Analysis of the Effect of High Opening Variation on the Performance of Castellated Beams using the Reduced Beam Section Method

Nini H. Aswad
Department of Civil Engineering, Faculty of Engineering, Halu Oleo University, Indonesia
niniaswad@gmail.com (corresponding author)

Dendi Pongsimpin
Department of Civil Engineering, Faculty of Engineering, Halu Oleo University, Indonesia
dendipongsimpin4211@gmail.com

Thahir Asikin
Department of Civil Engineering, Faculty of Engineering, Halu Oleo University, Indonesia
thahirazikin@gmail.com

Ranno Marlany Rachman
Department of Electrical Engineering, Faculty of Engineering, Halu Oleo University, Indonesia
rannorachman@uho.ac.id

Tachrir
Department of Electrical Engineering, Faculty of Engineering, Halu Oleo University, Indonesia
Tachrir@gmail.com

Miswar Tumpu
Disaster Management Study Program, The Graduate School, Hasanuddin University, Indonesia
miswartumpu@unhas.ac.id

Received: 16 January 2025 | Revised: 15 February 2025 and 24 February 2025 | Accepted: 27 February 2025

DOI: https://doi.org/10.48084/etasr.10260

ABSTRACT

Castellated beams are widely used in structural applications due to their improved load-bearing capacity and material efficiency. This study examines the effect of the variations in the opening height of castellated beams using the Reduced Beam Section (RBS) method, aiming to determine the optimal opening height based on tension, strain, deflection, and stiffness. The modeling results show that increasing the opening height leads to higher stress and strain in the beam. Modeling with an opening height of 190 mm resulted in the highest tension of 311.03 MPa and strain of 0.016, while an opening height of 110 mm recorded a stress of 269.41 MPa and a strain of 0.003. The lowest deflection of 9.87 mm and the highest stiffness of 8.22 kN/mm were obtained at an opening height of 150 mm, rendering it the optimal opening height. It is concluded that this opening height provides the most efficient balance between tension, strain, deflection, and stiffness in castellated beams with RBS. Further research is proposed to analyze the fatigue behavior and long-term performance of the castellated beams with different opening configurations under dynamic loading conditions.

Keywords-castellated beam; reduced beam section; opening height

I. INTRODUCTION

Understanding the impact of the RBS method on aperture size in castellated beams is essential for resource conservation and environmental sustainability. By optimizing structural design and minimizing material usage, construction waste can be significantly reduced without compromising performance. Additionally, this method enhances labor efficiency through a more precise and strategic approach, increasing productivity while reducing workplace accidents. As infrastructure demands grow, structural systems must be designed to achieve greater effectiveness and efficiency. Steel structures have become a preferred choice over wood and concrete in modern construction due to their strength, flexibility, durability, and lightweight properties. These advantages allow steel structures to support heavy loads while simplifying the construction process [1-3].

Castella beams are a modification of steel beams that have openings in the beam body [4]. However, castella beams also present challenges, such as stress concentration near the orifice, reduced shear capacity, susceptibility to bending, and different failures compared to solid beams [5]. Authors in [6] evaluated the increase in the bending capacity of castella profile steel columns with variation in cut height, and found that castella profiles with even holes, 160 mm opening height, and 39-degree angles gave a nominal compressive strength result of 245.73 tons, and an increase of 11.2% compared to the whole profile. In addition, the research in [6] shows that the position of the opening on the castellated beam and the position of the RBS affect structure performance, with an increase in the strain ability from the melting point to break in the castellated beam using RBS. In this study, the variation in the height of the opening in the castellated beam was evaluated to determine beam's the tension, strain, deflection, and stiffness. The goal is to find the optimal opening height that can provide the best balance between these parameters, to improve the performance and efficiency of the beam in real applications. The findings of this study provide valuable insights in optimizing the design and application of castellated beams, particularly in determining the most effective opening height to enhance structural performance. The research establishes a clear relationship between opening height variations and key mechanical properties, including stress, strain, deflection, and stiffness, allowing engineers to make informed decisions in beam design. The optimal opening height identified in this study improves load-bearing efficiency, minimizes excessive deflection, and enhances beam stiffness, leading to safer and more cost-effective structural applications. Additionally, the integration of the RBS method in the analysis contributes to better ductility and failure control, making the findings applicable to the design of earthquake-resistant structures and other load-bearing frameworks. These functions ultimately support the development of more efficient and sustainable steel structures in construction engineering.

Despite the numerous studies on castellated beams, limited research has focused on the effect of opening height variations in conjunction with the RBS method. Previous studies have mainly explored the overall performance of castellated beams or investigated various strengthening techniques. However, there is still a lack of systematic analysis on how the opening height affects key mechanical properties such as stress, strain, deflection, and stiffness. Moreover, most existing research does not offer a clear recommendation on the optimal opening height for maximizing structural performance. This study aims to fill that gap by conducting a comprehensive numerical analysis to determine the most effective opening height, contributing to the advancement of knowledge in the design and application of castellated beams.

II. RESEARCH METHODOLOGY

The methodology for analyzing structural elements using Ansys R2 Software begins with defining the geometry of the structure to be analyzed, whether in 2D or 3D form. Once the geometry is created, the next step is to determine the material and its mechanical properties, such as modulus of elasticity and Poisson ratio. Next, the mesh or division of the elements is done to obtain accurate results, where the size of the elements must be adjusted to the complexity of the geometry. After the mesh is completed, the boundary and load conditions are applied according to the analysis scenario, namely static load analysis. The analysis process is carried out to calculate the deflection, stress, and load values on the structure [21]. The results of the analysis can be evaluated through visualization of contours and graphs, and verification is carried out with analytical methods to ensure model accuracy. The used materials in this study are castellated beams with a WF 150.75.5.7 profile and secondary data in the form of material properties derived from fabrication data, consisting of mechanical characteristics of steel where: Specific Gravity = 7850 Kg/m^3, Ultimate stress (fu) = 410 MPa, Yield stress (Fy) = 250 MPa, Young's Modulus (E) = 200000 MPa, and Poisson numbers (v) = 0.3.

The castellated beam is modeled with both ends of the clamp support on both sides of its cross-section and the connection between the beams (Figure 1). The column has been modified using the RBS connection method. Subsequently, it varies based on the height of the hole cutting. The height variation data of the castellated beam hole cutting were taken from previous research, and can be seen in Table I, where d_g is the castellated beam height, db is the castellated beam hole height, e is the welding length, S is the aperture spacing, and (θ) is the opening angle. Figure 1 shows a modified steel beam design with a hexagonal opening and RBS section. The dimensions of the beams, which include a total length of 285 mm and a width of 180 mm, indicate the overall size of the structure. The hexagonal openings located in the center of the beam are designed to reduce weight while maintaining structural strength, with dimensions that include diameter (Ø) and spacing between openings (e, b, and S). In addition, the RBS area at the bottom of the beam improves performance in bearing loads and reduces stress concentration around the connection points. Additional dimensional details, including the radius (r) and the specific size of the opening and section of the RBS, are critical for structural analysis and fabrication processes, promoting beam efficiency and performance in construction applications. Table II depicts the research flow.

TABLE I. HIGH VARIATION OF HOLE CUTTING CASTELLATED BEAM

Variation	**Sudut (θ)**	**b**	**d_g**	**db**	**e**	**S**
		mm	**mm**	**mm**	**mm**	**mm**
db190	69.78°	35	245	190	70	210
db170	67.62°	35	235	170	70	210
db150	64.98°	35	225	150	70	210
db130	61.70°	35	215	130	70	210
db110	57.53°	35	205	110	70	210

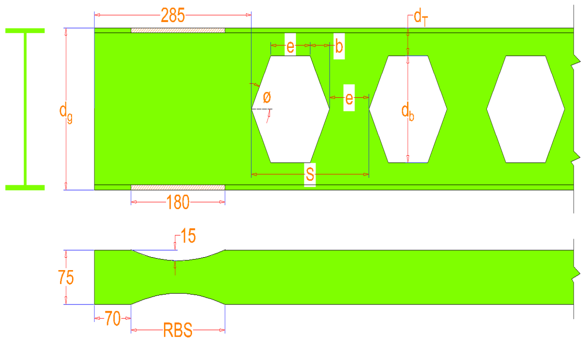

Fig. 1. Properties of RBS and castellated dimension details.

TABLE II. RESEARCH FLOW

Step	**Description**
Problem identification	Understanding the need for optimized castellated beams.
Literature review	Reviewing previous studies on castellated beams and RBS.
Objective definition	Setting research goals to find the optimal opening height.
Methodology	Performing numerical modeling and simulations.
Data collection and analysis	Measuring tension, strain, deflection, and stiffness.
Results and discussion	Comparing results for different opening heights.
Conclusion and recommendations	Identifying the best opening height and proposing future research.

The selection of specific models and opening heights in this study was based on structural efficiency, common industry practices, and previous research findings on castellated beams. The chosen opening heights of 110 mm, 150 mm, and 190 mm represent a range that allows for the evaluation of structural performance variations while maintaining practical applicability in construction. The 150 mm opening height was selected as an intermediate value to assess whether a balanced performance could be achieved between mechanical properties, such as stress, strain, deflection, and stiffness. For numerical analysis and simulation, ANSYS R2 was utilized due to its proven reliability in structural modeling and Finite Element Analysis (FEA) of steel structures. This software provides accurate stress-strain predictions. It enables a comprehensive evaluation of the beam's mechanical behavior under different opening height variations. Its ability to handle complex geometries and material nonlinearities makes it highly suitable for the study of castellated beams, particularly when applying the RBS method. The software's validation against the experimental results in previous studies further reinforces its appropriateness for this type of structural analysis.

III. RESULTS AND DISCUSSION

Based on the results obtained using ANSYS R2 the relationship between the load (in kN) and the deflection (Δ) of various material models (db) is exhibited in Figure 2. An explanation of the relationship between the load and deflection is provided, indicating that as the load applied to the material increases, the deflection also increases [23]. This is the expected behavior of elastic materials, where deformation (deflection) occurs in response to the load [24]. The db 190 model has a high load-bearing ability with relatively little deflection, indicating good strength and rigidity. The db 170 model has good performance, with a higher load on the same deflection as the lower model. The moderate performance of db 150 model, with a lower load on the same deflection, indicates that this material is less robust than the db 170 and db 190. The db 130 model has a lower curve, exhibiting that this material is more susceptible to greater deflection under the same load. The db 110 model shows the lowest performance, with the lowest load at the same deflection, reflecting structural weakness and inability to withstand higher loads. The points on the curve represent the specific load and deflection values for each model. For example, in the db190 model, a load of 83 kN results in a deflection of 10.29 mm, indicating relatively low deformation under this load. Models that sustain higher loads with minimal deflection demonstrate greater strength and resistance to deformation. In contrast, models that support lower loads tend to be more susceptible to deformation. This relationship is critical in structural design, as selecting the appropriate material based on strength and allowable deflection is essential for ensuring both safety and performance [24].

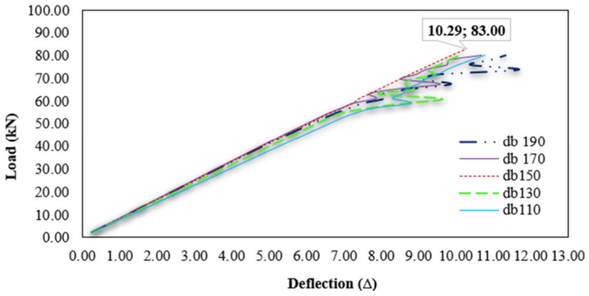

Fig. 2. Relationship between load and deflection (Δ).

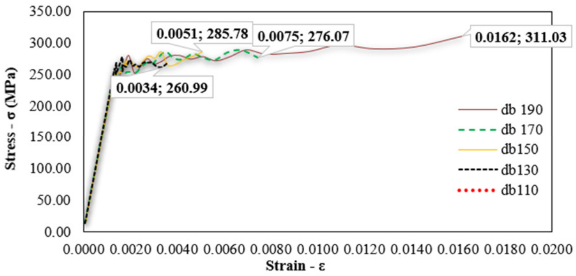

Fig. 3. Relationship between load (in kN) and deflection (Δ).

Figure 3 presents a graph of the relationship between stress (σ) in MPa and strain (ε) in various models (db) of the material, indicating that further explanation of the elements in the graph is required. There is a Y-axis that shows the value of stress in Megapascal units (MPa). It is also depicted how much force is applied per unit area to the material, while the X-axis shows the value of strain (ε), which is the change in length relative to the initial length of the material, reflecting the deformation experienced when subjected to load. Several curves represent different models, namely db 110, db 130, db 150, db 170, and db 190, where each curve shows different material behavior in response to stress and strain. The db 190 model exhibits the best performance with high voltage at a given strain, followed by the db 170 which also displays good performance albeit slightly lower. The db 150 model has moderate performance with lower voltage, while the db 130 shows lower power than the other models. The db 110 model has the lowest performance, reflecting structural weaknesses and potential vulnerability to damage under load.

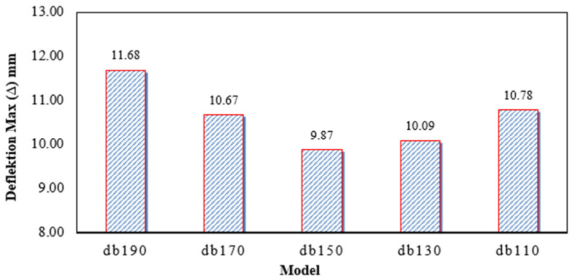

Fig. 4. Comparison graph of deflection results.

Figure 4 illustrates the maximum deflection values (Δ) in millimeters for the various models labeled as db190, db170, db150, db130, and db110. Each bar represents the maximum deflection measured, with the db190 showing the highest value of 11.68 mm, followed by the db170 with 10.67 mm, and so on. The db150 model has the lowest deflection, which is 9.87 mm, indicating that the model has better rigidity compared to other models. Therefore, it can withstand applied loads more effectively and experience less deformation. This demonstrates higher structural strength and better stability, making it safer as the risk of damage due to excessive deformation is reduced. Additionally, this model may reflect a more efficient design in the use of materials, which can reduce the total cost and weight of the structure. In practical applications, models with low deflection will be better at maintaining form and function, especially under dynamic or static load conditions, rendering them a positive indicator in structural analysis that demonstrates the model's ability to meet performance requirements.

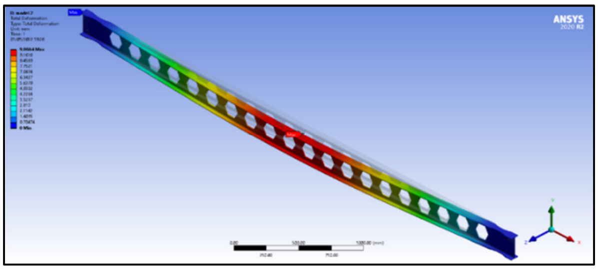

Fig. 5. Model db model center deflection = 150 mm.

Figure 5 provides the results of the total deformation analysis on a structural model using ANSYS 2020 R2 software. This model has a curved shape with several holes, which may indicate that it is part of a frame or beam. The color scale on the left side depicts the degree of deformation, with red indicating a maximum deformation of 8.3666 mm, while blue represents a minimum deformation. The numbers on the left show the deformation values at specific points along with the model, with the highest value being 11.68 mm and the lowest value 1.49 mm. At the bottom, there is a scale that displays the range of deformation in millimeters, providing a visual context of how much deformation has occurred. These graphs are crucial in structural analysis, as they help engineers understand how the model responds to applied loads and ensure that the design is safe and efficient. In Figure 6, the graph demonstrates the relationship between the variation in the height of the castellated beam opening (db190, db170, db150, db130, db110) and the maximum voltage (σ) in MPa. The db190 model, with an opening height of 190 mm, produces the highest maximum voltage of 311.03 MPa, indicating that the larger opening height tends to increase the voltage. The maximum voltage decreases as the opening height decreases, obtaining values of 287.78 MPa on the db170 model, 283.94 MPa on the db150, 277.07 MPa on the db130, and 269.41 MPa on the db110. This decrease indicates that the smaller opening height tends to reduce the stress on the beam. Overall, variations in the height of the opening affect the voltage distribution, where models with smaller openings provide lower stresses but potentially increase the rigidity of the structure. Figure 7 shows the relationship between the variation in the height of the castellated beam opening (db190, db170, db150, db130, db110) and the maximum strain (ε). The db190 model, with an opening height of 190 mm, produces the highest maximum strain of 0.016, which indicates the highest degree of deformation. The maximum strain decreases significantly with a decrease in the height of the opening. The db170 model recorded a maximum strain of 0.007, while the db150, db130, and db110 models recorded a strain of 0.005, 0.004, and 0.003, respectively. This decrease in strain suggests that a smaller opening height provides lower deformation. Thus, the variation in the height of the opening affects the deformation of the beam, and the smaller height of the opening provides better strain stability.

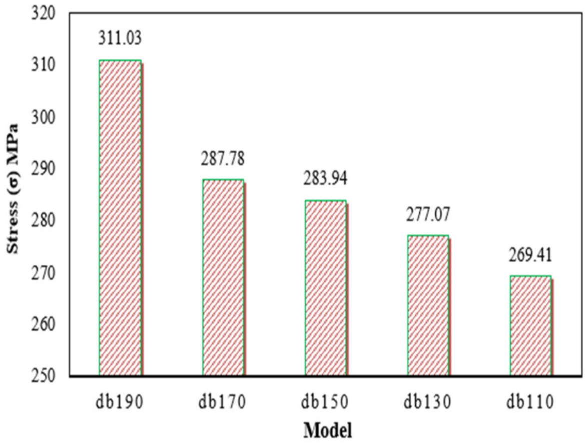

Fig. 6. Voltage comparison results.

Figure 8 presents the relationship between the variation in the height of the opening in the castellated beam (db190, db170, db150, db130, db110) and the stiffness (kN/mm). The analysis results show that the model with an opening height of 150 mm (db150) has the highest stiffness of 8.22 kN/mm, making it the most optimal variation in supporting beam stiffness. Stiffness tends to decrease at larger aperture heights, such as in the db190 model with a stiffness of 7.70 kN/mm, and at smaller aperture heights, such as the db110 model with a stiffness of 7.47 kN/mm. The db170 model has the second-highest stiffness of 8.07 kN/mm, followed by the db130, with a stiffness of 7.77 kN/mm. From these data, it can be concluded that the opening height of 150 mm provides optimal performance in maximizing the rigidity of the castellated beam.

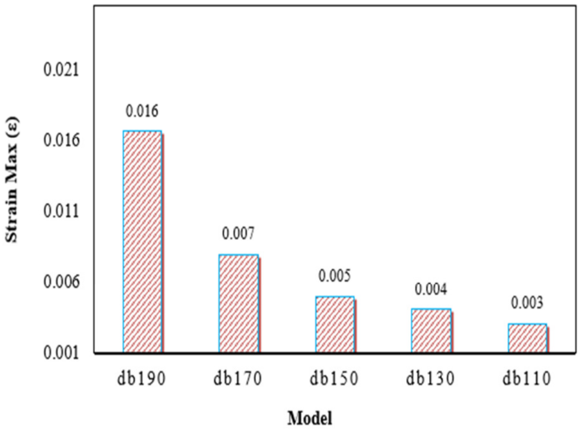

Fig. 7. Strain comparison results.

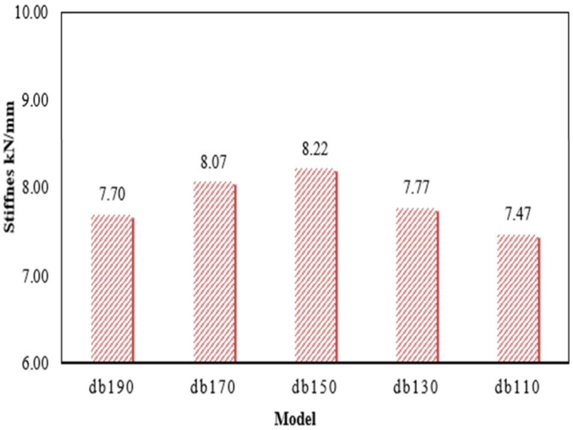

Fig. 8. Stiffness comparison results.

IV. CONCLUSION

Based on the results of modeling the variation in the height of the opening on the castellated beam using the Reduced Beam Section (RBS) method, several significant findings were obtained:

- The increase in the height of the opening indicates a tendency to increase the tension and strain on the beam. These findings show that the variation in the height of the opening has a significant impact on the mechanical behavior of the beam, the variation in the height of the 150 mm opening demonstrates that the height of the 150 mm opening provides the best performance in terms of deflection and rigidity, which are important parameters in structure design.
- Based on a thorough analysis of tension, strain, deflection, and stiffness, the opening height of 150 mm is the most optimal. This opening height can provide the best balance between the four parameters tested, making it the most efficient choice for applications on castellated beams. Therefore, an opening height of 150 mm is proposed as the optimal opening height for castellated beam 225.75.5.7, to improve the efficiency and performance of the structure.
- To further optimize the application of the RBS method, a more in-depth study of additional parameters beyond opening height is proposed. Additionally, considering cyclic loading is crucial, especially given Indonesia's high earthquake frequency. By addressing these factors, the RBS method has the potential to become a key solution for developing earthquake-resistant infrastructure.

Future research should prioritize experimental validation of numerical findings to confirm the optimal opening height for castellated beams using the RBS method. Additionally, examining the fatigue behavior and long-term performance of these beams under cyclic and dynamic loading conditions is crucial for improving their structural reliability. Further investigation into different geometric configurations, material properties, and connection types could provide valuable insights for improving the efficiency and practical applications of castellated beams in engineering.

REFERENCES

[1] F. Rachim, M. Tumpu, and M. Mansyur, "Research on Predicting Skilled Labor Availability to Enhance Sustainability Building Practices," *International Journal of Sustainable Development and Planning*, vol. 19, no. 11, pp. 4183–4192, 2024.

[2] B. Wibawa, I. Fauzi, D. A. Novianti, N. Shabrina, A. D. Saputra, and S. A. Latief, "Development of Sustainable Infrastructure in Eastern Indonesia," *IOP Conference Series: Earth and Environmental Science*, vol. 832, no. 1, Apr. 2021, Art. no. 012045, https://doi.org/10.1088/1755-1315/832/1/012045.

[3] A. S. P. Putra and Y. Latief, "Analysis of safety cost structure in infrastructure project of cable stayed bridge based on Work Breakdown Structure (WBS)," *IOP Conference Series: Materials Science and Engineering*, vol. 830, no. 2, Dec. 2020, Art. no. 022075, https://doi.org/10.1088/1757-899X/830/2/022075.

[4] S. Mathur, M. Senthilpandian, and K. Karthikeyan, "Static and Dynamic Analysis of Steel Beams with Web Openings," *Journal of Physics: Conference Series*, vol. 1716, no. 1, Sep. 2020, Art. no. 012016, https://doi.org/10.1088/1742-6596/1716/1/012016.

[5] A. Murtopo, D. Firmansyah, and R. M. Jannah, "Perilaku Geser Balok Castellated Bukaan Segi Empat Penuh dengan Pengaku Diagonal," *Reviews in Civil Engineering*, vol. 3, no. 1, Mar. 2019, https://doi.org/10.31002/rice.v3i1.1205.

[6] W. Murdianto, B. D. Handono, and R. S. Windah, "Evaluasi Peningkatan Kapasitas Tekuk Kolom Baja Profil Kastela Dengan Variasi Tinggi Potongan," *Jurnal Sipil Statik*, vol. 7, no. 2, pp. 237–250, Feb. 2019.

[7] N. H. Aswad, H. Parung, R. Irmawaty, and A. A. Amiruddin, "Performance of Reduced Beam Section in Castellated Beam Subjected

to Cyclic Loading," *Journal of Engineering Science and Technology*, vol. 13, no. 9, pp. 2872–2882, Sep. 2018.

[8] *J. P. Boyer,* "Castellated Beams - New Developments," *Engineering Journal,* vol. 1, no. 3, pp. 104–108, Sep. 1964, https://doi.org/10.62913/engj.v1i3.14.

[9] R. Royki and L. S. Tedianto, "Analisis Pengaruh Lubang Pada Balok Kastela Terhadap Defleksi Dan Lateral-Torsional Buckling Dengan Metode Elemen Hingga," *JMTS: Jurnal Mitra Teknik Sipil*, vol. 1, no. 1, pp. 149–158, Aug. 2018, https://doi.org/10.24912/jmts.v1i1.2252.

[10] A. Kaveh and A. Fakoor, "Cost Optimization of Steel-concrete Composite Floor Systems with Castellated Steel Beams,"z *Periodica Polytechnica Civil Engineering*, vol. 65, no. 2, pp. 353–375, 2021, https://doi.org/10.3311/PPci.17184.

[11] Y. Sharifi, M. Hosseinpour, A. Moghbeli, and H. Sharifi, "Lateral Torsional Buckling Capacity Assessment of Castellated Steel Beams Using Artificial Neural Networks," *International Journal of Steel Structures*, vol. 19, no. 5, pp. 1408–1420, Oct. 2019, https://doi.org/10.1007/s13296-019-00217-3.

[12] A. Kaveh and M. H. Ghafari, "Optimum design of castellated beams: Effects of composite action and semi-rigid connections," *Scientia Iranica*, vol. 25, no. 1, pp. 162–173, Feb. 2018, https://doi.org/10.24200/sci.2017.4195.

[13] G. Indupriya and B. Anupriya, "Analytical Evaluation of RBS Moment Connection for Indian Profiles Under Seismic Behavior," *International Journal of Sustainable Construction Engineering and Technology*, vol. 13, no. 3, pp. 90–106, Oct. 2022.

[14] R. O. Hamburger, "Prequalified Connections for Special and Intermediate Steel Moment Frames for Seismic Applications, ANSI/AISC 358-05," *Structural Engineering and Public Safety*, pp. 1–8, Jun. 2012, https://doi.org/10.1061/40889(201)5.

[15] A. M. Tabar, A. Alonso-Rodriguez, and K. D. Tsavdaridis, "Building retrofit with reduced web (RWS) and beam (RBS) section limited-ductility connections," *Journal of Constructional Steel Research*, vol. 197, Oct. 2022, Art. no. 107459, https://doi.org/10.1016/j.jcsr.2022.107459.

[16] D. V. Bompa, A. Y. Elghazouli, T. Bogdan, M. R. Eatherthon, and R. T. Leon, "Inelastic cyclic response of RBS connections with jumbo sections," *Engineering Structures*, vol. 281, Apr. 2023, Art. no. 115758, https://doi.org/10.1016/j.engstruct.2023.115758.

[17] T. A. Horton, I. Hajirasouliha, B. Davison, and Z. Ozdemir, "More efficient design of reduced beam sections (RBS) for maximum seismic performance," *Journal of Constructional Steel Research*, vol. 183, Aug. 2021, Art. no. 106728, https://doi.org/10.1016/j.jcsr.2021.106728.

[18] S. Di Benedetto, A. B. Francavilla, M. Latour, G. Ferrante Cavallaro, V. Piluso, and G. Rizzano, "Seismic Behavior of Moment-Resisting Frames with Conventional and Innovative Connections," *Symmetry*, vol. 12, no. 12, Dec. 2020, Art. no. 2091, https://doi.org/10.3390/sym12122091.

[19] J. Bai, J. He, C. Li, S. Jin, and H. Yang, "Experimental investigation on the seismic performance of a novel damage-control replaceable RC beam-to-column joint," *Engineering Structures*, vol. 267, Sep. 2022, Art. no. 114692, https://doi.org/10.1016/j.engstruct.2022.114692.

[20] B. Astudillo, *Structural behavior checks prior performing nonlinear dynamic analysis*. Earthquake Engineering Research Institute, 2018.

[21] P. S. Tickoo, *ANSYS Workbench 2019 R2: A Tutorial Approach, 3rd Edition*. CADCIM Technologies, 2024.

[22] D. Sandy, H. R. Limbong, D. Runtulalo, and H. Rante, "Experimental Study on Castellated Beams with Hexagonal Variation Using Monotonic Loading," *International Journal of Engineering and Science Applications*, vol. 1, no. 1, pp. 67–75, Jan. 2016.

[23] D. Gao, Z. Gu, and C. Wu, "Bending Behavior and Deflection Prediction of High-Strength SFRC Beams under Fatigue Loading," *Journal of Materials Research and Technology*, vol. 9, no. 3, pp. 6143–6159, May 2020, https://doi.org/10.1016/j.jmrt.2020.04.017.

[24] Q. Hu, L. Zhu, and T. X. Yu, "Elastic effects on the dynamic plastic deflection of pulse-loaded beams," *International Journal of Impact Engineering*, vol. 176, Apr. 2023, Art. no. 104550, https://doi.org/10.1016/j.ijimpeng.2023.104550.