Evaluating Design Methods for Cellular Steel Beams Through Parametric Modelling

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Abstract. Under some design conditions, cellular beams can be a better structural solution than I-section beams due to their enhanced strength-to-weight ratio, allowing for more lightweight and cost-effective constructions. However, their varying cross-sections lead to additional failure mechanisms, which require further research due to the lack of specific standardized design procedures covering this topic in Brazil. This paper evaluates five different design methods, as proposed by Ward [1], Annex-N [2], Veríssimo et al. [3], Fares et al. [4] and Grilo et al. [5]. Using a parametric approach, this research investigates the geometric variations in cellular beams with the mentioned design methods, in comparison to shell finite element models already validated by Benincá and Morsch [6]. The results reveal that while the design methods are generally conservative for longer spans, they might underperform in terms of safety for shorter spans. The Ward [1] method was the most effective in identifying failure modes based on Formation of Vierendeel Mechanism (FMV) and Web-Post Buckling (WPB). In contrast, the adaptation of the Veríssimo et al. [3] method, combined with the WPB check from the Grilo et al. [5] method, was more sensitive in evaluating the WPB failure load.

Keywords: cellular beams, parametric analysis, finite elements method, failure modes, design method.

1 Introduction

In steel structures, beams with web openings are commonly used to accommodate underfloor service ducts. Cellular beams, a type of girder characterized by evenly spaced circular web openings, are frequently employed for this purpose. These beams are usually produced through a specific industrial process that involves flame-cutting the web of an existing I-shaped, hot-rolled profile along a predetermined path, followed by re-welding the separated T-sections. This resulting geometry enhances bending stiffness and optimizes the strength-to-weight ratio. Consequently, cellular beams also offer an efficient solution for integrating building services within the structural depth of the floor.

According to Cimadevila et al. [7], these beams operate under relatively low stresses, and material efficiency is optimized by maximizing the second moment of area to minimize deflections. However, web openings can reduce shear strength. Therefore, evaluating the structural behavior of cellular steel beams involves considering several ultimate limit state (ELU) specifications, such as local and global buckling and plastic hinge formation. Kerdal and Nethercot [8] identified five potential failure modes in this kind of beams: Formation of the Vierendeel Mechanism (FVM), Web-Post Buckling (WPB), Rupture of Welded Joints (RWJ), Lateral-Torsional Buckling (LTB), and Formation of a Flexure Mechanism (FFM).

These failure modes are influenced by the beam's geometry, web slenderness, opening shape, loading types, and lateral support. Consequently, further research is required due to the lack of specific standardized design procedures addressing this topic in Brazil. Therefore, this paper aims to address this gap by providing analytic data results on the behavior of cellular beams through numerical simulations. These simulations utilize design methods proposed by Ward [1], Annex-N [2], Veríssimo et al. [3], Fares et al. [4], and Grilo et al. [5], implemented using Python. A parametric analysis is conducted on 80 different geometries of cellular beams. The results from these design methods are compared with those obtained through finite element nonlinear analysis.

2 Design Methods

When designing cellular beams, it is crucial to verify their strength (ULS) and serviceability (SLS), which involves involves assessing displacement constraints and evaluating flexural and shear capacities to prevent failure. Failure checks for FFM and LTB are similar to those for regular I-section Beams. However, the failure modes of RWJ, WPB and FVM are specific to cellular beams.

The rupture of welded joints (RWJ) occurs in the web region due to changes in axial forces in the T-region of the beam. The horizontal shear force (V_h) acting in the weld region is calculated based on the bending moment (M_{rd}) in the area between two beam openings, as shown in Fig. 1 (a). This horizontal force generates an internal moment in section *S* of cellular beams, balanced by tensile and compressive stresses. A similar phenomenon occurs at the bottom of the beam but in the opposite direction, causing double bending in the web and leading to failure by web-post buckling (WPB)(Fig. 1 (b)). In the case of Vierendeel mechanism failure (FVM), the vertical shear acting on the T-section plus distance x_p generates a second-order moment that intensifies stresses at four points around the openings, potentially leading to the formation of four plastic hinges (Fig. 1 (c)).

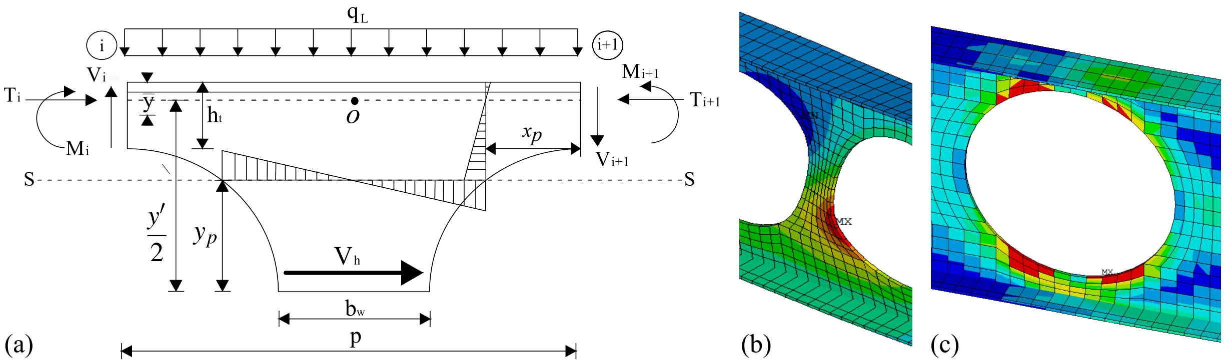

Figure 1. (a) Horizontal shear in the web post of cellular beam (b) WPB (c) FVM

This study evaluates five different procedures to design cellular steel beams: (1) Veríssimo et al. [3] (VER); (2) the Steel Construction Institute (SCI) publication by Ward [1]; (3) ASCI Design Guide 31 by Fares et al. [4] (GUIDE 31); (4) a modified design procedure from VER incorporating web buckling verification as per Grilo et al. [5] (GRI); and (5) 3emAnnex-N [2], which was a proposed implementation in the version of Eurocode ENV 1993-1-1:1992. To optimize the verifications using these methodologies, a Python code was developed, utilizing version 3.8.8. Fundamental libraries such as *numpy*, *scipy*, and *pandas* were employed. To find out more details, you can access the online repository at Aguiar [9].

Although structural engineers have the flexibility to determine the diameter of circular openings and the spacing between their centers, it is crucial to adhere to the ratios prescribed in eq. (1), where Fig. 2 illustrates the fundamental geometry and notations for these beams. It should be noted that the Annex N - ENV (1998) design method is more restrictive, with the lower value ratio p/D_0 being 1.25.

$$1.10 < \frac{p}{D_0} < 1.50 \quad \textit{and} \quad 1.25 < \frac{d_g}{D_0} < 1.75 \tag{1}$$

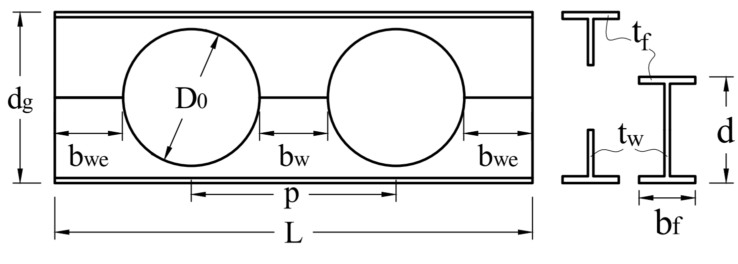

Figure 2. Geometric parameters of cellular beams

3 Numerical Model

Finite Element (FE) models of I-section beams with circular web openings were developed using Ansys Mechanical APDL version 2021R2. The beam was modeled with quadrilateral shell elements considering full integration and five integration points along the shell thickness. The material was modeled using a bilinear isotropic material model with the von Mises yield criterion, in order to capture nonlinear material behavior.

The supported beam models had boundary conditions illustrated in Fig 3. Loads can be applied at the top flange nodes to accommodate uniformly distributed and/or concentrated loads, with precise application points specified for the latter. For the validation examples of item 3.1, the positioning (x) of the stiffeners, lateral supports and concentrated loads was determined based on data from the experimental tests. On the other hand, for the parametric analysis, a uniformly distributed load was applied along the beam, and to prevent lateral (z-horizontal) displacement, the entire upper flange's lateral movement was restricted. Additionally, stiffeners were placed in the support region to enhance stability.

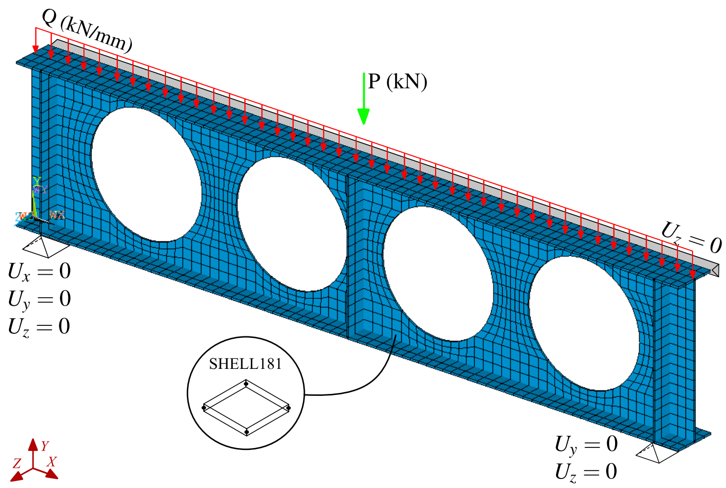

Figure 3. Overview of a generic cellular beam modeling in Ansys

Four steps are employed to address the numerical problem, as outlined below:

1. A base static solution is computed to define the geometric stiffness matrix.
2. An elastic stability analysis is conducted to identify the instability modes and the associated critical loads.
3. Initial geometric imperfections are introduced to the beams, associated with specific instability modes, to represent irregularities in cellular beams.
4. A nonlinear analysis is performed using the Newton-Raphson method in conjunction with the Arc-Length technique to determine the failure load, beam deflection, and failure mode.

To accurately represent the real irregularities that occur from manufacturing to assembly, geometric imperfections were incorporated in the model. In this research, the first mode of instability was considered, following previous research by Soltani et al. [10], Braga et al. [11], Shamass and Guarracino [12], Bake [13], and Panedpojaman et al. [14]. The amplitude of the initial geometric imperfection adopted was $dg/600$, the same value recommended by Bake [13].

3.1 Validation of FE model

It is noteworthy that this model was previously developed and validated by Benincá and Morsch [6]. To expand the validation cases and evaluate the primary failure modes of cellular beams, three distinct beams were selected based on experimental tests conducted by other researchers: Warren [15], Erdal and Saka [16], and Grilo et al. [5]. This selection aimed to enhance the validation of the numerical model through a diverse set of specimens, designated as 2A, NPI240-Test3, and A2. The first specimen failed due to the Vierendeel mechanism, while the second and third specimens experienced web-post buckling (WPB). The geometry of these beams and material properties of these beams are given in Table 1, where f_{yf} is the flange yield stress, f_{yw} is the web yield stress, and f_u is the ultimate steel stress of the beam.

Table 1. Geometrical and material properties of three experimental cellular beams

Reference	Specimen	d	t_w	t_f	b_f	b_w	d_g	L	D_0	f_{yw}	f_{yf}	f_u	E_w	E_f
		mm	mm	mm	mm	mm	mm	mm	mm	MPa	MPa	MPa	GPa	GPa
Warren [15]	2A	203	5.8	7.8	133.4	75	289.8	3800	225	347	320	430	187.89	196.74
Erdal and Saka [16]	NPI-240 (test 3)	304.9	8.7	13.1	106	94	355.6	1423	345	390	390	495	190	190
Grilo et al. [5]	A2	303	4.8	5.6	102	103.3	433	1874	342.5	416	416	480	188	188

Figure 4 compares the results from the Finite Element Model (FEM), Experimental data from the other authors' (Exp), and their numerical results (N). The numerical model shows excellent agreement with the experimental load-displacement curves. The failure modes predicted by the numerical simulations matched those observed in the experimental tests of the beams.

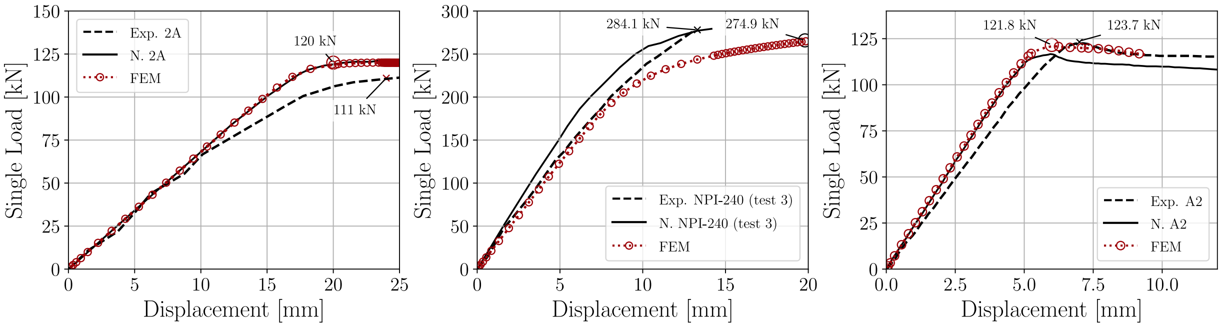

Figure 4. Mid-span displacement response of cellular steel beams under single load

4 Parametric Analysis

A set of beams derived from the W310x21 profile was considered to the design methods responses, focusing on the geometric relationships defined by the values in Equation 1 and the ratio between the span length and the height of the cellular beam (L/d_g). In this way, 80 beams are evaluated. Figure 5 illustrates the geometric variations of the circular openings in the beams.

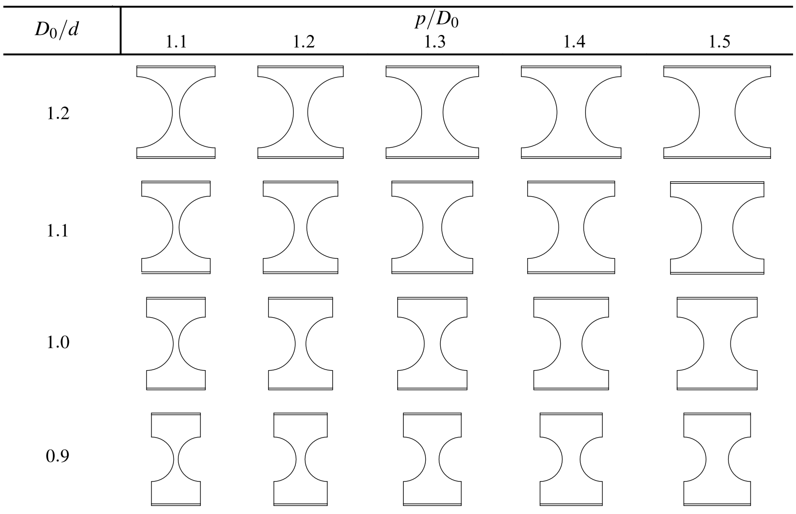

Figure 5. Geometry of cellular beams analyzed

Each of the cellular beams studied has a fixed expansion ratio (k) of 1.5, a value recommended for roof applications by ArcelorMittal [17]. These beams are simply supported and subjected to uniformly distributed loads along their spans, which also serve as service loads. The steel's profile is ASTM A572 grade 50, with $E = 200$ GPa, $f_y = 345$ MPa, $f_u = 450$ MPa, and a Poisson's ratio (ν) of 0.3.

Figure 6 displays the four graphs generated for the specific D_0/d ratios. Additionally, the comparison between the methods and the numerical simulation is presented in a normalized format as follows: F_{MTH}/F_{FEM}, where F_{MTH} represents the design method load and F_{FEM} represents the load obtained from the FE simulation, both expressed in kN/m.

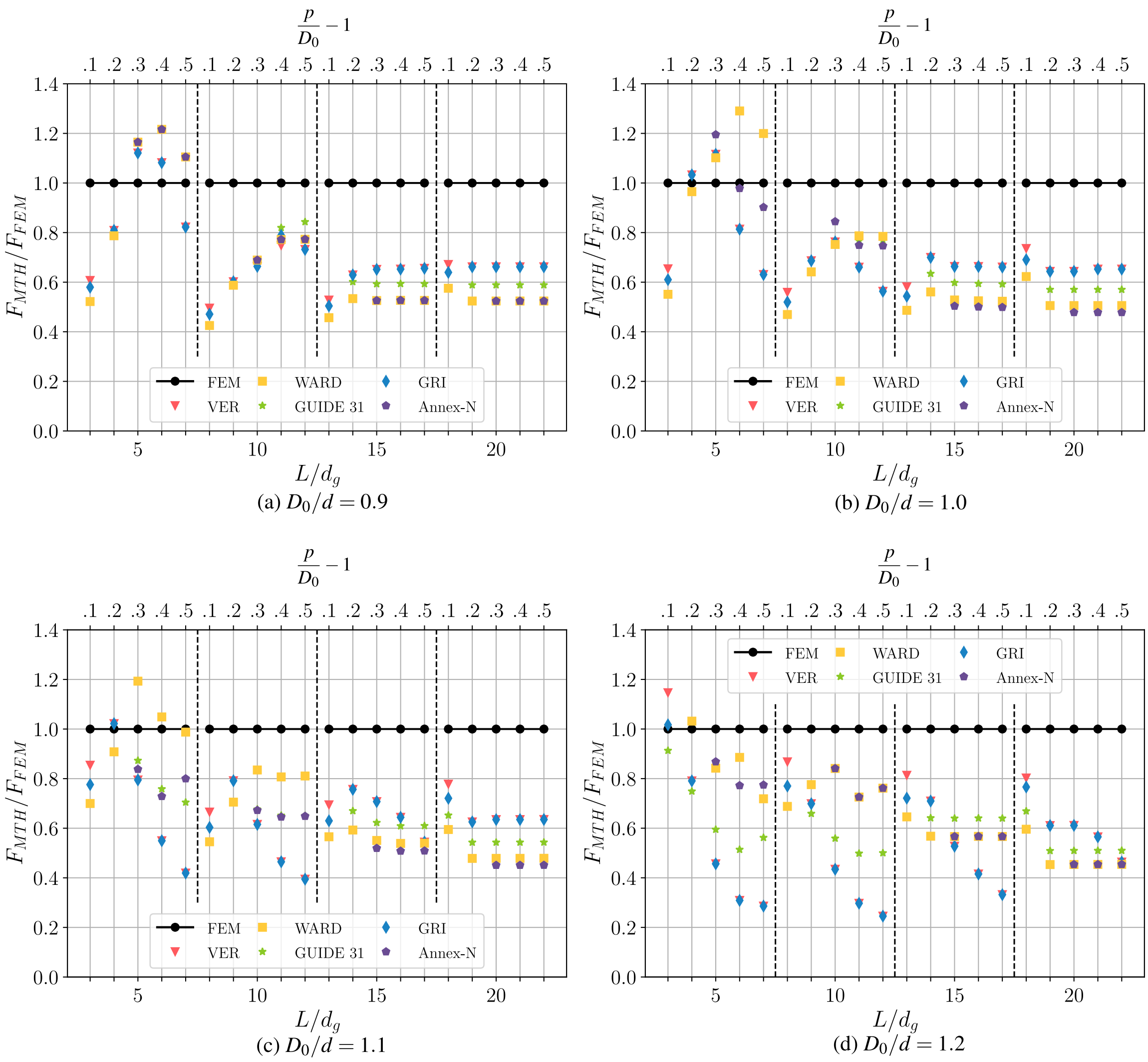

Figure 6. Scatter plots comparing numerical results with design method outcomes

Generally, the results of the cellular beam design methods showed lower failure loads compared to the reference (FEM results). However, for beams classified as very short spans ($L/d_g = 5$), the design methods produced higher values. It is noteworthy that the design limit loads for longer beams reached a constant state. This stabilization occurs because excessive deflection governs the limiting criterion for these beams. Although each design method uses a simplified deflection calculation methodology, this study adopted the vertical displacement limit of $L/250$, as recommended for roof beams by NBR 8800 [18].

The WARD method shows higher failure loads for larger L/d_g ratios. However, for shorter beams with lower L/d_g ratios, WARD failure loads results that are closer to those from FEM analysis, in some cases these results show a tendency to overestimate the load capacity. Regarding variations, the GRI method exhibits the greatest variability between the results, followed by the VER method. The Annex-N method demonstrated less data dispersion, but it is important to note that due to its more restricted applicability, only 12 beams of each L/d_g ratio were evaluated.

In general, the relative mean differences between the limit loads obtained by the VER, SCI, Guide 31, GRI, and Annex-N methods compared to the FEM reference (Table 2) were 30.50%, 35.40%, 35.81%, 36.03%, and

53.47%, respectively. The Annex-N [2] method encompasses a narrower range of geometric rearrangements, which limits its capability to evaluate all beams. Conversely, the GRI method shows a higher disparity when compared to the VER method.

Table 2. The limit load identified through FEM analysis (F_{FEM} $[kN/m]$)

$\frac{p}{D_0}$	$\frac{L}{d_g}$	$\frac{D_0}{d}$			
		0.9	1.0	1.1	1.2
1.1	5	69.4	59.3	56.3	58.7
	10	28.5	27.9	24.2	19.5
	14	16.9	15.8	14.0	11.9
	20	9.4	8.8	8.7	8.2
1.2	5	87.4	84.1	79.1	80.9
	10	42.7	42.2	38.3	35.1
	14	25.1	23.0	20.7	20.4
	20	10.9	10.9	10.9	10.8
1.3	5	107.5	99.5	99.7	96.2
	10	54.6	48.7	49.2	39.4
	14	25.5	24.4	22.3	20.5
	20	10.9	10.9	10.9	10.8
1.4	5	118.4	119.2	111.2	104.9
	10	58.6	55.4	51.4	45.8
	14	25.4	24.6	22.8	20.5
	20	10.9	10.9	10.9	10.8
1.5	5	130.6	127.1	116.1	119.9
	10	58.5	55.6	51.2	43.6
	14	25.5	24.7	22.8	20.5
	20	10.9	10.9	10.9	10.8

When identifying failure modes, the lowest critical load determined by the design method was compared with the failure mode characterized in the finite element simulation. For a more detailed explanation of the criteria used to identify failure, we suggest referring to Aguiar [19]. The results indicate that the Ward [1] method was the most effective in identifying failure modes based on the FMV and WPB. Although the adaptation by Veríssimo et al. [3], in conjunction with the WPB verification from Grilo et al. [5] (GRI), shows greater accuracy in identifying failure modes, it only detects these modes when the limit load is lower than that obtained through the purely VER methodology.

5 Conclusions

This paper evaluates five different design methods (VER, WARD, GUIDE 31, GRI, Annex-N, and HDM) against Finite Element Method (FEM) analysis. Firstly, the FE model was validated using experimental data from Warren [15], Erdal and Saka [16], and Grilo et al. [5]. Then, a parametric analysis of 80 cellular beams was performed, based on simply supported beams with varying geometries, subjected to uniformly distributed loads. The primary parameters evaluated include the different lengths and variations in the diameter of web openings.

The results showed the design methods yielded lower limit load values compared to FEM results, except for very short spans ($L/d_g = 5$), where they produced higher values, which highlights the limitations of the methods, because its use in very short spans may compromise safety.. Among the methods, WARD exhibited a tendency to overestimate load capacity for smaller L/d_g ratios while aligning more closely with FEM results for longer beams. This aproximation, along with the observed stabilization of design limit loads for longer beams due to excessive deflection, underscores the need for cautious application of these methods in practical scenarios.

Moreover, the variability in results among the different methods provides critical insights into their reliability. The GRI method showed the greatest variability, followed by VER, indicating a need for further refinement to enhance consistency. Conversely, the Annex-N method, while demonstrating less data dispersion, was restricted in its applicability, evaluating only a limited number of beams per L/d_g ratio. Futhermore, the relative mean differences between the design methods and FEM further underscore these findings, with Annex-N showing the highest mean difference at 53.47%. The study also highlights the importance of comprehensive evaluation criteria, as the GRI method, despite its higher disparity, accurately identified failure modes when the limit load was lower than that obtained through VER. These insights emphasize the importance of selecting appropriate design methods based on specific beam characteristics and load conditions to ensure structural integrity and safety.

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