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Original Research Article

MEASURES OF AGREEMENT BETWEEN COMPUTATION PROGRAMS AND EXPERIMENT: THE CASE OF BEAMS WITH CIRCULAR CUTS IN THEIR WEBS

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Abstract

In the field of metal construction, cellular beams represent an attractive solution to meeting the various technical and economic constraints, especially for large-span buildings. In particular, they allow components linked to the construction to pass through their openings (ventilation ducts, electrical threads, etc.) and thus contribute to significantly reducing the thickness of the floors. However, the use of such beams requires special attention to comply with the regulations in force, in order to guarantee stability and behavior in line with the challenge of preserving the structures. This article focuses on the analysis of the measures of agreement between experiment and computation programs (strength of materials, Robot structures, and Inflexion-EF) results of the beams with circular cuts in their webs (IPE A 100), supported simply and subjected to a concentrated load. The experimental results show that the vertical displacement resulting

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from transverse compression is induced by various factors: length, cuts in their webs, location of the load, and stiffening of the beams. The comparison of experimental and theoretical results demonstrates the importance of experimental tests in validating theoretical results.

Keywords: cellular beam, circular cut, length, openings, load location, Robot structures, Inflexion-EF

1. INTRODUCTION

The design of a building meets architectural and economic requirements, while ensuring the safety and comfort of the occupants. One of the new trends in modern constructions is to increase the span of the beams, thereby increasing the size of the spaces used. In this context, reducing the weight of the sections must receive special attention. The use of steel beams, with circular openings in the circular core (cellular beams) allow the passage of the pipes within them, which considerably reduces the thickness of the floors; this explains designers' growing interest in them over many years, even before specific and appropriate calculation procedures were developed [1-4].

Several studies have been carried out with the aim of determining the behavior of the cellular beams. Sweedan and El-Sawy [5] studied the elastic behavior of the core of the cellular beam when buckling under different loads. The results showed that the stability is considerably reduced by the existence of the perforations. This influence is presented in dimensional terms, as the buckling coefficient k. It is recommended that exceeding the limit S/D = 3.5 (S : distance between openings , D: diameter of openings) should be avoided, because an increase beyond this has no significant effect on the improvement of the stability .

Nseir et al. [6] focused their research on the behavior of cellular beams at spillage. The main objective was the validation of the finite element model by comparing it with an experimental model in which many parameters (the relative slenderness, steel grades, shapes of the cross sections, moment distribution bending, and size of the openings) underwent variation. The comparison between the tests and the finite element models showed good agreement. A comparison of the two sources of results demonstrated that the finite element models are able to provide reliable results and can be safely substituted for experimental tests.

Sweedan [7] studied the elastic stability of doubly symmetrical, I-shaped cellular beams under different loading conditions. The beam was subjected to moments of equal extremities, and, at mid-span, to concentrated loads and to uniformly distributed loads. The results indicated that cellular beams with thin plates (having a small h_w/t_w value) and cellular beams with large holes (d_h/h_w) are more prone to shear deformation. In addition, wide spacing of the holes in the core (large S/h_w value) leads to greater shear stiffness, and the distortions of the core are therefore small or negligible. In addition, the reduction in the coefficient of the gradient moment (C_b) is more pronounced in short-span beams where the shear stresses are greater than in long-span beams, which leads to deformations in the core accompanied by spillage. Finally, beams subjected to a concentrated load at mid-span can withstand higher moments than those due to uniformly distributed loads.

Researchers [8,9] studied the nonlinear analysis of normal-strength and high-strength cellular beams under different configurations of concentrated load. A nonlinear 3D finite element model (ABAQUS) was developed and verified by tests on cellular beams. The results of the study showed that the cellular steel beams failed due to the rapid deformation of the web post, which presented a considerable decrease in the breaking load. It was also demonstrated that the use of high-strength steel offers a considerable increase in breaking loads compared with normal-strength cellular beams. Finally, the predictions of the experimentally observed failure mode were confirmed numerically.

Researchers [10,11] have studied the behavior of stainless steel cellular beams with stiffened webs during a fire. It was found that the unprotected beam lasted for 29 minutes during the test after being exposed to a standard fire, and the model developed in the ABAQUS software was shown to provide an excellent depiction of the behavior.

In addition, research [12-14] has been conducted to suggest a numerical model for predicting the behavior of steel castellated beams. The results showed that lateral distortional buckling solutions are very close to numerical model results (FEA) for alveolar beams with wide and thick flanges. Tsavdaridis et al. [15] presented an experimental and analytical study on the behavior of seven cellular steel beams with different web opening configurations. By comparing the samples, it was concluded that it is the critical opening length (longitudinal) that affects the capacity of the beam, not the core opening area (transverse). In addition, the results demonstrated how the width of the strip located between the openings (upright) affects the carrying capacity of the cellular beams.

In this regard, our study was conducted on two axes, one theoretical and the other experimental. First, a series of tests was carried out on beams with circular cuts in their webs based on IPE A 100, supported simply and subjected to a concentrated load. Finally, an analysis was performed of the experimental results obtained and their comparison with theoretical results from the strength of materials (SOM), Robot structures, and Inflexion-EF programs.

2. MATERIALS AND METHODS

The beams on which the drilling was carried out were IPE A 100 laminated sections, certified by the German Standards and Standardization Institute (Deutsches Institut für Normung; DIN). These beams were of different lengths in order to enable the influence of length on the behavior of circular cuts in their web to be studied. Table 1 summarizes the different beams used.

Table 1. Beams used in the experimental test

Abbreviation	Type of Profiles	Lengthr (cm)
CB1	IPE A 100 (circular cuts in their web)	200
CB2	IPE A 100 (circular cuts in their web)	260
CB3	IPE A 100 (circular cuts in their web)	298,5
B4	IPE A 100 (solid web)	298,5

The steel designations of IPE A 100 adopted in DIN 17100 is ST 37-2 and has an equivalence in Eurocode 3 [16] of S235 JR.

2.1. Creation of circular cuts in the web of beams

The openings in the web of beams were created in a turning workshop, requiring the mobilization of a CONSTAN 565 radial drill for several days. This radial drill had adequate freedom of movement and inclination for making the openings (figure. 1). The holes were gradually widened to 15 mm, 25 mm, and then 38 mm.

Fig. 1. Locking device for the beam in the base of the radial drill

2.2. Test device

The tests were carried out using a SCHENCK-TREBEL compression machine, which can reach 3000 kN (figure. 2). The tests were carried out in several stages.

• First step: complex installation of a metal support on the lower plate, then the addition of two simple supports that supported the tested beams CB1, CB2, CB3, and B4.

• Second step: the welding of transverse stiffeners, pre-cut to be adapted to the beams, on both sides and in the middle of the beam, in order to reduce the risk of deformation of the web.

• Third step: the tracing of reference lines (L/2 and L/3); in L/2, the manufacture of load transmission elements (metal tubes filled with concrete).

• Fourth step: the setting up in L/2 and L/3 using suitable fixing devices of dial indicators for measuring displacements.

At the end of these steps, the beams were ready for loading. Figures 2, 3 and 4 illustrate the devices used.

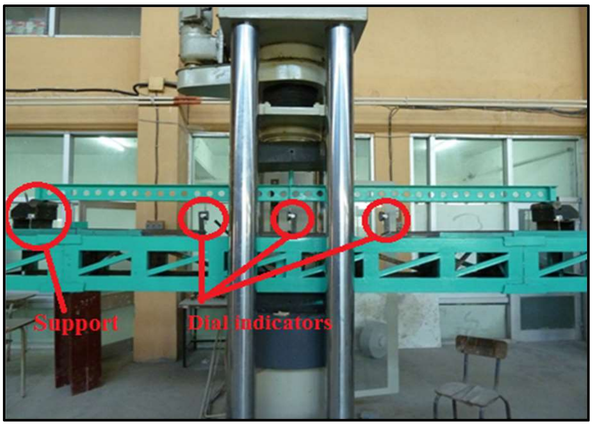


Fig. 2. Beams ready to load

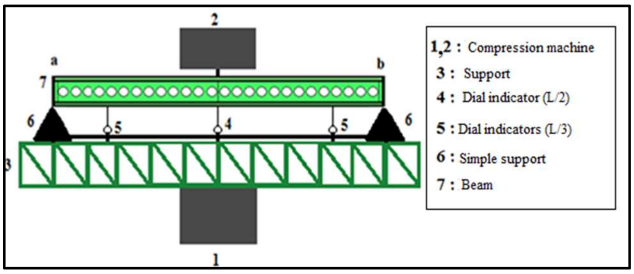


Fig. 3. Test device

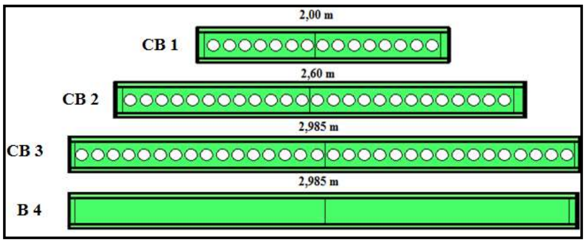
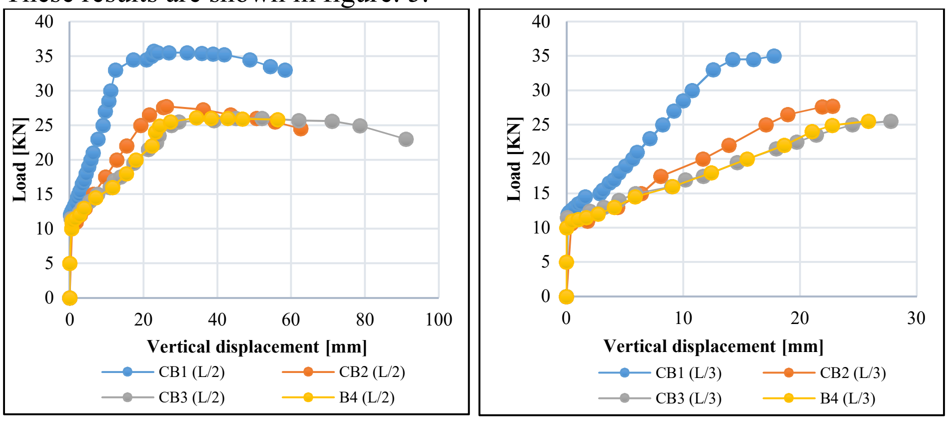


Fig.4. Representation of the beams used

3. ANALYSIS OF EXPERIMENTAL RESULTS

For each of the beams studied, the variations in vertical displacement were measured at L/2 and L/3, as a function of the different levels of transverse load. These results are shown in figure. 5.



(a) (b)

Fig. 5.Variations in vertical displacement as a function of transverse load: a) Vertical displacement (L/2), b) Vertical displacement (L/3)

3.1. Influence of length on the behavior of beams with circular cuts in their webs

Figure. 5 presents the comparison of the vertical displacement measured at L/2 and L/3 for all the beams studied and for different loading values. Analysis of the curves shows that the beam CB1 reached a loading capacity that was 22% greater than that of the beam CB2 and 27% greater than that of the beam CB3. The vertical displacement of the beam CB1 was half of that relating to the beam CB2 and a fifth of that relating to the beam CB3, for the two intervals L/2 and L/3.

This reflects the influence of the length parameter on the behavior of these beams. As a result, long beams are more prone to large vertical displacement.

3.2. Influence of circular cuts on the behavior of beams

Figure.5 also shows the comparison between the vertical displacements measured for a solid web beam and beams with circular cuts, both of a length equal to 2.985 m. The two beams were placed in the same test device and were subjected to the same support conditions. The maximum loading achieved by the solid beam (26.1 KN) was slightly higher than the maximum loading of the beam with circular cuts in their webs (26 KN). With regard to the deflection measured, it is notable that, for the same loading rate (26 KN), the vertical displacement at L/2 of the beams with circular cuts in their webs was 22% greater than that of the solid beam B4. The same phenomenon was observed with a load of 25.7 KN at L/3, with the vertical displacement of the beams with circular cuts being 8% greater than the vertical displacement of the solid beam.

These results are explained by the fact that the solid web beam is more rigid than beams with circular cuts. Therefore, solid web beams can reach a higher loading capacity than beams with circular cuts, with a reduced vertical displacement. Which confirms the result of previous research [17] , regarding the presence of openings in the web with all the hole shapes causes a significant reduction in shear capacity.

4. COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS:

4.1. Comparison of experimental vertical displacement with theoretical results calculated with the SOM software

The study of vertical displacement was performed on a beam that was supported simply and subjected to a vertical loading. According to SOM, the calculation of the vertical displacement at L/2 and L/3 is carried out as in Equations 4.1 and 4.2. The results of the calculation of the vertical displacement at L/2 and L/3 as a function of loading F are presented in table 2.

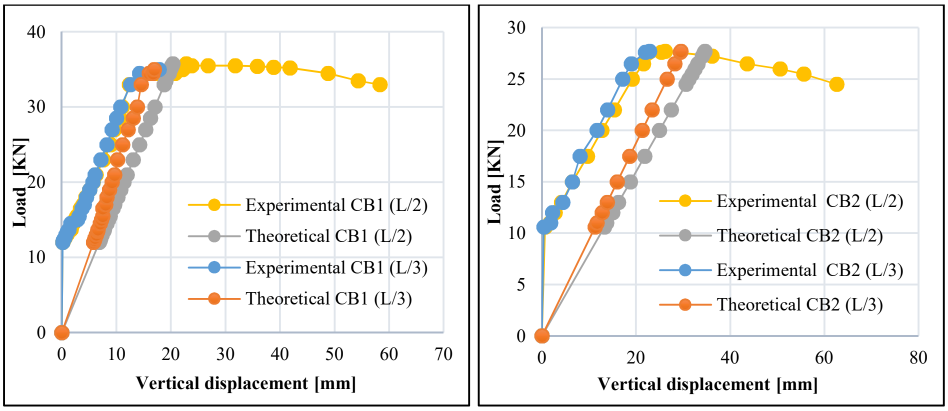
$$F_{L/2}= \frac{F\,L^3}{48\,E\,I} \tag{4.1}$$

$$F_{L/3}= \frac{F\,L^3}{48\,E\,I}\left(3\frac{x}{L} - 4\frac{x^3}{L^3}\right) = -\frac{23\,F\,L^3}{1296\,E\,I} \tag{4.2}$$

Table 2. Verticals displacement as a function of loading F

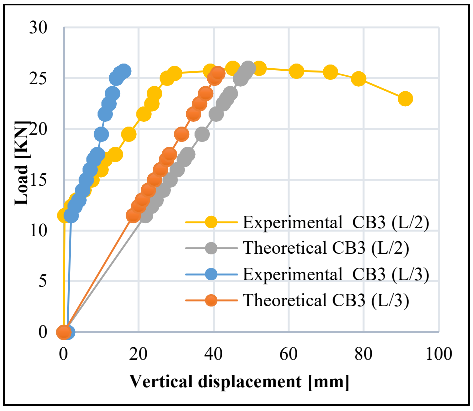
Length *(m)*	Verticals displacement *(mm)*	
	L/2	L/3
2,00 (circular cuts in their web)	$5{,}683 \times 10^{-4}$ F	$4{,}841\times 10^{-4}$ F
2,60 (circular cuts in their web)	$1{,}245\times 10^{-3}$ F	$1{,}063\times 10^{-3}$ F
2,985(circular cuts in their web)	$1{,}889\times 10^{-3}$ F	$1{,}609\times 10^{-3}$ F
2,985 (solid web)	$1{,}868 \times 10^{-3}$ F	$1{,}591\times 10^{-3}$ F

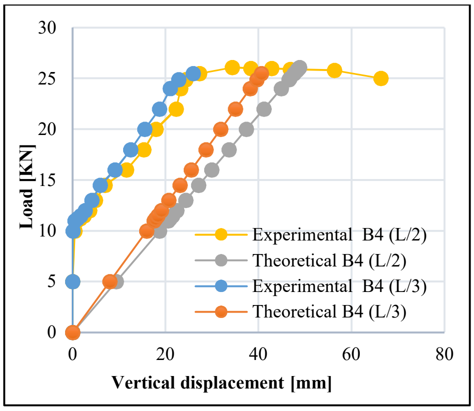
Figures 6 and 7 shows the differences between the experimental vertical displacement and theoretical vertical displacement.



(a) (b)

Fig. 6. Comparison of experimental verticals displacement with theoretical results: a) Beam CB1, b) Beam CB2





(c) (d)

Fig. 7. Comparison of experimental verticals displacement with theoretical results:
c) Beam CB3, d) Beam B4

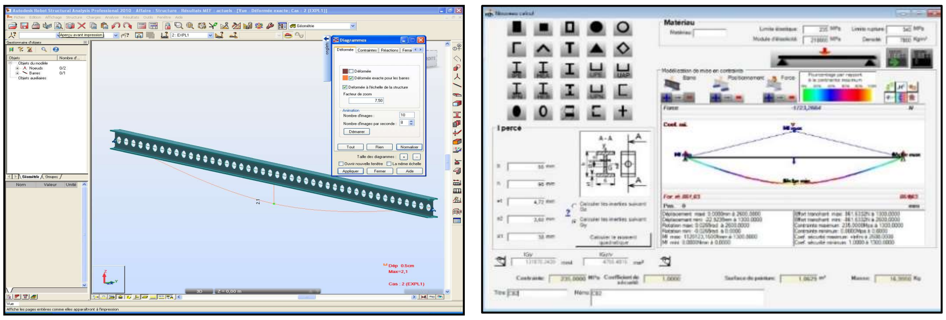
Analysis of figures 6 and 7 shows discrepancy between the experimental and theoretical vertical displacement. In general, the values of vertical displacement at the start of the test were less than the vertical displacement calculated with SOM. This is probably due to the fact that experimental beams have stiffeners, whereas theoretical beams do not take into account the stiffeners. The stiffeners improve stiffness and reduce the amplitude of the vertical displacement.

We can see in figures 6 and 7 that the experimental values of the beam CB1 were closer than theoretical values compared with the other beams. This is attributed to the influence of the length on the vertical displacement. Therefore, short beams offer the advantage of reduced vertical displacement compared with long beams and with greater loading capacity.

We note that, after reaching the ultimate charge, the amplitude of the vertical displacement was no longer in a relationship of proportionality with the load (load; vertical displacement). Indeed, an increase in the load generated an increase in the experimental displacement contrary to the theoretical displacement. This was because the plastic bearing was reached, and therefore the deformation continued to increase.

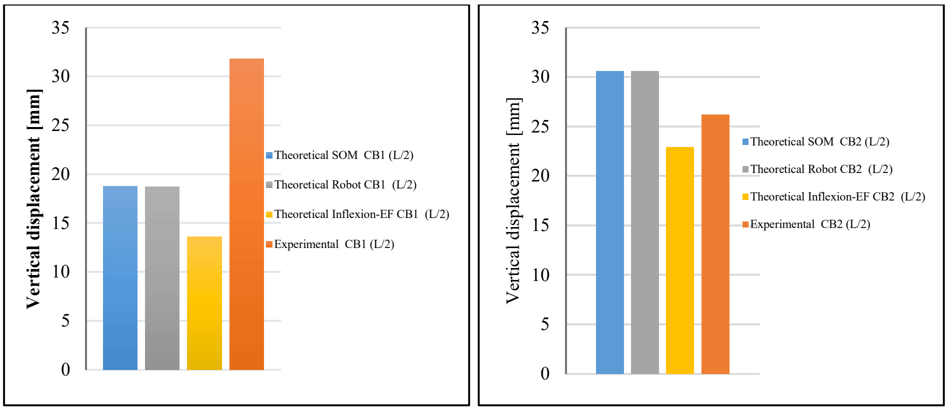
4.2. Comparison of experimental maximum vertical displacement with theoretical results calculated with the SOM, Robot structures, and Inflexion-EF programs

After having inserted all the parameters of the beams in the software (figure. 8), we compared the experimental results with the theoretical results of the SOM, Robot structures and Inflexion-EF programs. The results of the maximum vertical displacement are presented in figures. 9 and 10.



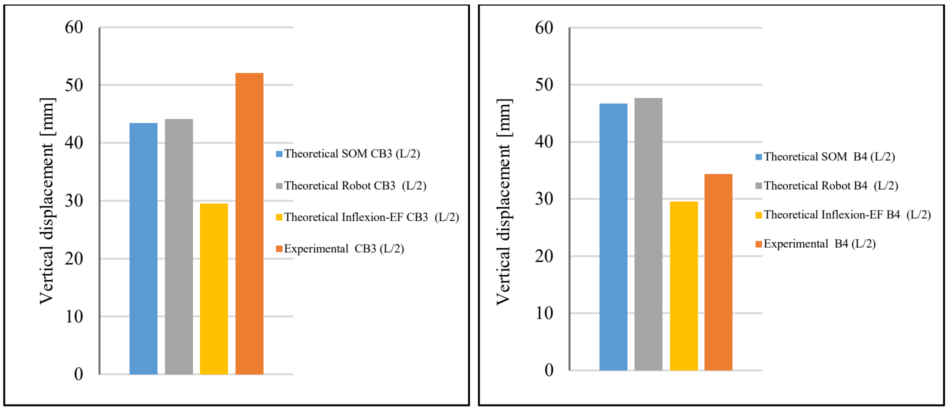
(a) (b)

Fig. 8. Insertion of the parameters of the beams into the software:
a) Robot structures, b) Inflexion-EF



(a) (b)

Fig. 9. Comparison of the maximum experimental vertical displacement of beams with the maximum theoretical vertical displacement from the SOM, Robot structures and Inflexion-EF programs: a) CB1, b) CB2



(c) (d)

Fig. 10. Comparison of the maximum experimental vertical displacement of beams with the maximum theoretical vertical displacement from the SOM, Robot structures and Inflexion-EF programs: c) CB3, s) B4

Figures 9 and 10 show that the calculated maximum theoretical vertical displacement from SOM were in agreement with those evaluated from the Robot structures software, as this integrates the method of theoretical analysis making reference to the same notions.

Conversely, the values of vertical displacement estimated by the Inflexion-EF software were lower than the other theoretical values (SOM, Robot structures). This difference varied from 38.27% to 58.31%. These results are attributable to the fact that the software takes into account the data and calculations for reference, and only the bending behavior is calculated. In addition, no safety factor is considered, because the software is based on the assumptions of strength of materials. This result shows the importance of the experimental test in validating the results.

On the other hand, we can see in figures. 9 and 10 that the experimental results of the maximum vertical displacement at the elastic limit are close to the results estimated theoretically by SOM and Robot structures (maximum difference of 13 mm). This shows the importance of the theoretical calculation and its reliability without neglecting the experimental test, which allowed us to validate the theoretical calculation.

Finally, from the perspective of this article we will complete the study with comparison between experimental and a finite element (FE) model developing by ABAQUS software to analyse failure mode of beams and beams with circular cuts in their webs. Figure 11 shows an example of beam with circular cuts in their webs, indicating that the stresses are higher on circular cuts.

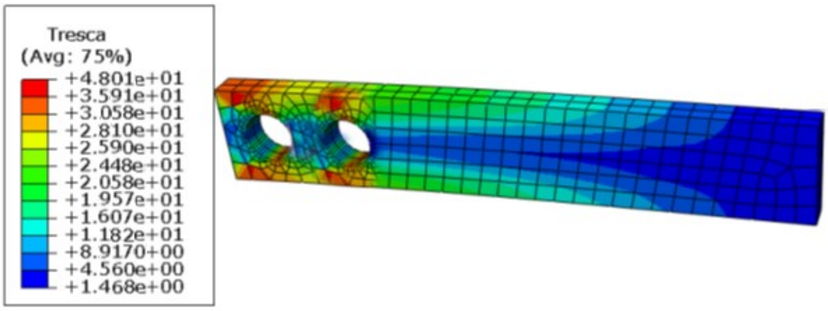


Fig. 11. FE model for beam with circular cuts in their webs

5. CONCLUSION

In this paper, measures of agreement between computation programs (strength of materials, robot structures, and inflexion-EF) and experiment have been conducted in the case of beams with circular cuts in their webs. From the experimental and theoretical results of this investigation, the following conclusions can be drawn:

-The point of application of the load (in our case L/2) is where the highest deflection occurs.

- Beams with a solid web offer the advantage of reduced vertical displacement compared with beams with circular cuts in their webs.

- Solid beams have a higher loading capacity than beams with circular cuts in their webs due to their greater rigidity.

-The stiffeners increase the rigidity of the beams, which enhances the amplitude of the deflection and the resistance to shearing buckling.

- The comparison of the experimental results with the theoretical results shows that the use of the SOM and Robot structures programs provides results in perfect agreement when compared to results of Inflexion-EF software. This shows the importance of the experimental phase.

The work presented in this paper is an initial step in a wider study, which will aim to use the developed finite element model (FE) in order to fully understand the behavior of beams with circular cuts in their webs.

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