated and cellular columns will be different than that of plain-webbed columns of the same dimensions. The first difference is caused by the modified geometry: around the web openings, local normal forces, shear forces and bending moments will be present [1]. These local forces will cause additional deformations around the openings, which results in a lower critical buckling load about the strong axis [2–5]. Additionally, compared with the same member without web openings, the plastic resistance of the cross-section will be reduced due to the presence of the openings. Secondly, it has been shown in earlier work by the authors that the thermal influences during the fabrication process modify the already present residual stresses in the parent section: the compressive residual stresses in the flanges increase [6]. As illustrated for plain-webbed I-section members by different authors [7–11], an increase in compressive residual stresses in the flanges causes an earlier onset of plastic yielding at these locations. Consequently, the effective bending stiffness will decrease more quickly with increasing load, decreasing the flexural buckling resistance. However, to the authors' best knowledge, no research is available in which the latter detrimental effect has been included in the study of the flexural buckling resistance of castellated and cellular columns. This could lead to unsafe results.

In this paper, the weak-axis FB behaviour of cellular and castellated members (Fig. 2) was investigated numerically for a large number of geometries. Both the elastic critical buckling load N_{cr} and the FB resistance N_{Rd} were considered, so that the influence of the modified geometry and the modified residual stress pattern could be determined. The obtained resistances N_{Rd} will be compared with the buckling curves for plain-webbed members which are currently used in the European standard

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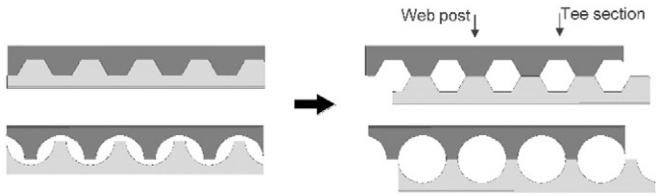

Fig. 1. Standard fabrication method of castellated and cellular members starting from a plain-webbed parent section.

Eurocode 3 [12], which will be further referred to as EC3. In this work, only simply supported, doubly symmetric, cellular and castellated members loaded by a compressive axial load will be considered (Fig. 2).

First, an overview will be given of the considered geometries. Next, the proposed design approach and the existing approach for plain-webbed members will be described. Subsequently, the used finite element model will be described. To conclude, the results for the critical buckling load N_{cr} and the flexural buckling resistance N_{Rd} will be presented, discussed and compared with the proposed design approach.

2. Examined geometries

As mentioned above, cellular and castellated members are made by cutting and rewelding a hot-rolled I-section, which is referred to as the parent section. By varying the cutting pattern and the fabrication procedure, it is possible to obtain a large variety in member and opening geometries, such as tapered and even curved members, or asymmetric members with a different top- and bottom section. However, only prismatic members with a doubly symmetric cross-section, made from the same parent section will be considered in this work.

In the numerical study, the critical weak-axis buckling load N_{cr} and the weak-axis buckling resistance N_{Rd} were determined for a large number of simply supported compressed castellated and cellular columns. The considered geometries were all made starting from the six hot-rolled parent sections listed in Table 1. For the cellular columns, the complete range of commonly used and feasible geometries starting from these parent sections was considered by varying the opening height $a = f_a \cdot h$ and the web post width $w = f_w \cdot \ell_0 = f_w \cdot a$ (Fig. 3) according to Table 2. For each of these geometries, the resulting total cellular member height can be calculated according to Eq. (1), with r_b being the cut width used during the cutting procedure, taken equal to a typical value of 8 mm. The dimensions of each obtained geometry were checked against the constraints given by existing technical documentation and standards [13,14], to obtain all feasible geometries made from the six parent sections.

$$H = h + \frac{\sqrt{(a - 2r_b)^2 - w^2}}{2} \tag{1}$$

For the castellated columns, a wide range of possible geometries was considered by varying the final member height $H = f_H \cdot h = h + a/2$, as well as the value of the opening angle α and the web post width $w = f_w \cdot \ell_0 = f_w \cdot (w + 2c)$ (Fig. 3). The chosen values for the three parameters f_H, α and f_w are listed in Table 2. The variation of the opening angle α and the web post width w allowed for a large variety of opening shapes, going from very narrow diamond web openings to very wide web openings, similar to those that would occur in an Angelina™ beam with wide sinusoidal openings, as investigated (amongst others) by Durif [15]. Additionally, it was checked whether the obtained geometries were feasible by comparing them with the geometric constraints given in the previously mentioned technical standards and documentation [13,14].

Table 1
Dimensions of the parent sections (in mm) according to Fig. 3.

	IPE300	IPE600	HE320A	HE650A	HE320M	HE650M
h [mm]	300	600	310	640	359	668
b [mm]	150	220	300	300	309	305
t_w [mm])	7.1	12.0	9.0	13.5	21.0	21.0
t_f [mm]	10.7	19.0	15.5	26.0	40.0	40.0

For each cellular and castellated member geometry, the lengths of the columns were varied so that the slenderness $\overline{\lambda}$ of the considered geometries varied between approximately 0.5, 1, 1.5, 2 or 2.5, taking into account a minimum member length L_{min} of $5H$. In total, 980 geometries were considered for the cellular and castellated columns. In Fig. 4, a typical selection of the shortest IPE300 cellular and castellated geometries is depicted.

3. Proposed design approach for weak-axis FB of castellated and cellular members

It is expected that the weak-axis flexural buckling (FB) behaviour of castellated and cellular members can be treated in the same way as the lateral-torsional buckling (LTB) behaviour of these members. For the latter failure mode, it has been shown that the buckling behaviour is qualitatively similar to that of plain webbed-members [16,17]. Furthermore, the LTB resistance could be calculated by using a 2T approach, calculating all cross-sectional properties for the cross-section at the location of the openings (as depicted in Fig. 5), and using these in the design rules for plain-webbed I-section members. In earlier investigations by various authors, the LTB resistance was examined numerically using either an equivalent geometric imperfection, the original residual stress pattern of the parent section, or even no residual stresses [18–23]. Only in earlier work by the authors [24,25], the additional detrimental effect of the modified residual stress pattern on the LTB resistance was taken into account. In the latter works, it was shown numerically that the modified residual stress pattern influences the LTB resistance detrimentally. Considering the design guidelines from the current European standard EC3 [12] (see next section), the LTB resistances would lie one buckling curve lower if the modified residual stress pattern (Fig. 6b) was used instead of the original residual stress pattern (Fig. 6a).

Considering the lateral-torsional buckling behaviour, it is expected that the weak-axis flexural buckling behaviour of castellated and cellular members will also be qualitatively similar to that of I-section members. Thus, the weak-axis flexural buckling resistance can be calculated using the design rules valid for I-section members, but with all cross-sectional properties calculated for the cross-section at the centre of the opening (2T approach). The proposed design approach for

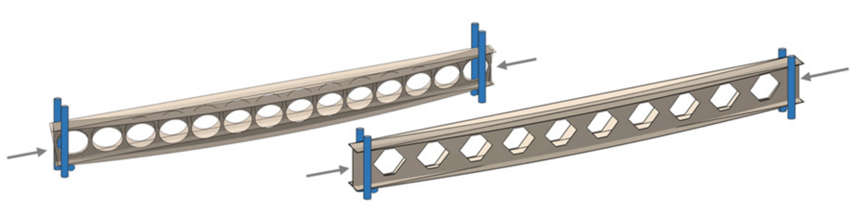

Fig. 2. Weak-axis flexural buckling failure of cellular and castellated members loaded by a central compressive force.