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Analysis Beam-Column Cellular By Finite Element Method

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Abstract

Nowadays in the construction of modem buildings, it is necessary to accommodate pipes and ducts necessary services, such as air conditioning, water supply, sewerage, electricity, computer networks, and telephone networks. Cellular members ‐ steel I ‐ shaped structural elements with circular web openings at regular intervals – have been used as beams for more than 35 years now. Although in the past already a large deal of research was performed into the subject of the behavior of cellular beams, almost no attention has been paid to the application of cellular members as columns. The column will be analyzed using the finite element method to calculate the critical load and compared with the Eurocode3 standard, web-post buckling, and frame using cellular member by FEM.

Keywords: cellular column, cellular beam, web-post buckling, frame, FEM

1 Introduction

The use of cellular beams allows a new architectural expression. Structures are lightened and spans increased, pulling spaces together. This flexibility goes together with the functionality of allowing technical installations (pipes and ducts) to pass through the openings. The lightweight appearance of cellular beams, combined with their high strength, never ceases to inspire architects to new structural forms [1].

Cellular members – steel I- shaped structural elements with circular web openings at regular intervals – have been used as beams for more than 35 years now. However, in certain countries, like the Netherlands and Belgium, application seems to lack behind. This can probably be attributed to a

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combi- nation of factors: unfamiliarity with these beams, the present concrete- minded practice for multi- story buildings, and a lack of localized design guides. Cellular beam- columns – shortly cellular beams – belong to the larger group of steel sections with web openings, thus creating a higher moment- of- inertia- to- weight ratio. When used as floor beams, open- web sections on their turn are a part of the group of floor systems which provide a means to incorporate building services within the structural depth of the floor. The web of the girder is cut into custom shapes, then welded with a hole that takes up more than 40-60% of the girder web. Finished round hole thickness, diameter, distance can be adjusted according to specific needs.

Although cellular columns are less common, examples are available. However, in research publications no attention is paid to this topic. Structural engineers therefore have to base their designs on simplified methods of analysis and good engineering judgement. In order to exploit the full capacity of cellular columns a sound basis is needed and thus a desire exists for a more refined approach [2].

Cellular beam has been a popular research topic over the past few decades. Many research projects, including both theoretical and experimental research, can be divided into two main categories: beams with individual openings or multiple continuous openings in the (spaced) abdomen. Finite element analysis for torsion behavior of flat web profile beam steel section with opening (2015) - Fatimah De'nana, Hazwani Hasana, Duaa Khaled Nassira, Mohd Hanim Osmanb, Sariffuddin Saadb [3] objective of this paper is to determine the torsion angle of beam steel section with opening of different shapes and sizes using LUSAS software. Finite Element Analysis of Castellated Steel Beam M.R.Wakchaure, A.V. Sagade [4] to analyze the behavior of castellated steel beams having an I-shaped cross-section, modeling is conducted using finite element software package ANSYS14. Buckling Analysis of Cellular Beams Shwetha Saju, Manju George (2015) Analytical study is also done by varying different parameters in cellular beam such as cell diameter, cell spacing, cell shape [5]. Parametric study of the behavior of steel cellular beams with various web opening diameters (2020) - Abdimalik Sheikh Muhumed [6]. However, the behavior of cellular column has received little attention.

In this report, section 2 will present the theory, section 3 presents Finite element model and at the end of section 4 presents the conclusions and comments.

2 Theoretical Analysis

The main goal is to determine global buckling of cellular column. The global buckling behavior of cellular columns is also similar to that of standard hot- rolled section. The easiest method to deal with the reduction in flexural stiffness of a cellular column due to the presence of multiple web openings, is to use the properties of the net section at the location of an opening in the formulae that are valid for a plain- webbed section.

$$\bar{\lambda} = \sqrt{\frac{N_{pl}}{N_{cr}}} \tag{1}$$

where

$$N_{pl} = Af_y \tag{2}$$

$$N_{cr} = \frac{\pi^2 EI}{l^2} \tag{3}$$

The amount by which the plastic capacity of the net section is reduced is independent of the buckling direction considered. However, the amount by which N_{cr} is reduced — which is directly related to the reduction factor for buckling χ— does depend on the buckling direction that is considered.

For buckling in the weak direction, the weak second moment of area I_z applies. This quantity is hardly affected by the presence of a web opening and so N_{cr} remains almost unchanged.

Therefore, the slenderness $\bar{\lambda} = \bar{\lambda_z}$ decreases with increasing opening diameter, thereby increasing the reduction factor $\chi = \chi_z$. However, it turns out that for practical dimensions the reduction in net area outweighs the increase of the reduction factor for buckling, and so the global buckling capacity: $N_{b,Rd,z} = \chi_z N_{pl}$ is effectively reduced indeed due to the presence of web openings.

The second moment of area I_y the net section, which applies for flexural buckling about the strong axis, is also reduced, but to a stronger extend than I_z. Therefore qualitatively the effect of the web openings (a reduction) is the same as for buckling in the weak direction.

Buckling tends to be in the direction where the second moment of area is smaller. Example $I_z < I_y$ buckling will occur on the weak direction.

SHELL181 is suitable for analyzing thin to moderately-thick shell structures. It is a four-node element with six degrees of freedom at each node: translations in the x, y, and z directions, and rotations about the x, y, and z-axes. (If the membrane option is used, the element has translational degrees of freedom only). The degenerate triangular option should only be used as filler elements in mesh generation.

SHELL181 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. In the element domain, both full and reduced integration schemes are supported. SHELL181 accounts for follower (load stiffness) effects of distributed pressures.

SHELL181 can be used for layered applications for modeling composite shells or sandwich construction. The accuracy in modeling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reissner shell theory [7].

Cellular column can be considered as many panels, so shell181 should be used for analysis. The results of the FEM analysis will be compared with the Eurocode 3 standard.

3 Finite Element Model

3.1 Cellular column FEM model

In the first example, the inhomogeneous compression problem is studied. The objective of this problem is to investigate the stable of result due to high compression level. The problem is a rectangular plate subjects a constant distributed force. The horizontal displacement at the top edge and vertical displacement at bottom edge are set to be zero. It should be noted that due to the symmetry, only half of the plate is studied.

Materials use S235 steel. *Property of* S235 with thickness $t \leq 40\ mm$ include:

- Young Modulus $E = 210\ GPa$
- Poisson ratio $\nu = 0,3$
- Density $\rho = 7850\ kg / m^3$

- Yield strength $f_y = 235\,MPa$
- Ultimate strength $f_u = 360\ MPa$.

Boundary

Flexural buckling of a pin-ended strut is commonly regarded as the most elementary case for flexural buckling of a single column. It would therefore be reasonable to investigate this specific case.

In 2D finite element simulations using beam elements this is quite easy to achieve. At the supports, only the translations have to be prevented (i.e., prescribed value equal to zero), while rotations are allowed to occur freely. However, in a full 3D analysis using shell elements a correct modelling of pinned supports is far more difficult to obtain.

In plain-webbed columns the flange area constitutes the biggest part of the total area of a cross-section. For cellular columns this holds even more. Therefore, the largest part of the axial force will be carried by the flanges.

In order to transmit this force to its supporting structure, whether it be a beam, another column or the foundation structure, the nodal points representing the flanges thus have to be fixed axially.

The prime difficulty then is that the fixation of the flange nodes automatically prevents the rotations of the cellular members at the supports, about both axes. This cannot be avoided even partially by fixing the web only, as high local deformations due to the force transfer from the flanges to the web would then limit the ultimate capacity, and the column would fail even before reaching its flexural buckling capacity. The goal being to investigate global member buckling, such local failures have to be prevented.

Load application

In the preliminary stage of the research, it was also investigated how to apply the axial loads at best, such that the global behavior is not affected. As the axial load has to be transmitted mainly by the flanges, the introduction of this load should match the corresponding stress pattern as close as possible. Therefore, the axial force cannot be introduced simply by one single point load. Besides causing a severe local deformation of the beam end, this would nevertheless introduce a disrupting additional stress flow from the point of load application to the flanges.

Probably the best option is to distribute the load over the section minus the web hole area according to their respective areas:

$$N_{flange} = \frac{bt_f}{A - d_0 \cdot t_w} \cdot N_{Ed} \qquad (20)$$

$$N_{web\ outstand} = \frac{d_t t_w}{A - d_0 t_w} \cdot N_{Ed} \qquad (20)$$

$$N_{Ed} = 2 \cdot (N_{flange} + N_{web\ part}) \qquad (20)$$

The convergence analysis of this problem is conducted in

However, as the area of both flanges easily constitutes more than 75% of the total area at an opening location, for convenience the loads were applied to the flanges only

Set up model

The main concern in the part of the research that is presented here, has been to verify whether a simplified design rule applies to determine the flexural buckling capacity of a cellular column, based on the section properties of the net section.

In order to maximize the possibility of occurrence of deviating results due to the presence of web openings, the opening size was maximized for each section analyzed, while at the same time the web-post width was minimized (within the fabrication limits).

Two hot-rolled sections were selected which served as base profiles for as much cellular beam-columns. Thus, the whole range of available standard hot-rolled sections has been covered. The dimensions of the analyzed ACBs are given in Table 1. The precise choice of the dimensions of the sections was made using the program ARCELOR Cellular Beams.

Base profile	**IPE140**	**IPE600**
Base height (h)	140	600
Opening diameter (a_0)	97	787
Resulting height (H)	172	984
Flange width (b_f)	73	220
Flange thickness (t_f)	6.9	19
Web thickness (t_w)	4.7	12
Web-post witdth (s_0)	50	62

Table 1: Section data of the cellular column (dimensions in mm) [8]

Sections are analyzed with different lengths. These lengths have been chosen such that the non-dimensional slenderness of the member with respect to the gross section (i.e., at a web- post location) successively was equal to

$\bar{\lambda} = 0{,}2$ (limit for onset of buckling)

$\bar{\lambda} = 0{,}6$ (intermediate value)

$\bar{\lambda} = 1{,}4$ (quite high value)

The ultimate load capacity of a column subjected to an axial force was determined for the beam-column with and without web-openings, for each of the three chosen slenderness values. This analysis was made for buckling about the weak axis. The analyses for the beam-columns with uniform section (without web-openings, thus referred to as the gross section) were made in order to be able to assess the accuracy of the analyses by comparing the results with the buckling capacity according to Eurocode 3. The value in Eurocode 3 will be set to 100% and the symbol EC3.

3.2 Result

3.2.1. IPE140

The minimum depth of the base profile for an ACB is 140 mm, because of fabrication limits. Therefore, an IPE140 is the smallest possible section from the IPE-range. In total 16 different analyses have been performed for beams using this base section. The results of the runs with the slenderness values which are common for all runs (i.e. $\bar{\lambda} = 0{,}2$, $\bar{\lambda} = 0{,}6$ and $\bar{\lambda} = 1{,}4$) are presented in Figure 1, together with the curves depicting the flexural buckling capacity according to Eurocode 3. These predicted EC3 buckling capacities are referred to as 100%-values.

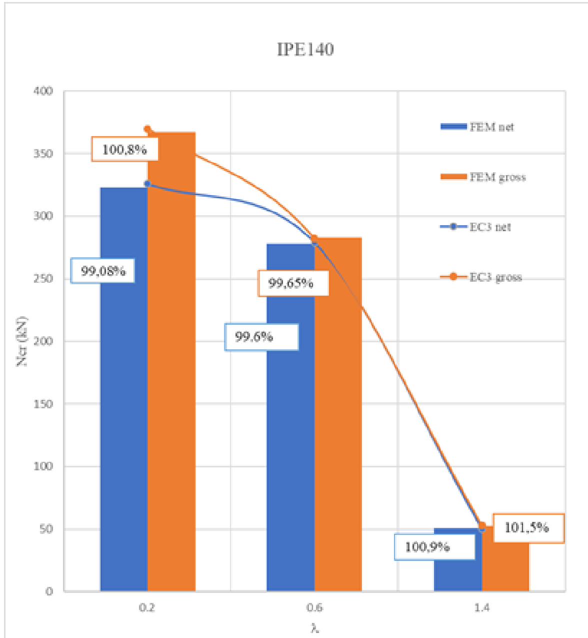

Figure 1: Chart relative slender and critical load of IPE140

IPE140						
λ	0,2		0,6		1,4	
	Gross	Net	Gross	Net	Gross	Net
EC3	370	326	282	279	53	52,4
FEM	367	323	283	278	52,2	51,9
Δ(%)	0,8	0,9	-0,35	0,35	1,5	1

Table 2: Relative error of critical loads for ACBs cut from a IPE140 section with/without web holes (dimension in kN)

Another relationship that can be observed most times, is that when for buckling about the weak axis the result for the gross section is larger than that for the net section. The values of FEM are close to the predicted EC3 values.

One observation is that the curve of the critical load decreases with increasing slenderness.

The result of slenderness $\bar{\lambda} = 0{,}2$ is critical load before column reach yield strength.

Commonly used range of slenderness values $\bar{\lambda} = 0{,}6$ it appears that when the numerical results are compared to the values predicted EC3 buckling load using the properties of the net section, at the location of a web opening the differences are either small (less than 2%)

Buckling load of gross section and net section with slenderness $\bar{\lambda} = 1{,}4$ approximately the same.

The results of critical load are presented in table 2. With the increase of the critical load of the cellular column, it approximates the critical load of the column I.

Shape buckling and chart of force with displacement in the direction x of cellular column IPE140 with slenderness value 0,6 are presented in figure 2 and 3.

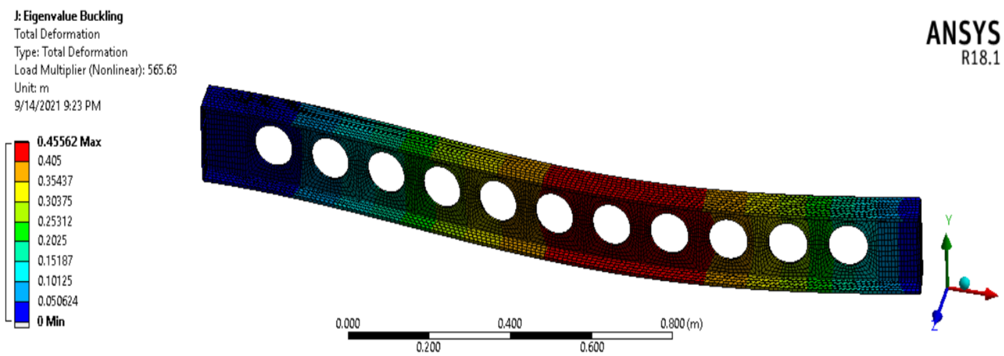

Figure 2: Shape buckling of IPE140 cellular column at slenderness $\bar{\lambda} = 0.6$

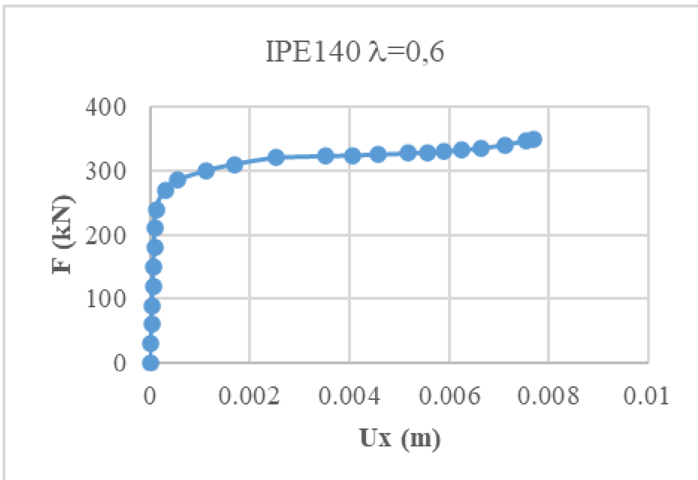

Figure 3: Chart of force with displacement in the direction x of cellular column IPE140 with slenderness λ =0,6

3.2.2. IPE600

The last base section from the IPE range whereof the global buckling behavior was investigated, is an IPE600 – the biggest section from the 'normal' IPE range.

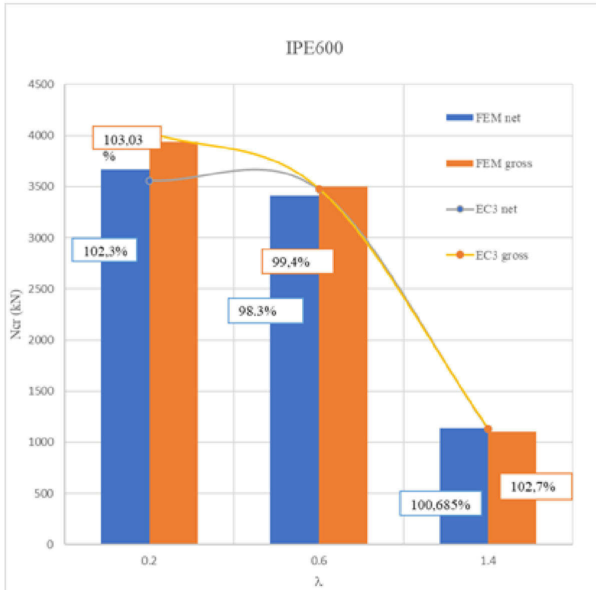

Figure 4: Chart relative slender and critical load of IPE600

IPE600						
λ	0,2		0,6		1,4	
	Gross	Net	Gross	Net	Gross	Net
EC3	4028	3761	3481	3470	1131	1128
FEM	3936	3669	3469	3412	1101	1137
Δ(%)	2,3	3	0,5	1,6	2,7	-0,8

Table 3: Relative error of critical loads for ACBs cut from a IPE140 section with/without web holes (dimension in kN)

From the results of Figure 4 and Table 3, the behavior of the cellularcolumn is quite similar to the previous tests.

- for the small slenderness value 0.2 the FEM result is somehow lower than the EC3 prediction
- for the medium slenderness value 0,6 the FEM result is less than 10 percent above the EC3 prediction.
- for the higher slenderness value 1,4 critical load FEM is higher than the predicted EC3 value at net section.

At a slenderness value of 0,2 the structure fails due to yield strength before it fails due to buckling. Buckling of cellular column IPE600 with slenderness $\bar{\lambda} = 1{,}4$ is presented in figure 5

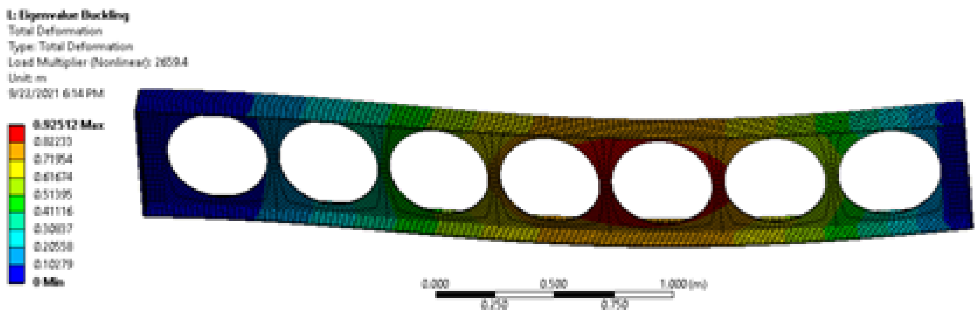

Figure 5: Buckling of cellular column IPE600 with slenderness λ =1,4

3.3 Web-post buckling

3.3.1. Theorety

As so far no experimental evidence is available structural behaviour of cellular members loaded in axial compression, the next objective of the here presented research has been to study the influence of an applied axial force on the web-post buckling failure mechanism.

The main difference in behaviour between beams and columns lies in the presence of an not-negligible axial (compression) force, which might influence the web-post buckling capacity.

As this concerns local buckling behaviour, another model is required than that which was used to study the global buckling failure mode.

First an analytical analysis was made of both described approaches for checking the web-post buckling capacity, in order to evaluate

whether they can allow for the presence of an axial force. This theoretical investigation is followed - and affirmed - by the subsequent numerical evaluation.

LWO model

The ECSC project Large web openings for service integration in composite floors (LWQO) aimed to investigate experimentally and theoretically the behavior of steel and composite beams with web openings. One of the outcomes has been a detailed design procedure that is consistent with the Eurocodes.[9]

In LWO model of a single web-post was subjected to only a vertical shear force. As bending will utilise some capacity of the flanges already, the part of the axial load that is transmitted by the webs of the tee sections will increase. LWO model the web- post buckling phenomenon is not influenced by the presence of an axial force.

The result of LWO model from report Cellular Beam-Columns In Portal Frame Structures.

Finite element model

For the verification of the described web-post buckling behavior in the presence of an axial force, a new FEM model was developed. This model basically consists of a simply supported cellular beam, loaded by a combination of a point load 2F in the middle and an axial force N at both outer ends. The beam length is chosen such that there are two circular web openings with a single web- post in between on each half of the beam.

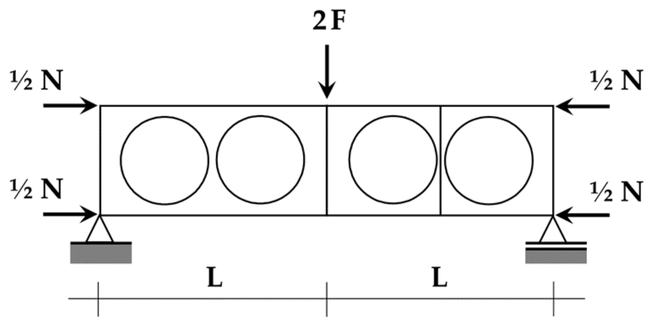

Figure 6: Loading configuration

For the verification of the described web-post buckling behaviour in the presence of an axial force, a new FEM model was developed.

This model basically consists of a simply supported cellular beam, loaded by a combination of a point load 2F in the middle and an axial force N at both outer ends.

The beam length is chosen such that there are two circular web openings with a single web- post in between on each half of the beam. For each base section, two web-post widths have been researched numerically. The first time with the minimum web-post width according to the geometrical limitations of the ARCELOR Cellular Beams, and the second time with a web-post width twice as big.

In all simulations, the steel grade used is S235.

The simulations are carried out to determine the ultimate vertical load for a given axial load. In the FEM calculation, first the axial load is applied in a few steps. Then the vertical load is increased until failure occurs.

The base section use IPE330 to analyses.

3.3.2. Result

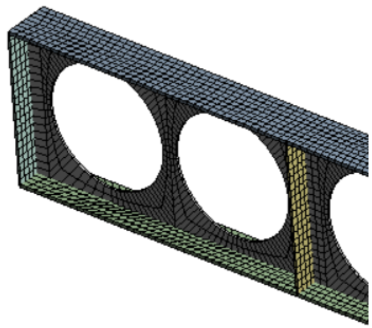

Figure 7: IPE330 with $s_0 = 50$mm

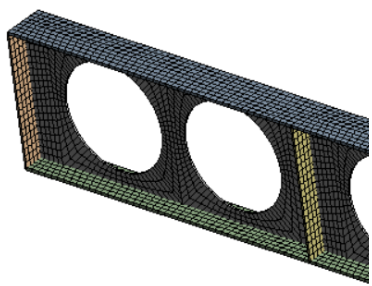

Figure 8: IPE330 with $s_0 = 100$mm

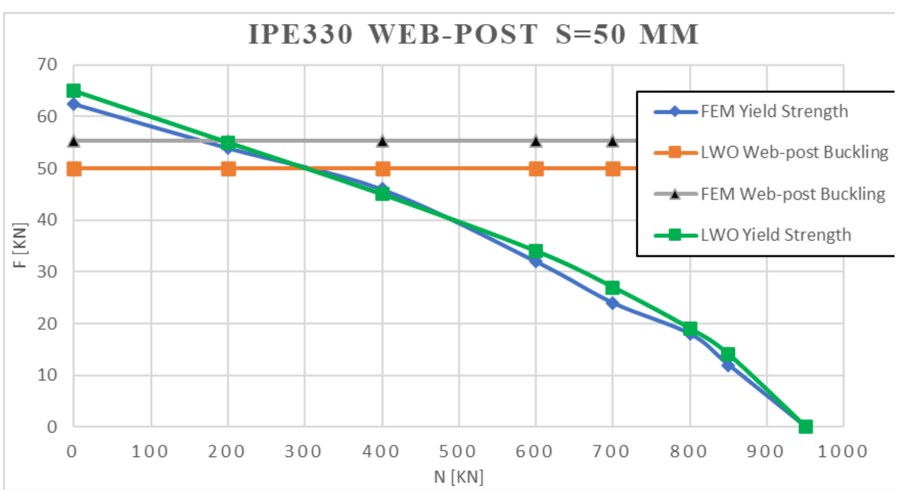

Figure 9: Results for web- post buckling IPE330 with $s_0 = 50$mm

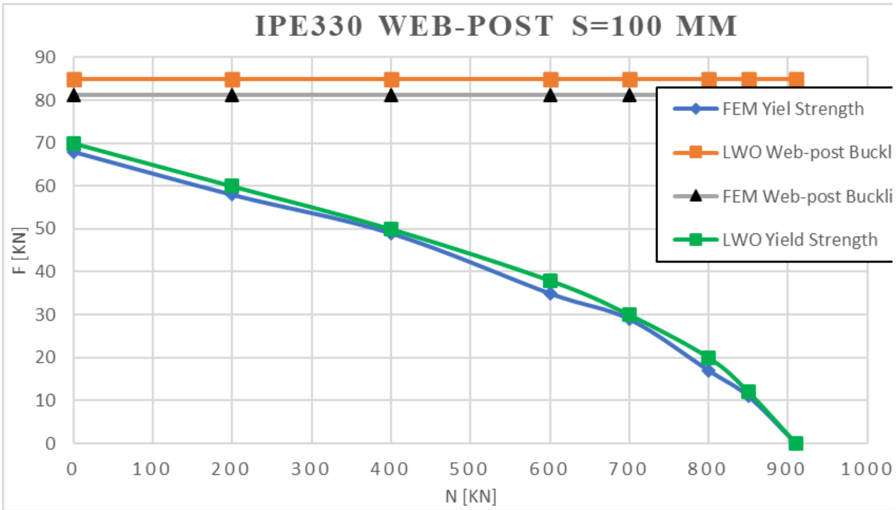

Figure 10: Results for web- post buckling IPE330 with $s_0\,=\,100$mm

For base profile IPE330 web-post buckling is much more likely to occur. Now for low axial force, web-post buckling does govern the design, while for higher normal load action model obtain yield strength. Again, the FEM results are above the predictions of both models, which are thus safe. Especially for the double web-post width the models are rather conservative, given the margin seen between the FEM result and the predictions from the theoretical models.

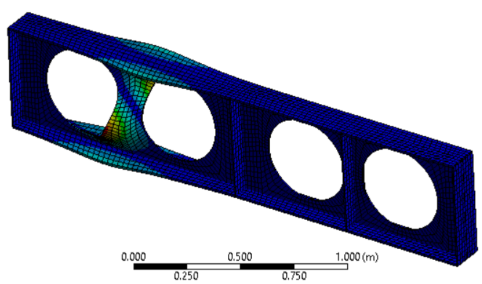

Figure 11: Web- post buckling IPE330 with $s_0\,=\,50$mm N=200kN

3.4 Frame structures using cellular member

Frame structure has been analyzed for a number of load cases. Vierendeel mechanism is common failure for cellular member. The shear force, which transfers across the opening, causes some secondary moments (Vierendeel bending) in the top and bottom tee sections as shown in Fig. 12.

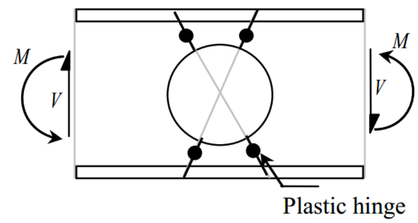

Figure 12: Plastic hinge

Both geometrically and materially, the analysis behavior modelled according to EN1993-1.

Material use S355 with yield strength f_y=355 MPa

The frame considered is described by the following characteristics:

- span d=15m
- top height H=5m
- roof inclination ∝=6°

The members have been chosen as:

- columns ACB from HE200A with:

  H_0=275; d_0=195; s_0=50 [mm]

- rafters ACB from IPE240 with:

  H_0=360; d_0=275; s_0=100 [mm]

The support conditions have been chosen as fully clamped. In practice pinned supports may be encountered more frequently, but in

3D finite element calculations clamped supports are easier to model.

Lateral supports have been added to prevent out-of-plane flexural buckling an lateral- torsional buckling to occur. Hereafter the results for a number of simplified load cases are discussed and compared.

Load is distributed vertical load in Fig. 13.

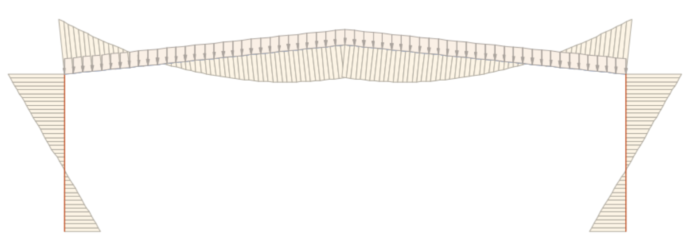

Figure 13: Distributed vertical load

Structure failure occurs when the plastic capacity of the rafter at both ends is reached in Fig. 14. The frame is able to resist an increase loading, although with reduced stiffness, until another plastic hinge has been formed.

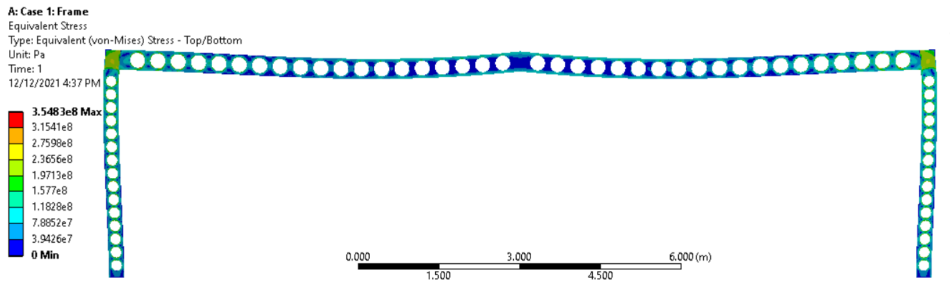

Figure 14: Stress in frame using cellular member

The Vierendeel bending appear in the fist opening in rafter. Opening is plastic hinge in Fig. 15. For increased load this would also occur at the next openings in the rafter (and subsequently in the columns) if only the bending moment could increase at the eaves.

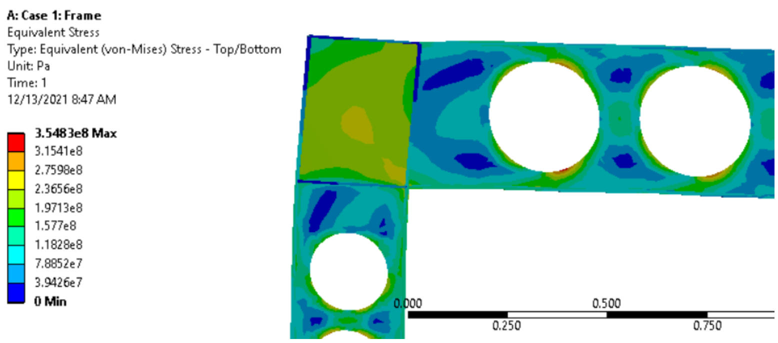

Figure 15: Plastic hinge in opening

Failure finally occurs when the web-post shear capacity in the columns in reached, as no redistribution of these forces is possible.

Theoretical results LWO the value of the load causing plastic hinge in opening is 7100 N/m. When comparing FEM is 6840 N/m to LWO results, there is an error of 3.66%

4 Conclusion

4.1 Global buckling cellular column

From the presented results, slenderness $\bar{\lambda} = 0{,}2$ structure is failure by yield strength before buckling. For slenderness $\bar{\lambda} = 0{,}6$ and structure $\bar{\lambda} = 1{,}4$ flexural buckling but still ensuring safety.

The maximum error when compared with the critical force according to EC3 at the HE200A section with a slenderness value of 0,2 is 4,4%. However, the behavior case is not destroyed by buckling.

Buckling load analysis by FEM with slenderness has an error of not more than 2% when compared $\bar{\lambda} = 0{,}6$ with EC3.

The results obtained by the proposed method for testing the flexural buckling force of the EC3 cellular column at the net section are good. But the results of this method do not seem to be suitable for high slenderness.

However, the results are still valuable, as the results for the gross and the net section can be compared to each other. Thereby it is also possible to assess the accuracy of the FEM analyses.

Relative errors between gross and net section in equation 7:

$$\frac{relative\ error\ for\ net\ section}{relative\ error\ for\ goss\ section} = \frac{1+\Delta_{net}}{1+\Delta_{gross}} \tag{1}$$

With Δ = Δ(100%)/ Δ

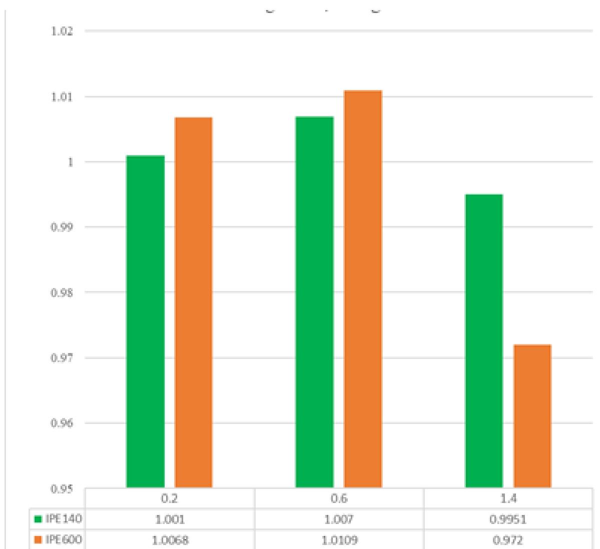

Figure 15: Comparison of relative errors between gross and net section

From Fig. 15 most behave relatively well. However, at the slenderness of 1,4 the IPE600 section has a large error.

Furthermore, a few general observations about the error relationship for buckling: with slenderness $\bar{\lambda} = 0{,}2$; $\bar{\lambda} = 0{,}6$ has a value greater than 1, with slenderness $\bar{\lambda} = 1{,}4$ has a value less than 1.

The presented results suggest that the unstable method of cellular beam is safe.

4.2 Web-post buckling

From the analyses presented in the preceding paragraphs for each base section considered, the following conclusions may be drawn an approximately linear relation has been observed for the influence from an axial force on the web-post buckling capacity of cellular member.

The FEM model gives web-post buckling predictions which are more close to the LWO curve.

4.3 Frame using cellular member

Frame is plastic hinge before structure failure.

When compared with FEM result with LWO error less than 5%, FEM result is safe

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgment

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Anexo A_Elemento tipo Shell 181 de ANSYS

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