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<u>**Research Paper**</u>

Tapered Plate Girders with Web Openings: Behaviour, Design Provisions, and Research Gaps

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ABSTRACT

Tapered plate girders are widely used in steel bridges and buildings because they place material where stresses are highest, allowing significant weight and cost savings compared to prismatic members. In practice, these girders frequently contain web openings to accommodate services, ducts, and access. However, combining tapered geometry, slender webs, and web openings produces a structural system that is more complex than what current design codes explicitly address. This paper presents a focused literature review on tapered plate girders with web openings, with emphasis on slender webs under shear-dominated loading. First, the development and behaviour of tapered plate girders are summarized, including bending, shear, and buckling performance. Then, research on girders and plates with openings is reviewed, highlighting the influence of opening shape, size, and position on shear strength, flexural resistance, and local buckling. Design provisions in AISC, Eurocode 3, and the Egyptian Code of Practice are discussed, together with analytical, numerical, and machine-learning-based approaches to predict buckling and shear capacity. The review shows that most available studies consider either tapered members without openings or prismatic members with openings, while tapered plate girders with slender webs and web openings remain largely unexplored experimentally. Recent experimental work on slender web tapered plate girders with circular openings, accompanied by a new semi-empirical shear capacity equation and comparisons to codes and advanced methods, demonstrates that existing design provisions can be markedly conservative or unconservative when applied to this configuration. Clear research gaps are identified regarding experimental data, parameter ranges, opening configurations, combined shear–moment behaviour, and reliability-based design. Recommendations are provided for future experimental, numerical, and code-development efforts targeting tapered plate girders with web openings.

1. Introduction

Plate girders are a key element in many bridges, industrial buildings, and long-span roofs. When hot-rolled sections become uneconomical, welded plate girders offer the freedom to tailor the cross-section to match the internal forces. Tapered plate girders extend this idea further by varying the depth along the span so that the girder is deeper where bending moments or shears are higher and shallower where they are lower [1]–[3], [6], [13]. In real structures, the web almost never remains solid. Openings are required for mechanical, electrical and plumbing (MEP) services, for inspection and access, and in some cases for additional weight reduction. These openings disturb the shear flow, reduce the effective web area, and can trigger local buckling around their edges [5], [25]–[27], [34], [35], [43], [44]. When openings are placed in slender tapered webs, the combination of non-uniform depth, high slenderness, and perforations leads to a complex stress and buckling behaviour that is not fully covered by current design rules. Existing standards such as AISC 360, AISC Design Guides 02 and 25, Eurocode 3 Part 1-5, and the Egyptian Code of Practice for Steel Construction and Bridges

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provide guidance for prismatic girders with openings, and for tapered members without openings, but no major code treats tapered webs with openings explicitly [38]–[42], [49]. As a result, designers often take ad-hoc approaches, such as reducing the web area by the opening and then applying prismatic web formulas, or relying on finite element analysis without clear codified checks. The objective of this paper is to: (i) synthesize the available knowledge on tapered plate girders; (ii) review research on girders and plates with web openings; (iii) examine design provisions and advanced prediction methods; and (iv) clearly identify research gaps for slender tapered webs with web openings under shear-dominated loading, with particular reference to the recent experimental work by Taher et al. [51].

2. Tapered Plate Girders: Development and Behaviour

2.1 Historical development

The idea of non-prismatic members is not new. Beedle [1] applied plastic design concepts to naval structural mechanics and showed that non-prismatic members can achieve efficient material use while maintaining ductility. Heithecker [2] later used dynamic programming to optimize plate girder geometry and demonstrated that tapering can provide cost-effective solutions when section dimensions are chosen carefully. Takeda [3] studied girders with variable web depth and proposed simplified methods for predicting buckling, ultimate load-carrying capacity, and deformation in tapered panels. Slockbower and Fisher [4] conducted full-scale tests on cover-plated beams and investigated fatigue resistance, revealing how changes in geometry and stiffness distribution affect stress ranges and fatigue life. Elgaaly's work on plate and box girders [6] summarized the understanding of shear behaviour and post-buckling strength, including tension-field action in webs where buckling precedes ultimate failure. Paavola [7] developed finite element techniques for thin-walled girders, allowing the analysis of local and global instabilities in non-uniform members. Whisenhunt [8] combined measurement and finite element modelling to study deflections of steel plate girder bridges, further clarifying the role of geometry and stiffness distribution. At smaller scales, Rajasekaran and Khaniki [9] explored bending, buckling, and vibration of small-scale tapered beams using nonlocal strain gradient theory, showing that variable thickness significantly affects both static and dynamic behaviour. These works collectively established tapering as a practical and powerful tool in structural design.

1. *Parameters*

Modern applications of tapered plate girders are particularly prominent in bridge engineering. Zevallos et al. [10] examined tapered bridge girder panels with corrugated steel webs near supports and showed that combining tapering with corrugation can increase shear capacity while reducing steel usage. Zhou and Li [11], and later Zhou et al. [12], investigated tapered beams with concrete flanges and corrugated steel webs through theory, experiments, and numerical simulations, clarifying shear performance and failure modes. Hasan et al. [13] presented a comprehensive state-of-the-art review on steel and steel–concrete composite straight plate girder bridges, highlighting the importance of optimizing girder geometry, including tapering, for long-span applications. In seismic design, Chen and Lin [14] studied beam–column connections and demonstrated how geometric detailing influences cyclic performance. Elkawas et al. [15] numerically investigated corrugated steel webs, emphasizing the effects of corrugation geometry on shear behaviour.

Tankova et al. [16] conducted a comprehensive experimental program on non-uniform members, including column, beam, and beam-column tests, and later performed full-scale tests on tapered columns, beams, and beam-columns [17]. Their results were used to validate and calibrate advanced numerical models, highlighting how tapering modifies global buckling modes, residual stresses, and effective strengths. To make such analysis methods more accessible, Kucukler and Gardner [18] proposed a stiffness reduction method for assessing lateral-torsional buckling of welded web-tapered steel beams. The method reduces material stiffness along the member based on the moment diagram and then uses a modified linear buckling analysis to obtain the design buckling resistance. Chockalingam et al. [19] derived closed-form expressions for shear stress distribution in tapered I-beams, verifying their formulas against finite element models and showing good agreement for typical geometries.

A series of works by Ibrahim and co-authors addressed buckling of non-prismatic plates and tapered webs. Ibrahim et al. [20] proposed axial plate buckling coefficients for non-prismatic steel plates, developed finite element models for tapered plates [21], and carried out experimental investigations on the ultimate shear strength of unstiffened slender web-tapered members [22]. S. M. Ibrahim [23] studied effective buckling lengths of frames with tapered columns and partially tapered beams, providing practical guidance for global stability checks. Couto [24] applied neural networks to predict the critical bending moment of tapered beams, illustrating the potential of machine learning to approximate complex structural behaviour. Overall, these studies show that tapering affects stress trajectories, shear and flexural buckling, and lateral-torsional buckling in ways not captured by simple prismatic formulas [9]–[12], [16]–[21], [36], [37].

3. Results

3.1.1 Opening shapes and stress distribution

Introducing openings into the web further complicates the behaviour. Narayanan and Der Avanessian [5] developed an equilibrium-based approach to predict the ultimate strength of webs with rectangular openings, including post-buckling tension-field action. The shape of the opening is critical. Circular openings produce smoother stress flow and lower peak stress concentration. Orun and Guler [25] studied the effect of hole reinforcement and observed that circular openings, especially with reinforcement, can maintain good strength and fatigue performance. Rectangular openings are convenient for services but introduce sharp corners and stress concentrations. Hashim and De'nan [26] numerically assessed stress around rectangular web openings and showed that local stresses can be critical if openings are large or placed near high-shear regions. Elliptical openings were investigated by Dai et al. [27], who studied plates with centre cut-outs and showed that carefully proportioned elliptical openings can balance stiffness and clearance. De'nan et al. [28], [32] performed structural and parametric analysis of tapered steel sections with perforations, including elliptical openings, and highlighted the influence of opening size and layout on shear buckling behaviour.

Castellated (hexagonal) openings are common in castellated beams. Maulana et al. [29] studied stress and deformation in tapered castellated beams numerically and found that stresses concentrate around the sharp corners of the hexagonal shapes, strongly influenced by opening size and spacing. Shanmugam [34] worked on plate girder webs with openings and clarified that the interaction between panel buckling and local buckling around openings can lead to complex failure modes, especially for slender webs. Rodrigues et al. [35] considered various web opening shapes and confirmed that both bending and shear capacities decrease when openings are large or poorly placed. In the context of connections, Amin et al. [44] numerically modelled the effect of openings on exterior beam–column connections under cyclic loading, showing that openings close to the column face or with large dimensions significantly reduce connection strength and stiffness.

3.1.2 Shear behavior and buckling with openings

Shear is usually the critical design criterion for thin webs. For tapered plates with circular openings, Gendy [30] studied the critical shear buckling load and showed that openings can reduce critical shear strength by up to about 30 %, depending on opening diameter and position. Trahair and Ansourian [31] analysed the in-plane behaviour of web-tapered beams and pointed out that radial stress trajectories provide a better representation of shear flow in tapered webs than the parallel trajectories assumed in prismatic theory. De'nan and co-workers [28], [32] carried out parametric finite element studies on tapered sections with perforations, concluding that smaller tapering ratios and smaller openings yield higher shear buckling capacities and better efficiency, even with weight reduction. Their nonlinear analysis of tapered steel sections with openings under bending [33] further revealed that large openings in bending-critical regions significantly reduce flexural strength and may trigger premature local buckling. The ultimate behaviour of plate girders with openings has also been explored. Shanmugam [34] reported that slender webs with openings may develop combined panel buckling and local buckling around the opening perimeter before reaching ultimate load. Rodrigues et al. [35] confirmed that irregular or oversized openings can cause substantial reductions in critical buckling loads and recommended careful control of opening geometry and placement. These works, however, mostly concern prismatic girders with openings. When the web is both tapered and perforated, the behaviour becomes more sensitive to geometry. De'nan et al. [28], [32], [33] considered tapered sections with perforations, but experimental verification for slender webs is still limited.

3.2 Design Codes and Prediction Methods

3.2.1 Current design provisions

In practice, designers rely on major standards and manuals, notably the AISC Steel Construction Manual [38]; AISC 360 – Specification for Structural Steel Buildings [39]; AISC Design Guide 02 – Design of Steel and Composite Beams with Web Openings [40]; AISC Design Guide 25 – Frame Design Using Nonprismatic Members [41]; Eurocode 3 Part 1-5 – Plated Structural Elements [42]; and the Egyptian Code of Practice for Steel Construction and Bridges (ASD) [49]. AISC 360 [39] and Eurocode 3 [42] provide rules for shear resistance, shear buckling, and tension-field action of webs, but these rules are derived for prismatic webs and do not explicitly consider tapering or web openings simultaneously. AISC Design Guide 02 [40] gives detailed procedures for beams with web openings, including interaction of shear and bending and the distinction between reinforced and unreinforced openings. However, its scope is mainly prismatic beams, and it does not account for the non-uniform depth and stress redistribution in tapered webs.

AISC Design Guide 25 [41] focuses on nonprismatic members and provides approaches to evaluate stability and strength, often using averaged cross-section properties along each segment. Nevertheless, it does not explicitly cover web openings, and combining DG 02 and DG 25 is beyond their calibrated range. The Egyptian Code of Practice [49] uses an allowable stress format and provides shear buckling factors for webs, but, again, the rules are calibrated primarily for prismatic members without openings. In summary, no major design standard currently provides dedicated provisions for slender tapered plate girders with web openings, especially for shear-dominated failures.

3.2.2 Advanced analytical, numerical, and machine-learning approaches

Because of these limitations, researchers have developed several advanced methods. Finite element models of tapered webs and plates under shear and bending have been developed and validated by many authors [7], [10]–[12], [15]–[17], [20]–[22], [28]–[33], [35], [36], [37]. These models can capture local and global buckling, post-buckling behaviour, and the influence of tapering and openings with high fidelity. Analytical models such as Chockalingam's closed-form expression for shear stress distribution in tapered I-beams [19] and Ibrahim's buckling coefficients for non-prismatic plates [20], [21] provide more designer-friendly formulas that still include key geometric effects.

Enhanced tension-field theories have been proposed for tapered webs, modifying shear buckling coefficients and tension-field factors to include panel aspect ratio, tapering ratio, and web slenderness [20]–[22], [31]. Machine learning has also entered this field. El-Aghoury et al. [45] used ANN and other optimization techniques to find the optimum design of hybrid composite girders. Jayabalan et al. [46] estimated buckling loads of steel plates with central cut-outs using ANN, gene expression programming, and evolutionary polynomial regression, finding ANN to be the most accurate among the tested approaches. Shahin and co-authors [47], [48] developed ANN models to predict the elastic critical buckling coefficients of prismatic tapered steel web plates under stress gradients and under shear, demonstrating that ML can significantly reduce analysis time once a sufficiently rich dataset is available. These advanced methods are powerful, but they have mostly been calibrated either for solid tapered webs or for prismatic members with cut-outs, not specifically for slender tapered webs with web openings.

3.2.3 Recent experiments and code comparisons on tapered plate girders with openings

A key recent contribution is the experimental program by Taher et al. [51], who tested slender web tapered built-up plate girders with circular web openings under shear-dominated loading. The specimens covered variations in panel aspect ratio B/H, average web slenderness h_avg/t_w, opening diameter-to-average web height ratio φ/h_avg, and tapering ratio tanθ. The experimental shear capacities and observed failure modes were used to evaluate the performance of existing design methods, including AISC 360 [39], DG 02 [40], DG 25 [41], Eurocode 3 Part 1-5 [42], the Egyptian Code [49], and research-based methods by Serror et al. [43], Ibrahim et al. [20]–[22], and Shahin et al. [47], [48]. The main findings were that AISC 360 [39] and the Egyptian Code [49] significantly underestimated the shear capacity because they ignore the beneficial influence of tapering and use conservative prismatic assumptions for slender webs [51].

AISC Design Guide 02 [40] and the method of Serror et al. [43] tended to overestimate the shear strength, particularly for highly slender webs with relatively large openings, indicating that their parameters are not directly transferable to slender tapered members [51]. AISC Design Guide 25 [41], Eurocode 3 Part 1-5 [42], and the methods by Ibrahim [20]–[22] and Shahin [47], [48] provided closer but still scattered results, sometimes conservative and sometimes unconservative, depending on geometry and opening size [51]. Based on the test data, Taher et al. [51] proposed a new semi-empirical shear capacity equation for slender web tapered plate girders with circular openings, which explicitly includes aspect ratio, opening size ratio, tapering ratio, and web slenderness. Within the investigated parameter range, the proposed formula achieved significantly improved accuracy compared to existing methods.

4.Identified Research Gaps

4.1 Limited experimental database for tapered girders with web openings

Most experimental studies focus on either tapered members without openings [10]–[12], [16], [17], [20]–[23], [31], [36], [37] or prismatic members with openings [5], [25]–[27], [34], [35], [43], [44]. The recent campaign by Taher et al. [51] is one of the few systematic test programs on slender web tapered plate girders with web openings, and even then, only a relatively small number of specimens and parameter combinations were covered. More experimental work is needed to explore different boundary conditions, multiple openings, various opening shapes, and combined shear–bending loading.

4.2 Narrow coverage of geometric parameter space

The behaviour of tapered girders with openings depends on web slenderness, panel aspect ratio, opening size, tapering ratio, and the number and spacing of openings [28], [30]–[33], [51]. Existing studies typically vary only one or two of these parameters at a time and often within limited ranges. Consequently, new formulas such as the shear capacity equation proposed by Taher et al. [51] are valid only within the tested ranges, and extrapolation beyond those ranges is not guaranteed.

4.3 Incomplete treatment of combined shear and bending

Many design and research methods treat shear-dominated and bending-dominated behaviour separately, using interaction equations originally developed for prismatic beams [5], [34], [35], [38]–[42]. For slender tapered webs with openings, shear and bending are strongly coupled due to non-uniform depth and redistribution of stresses around the openings [32], [33], [51]. A unified interaction framework specifically calibrated for tapered webs with openings is still lacking.

4.4 Design codes not calibrated for this configuration

As shown by Taher et al. [51], applying AISC 360 [39], DG 02 [40], DG 25 [41], Eurocode 3 Part 1-5 [42], or the ECP [49] directly to slender tapered girders with web openings can lead to large underestimation or overestimation of the true shear capacity. The underlying reasons are that shear buckling coefficients and tension-field models are calibrated for prismatic webs, the beneficial effect of tapering on shear resistance is underestimated or neglected, and local buckling and stress redistribution around openings in slender tapered panels are not explicitly considered.

There is a clear need for modified or new code provisions that explicitly address this configuration.

4.5 Under-utilization of machine learning for tapered members with openings

Although machine learning has been successfully used for buckling of plates with cut-outs and for prismatic tapered webs [24], [45]–[48], no dedicated ML model currently exists for tapered plate girders with web openings. The combination of more experimental data (e.g., extensions of Taher et al. [51]) and large-scale finite element simulation could provide a rich dataset to train ML-based models capable of predicting shear and buckling capacities across a wide parameter space.

4.6 Imperfections, fabrication tolerances, and real structures

Several studies highlight the importance of initial imperfections and residual stresses on the buckling behaviour of tapered members [16], [17], [20]–[23], [31]. Taher et al. [51] also measured and visualized initial web imperfections. However, most simplified models and many numerical studies still assume idealized or generic imperfection shapes. A more systematic inclusion of measured imperfection patterns into parametric FE studies and design formulations is needed.

4.7 Reliability and calibration of resistance factors

Existing resistance and safety factors in AISC, Eurocode, and the ECP are calibrated primarily on datasets dominated by prismatic members [38]–[42], [49]. For slender tapered girders with web openings, no dedicated reliability studies exist. Before new semi-empirical formulas or ML models are adopted in codes, their statistical variability and bias must be quantified, and new resistance factors may need to be calibrated to ensure consistent safety levels.

5 Conclusions and Recommendations

This literature review has summarized the current state of knowledge on tapered plate girders with web openings, combining: (i) the behaviour and applications of tapered plate girders; (ii) the structural effects of web openings in girders and plates; and (iii) the available design provisions and advanced prediction methods. The key message is that while tapered members without openings and prismatic members with openings are relatively well understood, the combination of tapered, slender webs with significant web openings is still under-researched. Design codes do not explicitly cover this case, and naïve extensions of existing formulas can be either overly conservative or dangerously unconservative [38]–[42], [49], [51].

The recent work of Taher et al. [51] provides crucial experimental data and a new semi-empirical shear capacity equation, demonstrating both the limitations of existing methods and the potential for improved design rules. However, further research is needed to generalize these findings across a broader range of geometries, loading conditions, and structural configurations. Future work should prioritize: expanding the experimental database on tapered plate girders with various opening shapes and layouts; conducting comprehensive FE parametric studies calibrated against experiments; developing unified shear–bending interaction models for tapered webs with openings; leveraging machine learning for fast and accurate capacity predictions; proposing and calibrating new or modified design provisions in major codes; and performing reliability analyses to ensure consistent safety levels. By filling these gaps, tapered plate girders with web openings can move from a "special case" requiring bespoke analysis to a well-understood, codified structural solution, enabling more efficient and economical steel structures without compromising safety.

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