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Structural behavior of inverted RC girder with hollow web strengthened by TRM under repeated loads

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Abstract

In the quest for sustainable construction, this study presents a quantitative analysis of reinforced concrete hollow web inverted T-girders, the key to reducing material use while maintaining structural integrity. The investigation zeroes in on the torsional and shear performance of these girders, accentuating the hollow web's role in optimizing structural behavior. Experimentation with Textile Reinforced Mortar (HWIT-G) techniques illustrates distinct effects on load-deflection characteristics: HWIT-G2 enhanced load capacity by 2.36% with a slight deflection increase of 3.79%, suggesting its potential for load-intensive applications. In contrast, HWIT-G3 and HWIT-G4 demonstrated an excellent stiffness boom, with deflection reduced by 68%, but at a 9.45% reduction in load capacity. The performance of HWIT-G5 showed a substantial increase in stiffness and a 78.66% reduction in deflection, but a 34.25% reduction in load capacity. This demonstrates that through the strategic application of HWIT-G, beams can be adapted to specific structural requirements, especially in earthquake-prone areas. It is understood that the cracked condition on the tension side of a hollow-web T-beam may cause damage because of a concrete stress imbalance. The current investigation attempts to assess the efficacy of the hollow guide method of rolling design as a means of saving resources and as a dependable and practical technique for modern engineering.

Keywords: Shear force, hollow webs, structural optimization, sustainability

1. Introduction

Within the field of civil engineering, there exists an unwavering drive to achieve optimal structural efficiency. This practice lies at the heart of the field, where the focus is on innovation in design processes and material properties. What lies before us is not a mere technical problem but rather a dynamic endeavor aimed at improving the performance and resilience of fundamental structures that make up our built environment Altun *et al.* [1].

This project is all about the development of concrete elements reinforced with hollow webs an innovative approach indeed. Introducing inverted T-beams with webs in building structures signifies a radical shift towards an economically viable and environmentally friendly construction era. The use of these materials tells a story of sustainability: it's a story of cost-cutting efforts and leaving smaller footprints Al-Maliki *et al.* [2]. And while the upfront benefits already seem astounding, we're just starting to uncover their strength potential through structural design modifications. There are still uncharted waters in how these beams respond to various loads Varghese and Joy [3].

The typical load would be nothing for such structures because we make sure to include specific design features that take full advantage of what these beams can offer**.** Use of the reinforced jacketing is a practical strategy for modification of T-beams' behavior and performance. It is known that this approach considerably improves ductility and serviceability plus flexural stiffness by 40% for the deflection after the failure of Shousha *et al.* [4] and Liu *et al.* [5].

This action results in the ductile mode of failure due to higher concrete compressive strain. An insight into the intricate behavior expressed by these beams when subjected to repeated loading can be very much appreciated from the viewpoints of both theoretical formulation and practical applications as reported in Arunachalam [6]. The significance of such beams in seismic engineering is never to be underestimated. The proper development of building structures that can resist earthquake action and retain their stability after disaster in earthquake-prone areas is a great challenge observed by Ibrahim *et al.* [7].

An insight into the intricate behavior portrayed by these beams under repeated strain would be appreciable enough from both theoretical and practical points of view, as in Atea and Atea [8]. The relevance of such beams in seismic engineering is overwhelming. According to Murugesan and Arunachalam [9].

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The problem noted in earthquake-prone areas by challenges majorly of building structures to resist earthquakes and remain stable post-disaster.

An insight into the complicated behavior these beams portray when subjected to repeated strain would be highly commendable from the viewpoint of theory and practical applications as indicated in Murugesan and Arunachalam [10]. The value of such beams in seismic engineering can never be underestimated. According to Kadhim and Al-Jabar [11] one of the major challenges is that of building structures in earthquake-prone areas that can resist earthquakes and remain stable post-disaster. Structural beams under study: it's as much about knowing them as it is about knowing ourselves Mirza and Furlong [12].

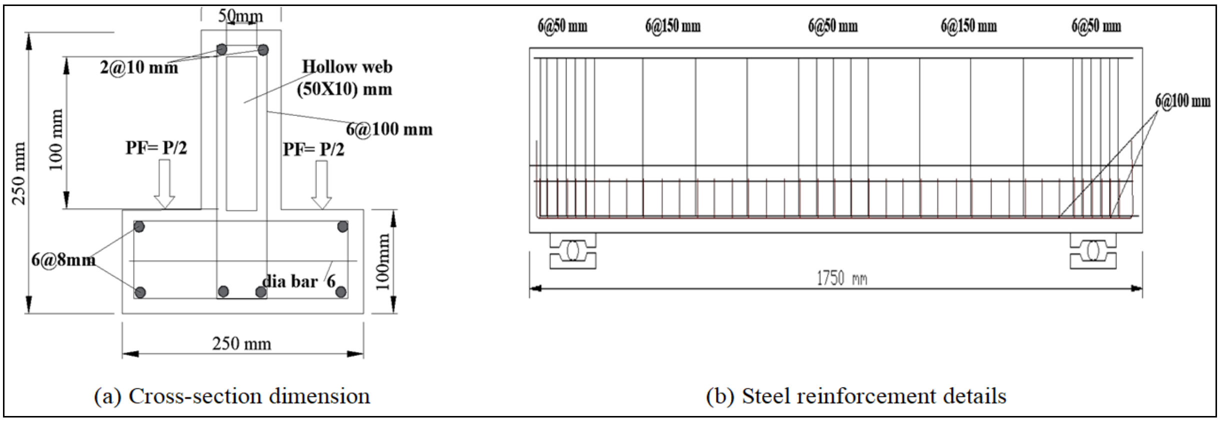
The field of civil engineering is synonymous with innovation. An example of this can be seen in the study of reinforced concrete hollow web inverted T-beams. These innovations are not only theoretical but also practical, providing a basis for addressing the needs of contemporary design and development ACI Structural Journal [13]. Detailed scrutiny into these horizons ensures structurally strong, technologically sound, and environmentally conscious edifices at a time when mediocrity is not an option Garber *et al.* [14].

The main goal of this research is to look at the structural response that comes out in a detailed way with hollow web T-beams in concrete. We need to understand different load conditions. The key focus area will be on how the reinforced jacketing impacts these beams in terms of strength, flexibility, and functionality. This investigation will look into the first applications of such beams especially looking if they can be used for seismic engineering which is a great topic as well as sustainable construction practices that have been discussed widely too. As well as this study aims to make substantial contributions to civil engineering by closing the disparity between theoretical learning and real-world applications. This would enable people working in the field to use practical applications that enhance performance (The effectiveness of a structure), resilience (It's capacity to withhold loads), and environmental sustainability based on technically generated information through research findings, thus all be adopted into practice and be able to improve work with this new knowledge generated technically

2. Experimental Scheme

2.1 Specimens Description

The research covered the advent and evaluation of five hollow webs inverted T-girder specimens made from reinforced concrete (R.C.). As shown in Fig. (1-a)**,** these girders were designed with parameters of a 250 mm wide flange, an 80 mm deep flange, a 110 mm web width, a total girder height of 250 mm, and a length of 1750 mm. Additionally, a solid girder was prepared for comparative purposes. This reference girder, labeled HWITG (1), shared the same dimensions and reinforcement details as the hollow web girders and was tested to identify the point at which brittle failure first occurred. Within the hanger area, stirrups were placed 102 mm apart, and the spacing of shear reinforcement in the web and flange reinforcement was maintained at 305 mm and 102 mm, respectively. Fig. (1-b) also detailed the arrangement of longitudinal reinforcement within the girders. The aim of the control girder, HWITG1, was to assess the performance of the hollow web inverted T-girder construction method.



(a) Cross-section dimension

(b) Steel reinforcement details

Fig 1: Typical size and test beams with longitudinal strengthening of the girders: (1-a) cross-section, (1-b) steel reinforcement detail dimensions

2.2 Materials

2.2.1 Cement

The research used ALMAS brand Ordinary Portland Cement (O.P.C.) that met Iraqi standard (I.Q.S.) NO.5/1984. The cement's specific surface area measured by the Blaine method, was found to be 314 m²/kg, indicating a fine particle composition that enhances the reactivity and strength of the concrete.

2.2.2 Fine Aggregate (Sand)

Local natural sand underwent extensive washing and air drying before use, aligning with the Iraqi specification (I.Q.S) NO.45/1984 zone. Sieve analysis confirmed the sand's particle size distribution, with passing percentages of 42.7% at 600 µm, 22.1% at 300 µm, and 6.5% at 150 µm, ensuring optimal workability and concrete strength.

2.2.3 Coarse Aggregate (Gravel)

Crushed gravel with a size of 14 mm was chosen, thoroughly cleaned with water, and air dried. Its chemical and mechanical properties, including sieve assessment effects, comply with Iraqi Specification (I.Q.S.) No. 45/1984. The gravel sieve examination showed that 100% passed at 19 mm, 96% at 14 mm, and 46.6% at 10 mm, with a sulfate level of 0.06%, making it appropriate for concrete applications.

2.2.4 Mixing Water

Regular Tap water was used to cast and cure the specimens, ensuring consistent material quality and experiment reproducibility.

2.2.5 Steel Reinforcement Bars

ASTM A615 requirements were satisfied during tensile testing of Ukrainian steel bars with diameters of 6 mm, 8 mm, and 10 mm. The tension reinforcement bar consisted of a 10 mm deformed steel rebar (9.5 mm diameter) with a cross-sectional area of 70.70 mm² and an 8 mm deformed steel rebar (7.5 mm diameter) with a cross-sectional area of 44.19 mm². Additionally, the web and flanges used a 6 mm rebar with a cross-sectional area of 24.67 mm², having an average yield stress value at 2200 microstrain.

2.2.6 Ready-mix concrete

A concrete mix design that would deliver a compressive strength of 30 MPa and a slump measurement of 125 mm was provided to the civil engineering laboratory at the University of Babylon. Beam specimens were cast and cured under controlled conditions to develop specified properties. Compressive and tensile strengths were tested at intervals, with notable results documented in the research findings as shown in Table (1).

Table 1: The mechanical properties of hardened concrete

Materials	Cement kg/m^3	Sand kg/m^3	Gravel kg/m^3	Water (kg / m^3)	Water cement ratio
Quantities	375	710	1060	208	0.56

2.2.7 Textile-reinforced mortar (TRM)

Textile-reinforced mortar (TRM), also known as material-bolstered cementation mortar (FRCM), is a key development in reinforcing homes towards earthquakes. It consists of excessive-power Textile-reinforced mortars (carbon, glass, aramid, basalt, PBO) within a cement mortar, making use of open-grid textiles for better bonding and cloth compatibility. HWIT-G gives advanced hearth resistance and temperature patience, making it best for seismic enhancements. Its effectiveness in improving concrete and masonry structures is well-researched, showing promise for complete seismic and energy retrofitting as shown in Fig. 2-a.

2.2.8 Conmix ReCon HS

In this research, ReCon HS, a Conmix product, was utilized. This single-component, polymer-modified, and non-shrinking repair mortar is enhanced with Textile-reinforced mortars and silica fume for its high-strength and smooth finish qualities. It was chosen for its contribution to structural durability, ease of application, low permeability, superior resistance to environmental aggressors, significant carbonation reduction, and robust adhesion capabilities without the risk of corrosion often associated with chlorides. The properties of this material shown in as shown in Table (2) and in Fig. 2-b.


(2-a) Textile-reinforced mortars (TRM) (2-b) Adhesive material type Conmix (ReCon HS)

Fig 2: Textile-reinforced mortars (TRM) (2-a), and Adhesive material type Conmix (ReCon HS) (2-b)

Table 2: Mechanical properties of type Conmix (ReCon HS)

Property	Value
Compressive Strength	1 day: 40 N/mm², 28 days: 75 N/mm²
Flexural Strength	11 N/mm² at 28 days
Tensile Strength	6 N/mm² at 28 days
Bond Strength	> 2 N/mm² at 28 days
Rapid Chloride Permeability	< 650 coulombs

3. Experimental Setup and Design

The girder specimens were designed and cast incorporating the specified materials, with detailed attention to the mix proportions and reinforcement layout to address the study objectives. The loading conditions were meticulously planned to simulate real-world stresses, including shear and torsion, allowing a thorough examination of Reinforced concrete hollow web inverted T-girders: structural characteristics. Table (3) and Fig 3 provide more information on each of these.

Table 3: The Table illustrates the beam label design and description for each one

No.	Girder simple	Description
1.	HWITG1	Without TRM
2.	HWITG2	The purpose of the investigation was to deal with and avoid future non-ductile failures within the girder's web (shear-compression) as well as its hanger section, which had been noted before.
3.	HWITG3	An investigation of a retrofit scheme was carried out to eliminate non-ductile failure in the web and hanger failure mode, while also addressing the torsion identified in the girder.
4.	HWITG4	To shift forces from the HWIT-G wrap to the web of the girder.
5.	HWITG5	This sample test is conducted to assess the effectiveness of using HWIT-G (Textile-strengthened mortars) sheets in enhancing the shear strength capacity of the web in inverted T-girders

3.4 Test Setup and Instrumentation for Hollow Web Inverted T-Girder

The test setup and instrumentation for the hollow web inverted T-girder involved a comprehensive approach. Before testing, each beam specimen underwent a thorough cleaning and was coated with white paint to enhance crack visibility. Tests were conducted in the civil engineering laboratory at Babylon University using a universal hydraulic testing machine with a 1000 kN capacity. This tool was used to easily examine control and experimental beams and the actual boundary condition of simply supported beams Galal and Sekar [15]. The deflections of each beam under the loading point were measured as an even finer detail through the use of a Linear Variable.

A fine mechanical dial gauge was placed under the beam at the center with the help of Deflection sensors LVDT (Linear Variable Differential Transformer) located at both midspan and ends of the simply supported beam. The deflection monitor is observed as its output changes Shousha *et al.* [16]. In the experimental setup, each of the beams was subjected to two specific locations for point loadings using specially fabricated loading points. Beams were then made to rest on a span of 1550 mm with one end supported freely (Hinged support) while the other end was restrained against horizontal movement but free to rotate (Roller support), as shown in Fig. 3. The load was applied symmetrically and repeatedly until failure from a specially designed equipment based on following testing scenario. To prevent the concrete from being crushed at loading and support areas, support plates were used. The strain measurement is a multi-channel automatic data logger.

The strain gauges and transducers were connected to a dedicated computer program for data visualization in Excel format to measure the beams Elamary *et al*. [17]. Each beam was a separate test to ensure precision with the load points and supports adequately aligned.

Strain, crack width, and deflection data were collected using gauges during the loading process. Insights into the interaction were obtained through data analysis that recorded critical stress points systematically from Mahdi and Ismael [18].

The research of Zhu and Hsu [19] addressed the physical properties of the beams and their performance. After going through the test results of their experiments on reinforced concrete members loaded to shear, it can be concluded that shear resistance is very highly improved by the application of textile-mortar jacketing Sirisonthi *et al*. [20]. For high growth in this enhancement, specifically depending on the layers' number, it works as an effective measure to avert shear-type failure and instead makes it flexural Deifalla and Ghobarah [21].


(a) HWITG4 details. (b) Strengthening of hollow web inverted T-girders

Fig 3: On each side, the beam experiences a common two-point loading scenario (a), while (b) involves the utilization of (TRM) for mechanical reinforcement of hollow web inverted T-girders

4. Results and Discussion

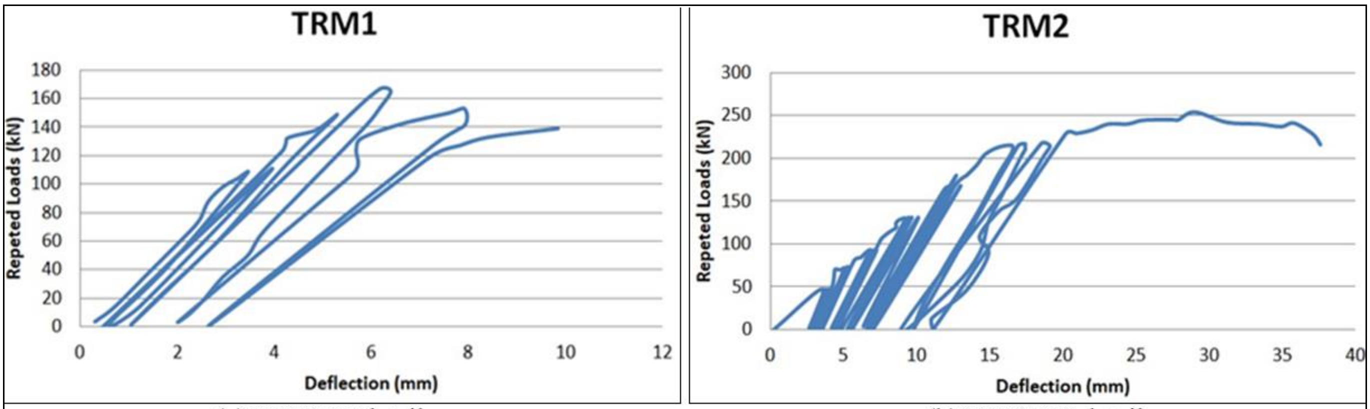
The objective of this study was to investigate the impact of Textile Reinforced Mortar (HWIT-G) on the load-deflection behavior of hollow web inverted T-girders, as depicted in Fig. 4. The control specimen, HWIT-G1, was compared to HWIT-G2. HWIT-G2 exhibited a slight enhancement in peak load capacity, with an approximate increase of 2.36% compared to HWIT-G1. Additionally, it displayed a higher deflection at peak load, with an increase of approximately 3.79%. In comparing HWIT-G3 and HWIT-G4 to HWIT-G1, both show a decrease in peak load capacity of about 9.45%. However, they also have a remarkable decrease in deflections at peak load, showing a 68.76% fall. A very stiff increase with quite low reduced deflection may be very useful where deflection requires being minimized such as those structures that are vibration-sensitive or critical to maintaining the position.

A comparison of HWIT-G3 and HWIT-G4 to HWIT-G1 shows a decrease in peak load capacity by about 9.45%, as with HWIT-G1. However, they also show a significant decrease in deflection at peak load, amounting to about 68.76%. The major increase in stiffness accompanying such a small decrease in the capacity may be very useful where deflection has to be curtailed, such as in structures sensitive to vibrations or when retaining the position is critical

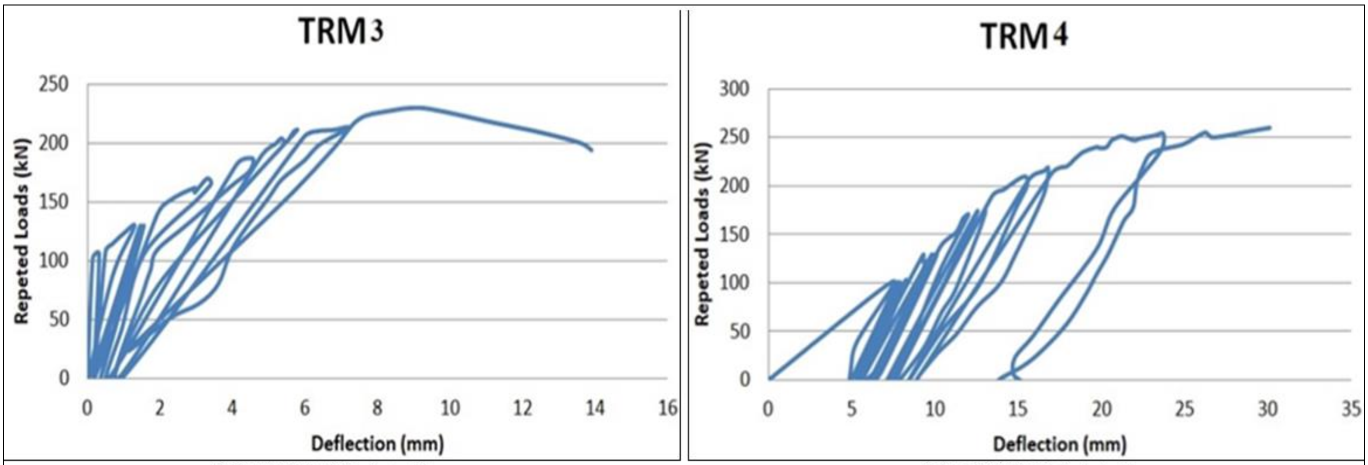
HWIT-G5: This shows a considerable decrease in peak load capacity by approximately 34.25% from HWIT-G1. This indicates a markedly increased stiffness, potentially suitable for applications where deflection control is far more critical than load-bearing capacity.

HWIT-G3 and HWIT-G4 exhibit the most balanced performance, offering a considerable boost in stiffness as evidenced by the marked reduction in deflection, despite their lower load-bearing capacity. These techniques may be particularly advantageous for retrofitting projects or other applications where enhanced structural rigidity is required without a substantial compromise on the load-bearing capacity.

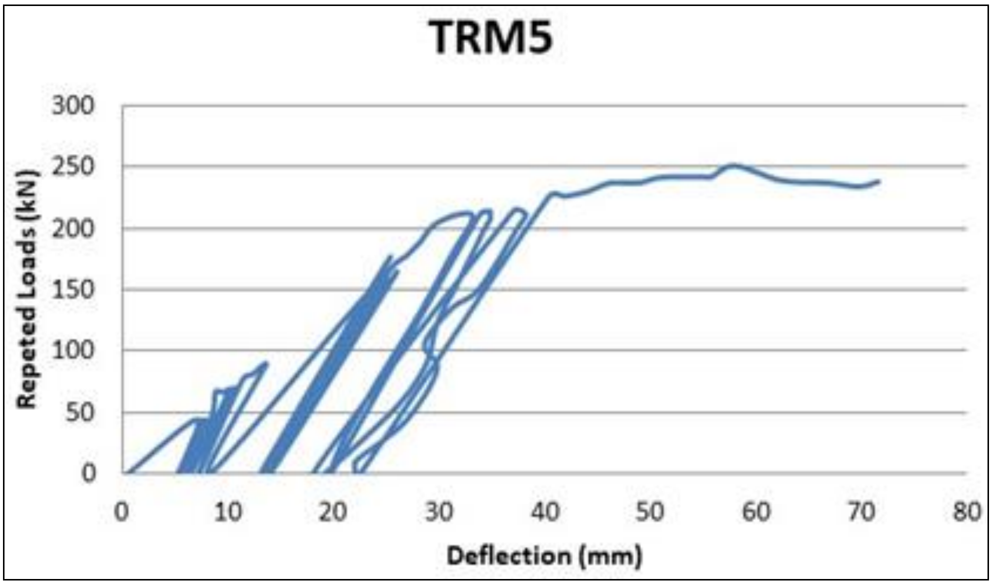
In projects where deflection criteria are as crucial as load capacity, engineers might find the balanced performance of HWIT-G3 and HWIT-G4 to be the optimal solution, even with a 9.45% reduction in load capacity if it comes with a 68.76% enhancement in stiffness.



(a) HWITG1details (b) HWITG2 details



(c) HWITG3 details. (d) HWITG4 details.



(e) HWITG 5 details.

Fig 4: Load-deflection response for all Holow web inverted T-girder (HWITG)

In this research, the failure modes observed in the hollow web inverted T-girder subjected to concentric loading are predominantly flexural and shear. The presence of some diagonally oriented cracks suggests shear failure, especially within the web of the girder as shown in Fig. 5. Additionally, potential interface deboning at the flange-web junction and localized distress near the supports might point to weaknesses in bond strength and stress concentration issues, respectively. Despite these failure indications, the girder maintained its overall structural integrity, suggesting that the internal reinforcement provided a measure of residual strength. The research would benefit from further analysis of these observations to inform and improve the design of similar structures.

(a)Shear and flexural failure mechanism for T-girder HWITG4.

(b) Flange failure mechanism for T-girder HWITG5

Fig 5: The failure mode response for all Hollow web inverted T-girder (HWITG)

5. Conclusion

This study has affirmed the viability of reinforced concrete hollow web inverted T-girders as a robust and resource-efficient alternative in the realm of construction. The investigative focus on the impacts of diverse strengthening techniques has yielded significant insights, demonstrating that these girders can attain commendable degrees of torsional stiffness and enhanced durability. The application of Textile Reinforced Mortar methods has particularly revealed variable effects on the load-deflection properties of the girders. HWIT-G2 showed a modest increase in load capacity of approximately 2.36%, with a 3.79% rise in deflection, suggesting its suitability for applications where a higher load bearing is required without a considerable penalty in deflection. HWIT-G3 and HWIT-G4, on the other hand, indicated a decrease in load capacity by about 9.45% but reflected significantly higher stiffness with accepted reductions in deflection values of about 68.76%. Moreover, the findings stress the importance of strategic design and proper detailing for the enhancement of performance benefits of hollow web girders. In seismic engineering, these findings are very useful for increasing torsional strength demand. Fundamental approaches dealing with a broader spectrum of failure modes have been very successful, stressing complexities while giving out details on reinforcing hollow web girders.

Also, the cracks that occur horizontally on the tension face and indicate a hollow web inverted mode of failure in T-beams confirm the flexural failure. This conclusion aligns with the cracking patterns typical of bending stress exceeding the material's tensile capacity.

Conclusively, this research contributes invaluable perspectives on the optimization of hollow web girders and encourages their broader integration into structural design and construction protocols. By underlining the specific strengths of each rehabilitation technique, the study advocates for a tailored approach in the adoption of hollow web girders, tailored to the distinct demands of modern structural engineering challenges.

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