



Article

Behavior of Composite Concrete-Filled Double-Web Steel Beams: A Numerical and Experimental Investigation

Abbas Jalal Kaishesh¹, Ghazi Jalal Kashesh^{1,2}, Sadjad Amir Hemzah¹, Bahaa Hussain Mohammed¹ ,
Anmar Dulaimi^{1,3,*} and Luís Filipe Almeida Bernardo^{4,*}

¹ Department of Civil Engineering, College of Engineering, University of Kerbala, Karbala 56001, Iraq; abbas.jalal@uokerbala.edu.iq (A.J.K.); ghazi.alsaidy@gmail.com (G.J.K.); sajjad.a@uokerbala.edu.iq (S.A.H.); bahaa.hussain@uokerbala.edu.iq (B.H.M.)

² Civil Engineering Department, Faculty of Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq

³ School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 2ET, UK

⁴ GeoBioTec, Department of Civil Engineering and Architecture, University of Beira Interior, 6201-001 Covilhã, Portugal

* Correspondence: a.f.dulaimi@ljmu.ac.uk (A.D.); lfb@ubi.pt (L.F.A.B.)

Abstract

This study investigates the structural behavior of composite double-web steel beams filled with different types of concrete made from a combination of recycled concrete aggregates and normal aggregates. The research includes both experimental and numerical analyses. Seven specimens were tested under symmetrical two-point loading, all having identical geometric properties: a span length of 1100 mm, flange plates 120 mm wide and 6 mm thick, and web plates 3 mm thick and 188 mm deep. The specimens were divided into two groups, with a control beam without concrete infill. Group one included beams filled with normal concrete in different locations (middle region, two sides, and fully filled), while group two mirrored the same fill locations but used recycled concrete instead. The experimental results showed that using normal concrete improved the ultimate load by 10.19% to 55.30%, with the fully filled beam achieving a maximum increase in ductility of about 568% and a stiffness improvement ranging from 2.6% to 39% compared to the control beam. Beams filled with recycled concrete showed increases in ultimate load from 9.52% to 42.03%, ductility improvements of up to 380%, and stiffness enhancements between 4.5% and 8.03%. Numerical modeling using ABAQUS (2021) showed excellent agreement with the experimental results, with differences in ultimate load and maximum deflection averaging 5.5% and 7.9%, respectively.

Keywords: composite concrete-filled steel tube (CFST); double-web; beams; energy absorption; composite action; recycled aggregate; finite element method (FEM); stiffness; waste material



Academic Editor: Zhong Hu

Received: 25 August 2025

Revised: 29 September 2025

Accepted: 1 October 2025

Published: 3 October 2025

Citation: Kaishesh, A.J.; Kashesh, G.J.; Hemzah, S.A.; Mohammed, B.H.; Dulaimi, A.; Bernardo, L.F.A. Behavior of Composite Concrete-Filled Double-Web Steel Beams: A Numerical and Experimental Investigation. *J. Compos. Sci.* **2025**, *9*, 541. <https://doi.org/10.3390/jcs9100541>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Composite concrete-filled steel (CFS) structural elements have emerged as a highly innovative and efficient solution in modern civil engineering. The core of their effectiveness lies in the remarkable synergistic composite action between their primary components: the steel section (open or closed) and the concrete infill. This synergistic interaction allows each material to compensate for the other's weaknesses and enhance its strengths, resulting in superior structural performance [1,2]. Specifically, the steel section provides high tensile strength, while the concrete infill primarily enhances compressive capacity and provides continuous support to the steel elements, reducing local buckling in the webs and flanges.

Unlike closed steel tubes, open steel sections offer only partial confinement and torsional resistance, so the improvement in ductility and strength is due more to composite action than to full triaxial confinement [3].

Composite concrete-filled steel tube (CFST) members offer several significant advantages in structural applications due to the synergistic interaction between steel and concrete. Specifically, the steel section in composite Concrete-Filled Steel Tube (CFST) members provides excellent torsional resistance and effective confinement of the concrete [4–7], thereby preventing premature local buckling. In turn, the concrete infill significantly enhances the element's compressive strength and offers continuous internal support to the steel walls, delaying or preventing their inward buckling. The steel's confinement greatly enhances the concrete's ability to deform before failure, while the concrete's support improves the stability of the steel section. This composite action between steel and concrete not only increases load-bearing capacity and durability but also improves ductility and provides a high capacity for energy absorption, which is particularly beneficial for structures subjected to dynamic loads, such as those arising from seismic events [8–13]. This leads to superior seismic performance and overall structural resilience. Consequently, CFST structures have become a preferred choice in a wide array of applications, from high-rise buildings and bridges to columns and beams in complex constructions, reflecting their economic and structural efficacy [10,14,15].

In addition, construction is notably simplified and accelerated, as the steel tube acts as permanent formwork for concrete casting, thereby eliminating the need for temporary formwork and reducing overall time and costs. Moreover, CFST members demonstrate improved fire safety, with the concrete infill acting as an effective insulator to protect the steel from rapid temperature increases, thus maintaining structural integrity for longer durations during fire events.

Despite their numerous advantages, CFST members also present several drawbacks. First, the exposed steel tube is susceptible to corrosion from air and humidity, necessitating continuous painting and maintenance, which can lead to increased long-term costs. Second, while the concrete provides some insulation, the steel component loses significant strength at high temperatures, often requiring additional fire protection measures to ensure its load-carrying capacity is maintained, thereby increasing the initial construction cost. Third, the inclusion of concrete significantly increases the self-weight of the member, and this greater dead load can, in turn, increase the design loads on supporting elements such as foundations, potentially leading to larger and more costly substructures. Finally, a critical disadvantage lies in the uncertainty regarding the long-term bond strength between the infill concrete and the hollow steel section, as inadequate bond can compromise the composite action and negatively affect the overall structural performance [10,16–18].

The integration of recycled concrete aggregate (RCA) into the construction industry represents a significant stride towards sustainability. This practice offers two key environmental benefits: it mitigates the ever-growing challenge of waste disposal by reducing the need for continuous landfill storage, and it conserves finite natural resources by decreasing dependence on virgin natural aggregates (NA). RCA can effectively substitute for NA in concrete mixes, with its production involving the crushing, washing, and grading of concrete elements salvaged from demolished older structures. However, despite its environmental merits, concrete made with RCA generally exhibits inferior mechanical properties when compared with concrete made with NA. This is largely attributed to the “accumulated internal damage” sustained by RCA during the secondary crushing process. Numerous experimental studies have consistently confirmed that RCA typically demonstrates lower strength, reduced elastic modulus, and diminished energy dissipation capabilities [19–21].

2. Literature Review

In this section, relevant theoretical and experimental investigations on steel beams filled with concrete are reviewed.

Ghannam [22] conducted an experimental program on six rectangular CFST beam specimens to assess their flexural behavior. Two distinct cross-sectional sizes were used: 88.9 mm × 88.9 mm with a 3.2 mm wall thickness, and 114.3 mm × 114.3 mm with a 4.8 mm wall thickness. All specimens had a constant length of 1200 mm. The primary objective was to ascertain the feasibility and impact of substituting a portion of the coarse aggregate with granite in the concrete infill. The concrete mixes had compressive strengths of 24.0 MPa for the granite-substituted concrete and 26.0 MPa for the control specimens filled with ordinary concrete. The findings revealed that the partial replacement of coarse aggregate with granite did not significantly affect the flexural performance of the CFST beams compared with those filled with conventional concrete, suggesting that granite can be a viable partial substitute without compromising flexural capacity.

Al-Obaidi et al. [23] experimentally investigated the flexural behavior of eight rectangular CFST beam specimens, grouped by steel tube thickness: 100 mm × 50 mm × 2 mm and 100 mm × 50 mm × 3 mm, both with a length of 900 mm. The aim was to assess the flexural performance of these composite beams when filled with different concrete types—normal concrete, high-strength concrete, and concrete with waste aggregates—while also evaluating the influence of steel tube thickness. The results indicated that CFST composite beams exhibited greater ductility and overall flexural capacity than hollow steel tube beams. Interestingly, the compressive strength of the concrete infill did not significantly influence the flexural bending capacity.

Wang et al. [13] carried out a combined experimental and numerical investigation on the flexural performance of Steel-Reinforced Concrete-Filled Steel Tubular (SRCFST) members. The experimental stage involved testing ten specimens—six square and four rectangular—under four-point bending conditions to analyze failure modes, deformation characteristics, and ultimate load capacity. The study also explored the influence of key variables, namely the shear span-to-depth ratios (a/D) and the depth-to-width ratios (D/B), on the overall bending behavior. The experimental results were validated through finite element analysis, showing strong agreement in predicting ultimate capacity and failure mechanisms. Additionally, the research compared its results with Eurocode 4 (EC4) (2004) provisions, demonstrating that the proposed analytical and numerical approaches can accurately predict the bending capacity of SRCFST members.

While previous research has provided valuable insights into the flexural performance of CFST beams and related composite members, several important gaps remain. Most studies have focused on conventional concrete infills using NA, with limited attention given to the use of RCA in composite steel–concrete systems, particularly in double-web steel beam configurations. Furthermore, the majority of experimental programs have examined fully filled sections, offering little comparative analysis of different partial infill arrangements and their influence on structural behavior. There is also a scarcity of integrated numerical and experimental studies that validate finite element models for such members incorporating RCA. To address these gaps, the present study combines laboratory testing and advanced finite element modeling to evaluate the structural performance of concrete-filled double-web steel composite beams, considering both NA and RCA for the infill concrete, and comparing fully and partially filled configurations. This approach provides new insights into the influence of infill type and placement on load capacity, stiffness, ductility, and energy absorption, thereby extending the existing body of knowledge on sustainable composite beam design.

2.1. Innovation of Concrete Filled Steel Sections

2.1.1. High-Performance Technology

The utilization of high-performance beams can reduce the cross-sectional dimensions required to sustain applied loads. In contrast, mega-structures and long-span systems demand considerably higher flexural strength, where ductility is particularly critical. Under these conditions, Concrete-Filled Steel Sections (CFSS) offer pronounced advantages. The synergy between steel and concrete not only enhances the performance of individual elements but also improves the behavior of the entire structure by increasing stiffness, ductility, and seismic resistance.

In recent years, high-strength materials have become increasingly common in structural design, as engineers continually seek innovative strategies to enhance load-bearing capacity and prevent structural failure. CFSS have proven especially effective in meeting these demands. In addition, they exhibit significantly greater fire resistance than conventional plain steel sections or reinforced concrete, an attribute of particular importance in the design of residential and commercial buildings.

2.1.2. Time- and Cost-Effective Technology

Fabricated CFSS elements, whether produced on-site or prefabricated, substantially reduce the time and effort required for project completion by eliminating the need for temporary formwork and reinforcement, both of which are resource- and labor-intensive. As a result, this approach lowers overall construction costs, minimizes equipment usage, and reduces labor demands. A principal advantage of adopting such systems is their efficiency, which can be further enhanced through prefabrication and prestressing, thereby providing additional improvements in structural performance.

2.1.3. Sustainable Technology

Sustainable design has gained increasing importance in recent years due to the depletion of natural resources and the growing problem of waste accumulation. Integrating CFSS with environmentally friendly materials provides an effective way to address these challenges. For the steel component, scrap from demolished buildings, discarded vehicles, and industrial by-products can be reused, thereby reducing reliance on newly manufactured steel. Similarly, the concrete core can be produced using recycled aggregates or by incorporating waste materials as fiber additives, resulting in recycled concrete with enhanced sustainability. These strategies to reduce environmental impact contribute to the advancement of more sustainable construction practices.

2.1.4. Applicable Technology in Analysis Software

One of the main advantages of CFSS lies in its compatibility with structural analysis software, as these members are composed of two primary materials: concrete and steel. Most modern design programs already include standard CFSS sections in their library making them straightforward to model. However, concrete-filled double-web steel sections are not available in such software, which highlights the innovation of the present study. Although modeling double-web sections is more challenging, this work demonstrates that their behavior can be successfully simulated in ABAQUS with a high level of accuracy, providing reliable predictions of real structural performance for practical applications.

3. Materials and Methods

3.1. Specimens Description

Seven simply supported steel beams were fabricated and evaluated as part of the experimental research. Each beam was tested under identical loading conditions and

boundary constraints, with a uniform span length and cross-section (I-section). The steel beams were constructed using web plates 188 mm deep and 3 mm thick, while the flange plates measured 120 mm wide and 6 mm thick. The span between the two supports of each beam specimen was set at 1200 mm. Of the seven specimens, one beam without concrete infill served as the reference specimen, while the remaining six were divided into two groups. Group one consisted of three double-web I-section steel composite beams filled with conventional concrete, whereas Group two consisted of three double-web I-section steel composite beams filled with recycled concrete. Table 1 illustrates the concrete placement and sample details. Figure 1 depicts the geometry and specifications of the double web beam's cross-section, while Figure 2 presents the setup of all specimens. An LVDT was positioned at mid-span beneath each specimen, and the specimens were gradually loaded to failure.

In Table 1, the meaning of the nomenclature is the following:

- NMF: Normal concrete beam middle-filled (filled between loads)
- NEF: Normal concrete beam edges-filled (hollow between loads)
- NFF: Normal concrete beam fully filled
- RMF: Recycle concrete beam middle-filled (filled between loads)
- REF: Recycle concrete beam edges-filled (hollow between loads)
- RFF: Recycle concrete beam fully filled.

Table 1. Details of the tested specimens and the location of the concrete infill.

Group	Reference Beam	Group One			Group Two		
Sample	Control	NMF	NEF	NFF	RMF	REF	RFF
Concrete location	----	Middle of the beam	Both sides of the beam (partial)	Middle and sides of the beam (full)	Middle of the beam	Both sides of the beam (partial)	Middle and sides of the beam (full)

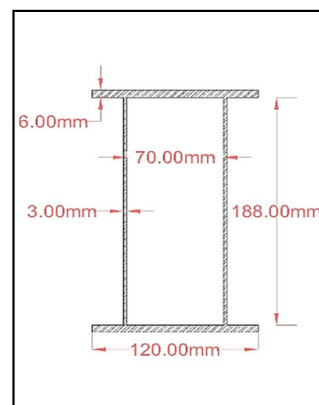


Figure 1. Geometry of the I-double web steel section.

3.2. Material Properties

3.2.1. Cement

Sulfate-resistant cement (R32.5) produced in Iraq by the Lafarge Al-Jisr company was used in all experimental tasks. This type of cement satisfies the Iraqi standards [24]. The physical and chemical properties of the cement are presented in Tables 2 and 3.

Table 3. Physical properties of cement.

Physical Property	Test Result	Limit According to IQS. No. 5/2019
Setting time (Vicat's method):		
Initial setting time (min)	120	≥ 45
Final setting time (hr:min)	3:38	≤ 10
Compressive strength (MPa):		
Two days	13.5	≥ 10
Twenty-eight days	33	≥ 32.5

Note: The physical analysis was carried out at the University of Kerbala's Consulting Office's Central Laboratory.

3.2.2. Fine Aggregate

The natural sand, with a maximum particle size of 4.75 mm, sourced from the Al-Ukhader region, was used in the experiment. The sieve analysis of the fine aggregate and the grading curve, in accordance with Iraqi Standards [25], are displayed in Table 4 and Figure 3. The same specification was used to detail the physical and chemical properties, as shown in Table 5.

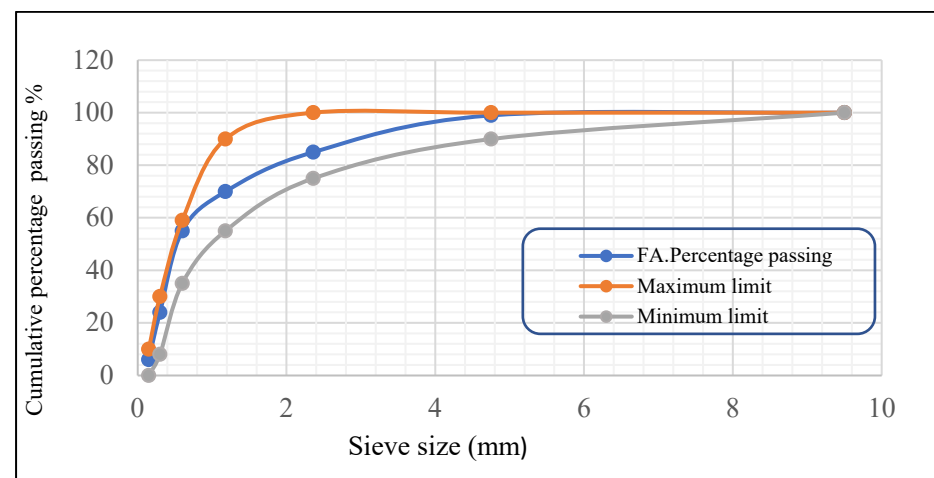
Table 4. Grading of the fine aggregate.

Sieve Size (mm)	% Passing of Fine Aggregate	Limit According to IQS. No. 45/1984 (zone 2)	
		Max. Limit	Min. Limit
9.5	100	100	100
4.75	99	100	90
2.36	83	100	75
1.18	70	90	55
0.6	58	59	35
0.3	26	30	8
0.15	5	10	0

Table 5. Physical and chemical properties of the fine aggregate.

Characteristics	Test Result	Limit According to IQS. No. 45/1984
Sulfate content (SO_3), %	0.1	0.5% (max.)
Material finer than 75 μm	2.1	5% (max.)

Note: The physical and chemical analysis was carried out at Engineering Consulting Bureau / University of Kerbala.

**Figure 3.** Grading curve for fine aggregate according to ASTM C33 (2003).

3.2.3. Coarse Aggregate

Pre-graded gravel from the Al-Ukhidir region was used in the experiments, with a maximum particle size of 10 mm. The gravel was washed to remove any dust and then dried in the air to achieve a surface-dry condition for each batch. Table 6 and Figure 4 present the gravel sieve analysis and grading curve according to ASTM standards [26]. The physical and chemical characteristics of the coarse aggregate are provided and compared to the Iraqi standards [25] in Table 7.

Table 6. Grading of the coarse aggregate.

Sieve Size (mm)	% Passing of Coarse Aggregate	Limit According to ASTM C33/2003	Limit According to IQS. No. 45/1984
12.5	100	100	100
9.5	100	100–85	100–85
4.75	14	30–10	30–10
2.36	3	10–0	10–0
1.8	0	5–0	5–0

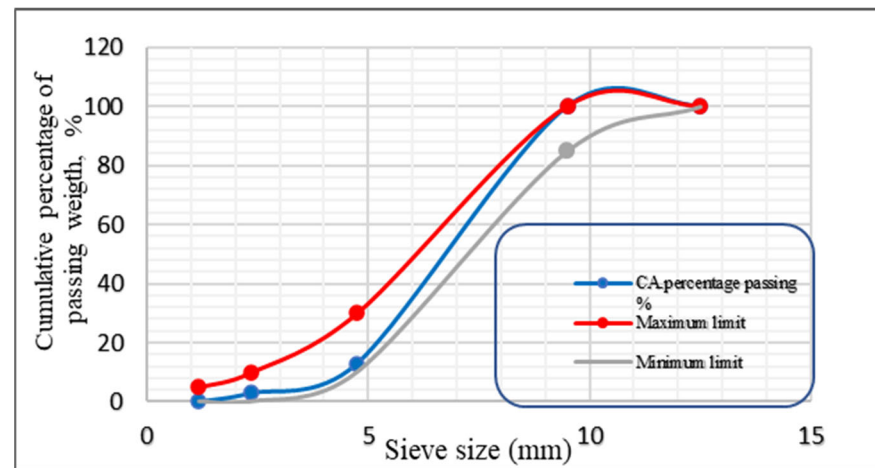


Figure 4. Grading curve for coarse aggregate according to ASTM C33 (2003).

Table 7. Physical and chemical properties of the coarse aggregate.

Characteristics	Test Result	Limit According to IQS. No. 45/1984
Sulfate content (SO_3), %	0.062	0.1% (max.)
Material finer than $75 \mu\text{m}$	0.3	3% (max.)

Note: The physical and chemical analysis was carried out at the University of Kerbala's Consulting Office Central Laboratory.

3.2.4. Recycle Coarse Aggregate

In the experimental work, recycled gravel was used, obtained from waste concrete cubes. Cubes that broke after 28 days were selected to ensure the completion of cement hydration, and then crushed by a steel hammer with different gradations (Figure 5). A grading process was carried out so that the recycled gravel closely matched the gradation of natural aggregates. The recycled gravel was washed to remove dust and then air-dried to achieve a saturated surface-dry condition. According to ASTM C33/2003, the gravel sieve analysis and grading curve are shown in Table 8 and Figure 6, respectively.



Figure 5. Assembly and crushing of waste concrete cubes.

Table 8. Grading of the recycled coarse aggregate.

Sieve Size (mm)	% Passing of Recycled Coarse Aggregate	Limit According to ASTM C33/2003	
		Max. Limit	Min. Limit
12.5	100	100	100
9.5	100	100	85
4.75	13	30	10
2.36	2	10	0
1.8	0	5	0

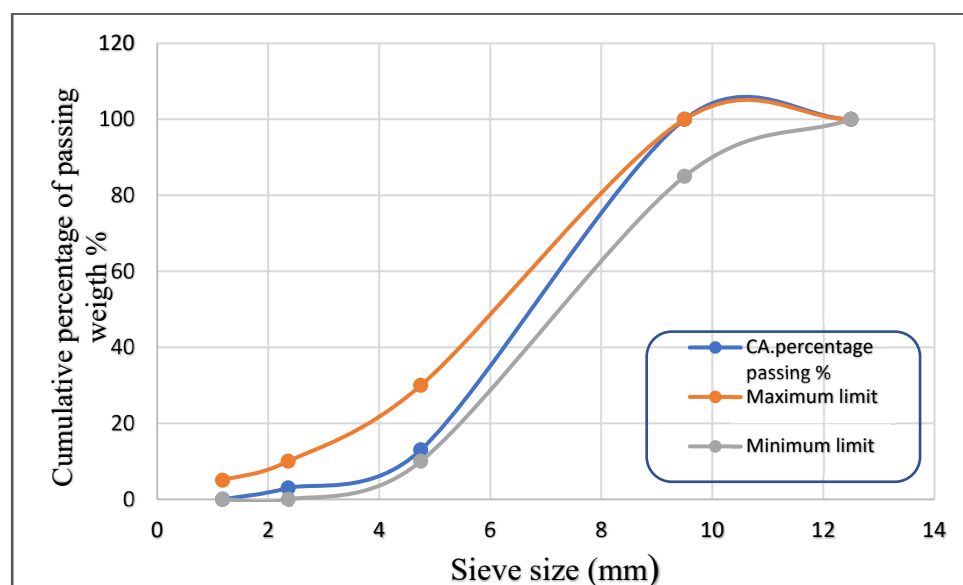


Figure 6. Grading curve for recycled coarse aggregate according to ASTM C33 (2003).

3.2.5. Water

Clean water, meeting the conditions and requirements of the Iraqi specifications [27], was used in the experimental program.

3.2.6. Concrete Mixes and Compressive Strength

Normal Concrete

A variety of trial concrete mixtures were formulated to identify a composition that met the criteria adopted for this study. The reference concrete mix was designed to achieve

a compressive strength of approximately 38 MPa at 28 days. The mixing ratios were determined using ACI 211.1-91 [28] method for concrete mix design, based on the material properties and the required strength. The final mixing ratios are presented in Table 9.

Table 9. Mix design for normal concrete (Kg/m³).

Cement	Fine Aggregate	Coarse Aggregate	Water
400	720	1073	160

Recycled Aggregate Concrete

The mixture for this concrete consists of the same components as the mixture for normal concrete, except that the natural coarse aggregate was replaced with recycled coarse aggregate obtained from concrete cubes (waste material) aged more than 28 days to ensure the completion of cement hydration reactions. Table 10 presents the mixing ratios.

Table 10. Mix design for recycled aggregate concrete (Kg/m³).

Cement	Fine Aggregate	Recycled Aggregate	Water
400	720	1073	160

Compressive Strength

The compressive strength of cylindrical concrete specimens was determined in accordance with ASTM C39-05. Three cylinders (100 × 200 mm) from each normal concrete and recycled aggregate concrete mix (see Table 11) were tested at 28 days using a digital compression testing machine with a capacity of 2000 kN, as shown in Figure 7.

Table 11. Compressive strength of concretes (MPa).

No. of Cylinder	Normal Concrete	Recycled Aggregate Concrete
C1	37.2	30.7
C2	38.5	28.1
C3	38.5	31.4
Average	38	30



Figure 7. Compression strength testing.

3.2.7. Steel Plates

All samples were tested at the National Center for Laboratories and Structural Research in Baghdad Governorate, Iraq, to determine the properties of the steel plates used in the manufacture of the double-web beams. Four tensile coupons were cut from the flange

plates (6 mm thick) and web plates (3 mm thick), respectively. The coupon dimensions complied with the requirements of ASTM standards [29] for the tensile testing of steel products, with a length of 450 mm. Figure 8 illustrates the dimensions of the tensile test specimens, while Figure 9 shows a typical tensile test coupon under load. Table 12 presents the yield stress, ultimate tensile stress, and modulus of elasticity obtained from the tests.

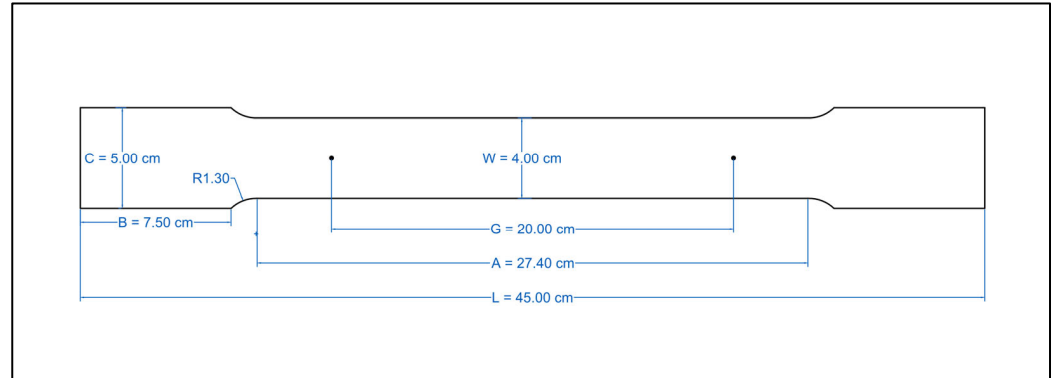


Figure 8. Dimensions of tensile test coupon according to ASTM A370.

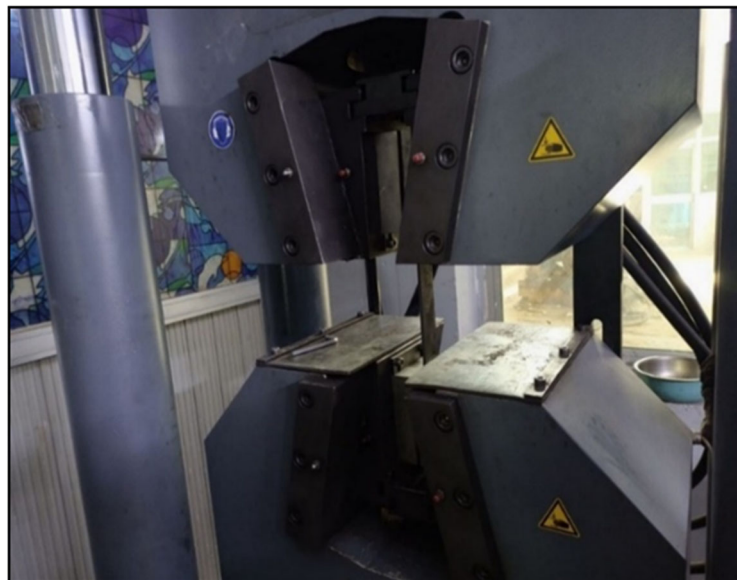


Figure 9. Typical tensile test setup for a steel coupon.

Table 12. Mechanical properties of the steel coupons.

No. of Coupon	Part	Yield Stress (N/mm ²)	Ultimate Stress (N/mm ²)	Modulus of Elasticity (GPa)
1	Flange (6 mm)	267	392	190
2		287	408	190
3		289	404	190
4		273	404	190
Mean		279.0	402.0	190
5	Web (3 mm)	-	352	190
6		286	350	190
7		287	358	190
8		308	358	190
Mean		293.7	354.5	190

3.2.8. Procedure of Beam Assembling

The beam sections were fabricated by welding steel plates together while leaving the top flange open to allow casting of the concrete mix in the designated regions. Cylindrical

concrete specimens were prepared at the same time and cured for 28 days. Prior to casting, all steel components were coated with two layers of anti-oxide paint. After curing, the top flange was kept open to allow proper curing of the concrete, after which it was welded in place. Subsequently, the entire beam was coated with two layers of white paint, and a mesh pattern was marked on the surface to facilitate the observation of failure modes and crack propagation. Finally, the beam specimens were tested to failure, and the corresponding results were recorded.

3.3. Experimental Testing Procedures and Numerical Analysis Model

3.3.1. Experimental Testing Procedure

The test specimens were manufactured in the Civil Engineering Department of the Engineering College at Kerbala University. After coating and preparing the specimens with a mesh pattern, the specimens were examined to confirm the dimensions. Tests were then carried out using a hydraulic universal testing machine with a maximum capacity of approximately 2000 kN. The testing procedure includes a hydraulic actuator, load cells, extension supports, and a computer interface for data acquisition. The specimens were loaded at two points and monitored at each loading stage during testing, as shown in Figure 10. A steel plate was placed to prevent local failure in the flange and to ensure proper load transfer. The support system consisted of a simply supported beam (roller and pin). All specimens were tested up to failure.

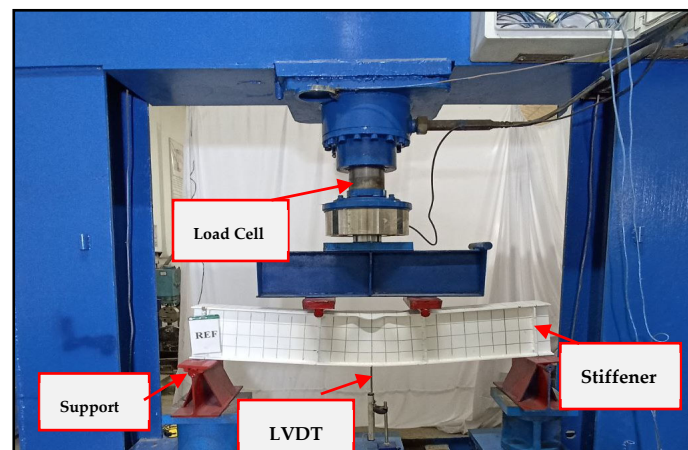


Figure 10. Hydraulic testing machine and details of the test setup.

The instruments included one Linear Variable Displacement Transducer (LVDT) positioned below the beam's midspan, with a 100 mm vertical measuring capacity. The LVDT was calibrated to ensure accuracy and reliability. A hydraulic jack was manually operated with the aid of a hydraulic pump. A load cell was installed between the hydraulic jack and a highly rigid steel beam sitting on load plates at the top of the compression flange to control the load. The load and displacement values were then stored using computer software, as shown in Figure 11.

3.3.2. Numerical Analysis Model

A numerical study was conducted using ABAQUS software. All the double-web steel beams in this study were modeled with three main components (top and bottom flanges and the middle web) along with steel rods. Each component of the steel beam was modeled separately and then assembled to obtain a complete double-web steel beam. Figure 12 illustrates the assembly process used for modeling the specimens. Material properties, boundary conditions, and loading configurations were carefully defined to

replicate the experimental setup as closely as possible. The numerical outcomes—including ultimate load capacity, load–displacement responses, and failure modes—showed very good agreement with the experimental results. This strong correlation validates the finite element model and demonstrates its robustness, thereby reinforcing the credibility and reproducibility of the study.

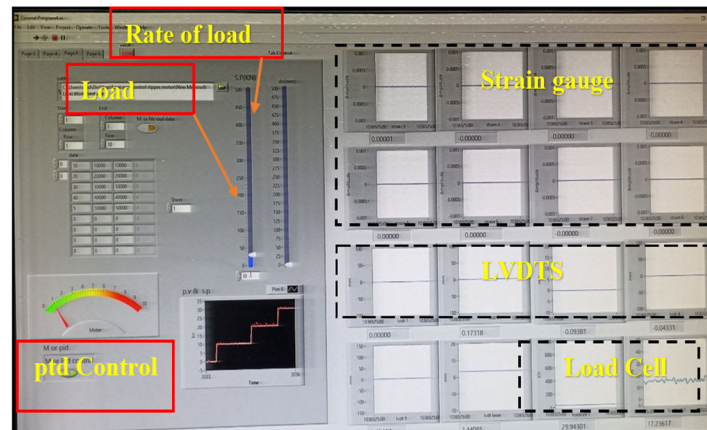


Figure 11. Interface of the controlling software.

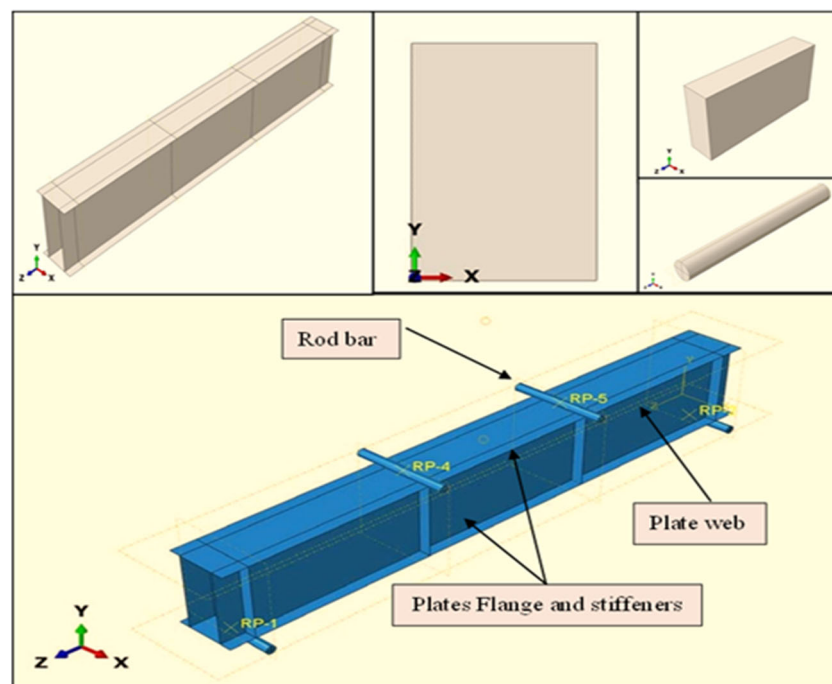


Figure 12. Assembly of the components of the composite beam.

For a composite system to behave effectively, the components must be properly connected once assembled and their properties determined. Using ABAQUS contact algorithm options, the interaction between the steel section and the concrete infill was modeled. The specification of the master and slave surfaces is necessary for ABAQUS to apply the contact algorithm. When selecting these surfaces, it is essential to follow the guidelines stating that the softer material and the finer mesh should be designated as the slave surface. In this model, the concrete infill was assigned as the slave surface, while the steel surface was defined as the master surface. The behavior of the surfaces under normal and tangential stress was governed by the contact interaction. The isotropic penalty formulation was adopted in the tangential direction, and the default ABAQUS option of

“hard contact” was used in the normal direction. For the penalty model, a coefficient of friction of 0.6 was assumed [30,31]. In the numerical study, two-point loads were applied to the double-web beams, both with and without concrete. As illustrated in Figure 13, two steel rods were positioned on the upper flange, each located at one-third of the span length from the supports, to transfer the loads to the tested beam.

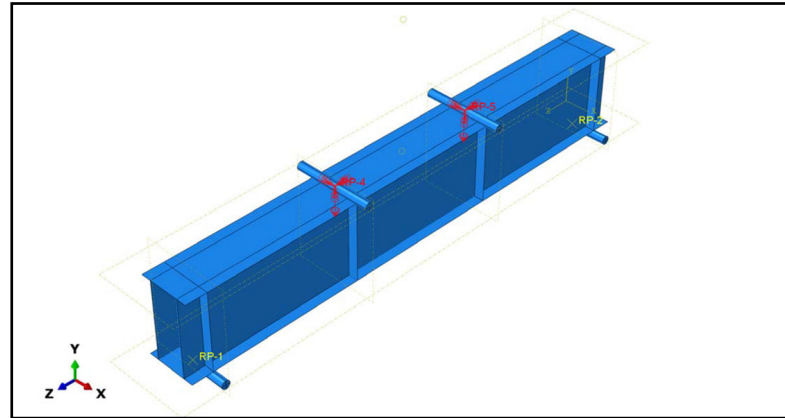


Figure 13. Applied load on the I-double web beam.

4. Discussion of Experimental and Numerical Results

This section presents a detailed discussion of the structural behavior of double-web steel beams, comparing hollow specimens with those filled with normal concrete and recycled aggregate concrete. The analysis integrates both experimental observations and numerical simulations, with emphasis on load-bearing capacity, stiffness, ductility, and failure modes. Particular attention is given to the influence of concrete type and placement on the overall performance of the beams, as well as the level of agreement between experimental outcomes and finite element predictions.

The ductility index, which represents the ability of a specimen to resist inelastic deformation without a re-reduction in ultimate load until failure, is calculated as $DI = \Delta u / \Delta y$, where Δy is the deflection at yielding load and Δu is the deflection at ultimate load. In addition, the stiffness (K) of a specimen is a measure of the resistance offered by an elastic body to deformation. It is calculated as $K = P_s / \Delta s$, where P_s is the service load and Δs is the deflection at the service load.

4.1. Control Beam CB

After setting up and loading the specimen, ultimate failure occurred at a maximum load of 320.5 kN, primarily due to web shear buckling. The vertical load–deflection response indicated a ductility index of 2.10 and a stiffness of 56 kN/mm. Figure 14 presents the load–midspan displacement curves (both numerical and experimental curves) for the control beam (CB), while Figure 15 illustrates the corresponding failure modes observed during laboratory testing and predicted numerically. The finite element analysis conducted in ABAQUS showed strong agreement with the experimental results, with differences in ultimate load and displacement limited to 2.09% and 3.98%, respectively. This confirms the reliability of the numerical model in capturing both the global response and the failure mechanisms of the control beam.

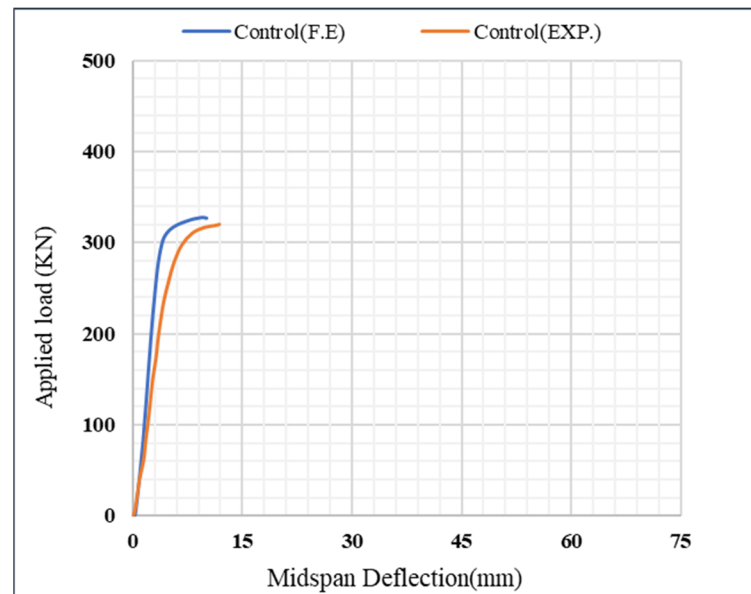


Figure 14. Experimental and numerical load-deflection curves for beam CB.

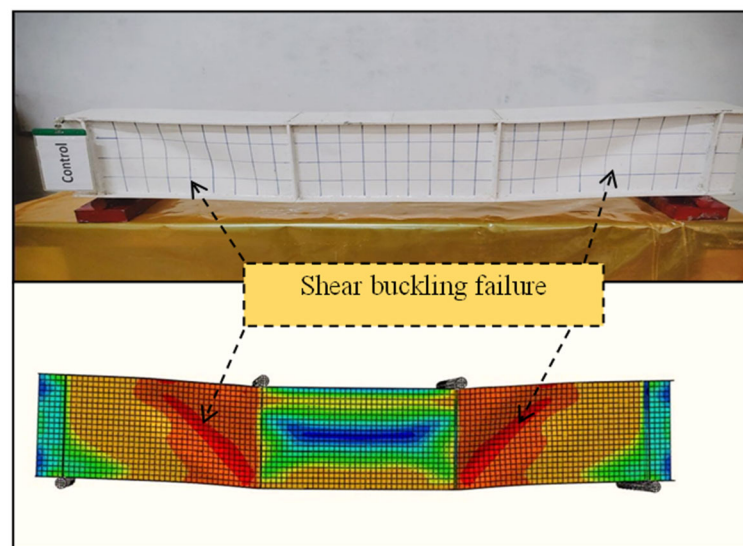


Figure 15. Experimental and numerical failure mode for beam CB.

4.2. Beams Filled with Normal Concrete

4.2.1. Beam NMF (Group One)

Following specimen setup and loading, ultimate failure occurred at a maximum load of 353.2 kN due to web shear buckling. Based on the vertical load–deflection curve, the stiffness and ductility index were determined to be 57.5 kN/mm and 2.05, respectively. The control beam's load–midspan displacement curves (both theoretical and experimental) are shown in Figure 16, while Figure 17 illustrates the corresponding failure modes observed during laboratory testing and predicted numerically for beam NMF. The finite element analysis performed in ABAQUS demonstrated strong agreement with the experimental results, with differences in ultimate load and displacement limited to 1.4% and 4.6%, respectively. Furthermore, the addition of the concrete infill enhanced both the flexural strength and stiffness of the specimen by providing resistance to local buckling in the central region.

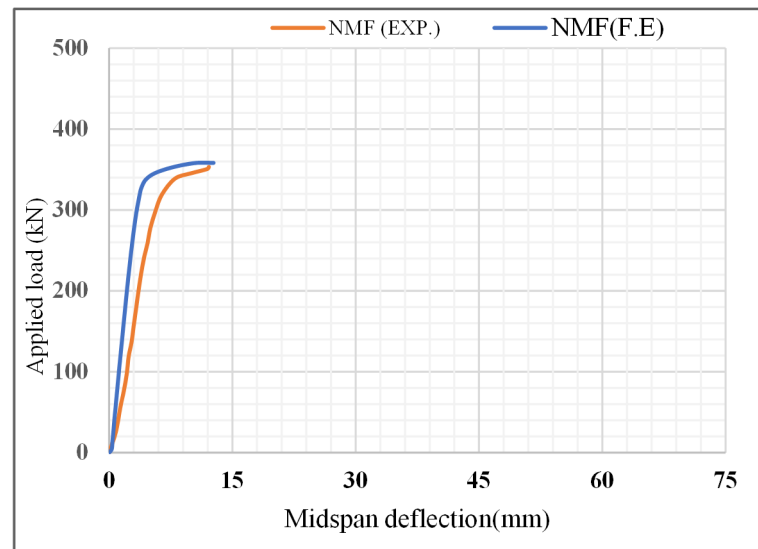


Figure 16. Experimental and numerical load-deflection curves for beam NMF (Group one).

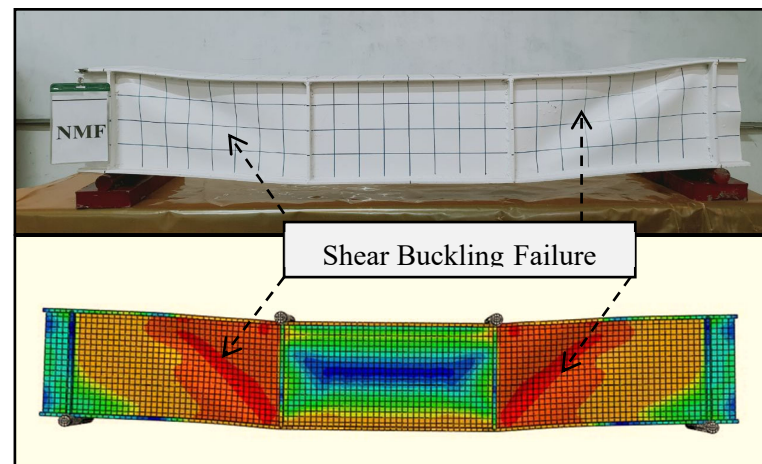


Figure 17. Experimental and numerical failure mode for beam NMF (Group one).

4.2.2. Beam NEF (Group One)

After specimen setup and loading, ultimate failure occurred at a maximum load of 399.7 kN due to web shear buckling. From the vertical load–deflection curve, the ductility index and stiffness were calculated as 5.24 and 60.8 kN/mm, respectively. Figure 18 shows the load–midspan displacement curves (experimental and numerical), while Figure 19 illustrates the failure modes obtained experimentally and numerically for beam NMF. The finite element analysis performed in ABAQUS demonstrated strong agreement with the experimental results, with differences of only 1.4% in ultimate load and 4.6% in displacement. Moreover, the inclusion of concrete infill provided resistance to local buckling in the middle region, thereby enhancing both the flexural strength and stiffness of the specimen.

4.2.3. Beam NFF (Group One)

The failure mode of the specimen was flexural, attributed to the presence of concrete in the middle and sides of the double-web beam, as illustrated in Figure 20. The inclusion of normal concrete infill significantly enhanced the beam's flexural behavior. Finite element analysis further confirmed these findings, showing that the ultimate load capacity was 2.09% higher than the experimental results, while the maximum deflection was 5.62% lower than the experimental value, as shown in Figure 21. The numerical results exhibited

minor dents in the load–displacement curve that were not observed experimentally. This discrepancy may be attributed to the release of stored strain energy, which can occur due to instability in concrete damage plasticity (CDP) model, instability caused by interaction between concrete and steel in the simulation, or localized contributions of concrete strength at specific strain point levels.

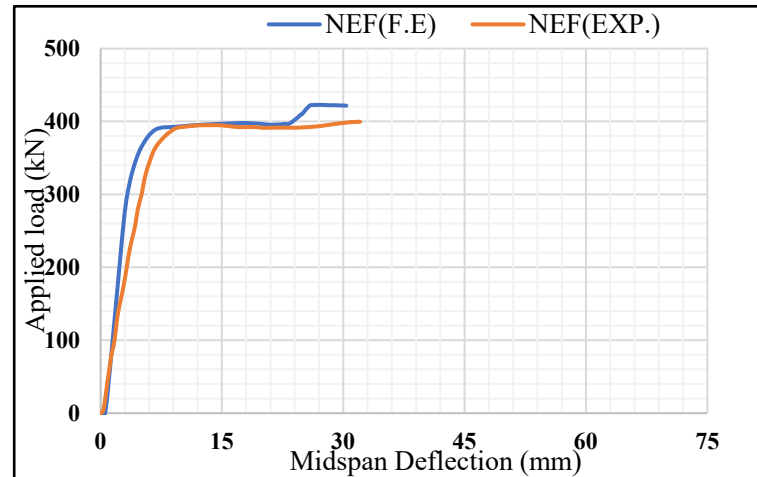


Figure 18. Experimental and numerical load-deflection curves for beam NEF (Group 1).

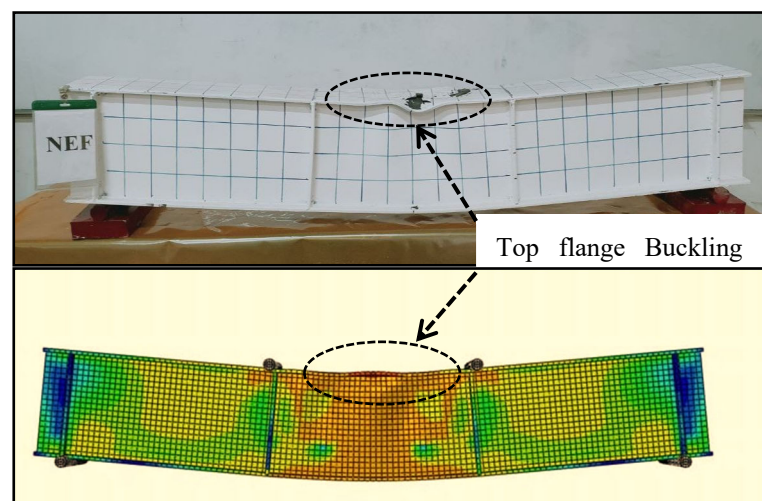


Figure 19. Experimental and numerical failure mode for beam NEF (Group one).

4.2.4. Comparative Analysis of Beams in Group One

This section presents a comparative analysis between the three double-web specimens filled with normal concrete in different regions: the middle web area, the edges, and the entire section. The placement of normal concrete in the web area has a significant effect on the structural performance of the composite double-web specimens, leading to noticeable increases in ultimate load. Beams NMF, NEF, and NFF exhibited increases in the load of 10.19%, 24.60%, and 55.30%, as shown in Figure 22, respectively, when compared with the control beam CB. The normal concrete infill enhanced the ultimate shear capacity by stiffening the web and delaying shear buckling.

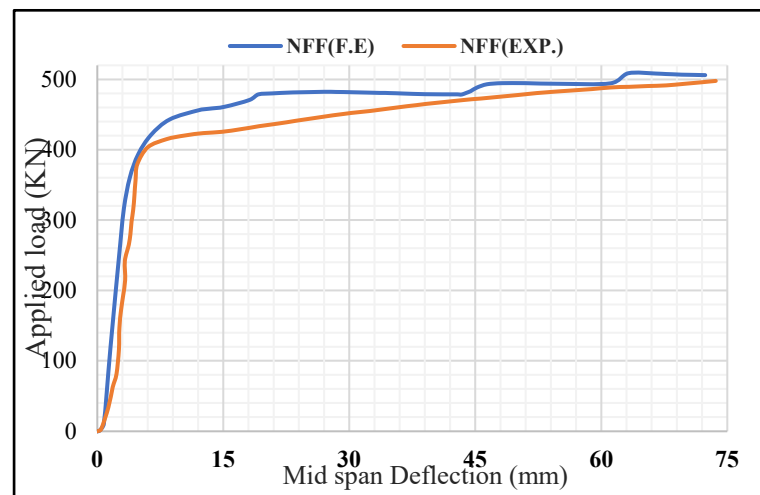


Figure 20. Experimental and numerical load-deflection curves for beam NFF (Group 1).

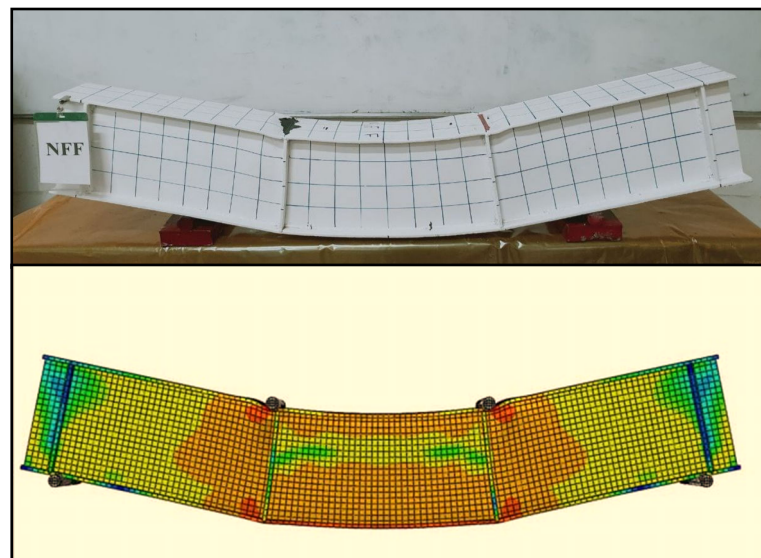


Figure 21. Experimental and numerical failure mode for beam NFF (Group one).

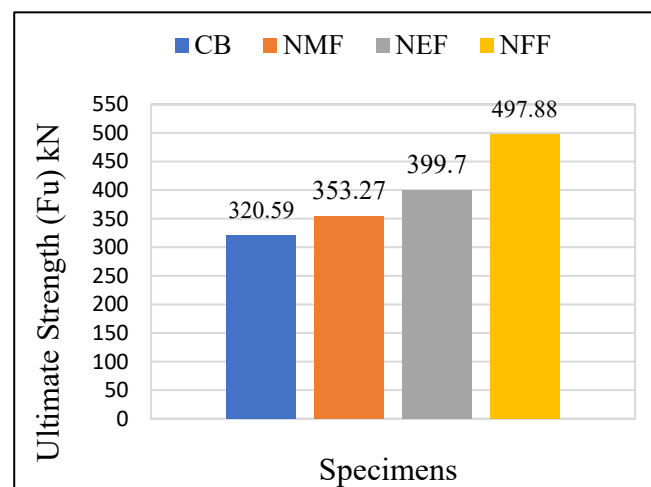


Figure 22. Comparison of load capacity among the tested beams (Group one).

The observed failure modes varied with the infill location: the middle-filled specimen failed due to web shear buckling, the edge-filled specimen exhibited top flange buckling,

and the fully filled specimen failed in flexure. In terms of ductility, the specimens with edge and full filling demonstrated significant improvements, with ductility indices increasing by 149% and 568%, respectively, compared to the control beam (Figure 23). Similarly, stiffness increased by 2.67% to 39.6% (Figure 24). These results confirm that normal concrete infill effectively prevents local buckling of the double-web steel section while contributing to the section's moment of inertia and internal force distribution, thereby enhancing both flexural strength and stiffness.

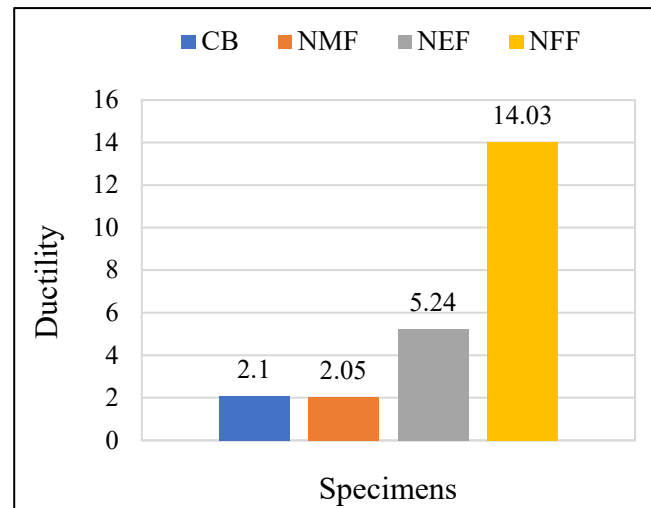


Figure 23. Comparison of ductility factor among the tested beams (Group one).

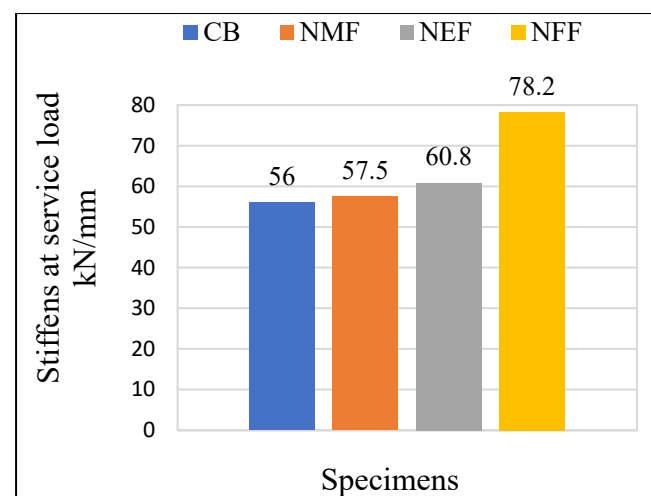


Figure 24. Comparison of stiffness among the tested beams (Group one).

4.2.5. Comparison with Other Research Results

The results of this study were compared with findings from previous research. In general, the ductility index was significantly higher than that of hollow steel or plain concrete beams. Concrete infill was also found to increase the initial stiffness, while providing much higher energy absorption due to enhanced ductility.

For example, Han (2014) [32] reported that concrete-filled tubular beams exhibited an ultimate flexural capacity approximately twice that of hollow steel beams, essentially equal to the combined capacities of the steel and concrete. Al Mustawfi (2024) [33] showed that composite girder with concrete infill achieved a 116% improvement in ultimate flexural capacity compared to double-web steel alone, and that prestressing could further raise this capacity to about 126% of the original. Similarly, Abdulridha (2025) [34] reviewed several

studies and concluded that concrete filling can enhance the flexural capacity of hollow steel tubes by up to 150% through improved confinement and delayed local buckling. Huang (2024) [35] investigated damaged reinforced concrete T-beams repaired with ultra-high performance concrete (UHPC) infill, reporting improvements in flexural capacity ranging from 6% to 34%, depending on beam length.

In comparison, the present study found an increase in ultimate flexural capacity of approximately 110% to 155%. This difference can be partly attributed to the inherently higher moment capacity of the I-section configuration compared with tubular sections.

4.3. Beams Filled with Recycled Concrete

4.3.1. Beam RMF (Group Two)

Figure 25 presents the load-deflection curve for the double-web beam RMF, obtained from both finite element analysis and experimental testing. For this beam, which contained recycled aggregate concrete in its middle zone, the numerical ultimate load capacity increased by approximately 1%, while the maximum numerical deflection decreased by about 5.65% compared with the experimental results. The observed failure mode was shear buckling in the web, as illustrated in Figure 26.

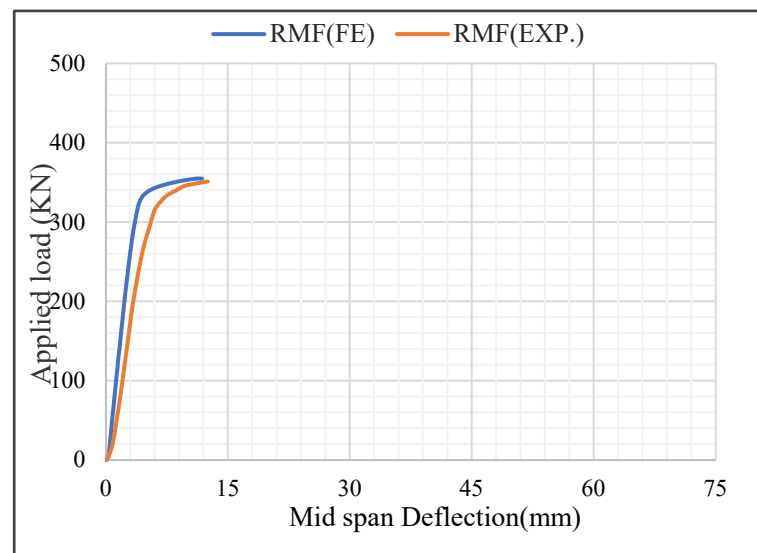


Figure 25. Experimental and numerical load-deflection curves for beam RMF (Group two).

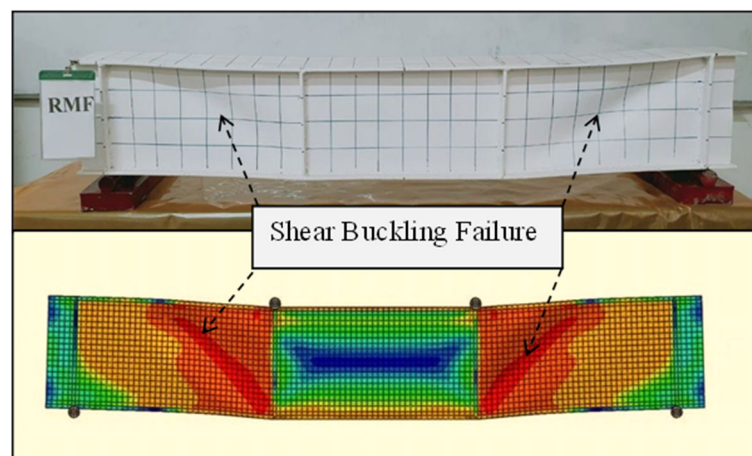


Figure 26. Experimental and numerical failure mode for beam RMF (Group two).

4.3.2. Beam REF (Group Two)

Figure 27 shows the load–deflection response of double-web beam REF, filled on both sides with recycled aggregate concrete, obtained from finite element analysis and experimental investigation. The ultimate load capacity predicted by the finite element model showed good agreement with the experimental results, recording an increase of about 3.78%. However, the maximum deflection increased by approximately 7.66% compared to the experimental value. The observed failure mechanism was a combination of top flange buckling and shear buckling, as illustrated in Figure 28. The absence of concrete in the intermediate zone made the beam more susceptible to local buckling in this region.

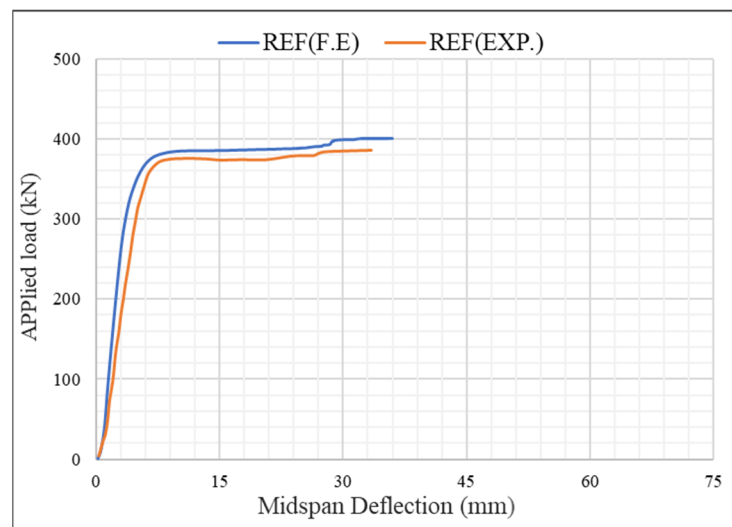


Figure 27. Experimental and numerical load-deflection curves for beam REF (Group two).

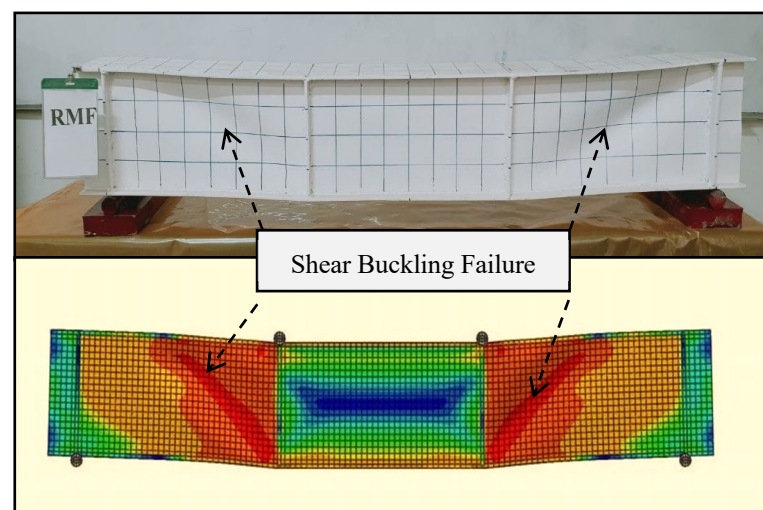


Figure 28. Experimental and numerical failure mode for beam REF (Group two).

4.3.3. Beam RFF (Group Two)

The results for double-web steel beam RFF, filled with recycled aggregate concrete, demonstrated good convergence between the numerical and experimental findings in terms of load, displacement, and failure modes. The percentage differences between the experimental and numerical values of ultimate load and maximum displacement were approximately 5.27% and 7.90%, respectively. The load–deflection response of the RFF specimen is presented in Figure 29, while the corresponding failure mode is illustrated

in Figure 30. The observed failure was primarily flexural, attributed to the presence of recycled concrete in both the middle and side regions of the double-web beam.

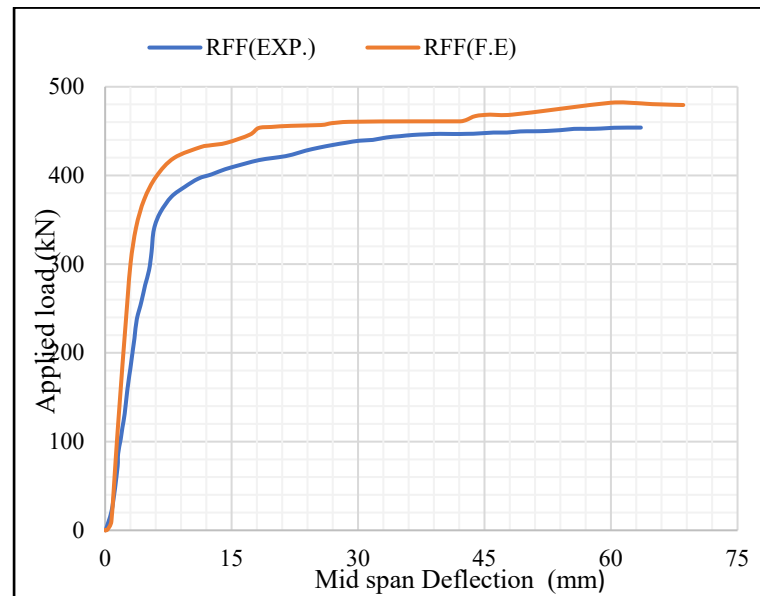


Figure 29. Experimental and numerical load-deflection curves for beam RFF (Group two).

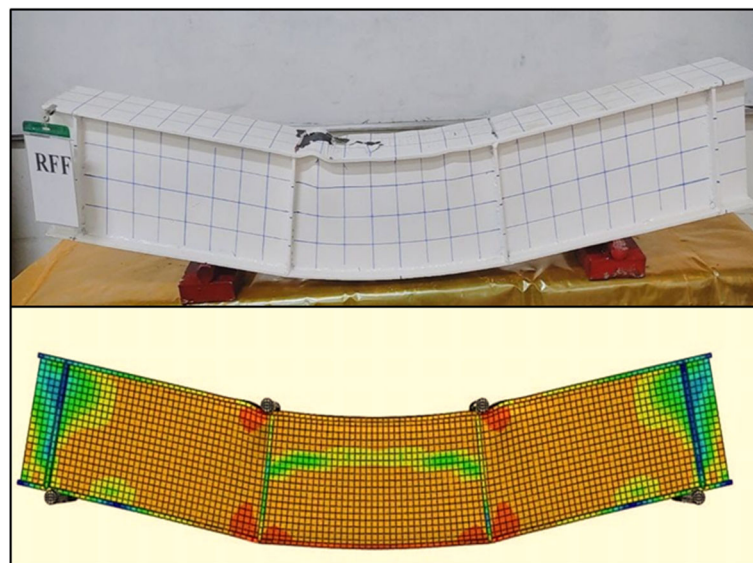


Figure 30. Experimental and numerical failure mode for beam RFF (Group two).

4.3.4. Comparative Analysis of Beams in Group Two

This section presents a comparative analysis of three double-web specimens filled with recycled aggregate concrete, placed either in the center, on the sides, or throughout the entire section. The placement of recycled aggregate concrete within the web region had a marked influence on structural performance, leading to increases in ultimate load capacity. Relative to the control specimen, the ultimate load increased by 9.52%, 20.60%, and 42.03% for RMF, REF, and RFF beams, respectively (Figure 31). From the previous sections, the middle-filled specimen failed by shear buckling in the web, the side-filled specimen by top flange buckling, and the fully filled specimen by flexure. The recycled concrete infill enhanced the shear capacity by strengthening the web and delaying shear buckling.

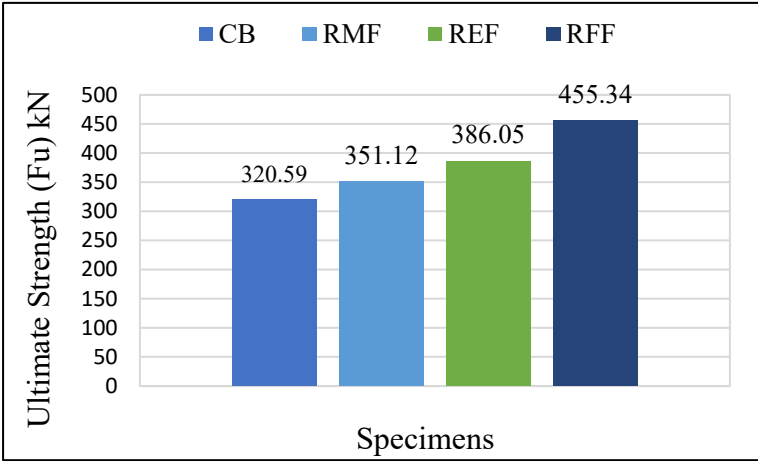


Figure 31. Comparison of load capacity among the tested beams (Group two).

The ductility indices of the side-filled and fully filled specimens increased by up to 154% and 380%, respectively, compared with the control beam, as shown in Figure 32. Furthermore, the stiffness of the composite double-web beams improved by between 2.67% to 39.6%, as presented in Figure 33.

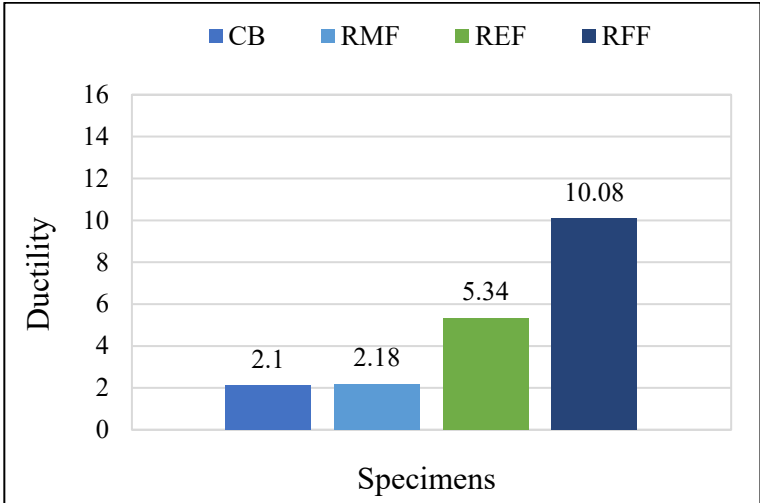


Figure 32. Comparison of ductility factor among the tested beams (Group two).

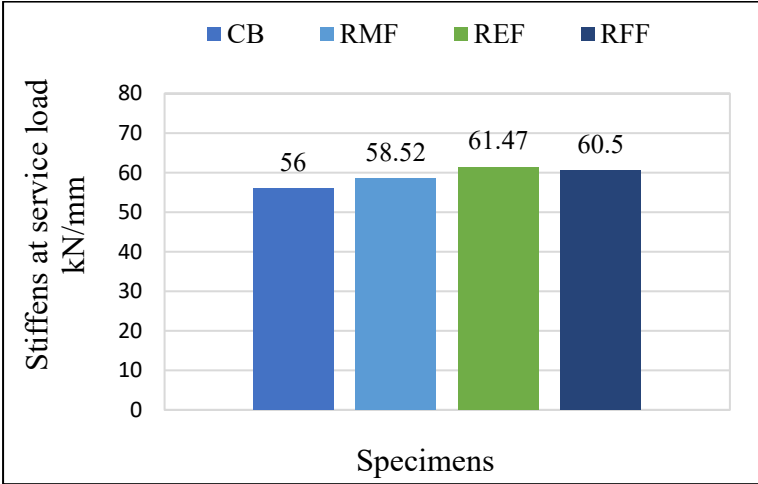


Figure 33. Comparison of stiffness among the tested beams (Group two).

These results indicate that recycled aggregate concrete infill effectively prevents local buckling of the steel shell and contributes to greater section inertia and internal force resistance, thereby enhancing both flexural strength and stiffness of the members.

4.4. Stress Distribution

This section presents the stress distribution at the ultimate loading stage, obtained from finite element analysis using ABAQUS for the specimens tested in the experimental program. Figures 34–40 illustrate the stress patterns for the I-double web steel models. It was observed that buckling occurred primarily in regions not filled with normal or recycled concrete, since the presence of concrete effectively prevented local buckling of the steel and enhanced the section's inertia and internal force resistance, thereby increasing both flexural strength and stiffness. The maximum steel stresses were consistently located in the areas where buckling developed.

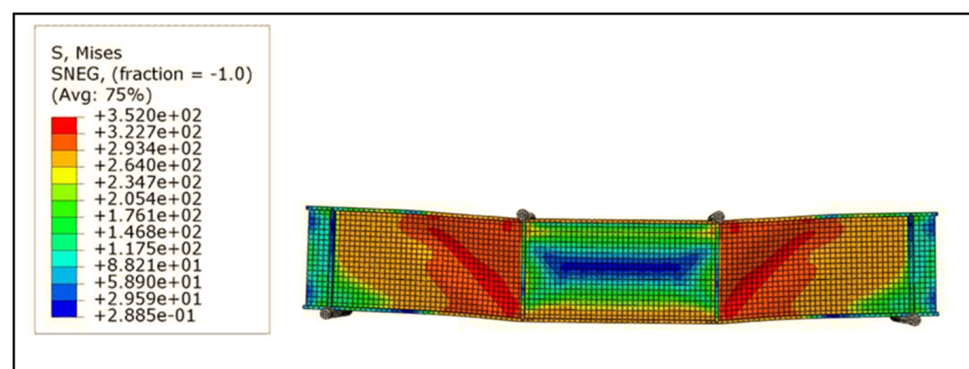


Figure 34. Stress Distribution for beam CB (control beam).

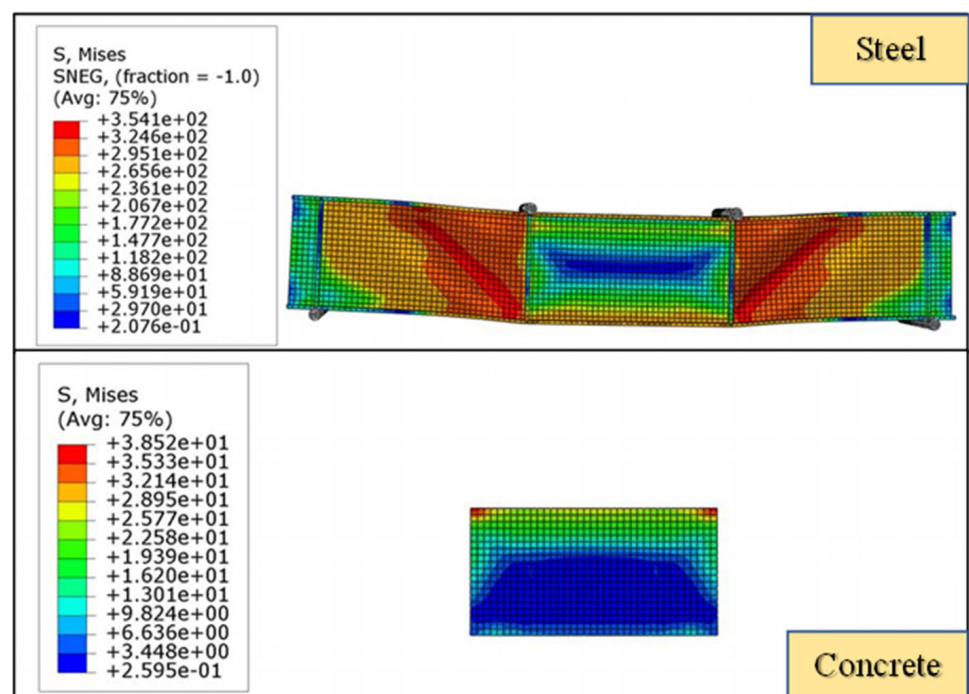


Figure 35. Stress Distribution for beam NMF (Group one).

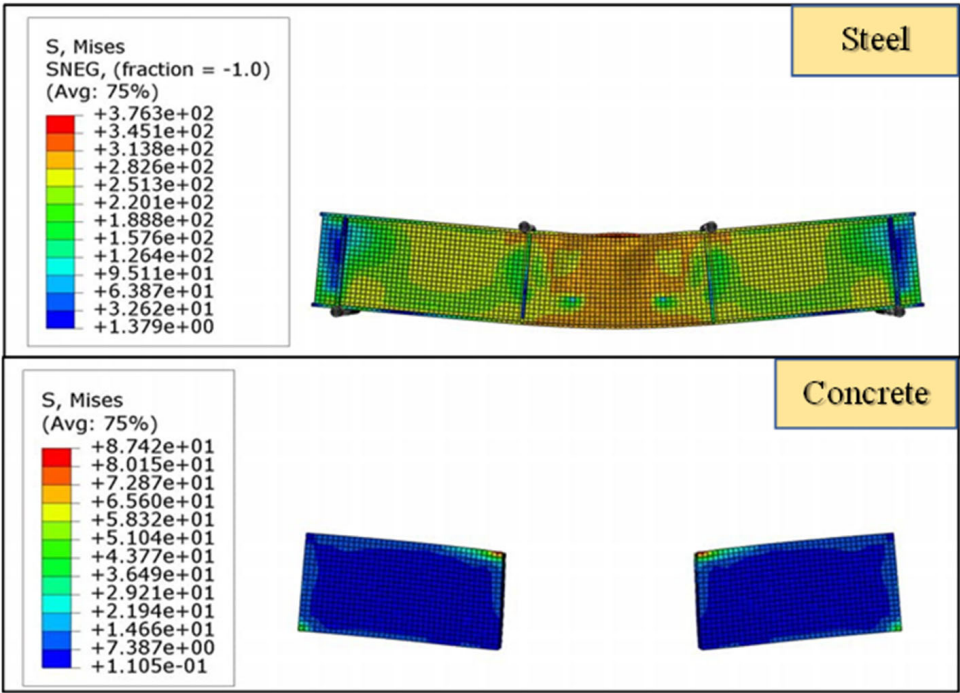


Figure 36. Stress Distribution for beam NEF (Group one).

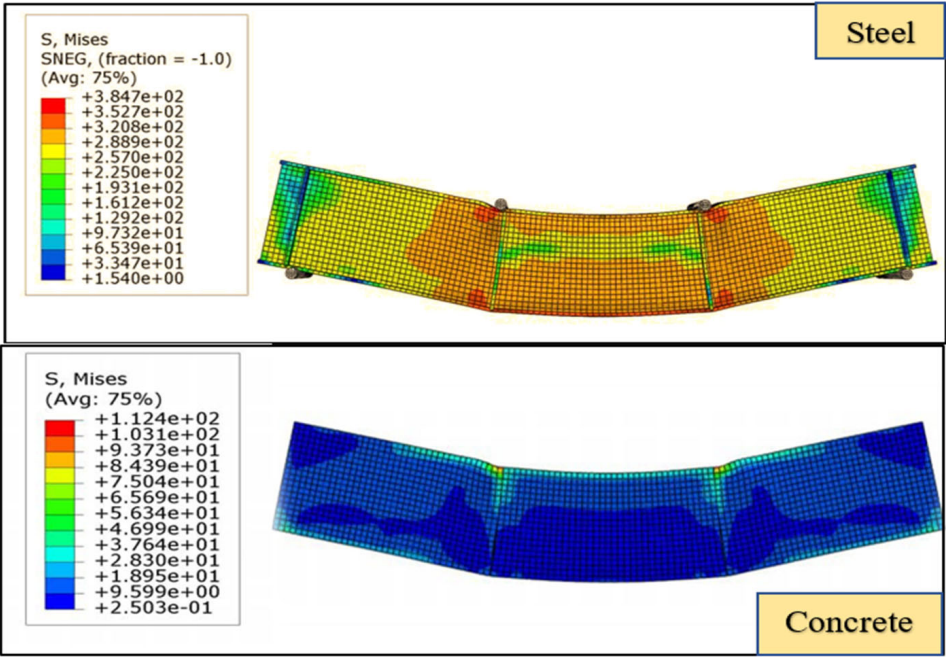


Figure 37. Stress Distribution for beam NFF (Group one).

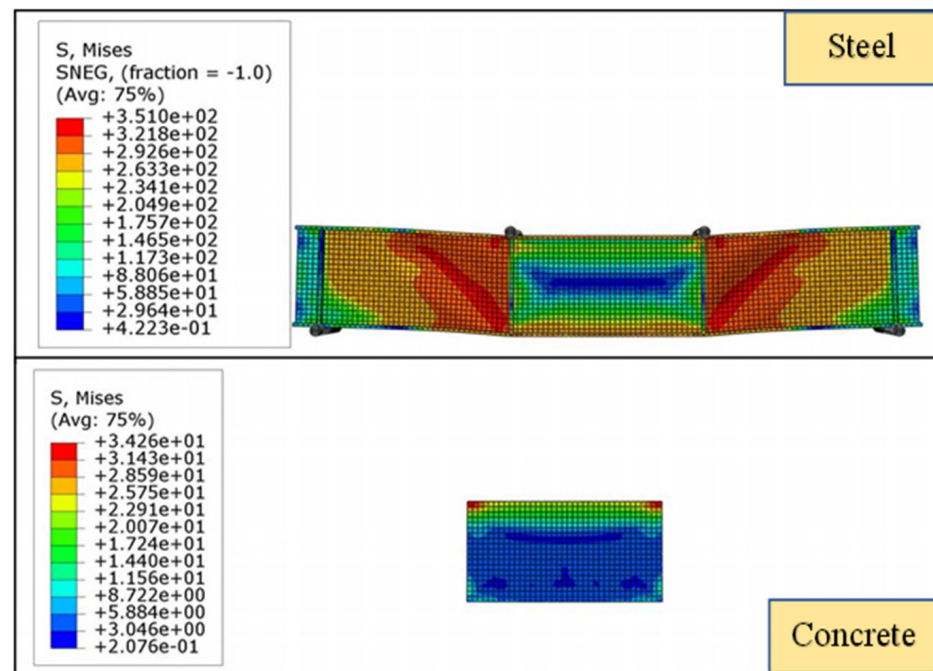


Figure 38. Stress Distribution for beam RMF (Group two).

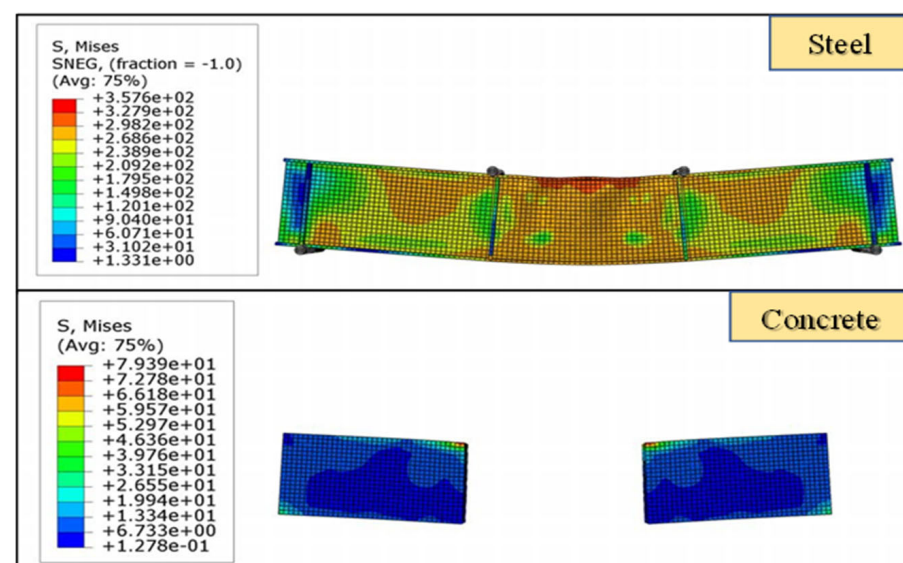


Figure 39. Stress Distribution for beam REF (Group two).

For specimens filled in the middle zone, stresses were concentrated in the web region adjacent to the unfilled sides; for side-filled specimens, stresses were concentrated in the central web region; and for fully filled specimens, stresses were concentrated beneath the applied point loads. Additionally, the maximum concrete stresses were observed beneath the loading points, particularly at the edges of the concrete block, due to the confinement effect provided by the surrounding steel.

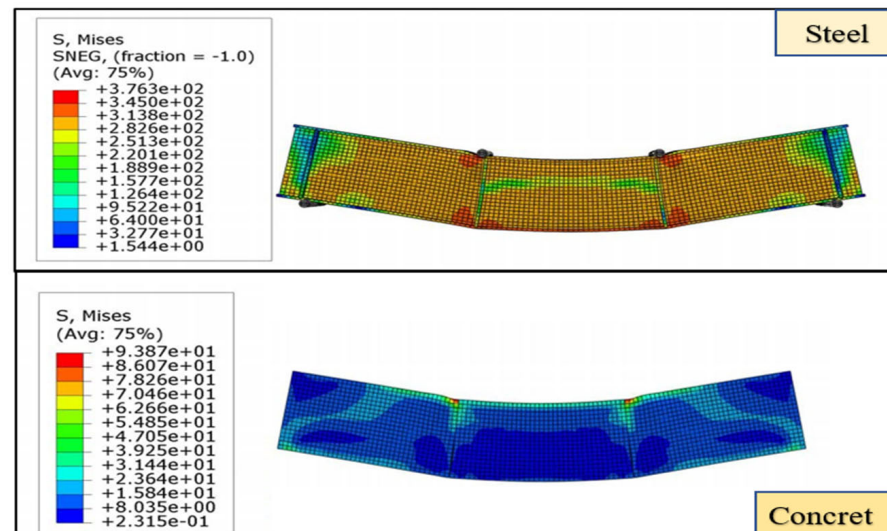


Figure 40. Stress Distribution for beam RFF (Group two).

5. Conclusions

This study included a numerical investigation into the structural behavior of innovative composite double-web steel beams filled with either normal concrete or recycled aggregate concrete. The results highlighted the significant influence of concrete type and placement within the web region on the beams' ultimate capacity, stiffness, ductility, and failure modes. Furthermore, the comparison between experimental findings and finite element simulations using ABAQUS demonstrated strong agreement, confirming the reliability of the numerical approach in predicting the performance of such composite members. Based on these findings, the following key conclusions can be drawn:

- The main innovation of this study is the modeling of a novel composite section (double web filled with concrete) in ABAQUS, followed by validation through experimental results. Previous studies on this section type focused mainly on experimental investigations, while this work demonstrates the feasibility of reliable numerical modeling. The approach presented here can serve as a reference for the analysis and design of structures where high performance girders are required, such as bridges, long-span decks, and mega-structures.
- The performance of composite beams was consistently superior to that of the control specimens due to the inclusion of various concrete types within the webs. Although the incorporation of conventional concrete in the central, peripheral, or full cross-sectional zones increases self-weight, it significantly enhances structural behavior and modifies failure patterns, thereby providing substantially higher load-carrying capacity compared to hollow specimens.
- Filling the beam's web at mid-span prevents buckling, while filling the web near the supports enhances shear resistance and delays flexure–shear interaction failure. Thus, variations in concrete placement strongly affect the bearing capacity and bending performance of composite double-web beams.
- Incorporating recycled waste materials in the concrete mix consistently enhanced the structural performance and ductility of composite double-web beams compared to the control specimen.
- Recycled aggregate concrete is both sustainable and environmentally friendly, as it enhances flexural strength and stiffness by increasing sectional inertia and delaying local buckling of the double web while also providing an effective alternative to conventional concrete.

- The finite element models developed in ABAQUS demonstrated reliable accuracy in predicting the actual behavior of the double-web beams, including maximum load, load–displacement curves, and failure modes.

A key limitation of this study is the additional self-weight introduced by the use of conventional and recycled concrete, which may restrict the applicability of these sections in certain lightweight structures. Future research should therefore investigate the integration of lightweight or alternative infill materials to reduce self-weight while maintaining the mechanical advantages demonstrated in this work.

Author Contributions: A.J.K.: Investigation, conceptualization, formal analysis, data curation, writing—review and editing. G.J.K.: Conceptualization, validation, writing—review and editing. S.A.H.: Conceptualization, validation, writing—review and editing. B.H.M.: Conceptualization, validation, writing—review and editing. A.D.: Conceptualization, formal analysis, validation, supervision, funding acquisition, writing—review and editing. L.F.A.B.: Writing—review and editing, formal analysis, validation, visualization, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The authors declare that the data supporting the findings of this study are available within the paper.

Acknowledgments: The authors express sincere gratitude for the support received from Kerbala University in Iraq.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sara Simon, S.; Kafle, B.; Al-Ameri, R. A critical review of cold-formed steel built-up composite columns with Geopolymer concrete infill. *J. Compos. Sci.* **2024**, *8*, 238.
2. Taufiq, H. *Composite Action Between Light Steel Sections and Concrete for Beams and Columns*; University of Surrey: Guildford, UK, 2020.
3. Fadhel, M.; AlSaraj, W. Steel Tubes Filled by Concrete Under Flexural and Compression: A Review. *Al-Rafidain J. Eng. Sci.* **2025**, *3*, 530–555.
4. Abdalla, S.H. Behavior of Concrete Filled Steel Tube (CFST) Under Different Loading Conditions. Ph.D. Thesis, American University of Sharjah, Sharjah, United Arab Emirates, 2012.
5. Al Zand, A.W.; Ali, M.M.; Al-Ameri, R.; Badaruzzaman, W.H.W.; Tawfeeq, W.M.; Hosseinpour, E.; Yaseen, Z.M. Flexural strength of internally stiffened tubular steel beam filled with recycled concrete materials. *Materials* **2021**, *14*, 6334. [[CrossRef](#)] [[PubMed](#)]
6. Behera, M.; Bhattacharyya, S.; Minocha, A.; Deoliya, R.; Maiti, S. Recycled aggregate from C&D waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review. *Constr. Build. Mater.* **2014**, *68*, 501–516.
7. Sabih, S.M.; Hilo, S.J.; Hamood, M.J.; Salih, S.S.; Faris, M.M.; Yousif, M.A. Numerical investigation into the strengthening of concrete-filled steel tube composite columns using carbon fiber-reinforced polymers. *Buildings* **2024**, *14*, 441. [[CrossRef](#)]
8. Abed, F.H.; Nazzal, M.D.; Attom, M.F.; El-Emam, M.E.; ElMessalami, N. Use of treated wastewater in the construction of base course layers for sustainable pavement structures. *J. Mater. Civ. Eng.* **2018**, *30*, 04018140. [[CrossRef](#)]
9. Chen, Y.; Wang, K.; Feng, R.; He, K.; Wang, L. Flexural behaviour of concrete-filled stainless steel CHS subjected to static loading. *J. Constr. Steel Res.* **2017**, *139*, 30–43. [[CrossRef](#)]
10. Kaishesh, A.J.; Hemzah, S.A.; Mohammed, B.H. Experimental Investigation of Double Web Steel Beam Filled with Recycled Aggregate Concrete (RAC). In Proceedings of the 2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT), Ankara, Turkey, 20–22 October 2022; pp. 128–133.
11. Dassault Systemes Simulia Corp. *ABAQUS/CAE User's Manual, Version 6.14*; Dassault Systemes Simulia Corp: Providence, RI, USA, 2014.
12. Ellobody, E. *Finite Element Analysis and Design of Steel and Steel–Concrete Composite Bridges*; Butterworth-Heinemann: Oxford, UK, 2014.
13. Wang, W.-D.; Xian, W.; Hou, C.; Shi, Y.-L. Experimental investigation and FE modelling of the flexural performance of square and rectangular SRCFST members. In *Structures*; Elsevier: Amsterdam, The Netherlands, 2020.

14. Zhang, Z.; Chen, W.; Wang, K.; Guo, X. Concrete-filled double steel tubular beams under lateral impact. *Case Stud. Constr. Mater.* **2022**, *17*, e01252. [\[CrossRef\]](#)
15. Kaishesh, A.J.; Hemzah, S.A.; Mohammed, B.H. Experimental investigation of double web filled steel beam. In *AIP Conference Proceedings*; AIP Publishing LLC: Melville, NY, USA, 2024; p. 030123.
16. Al-Zand, A.W.; Hosseinpour, E.; Tawfeeq, W.M. The effects of filling the rectangular hollow steel tube beam with concrete: An experimental case study. *J. Civ. Eng. Res.* **2017**, *1*, 23–30.
17. Chang, Q.; Zhao, C.; Xing, L.; Ahmad, W.; Javed, M.F.; Fahid, A.; Musarat, M.A.; Vatin, N.I. *Concrete Filled Double Steel Tube Columns Incorporating UPVC Pipes Under Uniaxial Compressive Load at Ambient and Elevated Temperature*; Elsevier: Amsterdam, The Netherlands, 2022.
18. Pereira, P.; Evangelista, L.; De Brito, J. The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates. *Cem. Concr. Compos.* **2012**, *34*, 1044–1052. [\[CrossRef\]](#)
19. Abed, F.H.; Nazzal, M.D.; Attom, M.F.; El-Emam, M.E.; ElMessalami, N.; Al-Dabagh, S. The use of wastewater in construction of base course layers in pavement structures. In *International Congress and Exhibition Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 31–37.
20. Attom, M.; Abed, F.; Elemam, M.; Nazal, M.; ElMessalami, N. The effect of treated waste-water on compaction and compression of fine soil. *Int. J. Civ. Environ. Eng.* **2016**, *10*, 1122–1126.
21. Hansen, T.C. *Recycling of Demolished Concrete and Masonry*; CRC Press: Boca Raton, FL, USA, 1992.
22. Ghannam, S. Flexural strength of concrete-filled Steel tubular beam with partial replacement of coarse aggregate by granite. *Int. J. Civ. Eng. Technol.* **2016**, *7*, 161–168.
23. Al-Obaidi, S.; Salim, T.; Hemzah, S.A. Flexural behavior of concrete filled steel tube composite with different concrete compressive strength. *Int. J. Civ. Eng. Technol.* **2018**, *9*, 824–832.
24. No. 5/2019; “Portland Cement”, The Central Organization for Standardization and Quality Control. IQS: Baghdad, Iraq, 2019.
25. No. 45/1984; Aggregate from Natural Sources for Concrete and Construction. IQS: Baghdad, Iraq, 1984.
26. ASTM C33-03; Standard Specification for Concrete Aggregates. ASTM: West Hoboken, NJ, USA, 2010.
27. No. 1703/1992; Iraqi Standard (Materials Specification & Construction Works). IQS: Baghdad, Iraq, 1992.
28. ACI 211.1-91; Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete. American Concrete Institute: Farmington Hills, MI, USA, 2001.
29. ASTM A370; Standard Test Methods and Definitions for Mechanical Testing of Steel Products. ASTM: West Hoboken, NJ, USA, 2017.
30. Ahmed, M.; Emara, M.; Patel, V.I.; Chen, W.; Zhang, X.; Hamoda, A. Experimental and numerical analysis of the flexural performance of concrete-filled steel tubular members with partial replacement of fine aggregates with sawdust. *Eng. Struct.* **2025**, *343*, 121050. [\[CrossRef\]](#)
31. Zhang, C.-C.; Ding, F.-X.; Sadat, S.I.; Lyu, F.; Huang, X.-Y.; Gao, R.; Yu, T.; Liu, Y.-L. Flexural Behavior of Desert Sand Concrete-Filled Steel Tube: Experimental Validation, FEM Analysis, and Design Formulas. *Materials* **2025**, *18*, 2371. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Han, L.-H.; Li, W.; Bjorhovde, R. Developments and advanced applications of concrete-filled steel tubular (CFST) structures: Members. *J. Constr. Steel Res.* **2014**, *100*, 211–228. [\[CrossRef\]](#)
33. Al Mustawfi, S.; Safiee, N.A.; Bakar, N.A.; Karim, I.A.; Mohd Nasir, N.A. Experiment and Analysis of a Hybrid Composite Post-tension Plate Girder. *Pertanika J. Sci. Technol.* **2024**, *32*, 1501–15026. [\[CrossRef\]](#)
34. Abdulridha, A.M.; Al Zaidee, S.R. Experimental and Numerical Investigation of Concrete-Filled Tube Beams: A Review Paper. *J. Eng.* **2025**, *31*, 18–41. [\[CrossRef\]](#)
35. Huang, S.; Xi, Y.; Li, X.; Men, P.; Wu, G. Flexural behaviour of damaged concrete T-beams reinforced with ultra-high performance concrete filling. *Front. Mater.* **2024**, *11*, 1410016. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.