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Comparative Study of Flexural Strengthening of Reinforced Concrete Beams Using TRM and Conventional Strengthening Techniques

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Abstract
This study experimentally investigates the flexural strengthening of reinforced concrete (RC) beams using Textile Reinforced Mortar (TRM) as an advanced composite strengthening technique. The performance of TRM was evaluated and compared with conventional methods, including externally bonded steel plate, ferrocement, and externally attached mild steel bars. In addition, the effectiveness of TRM for strengthening a pre-cracked beam was examined to simulate a realistic rehabilitation scenario.
All specimens were tested under four-point bending to assess load–deflection behavior, strain response, crack development, and failure mode. The reference beam showed yielding at 3.5 tons and an ultimate load of 12.5 tons. Strengthening with steel plate, mild steel bars, and ferrocement increased the ultimate load to 15, 14.5, and 14 tons, respectively. The TRM-strengthened beam achieved the highest improvement, reaching an ultimate load of 16.5 tons with yielding at 6.5 tons. Furthermore, the pre-cracked beam strengthened with TRM successfully restored its flexural capacity, reaching 14.5 tons.
All strengthened beams mainly failed in flexure with controlled cracking and concrete crushing in the compression zone. The results confirm that TRM provides superior stiffness, crack control, and ductility compared to conventional strengthening techniques, proving its efficiency for strengthening and rehabilitation of RC beams.
Keywords: *Textile Reinforced Mortar (TRM); Reinforced Concrete Beams; Flexural Strengthening; Carbon Textile; Pre-cracked Beams; Ferrocement; Steel Plate Strengthening; Load–Deflection Behavior; Crack Control; Structural Rehabilitation.*
Yield.

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I. INTRODUCTION

II. Reinforced concrete (RC) beams are essential structural elements, and their flexural behavior plays a key role in ensuring structural safety, serviceability, and durability. Flexural performance governs cracking, stiffness reduction, and ultimate load capacity, which are critical for both design and structural assessment. Consequently, understanding the flexural response of RC beams remains a major focus of experimental and analytical research aimed at improving design methods and strengthening techniques(1).

III. In recent years, a growing number of RC structures have exhibited structural deficiencies caused by aging, environmental exposure, increased service loads, and changes in usage requirements. These deficiencies often appear in the form of flexural cracking, excessive deflections, and reduced load-carrying capacity. Consequently, strengthening and rehabilitation of existing RC beams have become essential engineering practices to extend service life and avoid costly demolition and reconstruction(2).

1.1 Literature Review of Recent Relevant Works

The flexural behavior of reinforced concrete (RC) beams has been extensively studied due to its direct influence on structural safety, serviceability, and failure mechanisms. Under flexural loading, RC beams exhibit a nonlinear response governed by the interaction between concrete in compression and steel reinforcement in tension. A clear understanding of this behavior is essential for assessing the effectiveness of strengthening and rehabilitation techniques applied to RC beams(3).

As the applied load increases, the flexural response of RC beams can be generally described through three distinct stages. The first stage corresponds to the uncracked elastic behavior, during which both concrete and steel behave elastically and act compositely. In this stage, the load–deflection relationship remains nearly linear, and no visible cracks are observed on the beam surface (4).

The second stage begins with the initiation of flexural cracking in the tension zone once the tensile stress exceeds the cracking strength of concrete. Flexural cracks typically develop in regions of maximum bending moment, such as the mid-span of beams subjected to two-point loading. The cracking load and subsequent crack propagation are influenced by concrete tensile strength, reinforcement ratio, and beam geometry. After cracking, beam stiffness decreases, and tensile forces are mainly resisted by the steel reinforcement, while concrete continues to carry compressive stresses(5).

With further increase in load, flexural cracks propagate vertically toward the compression zone and extend along the beam length. The number and width of cracks increase, leading to larger deflections. Experimental investigations have shown that crack distribution and stiffness degradation play a significant role in defining the serviceability performance of RC beams under flexural loading(6).

Several techniques are available for strengthening reinforced concrete (RC) beams to improve their load-carrying capacity and structural performance. These techniques include traditional methods such as steel plate bonding and concrete jacketing, as well as modern composite-based systems. In recent years, fiber-reinforced polymers (FRP) and textile-reinforced mortars (TRM) have been increasingly used due to their high efficiency, durability, and ease of application. The choice of a strengthening technique depends on the required performance, cost, material availability, and ease of execution(7).

(Khan, S., et al. (2013) This experimental study evaluates the effectiveness of ferrocement strengthening techniques using cast in situ ferro-mesh layers and precast ferrocement laminates on reinforced concrete beams failing in flexure. The strengthened beams showed notable improvements in load-carrying capacity, stiffness, and ductility compared to the control beam. Results indicated that cast in situ ferro-mesh layers provided the highest strengthening efficiency, while precast ferrocement laminates offered ease of application and satisfactory structural performance. The study also confirmed the reliability of ACI 549.1R-93 in predicting the flexural capacity of ferrocement-strengthened beams, with bond quality playing a key role in overall effectiveness(8).

Awad, F., et al. (2022) The study confirmed that engineered cementitious composites (ECC) provide superior flexural performance when used as a bonding and strengthening material for RC beams with near-surface mounted steel bars. Experimental results showed that ECC-bonded steel bars significantly enhanced ductility, crack control, and load-sharing efficiency with steel reinforcement compared to epoxy-bonded systems. The tight crack width and high tensile ductility of ECC improved durability and allowed better utilization of steel reinforcement, while maintaining compressive strength comparable to conventional concrete. Overall, ECC proved to be an effective, economical, and sustainable strengthening material for flexural and shear rehabilitation of RC(9).

(Aykac, S., et al. (2013) The experimental investigation showed that externally plated reinforced concrete beams exhibited significant improvements in flexural performance, strongly influenced by plate thickness, anchorage method, and plate configuration. Beam ductility increased with decreasing plate thickness, while anchorage using bolts or U-shaped collars effectively prevented premature plate peeling, particularly for thick plates. The use of perforated steel plates improved beam ductility, although it slightly reduced ultimate load capacity due to the reduction in plate cross-sectional area; nevertheless, repaired beams with perforated plates anchored by collars achieved load-carrying capacities close to those of undamaged beams. Experimental results also indicated that diagonal cracking occurred when the shear force at the plate ends exceeded approximately 40% of the nominal shear strength, and analytical predictions based on ACI 318M-11 and the Todeschini model showed good agreement with measured ultimate flexural moments, while the proposed by Oehlers was found to be overly conservative(10).

A few studies have investigated this subject to strength concrete beam. The TRM system comprises one or more layers of textile reinforcements, such as carbon or polyparaphenylenebenzobisoxazole (PBO) grids, embedded within and bonded by cementitious mortar layers(7).

Textile Reinforced Mortar (TRM) systems represent an innovative strengthening technique for enhancing the flexural capacity of reinforced concrete (RC) beams, utilizing inorganic mortars combined with high-strength textiles such as carbon, basalt, alkali-resistant (AR) glass, and polyparaphenylene benzobisoxazole (PBO). Experimental studies consistently demonstrate substantial improvements in load-carrying capacity, stiffness, and ductility, with gains ranging from 6.6% to 77.51% depending on textile type, number of layers, and configuration (7).

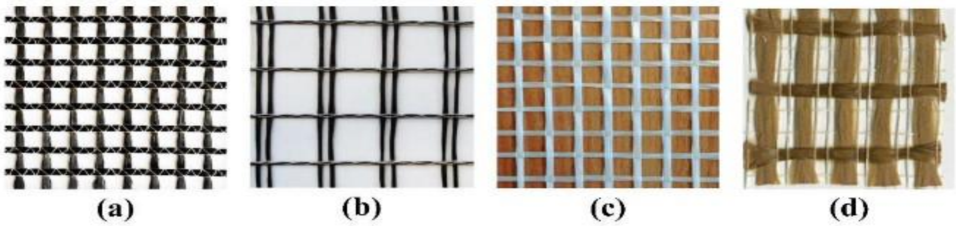

Figure 1.1. Textile fiber reinforcements: (a) carbon-fiber textile; (b) basalt-fiber textile; (c) glass -fiber textile; and (d) PBO-fiber textile (Raoof, S. M., et al. (2016)(11).

2.1 Experimental Program

A total of six reinforced concrete beams were cast and tested under two-point loading. One beam was tested as a control specimen without strengthening, while the remaining beams were strengthened using different techniques. All beams were designed with identical geometry, reinforcement details, material properties, and loading configuration to ensure a reliable and direct comparison between the strengthening methods .

2.2 Material Characterization

The concrete mix proportions were selected to ensure adequate workability for casting the beam specimens and to achieve the required mechanical properties. Concrete mixing was carried out using a mechanical mixer to ensure homogeneity of the mix before casting. The concrete mix was designed with a cement content of 350 kg/m³, coarse aggregate of 1200 kg/m³, fine aggregate of 600 kg/m³, and water content of 200 liters/m³, resulting in a water–cement ratio of 0.57. This mix was adopted for all beam specimens to ensure consistency in the experimental results table 1.

Material	Quantity
Cement	350 kg
Coarse Aggregate	1200 kg
Fine Aggregate (Sand)	600 kg
Water	200 liters
Water–Cement Ratio (w/c)	0.57

Table1: Concrete Mix Proportions

The mechanical properties of the steel reinforcement, including yield strength, ultimate strength, and modulus of elasticity, were obtained from manufacturer data and verified through standard tensile testing. The properties of the steel reinforcement are summarized in Table 2.

Bar Diameter (mm)	Steel Type	Yield Strength fy (MPa)	Ultimate Strength fu (MPa)	Modulus of Elasticity Es (GPa)
8	Ezz Steel	360	520	200
10	Ezz Steel	360	520	200

Table 2: The properties of the steel reinforcement

2.3 Compressive Strength Test of Concrete Cubes

A total of six concrete cubes were cast simultaneously with the beam specimens using the same concrete mix. The cubes were demolded after 24 hours and cured under the same conditions as the beam specimens. Three cubes were tested at the age of 7 days to monitor the early strength development, while the remaining three cubes were tested at the age of 28 days to determine the compressive strength at the design age. Concrete cube specimens were tested in compression according to the relevant standards. The test results indicated that the average compressive strength of the concrete was 274 kg/cm², which was considered as the reference concrete strength for the experimental program.

2.4 Cementitious Mortar Composition

The cementitious mortar used in the strengthening system consisted of ordinary Portland cement, fine aggregate (sand), and water. The mortar mix was designed to provide adequate workability, bond performance, and mechanical strength suitable for strengthening applications. The selected mortar composition ensured proper penetration and adhesion to the concrete surface during application.

2.5 Textile Properties

Carbon fiber textile mesh was used as the main reinforcement in the TRM strengthening system, and its mechanical properties were taken from the manufacturer's technical data sheet. Three textile layers were applied to improve the flexural performance due to their high tensile strength, corrosion resistance, and compatibility with cement-based matrices.

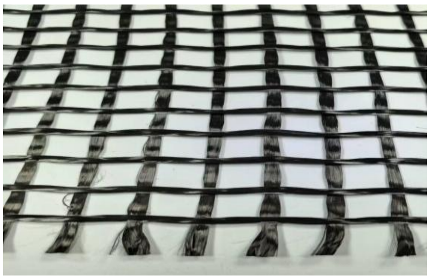

Figure 1: Carbon fiber textile mesh

Property	Value	Unit
Fiber type	Carbon fiber textile mesh	—

Property	Value	Unit
Areal weight	160	g/m²
Mesh size	20 × 20	mm
Tensile strength	3000–3500	MPa
Elastic modulus	230–240	GPa
Ultimate strain	1.6–1.8	%
Equivalent thickness (single layer)	0.089	mm
Number of layers used	3	—
Manufacturer	Horyen	—

Table 3: Mechanical and Physical Properties of Carbon Fiber Textile Mesh. Note: Properties were obtained from the manufacturer’s technical data s.

2.6 Strengthening Using Steel Plate

In the present study, a mild steel plate with a thickness of 1 mm was externally bonded to the tension face of the beam along the effective span. The dimensions of the steel plate were selected based on the tensile capacity equivalence with the reference carbon textile reinforcement system. Proper surface preparation was carried out prior to plate installation to enhance bond performance between the steel plate and the concrete substrate. The steel plate was intended to act compositely with the concrete section under flexural loading.

2.7 Strengthening Ferro Cement

Ferrocement strengthening was adopted as an alternative cement-based strengthening technique due to its compatibility with concrete substrates and its ability to provide distributed tensile reinforcement. The ferrocement system used in this study consisted of a cementitious mortar reinforced with glass fibers, applied in three successive layers, with an embedded steel wire mesh acting as the primary tensile reinforcement (fig 2.2).

Figure 2: Ferrocement Reinforcement

2.7 Strengthening Using Mild Steel Bars (Ø6 mm)

The number of Ø6 mm mild steel bars was determined based on the tensile capacity equivalence with the reference carbon textile reinforcement system, as described in Section 3.2. This approach allows direct comparison between discrete steel reinforcement and fiber-based strengthening systems under identical experimental conditions. The use of mild steel bars represents a practical and economical strengthening solution and enables assessment of the influence of reinforcement form on the flexural behavior of strengthened beams (5).

2.8 Strengthening Equivalence Methodology

According to first principles, the tensile force resisted by a reinforcement material may be expressed as the product of its cross-sectional area and the corresponding tensile stress. Under elastic behavior, tensile stress is proportional to strain through the elastic modulus. Accordingly, for different strengthening materials subjected to the same level of strain, equivalence may be established by equating their axial stiffness, defined as the product of elastic modulus and effective cross-sectional area:

$$A1E1 = A2E2$$

In the present study, this approach was used to establish equivalence between textile carbon fiber reinforcement and conventional steel-based strengthening systems, including steel plates, mild steel bars, and mild steel wire mesh. The mechanical properties of the textile carbon fiber reinforcement were adopted based on the manufacturer's technical data sheet, while the mechanical properties of steel were taken in accordance with ECP 203 (34).

System	Equivalent to 3 Layers Carbon Textile
Steel Plate	≈ 1.0 mm thickness
Mild Steel Bars	≈ 4 bars Ø6 mm
Mild Steel Mesh	≈ 2–3 layers

Table 4: Equivalency Between Carbon Textile Layers and Steel Reinforcement Systems

2.9 Detailing of Beam Specimens

A total of six reinforced concrete beam specimens were prepared and tested in this study. All beams were designed with identical geometry and internal reinforcement details to ensure flexural failure during testing and to isolate the effect of the applied strengthening techniques.

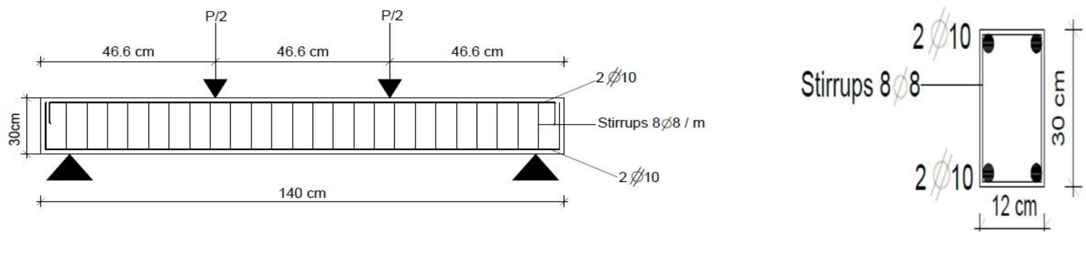

Figure 3: Longitudinal reinforcement detailing and loading configuration of the reinforced concrete beam specimen

2.10 Detailing of strengthened beam specimens

The strengthened beam specimens were detailed using different external strengthening techniques applied to the tension face of beams with identical geometry and internal reinforcement. The strengthening systems included textile reinforced mortar (TRM) with three layers of carbon textile, ferrocement systems using fiber-reinforced mortar with either wire mesh or mild steel bars, and externally bonded mild steel plates with a thickness of 1 mm. All strengthening configurations were designed based on the equivalence criteria described in Section 3.2 to ensure a consistent and fair comparison between the tested specimens. The details are given in Section 3.3. The longitudinal and a mid-span cross section of a typical TRM strengthened beam specimen is shown in Fig.3.5. All the dimensions are in cm for beams. Fig .4 (B-TRM - B-FM - B-PC-TRM), Fig .5 for (B-MS). Fig .6 for beam (B-SP) and

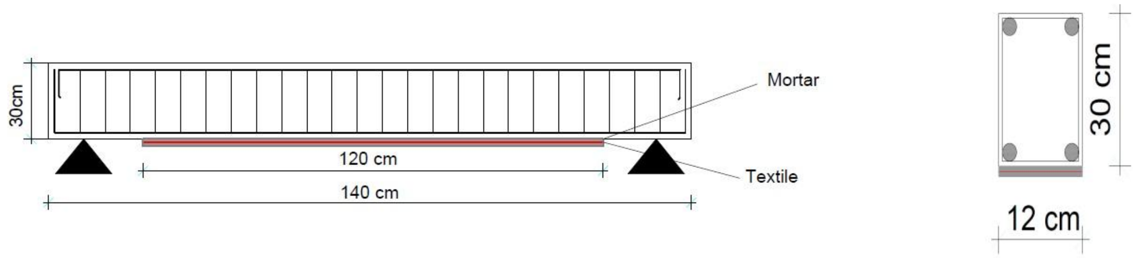

Figure 4: Longitudinal and mid span cross-section of strengthened specimen

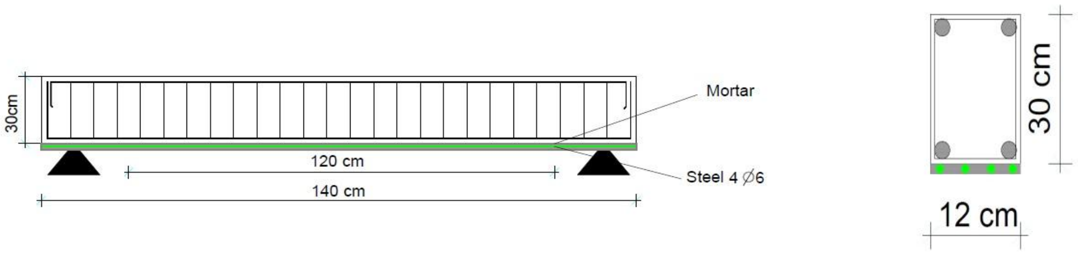

Figure 5: Longitudinal and mid span cross-section of strengthened specimen (B-MS)

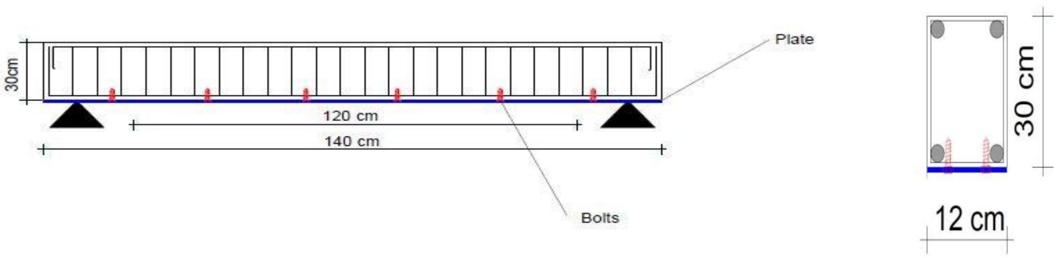

Figure 6: Longitudinal and mid span cross-section of strengthened specimen (B-SP)

2.11 Preparation of beam specimens

The reinforcement cages were then placed inside the wooden molds, which were carefully prepared and cleaned before casting. Adequate measures were taken to maintain the correct position of the reinforcement during the casting process (figure 7).

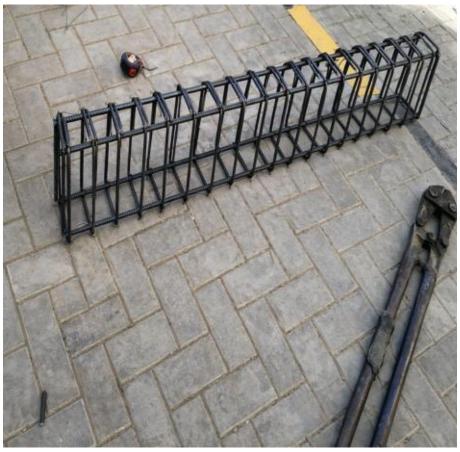

Figure 7: Reinforcement cage of the reinforced concrete beam, Steel reinforcement cages inside the wooden form work

Concrete mixing was carried out using a mechanical mixer to ensure homogeneity of the mix. The concrete was poured into the molds in layers and compacted using mechanical vibration to eliminate air voids and achieve proper consolidation. After casting, the concrete surface was leveled and finished to obtain a smooth surface.

Figure 8: Concrete casting into molds

After demolding, all beam specimens were subjected to a controlled curing regime to ensure proper hydration of the cement and to achieve the target mechanical properties of concrete. The specimens were covered with wet burlap and continuously cured by regular water sprinkling for a period of 28 days.

Figure 9: Curing of reinforced concrete beam specimens using wet burlap and continuous water sprinkling for 28 days

2.12 Steps for Strengthening of Concrete Beams

For the TRM-strengthened beam, the concrete surface at the tension face was first mechanically roughened and cleaned to remove any loose particles. A thin layer of cementitious mortar was then applied to the prepared surface. The carbon textile reinforcement was placed onto the fresh mortar and gently pressed to ensure proper embedment. Subsequently, additional mortar layers were applied to fully cover the textile reinforcement (Figure10). This procedure was repeated until three layers of carbon textile reinforcement were embedded within the mortar matrix. The surface was then finished smoothly, and the strengthened beam was cured under controlled conditions prior to testing.

Figure 10: The carbon textile reinforcement was placed onto the fresh mortar and additional mortar layers were applied to fully cover the textile reinforcement

For the Ferrocement strengthened beam, an initial layer of cementitious mortar was first applied to the prepared concrete surface. Subsequently, three layers of steel wire mesh were placed over the fresh mortar and mechanically fixed using steel nails to ensure stability during application. The steel nails had a diameter of 13 mm and were embedded approximately 30 mm into the concrete substrate (figure 11).

Figure 11: Three layers of steel wire mesh were placed over the fresh mortar and an additional layer of cementitious mortar was applied to fully cover the mesh

In the steel plate–strengthened beam, the concrete surface was mechanically roughened and cleaned prior to strengthening. A thin layer of cementitious mortar was applied to the tension face, after which a mild steel plate with a thickness of 1 mm was placed onto the fresh mortar. The steel plate was mechanically anchored using steel bolts distributed along its length to prevent premature debonding. After installation, additional mortar was applied along the plate edges and around the bolts to improve bonding and stress distribution The strengthened beam was then cured before testing (Figure 12).

Figure 12: The steel plate was mechanically anchored using steel bolts.

For the beam strengthened with mild steel bars, the surface preparation procedure was similar to that used for the ferrocement system. After applying the initial mortar layer, the Ø6 mm mild steel bars were placed longitudinally within the strengthening zone at the tension face of the beam (figure 13). The number of steel bars was selected based on the equivalence criteria described in Section 3.2. Additional mortar layers were applied to fully embed the steel bars and ensure proper bond and stress transfer between the strengthening system and the concrete beam.

Figure 13: Steel bars placed within the cementitious mortar, followed by application of a covering mortar layer.

One beam specimen was initially loaded up to 40% of the ultimate load of the reference beam to induce flexural cracking. After unloading, the damaged beam was prepared for strengthening by roughening and cleaning the concrete surface. The pre-cracked beam was then strengthened using a textile reinforced mortar system, consisting of carbon textile reinforcement embedded within a cementitious mortar containing glass fibers. The strengthening procedure followed the same application sequence adopted for the TRM-strengthened beam. This specimen was intended to evaluate the effectiveness of textile carbon fiber reinforcement in the rehabilitation of pre-cracked reinforced concrete beams (figure 14).

Figure 14: The carbon textile reinforcement was placed onto the fresh mortar and additional mortar layers were applied to fully cover the textile reinforcement after Beam Cracking.

3.1 Results and discussion

The reference beam B-REF showed typical under-reinforced flexural behavior under two-point loading. Initial flexural cracks appeared at mid-span early, followed by steel yielding at 3.5 tons with increased crack width and deflection. The beam reached an ultimate load of 12.5 tons, then failed in a ductile flexural mode due to concrete crushing in the compression zone and wide mid-span cracks.

Figure 15: Crack pattern of reference beam (B-REF) at different load stage.

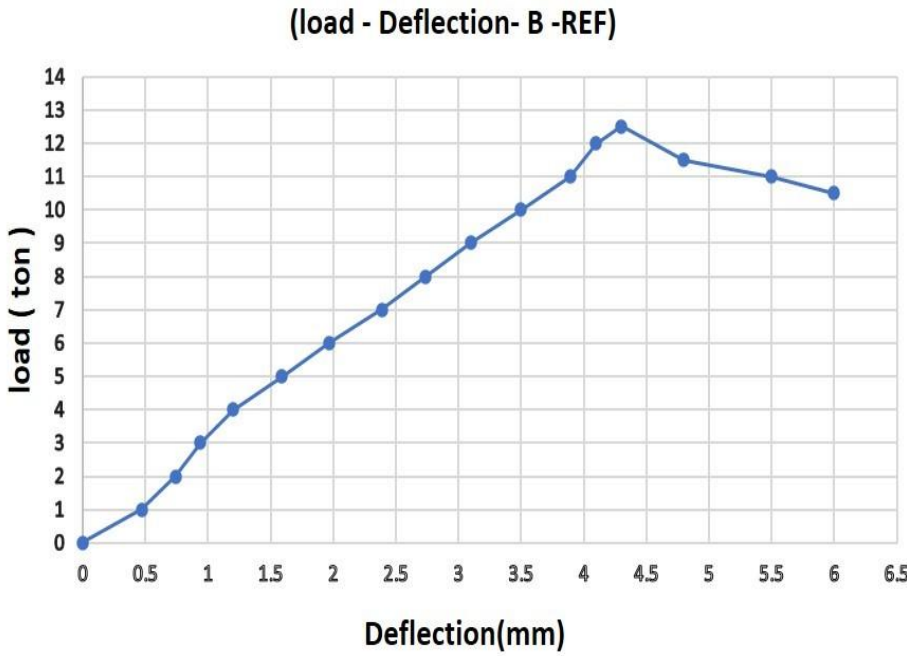

Figure 16: Load–deflection relationship of beam B-REF, Load–strain relationship of beam B-REF.

Beam B-SP, strengthened with a 1 mm steel plate, showed typical flexural cracking under two-point loading, with initial cracks at mid-span. Steel yielding occurred at 4.5 tons with limited crack widening and lower deflection compared to the reference beam. The beam reached an ultimate load of 15 tons and failed in a ductile flexural mode due to concrete crushing in the compression zone, confirming improved stiffness and crack control.

Figure 17: Crack pattern of reference beam (B-SP) at different load stage.

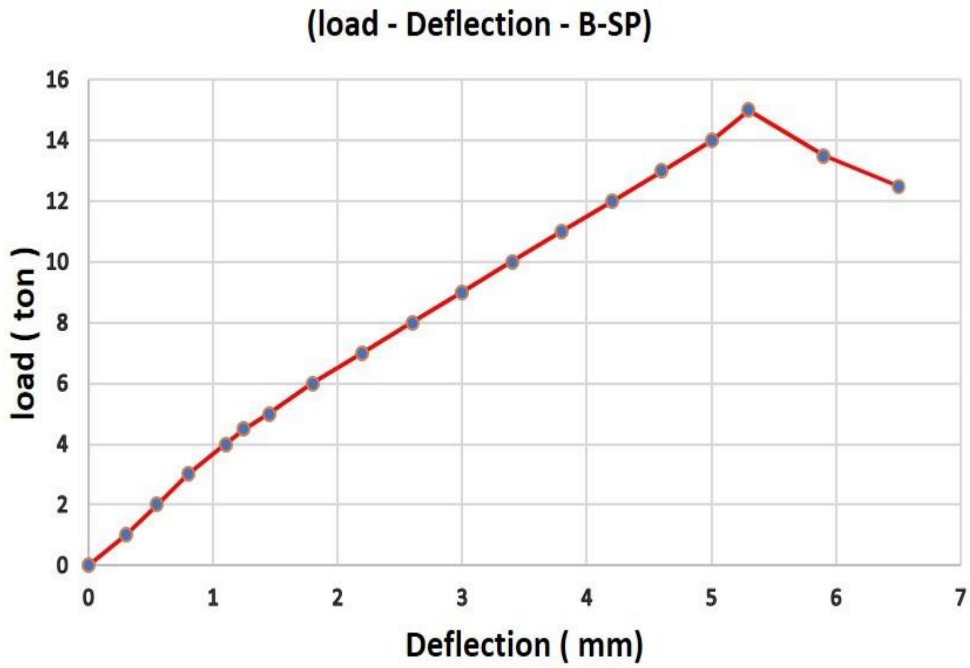

Figure 18: Load–deflection relationship of beam B- SP, Load–strain relationship of beam B-S.

Beam B-MS, strengthened with four mild steel bars (6 mm diameter), showed typical flexural cracking under two-point loading, with initial cracks at mid-span and gradual vertical propagation. Steel yielding occurred at 6 tons with smooth crack widening and stable response. The beam reached an ultimate load of 14.5 tons and failed in a ductile flexural mode due to concrete crushing, confirming improved flexural capacity and crack control compared to the reference beam.

Figure 19: Crack pattern of reference beam (B-MS) at different load stage.

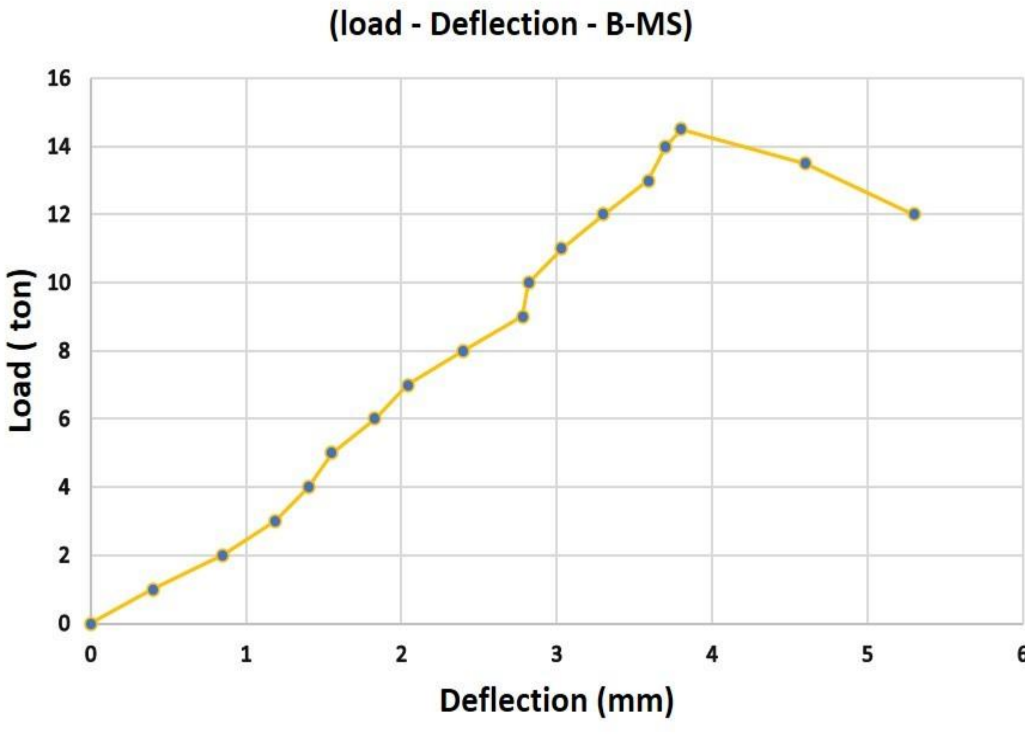

Figure 20: Load–deflection relationship of beam B- MS, Load–strain relationship of beam B-MS.

Beam B-FM, strengthened with a ferrocement layer of three mesh layers at the soffit, showed typical flexural cracking with dense distribution and controlled crack widths. Yielding occurred at 5 tons, and the beam reached an ultimate load of 14 tons at a deflection of 4.5 mm, followed by concrete crushing in the compression zone. Post-peak behavior showed a gradual load reduction, indicating a ductile and stable flexural response.

Figure 21: Crack pattern of reference beam (B-FM) at different load stage.

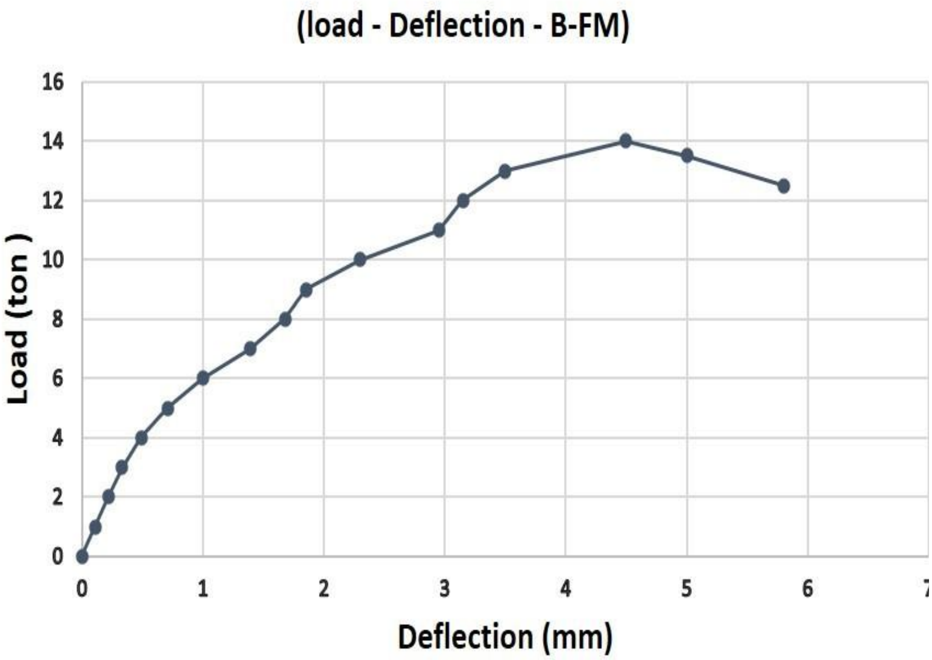

Figure 22: Load–deflection relationship of beam B- FM, Load–strain relationship of beam B-FM.

Beam B-TRM, strengthened with three layers of carbon textile TRM, showed typical flexural cracking under two-point loading with uniform crack distribution and controlled widths. Yielding occurred at 6.5 tons, and the beam reached an ultimate load of 16.5 tons at a deflection of 5.0 mm, followed by localized concrete crushing in the compression zone. Post-peak behavior showed gradual load reduction, indicating a ductile and stable flexural response.

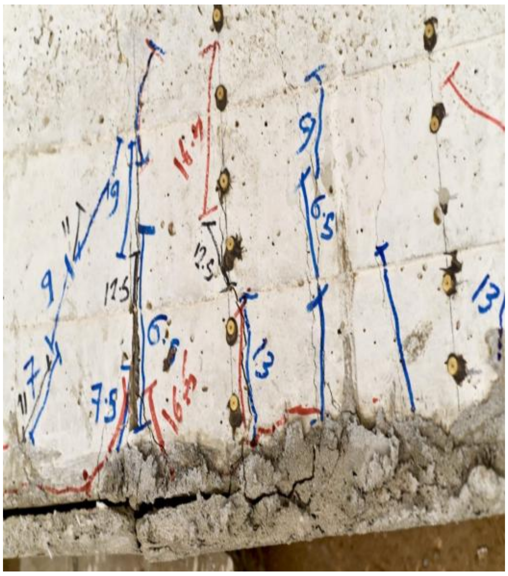

Figure 23: Crack pattern of reference beam (B-TRM) at different load stage.

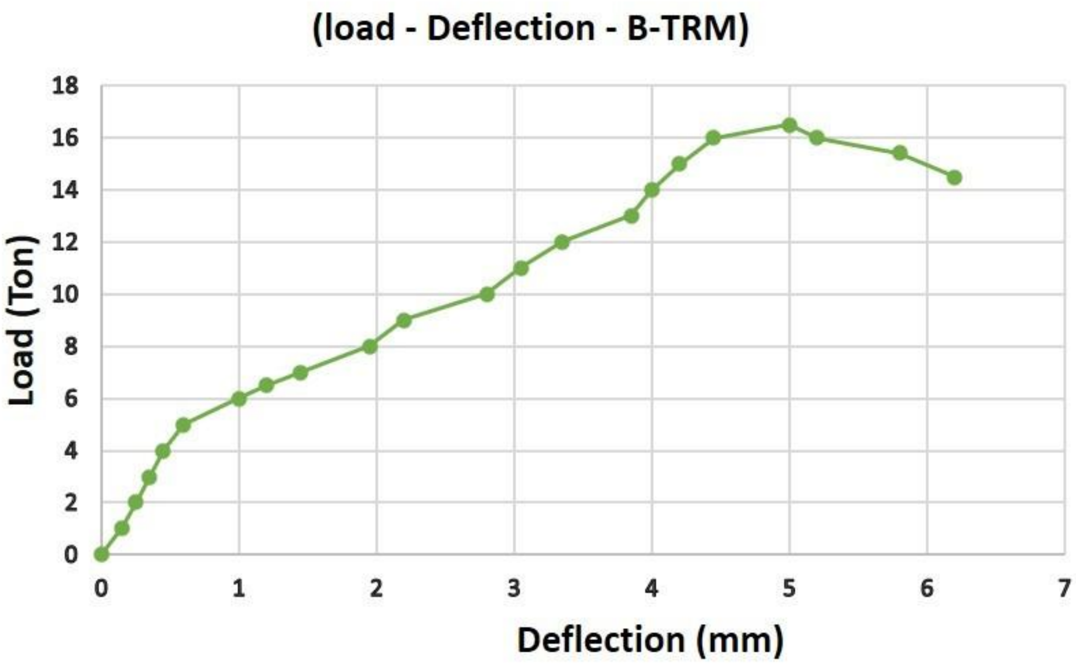

Figure 24: Load–deflection relationship of beam B- TRM, Load–strain relationship of beam TRM.

The pre-cracked beam B-PC-TRM was initially loaded to 4 tons to induce hairline cracks, then repaired and strengthened with three layers of carbon textile in the tension zone. The beam showed nearly linear behavior followed by stiffness reduction after cracking, reaching an ultimate load of 14.5 tons at a deflection of 5.1 mm with a controlled post-peak response. Flexural failure was observed with multiple mid-span cracks and no sudden brittle failure, confirming improved ductility and load capacity due to TRM strengthening

Figure 25: Crack pattern of reference beam (B-PC-TRM) at different load stage.

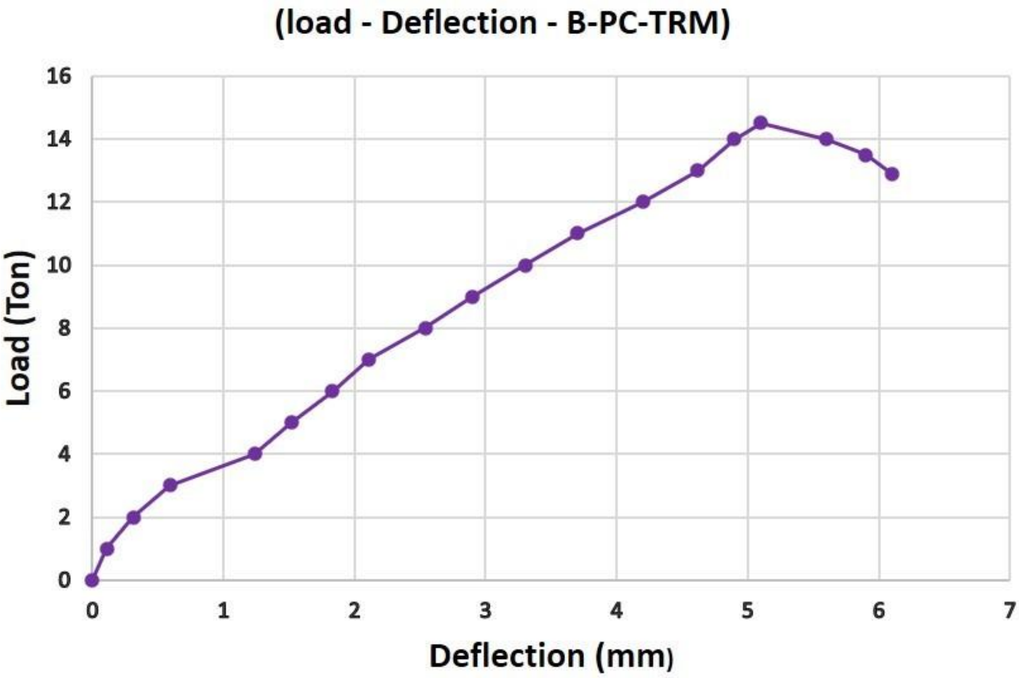

Figure 24: Load–deflection relationship of beam B- PC-TRM, Load–strain relationship of beam B-PC-TRM.

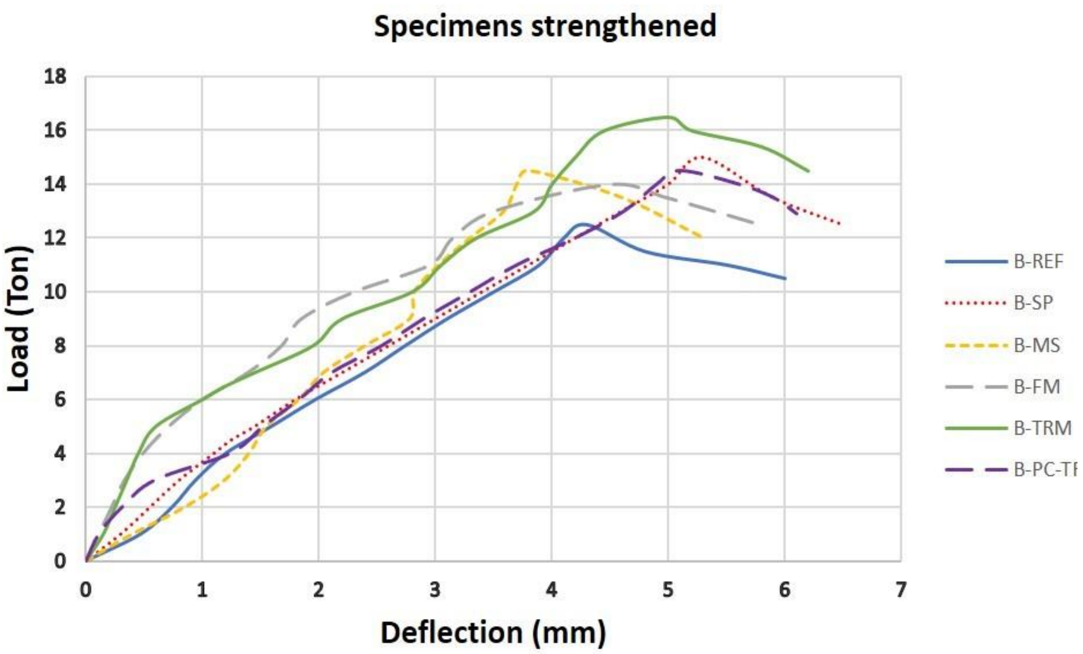

Figure 25: Specimens strengthened.

Specimen	Yield Load (Ton)	Ultimate Load (Ton)	Increase in Ultimate Load (%)
B-REF	3.5	12.5	—
B-SP	4.5	15	20.0
B-MS	6.0	14.5	16.0
B-FM	5.0	14.0	12.0
B-TRM	6.5	16.5	32.0
B-TRM-PC	4.0	14.5	20.0

Table 5: Yield and Ultimate Loads and Percentage Increase of Tested Beams.

IV. CONCLUSION

This study successfully demonstrated the effectiveness of the Textile Reinforced Mortar (TRM) strengthening technique for reinforced concrete beams. The experimental results revealed that the beam strengthened with TRM exhibited the best overall performance in terms of load-carrying capacity, achieving an increase of approximately 32% compared to the reference control beam. In addition, the TRM system showed a high level of efficiency when applied as a rehabilitation technique for pre-cracked beams. The repaired beam strengthened with TRM achieved an improvement of about 20% in ultimate load capacity relative to the reference beam, confirming the strong potential of TRM not only for strengthening but also for structural rehabilitation purposes. When compared with conventional strengthening methods, the beam strengthened using steel Plate (SP) showed an increase in ultimate load capacity of approximately 20%. This was followed by the beam strengthened with steel bar, which achieved an improvement of about 16%. The ferrocement strengthened beam showed the lowest enhancement, with an increase of approximately 12% in ultimate load capacity. Overall, the findings of this study confirm the superior efficiency of the TRM system in both strengthening and repairing applications, highlighting its effectiveness compared to traditional strengthening techniques.

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