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VIERENDEEL BEHAVIOUR OF BEAMS WITH SINUSOIDAL WEB OPENINGS

Summary: This paper reviews the structural behaviour of perforated elements subjected to bending, with particular emphasis on the Vierendeel failure, which governs the resistance of these members. The stress distribution around web openings and the development of the Vierendeel failure mechanism are examined using experimental observations and finite element analyses. Furthermore, the paper presents an overview of the design methodology incorporated in the recently developed prEN 1993-1-13 for evaluating the Vierendeel resistance of cellular beams. Finally, an ongoing experimental research programme at the Faculty of Civil Engineering, University of Belgrade, focusing on welded stainless steel beams and columns with sinusoidal web openings, is introduced to highlight current research efforts towards the development of design guidance for stainless steel perforated members.

Keywords: Vierendeel analogy, Tee yielding, plastic hinges, design resistance

VIRENDEL MEHANIZAM LOMA KOD GREDA SA SINUSOIDALNIM OTVORIMA U REBRU

Rezime: U radu je dat pregled konstrukcijskog ponašanja grednih nosača sa otvorima u rebru, sa posebnim osvrtom na Virendel mehanizam loma, koji predstavlja jedan od dominantnih mehanizama koji određuju nosivost ovih elemenata. Razmatrani su raspodela napona oko otvora i razvoj Virendel mehanizma loma na osnovu eksperimentalnih ispitivanja i numeričkih analiza metodom konačnih elemenata. Dat je pregled odredbi novorazvijenog standarda prEN 1993-1-13 koje se odnose na proračun Virendel nosivosti greda sa otvorima u rebru. Dodatno, predstavljeno je eksperimentalno istraživanje na Građevinskom fakultetu Univerziteta u Beogradu, koje obuhvata ispitivanja zavarenih greda i stubova od nerđajućeg čelika sa sinusoidalnim otvorima u rebru, sa ciljem unapređenja postojećih i razvoja novih preporuka za dimenzionisanje saćastih nosača od nerđajućeg čelika.

Ključne reči: Virendel analogija, plastifikacija T-preseka, plastični zglobovi, proračunska nosivost

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1. INTRODUCTION

Perforated steel members mark a significant technological innovation in steel construction. Web openings are commonly introduced in structural elements to accommodate building services, leading to the increasing use of perforated steel members in mid- and long-span structures (Figure 1). Compared with conventional steel members, perforated members offer several advantages, including: (i) increased section depth, resulting in enhanced flexural stiffness and bending resistance without additional material; (ii) lightweight and efficient long-span structural solutions; (iii) reduced overall structural depth through the integration of building services within the web opening, thereby improving space efficiency; and (iv) improved architectural appearance.

Figure 1: Application example of cellular beams and columns [1]

However, the presence of web openings modifies the stress distribution and stiffness of the member and may lead to different localised failure modes, including Vierendeel action, shear buckling, web-post buckling, and yielding or local buckling of the Tee sections [2,3]. These phenomena have been extensively investigated over the past decades, resulting in a comprehensive understanding of the structural behaviour, failure modes and resistance of carbon steel cellular beams [4–7]. The knowledge gained from these experimental and numerical studies has formed the basis for the development of design provisions for carbon steel members with web openings, which are currently incorporated in prEN 1993-1-13 [8].

Among the various opening geometries adopted in practice, sinusoidal web openings, as employed in the Angelina™ beam developed by ArcelorMittal [9], have attracted increasing attention owing to their favourable structural behaviour and manufacturing advantages. Compared to circular openings, which require the removal of discrete portions of the web plate and generate significant material waste (Figure 2), sinusoidal openings can be produced by a single continuous cutting operation that separates the web into two complementary halves with minimal material loss.

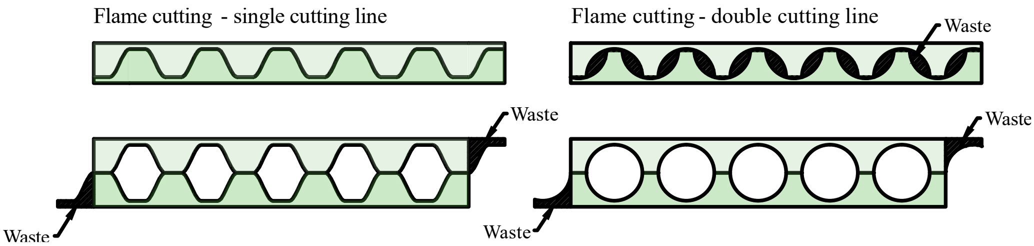


Figure 2: Comparison of the manufacturing efficiency of (a) sinusoidal, and (b) circular web openings

While research on perforated members has traditionally focused on carbon steel, growing interest in stainless steel structures has highlighted the need to investigate the structural behaviour of perforated stainless steel members. Stainless steel offers several advantages over carbon steel, including superior corrosion resistance, improved durability, reduced maintenance requirements and favourable life-cycle performance. However, its considerably higher initial material cost places greater emphasis on efficient material utilisation. By increasing the structural depth without adding material, web openings enable material-efficient structural solutions, thereby improving both the economic and sustainability performance of stainless steel structures.

In recent years, research has gradually expanded to stainless steel I-section perforated beams, although the available studies have predominantly focused on circular openings. Previous studies on stainless steel perforated beams have predominantly focused on their susceptibility to local failure modes, particularly web shear buckling and patch loading [10–13]. More recently, the behaviour of stainless steel beams featuring sinusoidal web openings has been investigated through finite element modelling supported by artificial neural network techniques [14].

In response to the limited experimental evidence available in the literature, a comprehensive research program is currently underway at the Faculty of Civil Engineering, University of Belgrade (as illustrated in Figure 3). The programme focuses on welded stainless steel I-section beams and stub columns with closely spaced sinusoidal web openings, and includes both symmetric and monosymmetric cross-sections. The experimental programme has been designed to investigate the influence of geometric and material parameters on the structural behaviour and failure mechanisms of perforated stainless steel members. The test matrix comprises conventional sections fabricated from austenitic stainless steel and hybrid sections combining austenitic and lean duplex stainless steel grades. Also, the programme includes members of different lengths and three opening sizes, classified as small, medium and large.

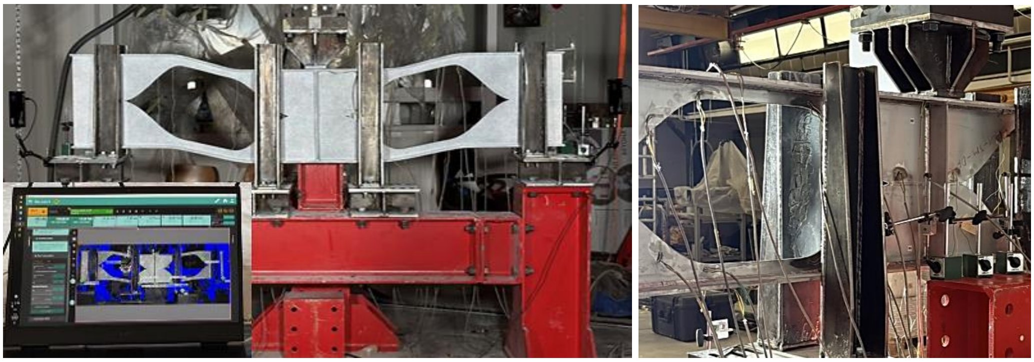


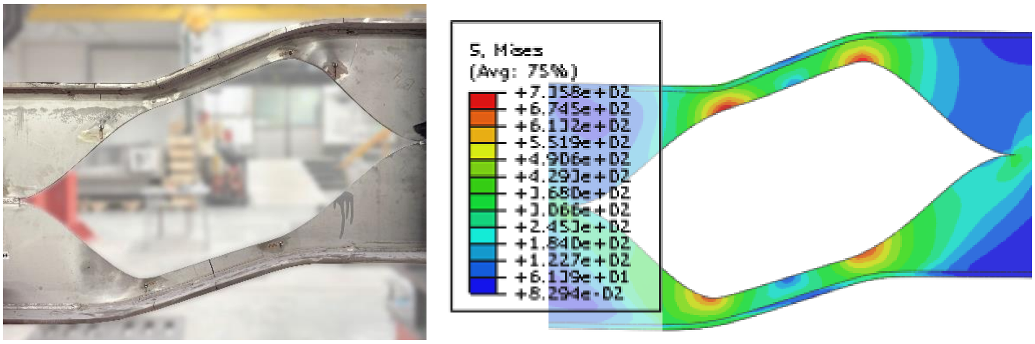
Figure 3: Experimental research at the Faculty of Civil Engineering, University of Belgrade

In beams with web openings (subjected to bending), Vierendeel action is acknowledged as a governing failure mechanism among the various modes that may arise [15–17]. The interaction between shear forces and local bending moments around the web openings induces significant stresses in the Tee sections and may govern the structural response, either independently or in combination with other failure mechanisms, such as web-post buckling or lateral-torsional buckling.

This paper presents an overview of the Vierendeel failure mechanism governing perforated beams, together with the design methodology stated in prEN 1993-1-13 [8]. The results of ongoing experimental and numerical research on stainless steel beams with sinusoidal web openings, conducted at the Faculty of Civil Engineering, University of Belgrade, are used to illustrate the Vierendeel behaviour and familiarise readers with this phenomenon.

2. VIERENDEEL BEHAVIOUR

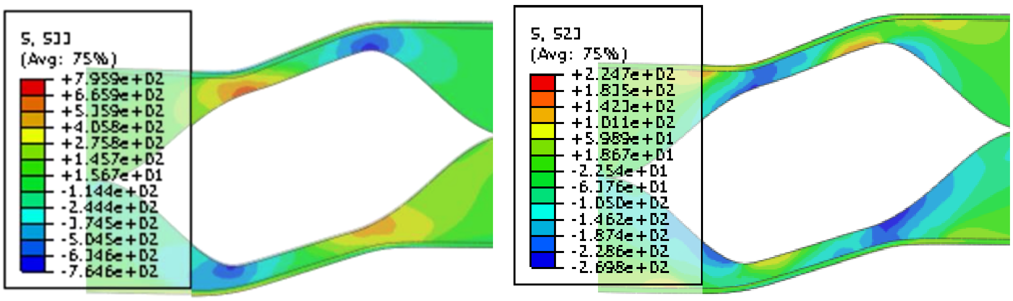
The structural behaviour of perforated members subjected to bending is commonly interpreted using the Vierendeel analogy, in which the beam is idealised as an assembly of horizontal Tee sections surrounding the web openings and vertical web posts between adjacent openings. The interruption of the web significantly modifies the internal force transfer and the stress distribution within the member. As shear forces are transferred across the opening, local Vierendeel bending moments are generated in the upper and lower Tee sections, resulting in a complex interaction of axial, shear and bending stresses. Consequently, pronounced stress concentrations develop at the opening corners, where yielding is expected to initiate. Figure 4 compares the experimentally observed deformation pattern with the corresponding finite element von Mises stress distribution, demonstrating that the highest equivalent stresses occur in these critical regions.



(a) *(b)*

Figure 4: Vierendeel bending: (a) experimental testing, and (b) finite element model

Further insight into the development of the Vierendeel mechanism is provided by the componential normal and shear stress distributions shown in Figure 5. Under the combined action of global bending moments and shear forces, the Tee sections are subjected to three local actions: (i) axial forces induced by the global bending moment, (ii) shear forces associated with the applied shear, and (iii) local Vierendeel bending moments generated by the transfer of shear across the opening. The resulting normal stress distribution reveals the characteristic stress pattern of the Vierendeel mechanism, with two diagonally opposite Tee sections predominantly subjected to tension and the remaining two to compression. The interaction of these stresses causes yielding to initiate at the opening corners and progressively spread through the Tee sections. As loading continues, four plastic hinges develop around the opening, while the compressed Tee sections exhibit local out-of-plane buckling during the post-peak stage. Ultimately, the opening behaves as a local Vierendeel frame, and failure occurs through the Vierendeel mechanism.



(a) Normal stress distribution *(b) Shear stress distribution*

Figure 5: Componential stress distributions around the web opening

The ultimate resistance associated with the Vierendeel mechanism depends primarily on the geometry of the web opening and the slenderness of the Tee sections. In members with relatively small (non-long) openings, failure is generally governed by yielding of the Tee sections and the development of a plastic hinges. As the opening size increases (long openings), the Tee sections become slender and develop higher compressive stresses, making local out-of-plane buckling of the compressed Tee sections increasingly likely to govern the ultimate resistance [18].

3. DESIGN OF VIERENDEEL BENDING RESISTANCE

The design of conventional steel beams with web openings is covered by the recently developed prEN 1993-1-13 [8], which extends the provisions of EN 1993-1-1 [19] and EN 1993-1-5 [20] to rolled and welded I- and H-section elements under bending with different web opening geometries. The standard provides design procedures for verifying both the local resistance at web openings and their influence on the members global structural behaviour. Accordingly, the design includes verification of the: (i) global bending resistance, (ii) shear resistance of the beam, (iii) combined Vierendeel resistance of the Tee sections under the interaction of axial force, shear force and local bending moments, (iv) stability of compressed Tee sections at long openings, and (v) resistance of the web posts to shear, bending and buckling. In addition, global stability and serviceability requirements, including lateral-torsional buckling and beam deflections, are considered.

According to prEN 1993-1-13 [8], the Vierendeel resistance at the opening should be verified using the criterion given in Eq. (1):

$$V_{\mathrm{Ed}}/V_{\mathrm{ier,Rd}} \leq 1.0 \tag{1}$$

The design Vierendeel shear resistance $V_{\mathrm{ier,Rd}}$ is determined from the bending resistance of the upper, $M_{\mathrm{NV,tT,Rd}}$, and lower, $M_{\mathrm{NV,bT,Rd}}$, Tee sections according to Eq. (2):

$$V_{\mathrm{ier,Rd}} = \left(2M_{\mathrm{NV,bT,Rd}} + 2M_{\mathrm{NV,tT,Rd}}\right)/a_{\mathrm{eq}} \tag{2}$$

The parameter a_{eq} denotes the equivalent rectangular opening length used to represent non-rectangular web openings in the evaluation of the Vierendeel resistance. Its value depends on the opening geometry and is determined according to the expressions provided in prEN 1993-1-13 [8] for the corresponding opening shape, including circular, hexagonal, elongated and sinusoidal web openings.

The bending resistance of each Tee section is evaluated using either the plastic or elastic resistance, depending on the cross-sectional class, while accounting for the reduction caused by the presence of shear and axial forces. The effect of shear is taken into account using the approach adopted in EN 1993-1-1 [19], while the influence of axial force is considered through the interaction expressions given in Eq. (3) and (4).

$$M_{\mathrm{NV,T,Rd}} = M_{\mathrm{T,pl,Rd}}\left(1 - \left(N_{\mathrm{m,Ed}}/N_{\mathrm{T,pl.Rd}}\right)^2\right) \quad \text{plastic resistance for Tee Class 1 and 2} \tag{3}$$

$$M_{\mathrm{NV,T,Rd}} = M_{\mathrm{T,el,Rd}}\left(1 - N_{\mathrm{m,Ed}}/N_{\mathrm{T,el.Rd}}\right) \quad \text{elastic resistance for Tee Class 3 and 4} \tag{4}$$

where:

$N_{\mathrm{m,Ed}}$ is the design value of the axial force acting on a Tee due to the global bending at the centre-line of the opening, and due to the global axial force, where applicable,

$N_{\mathrm{T,pl,Rd}}$ and $N_{\mathrm{T,el.Rd}}$ denote the plastic and elastic compressive resistances of the Tee section, respectively, determined in accordance with the provisions of prEN 1993-1-13 [8], including the reductions in yield strength or effective web thickness specified by the standard.

Unlike the global cross-section classification performed according to EN 1993-1-1 [19], the classification of the Tee sections for the Vierendeel resistance verification is carried out separately, considering their specific boundary conditions, stress-deformation characteristics, and local buckling responses.

4. SUMMARY

The Vierendeel mechanism represents one of the key aspects governing the design and ultimate limit state behaviour of beams with web openings. Understanding the stress redistribution around the openings and the corresponding design provisions given in prEN 1993-1-13 [8] is essential for the safe and efficient design of perforated carbon steel members. This paper provides a comprehensive overview of Vierendeel behaviour and the design approaches proposed in the next generation of Eurocodes, aiming to introduce this phenomenon to engineering practice.

Nevertheless, while the design guidelines in prEN 1993-1-13 [8] have been established for conventional carbon steel, their applicability to stainless steel members remains uncertain. Further experimental and numerical research are required before similar design methodologies can be confidently extended to stainless steel members with web openings. The experimental findings obtained within the ongoing research programme at the Faculty of Civil Engineering, University of Belgrade, are expected to facilitate the expansion of current design techniques to include stainless steel perforated members with sinusoidal web openings.

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