REINFORCED CONCRETE T-BEAMS STRENGTHENED IN SHEAR WITH STEEL FIBER REINFORCED POLYMERS

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Abstract

This paper presents results of an experimental study on the seismic response of reinforced concrete (RC) T-beams with shear deficiencies strengthened with externally bonded steel fiber reinforced polymer (SFRP) tapes. Four cantilever RC beams were strengthened with externally bonded uni-axial SFRP tapes in a U-shape configuration and were tested under cycling loading conditions. The main variable was the use or not of an anchoring system for the SFRP tapes. The results from the presented study were compared with results reported in the literature from similar T-beams strengthened with carbon fibers with and without anchoring. The examination of the results leads to the conclusion that steel fibers have a great potential to be used for shear strengthening, especially since the use of mechanical anchoring systems does not seem to negatively affect their performance. As expected, the lack of mechanical anchoring results in premature delamination of the strengthening system, and thus an undesirable SFRP material performance.

Keywords: Anchorage, Cycle loading conditions, Reinforced concrete, Steel fiber reinforced polymers (SFRP), T-Beam section.

1. Introduction

The use of fiber reinforced polymers (FRP) for strengthening of reinforced concrete structures has shown great potential as it provides a relatively easy and inexpensive way to provide additional strength and prolong the life of structures. FRP overlays have been investigated and used for flexural and shear strengthening of reinforced concrete (RC) members. Most of the research work related to FRP strengthening systems focused on flexural strengthening and design and analysis models have been adopted. On the contrary, there is relatively less available experimental data on shear strengthening. This is especially true for the best performing strengthening schemes that include anchoring mechanisms or full wrap of the RC member.

It should be noted that there are several parameters that play important role in the shear strengthening of RC concrete beams. Some of these parameters are the bond strength, alignment of the fibers, resin type, anchoring system, brittleness of the fibers. The existing
experimental results are limited in terms of variability and although very useful they only shed limited light to the problem.

It has been proven that externally bonded glass and carbon FRPs can provide a significant increase in the maximum shear capacity of RC structural members. Strengthening systems could either consist of continuous fabrics covering the whole length of the specimen or uniaxial tapes placed at some intervals. However, it has been identified that the continuous fabrics do not result in better performance and therefore they do not provide an economical solution. In most cases the fiber direction is typically vertical to the longitudinal axis of the structural element. Due to the nature of the FRP tapes, positioning of the fibers at 45 degrees presents difficulties especially in the case of a U-shape configuration.

Most of the studies in the literature deal with the use of carbon fibers and few with the use of glass fibers. Furthermore, there is a lack of experimental data on the use of other type emerging fibers, such as the high strength steel fibers.

High strength steel fibers have been used recently by several researchers. Tapes made with high strength steel fibers (known as SRG or SFRP) have been used either with cementitious grouts (SRG) or with organic resins (SFRP) by several researchers [1-4]. It was shown that the addition of these strengthening systems could be an effective alternative for repairs and retrofit of reinforced concrete structural elements. The SFRP is relatively lightweight in comparison to steel plates and is ductile unlike the carbon, glass or aramid fibers. In all published studies the mode of failure was based on the delamination of the SFRP [1-4], which resembles the most common mode of failure of typical FRP systems based on organic resins [5, 6]. To the best of our knowledge there are no experimental data on the use of SFRP tapes in shear strengthening applications and also in combination with mechanical anchors.

In terms of shear strengthening reinforced concrete beams subjected to cyclic load the number of experimental results is quite limited. More specifically, Anil and Tanarslan [7-10] reported on RC shear deficient T-beams strengthened with CFRP systems with and without mechanical anchoring in several different configurations. Their findings suggest that the shear strengthening effectiveness of the CFRP strips varies with CFRP width, strip orientation, and anchorage usage. The latter was found to be the dominant parameter in order to prevent premature failure (debonding) and to maximize shear strength. Another significant finding was that the use of CFRP tapes significantly improved the cumulative energy dissipation capacity of the strengthened specimens. However, it was reported that side bonding of the tapes without mechanical anchoring system did not produce significant increase of shear strength.

The present study deals with the use of SFRP shear strengthening systems on reinforced concrete T-beams subjected to seismic loading conditions. More specifically, a series of cantilever reinforced concrete T-beams were reinforced with tapes consisting of steel fiber reinforced polymers (SFRP). The SFRPs were attached using a U-shape configuration and in some cases additional mechanical anchoring devices were used as well.

2. Specimens and Materials

A total of four reinforced concrete T-beams were tested under cyclic load in the experimental program. Dimensions and reinforcement details are shown in Fig. 1. The cross-sections and conventional steel reinforcement details were identical for all specimens. Three 20 mm diameter steel rebars were positioned longitudinally at the top and bottom of the beam section. No stirrups were placed in the beams. The strengthening scheme consisted of uniaxial high strength steel fiber tapes and a commonly used organic resin (Sikadur 330). SFRP tapes were provided by Bekaert Industries. The width of the tapes was kept constant and equal to 100mm and resulted to an equivalent width equal to 0,1184mm. The organic resin was provided by Sika Hellas which is gratefully acknowledged. Mechanical anchorages were used in two specimens. Table 1 summarizes the specimens’ properties.
Average 28 day compressive strengths of concrete were obtained from uniaxial compressive tests of 150 by 300 mm cylinders that were cast using the same concrete mix used for the beams. Three cylinders were tested for each beam. The average compressive strength of concrete was approximately 22 MPa. The steel fibers have an elastic modulus of 210 Gpa and from coupon testing we recorded ultimate tensile strain of 0.009. The matrix is a typical epoxy resin (Sikadur-330) and the specifications can be provided by the manufacturer.

CTB was the control specimen that was tested without strengthening. The remaining specimens were strengthened with SFRP tapes. Shear deficient beams that were manufactured without stirrups were strengthened with SFRP tapes which were bonded along the shear span. Specimen TB150 was strengthened with 100mm wide U-shape SFRP uniaxial tapes placed at a distance of 150 mm. No anchoring devices were used in this specimen. The remaining two specimens were strengthened with SFRP tapes with the use of epoxy resin and mechanical anchors (see Table 2). The following naming scheme was used; TBXAYz that includes information related to SFRP spacing and anchoring. The character “X” shows the spacing of the tapes, “A” denotes the type of plate used (L for steel angles and P for rectangular plate), while “y” shows the number of bolts used in the anchoring system, and finally “z” indicates if a bolt was screwed through the slab (t) or not (b). Thus, specimens TB150L2t, TB150P1b were anchored systems with spacing of 150mm and L shape or Plate anchor, respectively. The details of strengthening schemes for each specimen are shown in Table 2.

TB150B1b was strengthened with 100 mm wide U shaped SFRP tapes spaced at 150 mm. Each U shaped tape was anchored using a 20 by 5 mm rectangular steel plate secured with a 6mm bolt. TB150L2t was strengthened with 100mm wide U shaped SFRP tapes spaced at 150 mm. Each tape was anchored at the bottom of the slab using a 50 x 5 mm steel angle. Two 8mm diameter bolts were used to secure the tapes. The bolts were positioned through the slab in order to avoid pull-out type failure of the anchors.
### Table 1. Specimen Details and Summary of Experimental Results

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Anchoring system</th>
<th>Maximum Experimental Shear Force Vf,max (kN)</th>
<th>Strain #1 (μstrain)</th>
<th>Strain #2 (μstrain)</th>
<th>Calculated shear force from SFRP strains (kN)</th>
<th>Dissipated Energy (kNmm)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTB</td>
<td>-</td>
<td>37.25</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>316</td>
<td>Shear crack</td>
</tr>
<tr>
<td>TB150</td>
<td>No</td>
<td>73.2</td>
<td>2 sg4-5</td>
<td>5075</td>
<td>245</td>
<td>26.46</td>
<td>801</td>
</tr>
<tr>
<td>TB150 L2t</td>
<td>L-shape 50X5</td>
<td>106.7</td>
<td>2 sg2-3</td>
<td>5180</td>
<td>5160</td>
<td>51.42</td>
<td>15114</td>
</tr>
<tr>
<td></td>
<td>2 bolts 8mm M8.8 through the slab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shear crack, yielding of longitudinal steel rebar and fracture of SFRP</td>
</tr>
<tr>
<td>TB150P1b</td>
<td>plate 20X5</td>
<td>95.5</td>
<td>2 sg3-4</td>
<td>5455</td>
<td>3855</td>
<td>46.30</td>
<td>3862</td>
</tr>
<tr>
<td></td>
<td>1 bolt HILTI HUS 6mm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Shear crack Anchoring bolt pull-out</td>
</tr>
</tbody>
</table>

### 3. Strengthening system application

All specimens were fabricated in the laboratory at room temperature (controlled environment). The formwork was removed 8 days after casting and the specimens were conditioned with wet burlap for additional 20 days. The application of the strengthening system took place at least 60 days after casting. Before the application of the strengthening system the surface of the beams was cleaned and the bottom corners were rounded. A first layer of resin was applied on the surface and the SFRP tape was positioned on the resin. Using grooved rollers it was ensured that no air voids were left in the resin. It should be noted that the SFRP tapes are relatively stiff and in order to obtain the U-shape that was needed for the strengthening scheme, it was necessary to pre-bend them in their final shape.

### Table 2. Details of anchoring system

<table>
<thead>
<tr>
<th>Beam ID</th>
<th>TB150L2t</th>
<th>TB150P1b</th>
</tr>
</thead>
<tbody>
<tr>
<td># layers</td>
<td>1 layer</td>
<td>1 layer</td>
</tr>
<tr>
<td>Anchoring System</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SFRP width (mm)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>SFRP Spacing (mm)</td>
<td>150</td>
<td>150</td>
</tr>
</tbody>
</table>

The mechanical anchoring system in specimen TB150B1b consists of a rectangular steel plate and a 6mm bolt, which is specifically fabricated for usage in concrete. The plates were predrilled in the middle (7mm hole). Using a drill bit a hole was drilled in the slab. The SFRP tape was applied using resin and subsequently the steel plate was positioned on top of the hole. Finally, the bolt was screwed in the concrete hole through the steel plate and the SFRP.
The same procedure was followed for specimen TB150L2t. The only difference was that for the latter beam 50 x 5 mm steel angle was used instead of the rectangular plate. 9mm bits were used to drill holes throughout the 75mm deep slab. The bolts were pushed from the bottom of the slab and were secured with lug nuts on the top of the slab. A 2mm thick steel plate was used as a washer on the top.

4. Experimental Setup

Four cantilever reinforced concrete beams with a T-section were fabricated and tested under cycling loading conditions at the Laboratory of Strength of Materials and Structures of Aristotle University of Thessaloniki. A schematic view of experimental setup and the arrangement of the measurement devices are shown in Fig. 2. The setup consists of a T-beam with dimensions 120 by 360 mm with a slab width of 360mm and a rectangular column with cross sectional dimensions 400 by 500 mm. The part of the specimen that resembles the column was securely fastened to a rigid wall using two steel I-beams. The free end of the beam was attached via a hinge to a 2500 kN capacity hydraulic actuator which was used to apply the cycling load. The load was controlled with a 1000 kN capacity load cell under deflection control, driven by a personal computer. After applying three cycles in elastic region, loading cycles were increased gradually up to failure. Same loading methodology was applied to all specimens. The ratio of the shear span length, 1675 mm, to the effective height of the beam, 335 mm, was 5.0, and was the identical for all specimens. The beam’s free end deflection and moment curvature at the maximum moment region were measured using LVDT’s. LVDT’s were also positioned vertical to the longitudinal axis of the beam to ensure that the beam did not deflect out of plain. LVDT’s were also placed at an angle of 45°. SFRP strains were measured with strain gauges. Strain gauges were attached on 8 consecutive SFRP tapes starting from the second from the fixed end. A strain gauge was attached to the midheight of each SFRP tape along the fiber direction.

5. Experimental results and discussion

CTB was the first tested specimen. Due to the fact that no shear reinforcement was used the beam failed in a brittle shear manner. Two relatively big shear cracks initiated on the beam web and propagated until the bottom of the slab. At that point the crack propagated along the interface between the top of the beam and the bottom of the slab. At failure, the slab was separated from the beam. Failure occurred at 37.25 kN.

Specimen TB150 suffered a relatively brittle failure. Failure occurred due to delamination of the SFRP strips. More specifically 5 shear cracks initiated at midheight of the beam, and one of them propagated quite quickly when the load exceeded the 60kN threshold to the top and bottom of the beam. The increasing width of the crack resulted in the debonding which initiated at the location of the crack and propagated to the top of the SFRP tape.

Several shear cracks were initiated in specimen TB150B1b both at +45 and at -45 degrees, due to the cycling load. The most considerable shear crack initiated at a distance of 700mm approximately from the fixed end of the beam. The crack propagated through the cycles and resulted in a local debonding of the SFRP tape due to an increasing crack width. Following, the debonding propagated to the top of the beam until the mechanical anchor. At that point the anchor failed due to the pull-out of the bolt. The pull out failure of the anchor resulted in the failure of the second tape that was resisting the shear crack. In a very short time both tapes due to anchorage failure failed and therefore the T-beam failed.

In specimen TB150L2t a similar shear crack pattern to TB150B1b was observed. The most significant shear crack occurred at a distance of 850mm from the fixed end of the beam. The crack propagated through out the loading cycles and was bridged by two SFRP tapes.
However, the failure of the beam was not the typical brittle shear failure that occurred in TB150B1b. Yielding of longitudinal rebars was firstly observed which resulted to fracture of the SFRP tapes at stress concentration locations due to the increase of deformations. It should be noted that the double bolt through the slab anchoring system did not show any signs of failure. It has to be pointed out that there was 3Ø20mm bars as longitudinal reinforcement, for a cross section of 120X360 mm (2.42%), and there were not any stirrups. Despite this fact the external shear reinforcement (anchored-SFRP) strengthened the beam satisfactorily and led the failure, firstly to the yielding of longitudinal bars and finally to the fracture of SFRP tapes.

5.1 Deflections

Load – deflection response envelopes for all the specimens are shown in Fig. 3. It can be seen that the maximum deflections for anchored specimens are significantly higher (40-65 mm) compared to specimen with no anchorage (less than 20mm). The energy dissipation for the non strengthened specimen is rather small. It was observed that non-anchored SFRP tapes delaminated in a brittle fashion. On the contrary anchored specimens exhibited a significantly more ductile behavior. Therefore anchored specimens were able to absorb considerable
amounts of energy up to failure (Table 1). More specifically TB150B1b can absorb 12.22 times more energy than TB150 whereas TB150L2t can dissipate 47.83 times more.

**Fig. 3. Shear Load vs Displacement curves for all specimens**

### 5.2 SFRP Strains

In order to evaluate the shear resistance contribution of the SFRP tapes strain gages were attached at midheight of each tape along the direction of the fibers. It should be mentioned that the reported strains for each specimen are the recorded strains from the tapes that the shear crack intersected. Additionally the number of SFRP that resisted the formed shear crack is shown in Table 1. The average recorded strains of the tapes that resisted the opening of the shear cracks can be used to calculate the shear resisting force that is contributed by the SFRP tapes.

The highest recorded strains were obtained for specimen TB150L2t. In this case, the maximum, average recorded strains exceeded 5200 με. In contrast the specimens that were strengthened with SFRP without the use of mechanical anchors, maximum strains were kept to significantly lower values (average of 2600 με). This observation indicates that the use of mechanical anchors results in better utilization and performance of the strengthening material. Specimen TB150 failed due to debonding of the SFRP tape, so the maximum recorded SFRP strain indicate values lower than the maximum effective strain. However, the recorded strain could be used to obtain shear performance related analytical expressions for the anchored SFRP tapes (see Table 1.).

ACI 440-08 and Fib report that the maximum effective strain should be limited to 0.004 mm/mm, whereas Eurocode does not provide a specific numerical limit but the effective strain is calculated using formulas that depend upon the strengthening scheme. The rather small strain value is based on the assumption that typical composite materials do not cope well with stress concentrations that occur at the corners of the beams. This however is not necessarily the case with steel fibers that are tougher than carbon and glass fibers. It should be noted that the steel fibers did not fail at the bottom corners of the beams.

Laboratory experiments conducted in similar specimens strengthened with Carbon fibers subjected to seismic load have shown that the maximum strains were less than 4500 με when CFRP tapes were placed at 45 degrees [7] or in a U-shape configuration with anchors, while the maximum recorded strains were less than 3500 με when the CFRP tapes were not anchored [8, 10]. It is therefore evident that SFRP tapes having a similar modulus of elasticity with...
CFRP tapes can carry higher stresses and therefore perform better than CFRP tapes for shear strengthening applications.

6. Conclusions

- SFRP tapes can be used for shear strengthening of reinforced concrete beams instead of CFRP or GFRP.
- Mechanical anchors greatly improve the performance of shear strengthening SFRP tapes.
- Both maximum deflections and recorded maximum SFRP strains are significantly higher for anchored specimens. The recorded SFRP strains were higher than recorded CFRP strains performed on similar specimens.
- The presented results are part of an ongoing research that is currently conducted at the Laboratory of Strength of Materials and Structures of Aristotle University.

7. Acknowledgements

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- Steel fibers are not commercially available and were provided from Bekaert Industries for the present study.
- Carbon fibers and epoxy resins were provided from Sika Hellas, which is gratefully acknowledged.

8. References