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Numerical and Analytical Evaluation of Elastic Lateral-Torsional Buckling in Cellular Steel Beams

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Abstract. Cellular beams are, characterized by the presence of circular openings at the web surface. These beams are produced through a periodic longitudinal cut along the web of a hot-rolled steel I-section. The resulting parts from the cut are then shifted and welded together, forming profiles with increased height and sequential openings in the web. This increase in the effective depth, combined with the presence of openings, makes this type of beam more susceptible to new failure modes, as well as intensifying existing collapse mechanisms. This study investigates steel cellular beams through numerical analysis using the Abaqus 2021 software, with emphasis on the failure mode known as Lateral–Torsional Buckling (LTB), which occurs when a beam subjected to bending moments undergoes lateral displacement combined with rotation about its longitudinal axis. The research also addresses the numerical methodologies employed to evaluate this phenomenon, taking as reference the Brazilian standard ABNT NBR 8800:2024, limited to solid-web beams, and the European standard EN 1993-1-13:2024, which already accounts for the specific characteristics of cellular beams. After calibrating the cellular beam models, the elastic critical moment results, obtained both through the analytical method of the Brazilian standard and by numerical modeling in Abaqus, showed good agreement, demonstrating the reliability of the methods applied. The results highlight that cellular beams can sustain loads equal to or greater than those of solid-web beams, allowing for cost savings and optimization in steel beam structural design. It was also observed that geometric and mechanical parameters influence the LTB resistance of the beams, with flange dimensions having the greatest impact, due to their strong relationship with bending moment capacity.

Keywords: Steel cellular beams; Lateral–torsional buckling; Finite element analysis.

1 Introduction

Steel is widely used in civil construction due to its strength, ductility, and ease of assembly Fakury et al. [1]. Among steel structural elements, cellular beams stand out for their lightness, architectural flexibility, and ability to allow the passage of pipes and ducts through the web openings. These beams are manufactured by cutting and welding transversely shifted I-sections Veríssimo [2], resulting in profiles with increased depth and periodic web openings. This configuration allows for the spanning of large distances with reduced self-weight, as illustrated in Fig. 1.

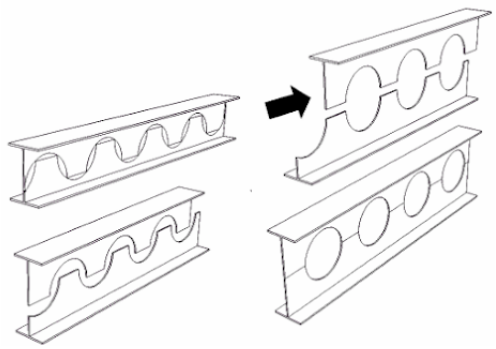


Figure 1. Manufacturing process of cellular beams

However, the presence of these openings alters the structural behavior, particularly with respect to lateral–torsional buckling (LTB) of the beam element. This phenomenon is a global instability mode which occurs under bending about the major axis of the section, leading to a coupled collapse by lateral displacement and rotation, as shown in Fig. 2, Abreu [3]. In cellular beams, torsional and warping stiffness are reduced, intensifying the LTB phenomenon.

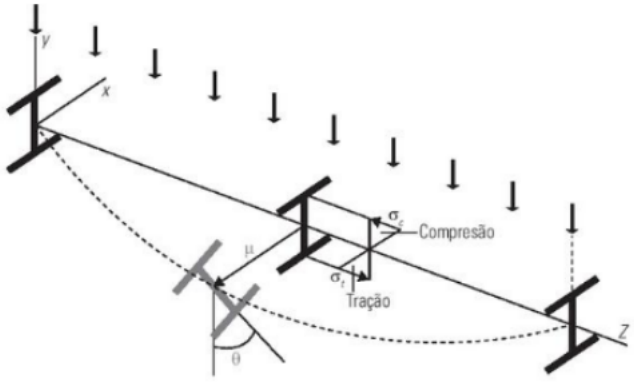


Figure 2. Lateral Torsional Buckling (LTB) of I-Section Beams

The analytical expression for the elastic critical moment associated with lateral–torsional buckling of solid-web beams under uniform bending was originally developed by Timoshenko and Gere [4]. The Brazilian standard ABNT NBR 8800:2024 [5] and the European standard EN EN 1993-1-13:2024 [6] are both grounded in the classical elastic buckling theory proposed by Timoshenko and Gere [4]. However, the Brazilian code does not provide any additional guidance for applying this formulation to beams with web openings, such as cellular beams. In contrast, sub-clause 8.12 of EN 1993-1-13:2024 [6] specifies that this formulation remains applicable to beams with openings when the geometric properties of the section are evaluated at the location of the largest opening under specific conditions, thus accounting for the local reduction in stiffness and torsional resistance. This becomes not valid in beams with non-regular spacing or complex loading conditions, closely spaced openings, eccentric openings, or elongated and sinusoidal openings.

These normative limitations highlight the need for a more detailed investigation of cellular beams. In this context, the present study aims to evaluate the lateral–torsional buckling (LTB) behavior of cellular beams through numerical simulations and analytical comparison, focusing on cases where failure is governed by elastic buckling. The analyses were performed using the finite element software SIMULIA SIMULIA by Dassault Systèmes [7], and the results were compared against the analytical estimations from ABNT NBR 8800:2024 [5] and EN 1993-1-13:2024 [6].

1.1 Failure Modes

1.1.1 Lateral Torsional Buckling (LTB)

When an I-section beam is subjected to a constant bending moment along its length, lateral torsional buckling (LTB) becomes one of the most critical forms of global instability. This phenomenon occurs when the compressed flange loses stability, inducing a torsional stress that the structure cannot resist, resulting in the beam twisting about its longitudinal axis Oliveira [8].

1.1.2 LTB Design Criteria and Applicability to Cellular Beams

The design for lateral torsional buckling (LTB) in steel beams according to ABNT NBR 8800:2024 [5] is presented in Annex D, item D.2.8-a. The standard addresses I-section beams with two axes of symmetry, subjected to bending about the major axis (x), under elastic behavior. The elastic critical moment (M_{cr}) is calculated by Equation 1, considering various mechanical and geometric section properties.

Key parameters include the equivalent moment factor (C_b), which accounts for variable bending moments and is always greater than 1, and the unbraced length (L_b). The calculation also incorporates the steel modulus of elasticity (E), the moment of inertia about the y-axis (I_y), the torsional constant (J), and the warping constant (C_w), reflecting section geometry and loading conditions interaction.

$$M_{cr} = \frac{C_b \pi^2 E I_y}{L_b^2} \sqrt{\frac{C_w}{I_y}\left(1 + 0.039 \frac{L_b^2}{C_w}\right)} \tag{1}$$

Lateral torsional buckling (LTB) instability occurs when the slenderness parameter λ exceeds a critical limit λ_r. The slenderness λ is defined as the ratio between the unbraced length and the radius of gyration of the cross-section about the y-axis, i.e., $\lambda = L_b/r_y$. The elastic LTB occurs when λ surpasses the critical limit λ_r (Equation 2).

$$\lambda_r = \frac{1{,}38C_b\sqrt{I_y J}}{r_y J\beta_1}\sqrt{1+\sqrt{1+\frac{27C_w\beta_1^2}{C_b^2 I_y}}} \tag{2}$$

Where r_y is the radius of gyration of the section about the y-axis, and β_1 is calculated according to Equation (3).

$$\beta_1 = \frac{(f_y - \sigma_r)W}{EJ} \tag{3}$$

Where f_y is the steel yield strength, σ_r is the residual stress, commonly taken as 30% of f_y, and W is the elastic section modulus about the bending axis. The constant C_w is defined in Equation (4):

$$C_w = \frac{I_y(d-t_f)^2}{4} \tag{4}$$

Where d is the total external height of the section and t_f is the flange thickness of the beam.

As mentioned previously, the design rules for LTB phenomenon presented by ABNT NBR 8800:2024 [5] only apply for solid-web sections. This could lead to a overestimation of the load beam capacity if the geometric and mechanical properties considered in the design rules are not estimated by considering the reduction of web section at the opening regions. EN EN 1993-1-13:2024 [6], ArcelorMittal [9] and SCI P355 Steel Construction Institute [10] establish specific geometric limits and design recommendations for cellular beams, such as width of the end-post (s_0), i.e. edge-to-edge spacing of adjacent openings; center to center spacing to adjacent openings (s); depth of opening or diameter of circular opening (h_0); depth of cellular beam (h); spacing between openings (b_0); web thickness (t_w); depth of the parent beam (D), corresponding to the original rolled section before cutting.

According to EN 1993-1-13:2024 [6], for beams with circular openings without stiffened openings, the geometric limitations must be satisfied as follows: $h_0 \leq 0.8h$; $s_0 \geq 0.1h_0$; and the web slenderness must comply with $h_w/t_w \leq 121\varepsilon$, where $\varepsilon = \sqrt{235/f_y}$.

According to the ArcelorMittal [9] ACB® catalog, two main configurations of cellular beams are commonly used. Design type 1, characterized by larger openings with $1.0D < h_0 < 1.3D$, $1.4D < h < 1.6D$ and $1.1h_0 < s < 1.3h_0$. This configuration is typically applied in roofing, footbridges, and wide-span purlins, where optimization of the height-to-weight ratio is the main objective. Design type 2, with smaller openings is defined by $0.8D < h_0 < 1.1D$, $1.3D < h < 1.4D$ and $1.2h_0 < s < 1.7h_0$. This latter configuration is mainly used in floors, parking structures, and offshore structures, where the optimization of the load-to-weight ratio is more relevant. In this study, only beams of Design type 2 were analyzed.

2 Numerical Model Description

The present study employs numerical modeling to investigate elastic lateral torsional buckling (LTB) in steel cellular beams, with particular emphasis to understand on the influence of web openings on torsional and warping stiffness — two key parameters governing LTB resistance. The simulations were developed on the basis of geometric parameters established by standards and technical guidelines, enabling a consistent evaluation of the structural response under bending in the web plane. The models were specifically designed to isolate the LTB phenomenon, adopting boundary conditions and loading representative of this global instability mode.

The LTB analyses were carried out using three-dimensional finite element modeling in *Abaqus* v.2021 (SIMULIA, Dassault Systèmes) [7], considering cellular beams with circular openings. The `BUCKLE` procedure was adopted to capture elastic instability modes. Boundary conditions included longitudinal displacement restraints ($U_x = 0$) and vertical displacement restraints ($U_y = 0$) at the initial end, vertical restraints ($U_y = 0$) at the final end, and a fork-type support restricting both horizontal displacement ($U_x = 0$) and rotation ($R_z = 0$). The applied loading consisted of a uniform bending moment along the beam length, as illustrated in Figure 3 and 4.

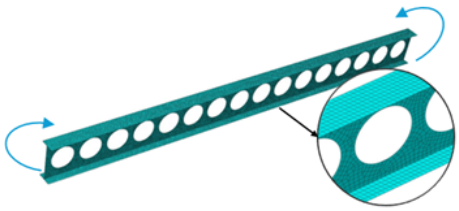


Figure 3. Modeling Criteria and Boundary Conditions for LTB

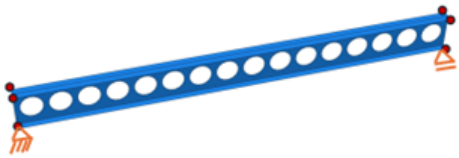


Figure 4. Modeling Criteria and Boundary Conditions for LTB

Table 1. Critical Lateral Torsional Buckling Moments Obtained from NBR and Abaqus Software

Model	**Lb (mm)**	M_{cr} **(NBR) [kN·cm]**	M_{cr} **(Abaqus) [kN·cm]**	**Ratio Abaqus/NBR**
VS 500X61	630,00	32.943,61	32.460,00	1,0149
VS 500X61	800,00	21.411,78	21.121,00	1,0138
VS 500X61	1300,00	9.549,36	9.490,90	1,0062
VS 500X61	2000,00	5.125,33	5.232,50	0,9795
VS 500X61	3000,00	3.075,82	3.304,50	0,9308
			Mean	**1,0062**

2.1 Parametric Study

For the LTB simulations, two main geometric configurations were developed, varying the total section height (H_t). The study evaluated the impact of the top flange translation and geometric variations on resistance to global instability.

The analyzed beams had total heights (H_t) ranging from 500 mm to 650 mm, with a constant web height (H_0) of 500 mm. The flange width (b_f) was fixed at 250 mm and the diameter of the circular openings (a_0) at 400 mm, following EN 1993-1-13:2024 [6] and the ArcelorMittal catalog. The spacing between openings (e) varied from 480 mm to 496 mm, depending on beam length and unbraced length.

Ten geometric models were used for the lateral torsional buckling (LTB) analysis, with flange width (b_f) fixed at 250 mm, opening diameter (a_0) at 400 mm, and web height (H_0) at 500 mm. Total section heights (H_t) were 500 mm and 650 mm. Opening spacing (e) varied from 480 mm to 496 mm according to unbraced lengths (L_b) of 630 cm, 800 cm, 1300 cm, 2000 cm, and 3000 cm. Web end width (W_{end}) ranged from 70 mm to 100 mm, adapting to model configurations M1 to M5.

Linear elastic buckling analyses determined the critical moment (M_{cr}), identifying the most critical failure modes and the beams' sensitivity to top flange translation, as well as the interaction between section height, unbraced length, and opening distribution on structural stability.

3 Results and Discussions

In the numerical analyses of LTB in cellular beams, critical moment (M_{cr}) results were initially presented as a function of slenderness (λ). To facilitate interpretation and comparison among configurations, unbraced length (L_b) was used as the independent variable without losing technical validity, since λ is proportional to L_b via the relation $\lambda = L_b/r_y$, where r_y is the radius of gyration about the y-axis. The moment of inertia (I_y) remained close to that of solid-web profiles despite increased slenderness and openings. This adjustment improves result communication, as shown in Figs. 5a and 5b.

Lateral torsional buckling (LTB) is a global instability typical of open-section beams, such as I-profiles, subjected to bending moments. It is characterized by a combination of lateral displacement and rotation of the section about the longitudinal axis, exacerbated by long spans or inadequate lateral bracing.

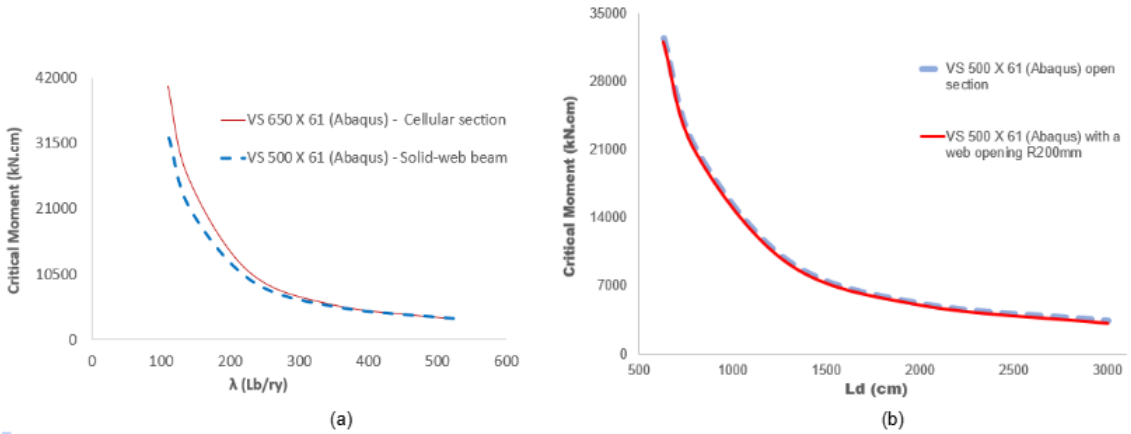


Figure 5. Simulation of Models in Abaqus with Equal and Different ht

The numerical LTB analysis evaluated the model and the influence of geometric parameters, such as section height, flange dimensions, and openings in cellular beams. As shown in Fig. 5b, comparing beams with and without openings but of the same height, the openings caused a slight reduction in the critical moment without compromising structural safety. LTB primarily depends on the moments of inertia (I_x and I_y), with flange dimensions and spacing being more critical than openings for resistance. Thus, cellular beams maintain good load capacity while offering material savings and ease of service integration.

Fig. 6 compares a 500 mm solid-web beam and a 650 mm cellular beam with equivalent material volume, showing that the cellular beam exhibits approximately a 20% significant increase in strength.

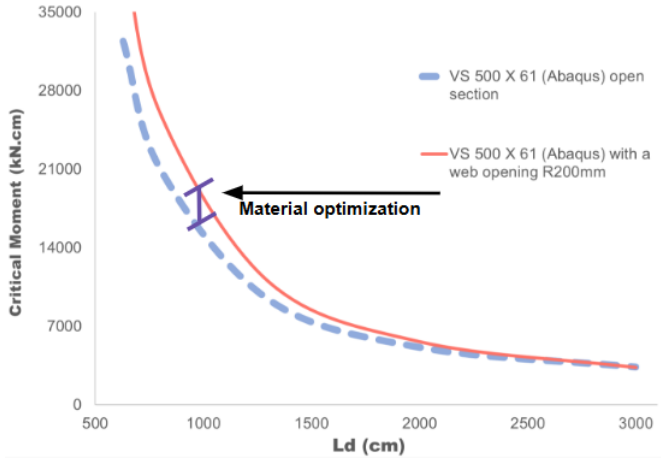


Figure 6. Analysis of Beam Optimization with Different ht

This performance increase results from the greater moment of inertia due to the amplified section height, enhancing LTB resistance without increasing weight. It highlights the potential of cellular beams to efficiently and safely span long distances, achieving approximately 20% structural optimization. As shown in Fig. 7, the parametric study demonstrated that increasing the flange width (b_f) and thickness (t_f) enhanced the beams' resistance to lateral torsional buckling (LTB).

Increasing flange thickness enhanced stiffness, delaying instability, while greater width improved stress distribution and reduced deformations. As shown in Fig. 8, widths up to 250 mm were effective with $t_f = 9.5$ mm, and up to 400 mm with $t_f = 16$ mm, highlighting the importance of balancing width and thickness to ensure strength, stiffness, and safety against LTB.

The comparison between numerical modeling results and values calculated per ABNT NBR 8800:2024 [5], adapted according to EN 1993-1-13:2024 [6] for cellular profiles, assessed the design accuracy. The critical moment (M_{cr}) analysis as a function of unbraced length (L_d) considered different configurations, including two section heights, VS 500 and VS 650, as shown in Fig. 9.

The critical lateral torsional buckling moment (M_{cr}) curves obtained by numerical modeling for cellular beams with section heights of 500 mm and 650 mm followed the trend of the ABNT NBR 8800:2024 [5] standard, with minor discrepancies at shorter unbraced lengths (L_d) due to better representation of three-dimensional effects in the model. The larger beam (VS 650 × 61 mm), with constant material volume, exhibited higher strength due

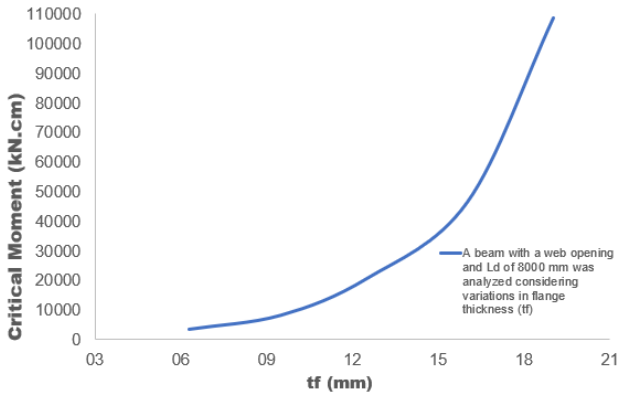


Figure 7. Variation of tf for Beams with Ld = 8000 cm

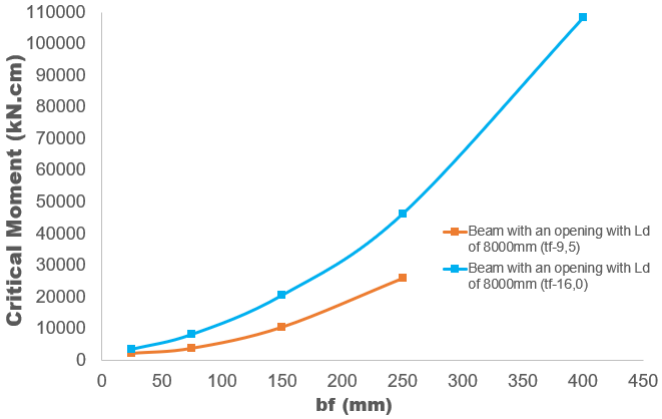


Figure 8. Variation of bf for Beams with Ld = 8000cm

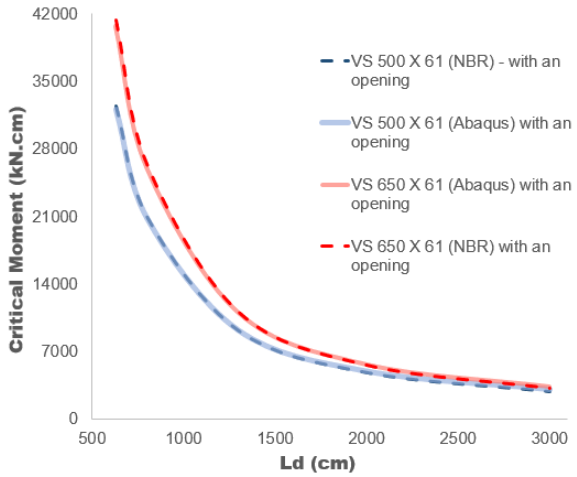


Figure 9. Calibrated Beam (NBR) vs. Cellular Beam

to increased moment of inertia, enhancing flexural-torsional stiffness without added weight. For low L_d, M_{cr} was higher, decreasing until stabilizing at L_d around 2000 cm, demonstrating sensitivity to slenderness and model accuracy in LTB analysis, as shown in Fig. 9.

4 Conclusion

This study numerically analyzed lateral torsional buckling (LTB) in steel cellular beams using finite element modeling in *Abaqus* v. 2021, considering variations in section height, flange dimensions, and the presence of web openings.

The results demonstrated that web openings do not significantly compromise LTB resistance, provided that geometric proportions are adequate. Increasing the section height at constant volume raised the critical buckling moment (M_{cr}) by up to 20%, due to the higher moment of inertia, which enhanced resistance to both torsional and lateral displacements (models VS 500×61 mm and VS 650×61 mm). Flange parameters such as thickness (t_f) and width (b_f) also contributed to greater stiffness and postponed instability, underscoring the importance of a balanced design to ensure both efficiency and safety.

The numerical modeling was validated with an error below 1.5% when compared to the reference values for solid-web beams. Furthermore, the comparison with ABNT NBR 8800:2024 [5] and EN 1993-1-13:2024 [6] indicated that the Brazilian standard, when adapted with Eurocode recommendations for members with web openings, is both applicable and conservative.

From a practical engineering perspective, these findings provide guidance for the safe and economical design of cellular beams, particularly in contexts where lightweight yet resistant structures are required. They also suggest that future updates to Brazilian standards could incorporate more detailed provisions for cellular and perforated sections, aligning national practice with international developments.

In conclusion, numerical modeling proves to be an effective and reliable tool for the design of cellular beams against LTB, especially in the absence of specific Brazilian standards. Future research should address dynamic behavior, long-term performance, and structural fatigue to further support the development, application, and codification of cellular beams in Brazilian civil engineering practice.

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