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Numerical Analysis of Castellated Steel Beams with Offset Reinforced Steel Rings Around Web Openings

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التحليل العددي للكمرات الفولاذية المسننة ذات الحلقات الفولاذية المقواة المزاحة حول فتحات الجذع

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Abstract:
This study investigates the behavior of castellated steel beams with circular and hexagonal web openings reinforced by ring stiffeners offset from the opening edge. Two depth-to-opening ratios (D/H = 0.4 and 0.7) were examined. Stiffeners were placed at four offset distances (0, 5, 10, and 15 mm). Finite element models were developed using the finite element analysis program Abaqus/CAE and verified with published experimental data. The results show that increasing offset can raise the ultimate load, particularly for castellated beams with large hexagonal openings (D/H=0.7). A moderate offset distance of 10 mm provided the best performance, especially for beams with large hexagonal opening ratios (D/H=0.7). The ductility also improves with moderate offset distance.

Keywords: Castellated steel beams, Web openings, Stiffener offset, Finite element analysis, Abaqus.

الملخص
تبحث هذه الدراسة سلوك الكمرات الفولاذية المسننة ذات الفتحات الدائرية والسداسية المدعمة بمقويات حلقية مزاحة من حافة الفتحة. تم فحص نسبتين للعمق إلى الفتحة (D/H =0.4 ,0.7)تم وضع الدعامات عند أربع مسافات إزاحة (0، 5، 10، و15 مم). تم تطوير نماذج العناصر المحدودة باستخدام برنامج تحليل العناصر المحدودة Abaqus/CAE وتم التحقق منها باستخدام البيانات التجريبية المنشورة. تظهر النتائج أن زيادة الإزاحة يمكن أن ترفع الحمل الأقصى، خاصة بالنسبة للكمرات المسننة ذات الفتحات السداسية الكبيرة (D/H=0.7). قدمت مسافة إزاحة معتدلة تبلغ 10 مم أفضل أداء، خاصة للكمرات ذات نسب الفتحات السداسية الكبيرة (D/H=0.7). لوحظ كذلك تحسن في المطيلية مع مسافة إزاحة متوسطة.

الكلمات المفتاحية: الكمرات الفولاذية المسننة، فتحات الجذع، إزاحة المقويات، تحليل العناصر المحدودة، الاباكوس.

I. Introduction

For many years, castellated steel beams have been considered a suitable solution for various civil engineering applications due to their numerous advantages. Among these advantages, the most significant is their ability to increase depth without adding weight, while also permitting the passage of equipment such as pipes, wires and air-conditioning ducts; this feature helps to reduce the overall height of buildings. Typically, these beams are created by cutting standard I- or H-sections along specified paths that determine the shape of the resulting openings. The two parts are then welded together to form a castellated steel beam, as shown in Figure 1 [1] On the other hand, the existence of these openings leads to a reduction in the load capacity and shear strength and thus exposes it to various failure modes such as web-post buckling, lateral-torsional buckling, welded joint rupture, and the Vierendeel mechanism [2].

For this reason, many researchers have studied several methods for strengthening web openings, one of which is the use of stiffeners around the web openings. Many of these studies have demonstrated the effectiveness of stiffeners around web openings, as they increase the strength of the reinforced steel beams.

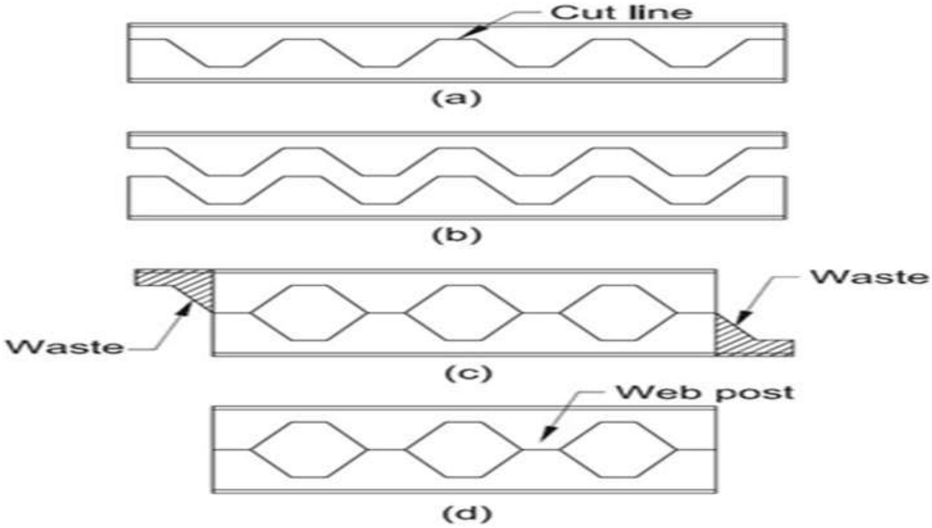


Figure 1: Manufacturing of a castellated beam. [1]

Current literature has not extensively investigated the effect of stiffener offset from the edges of Web openings. This study aims to fill this gap by conducting a numerical analysis of castellated steel beams with circular and hexagonal openings, with stiffeners positioned at varying offset distances (0, 5, 10, and 15 mm) from the edges of the openings. Two depth-to-opening ratios (D/H = 0.4 and 0.7) and two opening shapes (circular and hexagonal) were considered. Researchers created load-displacement diagrams for every case.

2. Literature Review

Many experimental and numerical studies have Investigated the structural behavior of castellated steel beams (CSBs) with various web opening shapes These studies mainly aim to improve the beam's strength and efficiency while minimizing its weight and the amount of material used. The most common shapes examined in the research include hexagonal, circular, diamond, and oval openings.

Tudjono et al. (2017) studied CSBs with oval openings and confirmed their FE model by comparing it with experimental results. They found that the orientation in which the openings are placed (horizontal or vertical) have an important role in how the beam resists buckling. Their analysis showed that beams with horizontally oriented oval openings have more load capacity and had less deformation than those with vertical openings [3].

Al-Thabhawee (2017) conducted an experimental investigation of the influence of hexagonal opening diameters on the performance of perforated beams. The results Indicated that the optimal performance of the hexagonal beams occurred at h/H = 0.56, leading to a 50% enhancement in ultimate strength compared to the control beam. The researcher additionally discussed the significance of opening spacing and number in influencing failure modes and stiffness [4].

Al-Thabhawee and Mohammed (2019) investigated the behavior of castellated steel beams with octagonal openings reinforced using ring stiffeners, both circular and octagonal in shape. The results concluded that the circular ring stiffeners around the openings could increase the load capacity up to 188%, while octagonal ring stiffeners led to an improvement of 77.6% [5].

Another important contribution comes from Ellobody (2011), who investigated the interaction between local web buckling and torsional failure in castellated beams [6].

Similarly, Jamadar & Khumbhar (2015) compared various web opening shapes. Their results indicated that diamond-shaped openings performed better under shear loads than circular ones, primarily because they offer a larger area for force transfer [7].

Morkhade et al. (2015) studied the behavior of steel beams with rectangular web openings, focusing on the effects of fillet radius, opening aspect ratio, stiffeners, and the position of openings within the neutral zone. Both experimental testing and a parametric study were conducted using a nonlinear finite element (FE) model developed in ANSYS v.12 The results indicated that the highest load capacity was achieved when the fillet radius was either 25 mm or equal to twice the web thickness—the minimum recommended value. An opening aspect ratio of 1.6, along with reinforcement using vertical or horizontal stiffeners around the openings, proved highly effective. The stress distribution at the corners of the openings was significantly improved with the use of fillets and stiffeners. Additionally, the study concluded that when openings are located within the middle two-thirds of the beam span (i.e., the neutral zone), the load capacity of beams with rectangular openings is nearly equivalent to that of solid-web beams [8].

Morkhade and Gupta (2019) investigated the behavior of ISMB-100 hot-rolled beams with web openings to determine the optimum spacing-to-diameter ratio simply supported beams were tested to failure and a FE model was developed using ANSYS software to simulate and extend the experimental findings. The study examined the effects of opening area, spacing-to-diameter ratio, and opening location on the ultimate load capacity. The results showed that increasing the opening diameter led to a reduction in ultimate load. Additionally, positioning the openings within the middle two-thirds of the beam span yielded the highest load capacity, comparable to that of a solid (unperforated) beam [9].

Morkhade et al. (2020) investigated the effect of adding stiffeners to the edges of web openings in steel beams. To achieve this, a finite element model (FEM) was developed using ANSYS software, incorporating material properties and their nonlinear behavior. The study examined beams with various opening shapes (circular, square, hexagonal, and octagonal) and different diameter ratios (D/H = 0.5, 0.625, and 0.75). The results indicated that strengthening the openings led to a significant increase in the ultimate load capacityl, with increases of +54.90% for circular openings, +27.41% for square openings, +46.15% for hexagonal openings, and +58.00% for octagonal openings at a diameter-to-height ratio (D/H) of 0.75. The addition of stiffeners effectively prevented web buckling; however, Vierendeel action remained the dominant failure mode [10].

Vinod A. Choudhari et al. (2023) conducted a numerical analysis utilizing ABAQUS software to evaluate the impact of incorporating steel ring stiffeners or carbon fiber-reinforced polymer (CFRP). The findings revealed that the application of steel ring stiffeners was more effective than other techniques, with the enhancement in the ultimate load ranging from 0.17% to 47.59% for beams with circular web openings. In comparison, CFRP reinforcement led to load increases ranging from 0.19% to 43.97%. The study indicated that employing both methods of reinforcement is highly advantageous, particularly when the diameter of the openings exceeds (D0.6), as the reduction in stiffness is more significant. The combined use of steel rings and CFRP effectively mitigated this reduction in stiffness [11].

Abbas (2023) conducted experimental tests and nonlinear finite element (FE) analysis using ABAQUS software on I-section steel beams with web openings. The study involved six beams with different opening shapes circular, rectangular, and hexagonal and varying diameter ratios. The results demonstrated that increasing the opening area led to a reduction in ultimate load capacity. Among the shapes analyzed, circular openings exhibited higher load-bearing capacity compared to rectangular openings [12].

3. Finite Element Model

In this study, a nonlinear finite element model (FEM) was developed in Abaqus simulate steel beams with circular and hexagonal web openings. The beam and connected components (stiffeners and loading plate) were modeled using three-dimensional solid elements (C3D8R), eight-node, reduced-integration brick elements, with each node having three translational degrees of freedom (x,y,z)[13]. Material behavior was modeled as isotropic. The main beam was connected to the stiffeners and the load/bearing plates using Tie constraints; the beam surface was defined as the master surface and the connected parts as slave surfaces to prevent relative slip.

The beams were modelled under simply supported conditions as shown in Figure **2**. One end of the beam was constrained in all translational directions, while the other end was allowed to move freely in the longitudinal direction to avoid any axial restraint. The load was applied at the mid-span of the top flange in a vertical direction using a displacement-controlled approach in order to capture the full nonlinear response of the beams up to failure. The assembly was meshed with an element size appropriate for capturing local stresses around the openings as shown in Figure **2**. The analysis was then executed, and the primary outputs—load–deflection response and deformed shapes were extracted for a parametric study.

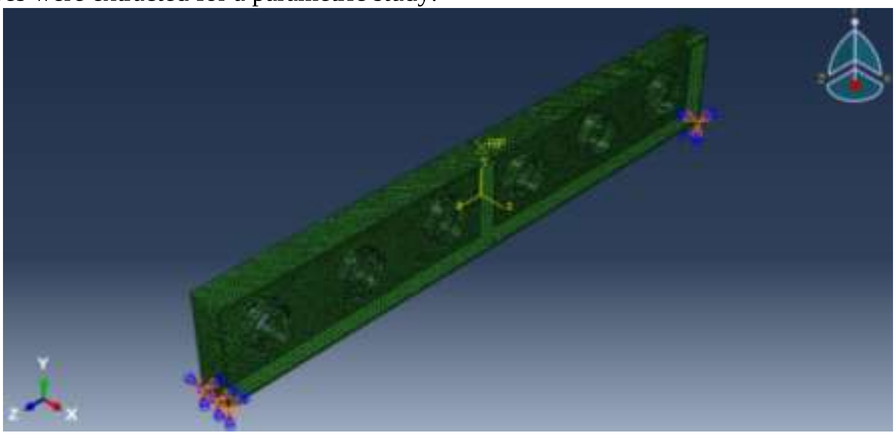


Figure 2: Boundary conditions and loading arrangement of the beam model

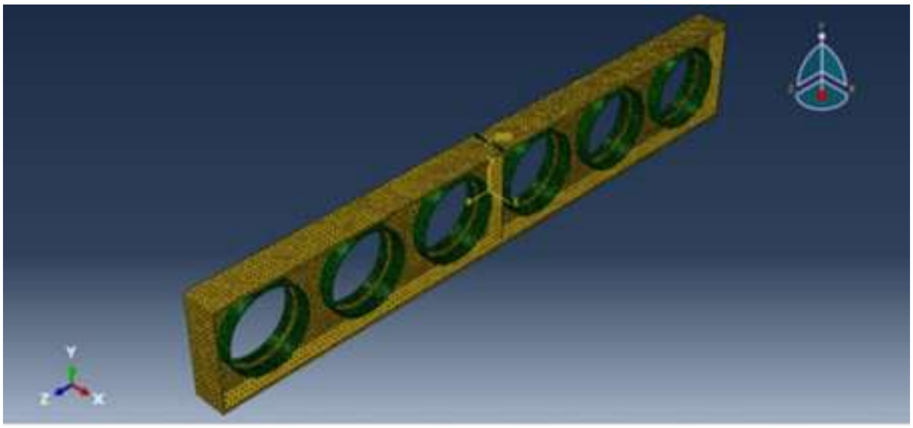


Figure 3: Meshing of castellated beam in Abaqus

4. Model Verification

To validate the numerical modelling approach, a reference model was developed to simulate a previously published experimental case (Morkhade et al. (2020)). Two beams (CBS1 and CBS2), featuring square and rectangular web openings, were modelled. The geometry was based on an ISMB 100 section with a total span of 1000 mm, as illustrated in Figure 4. The material properties were designed as perfectly elastic-plastic. Elastic modulus: E = 210 GPa, yield stress: σ_y = 250 MPa, ultimate strength: σ_u = 410 MPa, Poisson's ratio: ν = 0.3, strain hardening modulus: ET = 5000 MPa. Figures 5 and 6 present the comparison between experimental tests and the present FEM. Figure 7 illustrates comparison of deformed shape and stresses distribution between the proposed FE model and experimental results reported by Morkhade et al. (2020).
The mesh consisted of 8-node linear brick elements (C3D8R), with local mesh refinement applied around the web openings and stiffeners. To account for buckling sensitivity, an initial geometric imperfection equivalent to L/1000 was introduced. The numerical results showed good agreement with the experimental data reported by Morkhade et al. (2020), with less than 1% deviation in ultimate load. This confirmed the accuracy and reliability of the modelling assumptions, mesh density, and boundary conditions employed in this study.

5. Parametric Study

Following successful verification, a total of 16numerical models were developed for the parametric study as illustrated in Figure 8. These models were used to investigate the influence of three primary variables:

- Opening shape: Circular and Hexagonal.
- Opening-to-depth ratios (D/H): 0.4 and 0.7.
- Stiffener offset distances:(0mm, 5 mm, 10 mm, and 15 mm) from the edge of the opening.

The spacing between openings and beam ends was kept constant to isolate the effect of offset distance. All models employed the same material properties, boundary conditions, loading configuration as used in the verification study. The stiffener thickness was assumed to be equal to the web thickness. Each model was analyzed under static loading until failure or significant nonlinearity was observed. Key output parameters, including von Mises stress distribution, maximum deflection, and ultimate load were extracted and compared across all cases to evaluate the structural response.

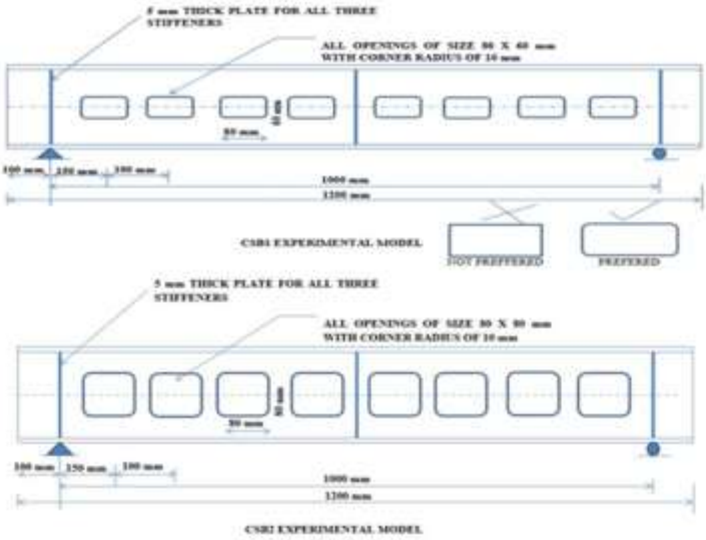
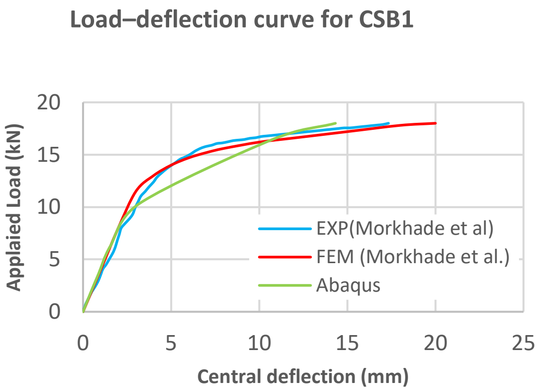


Figure 4: Geometric configuration of the tested CSBs used in verification. (Morkhade et al. (2020)) [10]



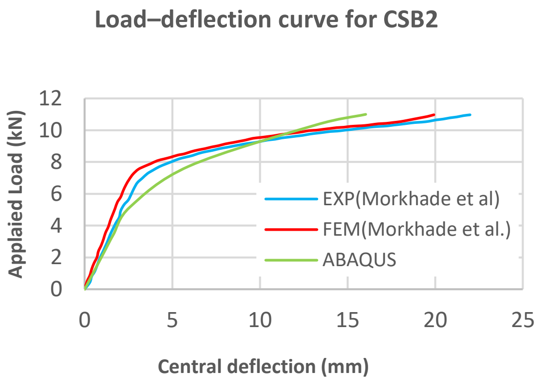


Figure5: Validation of the Abaqus FE model: CSB1

Figure 6: Validation of the Abaqus FE model: CSB2

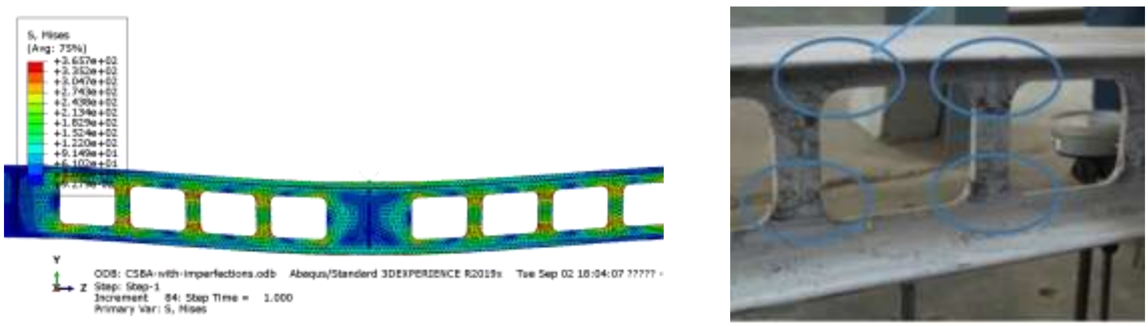


Figure 7: Comparison of experimental done by (Morkhade et al. (2020) and ABAQUS FE results for CSB1

6. Results and Discussion

The response of castellated steel beams subjected to a centrally applied load was investigated using finite element (FE) simulations. Tables **1** and **2** present the ultimate load and maximum displacement results for various beams configurations. Figures **9**, **10**, **11**, and **12** illustrate the corresponding load-displacement curves.

The two ratios (D/H = 0.4, 0.7) were chosen to represent two distinct structural responses, as previous study [11] indicated that openings greater than 0.6D lead to a significant loss of stiffness accompanied by critical failure mechanisms such as local buckling and the Vierendeel mechanism. Therefore, the chosen ratio D/H=0.4 represents a moderate condition with stable behavior, while the chosen ratio D/H=0.7 represents a large and critical formation, making the structural performance more sensitive.

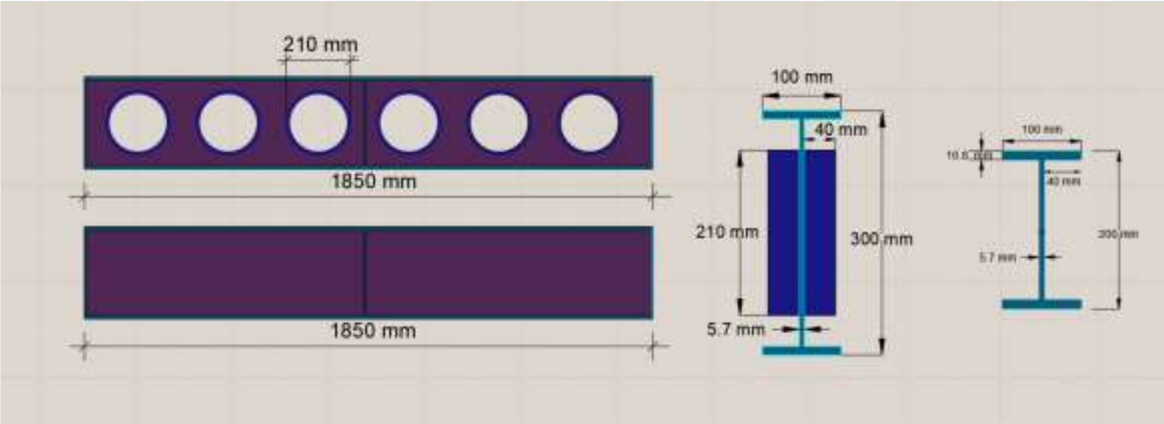


Figure 8: Geometrical details of castellated steel beam used in parametric study

6.1. Castellated beams

Figures **13** and **14** show the effect of stiffener offset distance on both the ultimate load capacity and maximum deflection for castellated steel beams with circular and hexagonal web openings at two opening ratios (D/H = 0.4 and D/H = 0.7). The results emphasize the importance of the opening geometry and the position of the stiffeners in controlling the structural resistance and deformation behavior of the beams.

Table 1. Results obtained from FE analysis for circular CSBs with varying offset (0–15 mm) at two D/H ratios (0.4, 0.7)

Sr No:	Beam Type	Opening Shape	D/H Ratio	Offset (mm)	Ultimate Load (kN)	Ultimate Load Difference %	Max disp (mm) Δu	Yield Displacement (mm) Δy	Ductility factor μΔ
1	CIR-DH0.4-O-00	Circular	0.4	0	346.95	0.00%	52.92	13.72	3.8
2	CIR-DH0.4-O-05	Circular	0.4	5	326.87	-5.79%	49.58	12.49	3.9
3	CIR-DH0.4-O-10	Circular	0.4	10	334.59	-3.56%	72.09	14.20	5.1
4	CIR-DH0.4-O-15	Circular	0.4	15	335.29	-3.36%	62.38	15.1	4.1
5	CIR-DH0.7-O-00	Circular	0.7	0	224.48	0.00%	25.47	7.06	3.6
6	CIR-DH0.7-O-05	Circular	0.7	5	224.10	-0.17%	47.12	10.17	4.6
7	CIR-DH0.7-O-10	Circular	0.7	10	249.46	+11.13%	75.35	17.71	4.2
8	CIR-DH0.7-O-15	Circular	0.7	15	224.91	+0.19%	33.71	11.24	3.0

CIR = Circular, DH=Depth-to Diameter ratio, O= Offset distance

Table 2. Results obtained from FE analysis for hexagonal CSBs with varying offset (0–15 mm) at two D/H ratios (0

Sr No:	Beam Type	Opening Shape	D/H Ratio	Offset (mm)	Ultimate Load (kN)	Ultimate Load Difference %	Max disp (mm) Δu	Yield Displacement (mm) Δy	Ductility factor μΔ
1	HEX-DH0.4-O-00	Hexagonal	0.4	0	311.44	0.00%	33.11	9.38	3.5
2	HEX-DH0.4-O-05	Hexagonal	0.4	5	311.07	-0.12%	35.81	10.06	3.6
3	HEX-DH0.4-O-10	Hexagonal	0.4	10	298.94	-4.01%	25.19	5.62	4.5
4	HEX-DH0.4-O-15	Hexagonal	0.4	15	331.56	+6.46%	51.12	9.93	5.1
5	HEX-DH0.7-O-00	Hexagonal	0.7	0	199.92	0.00%	38.28	13.19	2.9
6	HEX-DH0.7-O-05	Hexagonal	0.7	5	246.65	+23.37%	24.19	8.48	2.9
7	HEX-DH0.7-O-10	Hexagonal	0.7	10	272.45	+36.28%	84.25	14.80	5.7
8	HEX-DH0.7-O-15	Hexagonal	0.7	15	263.57	+31.84%	56.17	12.33	4.6

HEX = Hexagonal, DH=Depth-to Diameter ratio, O= Offset distance

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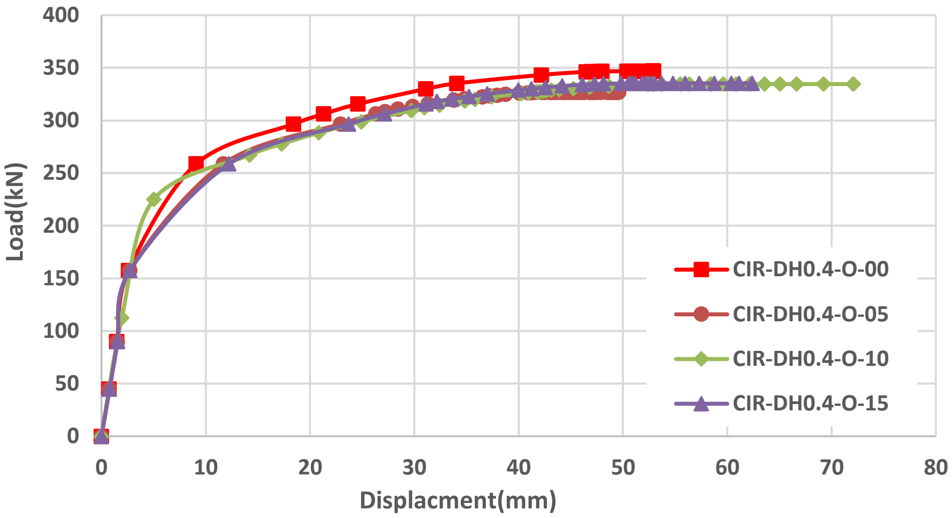


Figure 9: Load vs displacement of circular opening with 0.4 D/H ratio

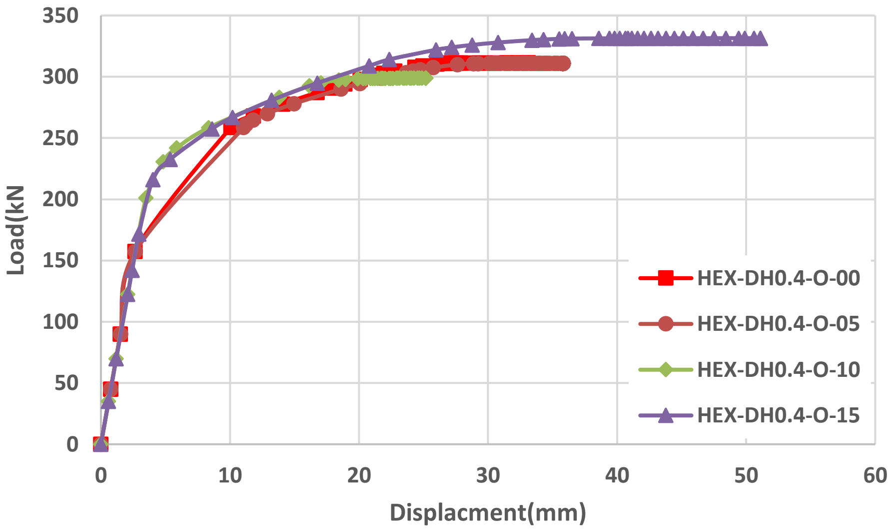
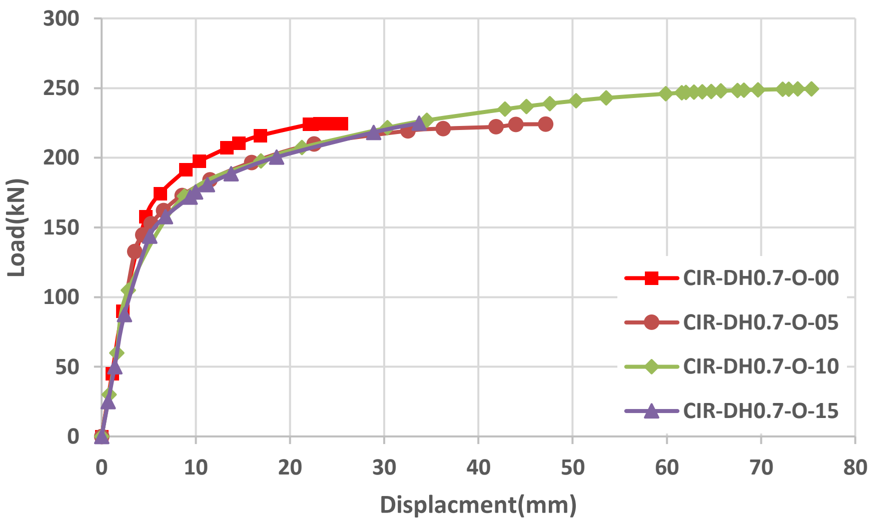


Figure 10: Load vs displacement of hexagonal opening with 0.4 D/H ratio



Figur11: Load vs displacement of circular opening with 0.7 D/H ratio.

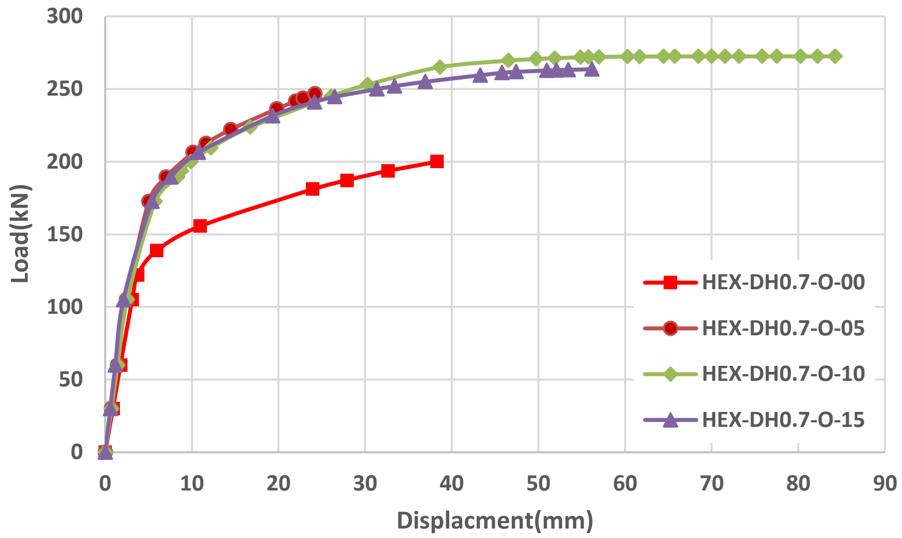


Figure 12: Load vs displacement of hexagonal opening with 0.7 D/H ratio.

6.2 Ultimate Load

Beams with smaller web openings (D/H = 0.4) showed better ultimate load capacity than beams with larger web openings (D/H = 0.7). This trend is primarily due to the increased effective web area and the consequent reduction in stress concentration effects associated with smaller opening sizes.
For circular opening with a D/H ratio of (D/H = 0.4), the ultimate load exhibited minimal variation over the range of offset distances considered, with values consistently falling between approximately 326 and 335 kN (−3.36% to -5.79% relative to 0 mm). These results show that for configurations with small circular openings, the position of the stiffeners has little effect on the load capacity of the beam.

For beams with circular openings at a D/H ratio of 0.7, the offset distance of 10 mm resulted in a more favorable stress redistribution around the opening, leading to a peak ultimate load of approximately 250kN (+11.13% relative to 0 mm). This observation indicates that an intermediate stiffener offset distance can effectively reduce local stress concentrations, thus delaying the development of local buckling or Vierendeel-type failure.

A similar trend was observed for the hexagonal openings beams with D/H of 0.7, where the ultimate load gradually increased with offset distance, reaching a maximum value of around 272 kN (+36.28% relative to 0 mm) at 10 mm, followed by a slight decrease at 15 mm. These results further confirm that a moderate offset distance improves stress distribution, especially around sharp corners, by reducing stress concentrations and improving overall structural performance.

Interestingly, the hexagonal openings configuration with a D/H ratio of 0.4 showed significant improvement only at an offset distance of 15 mm, reaching an ultimate load of approximately 331 kN (+6.46% relative to 0 mm). In summary, an offset distance of approximately 10 mm was found to be most effective for beams with larger openings (D/H = 0.7), while an offset of 15 mm was preferred for configurations with smaller hexagonal openings. In contrast, beams with circular openings and a D/H ratio of 0.4 showed minimal sensitivity to changes in stiffener offset.

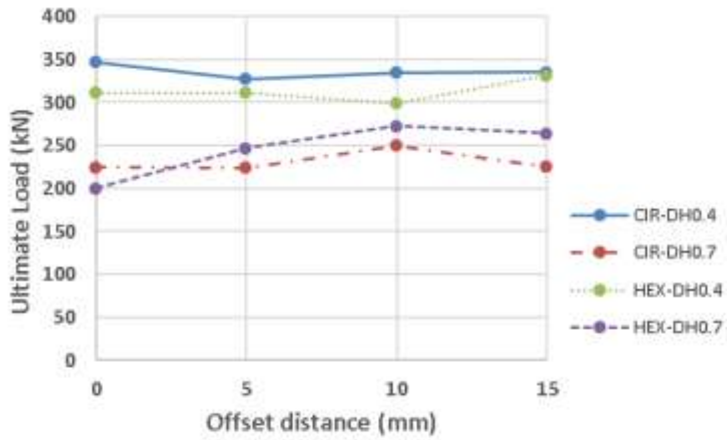


Figure 13: Ultimate load capacity vs offset distance for circular and hexagonal opening with D/H (0.4 and 0.7).

6.3 Maximum Deflection

The observed deflection trends are consistent with the load amplitude behavior. For beams with a circular opening and a D/H ratio of 0.4, the deflection reached a maximum at an offset of 10 mm (approximately 70 mm) of displacement, followed by a slight decrease at 15 mm, indicating increased ductility at intermediate offset distances.

The ductility factor utilized in this study was determined by the displacement-based methodology. The yielding plateau Py was determined in the transitional region of the load–displacement curves, equivalent to 80% of the ultimate load after the initiation of failure. This criterion provides a consistent description of the yield point in situations where a clear elastic–plastic transition is absent. The methodology for determining the ductility factor is illustrated in Figure **14** and formally expressed in Equation (**1**). The corresponding ductility factor values calculated using Eq. (1) are presented in Tables **1** and **2**.

$$\Delta_{\mu} = \frac{\Delta_u}{\Delta_y} \quad (1)$$

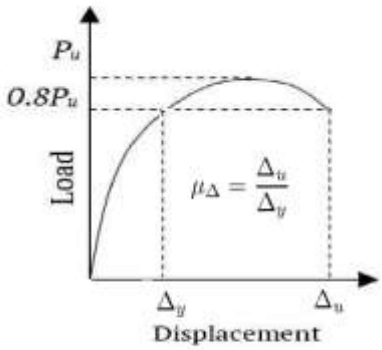


Figure 14: Definition of ductility factor from the Load–Displacement response [14]

Similarly, the beams with circular opening at D/H = 0.7 showed minimal deflection at zero offset, a clear peak at 10 mm, and a subsequent decline at 15 mm. This behavior indicates that moderate offsets increase flexibility while causing a marginal decrease in overall stiffness.

For beams with hexagonal openings and D/H = 0.4, the minimum deflection was observed at 10 mm (approximately 25 mm), indicating an improvement in stiffness at this offset despite the ultimate load is reached at 15 mm. On the contrary, beams with hexagonal openings at D/H = 0.7 showed a peak deflection of about 85 mm at 10 mm offset distance, that corresponds to the observed increase in load capacity, confirming that higher resistance is associated with higher deformation.

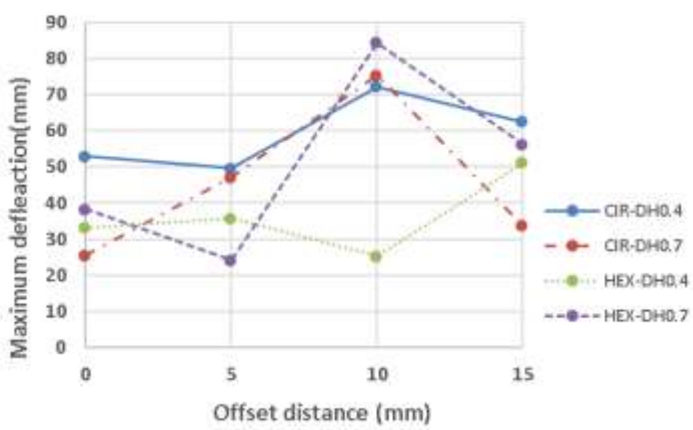


Figure 15: maximum deflection vs offset distance for circular and hexagonal opening with D/H (0.4 and 0.7).

6.4 Mechanical interpretation

The introduction of stiffener offsets modifies the internal load transfer mechanisms between the web and the flanges, thus affecting the shear and bending stress distributions across the web openings. Moderate offsets (about 10 mm) generally contribute to a more uniform stress distribution and effectively delay the development of local buckling, especially in beams with larger or sharp-cornered openings. Conversely, excessive offsets distances can weaken the structural compatibility between web plate and stiffeners, resulting in increased deflection and reduced stiffness.

In the case of smaller circular openings, the stress distribution is more uniform, that explains the observed insensitivity to changes in stiffener offset. Figure **14** displays the von Mises stress distributions, providing insight into the stress concentration and failure mechanisms across the different models.

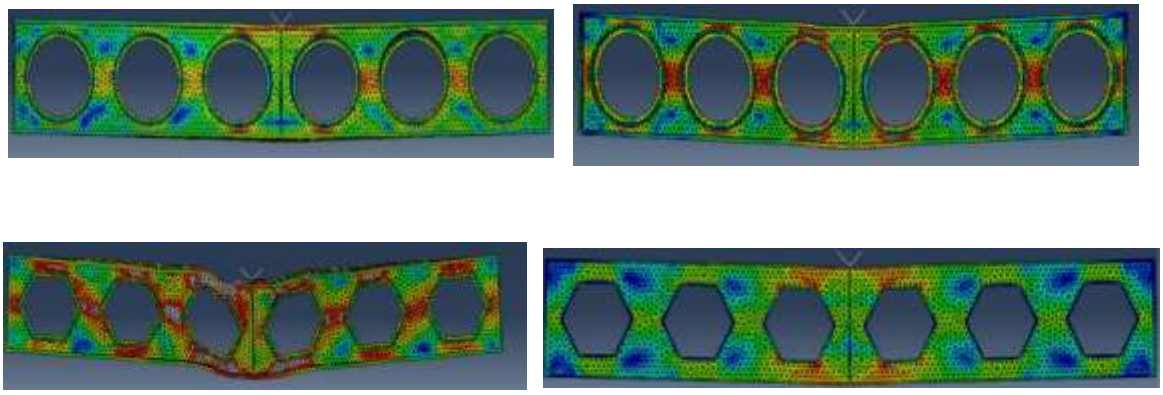


Figure 16: The Von Mises of selected CSBs with different configurations

7. Conclusion

This study examined the structural behavior of castellated steel beams with circular and hexagonal web openings, evaluating the effects of various stiffener offsets through finite element (FE) modelling. The main findings are summarized below:

- An offset distance of approximately 10 mm was found to be most effective for beams with larger openings (D/H = 0.7).
- beams with circular openings and a D/H ratio of 0.4 showed minimal sensitivity to changes in stiffener offset.
- using of a moderate offset stiffener significantly increases the strength and ductility of castellated steel beams, especially in configurations with larger openings.
- A higher opening ratio, indicated by an increased D/H value, reduces ultimate load capacity compared to beams with smaller openings. This reduction is primarily due to a decrease in the effective web area.
- The results emphasize the optimization of stiffener offset distance in terms of opening geometry and D/H ratio to achieve the desired balance between load- carrying capacity and structural stiffness.
- Overall, the findings show that improving ductility leads to a more stable and dependable structural response. Adjusting the stiffener offset proves to be a simple and practical design option that helps engineers enhance safety and performance without adding unnecessary cost.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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