A Critical Review on Analysis and Design of Castellated Beams and Rapid Metal Development (RMD) in Modern Steel Construction

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***Abstract*—Castellated beams are widely used in steel construction because they provide higher flexural stiffness and longer-span capability by increasing the effective depth of rolled sections without a proportional increase in self-weight. However, the introduction of regular web openings also changes the internal force path and creates local effects such as Vierendeel bending, web-post buckling, stress concentration, weld rupture, serviceability deflection, and lateral-torsional buckling. Rapid Metal Development (RMD), represented by CNC cutting, automated fitting, robotic welding, digital detailing, and quality-controlled prefabrication, has the potential to improve the dimensional accuracy and repeatability of castellated beam fabrication. This review paper synthesizes research on the behaviour, design, numerical modelling, failure mechanisms, opening-shape optimization, and fabrication requirements of castellated and cellular beams. The review shows that circular and sinusoidal openings generally reduce sharp-corner stress concentration, whereas hexagonal openings remain economical but require careful checks for web-post stability and Vierendeel action. Literature further indicates that numerical finite element models can predict key response parameters effectively when validated against experiments. A major research gap remains in the integrated evaluation of castellated beam performance with RMD-based fabrication tolerances, residual stresses, automated weld quality, fatigue, fire response, and code calibration for Indian construction practice. The paper concludes with research directions for AI-assisted opening optimization, experimental validation of RMD-fabricated beams, codal design development, and sustainability-oriented steel construction.**

***Index Terms*—Castellated beam; cellular beam; Rapid Metal Development; web opening; Vierendeel mechanism; web-post buckling; finite element analysis; steel construction; robotic welding; CNC cutting.**

I. INTRODUCTION

Steel construction increasingly demands structural members that can achieve long spans, low self-weight, service integration, rapid fabrication and economy. Castellated beams address these requirements by transforming a conventional rolled I-section into an expanded-depth member through a controlled cutting and re-welding process. The resulting openings enable the passage of building services while the increased depth improves flexural stiffness and section modulus. These benefits make castellated and cellular beams attractive for industrial buildings, composite floors, commercial buildings, parking structures, halls, auditoriums and pre-engineered building systems.

Despite these advantages, castellated beams cannot be treated as ordinary solid-web beams. Web perforation disturbs shear flow and causes local stress concentration near opening corners or edges. Depending on loading, geometry and support conditions, failure may occur through Vierendeel bending around the opening, web-post buckling, local yielding, lateral-torsional buckling or weld distress. Consequently, design requires integrated checks for global bending, shear, local opening action, deflection, stability and fabrication accuracy.

Rapid Metal Development (RMD) is used in this review as a broad term for fast, digitally controlled and quality-focused metal fabrication involving CNC cutting, laser/plasma profiling, robotic or semi-automatic welding, fixtures, modular assembly, and non-destructive inspection. RMD is particularly relevant to castellated beams because the structural reliability of these members depends strongly on opening geometry, weld continuity and alignment of the cut halves. This review therefore connects the structural research on castellated beams with the fabrication reliability offered by RMD.

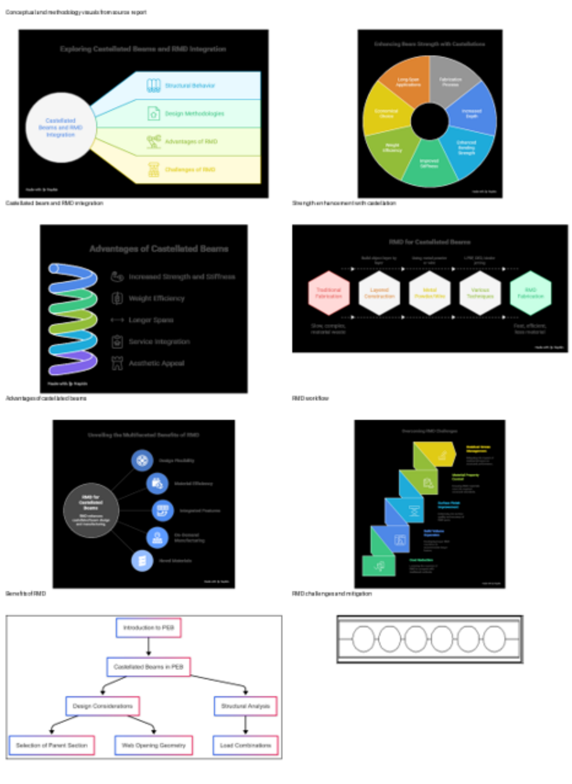

Fig. 1. Conceptual and methodology visuals related to castellated beam and RMD integration, redrawn/compiled from the source dissertation report.

II. REVIEW METHODOLOGY

The review was prepared using a structured literature synthesis approach. The uploaded dissertation report was first used to identify the research theme, technical keywords, figures, opening-shape results and key references. Additional verification was then performed through publisher pages and indexing-visible sources for high-relevance journal papers, design guides and recent studies. The search strings included combinations of “castellated beam”, “cellular beam”, “steel beam with web openings”, “Vierendeel mechanism”, “web-post buckling”, “finite element analysis”, “cyclic loading”, “CNC cutting”, “robotic welding” and “RMD welding”. Sources were screened for relevance to steel beams with repeated web openings, structural behaviour, numerical/experimental validation, design provisions and fabrication technology.

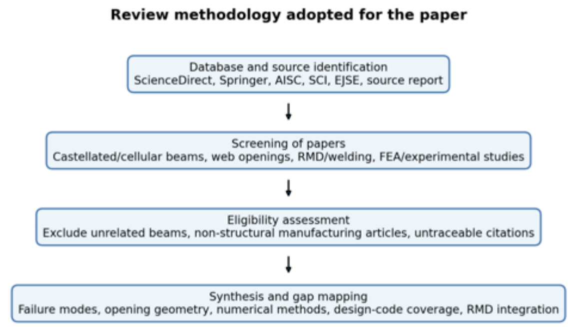

Fig. 2. Review methodology used for identifying, screening and synthesizing literature.

The review does not claim to be a bibliometric database census. Instead, it is a focused critical review suitable for transforming a dissertation topic into a Scopus-style review manuscript. Emphasis is placed on papers that directly inform structural performance, design decisions and future research on RMD-supported castellated beam fabrication.

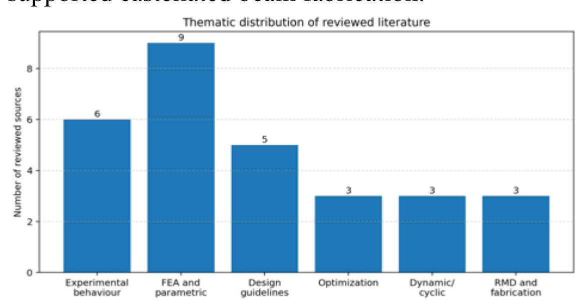

Fig. 3. Thematic classification of reviewed literature. Counts are based on the sources selected for this review synthesis.

III. HISTORICAL DEVELOPMENT AND STRUCTURAL CONCEPT

The use of castellated beams developed from the desire to increase bending capacity without increasing steel tonnage. A parent I-section is cut along the web in a selected pattern, the two halves are shifted, and the matching portions are welded to create a deeper section. This method improves moment of inertia and flexural stiffness while retaining approximately the original steel weight. Early applications focused on industrial long-span systems, while modern applications increasingly involve service integration and exposed architectural steelwork.

The geometry of the opening determines the local force transfer. Hexagonal openings are traditional and economical, but sharp corners can intensify local stresses. Circular or cellular openings reduce corner effects and are visually preferred in commercial structures. Sinusoidal or wave-form openings are an emerging geometry that can improve stress distribution and fatigue performance, provided the fabrication path and weld details are properly controlled.

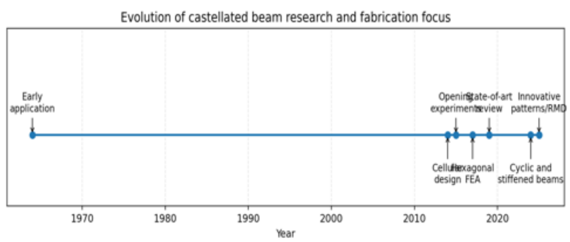

Fig. 4. Evolution of castellated beam research from early applications to recent numerical, cyclic and fabrication-oriented studies.

IV. MAJOR FAILURE MECHANISMS REPORTED IN LITERATURE

The most important distinction between solid-web and castellated beams is the presence of local failure modes. The designer must check both global and local actions because an otherwise safe flexural member may fail locally around an opening. The following mechanisms are consistently reported in experimental and finite element studies.

- Vierendeel mechanism: local bending occurs in the top and bottom tee sections around an opening because shear transfer across the opening produces secondary moments.
- Web-post buckling: the web segment between two adjacent openings may buckle under diagonal compression, horizontal shear or combined compression and bending.
- Stress concentration: sharp opening corners or insufficient fillet radius increase local stress and may trigger premature yielding or cracking.
- Lateral-torsional buckling: increased depth improves flexural capacity but can increase lateral instability risk unless compression flange restraint is provided.
- Weld failure or distortion: poor alignment, residual stresses or discontinuous welds can compromise the reconnected web path.
- Serviceability and vibration: long-span lightweight beams must satisfy deflection and floor vibration limits, especially in composite floor systems.

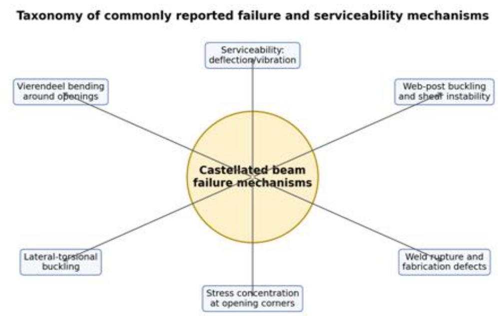

Fig. 5. Taxonomy of failure and serviceability mechanisms in castellated beams.

Table 1. Critical failure mechanisms and design control measures for castellated beams

Mechanism	Main causes	Observable behaviour	Design/fabrication control
Vierendeel bending	High shear near openings; large opening depth	Plastic hinges around corners; local tee bending	Opening size control, stiffeners, local moment checks
Web-post buckling	Closely spaced openings; thin web; high shear	Diagonal compression buckling or web-post distortion	Adequate spacing, web stiffeners, thickness control
Lateral-torsional buckling	Long unbraced span; compression flange instability	Twist and lateral displacement	Lateral restraint, composite slab action, bracing
Weld rupture/distortion	Poor cut alignment; discontinuous welding; residual stresses	Joint cracking or reduced stiffness	RMD/robotic welding, NDT, controlled heat input
Serviceability/vibration	Long span, reduced mass, inadequate damping	Excessive deflection or floor vibration	Deflection/vibration checks and composite action

V. OPENING GEOMETRY AND STRUCTURAL RESPONSE

Opening geometry is the controlling variable in castellated beam behaviour. Literature shows that load capacity and ductility are affected by opening angle, depth, spacing, corner radius and position with respect to high shear or high moment zones. Openings in shear-dominated regions require conservative checks because the remaining web area is reduced and Vierendeel action becomes severe.

The uploaded dissertation report compares sinusoidal, circular and hexagonal opening shapes using ANSYS response parameters. The values are useful as a case-based performance illustration for the review. In that dataset, sinusoidal openings show lower deformation and stress than circular and hexagonal openings, while hexagonal openings show the highest deformation and equivalent stress. This trend is consistent with the general understanding that smoother opening profiles reduce localized stress concentration compared with sharp-corner openings.

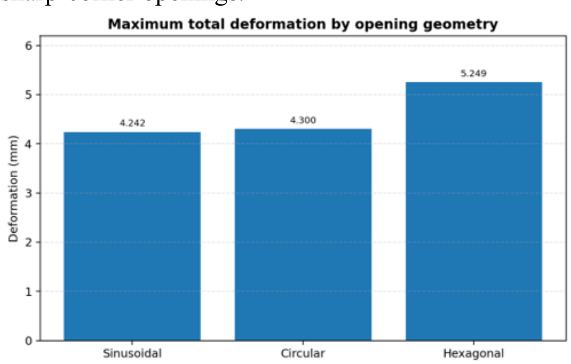

Fig. 6. Maximum total deformation for sinusoidal, circular and hexagonal opening shapes.

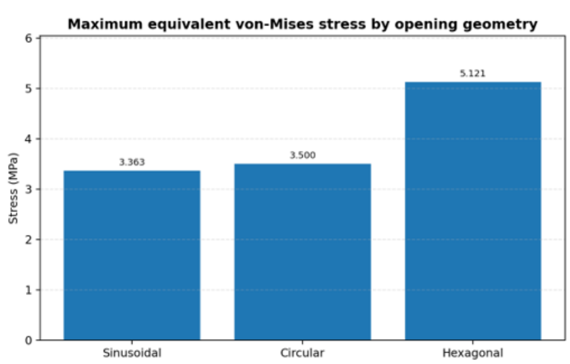

Fig. 7. Maximum equivalent Von-Mises stress for sinusoidal, circular and hexagonal opening shapes.

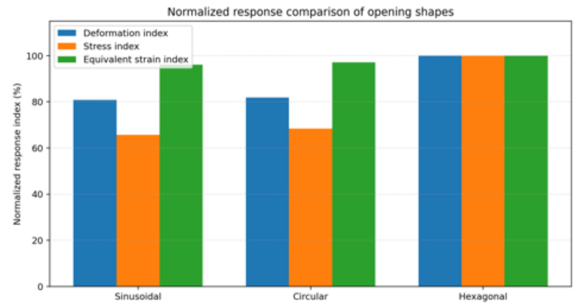

Fig. 8. Normalized response index based on extracted ANSYS result values from the source report.

Table 2. Opening-shape response values extracted from the source ANSYS results

Opening shape	Total deformation (mm)	Equivalent stress (MPa)	Normal strain	Equivalent strain
Sinusoidal	4.2418	3.3629	5.0914 x 10^-6	1.6824 x 10^-5
Circular /cellular	4.30	3.50	5.20 x 10^-6	1.70 x 10^-5
Hexagonal	5.249	5.121	5.30 x 10^-6	1.75 x 10^-5

The extracted values indicate that the sinusoidal opening provides the lowest deformation and stress in the selected model, circular/cellular openings offer balanced behaviour, and hexagonal openings require comparatively stronger web-post and stress-concentration checks.

VI. CRITICAL REVIEW OF EXPERIMENTAL, NUMERICAL AND DESIGN STUDIES

The reviewed literature can be grouped into five streams: early design and application studies, experimental studies on beams with web openings, finite element and parametric studies, optimization studies and recent work on dynamic/cyclic response. A review matrix is provided below to consolidate the main contribution of each important study.

Table 3. Review matrix of key literature on castellated beams and RMD-related fabrication

Author/year	Method	Focus	Major contribution
Boyer (1964)	Engineering practice	Castellated beam development and	Established practical relevance of expanded beams for economical long-

		early applications	span steel construction.
Pachpor et al. (2014)	Design + ANSYS verification	Cellular beam design based on BS 5950-type checks	Showed the need to verify tee-section, web-post and serviceability response using numerical models.
Morkhade & Gupta (2015)	Experimental + parametric	ISMB steel beams with circular/rectangular openings	Reported reduction in stiffness/ultimate load with increased opening area; highlighted spacing-to-diameter effects.
Frans et al. (2017)	FEA + comparison	Hexagonal opening angle and spacing	Identified opening angle/spacing as major performance variables and reported Vierendeel-type failure.
Kaveh & Ghafari (2018)	Optimization	Composite castellated beams and semi-rigid connections	Demonstrated that connection fixity and composite action influence economical optimal design.
Morkhade & Gupta (2019)	State-of-art review	Failure modes and influencing parameters	Synthesized Vierendeel action, web-post buckling, LTB, weld rupture and geometric effects.
Tanady & Suryoatmono (2024)	Nonlinear cyclic FEA	Beam-column assembly under cyclic loading	Showed local failure near openings before full plastic moment development under cyclic demand.
Ayash et al. (2024)	Comparative FE/analytical	Compactness ratios and stiffeners	Reported the role of stiffening and compactness in improving castellated beam performance.
Naji (2025)	Experimental + numerical	Double and zigzag castellated beams	Found that optimized double-castellated patterns can significantly improve load capacity; zigzag patterns require web-post control.
Dave et al. (2025)	Welding optimization	RMD and FCAW process variables	Supports the need for optimized welding parameters when automated/RMD fabrication is used.

Overall, experimental studies provide evidence of local failure mechanisms, while numerical studies expand the parameter space through opening geometry, spacing, material nonlinearity and boundary conditions. However, several numerical papers still require broader experimental validation because castellated beam behaviour is sensitive to residual stresses, fabrication tolerances, weld discontinuity and imperfection assumptions. The review also shows that cyclic and fatigue response remain less mature than static bending and monotonic loading studies.

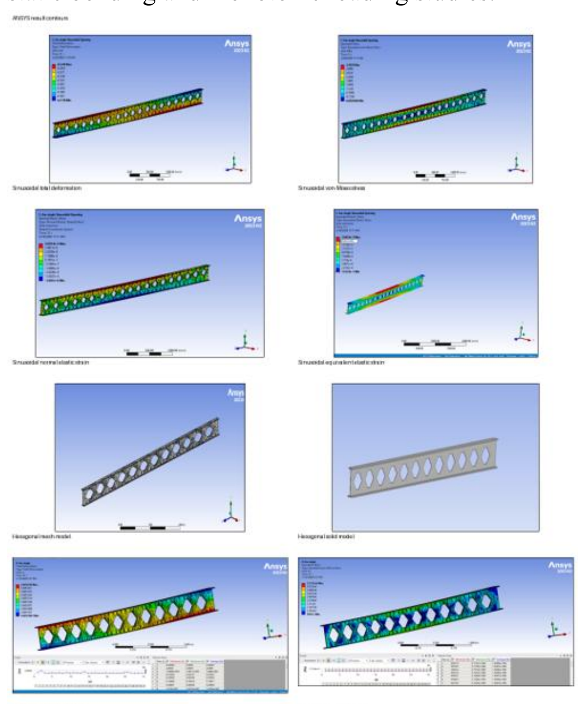

Fig. 9. Representative ANSYS results from the source report, including deformation and stress contours for castellated beam configurations.

VII. RMD INTEGRATION IN CASTELLATED BEAM FABRICATION

The structural efficiency of castellated beams is highly dependent on fabrication quality. Web opening geometry must be accurate, welds must be continuous and aligned, and the two cut halves must be repositioned without eccentricity. RMD can improve these requirements through digitally generated cutting paths, CNC plasma or laser cutting, automated assembly fixtures, robotic welding and dimensional inspection.

Compared with traditional manual fabrication, an RMD-based fabrication chain can reduce variation in opening size, improve weld consistency, reduce grinding and rework, and support digital traceability. For structural research, RMD should not be treated only as a productivity concept; it must be connected to residual stress, heat-affected zone properties, weld geometry, tolerance classes and inspection records because these factors directly influence fatigue and ultimate behaviour.

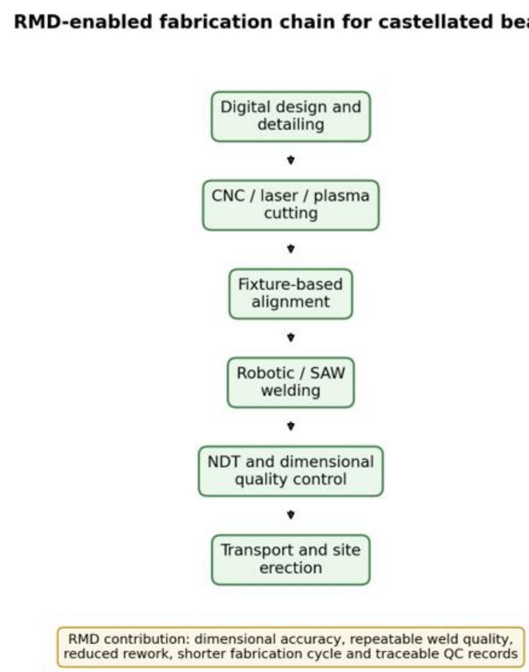

Fig. 10. RMD-enabled fabrication chain for castellated beam production.

Table 4. RMD technologies and their relevance to castellated beam reliability

RMD component	Structural/fabrication benefit	Implementation issue
Digital detailing/ BIM	Accurate opening layout, clash control, repeatable fabrication data	Requires strong model-to-machine data coordination
CNC plasma/laser cutting	Precise opening geometry and lower manual error	Heat input and edge quality must be controlled
Robotic/automated welding	Repeatable weld quality and reduced human variability	Requires optimized parameters and NDT verification
Fixtures and jigs	Improved alignment of shifted beam halves	Initial setup effort and calibration are needed
NDT and digital QC	Improved safety assurance, inspection records, and traceability	Cost and skilled operator requirements

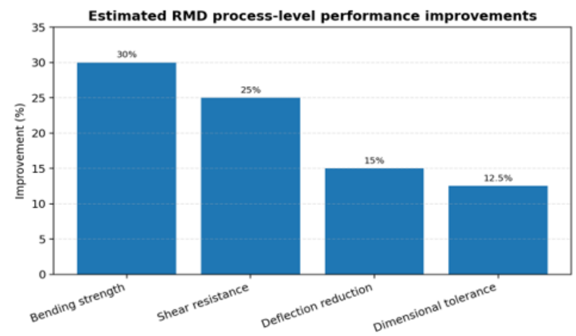

Fig. 11. Illustrative RMD improvement values compiled from the source report discussion.

VIII. DESIGN GUIDELINES AND CODAL CONSIDERATIONS

Design guides such as AISC Design Guide 31 and SCI guidance provide useful procedures for castellated and cellular beam design. These typically require checks for flexural capacity, vertical shear, horizontal shear, Vierendeel bending, web-post buckling, deflection and vibration. However, Indian steel design practice still lacks a dedicated and widely adopted design procedure for castellated beams in IS 800:2007. Hence, many Indian studies rely on a combination of IS 800 provisions for general steel design, international guidance for beams with large openings, numerical simulations and conservative engineering judgement.

Table 5. Design guidance landscape for castellated and cellular beams

Guideline / method	Coverage	Review comment
AISC Design Guide 31	Castellated and cellular beam design with state-of-practice checks	Useful for steel design workflow and failure-mode checks
SCI P355 / related SCI guidance	Composite beams and beams with large web openings	Useful for Vierendeel, web-post and composite opening checks

IS 800:2007	General steel design in India	Provides member design framework but not a complete castellated beam procedure
FEA-based validation	Local stress, buckling and nonlinear behaviour around openings	Requires mesh sensitivity, material model, contact and imperfection control

IX. RESEARCH GAPS IDENTIFIED

The literature has progressed considerably, but the following gaps remain important for developing a complete research programme on castellated beams fabricated through RMD.

- Limited experimental validation of sinusoidal and hybrid opening profiles under monotonic, fatigue and cyclic loading.
- Insufficient integration of fabrication tolerances, weld defects, residual stresses and heat-affected zone behaviour into FEA models.
- Need for India-specific design recommendations that connect IS 800 with international castellated beam design guides.
- Limited studies on RMD-fabricated beams where CNC cutting accuracy and robotic welding parameters are explicitly measured and correlated with structural response.
- Inadequate long-term serviceability studies on vibration, fatigue, fire exposure and durability of castellated beams with repeated openings.
- Few optimization studies combine opening geometry, construction cost, embodied carbon, service integration and fabrication constraints in one framework.

X. FUTURE RESEARCH DIRECTIONS

1 Experimental validation: full-scale tests should be performed on hexagonal, circular and sinusoidal castellated beams fabricated through both conventional and RMD routes.
2 RMD-linked structural modelling: numerical models should include weld geometry, residual stresses, cut-edge quality and fabrication imperfections measured from real production.
3 AI-assisted optimization: machine learning and metaheuristic optimization may be used to select opening size, spacing and shape based on strength, serviceability, cost and carbon indicators.
4 Cyclic and fatigue performance: future studies should evaluate beam-to-column assemblies and long-span floor beams under repeated and seismic-type loading.
5 Codal calibration: reliability-based calibration is needed to develop safe partial factors and design checks for Indian practice.
6 Sustainability assessment: life-cycle steel saving, fabrication energy, waste reduction and reuse potential should be quantified for RMD-fabricated castellated beams.

XI. CONCLUSION

- Castellated beams provide an efficient solution for long-span steel construction because they increase section depth and flexural stiffness without a proportional increase in self-weight.
- The main design challenge arises from local effects around web openings, especially Vierendeel bending, web-post buckling, stress concentration, lateral-torsional buckling and weld-related imperfections.
- Opening shape plays a major role in performance. Literature and the extracted source-report dataset suggest that smoother profiles such as circular and sinusoidal openings can reduce stress concentration compared with sharp-corner hexagonal openings.
- Finite element analysis is highly useful for evaluating castellated beam behaviour; however, reliable conclusions require mesh convergence, realistic material models, imperfections and experimental validation.
- RMD can improve castellated beam fabrication by enhancing cutting accuracy, weld repeatability, dimensional control and quality documentation, but its structural benefit must be quantified through controlled testing.
- The review identifies the need for an integrated research framework combining design-code checks, validated FEA, experimental testing and RMD fabrication quality metrics for future Scopus-level research.

XII. LIMITATIONS OF THE REVIEW

This review is based on a focused selection of literature and the uploaded dissertation report rather than a fully automated bibliometric search across all indexed databases. Some fabrication-related RMD literature addresses welding and rapid metal processing generally rather than castellated beams specifically. Therefore, the review should be used as a strong manuscript foundation and refined further if a target journal requires PRISMA-style database counts, meta-analysis or a strict systematic review protocol.

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Conflict of interest: The author declares no conflict of interest.
Data availability: The review uses literature-based synthesis and response values extracted from the source dissertation report.
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