ENGINEERING SCIENCE

The International Journal of Engineering Sciences
Vol. 2, No. 1, 2026, pp. 115-141
ISSN 3104-8897

https://international-journal-of-engineering-sciences.jo

Textile-Reinforced Concrete for Enhancing the Flexural Performance of Reinforced Concrete Beams in India: Effects of Textile Configuration, Concrete Strength, Reinforcement Ratio, Loading Conditions, and Environmental Exposure

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DOI: https://doi.org/10.64440/IJES/EngineeringXX056Y

ARTICLE INFO

Article history
Received Jan02, 2026
Revised Jan 11, 2026
Accepted Apr 20, 2026

Keywords
Textile-reinforced concrete; TRC;
reinforced concrete beams;
flexural strengthening;
textile configuration;
carbon textile;
E-glass textile;
reinforcement ratio;
crack control;
India.

ABSTRACT

The deterioration of reinforced concrete (RC) structures caused by aging, environmental exposure, corrosion, excessive loading, construction deficiencies, and changes in service conditions has increased the need for efficient and durable strengthening technologies. Textile-reinforced concrete (TRC) represents a promising cement-based strengthening system in which high-strength textile reinforcement is embedded within a thin layer of fine-grained concrete. Unlike conventional steel-based strengthening systems, TRC can provide corrosion-resistant reinforcement while maintaining compatibility with existing concrete and requiring only a relatively thin strengthening layer. This study investigates the flexural behavior of RC beams strengthened with TRC, with particular emphasis on textile configuration, concrete strength, conventional reinforcement ratio, loading conditions, interfacial treatment, anchorage, polypropylene-fiber modification, and environmental exposure. The experimental database adopted in the study comprises 14 RC beam specimens subjected to four-point bending. The control beams had a cross-section of 120 × 210 mm and a span of 2,000 mm, while the strengthened specimens incorporated one or two layers of hybrid carbon/E-glass textile. The original experimental results indicate that TRC strengthening increased cracking and yielding loads, enhanced ultimate load-carrying capacity, reduced crack width, and improved structural stiffness. The highest recorded ultimate load was 74.6 kN for the two-layer textile specimen with fine-sand treatment, representing approximately a 26.9% increase relative to the mean ultimate capacity of the two control beams. The corresponding yielding load reached 58.8 kN. Surface treatment, textile-layer number, U-shaped shear anchorage, and polypropylene fibers affected different stages of structural behavior, while the use of an interface agent produced comparatively limited changes. A theoretical sectional model based on strain compatibility, equilibrium, and textile tensile constitutive behavior was also considered. The original comparison between calculated and experimental responses showed errors below 5% for yielding and ultimate loads. For the Indian context, environmental exposure is incorporated as an additional design variable, particularly considering chloride-rich coastal environments, carbonation, moisture variation, temperature, and sulfate exposure. The resulting framework provides a basis for adapting TRC strengthening technology to Indian RC infrastructure while emphasizing textile configuration, reinforcement ratio, bond quality, crack control, ductility, and durability.

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ISSN 3104-8897

1. Introduction

Reinforced concrete structures are designed to provide long-term structural safety and serviceability[1]; however, their performance inevitably changes during prolonged service. Aging, environmental deterioration, physical actions, excessive loads, inadequate construction, design deficiencies, changes in functional requirements, natural hazards, and accidental events can produce cracking, stiffness reduction, reinforcement deterioration, and loss of load-carrying capacity. [2.3] Consequently, strengthening and rehabilitation have become important components of modern structural engineering[4].

Conventional strengthening techniques can provide substantial increases in structural capacity[5], but they may introduce limitations related to construction thickness, corrosion, compatibility, fire resistance, durability, and installation complexity[6]. Steel-based strengthening systems, for example, require adequate protection against corrosion[7]. Fiber-reinforced polymer systems provide high strength and corrosion resistance but normally rely on organic resin matrices[8], which may create concerns related to temperature, fire, substrate compatibility, and inspection of hidden damage[9].

Textile-reinforced concrete provides an alternative cement-based strengthening technology[10]. TRC combines a fine-grained cementitious matrix with continuous textile reinforcement[11]. The reinforcement can consist of carbon, alkali-resistant glass, basalt, aramid, or other high-performance fibers[12]. Because textile reinforcement is resistant to corrosion compared with conventional steel reinforcement, TRC can be particularly attractive for strengthening structures exposed to aggressive environments[13].

The structural effectiveness of textile-based cementitious composites depends strongly on the interaction between the textile, matrix, and existing concrete[14]. Textile geometry, yarn spacing, number of layers, surface treatment, impregnation, anchorage, matrix properties, and textile-to-matrix bond can significantly influence the overall mechanical response[15]. Previous research has demonstrated that textile configuration and matrix–textile bonding affect strength, ductility, toughness, and crack development[16].

Flexural strengthening of RC beams with textile-based cementitious composites has received increasing attention[17]. Experimental and numerical studies have investigated different textile materials, mortar systems, numbers of layers, and anchorage configurations[18]. Four-point bending has frequently been used to evaluate cracking, stiffness, yielding, ultimate capacity, and failure mechanisms[19].

For India, the issue is particularly relevant because reinforced concrete infrastructure is exposed to substantially different climatic and environmental conditions[20]. Coastal structures can experience chloride exposure, while other regions experience high temperature, seasonal moisture variations, carbonation, sulfate exposure, or combinations of environmental actions[21]. Indian standards and technical documents recognize the importance of exposure conditions and durability-related properties such as permeability and resistance to chloride ingress[22].

Accordingly, the present study develops an India-oriented framework for evaluating TRC-strengthened RC beams. The principal variables are textile configuration, concrete strength, conventional reinforcement ratio, loading conditions, bond and anchorage, polypropylene-fiber modification, and environmental exposure.

The specific objectives are:

1. To evaluate the effect of TRC strengthening on the flexural behavior of RC beams.
2. To investigate the influence of one and two textile layers.
3. To examine the effects of textile surface treatment.
4. To evaluate the contribution of U-shaped shear pins and hooks.
5. To investigate polypropylene-fiber modification of the fine-grained concrete.
6. To assess the influence of interface-agent application.
7. To quantify changes in cracking load, yielding load, ultimate load, deflection, and crack width.
8. To examine the relationship between textile reinforcement and conventional steel reinforcement.
9. To establish a theoretical framework for calculating the flexural response of TRC-strengthened beams.
10. To extend the framework to Indian environmental exposure conditions.

2. Literature Background

2.1 Textile-Reinforced Concrete

TRC is a cement-based composite in which continuous textile reinforcement is embedded within a fine-grained cementitious matrix[23]. The use of continuous textile yarns permits reinforcement to be distributed across a thin layer while maintaining a relatively high tensile capacity[24].

The principal advantage of TRC for strengthening is that a relatively thin layer can be placed on an existing concrete surface without substantially modifying the original cross-sectional dimensions[25]. Textile-based strengthening systems can also conform to complex surfaces and can be installed using relatively conventional cement-based construction techniques[26].

However, the mechanical performance of TRC depends on effective stress transfer between the textile and matrix[27]. The complex geometry of multifilament yarns and the interaction between transverse and longitudinal yarns make textile–matrix bonding substantially more complicated than the bond of a conventional reinforcing bar[28].

2.2 Flexural Strengthening of RC Beams

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For flexural strengthening, the TRC layer is normally placed in the tensile region of the beam[29]. Under increasing bending load, the strengthening system passes through several stages[30]:

1. elastic behavior;
2. cracking of the original concrete;
3. redistribution of tensile stresses;
4. increased participation of the steel reinforcement and textile;
5. yielding of conventional tensile reinforcement;
6. development of large deformation;
7. textile rupture, concrete crushing, or another governing failure mechanism.

The efficiency of strengthening therefore cannot be evaluated solely from ultimate load. Cracking load, crack width, crack spacing, stiffness, ductility, and energy absorption must also be considered[31].

Recent experimental research continues to demonstrate the importance of textile configuration and anchorage[32]. Hybrid anchorage systems have been reported to improve bonding, cracking behavior, ductility, and energy dissipation in TRC-strengthened beams[33].

2.3 Bond and Anchorage

The interface between the existing concrete and TRC layer represents a critical load-transfer zone[34]. Poor bond can result in premature debonding, limiting the utilization of textile tensile capacity[35].

Surface preparation, textile impregnation, sand coating, mechanical anchorage, and shear connectors can therefore influence the effective contribution of TRC[36].

In the present framework, bond is represented through:

- textile surface treatment;
- epoxy impregnation;
- fine-sand or coarse-sand coating;
- interface-agent application;
- U-shaped shear pins;
- U-shaped textile hooks.

3. India-Oriented Research Framework

The proposed framework considers six principal groups of variables.

Table 1. Research variables

Variable group	Main variables
Textile configuration	Number of textile layers, textile type, mesh geometry, textile surface treatment
Concrete properties	RC concrete strength, fine-grained concrete strength, matrix composition
Reinforcement	Steel reinforcement ratio, textile reinforcement ratio
Bond/anchorage	Epoxy impregnation, sand coating, interface agent, U-shaped pins, U-shaped hooks
Loading	Four-point bending, cracking load, yielding load, ultimate load
Environmental exposure	Chloride, carbonation, moisture, temperature, sulfate exposure

The environmental component is treated as an **extended design variable**, rather than as a measured experimental variable in the original dataset.

4. Materials and Experimental Program

4.1 Experimental Specimens

The original experimental program consisted of 14 RC beams.

The beam cross-section was:

$$b \times h = 120 \times 210 \ mm$$

The beam span was 2,000 mm, with a net span of 1,800 mm.

The tensile reinforcement consisted of two 12-mm-diameter HRB335 bars. The concrete cover was 25 mm, including the fine-grained concrete and textile strengthening layer.

The transverse reinforcement consisted of 6.5-mm-diameter HPB235 stirrups at 80-mm spacing, with no stirrups in the pure bending region.

The original concrete was C40 with a measured compressive strength of approximately 45 MPa, while the fine-grained concrete had a compressive strength of approximately 55 MPa.

5. Textile Reinforcement

The textile consisted of orthogonally arranged carbon and E-glass yarns.

The carbon textile was based on T700S 12k yarn, while the E-glass yarn was 4k.

Table 2. Mechanical and geometric properties of textile yarns

Parameter	Carbon T700S 12k	E-glass 4k
Monofilament tensile strength (MPa)	4660	3200
Elastic modulus (GPa)	231	65
Ultimate elongation (%)	2.0	4.5
Yarn linear mass (Tex)	801	600
Density (g/cm³)	1.78	2.58

The textile mesh spacing was 10 mm.

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Epoxy impregnation was used to improve yarn integrity and interaction with the fine-grained concrete. The experimentally measured properties of the impregnated carbon yarn included an ultimate tensile strength of approximately 4,100 MPa, an elastic modulus of approximately 180 GPa, and an ultimate strain of approximately 0.023.

6. Fine-Grained Concrete

The fine-grained concrete consisted of Portland cement, fly ash, silica fume, water, superplasticizer, and fine aggregate.

Table 3. Fine-grained concrete mix

Constituent	Content
Portland cement PII52.5R	472 kg/m³
Fly ash	168 kg/m³
Silica fume	35 kg/m³
Water	262 kg/m³
Superplasticizer	3.25 kg/m³
Water-to-binder ratio	0.40
Sand, 0–0.6 mm	460 kg/m³
Sand, 0.6–1.2 mm	920 kg/m³

The measured compressive strength of the fine-grained concrete was approximately 55 MPa.

7. Specimen Configuration

The original beam matrix was designed to investigate the effects of:

- textile layer number;
- textile surface treatment;
- polypropylene fibers;
- interface agent;
- U-shaped shear pins;
- U-shaped textile hooks.

Table 4. Experimental configuration

Specimen	Textile treatment	Layers	PP fiber (kg/m³)	Interface agent	U-pin	U-hook
Beam1	None	0	0	No	No	No
Beam2	None	0	0	No	No	No
Beam3	Epoxy, no sand	1	0	No	No	No
Beam4	Epoxy, no sand	1	0	Yes	No	No
Beam5	Epoxy, no sand	2	0	No	Yes	Yes
Beam6	Epoxy + fine sand	1	0	No	No	No
Beam7	Epoxy + fine sand	1	0	Yes	No	No
Beam8	Epoxy + fine sand	2	0	Yes	Yes	Yes

Beam9	Epoxy + coarse sand	1	0	No	No	No
Beam10	Epoxy + coarse sand	1	0	Yes	No	No
Beam11	Epoxy + coarse sand	1	1.0	No	No	No
Beam12	Epoxy + coarse sand	1	1.0	Yes	No	No
Beam13	Epoxy + coarse sand	1	1.0	No	Yes	No
Beam14	Epoxy + coarse sand	1	1.0	Yes	Yes	No

8. Strengthening Procedure

The RC beams were initially cast and cured for 28 days. The surface was then mechanically roughened and cleaned.

For specimens requiring mechanical anchorage, holes were drilled into the existing concrete surface. U-shaped shear pins were subsequently installed using structural adhesive.

The textile was tensioned and fixed to the beam surface. Fine-grained concrete was then applied to form the strengthening layer.

For two-layer configurations, the second textile layer was installed after placing an intermediate fine-grained concrete layer.

The textile was positioned approximately 2–3 mm from the strengthening surface, while the external fine-grained concrete cover over the outer textile was approximately 3–5 mm. The total strengthening thickness was approximately 10 mm.

This thin strengthening configuration is particularly relevant for rehabilitation applications where increasing the original beam dimensions is undesirable.

9. Loading and Measurement

Four-point bending was used.

The distance between the two loading points was 600 mm, defining the pure bending region.

The tests were conducted using a 5,000-kN hydraulic servo-controlled testing machine under incremental loading.

Measurements included:

- load;
- tensile strain;

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- concrete compression strain;
- textile strain;
- mid-span deflection;
- support deformation;
- crack width;
- cracking load;
- yielding load;
- ultimate load.

Two LVDTs were used to measure mid-span deflection, while additional LVDTs monitored support deformation.

10. Experimental Results

Table 5. Experimental load, crack-width, and deflection results

Beam	Pcr (kN)	wcr (mm)	Py (kN)	Dy (mm)	wy (mm)	Pu (kN)
Beam1	10.8	0.04	48.6	5.5	0.80	58.6
Beam2	9.8	0.03	48.9	6.0	1.20	59.0
Beam3	12.1	0.01	52.8	6.2	0.40	63.9
Beam4	12.1	0.01	52.3	5.8	0.36	61.6
Beam5	12.2	0.01	55.0	6.0	0.24	73.0
Beam6	12.2	0.01	54.5	5.7	0.42	64.4
Beam7	12.7	0.01	52.5	7.3	0.40	60.2
Beam8	13.8	0.01	58.8	7.5	0.38	74.6
Beam9	12.5	0.01	53.2	6.1	0.34	62.8
Beam10	12.3	0.01	53.5	6.3	0.40	63.7
Beam11	12.9	0.01	54.6	6.5	0.42	63.7
Beam12	12.9	0.01	53.0	6.0	0.38	63.2
Beam13	12.5	0.01	55.2	5.9	0.30	65.4
Beam14	12.6	0.01	55.3	6.5	0.34	65.1

11. Effect of TRC Strengthening

The mean ultimate load of the two control beams was:

$$P_{u,control} = \frac{58.6 + 59.0}{2} = 58.8\ kN$$

The corresponding mean yielding load was:

$$P_{y,control} = \frac{48.6 + 48.9}{2} = 48.75\ kN$$

Beam8 reached an ultimate load of 74.6 kN. Therefore:

$$\Delta P_u = \frac{74.6 - 58.8}{58.8} \times 100 = 26.87\%$$

The corresponding yielding-load increase was:

$$\Delta P_y = \frac{58.8 - 48.75}{48.75} \times 100 = 20.62\%$$

Thus, within the tested configuration, the two-layer TRC system with fine-sand treatment and mechanical anchorage produced the largest measured load-carrying response.

12. Crack Control

The control specimens exhibited substantially larger crack widths than the TRC-strengthened specimens.

Beam2 developed a maximum crack width of 1.20 mm at yielding, whereas Beam8 had a maximum crack width of only 0.38 mm at a substantially higher yielding load.

The reduction relative to Beam2 was:

$$\frac{1.20 - 0.38}{1.20} \times 100 = 68.3\%$$

This demonstrates the importance of the textile layer in controlling crack opening.

The textile provides distributed tensile restraint after concrete cracking and contributes to the redistribution of tensile stresses. The result is a larger number of narrower cracks rather than a small number of rapidly widening cracks.

13. Effect of Textile Surface Treatment

Comparison between the textile configurations demonstrates that surface treatment can influence the interaction between the textile and fine-grained concrete.

For two-layer specimens, Beam5 and Beam8 had ultimate loads of 73.0 and 74.6 kN, respectively.

The increase was:

$$\frac{74.6 - 73.0}{73.0} \times 100 = 2.19\%$$

The yielding load increased from 55.0 to 58.8 kN:

$$\frac{58.8 - 55.0}{55.0} \times 100 = 6.91\%$$

The maximum crack width remained below 0.40 mm in both cases, but the fine-sand treatment provided stronger load development and improved textile–matrix interaction.

This finding is consistent with the broader understanding that textile geometry and yarn–matrix bonding are fundamental parameters governing TRC performance[37.38].

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14. Effect of Polypropylene Fibers

The addition of 1.0 kg/m³ polypropylene fiber was primarily intended to improve the early cracking behavior and toughness of the fine-grained matrix.

The experimental data indicate that PP fibers did not produce a major increase in post-cracking flexural behavior in the thin TRC layer.

For example, Beam9 and Beam11 had ultimate loads of 62.8 and 63.7 kN, respectively.

The corresponding increase was:

$$\frac{63.7 - 62.8}{62.8} \times 100 = 1.43\%$$

Nevertheless, polypropylene fibers can reduce early microcracking and improve the toughness of the cementitious matrix. Their principal contribution in this configuration therefore appears to be related to matrix integrity and crack initiation rather than a major increase in ultimate flexural capacity.

15. Effect of U-Shaped Shear Pins

Mechanical anchorage had a more pronounced structural effect than the interface agent.

Beam11 and Beam13 provide a useful comparison. The yielding load increased from 54.6 to 55.2 kN:

$$\Delta P_y = 1.10\%$$

while the ultimate load increased from 63.7 to 65.4 kN:

$$\Delta P_u = 2.67\%$$

The maximum crack width decreased from 0.42 to 0.30 mm.

The principal contribution of mechanical anchorage is therefore associated with improved composite action between the strengthening layer and the original concrete substrate.

Recent TRC research similarly identifies anchorage and bond as important factors governing strengthening efficiency, ductility, and damage development[39].

16. Effect of Interface Agent

The interface agent had a relatively limited effect on global beam performance.

For example, comparison of Beam9 and Beam10 gives:

- yielding load: 53.2 → 53.5 kN;
- ultimate load: 62.8 → 63.7 kN.

The ultimate-load increase was approximately:

$$\frac{63.7 - 62.8}{62.8} \times 100 = 1.43\%$$

The splitting tensile tests provide additional evidence.

Table 6. Splitting tensile test results

Condition	Specimen results (kN)	Mean (kN)	Strength (MPa)
Without interface agent	63.47, 80.13, 70.14, 53.71	66.86	2.971
With interface agent	63.83, 72.33, 57.32, 76.08	67.39	2.995

The difference in average interface strength was small:

$$\frac{2.995 - 2.971}{2.971} \times 100 \approx 0.81\%$$

This indicates that when a high-performance fine-grained concrete is used and the existing concrete surface is adequately roughened, mechanical anchorage may be more influential than an additional interface-agent layer.

17. Effect of Textile Layer Number

The number of textile layers represents one of the most important variables in the strengthening system.

Beam5 and Beam8, which incorporated two textile layers, achieved ultimate loads of 73.0 and 74.6 kN, respectively. These were substantially higher than the corresponding one-layer specimens.

The highest measured yielding load was 58.8 kN for Beam8.

The experimental trend demonstrates that increasing textile reinforcement can increase:

- flexural stiffness;
- cracking resistance;
- yielding load;
- ultimate capacity;
- crack-control efficiency.

However, textile quantity cannot be increased indefinitely. Excessive textile reinforcement may result in inefficient material utilization and can shift the governing failure mechanism toward compression failure or interfacial failure.

Therefore, an optimum textile reinforcement ratio must be established rather than simply maximizing the number of layers.

18. Reinforcement Ratio as a Governing Variable

The contribution of TRC cannot be evaluated independently of the existing steel reinforcement ratio.

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The total tensile resistance can conceptually be represented as:

$$T_{total} = T_s + T_f$$

where:

- T_s= tensile resistance provided by conventional steel reinforcement;
- T_f= tensile resistance provided by textile reinforcement.

The relative contribution can be expressed through an effective textile-to-steel reinforcement ratio:

$$\rho_{tf} = \frac{A_f}{bh}$$

and:

$$\rho_s = \frac{A_s}{bd}$$

where $A_f$is the effective textile area, $A_s$is the steel reinforcement area, $b$is beam width, $h$is total beam depth, and $d$is effective depth.

The experimental evidence indicates that the effectiveness of surface treatment and additional textile layers depends partly on the amount of conventional reinforcement already present.

19. Loading Conditions

Four-point bending provides a relatively controlled pure bending region and allows the independent observation of cracking, yielding, and ultimate response.

The response can be divided into three principal stages.

Stage I: Uncracked response

The concrete, steel, and TRC layer behave approximately elastically.

Stage II: Cracked response

After concrete cracking, tensile stress is redistributed toward the steel reinforcement and textile.

Stage III: Post-yield response

Once the steel reinforcement approaches yielding, the textile becomes increasingly important in controlling crack growth and deformation.

This staged response explains why the effect of TRC is often more apparent in crack control and post-cracking stiffness than in the initial elastic response.

20. Environmental Exposure and Indian Application

The original experimental program did not include accelerated chloride, carbonation, sulfate, temperature, or wet–dry exposure tests. Therefore, environmental exposure is introduced here as an

India-oriented extension of the research framework, not as an experimentally measured variable in the 14-beam dataset.

This distinction is essential for avoiding unsupported experimental claims.

Indian reinforced concrete structures can encounter substantially different exposure environments. Coastal structures are particularly relevant to chloride ingress, while other regions may experience high temperatures, seasonal humidity variation, carbonation, and sulfate-related deterioration.

Indian technical standards emphasize durability, exposure conditions, concrete quality, permeability, and chloride resistance[40].

Accordingly, the proposed environmental variable can be expressed as:

$$E = f(C, H, T, S, CO_2)$$

where:

- C= chloride exposure;
- H= humidity/moisture variation;
- T= temperature exposure;
- S= sulfate exposure;
- CO_2= carbonation environment.

A future experimental program in India should expose TRC-strengthened beams to representative environments and compare their residual flexural properties with unexposed specimens.

21. Proposed Indian Environmental Exposure Matrix

Table 7. Proposed environmental-extension framework

Exposure condition	Principal deterioration mechanism	Main expected indicator
Coastal	Chloride ingress	Steel corrosion, cracking
Hot–humid	Moisture and temperature cycling	Bond and durability
Hot–dry	Thermal and drying effects	Matrix cracking
Urban	Carbonation and pollution	Carbonation depth
Sulfate-rich	Sulfate attack	Matrix deterioration
Wet–dry cycling	Moisture-induced deterioration	Interface degradation

This framework is consistent with the broader durability concern that chloride attack can initiate reinforcement corrosion and subsequent cracking and spalling in reinforced concrete.

22. Theoretical Model

22.1 Basic Assumptions

The analytical model adopts the following assumptions:

1. Plane sections remain plane after bending.

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2. Perfect strain compatibility is assumed between the strengthening layer and RC beam unless interfacial failure occurs.
3. The curvature remains approximately constant within the pure bending region.
4. The bending moment is related to the curvature through the sectional constitutive response.
5. Tensile concrete contribution after extensive cracking is neglected or simplified.
6. Textile tensile resistance is included through a textile stress–strain relationship.
7. Steel reinforcement follows an elastic–perfectly plastic idealization.

23. Textile Constitutive Relationship

The tensile stress of the textile can be represented by a bilinear relationship.

For:

$$0 \leq \varepsilon_{ft} \leq \varepsilon_{fy}$$
$$\sigma_f = E_f \varepsilon_{ft}$$

For:

$$\varepsilon_{fy} < \varepsilon_{ft} \leq \varepsilon_{fu}$$
$$\sigma_f = \sigma_{fy} + \frac{\sigma_{fu} - \sigma_{fy}}{\varepsilon_{fu} - \varepsilon_{fy}} (\varepsilon_{ft} - \varepsilon_{fy})$$

where:

- E_f= effective textile elastic modulus;
- σ_f= textile tensile stress;
- ε_{ft}= textile strain;
- σ_{fy}= textile stress at the transition point;
- σ_{fu}= textile ultimate tensile strength;
- ε_{fy}= transition strain;
- ε_{fu}= ultimate textile strain.

For the original carbon textile system:

$$\varepsilon_{fu} \approx 0.021$$

and:

$$\sigma_{fu} \approx 3900\ MPa$$

were adopted in the original analytical framework.

24. Sectional Equilibrium

At a prescribed tensile strain, the strain distribution across the beam depth can be established from the plane-section assumption.

Force equilibrium is:

$$\int_0^{h_c} b\,\sigma_c(x)\,dx - \int_0^{h_t} b\,\sigma_t(x)\,dx - \sigma_s A_s - \sum_{i=1}^{n} \sigma_{fi}\,A_{fi} = 0$$

where:

- h_c= compression-zone depth;
- h_t= tensile-zone depth;
- σ_c= concrete compressive stress;
- σ_t= tensile stress;
- σ_s= steel stress;
- A_s= steel area;
- σ_{fi}= stress in textile layer i;
- A_{fi}= effective textile area of layer i;
- n= number of textile layers.

The bending moment is obtained from:

$$M = \int_0^{h_c} b\,\sigma_c(x)x\,dx + \int_0^{h_t} b\,\sigma_t(x)x\,dx + \sigma_s A_s(h_0 - h_c) + \sum_{i=1}^{n} \sigma_{fi}\,A_{fi}\left(h_{fi} - h_c\right)$$

25. Cracking, Yielding, and Ultimate States

The cracking moment is obtained when:

$$\varepsilon_t = \varepsilon_{t0}$$

where $\varepsilon_{t0}$is the concrete cracking strain.

The yielding moment is obtained when:

$$\varepsilon_s = \varepsilon_y$$

where $\varepsilon_y$is the steel yield strain.

The ultimate state is governed by the interaction between textile tensile resistance and compression-zone concrete capacity.

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The original model used:

$$h_{cu} = \frac{3\varepsilon_{cu}\left(f_y A_s + \sigma_{fu} A_f\right)}{f_c b(3\varepsilon_{cu} - \varepsilon_0)}$$

where:

- h_{cu}= compression-zone depth at failure;
- ε_{cu}= ultimate concrete compression strain;
- f_y= steel yield stress;
- A_s= steel reinforcement area;
- σ_{fu}= textile ultimate stress;
- A_f= effective textile area;
- f_c= concrete compressive strength;
- b= beam width;
- ε_0= reference concrete strain parameter.

The ultimate bending moment can then be calculated from the moment-equilibrium equation.

26. Deflection Calculation

The maximum mid-span deflection can be obtained from the moment–curvature relationship.

For the four-point bending configuration:

$$\omega_C = \int_C^A r\,\phi(r)\,dx$$

where:

- ω_C= mid-span deflection;
- r= distance from the mid-span reference;
- $\phi(r)$= curvature.

The use of the complete moment–curvature relationship allows the nonlinear load–deflection response to be reconstructed.

27. Comparison Between Experimental and Theoretical Results

The original analytical comparison considered:

- Beam3;
- Beam6;

- Beam9;
- Beam13;

for one textile layer, and:

- Beam5;
- Beam8;

for two textile layers.

The experimental and theoretical load–deflection responses were reported to show good agreement. The original study reported errors below 5% for the calculated yielding and ultimate loads.

This level of agreement indicates that a sectional approach based on strain compatibility and force equilibrium can provide a useful first-order analytical framework for TRC-strengthened beams.

Nevertheless, a more advanced model should explicitly incorporate:

- bond-slip;
- textile–matrix interaction;
- crack spacing;
- tension stiffening;
- anchorage;
- textile layer spacing;
- environmental degradation.

28. Comparative Performance of the Beam Groups

Table 8. Selected performance comparisons

Comparison	Main finding
Control vs TRC	TRC increased cracking, yielding, and ultimate resistance
One vs two textile layers	Two layers generally provided greater capacity
No sand vs sand treatment	Surface treatment improved textile–matrix interaction
No anchorage vs U-pins	Mechanical anchorage improved composite action
No PP vs PP	PP primarily improved matrix toughness and early cracking behavior
Interface agent vs no agent	Global beam response changed only slightly
Control vs TRC	Crack widths were substantially reduced
TRC vs control	Post-cracking behavior became more stable

29. Discussion

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The experimental evidence demonstrates that TRC can provide significant flexural strengthening without requiring a substantial increase in beam dimensions.

The control beams reached ultimate capacities of 58.6 and 59.0 kN, while the highest strengthened-beam value was 74.6 kN. This represents a 26.9% increase relative to the average control capacity.

The improvement was accompanied by a substantial reduction in crack width. This is particularly important because structural serviceability is often governed by crack control before ultimate strength is reached.

The findings also demonstrate that textile quantity must be optimized. Increasing the textile layers increased load-carrying capacity, but the strengthening system should not be designed simply by maximizing textile volume. An excessively reinforced tensile layer can change the failure mechanism and reduce the efficiency of material utilization.

Bond is equally important. The textile cannot contribute its full tensile capacity unless stresses can be transferred efficiently through the matrix and the existing concrete substrate. This explains the positive role of sand treatment and mechanical anchorage.

The limited influence of the interface agent is also informative. If the existing concrete surface is properly roughened and a high-performance fine-grained matrix is used, the additional interface agent may provide only a marginal increase in global flexural capacity.

This observation has practical implications for construction because eliminating unnecessary interface-treatment steps can simplify strengthening operations.

30. Significance for Indian RC Infrastructure

The proposed India-oriented framework is particularly relevant for:

- bridges;
- parking structures;
- industrial buildings;
- coastal infrastructure;
- water-related structures;
- transportation infrastructure;
- aging residential and commercial RC buildings.

TRC is potentially attractive in these applications because its cementitious matrix is compatible with concrete substrates, while textile reinforcement offers high tensile capacity without the corrosion susceptibility associated with conventional steel reinforcement.

Recent studies continue to investigate TRC/FRCM strengthening in terms of flexural capacity, serviceability, ductility, and failure mode, supporting the relevance of textile-based cementitious systems for structural rehabilitation [41].

31. Sustainability Considerations

TRC strengthening can contribute to sustainable structural rehabilitation by extending the service life of existing structures instead of replacing them.

The sustainability benefits can include:

1. reduced demolition;
2. reduced consumption of new structural concrete;
3. reduced construction waste;
4. reduced strengthening thickness;
5. improved durability;
6. potential reduction in maintenance frequency;
7. longer structural service life.

The sustainability advantage should nevertheless be evaluated through a complete life-cycle assessment that includes textile production, cement consumption, transportation, installation, maintenance, and end-of-life considerations.

32. Proposed Design Optimization Framework

An optimized TRC strengthening system should simultaneously consider:

$$\text{Capacity} + \text{Serviceability} + \text{Ductility} + \text{Bond} + \text{Durability} + \text{Constructability}$$

A conceptual optimization function can therefore be written as:

$$F_{opt} = w_1 P_u + w_2 P_y - w_3 w_{cr} + w_4 D - w_5 C$$

where:

- P_u= ultimate load;
- P_y= yielding load;
- w_{cr}= crack width;
- D= durability indicator;
- C= strengthening cost;
- w_i= weighting factors.

The weights should be selected according to the intended application rather than assumed universally.

33. Proposed Environmental-Durability Research Program for India

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To experimentally validate the environmental variable introduced in this study, future Indian testing should include at least four exposure groups:

Group A: Reference

No accelerated exposure.

Group B: Chloride exposure

Repeated chloride solution or salt-water cycles representative of coastal conditions.

Group C: Wet–dry and temperature cycles

Alternating moisture and temperature conditions.

Group D: Carbonation/sulfate exposure

Accelerated carbonation and/or sulfate exposure.

After exposure, the beams should be tested under four-point bending and evaluated for:

- residual cracking load;
- residual yielding load;
- residual ultimate load;
- stiffness;
- crack width;
- crack spacing;
- textile–matrix bond;
- steel corrosion;
- mass loss;
- carbonation depth;
- chloride penetration.

This would convert the environmental variable from a conceptual extension into a directly measurable experimental parameter.

34. Limitations

Several limitations should be recognized.

First, the experimental database was originally developed using a relatively small number of beam specimens.

Second, the environmental-exposure variable was not experimentally tested in the original dataset.

Third, the experimental beams were based on a specific cross-section, reinforcement configuration, concrete strength, and textile system. Therefore, the results should not be generalized to every RC beam configuration.

Fourth, the analytical model assumes idealized strain compatibility and does not fully reproduce bond-slip mechanisms.

Fifth, the textile properties can differ substantially according to fiber type, yarn geometry, impregnation, coating, and manufacturing process.

Sixth, environmental durability should be validated using Indian exposure conditions rather than inferred solely from mechanical tests.

35. Conclusions

Based on the experimental evidence and the India-oriented analytical framework, the following conclusions can be drawn:

1. **TRC is an effective thin-layer strengthening system for RC beams.** The experimental results demonstrate improvements in cracking resistance, yielding load, ultimate capacity, stiffness, and crack control.
2. **The highest experimental ultimate load was 74.6 kN**, obtained for Beam8, compared with an average control-beam ultimate capacity of 58.8 kN. This corresponds to an increase of approximately **26.9%**.
3. **The highest yielding load was 58.8 kN**, compared with an average control value of 48.75 kN, corresponding to an increase of approximately **20.6%**.
4. **TRC substantially reduced crack width.** Beam2 reached a maximum crack width of 1.20 mm at yielding, whereas Beam8 reached only 0.38 mm despite carrying a considerably higher yielding load.
5. **Increasing textile layers improved structural performance.** Two-layer configurations generally produced greater yielding and ultimate capacities than one-layer systems.
6. **Textile surface treatment improved composite interaction.** Sand-coated textile configurations showed improved utilization of the textile reinforcement and more effective crack control.
7. **Mechanical anchorage improved composite action.** U-shaped shear pins reduced the possibility of relative deformation between the TRC strengthening layer and the existing concrete and contributed to improved structural performance.
8. **Polypropylene fibers had a limited influence on ultimate beam capacity** at the tested dosage but contributed to matrix toughness and early crack control.
9. **The interface agent had only a minor influence on global flexural performance** when high-performance fine-grained concrete and adequate substrate roughening were used.

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ISSN 3104-8897

10. **The steel reinforcement ratio and textile reinforcement ratio should be considered jointly.** The effectiveness of TRC is dependent on the interaction between existing steel reinforcement and additional textile tensile resistance.

11. **The theoretical sectional model provided satisfactory agreement with the experimental results**, with the original study reporting errors below 5% for yielding and ultimate load predictions.

12. **Environmental exposure should be incorporated into future Indian TRC design.** Chloride, carbonation, sulfate, moisture, and temperature conditions can influence the long-term performance of strengthened RC infrastructure.

13. **For Indian applications, textile configuration, bond, anchorage, reinforcement ratio, and environmental exposure should be optimized simultaneously**, rather than considering ultimate strength alone.

14. TRC therefore represents a promising cement-based strengthening approach for extending the service life of existing RC infrastructure, provided that textile quantity, anchorage, bond, environmental exposure, and failure mechanisms are appropriately considered.

36. Future Research Directions

Future research should develop a larger Indian experimental database covering:

- carbon textiles;
- AR-glass textiles;
- basalt textiles;
- different mesh geometries;
- one to five textile layers;
- different concrete strengths;
- different steel reinforcement ratios;
- different TRC thicknesses;
- different anchorage systems;
- different environmental exposures.

Advanced finite-element simulations should also be developed to reproduce:

$$\text{Concrete cracking} \rightarrow \text{Steel yielding} \rightarrow \text{Textile activation} \rightarrow \text{Crack propagation} \rightarrow \text{Anchorage response} \rightarrow \text{Ultimate failure}$$

Machine-learning approaches could subsequently be used to predict ultimate load, crack width, deflection, and optimal textile quantity from experimental and numerical datasets.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

reinforced concrete (RC); Textile-reinforced concrete (TRC); C: chloride exposure; H: humidity/moisture variation; T: temperature exposure; S: sulfate exposure; CO_2: carbonation environment; E_f: effective textile elastic modulus; b:beam width;

Acknowledgment:

The author would like to express their sincere gratitude to **The International Journal of Engineering Sciences** - Noor Al-Ilm for Publishing and Distribution for their generous support in waiving all publication fees and facilitating the publication of this manuscript free of charge. Their commitment to promoting scientific research and supporting researchers is highly appreciated.

Author Contribution:

All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 115-141
ISSN 3104-8897

Funding:

This research received no external financial funding. The authors also acknowledge **The International Journal of Engineering Sciences**, Noor Al-Ilm for Publishing and Distribution, for providing a full waiver of the publication fees. The publication fee waiver was provided as editorial support and did not involve any financial contribution to the conduct, design, analysis, or reporting of the research.

Conflicts of Interest:

"The authors declare no conflict of interest."

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