



Experimental Investigation of Composite Beams with Asymmetric Steel Sections Featuring Expanded Web Openings

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ABSTRACT

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composite concrete beams, asymmetric steel sections, expanded web openings, connection configuration, web expansion ratio, ultimate load

Composite concrete beams are widely used in structural engineering, as they combine the compressive strength of concrete with the tensile capacity of steel, providing enhanced structural performance and load-carrying capacity. Steel beams with expanded web openings further improve this performance by increasing the section depth and promoting effective composite action when combined with concrete slabs. This study presents an experimental investigation of strategies to enhance beam depth at different web expansion ratios (30%, 50%, and 70%) compared with a control sample without expansion. The specimens were divided into three groups based on the web expansion ratio, and each group contained two models with different connection configurations for the asymmetrical steel sections. The first method used two plates with a combined thickness equal to that of the parent web, affixed on both sides of the web (2S). Meanwhile, the second method employed a single central plate of thickness equal to the web thickness, positioned between the two asymmetrical sections (1M), alongside a reference beam without expansion (solid). Experimental results revealed that the dual-plate configuration provided greater stiffness and strength at 30% and 50% expansion ratios than the single-plate configuration. Conversely, at a 70% web expansion ratio, the single-plate configuration was more effective.

1. INTRODUCTION

Steel-concrete composite beams are extensively used in structural engineering due to their high strength-to-weight ratio and efficient structural performance. Among these systems, castellated or expanded web steel beams have gained significant attention as they provide increased section depth and flexural capacity without a corresponding increase in material consumption [1]. Compared with traditional I-section building components, web-opening steel beams offer numerous advantages in contemporary structures. One of the advantages is the ability to integrate utilities such as ducting, electrical wiring, or piping without compromising the beam's structural integrity, as well as enhanced visual appeal and a better strength-to-weight ratio. Notably, this beam type is favored in projects with extensive spans, such as stadiums, multistory buildings, and bridges, due to its ability to facilitate installation and optimize space usage [2]. Silva et al. [3] and Morkhade and Gupta [4] introduced the Vierendeel mechanism in steel beams, including web holes through analytical and numerical methodologies. The simply supported castellated beams (CB) under a central focused load were the subject of a study by Zirakian [5]. Many researchers, including Khan et al. [6] and Osmani et al. [7], have presented finite element analyses of CBs with and without holes. When holes are punched into the steel, the beams become weaker, their deflection increases, their shear capacity drops, their

failure modes alter, and more intricate design considerations are required. The cost of manufacturing steel beams with extended webs is higher than that of standard webbed beams. Additionally, opening the steel beams introduces residual stresses that may affect the structural behavior of the beams [8-11]. Asymmetrical steel sections in composite concrete beams are an efficient means of enhancing structural performance and accommodating complex loading scenarios. Welded plate sections facilitate the creation of tailored geometries appropriate for asymmetric behavior. The use of welded steel plates along or within the web has been demonstrated to markedly improve stiffness, shear resistance, and load-carrying capacity. This is especially true in beams featuring openings or non-uniform stress distribution. In line with this, the composite interaction between steel and concrete enhances flexural performance and overall structural behavior [12]. A numerical study of the structural performance of composite and non-composite concrete castellated double-channel beams using alternate opening strategies was conducted by Abbas and Alshimmeri [13]. Ahmed and Said [14] investigated the use of additional plates to deepen wide-flange beams made of hot-rolled steel. Furthermore, an ABAQUS-created finite element numerical model was used to verify the experimental results. A study by Naji and Al-Shamaa [15] assessed the structural behavior of castellated steel beams, focusing on how design parameters, such as the number of apertures and the angle of cut, affect stiffness,

deflection, and load-bearing capacity. Thus, by transforming the web into circular, rectangular, or hexagonal openings, CBs aim to improve the strength-to-weight ratio of conventional I-beams. This, in turn, increases load-bearing capacity and reduces weight while preserving or increasing stiffness, making them a good choice for long-span structures.

In the current study, the experiment investigates the expansion ratio and performance differences of innovative expanded web plates in asymmetric steel-profile concrete composite beams under static loading.

2. EXPERIMENTAL PROGRAM

2.1 Fabricating of steel profiles

The expanded web asymmetrical steel profiles are applied only to the top and bottom parts of hot-rolled I-section steel shapes, IPE 180 and IPE 200, respectively. The fabrication process involves cutting the IPE 180 and IPE 200 along their centers throughout their lengths to produce two halves using a Computer Numerical Control (CNC), as displayed in Figure 1. Two different parts were then connected either by direct welding, by adding steel plates on their web sides, or by adding welded steel plates at the center between the two halves. At the same time, continuous electric welding with 3 mm-thick welds was also utilized to join all parts.



Figure 1. Fabricating process of asymmetric steel profiles



Figure 2. Tensile strength of steel control

Table 1. Steel mechanical characteristics

Sample	Thickness (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)	Elongation (%)
Web of IPE 180	5.4	417	531	22
Flange of IPE 180	8	367	546	26
Web of IPE 200	5.6	414	532	23
Flange of IPE 200	8.5	392	543	28
Stiffeners and expanded web plate	6	378	447	25
Expanded plate of web	3	361	452	23
Shear connectors	3	381	502	24
Rebar	8 (diameter)	521	653	21

In addition, vertical bearing stiffeners were welded to the web at concentrated point loads and above supports. The proper welding sequence is adopted, as distortion would occur if two welders were used. The weld is conducted from the center outward to the ends. This web steel plate was manufactured in accordance with the AISC-2016 specification and intended to join the two steel profile sections [16]. The steel materials characteristics of the rebar and the coupon for the steel sections were conducted according to ASTM A615 and ASTM A370 [17, 18]. The control coupons were conducted in the structural laboratory at the College of Engineering, University of Diyala, as illustrated in Figure 2 and Table 1.

2.2 Details of the specimens

In the current study, an innovative expanded web plate of asymmetric steel profiles-concrete composite beam is proposed. This was achieved by connecting the web in two different ways at expansion ratios of 30%, 50%, and 70%, compared to the solid specimen without expansion. Accordingly, the web steel was connected to the two asymmetrical sections in two ways: first, by adding a plate with a thickness of 3 mm on both sides of the web, approximately matching the thickness of the parent web. Second, by adding a plate with a thickness of 6 mm in the middle of the asymmetrical section. Following this, an experimental program was conducted on three groups of expanded-web asymmetric steel-concrete composite beams to evaluate the effectiveness of expanded ratios and connection types, as illustrated in Table 2 and Figures 3–9. The experimental study includes three groups. In particular, the first specimen is the solid specimen without web expansion, representing the reference specimen. Each group includes two specimens with the same web steel expansion ratio, though with different types of asymmetric steel-section connections, as presented in Table 2. To facilitate the description of the specimens, the following are established: the letter B refers to the composite concrete beams. The letter S indicates that the method of connecting the steel plate for the expanded web is on both sides of the asymmetrical sections. The letter M indicates that it is in the middle of the two asymmetrical sections, and the number that follows indicates the expansion ratio. Regarding the concrete slab, a target compressive

strength of 34 MPa was used. Additionally, channel steel shear connectors were employed to enhance composite action between the concrete slab and the steel section, spaced 150 mm center-to-center, with a length of 50 mm and several 18. Likewise, ACI 211.1.93 was used to produce concrete

mixtures with normal strength [19, 20]. The preparation and casting of the specimens were conducted in the structural engineering laboratory at the College of Engineering, University of Diyala, as displayed in Figures 10 and 11. The specimen testing procedure is illustrated in Figure 12.

Table 2. Details and designation of test specimens

Group No.	Specimen ID	Expansion Ratio (%)	Opening Height (mm)	Opening Length (mm)	Type of Connection
1	B-NN (ref.)	NA	NA	NA	NA
	B-2S.30	30	57	140	2S
	B-1M.30	30	57	140	1M
2	B-2S.50	50	95	140	2S
	B-1M.50	50	95	140	1M
3	B-2S.70	70	133	140	2S
	B-1M.70	70	133	140	1M

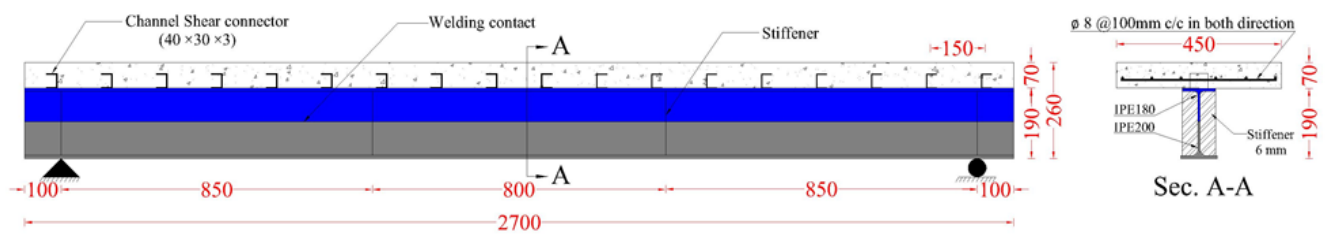


Figure 3. Details along the sample and cross-section for the B-NN specimen, all dimensions in mm

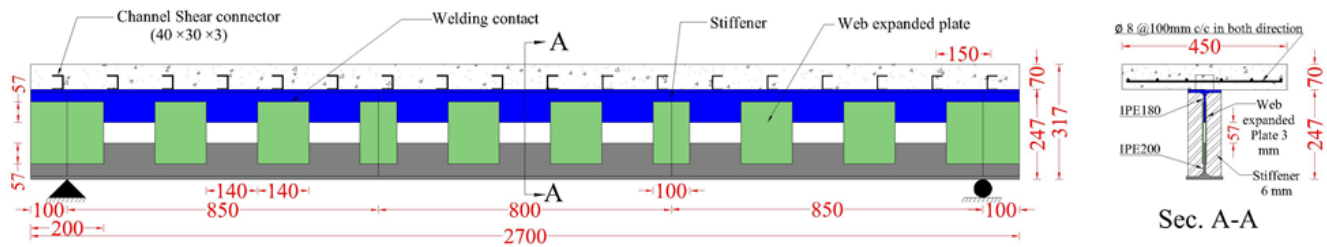


Figure 4. Details along the sample and cross-section for the B-2S.30 specimens, all dimensions in mm

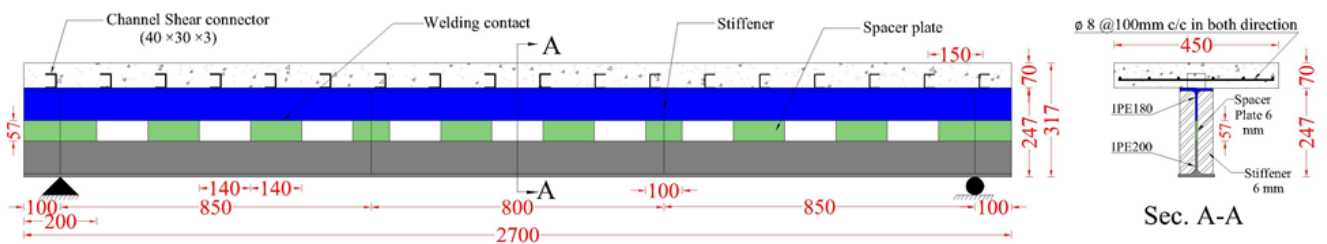


Figure 5. Details along the sample and cross-section for the B-1M.30 specimens, all dimensions in mm

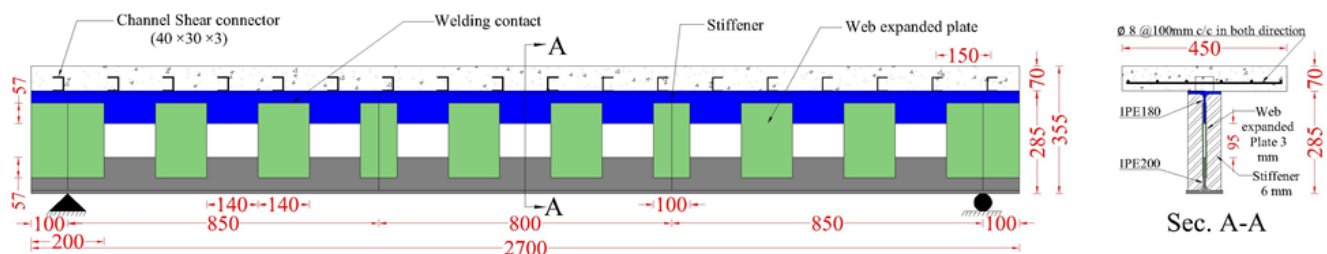


Figure 6. Details along the sample and cross-section for the B-2S.50 specimens, all dimensions in mm

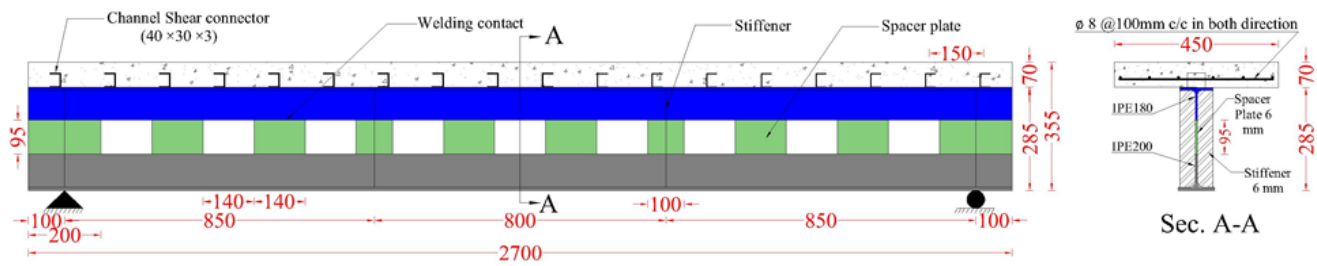


Figure 7. Details along the sample and cross-section for the B-1M.50 specimens, all dimensions in mm

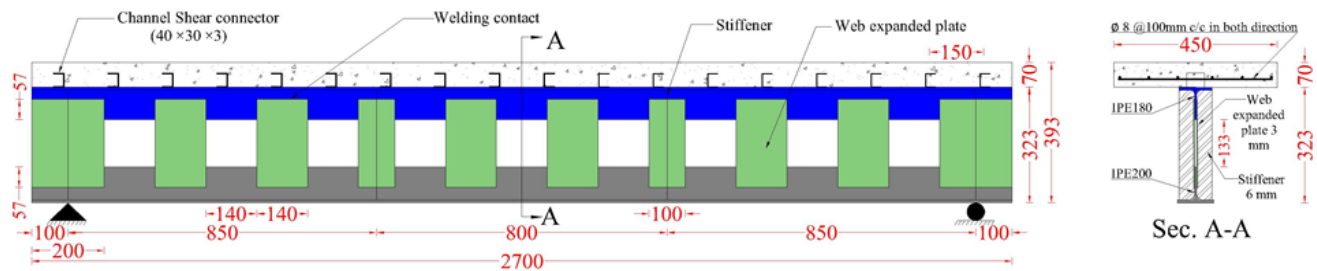


Figure 8. Details along the sample and cross-section for B-2S.70 specimens, all dimensions in mm

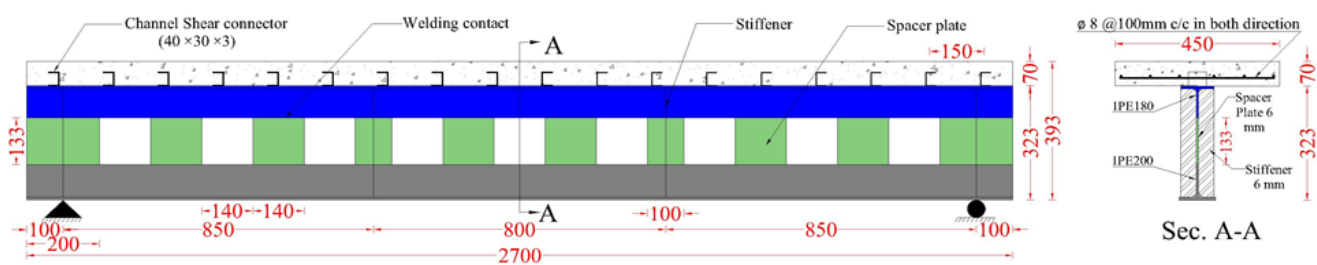


Figure 9. Details along the sample and cross-section for the B-1M.70 specimens, all dimensions in mm



Figure 10. Casting of the test specimens



Figure 11. Preparation of the test specimens

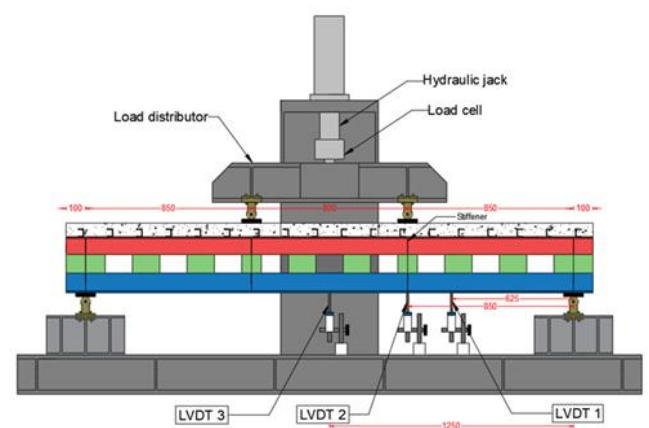


Figure 12. Instrumentation profile of the test configuration

3. RESULTS AND DISCUSSION

3.1 Properties of hardened concrete

Table 3 presents the characteristics of hardened concrete. The cube compression test followed BS 1881: Part 116, while the cylinder compression test and the splitting tensile strength were conducted in accordance with ASTM C39M-17 and ASTM C496/C496, respectively.

Table 3. Properties of hardened concrete

Compressive Strength (cubes) (MPa)	Compressive Strength (cylinders) (MPa)	Splitting Tensile Strength (MPa)
33.8	27.9	3.29

3.2 Load deflection

During the test, the applied load and mid-span deflection of each beam were recorded at each load increment and illustrated as load-versus-mid-span deflection curves (Figures 13–15). The results of the experimental investigation revealed that increasing the web expansion to 30% enhanced the

maximum load by 34.67% and 23.56% for models B-2S.30 and B-1M.30, respectively. In comparison, at a web expansion of 50%, the load increased by 31.65% and 31.22% for models B-2S.50 and B-1M.50, respectively. Additionally, the load increased by 10.81% and 41.95% for models B-2S.70 and B-1M.70, respectively, compared to the control sample without expansion, as depicted in Table 4. This is likely due to the increased effective depth of the steel section in resisting bending.

As for secant stiffness, it increased across all models, ranging from 11.87% to 18.52% relative to the reference sample. However, at 50% web expansion ratio for both models, the secant stiffness was almost identical, indicating stress redistribution along different paths.

Table 4. Ultimate load and mid-span deflection results

Group No.	Specimen ID	Ultimate Load (kN)	Ultimate Deflection (mm)	Percentage Increase in Load (%)	Secant Stiffness (kN/mm) (load /deflection)	Percentage Increase in Secant Stiffness (%)
	B-NN (ref.)	232.2	26.48	-	8.77	-
1	B-2S.30	312.7	26.34	34.67	11.87	35.38
	B-1M.30	286.9	21.5	23.56	13.34	52.18
2	B-2S.50	305.7	18.72	31.65	16.33	86.23
	B-1M.50	304.7	19.4	31.22	15.71	79.11
3	B-2S.70	257.3	19.58	10.81	13.14	49.86
	B-1M.70	329.6	17.8	41.95	18.52	111.17

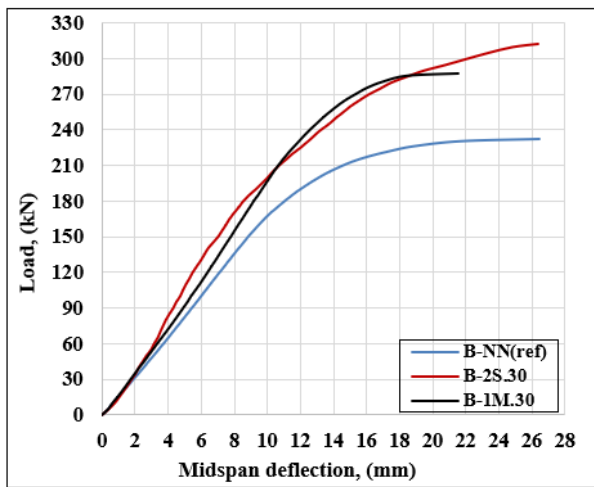
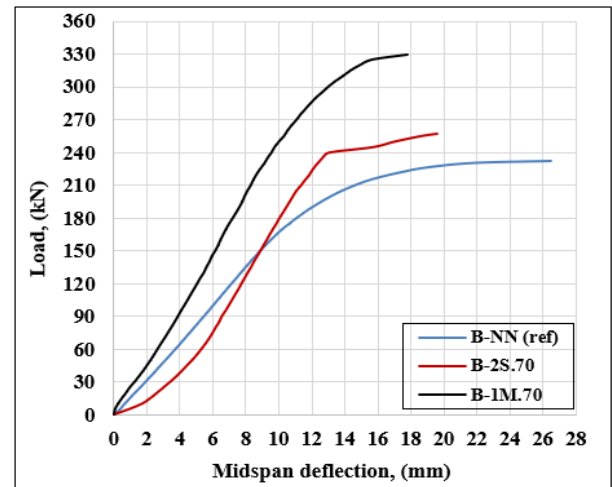
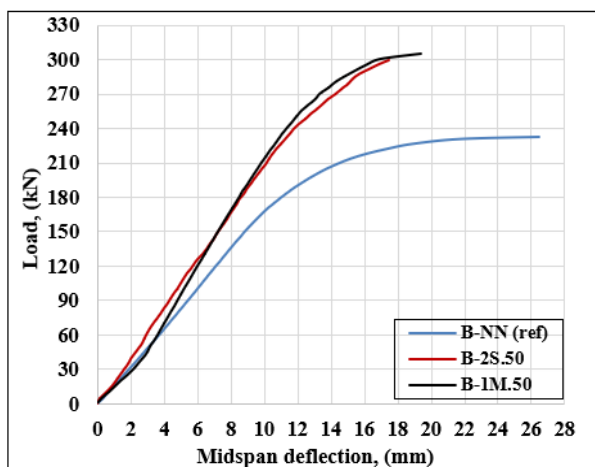
**Figure 13.** Load the verse deflection curve for Group 1**Figure 15.** Load the verse deflection curve for Group 3**Figure 14.** Load the verse deflection curve for Group 2**Figure 16.** Failure mode of specimen B-NN



Figure 17. Failure mode of specimen B-2S.30



Figure 18. Failure mode of specimen B-1M.30

3.3 Mode of failure

In the reference (solid) sample without an expanded web, the failure mechanism was flexural. In the first group (specimen B-2S.30), although failure was governed by local buckling at the web post, the web remained relatively stable. In contrast, in the second group (specimen B-1M.30), the failure was a flexural mechanism, as displayed in Figures 16–18. When the web expansion was increased to 50%, the failure occurred in the B-2S.50 specimens due to local buckling at the web post., whereas B-1M.50 exhibited fracture at the web post weld, as presented in Figures 19 and 20. At 70% web expansion, while the failure rate of B-2S.70 specimen decreased, the web post buckling occurred. Conversely, B-1M.70 presented an increase in tolerance until web post buckling failure occurred. This indicates the slenderness ratio of the web plate in model B-2S.70, since the web plate thickness was divided on both sides. In model B-1M.70, it was placed in the middle to connect the two asymmetrical sections, providing greater stiffness, as displayed in Figures 21 and 22.

3.4 Effect of type connection

At 30% web expansion ratio, the maximum load decreased by 8.25% for specimen B-1M.30 compared to specimen B-2S.30. This results in greater stability for the web plates connected on both sides of the asymmetrical steel section. At

50% web expansion ratio, the difference in maximum loads was significantly small, allowing the web plates connected on both sides to reach their maximum load capacity. Although the two connection types exhibited nearly identical ultimate load capacities, their failure modes differed. This indicates that comparable strength can be achieved through different internal load-transfer and stress redistribution mechanisms. In one connection configuration, the applied load was transferred through a relatively direct stress path, leading to localized damage concentration in the critical region. In the other configuration, the connection details allowed stresses to redistribute over a wider region, altering the failure mode while maintaining a similar ultimate resistance. Therefore, the close values of load capacity should not be interpreted as evidence of identical behavior. Instead, they suggest that the two connection types mobilized distinct resistance mechanisms, yielding comparable ultimate strengths. This difference in failure behavior highlights the notable role of connection detailing in controlling stress redistribution, local stiffness, and the progression of damage. In response, further investigation, including detailed strain measurements and numerical modeling, is recommended to confirm the stress redistribution patterns and better understand the governing mechanisms. Conversely, at 70% web expansion ratio, the load capacity of specimen B-1M.70 increased by 28.1% compared to that of B-2S.70 specimens. This is likely due to the increased section stiffness with increasing depth, as presented in Table 5 and Figure 23.



Figure 19. Failure mode of specimen B-2S.50



Figure 20. Failure mode of specimen B-1M.50



Figure 21. Failure mode of specimen B-2S.70



Figure 22. Failure mode of specimen B-1M.70

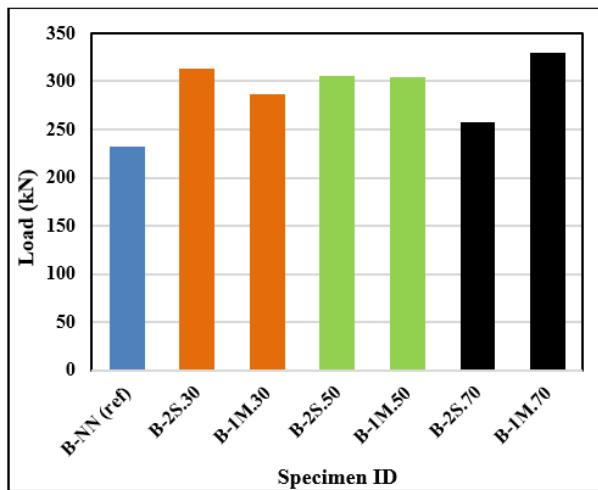


Figure 23. Comparison of the type of connection of the tested specimens

Table 5. Results of the type connection effect

Specimen ID	Expansion Ratio (%)	Ultimate Load (kN)	Different in Load (%)
B-2S.30	30	312.7	Ref.
B-1M.30	30	286.9	-8.25
B-2S.50	50	305.7	Ref.
B-1M.50	50	304.7	-0.3
B-2S.70	70	257.3	Ref.
B-1M.70	70	329.6	+28.1

Table 6. Results of the expansion ratio effect

Specimen ID	Expansion Ratio (%)	Ultimate Load (kN)	Different in Load (%)
B-2S.30	30	312.7	Ref.
B-2S.50	50	305.7	-2.24
B-2S.70	70	257.3	-17.71
B-1M.30	30	286.9	Ref.
B-1M.50	50	304.7	+6.2
B-1M.70	70	329.6	+14.88

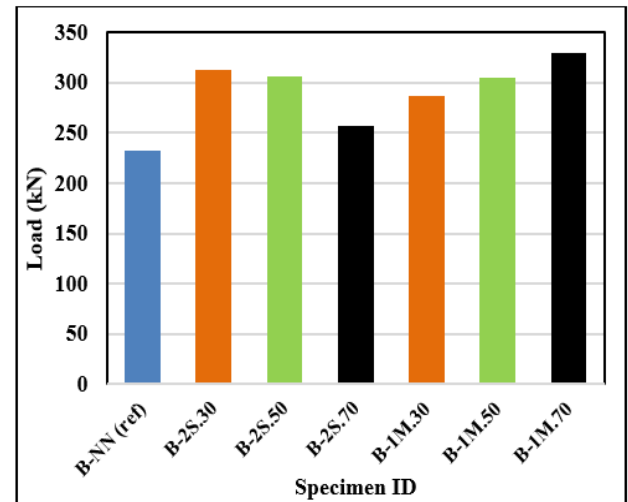


Figure 24. Comparison of the expansion ratio of the tested specimens

3.5 Effect of expansion ratio

Based on Table 6, the asymmetrical steel sections are connected by a web plate distributed on both sides, with a thickness comparable to the web thickness. When the web expansion ratio is raised to 50% and 70%, respectively, the maximum load capacity of models B-2S.50 and B-2S.70 drops by 2.24% and 17.71%, respectively, compared to model B-2S.30. This is due to a slenderness web plate and an increased effective depth. Conversely, when two asymmetrical sections are joined by a web plate with the same thickness as the steel section's web and is welded between them, increasing the web expansion ratio from 50% to 70% increased the load by 6.2% and 14.88% for models B-1M.50 and B-1M.70, respectively, in comparison to model B-1M.30. This is due to the increased depth and, consequently, the increased moment of inertia, as displayed in Figure 24.

4. CONCLUSIONS

An experimental investigation was conducted to evaluate the structural response of innovative composite concrete beams with web-expanded asymmetric steel profiles under monotonic static loading. Based on the findings of this study, the following conclusions can be drawn:

(1) Increasing the web expansion ratio to 30%, 50%, and 70% for models that connect the asymmetric sections through two plates on either side of the web increases the ultimate load by 34.67%, 31.65%, and 10.81%. This is in comparison to the reference sample without expansion. In contrast, when using a single plate of web connecting the asymmetric sections in the middle, the ultimate load increases by 23.56%, 31.22%, and

41.95% compared to the reference sample.

(2) Regarding failure modes, in models that employ web joints on both sides of an asymmetric steel section, the failure mode is web post buckling. Still, in models that employ a single joint, the failure changes into a flexural mechanism, fracture welding at the expanded web plate, and web post buckling failure due to the resistance of a single thickness with varying expansion ratios of 30%, 50%, and 70%, respectively.

(3) The models employed for a single, extended web with uniform thickness were stiffer than those that divided the web's thickness on both sides.

(4) It is worth noting that at 50% web expansion ratio, the maximum load differed by only 1 kN between the model with the web thickness divided on both sides (two plates) and the model with a single plate employed in the middle. However, the two configurations demonstrated different failure modes due to variations in stress redistribution paths.

(5) This innovative technique, which expanded the web, is effectively applied to connected asymmetric steel-section composite concrete beams.

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