Flexural Behavior of RC Beams Strengthened with Textile Reinforced Concrete

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Abstract. In RC structure, the role of beams is vital in resisting the flexural and shear stress due to the applied force. Many studies have been carried out in improving the shear resistance capacity of RC beams using various strengthening techniques such as externally bonded FRP, steel plate bonding, jacketing etc.., Similarly, near surface mounting techniques, FRP wrapping are employed in improving the flexural behaviour. Recently, the application of textile reinforced mortar is widely used to examine the flexural performance and observed significant improvement in terms of strength and ductility. The inelastic performance and increased moment carrying capacity is an advantage of Textile Reinforced Mortar (TRM). Textile Reinforced concrete (TRC) has been found as a promising technique in enhancing the desired performance of the structures. In this study, the TRM layers have been used at the tension region where cover concrete has been completely removed to avoid the increase in cross section. Many textiles have been used to increase the flexural performance of the RC elements. The effectiveness of glass textile fiber and polymer grid as reinforcement with cementitious composites was used in this strengthening work. All the strengthened beams were tested under monotonic loading until the failure occurs. The parameters include failure mode, load bearing capacity, crack bridging mechanism, energy dissipation are considered to evaluate the performance of the strengthening schemes adopted. The strengthening layer enhances the flexural performance of RC beam with improved ductility and increased damage tolerance capacity.

Keywords: TRC · Flexural strengthening · RC beams · Ductility · Glass fiber

1 Introduction

Structural members are subjected to different types of loading conditions which results reaction forces, if the strength of any member is insufficient to resist the induced stresses and strains due to the effect of the forces, it will result in deformation or deterioration. The need for strengthening or retrofitting of the members in order to reduce the stresses within the allowable limits or to increase the load carrying capacity of the

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member is required. Flexural strengthening of beam element can be done using external post tensioning, externally bonded Fiber Reinforced Polymer (FRP), near surface mounted FRP system, Reinforced Concrete Jacketing (RCJ) method, Fiber reinforced concrete/composites, Shotcrete with steel fiber reinforcement etc., to provide structural integrity. Over the past decades, externally bonded FRP system is widely used all over the world in retrofitting and strengthening beam element. This process consists of using closely knitted glass or carbon fibers with resins like epoxy, thermoset polymers etc., for bonding the fibers sheets with the existing concrete substrate. Even though FRP system found beneficial in strengthening or retrofitting of beam elements, some drawbacks associated with the FRP-epoxy system made a pathway for innovation of an alternative method. The main drawbacks of FRP-epoxy system are the use of epoxy resin which involves following defects – expensive, performance of the resin at high temperatures or at glass transition temperature is poor, poor fire resistance, resin cannot apply on wet or damp surfaces, and resin is incompatible to substrate materials (concrete or masonry) (Babaeidarabad et al. 2014). To address these drawbacks, many researches have been carried out to find an innovative material which results in an alternative use of inorganic cementitious mortars or composites. Thus, various researches concluded that the replacement of organic resins by inorganic cementitious material found effective and can overcome the drawbacks of the resins (Koutas et al. 2019). Thus, dealing with this drawback leads to an innovation called as Textile reinforced concrete (TRC) or Textile Reinforced Mortar (TRM) or Fabric Reinforced Cementitious Matrix (FRCM) which consists of mesh like arrangement of the fibers which are woven or stitched or knitted, to ensure easy penetration of the cementitious matrix. TRM is a promising technique due to fibers non-corrosive nature, ductile behavior, commendable load carrying capacity, light weight, low cost and easily available material which made this technique an effective one compared to other techniques. There are many textile fibers available such as carbon, aramid, basalt, AR-glass etc… The effectiveness of textile reinforced concrete were studied by many researchers concluding that using of TRC or Fabric reinforced cementitious composites (FRCC) offers an innovative alternate technology to rectify the strengthening problem with minimal cost and with thin elements. The used inorganic cementitious matrix should have enough consistency for easy application and penetration into the textile fibers, which can be ensured by the use of admixtures. The use of textile fibers enhances the performance of the beam thus by increasing elemental stiffness, moment carrying capacity; load carrying capacity, delaying crack propagation and improved deflection ductility (Yin et al. 2014). The failure mode associated with TRC includes slippage of fiber in case of one or two layer and debonding of fiber layers at textile-mortar interface in case of more layer (Raoof et al. 2016). Various researches investigated the use of geogrid in concrete in order to examine its performance and concluded that the geogrid possess increased load carrying capacity, stiffness degradation, energy dissipation excellent chemical resistance, high tensile strength, improved post cracking behavior, resistance to propagation of cracks and easily feasible for thin sections (Al-Hedad and Hadi 2019; Chidambaram and Agarwal 2014; El Meski and Chehab 2014; Tang et al. 2008). Further the addition of discontinuous fibers (like polyvinyl alcohol fiber) in the cementitious matrix which is termed as engineered cementitious composite (ECC) improves the desired performance of the TRM strengthened beams.

The previous studies revealed that the FRP grid-ECC strengthening system enhances the strength of the RC beam due to high strength of FRP grid and strain hardening behavior of ECC. Further this system can suppress the debonding of externally bonded materials and improve the cracking, yielding and ultimate loads. The addition of PVA fibers can improve the bond properties between textile and matrix (Deng et al. 2019; Elsanadedy et al. 2013; Zheng et al. 2016; Du et al. 2018).The provision of discontinuous fibers in the mortar can overcome the problems associated with brittle nature of the concrete by its crack-bridging mechanism (Chidambaram and Agarwal 2015). Crack bridging mechanism of fiber matrix leads to delaying of crack propagation and control its widening. Further many researchers investigated the use of discontinuous fibers and introduced the new system of Hybrid fiber reinforced cementitious composites (HFRCC). HFRCC involves using of combination of different fibers (such as synthetic and metallic fibers) in the matrix. Thus it can enhances the performances of the cementitious mix without increasing the volume of the mono fibers and provide better resistance to micro and macro level cracks (Chidambaram and Agarwal 2015).

1.1 Research Significance

Engineered cementitious composites (ECC) and Hybrid fiber reinforced cementitious composites (HFRCC) reinforced with textile fibers which is termed as textile reinforced cementitious composites (TRCC) are used to provide thin layer structures. In this research the polymer grid and glass textile fiber grid are used in layers for the strengthening purpose with ECC and HFRCC. The cementitious mortar consists of Cement, Sand, Fly Ash and Ground Granulated Blast Furnace Slag (GGBS). The ductile nature of the mortar is enhanced efficiently by adding of discontinuous polypropylene fibers and steel (metallic) fibers. The combined action of continuous and discontinuous fibers and their individual performances are analyzed and compared.

2 Experimental Investigation

2.1 Material Specification

The beam specimens are prepared using M25 grade of concrete with mix proportion of 1:1.225:2.35. Materials property includes Ordinary Portland Cement (OPC) of Grade 53, locally available river sand as fine aggregate, and well graded crushed coarse aggregate having 10 mm maximum size. The water cement ratio was maintained at 0.4. The strengthening layer comprises of cementitious matrix (with and without discontinuous fibers). The cementitious mortar consists of cement, sand, fly ash and GGBS as 1:0.5:0.25:0.25 with discontinuous fibers in different proportions. The workability of the mixture is enhanced by adding of admixtures. Polypropylene fibers had been added to the mortar in two different ratios (% by weight of cement) to prepare ECC specimens whereas HFRCC specimens consists of Hooked end steel fibers (1.5%) with an aspect ratio (l_f/d_f) of 60 (length of fibers, $l_f = 35$ mm and diameter of fibers, $d_f = 0.6$ mm) and Polypropylene fibers (1.5%) are added by weight of cement along with accelerator. The yield strength of the steel bars is 500 N/mm^2. The yield strength of the used geogrid is 400 kN/m. TRM sandwich layer consists of glass textile layer along with uniaxial geo-grid layer. The mix proportions are shown in Table 1.

2.2 Specimen Configuration

The experimental study consists of testing of RC beams with four different configuration along with one control specimen for comparison. Beam specimens are casted along with companion specimens to find out the properties of the concrete, composites and mortar. Figure 1 shows the typical details of RC beams. The detailed configurations of beam are shown in Table 2. Instead of increasing the thickness of tension region using strengthening layer, cover concrete was removed for strengthening layer. Three distinct cementitious mixes are involved in this study. A thin layer of epoxy coating is used for effective bonding between the old concrete surface and cementitious composites.

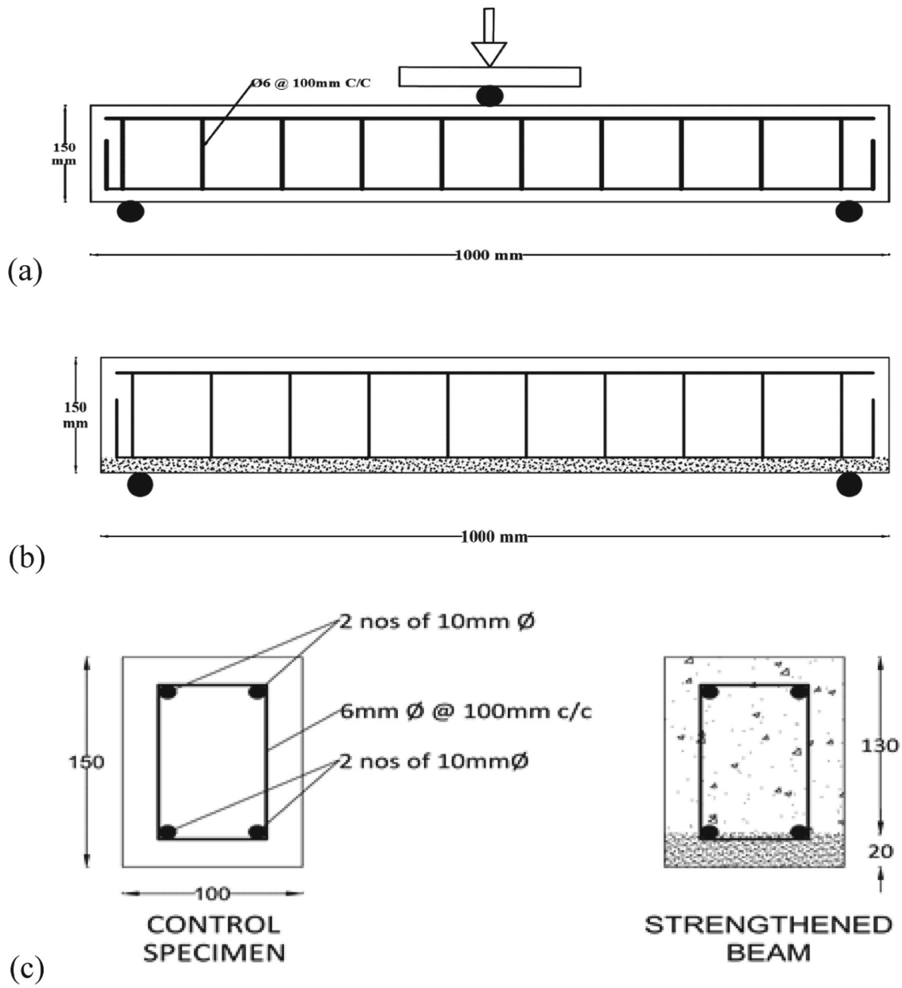

Fig. 1. Beam specifications-(a) Control specimen; (b) Strengthened beam; (c) Sectional view.

Table 1. Mix proportions

Specimen details	Cement	Sand	Coarse aggregate	Fly ash	GGBS	W/B Ratio	Types of fiber	Vol. of fiber (%)	Compressive strength (MPa)
CC	1	1.225	2.35	–	–	0.4	–	–	24.5
ECC	1	0.5	–	0.25	0.25	0.23	P_1 & P_2	0.64 & 0.5	27.3
HFRC	1	0.4	–	0.3	0.3	0.35	P + S	1.5 + 1.5	22.23
Mortar	1	0.5	–	0.25	0.25	0.23	–	–	23.7

Note: GGBS-Ground Granulated Blast Furnace Slag, P-Polypropylene Fiber, S-Steel Fiber

Table 2. Detailed configuration of beams

Specimen ID	Longitudinal reinforcement	No. of layers	Layer details	Percentage of discontinuous fibers (%)
B10	10 mm	–	–	–
B11	10 mm	3	T + G + T with polypropylene infused cementitious composites	0.64
B12	10 mm	1	G with steel and polypropylene infused cementitious composites	1.5 & 1.5
B13	10 mm	3	T + G + T with cementitious mortar	–
B14	10 mm	2	G + G with cementitious mortar	–

Note: T-Glass Textile, G-Geogrid

2.3 Strengthening Procedure

The strengthening layer was externally bonded to tension surface of the beam. In order to maintain the depth of beam, cover concrete were removed and replaced with TRM layers. The procedure involves the application of TRM with HPFRC, which involves following steps:

- The concrete surface was roughened and cleaned for application of fresh layer prior to strengthening to enhance the bond between the existing concrete surface and the TRM layer.
- The procedure for strengthening layer includes: (a) application of epoxy layer, (b) application of a thin layer of FRCC, (c) application of textile or geogrid layers and gently pressed to ensure penetration of matrix mix, (d) application of final layer of matrix.

2.4 Test Setup

The study consists of testing beams under three-point loading with a clear span of 910 mm. The load was applied through a steel section connected to a hydraulic jack of 50 ton capacity. The load cell and Linear variable Differential transducer (LVDT) were used to measure the applied load and the corresponding deflection at the mid span. All specimens were subjected to static loading. The data including load and corresponding deflection were acquired using data-acquisition system.

3 Results and Discussions

The parameters such as load bearing capacity, energy dissipation, stiffness retention, damage ratio and failure modes are considered to evaluate the performance of the beams.

3.1 Load - Deflection Behaviour

The load carrying capacity of the strengthened beams are compared with the corresponding control specimen and shown in Fig. 2. As demonstrated in the Fig 2, the beams B11 and B13 shows an increased load carrying capacity with a peak load of 47.96 kN and 48 kN respectively. The control specimen B10 shows sudden drop in load after peak, whereas the strengthened beams show better inelastic behavior compared to conventional beam. The specimens with strengthening layers show 7% to 28.5% enhancement in resistance to the applied load compared to the control specimen B10. The post peak load degradation of specimen B12 shows steady and gradual reduction in load carrying capacity after attaining the peak load. But beam specimens B11, B13 and B14 shows stable load carrying characteristic curve with enhanced post cracking behavior. In similar deflection conditions, the load carrying capacity and ductility of the strengthened beams are enhanced over the control beams. The post peak behaviour of the strengthened beams B11, B13 and B14 evidences a gradual decrease in the load deflection curve with the increased strength retention capacity compared to control specimens. Therefore, the provision of fiber layers contributes an improvement in load carrying capacity and ductility. It is also observed that the addition of synthetic fibers in the mortar further elevates the post peak performance over the plain cementitious mortar. It authenticates the synergetic action of FRCC with textiles which enhances the inelastic rotation and ductility.

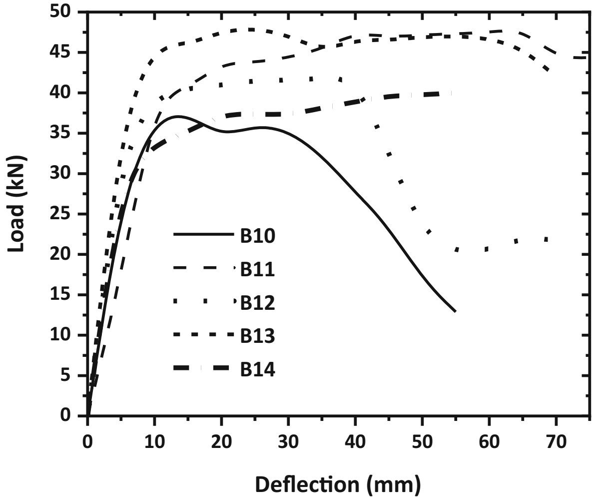

Fig. 2. Load vs deflection behavior of RC beams.

3.2 Cumulative Energy Dissipation vs Deflection

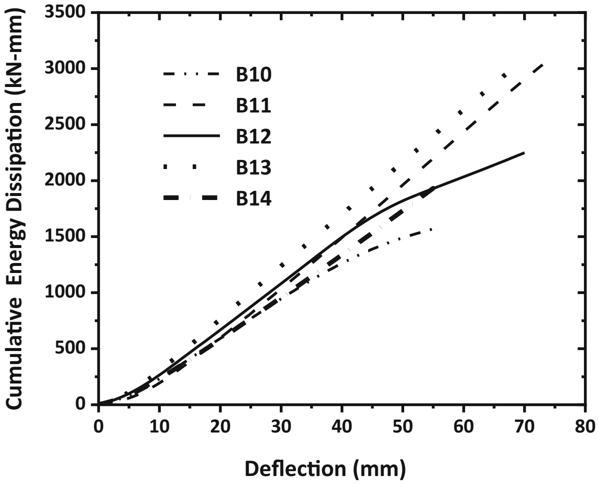

Fig. 3. Cumulative energy dissipation vs deflection.

The energy dissipation is generally calculated on the basis of the area enclosed by the load – deflection curve which is a significant parameter governing the ductile response of the structural members. The cumulative energy dissipation of the beams are compared and shown in Fig. 3. The rate of energy dissipation growth of strengthened specimen is higher than control specimen at every stage of loading. It shows that the strengthening measures employed adequately works in resisting the applied force with better deflection property which shows enhanced energy dissipation. The contribution of strengthening layers effectively works and shows 32.5% to 55% of enhancement in energy dissipation. The absence of TRM layer in control specimen shows reduction in energy dissipation. In spite of, all the strengthened beams, the beams B11 and B13 found effective in dissipating more energy compared to other specimens. Moreover, the beam B11 (TRM with polypropylene infused cementitious mortar) found effective in dissipating more energy and shows an increased ductile nature.

3.3 Failure Pattern and Damage Ratio

Crack pattern of all the beams are shown in the Fig. 4. The beams undergoes flexural and flexural-shear failure with crack having various width. The control specimen undergoes failure with wider cracks along with crushing of concrete at compression zone. The strengthened beam undergoes failure with reduced crack width compared to the control specimen due to the crack bridging mechanisms of the fibers. Moreover, the strengthened beams undergoes two types of failure modes namely, delamination and rupture of strengthened layer. The provide TRM layer at tension zone uniformly distributes the applied stress and effectively transfers the force across the cracks. The control specimen B 10 experienced single primary cracks whereas the strengthened beam specimens encountered various secondary cracks. The TRM with glass textiles ruptured whereas the layer reinforced with geo-grid sustained and delaminated as shown in Fig. 4(e).

The modified flexural damage ratio, MFDR, is an important factor as a member damage indicator which is defined as the ratio of the secant stiffness at the onset of failure (M_m/Φ_m) to the minimum secant stiffness (M_x/Φ_x) reached so far (Chidambaram and Agarwal 2019; Roufaiel and Meyer 1987). The term (M_y/Φ_y) is the initial elastic stiffness. The value of MFDR varies from 0 to 1. The value of MFDR = 0 indicates that there is no damage (i.e.) yield moment of the member had not been exceeded whereas MFDR = 1 indicates the onset of failure. The ratio is given in the Eq. (1). The calculated MFDR vs ductility for the beams are represented in the Fig. 5.

$$R_{mfd} = \left[\frac{\frac{\Phi_x}{M_x} - \frac{\Phi_y}{M_y}}{\frac{\Phi_m}{M_m} - \frac{\Phi_y}{M_y}} \right] \tag{1}$$

Figure 5 show that the control specimen exhibits failure in the earlier stage of loading compared to the strengthened beams. The number of layers used and the mortar strength in the strengthened specimen decides the damage resistance capacity. Strengthened beam shows minimum of 2 times and maximum of 4 times better damage tolerance capacity than the control specimen. The formation of micro cracks over the span and the external TRM layer supports the post peak deflection without sudden decrease in strength. This phenomenon increase the post peak stiffness retention capacity of specimen and allows ductile failure even with better damage tolerance than the unstrengthen specimen.

(a) B10

(b) B11

(c) B12

(d) B13

(e) B14

Fig. 4. Crack pattern and failure mode of beams-(a) B10; (b) B11; (c) B12; (d) B13; (e) B14.

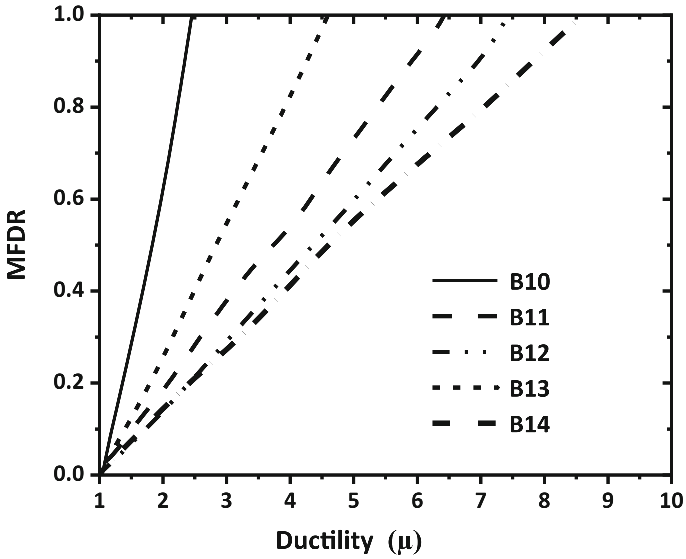

Fig. 5. Modified flexural damage ratio.

3.4 Stiffness Degradation

The stiffness of the structure element is the measure of the resistance to deformation, Eq. (2). Figure 6 shows inelastic stiffness degradation of all beam specimens.

$$Stiffness = \frac{Load\,(P)}{Deflection(\Delta)} \tag{2}$$

The initial slope of load deflection graph defines the initial stiffness of the specimen and the tangent to the yield point defines the yield stiffness. The tangent to the post yield curve shows secant stiffness which defines post yield stiffness retention capacity of RC elements. The rate of post yield stiffness degradation describes the capacity of RC element in resisting the inelastic deformation. The presence of TRM layers shows increased initial stiffness than the control specimen and rate of stiffness degradation is also better than control specimen. The post yield stiffness retention capacity of TRM strengthened beam shows the efficacy of techniques adopted in resisting the applied force. The strengthened specimen shows an average of 5% to 42% increase in initial and post yield stiffness and shows lesser rate of stiffness reduction compared to control specimen

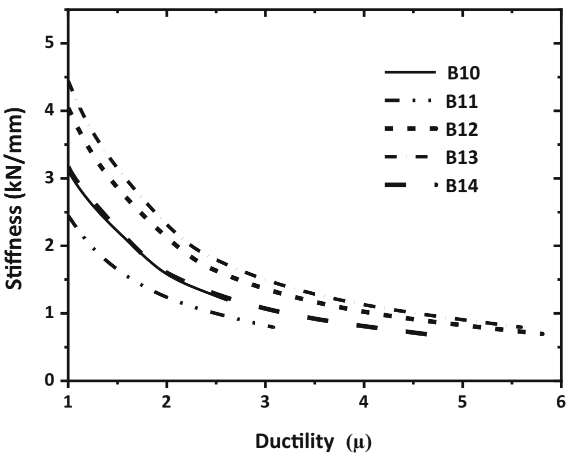

Fig. 6. Stiffness degradation.

4 Conclusions

The strengthening technique investigated in this study found effective in enhancing the flexural performance of the RC beams. The sandwich layer consisting of glass textile and geogrid found effective due to their superior tensile properties, ductile behavior, light weight, low cost and easily available. The parameters such as Load-deflection relationship, Energy dissipation, Flexural Damage Ratio, Stiffness Degradation are analyzed to estimate the efficiency of the strengthening schemes. Conclusions are made based on the test results obtained which reveals the potential benefit of TRCC strengthening layers in beams.

- The load carrying capacity of the strengthened beam increased without sudden loss after peak load. The provision of Glass textile and Geogrid layer with FRCC found effective in enhancing the flexural performance of the beam compared to the plain cement mortar.
- The initial stiffness and post peak stiffness of the strengthened beams are higher than the control beam. The rate of stiffness degradation also small compared to the control specimen. The observed 40% increase in initial stiffness shows that the employment of external TRM layer contributes in stiffness enhancement at initial, yield and post peak level.
- Energy dissipation level increases at every stage through the formation of micro cracks and resistance offered by the TRM layers. An average of 15% to 80% increase in energy dissipation with reference to the layer adopted shows the significance of TRM layer in contributing the ductility enhancement.
- The mode of failure shows that the bonding between the concrete substrates and TRM layer works better and allows multiple crack formation. The high strength geo-grid layer requires better bonding, the absence of the same shows evidence of debonding between the inter stratum. Whereas the glass textiles experiences rupture failure. It shows that the tensile strain capacity of geogrid is higher than the tensile strain

capacity of glass textiles. Hence delamination occurs rather than rupture of fibers. This behavior influences the damage ratio, the strengthened specimen shows 2 to 4 times higher damage tolerance capacity than control specimen. It can be concluded that effective use of TRM with high tensile material enhances flexural performances of RC beam with improved ductility and damage tolerance.

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