Monotonic and low cycle fatigue behaviour of concrete beams strengthened with textile reinforced concrete U-wrap

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This paper presents experimental details on the effectiveness of textile reinforced concrete (TRC) as a structural strengthening material under flexure and shear. Two types of specimens, namely, plain concrete beams and reinforced concrete beams are strengthened with U-wrap configuration of TRC. Two types of fabrics having different weight per unit area are used for the investigations. Strengthened plain concrete beams are tested under three-point bending to investigate the flexural load carrying capacity, mid-point deflection and failure pattern. Further, experimental investigations are carried out on shear deficient RC beam strengthened with TRC as U-wrap under monotonic and low cycle fatigue loading. It is observed that under monotonic loading, there is about 19% increase in ultimate load carrying capacity and 852% increase in energy absorption for strengthened beam compared with un-strengthened beam. When the strengthened beam is subjected to low cycle fatigue loading, there is 20% reduction in ultimate load carrying capacity. But the ultimate deflection and failure pattern is found to be similar in both the cases.

Keywords: Textile reinforced concrete, Flexural strengthening, Shear strengthening, U-wrap, RC beam, Monotonic, Low cycle fatigue

Reinforced concrete structures often have to face modification and improvement of their performance during their service life and retrofitting is performed at such situation to improve mechanical performance. In order to evaluate the performance of a structure and to verify that it fulfils structural requirements, it is necessary to express performance in terms of quantifiable physical quantities. The safety with respect to failure is verified by means of such indices as flexural load-carrying capacity of members, shear capacity, torsion capacity and so on. Retrofitting of flexural concrete elements is traditionally accomplished by externally bonding steel plates to concrete. Although this technique has proved to be effective in increasing strength and stiffness of reinforced concrete elements, it is the disadvantages of being susceptible to corrosion and difficult to install. Recent development in the field of composite materials, together with their inherent properties, which include high specific tensile strength, good fatigue and corrosion resistance and ease of use, make them an attractive alternative to steel plates in the field of repair and strengthening of concrete elements.

The effectiveness of using fiber reinforced composites in increasing strength and stiffness of reinforced concrete flexural elements is evident from results of earlier studies. It was shown that depending on the degree of damage, a concrete repair in conjunction with strengthening method such as bonded FRP composites can improve the strength and serviceability.

Upgrading civil structures with cement based bonding agents and high performance fibre materials give a more compatible repair or strengthening system with the base concrete. Consequently the use of cementitious bonding agents should prevent some of the disadvantages with the organic resins. Substituting the epoxy adherent with a cement based bonding agent will render a strengthening system with improved working environment and better compatibility to the base concrete structure. Consequently, if it is possible to use a cement based matrix instead of an epoxy matrix, cementitious composites could be used wherever fibre reinforced polymers are used for concrete strengthening today.

Shannag et al. developed optimal strategies for the maintenance and strengthening of RC beams that are subjected to different corrosion rates by replacing the cover zone with different high-performance fiber

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reinforced cementitious composites. Beams cast with glass fibre reinforced concrete cover zone showed the best performance compared to other beams. A good ductility and the least amount of strength reduction were observed in these cases.

Studies related to cement based composites for flexural strengthening and repair of RC beams are very limited in literature\(^4-15\). The strengthening technique using textile reinforced concrete is comprised of a cementitious matrix as the bonding agent and a textile fabric as reinforcement\(^16\). This cementitious matrix has a maximum aggregate size of 0.6 mm. The reinforcing fibers are predominantly made of AR-glass (alkali-resistant glass) produced into a textile fabric. There can be many designs of the textile fabrics depending on the load case and positioning of the fabric. Fabrics with relatively complicated yarn shapes, such as short weft knit, enhance the bonding and improve the composite performance\(^17,19\). Fabric reinforced cement based composites were investigated for its properties, interfacial behaviour and the damage parameters with respect to the overall mechanical response by Mobasher \textit{et al.}\(^20\). Triantafillou and Papanicolaou\(^6\) suggested that textile reinforced mortar (TRM) may be considered as an alternative to fiber reinforced polymers (FRP), providing solutions to many of the problems associated with the performance of strengthened members. Based on the experimental response of reinforced concrete members strengthened in shear it is concluded that textile-mortar jacketing provides substantial gain in shear resistance; this gain is higher as the number of layers increases and, depending on the number of layers, is sufficient to transform shear-type failure to flexural failure. Larbi \textit{et al.}\(^21\) studied the strengthening method using textile reinforced concrete (TRC) for the performance. The objective was to assess potential alternative solutions based on textile reinforced concrete (TRC) mainly in the control of cracking in reinforcement (undamaged beams), or hybrid solutions combining TRC and rods (carbon, glass or both) when it is important to satisfy the two limit states (ultimate and service) as part of the repair (previously damaged beams). The experimental part brought out the positive factors of TRC hybrid solutions in the repair of reinforced concrete beams, in terms of both ultimate and service behavior, with very similar performances to that of traditional solutions such as CFRP. Larbi \textit{et al.}\(^21\) conducted experimental and numerical studies related to the repair and strengthening of reinforced concrete beams with TRC and hybrid (TRC + carbon and glass rods) solutions that are positioned relative to the more traditional ones such as the CFRP solutions.

Present paper reports the experimental details on the behaviour of plain concrete beams and shear deficient RC beam strengthened with TRC using a U-wrap configuration.

**Textile Reinforced Concrete**

Textile reinforced concrete (TRC) consists of fine grained cementitious binder and an alkali resistant glass fabric.

**Fabric/textile reinforcement**

In textile reinforced concrete, the reinforcement can be made of carbon, aramid or alkali resistant glass fibres. There are various forms of fabrics such as warp knitted, woven or bonded type. These reinforcements are provided to increase the load capacity or avoid brittle failure of the structure. In the present study, alkali resistant glass fabrics have been used as reinforcement for TRC. One of the glass fabrics (AR1 shown in Fig. 1(a)) chosen for the study is of 10 mm × 10 mm mesh size and having a fineness of 320 tex. To resist the corrosive alkaline solution in the concrete, AR1 contains more than 15% (mass) of zircon. The tensile strength of AR1 is 29 kN/m in both directions and ultimate elongation is less than 3%. The second type of glass fabric reinforcement is

![Fig. 1 – (a)AR1 Glass fabric and (b) SRG-45 Glass fabric](image_url)
SRG-45 (Fig. 1(b)). It is supplied by Saint Gobain Technical Fabrics. These fabrics have a mesh size of 25 mm × 25 mm and fineness of 640 tex. To prevent alkali silica reaction in cement, this glass fabric is coated with an acrylic polymer. The tensile strength of SRG-45 is 45 kN/m in both directions and the ultimate elongation is less than 3%.

Binding matrix: FABmix

The binding matrix used is an in-house developed cementitious material. This material has high flowable consistency. The slump was measured by using mini slump apparatus and the binding matrix showed a spread of 80%. The composition of binding matrix are cement, silica fume, fly ash, quartz powder, quartz sand, water and super plasticizer. The maximum aggregate size is limited to 0.6 mm in order to ensure the penetration of binding matrix into the yarn. The compressive strength of the binding matrix is in the range of 42-50 MPa and split tensile stress is 4.5 MPa. The details related to these investigations were reported by Smitha et al.22

Strengthening of Plain Concrete Beams

Test specimens

Plain concrete beams of M30 grade concrete having a size of 500 × 100 × 100 mm have been cast. A mix proportion 1 : 2.12 : 2.23 with a water-cement ratio of 0.45 have been arrived at using Bureau of Indian Standard specifications. Beams have been cured in water for 28 days. After curing, the beams have been strengthened using TRC as strengthening material. For TRC strengthening, no additional surface preparation has been done. The cementitious binding matrix has been applied at the bottom face of the beam in approximately 2 mm thick layers with a smooth metal trowel. After application of the first matrix layer on the concrete surface, the layers of textiles have been applied and pressed slightly into the matrix. The final matrix layer has been then applied and levelled to the required thickness. Different specimens have been strengthened by varying the number of layers of the fabrics. The volume fractions (ν) used for SRG-45 are 0.36%, 0.45% and 0.58% respectively for 4 layer, 6 layer and 9 layer strengthening. Volume fraction is calculated as the ratio of area of all load bearing yarns to the cross-sectional area of concrete beam. In Table 1, PCB stands for Plain Concrete Beams, 4L_SRG, 6L_SRG, 9L_SRG for four, six and nine layers of SRG glass fabric strengthening respectively and 6L_AR1 for 6 layers of AR1 glass fabric.

Figure 2 shows the application method of fabrics combined with matrix to strengthen one of the specimens. After strengthening, the beams have been cured in water for 28 days before testing. The same procedure has been repeated for strengthening with AR1 as well. The volume fraction adopted for

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Number of specimens</th>
<th>Number of fabric layers</th>
<th>Thickness of TRC (mm)</th>
<th>Volume fraction (%)</th>
</tr>
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<tbody>
<tr>
<td>PCB</td>
<td>3</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<tr>
<td>4L_SRG</td>
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<td>4</td>
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<td>12</td>
<td>0.45</td>
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<td>9L_SRG</td>
<td>3</td>
<td>9</td>
<td>14</td>
<td>0.58</td>
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<tr>
<td>6L_AR1</td>
<td>3</td>
<td>6</td>
<td>10</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Fig. 2 – Typical specimen preparation
strengthening is 0.34%, which are about 6 layers of AR with 10 mm thickness along with FABmix.

**Experimental setup**

Three point bending tests have been performed on the strengthened and un-strengthened beams on a Material Testing System (MTS) under monotonic loading. The measuring span of the beam is 400 mm. The loading rate applied is in the range of 0.5 mm/min under displacement control loading. A typical view of the flexural test setup is shown in Fig. 3.

**Evaluation of test results**

The flexural load-deflection curves of the strengthened concrete beams with SRG fabric are presented in Fig. 4. From Fig. 4, it can be observed that the plain concrete beams under flexural loads are quite brittle. When the same beams are strengthened by TRC with 0.36% volume fraction of SRG-45, the flexural load carrying capacity of the strengthened beams is enhanced about 1.2 times over the load carrying capacity of plain concrete beams. In the case of TRC strengthened beams with 0.58% SRG-45, it is found that the flexural load is increased approximately by 1.7 times over un-strengthened beam. Hence, it can be concluded that the ultimate load carrying capacity increases with increase in volume fraction. From the deflection profile, it is clearly observed that till the first peak load both the beams follow a similar pattern, beyond the peak load the behaviour of the strengthened beam is different.

Table 2 shows the enhancement in load carrying capacity and ductility for the concrete beams strengthened with TRC, by using SRG-45 glass fabric. The failure pattern of the strengthened beams at the end of the tests corresponding to a displacement of 4 mm is presented in Fig. 5. In the case of strengthened beam, the cracks formed in the main beam had lesser crack width compared to un-strengthened beam. Multiple cracking is also observed in TRC layer. After reaching the ultimate load, there is a drop in load carrying capacity as shown in Fig. 4, which is mainly due to the matrix delamination from fabric. But again the load carrying capacity increased indicating that the load is transferred to the fabric from the matrix in the strengthened layer. The TRC is

| Table 2 – Results from three point bending tests for SRG strengthened beams |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                            | Plain concrete beam | Strengthened concrete beam $V_f$ | Percentage increase compared to plain beam |
| Energy absorption (N-mm)   | 3.55              | 13.64                        | 284.23                      |
| Peak load (kN)             | 9.91              | 11.79                        | 18.97                        |
| Deflection corresponding to peak load (mm) | 0.92 | 1.153 | 19.67 |
| Maximum deflection (mm)    | 1.29              | 3.6                          | 151.16                      |

Fig. 3 – Flexural set-up

Fig. 4 – Typical load vs deflection curves of TRC strengthened concrete beams with SRG fabric

Fig. 5 – Failure pattern in strengthened concrete beams
capable of elongating till the fabric ruptures. Since all the layers of fabric are provided as a single bunch, it is also possible that once one layer is ruptured, the force is transmitted to the remaining layers. This mechanism will help to increase the ductility of the strengthened beams.

While in the case of beams strengthened with TRC, which contains 0.34% volume fraction of AR1 type of glass fabrics, it is found that ultimate load carrying capacity is increased by 10%, energy absorption by 78% and maximum deflection by 58% compared to un-strengthened beams. The graphs in Fig. 6 depict the comparison between the load-deflection behaviour of plain concrete beam and TRC strengthened concrete beam with AR1 fabric. Further, Table 3 shows the enhancement in load carrying capacity and ductility for concrete beam strengthened with TRC. The failure pattern obtained for TRC strengthened with AR1 fabric is shown in Fig. 7. It is observed that multiple cracks are formed in TRC layer before the ultimate failure. Further, it is observed that there is no delamination, debonding and anchorage failure in the strengthened beams, which is due to the perfect bonding between concrete and TRC and between the fabrics and binding matrix. This is more advantageous because it opens up the possibility of direct TRC bonding for in-situ applications.

Shear Deficient RC Beam Strengthened with TRC
In order to investigate the effect of strengthening with TRC in RC beams, shear deficient beams have been cast. Shear deficient RC beams has a cross-sectional dimensions $100 \times 150$ mm and a clear span of 1500 mm tested under simply supported boundary conditions. It has both compression and tension reinforcing bars with 10 mm diameter of 2 numbers and stirrup of 6 mm diameter having a spacing of 150 mm from the left and right support up to one third of the span and the remaining centre span is with a stirrup spacing of 300 mm. The details of shear deficient RC beam is shown in Fig. 8. A mix proportion of 1:2.12 : 2.23 with a water-cement ratio of 0.45 is used for the concrete in RC beam. Beams have been cured in water for 28 days.

**Strengthening scheme**
Use of externally casting TRC is one of the convenient ways for strengthening of RC beams. For this purpose, four number of RC beams have been cast. The specimens are designed to be deficient in shear. In group, out of four beams, two beams were taken as a control specimen and the remaining two beams are strengthened using TRC strengthening schemes. For shear strengthening, TRC bonded surface configuration as shown in Fig. 9, is investigated. The sides and bottom of RC beam have been wrapped with TRC as U-wrap. The U-wrap is practical and is relatively effective in increasing the shear capacity of the beams. This option has a good

![Fig. 6 – Typical load vs deflection curves for TRC containing AR1](image1)

![Fig. 7 – Crack propagation in a strengthened concrete beam at various stages of loading](image2)

| Table 3 – Results from three point bending tests for AR1 strengthened beams |
|-------------------------------------------------|-----------------|-----------------|-----------------|
| Energy absorption ( kN-mm)                      | 3.55            | 19.55           | 450.70          |
| Peak load (kN)                                  | 9.91            | 11.24           | 13.42           |
| Deflection corresponding to peak load (mm)      | 0.915           | 0.97            | 5.79            |
| Maximum deflection (mm)                         | 1.29            | 3.13            | 142.64          |
bonding between the TRC layer and the sides of the beam. TRC is an anisotropic material with high strength in the direction of the fibers. The fibers may be oriented in such a way to best reinforce diagonal tension cracks. This is achieved by staggered arrangement of the TRC layers along the sides of the beam. Hence, five fabric layers are used for strengthening the beam in the present investigation.

**Casting procedures**

Hobart mixer is used for the mixing the ingredients of FABmix. The sequence followed for adding the materials was cement, silica fume, fly ash, quartz powder (0 to 0.2 mm), Quartz sand (0.2 to 0.6 mm). The mixture is dry mixed for 2 min, followed by addition of super plasticizer with 30% of water and mixed for one minute and finally the rest 70% of water is added and mixed for one minute. The efficiency of the mix is found to be best in the above sequence from the previous studies conducted by authors. In order to perform strengthening of the beam along the sides of the beam as a U-wrap, the thickness of TRC layer is maintained as 10 mm. While maintaining the thickness of the strengthened part, the volume fraction adopted is 0.5% which came around 5 layers of glass fabric with 10 mm thickness along the FABmix. Before strengthening, the bottom surface of the beam was made rough in order to provide better bonding between the beam and the strengthened part. The methodology followed was initially a layer of FABmix was poured at bottom surface of the beam, further the fabrics were rolled on a concrete cylinders this was done in order to provide small amount of prestressing to the fabrics. Then the fabrics were placed on one end of the beam and pulled to the other side. All the fabrics were placed together in a staggered pattern on the surface of the fabrics and levelled to the required thickness. It was made sure that the entire process was completed within five minutes so that there would be perfect bonding between the various layers present. On completion of the strengthening, the beams were left to cure before testing. The steps followed in strengthening procedure is shown in Fig. 10.

**Testing of strengthened RC beam under monotonic loading**

The beams were tested in UTM of 300Tonne capacity. Beams were subjected to two point loading and displacement controlled load was applied at rate of 0.5 mm/min. The load points were at a distance of one third of clear span. The results were obtained in terms of load versus deflection as shown in Fig. 11. From graph, it is clearly visualized that the failure in case of un-strengthened concrete beam is sudden.
Unlike the case of strengthened concrete beam where the failure is over very large area. From the deflection profile, it is clearly observed that till the peak load both the beams follow similar pattern beyond which strengthened beam behaviour is different due to the fact that further loading is taken by the fabric, which ultimately avoids brittle failure. From the graph shown in Fig. 11 it is observed that the ductile region was greater for strengthened beams. It is observed that there is about 19% increase in ultimate load carrying capacity and 852% increase in energy absorption for strengthened beam compared with un-strengthened beam for 15% drop of ultimate load.

Regarding the failure pattern, it is observed that un-strengthened RC beam failed as shown in Fig. 12 by widening of the shear crack. The failure pattern observed for strengthened beam is ductile, and the fabrics are found to have undergone rupture. Further it is observed that there is no delamination, due to the perfect bonding between concrete and TRC. The final failure pattern of strengthened beam is shown in Fig. 13. It is observed that TRC strengthening could change the shear mode of failure of shear deficient beam to flexural mode and hence it can be considered as a suitable material for strengthening of RC beams.

Testing of strengthened RC beam under low cycle fatigue loading

TRC strengthened RC beams with simply supported boundary condition were tested to failure under four point low cycle fatigue loading. The load was applied in 8 cycles using two point loading. Each cycle load is designed based on the ultimate load under monotonic loading. The initially load applied was 20 kN and afterwards the load was in 5 kN increment up to ultimate load. A minimum load of 10 kN was kept constant in all cycles. The load history adopted is shown in Fig. 14.

The load versus displacement behaviour obtained is shown in Fig. 15. It can be observed that there is...
20% reduction in ultimate carrying capacity when the strengthened beam is subjected to low cycle fatigue compared to its monotonic behaviour. It could be due to more stiffness degradation after 3rd cycle compared to monotonic loading. However, the displacement corresponding to ultimate load is same in both the cases. Further, it is observed that failure pattern in both the cases is similar as shown in Fig. 13. In the case of low cycle fatigue test, the experiment was stopped after eighth cycle, when the displacement was 25 mm since the roller was about to slip off.

Conclusions

Present study leads towards a possible effective solution for an alternative strengthening method for concrete structural elements by using TRC. Bending tests were carried out on plain concrete beams and shear deficient RC beams strengthened with TRC using U-wrap configuration. Effectiveness of two different glass fabrics as reinforcement for strengthening of plain concrete beams was studied in detail. It is observed that there is an increase in load carrying capacity and ductility with the use of TRC strengthening for plain concrete beams. For the shear deficient RC beams strengthened with TRC, it was observed that there is about 19% increase in ultimate load carrying capacity and 852% increase in energy absorption for strengthened beam compared with un-strengthened beam for 15% drop of ultimate load. Further, the failure mode of strengthened beam was ductile in both the cases. TRC strengthening could change the shear failure to flexural failure by making use of U-wrap. When the strengthened beam was subjected to low cycle fatigue load, there was about 20% reduction in the ultimate load carrying capacity compared to monotonic case, whereas the ultimate deflection was same in both the cases. Also, from the failure mode obtained from investigations, it can be concluded that TRC can be directly bonded to existing concrete structures and hence it is suitable for in-situ application.

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