

Enhanced Repair and Strengthening of Reinforced Concrete Beams Utilizing External Fiber Reinforced Polymer Sheets and Novel Anchoring Devices



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SUMMARY:

Results obtained from research conducted in the framework of an initiative introduced by the Hellenic Earthquake Planning and Protection Organization aiming to support relevant provisions of the Greek Code for the repair and strengthening of R/C structures are presented and discussed. When trying to utilize fiber polymer sheets, either made of carbon (CFRP) or steel (SFRP), as external shear reinforcement attached on R/C beams, their potential of high tensile strength is prevented by the FRP sheets' debonding mode of failure thus limiting the aimed at increase of the shear capacity. In order to confront this limitation the effectiveness of various types of anchoring devices that can be incorporated together with such FRP sheets was studied. The objective here is to find effective anchoring devices that, in combination with FRP sheets attached as external shear reinforcement, can be applicable in realistic repair and strengthening schemes of prototype R/C beams.

Keywords: Strengthening Shear capacity, R/C beams and FRP sheets, Novel anchoring devices.

1. INTRODUCTION

This paper presents results from an experimental investigation aiming to upgrade the shear capacity of reinforced concrete (R/C) beams of prototype dimensions strengthened with either CFRP or SFRP fiber reinforced polymer strips in the form of open hoop external transverse reinforcement. A wide range of fiber reinforced composite materials have been successfully used in the past for the repair and strengthening of existing reinforced concrete (R/C) structures (Manos et al., 2011). Strengthening with externally bonded FRPs is particularly common, due to the numerous advantages related to their use. These advantages include the speed and ease of installation, the low weight and their high tensile strength (Katakalos et al., 2008). The most commonly used strengthening systems are glass or carbon fiber reinforced polymer (FRP) composite materials (Casadei et al., 2005, Ceroni et al., 2007, Pecce et al., 2006). Lately, a new strengthening system based on high strength steel fibers known as steel reinforced polymers (SFRP) was introduced as an alternative (Prota et al., 2006) exhibiting high strength together with a small domain of inelastic deformations. The shear capacity of reinforced concrete (R/C) structural elements, with low value of the steel transverse reinforcement ratio (stirrups), can be enhanced by applying, as transverse external reinforcement, such materials in the form of strips (Manos et al., 2011 Papakonstantinou et al., 2009). However, the exploitation of the high tensile strength of such FRP's or SFRP's strips is usually rather low due to the debonding type of failure that prevails. The degree of exploitation of these materials increases, providing that these strips

can be fully wrapped around the structural member. It was demonstrated in the past that proper full wrapping all around the structural members by these strips can inhibit their debonding which leads to the fiber fracture mode of failure. This results in the development of much higher forces at these external shear reinforcement strips than the forces developed at them prior to their debonding (Manos et al., 2011, Plevris et al, 1994, Saadamanesh et al, 1998). However, there are many practical applications when full wrapping cannot be put into practice. This paper presents results from an experimental investigation that focuses on the upgrading of the shear capacity of full scale R/C beams strengthened with either CFRP or SFRP open hoop strips, placed with an anchoring device in order to avoid the debonding mode of failure and thus increase the exploitation of the CFRP/SFRP materials. A number of prototype R/C rectangular or T-beam specimens in need of shear strength upgrade were constructed and tested, being subjected for this purpose. The load was imposed monotonically for rectangular beams whereas cyclic loading conditions were imposed when T-section beams were investigated. The investigation studied the use of an anchoring devices developed and patented by the Laboratory of Strength of Materials and Structures, of Aristotle University, Greece under the patent number WO2011073696 (Manos et al., 2011). Finally, an analytical approach is applied for predicting the shear strength of such R/C beams which is validated by the measured results.

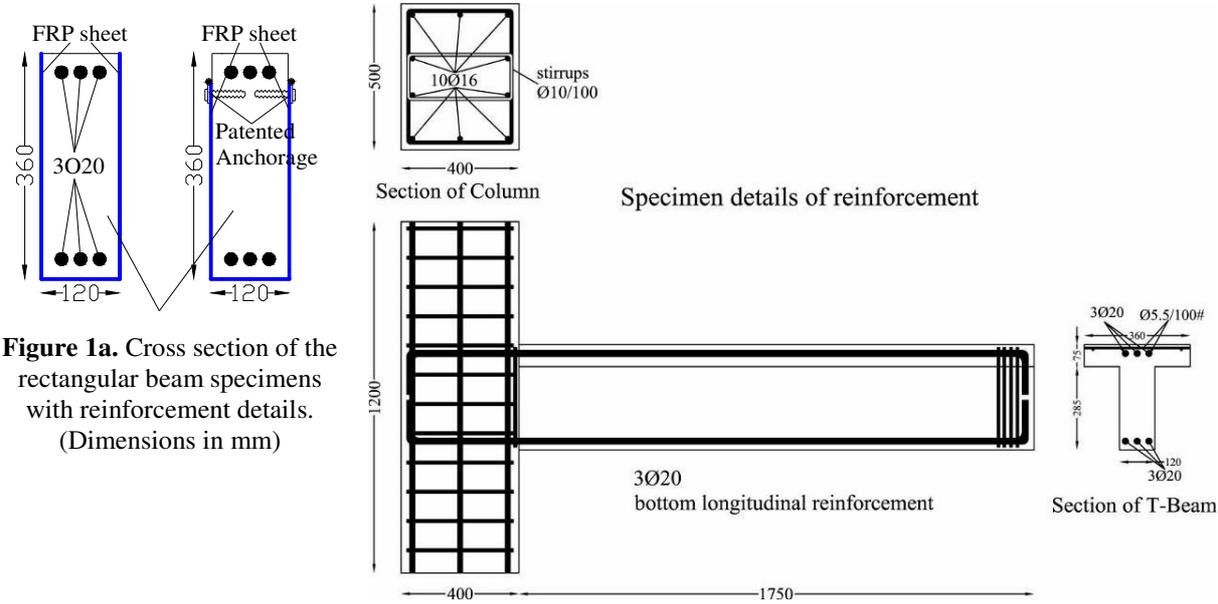


Figure 1b. Specimen details of T section (Dimensions in mm)

2. SPECIMENS AND MATERIALS

A considerable number of reinforced concrete (R/C) specimens either in the form of rectangular beams or T-beams were constructed and tested. This was done by applying the load up to failure in their virgin state and then applying the strengthening scheme of external shear reinforcement by attaching the fiber reinforcing polymer strips with or without anchoring. Alternatively, the strengthening scheme of external shear reinforcement was applied from the beginning at the virgin state of the specimens by attaching these fiber reinforcing polymer strips with or without anchoring. In this paper, results from a total number of nine reinforced concrete (R/C) beams will be presented. Six of these specimens were of rectangular section. Their cross-section dimensions were 120mm width by 360mm depth (Figure 1a). Their overall span was 2700mm whereas the shear span was equal to the 1/3 of the total length, thus 900mm. These rectangular section specimens were simply supported R/C and tested to failure, when subjected to four point monotonic loading conditions. (Figure 2a) The remaining three specimens that will be discussed in this paper have a T-section and they were tested under cyclic loading conditions. The T-beam dimensions are 120mm width by 360mm depth; the slab width is 360mm and the slab thickness is 75mm. (Figure 1b)

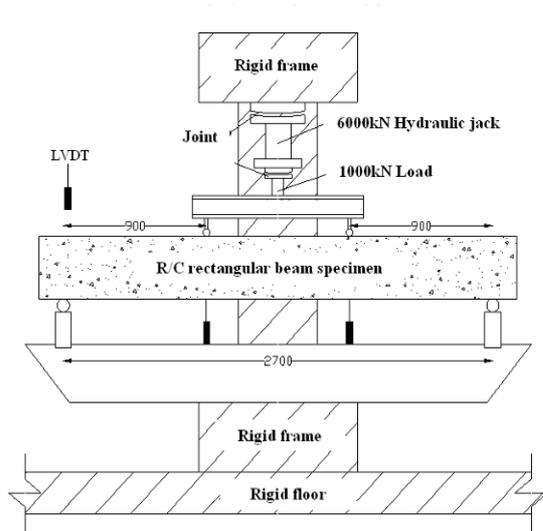


Figure 2a. Experimental set-up for the four-point bending of the rectangular cross-section specimens

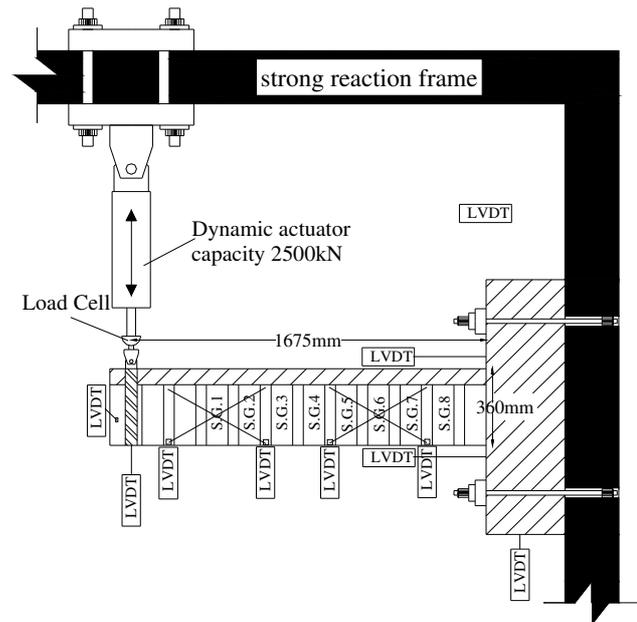


Figure 2b. Experimental set-up for T-Beam specimens

The loading arrangement for these T-beam specimens is depicted in figure 2b. The beam to column joint of the T-beam specimens was rigidly attached on a strong reaction laboratory frame. The T-beam specimens were thus in the form of cantilever with their free end linked via a hinge with a 2500 kN capacity dynamic hydraulic actuator which was used to apply the cyclic load which was monitored through a 1000 kN capacity load cell. The cyclic loading sequence was applied through the imposed displacement on the free end of the cantilever, at a distance of 1675mm from the right side of the beam to column joint; the dimensions of the cross-section of this joint were 400mm by 500 mm. The cyclic load was applied on the T-beam specimen by operating the dynamic actuator under displacement control, driven by a personal computer. After applying three cycles of the same imposed displacement amplitude, the same loading pattern was repeated, as shown in figure 3, with imposed displacement cycles being increased gradually up to failure. The same loading sequence was applied to all three specimens.

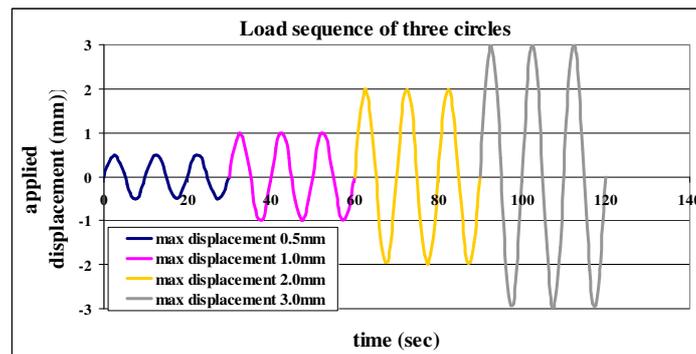


Figure 3. Cyclic loading pattern applied for cantilever T-section beams

Instrumentation was provided to monitor the applied load as well as the deformation of the specimens. Figure 2b depicts the instrumentation used for the T-beam specimens. Strain gages were placed on every FRP sheet in order to record the developed strains on them. The strain gages were placed along the direction of carbon or steel fibers, at the mid-distance of both width and height of the sheet, due to the fact that that the shear cracks are difficult to predict. The cross-sections and conventional steel reinforcement details were identical for all specimens (figures 1a and 1b). Three 20 mm diameter steel rebars were positioned longitudinally at the top and bottom of the beam section. No stirrups were placed in these beams. The strengthening scheme consisted of either uniaxial CFRPs or uniaxial high strength steel fiber (SFRP) sheets combined with a commonly used organic resin (Sikadur 330). CFRP sheets were provided by SIKA Hellas (SikaWrap230C) whereas SFRP sheets were provided by

Bekaert Industries. The width of the sheets was kept constant and equal to 100mm. The thickness of CFRP is equal to 0,131mm whereas the equivalent thickness of SFRP is equal to 0,1184mm. The organic resin was also provided by Sika Hellas which is gratefully acknowledged. Anchoring was used for the FRP strips in three 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 all beams. Three cylinders were tested for each beam. The average compressive strength of concrete was approximately 22 MPa. The mechanical properties of both CFRP and SFRP were acquired from coupon tests. CFRP sheets resulted in a modulus of elasticity equal to 230 GPa, and in a maximum recorded tensile strain equal to 0,009. The equivalent values of SFRP are 210 GPa and 0,009. The matrix is a typical epoxy resin (Sikadur-330) and the specifications can be provided by the manufacturer.

The axial distance of all FRP sheets was kept constant and equal to 200mm. Specimens RB, RBs and TB were used as control beams. The first letter R indicates that specimens have a rectangular cross section or T refers to beams with a T section. RBs is the only specimen with internal shear reinforcement ($\varnothing 8/250$), investigated for comparison purposes. RB200C, RB200S and TB200S are beams strengthened with either Carbon or Steel FRP sheets without any anchoring of the FRP strips. On the other hand, RB200Ca, RB200Sa and TB200Sa are specimens strengthened with either Carbon or Steel FRP sheets combined with the anchoring device developed and patented by Laboratory of Strength of Materials and Structures.

The anchoring device consists of a circular rod around which FRP sheets are wrapped, a rectangular steel plate which is placed over the FRP sheet and below the steel rod. (Figure 4). Two 8 mm diameter bolts, which are specifically fabricated for usage in concrete, secure the anchoring device into the concrete member. The plates were predrilled in the middle (9mm hole). Using a drill bit a hole was drilled in the concrete phase.

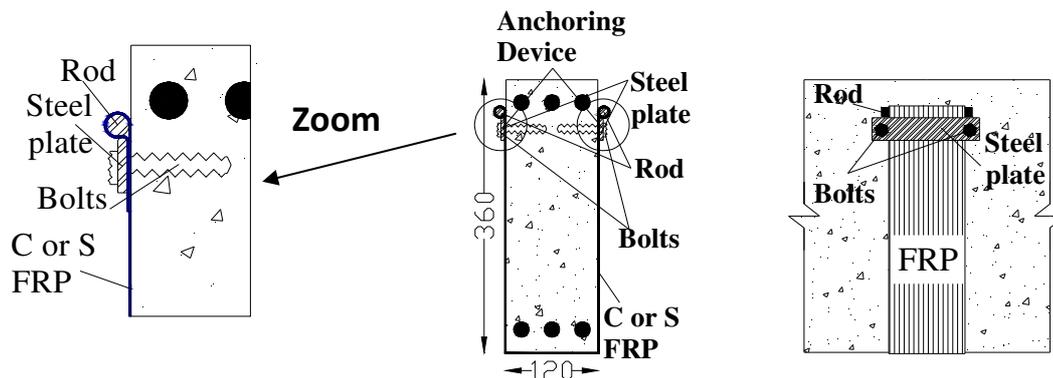


Figure 4. Patented Anchoring Device (WO2011073696)

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Increase of Strength – Modes of failure

In all, six R/C rectangular simple supported beams and three cantilever beams were investigated. For all specimens, load and vertical displacements were recorded as well as strains at each FRP sheet. Table 1 lists the measured values from this experimental investigation. The measured shear capacity is listed in column (4) of Table 1 whereas the measured maximum strain values of the attached FRP sheets that the shear crack intersects are listed in (5) and (6) columns of the same table.

Rectangular beam specimens

The shear strength of the control rectangular beam (RB) without any stirrups or CFRP strips was recorded equal to 39.4kN, whereas the specimen RBs with $\varnothing 8/250$ mm as transverse reinforcement was increased to 90.9kN. From the results shown in Table 1, it is evident that the maximum recorded shear capacity for all strengthened rectangular beams with CFRP strips was significantly greater than that of either the RB or the RBs shear capacity (see also Table 2a). The shear capacity of the

specimens strengthened with SFRP strips exhibited an increase of up to 210% when anchors were utilized. For this specimen, the mode of failure was the pull out of the anchoring system (figure 5b). Without anchors, the shear capacity increase was limited to 138%, due to the debonding mode of failure of the CFRP strips (figure 5a). When the shear capacity of the strengthened specimens is compared to that of the virgin specimen with nominal transverse reinforcement in the form of steel stirrups the resulting maximum shear capacity increase is equal to 7.6% when using CFRP strips without anchors and 34.2% when using SFRP strips with anchors (see table 2). The beneficial effect of anchoring the U-shape FRP strips in order to inhibit the debonding mode of failure is thus demonstrated.



Figure 5a. Debonding mode of failure



Figure 5b. CFRP failure of the anchoring

Table 1. Specimen Details and Summary of Experimental results

Name of specimen	Shear reinforcement	FRP with anchors	Experimental shear force V_{max} . (kN)	Strain of 1 st sheet (μ strain)	Strain of 2 nd sheet (μ strain)	Calculated shear force V_{cal} (kN)	Mode of failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
RB Rectangular	NO	-	39.4	-	-	-	Brittle shear crack
RBs Rectangular	Ø8/ 250 (internal)	-	90.9	-	-	-	Yield of stirrups
RB200C Rectangular	1 layer CFRP	NO	97.8	7390	610	98.05	Debonding
RB200Ca Rectangular	1 layer CFRP	YES	115.1	4580	6590	107.77	CFRP fracture
RB200S Rectangular	1 layer SFRP	NO	94	5935	4620	99.77	Debonding
RB200Sa Rectangular	1 layer SFRP	YES	122	6115	6415	104.68	Anchoring failure
TB T-beam	NO	-	37.25	-	-	-	Brittle shear crack
TB200S T-beam	1 layer SFRP	No	58.3	4010	-	57.19	Debonding
TB200Sa T-beam	2 layers SFRP	YES	120	4960*	3000*	116.42	Shear Crack Anchoring bolts pull out

* For this level of strain the force exercised through the FRP strip at the anchoring was for this specimen (2 layers per strip) twice the corresponding force exercised at the anchoring for all the other specimens (1 layer per strip) listed in this table.

Table 2a. Increase (%) of the shear capacity compared to RB and RBs

	RB	RBs	RB200C	RB200Ca	RB200S	RB200Sa
% Increase compared to RB	0	130.7	148.2	192.1	138.6	209.6
% increase compared to RBs	-	0	7.6	26.6	3.4	34.2

Table 2b. Increase of the shear capacity compared to TB

	TB	TB200S	TB200Sa
% Increase compared to TB	0	56.5	220.0

T-section beam specimens

The control cantilever beam (TB) failed in a brittle fashion, as expected, due to the absence of shear reinforcement. Two relatively big shear cracks initiated on the specimen's web and propagated to the bottom of the slab. The shear capacity at failure was equal to 37.25 kN. The shear capacity due to the contribution of the concrete is similar for both types of specimens (rectangular specimen–simply supported–monotonic load or T-beam specimen–cantilever–cyclic load). As the quality of the concrete was the same for both types of specimens it seems that the type of loading, either monotonic or cyclic, does not influence the shear strength of the control specimens.

**Figure 6.** Shear cracks of T-beam specimens during cyclic testing

The maximum shear capacity increase is of the order of 220% (See Table 2b) for specimen TB200Sa, utilizing the patented anchoring devices. Specimen TB200S, without anchors, exhibited an increase in the shear capacity of the order of 56.5% and suffered a relatively brittle failure due to the delamination of the SFRP sheets. Several shear cracks were initiated in specimen TB200Sa, both at +45 and at -45 degrees, due to the cyclic load (figure 6). By comparing the beams that were strengthened with CFRP strips vs. the ones that were strengthened with SFRP strips it could be observed that the overall behavior was similar in terms of maximum shear capacity and mode of failure. Thus, SFRP sheets could be utilized as an alternative for external shear reinforcement in strengthening applications of R/C beams. The type of loading does not influence the overall behavior of the strengthened beam specimens when the anchoring devices are utilized. However, in the absence of anchoring devices, when the debonding mode of failure is prevailing, the cyclic type of loading results in a decrease of the shear strength capacity. The prevention of the premature delamination resulted in a considerable increase of the shear capacity. The prevention of the delamination mode of failure through FRP strip anchoring leads to the appearance of alternative failure scenarios; that is, either fracture of the FRP or failure of the anchoring (see Table 1, specimens RB200Sa and TB200Sa). By proper design of the patented anchor this failure could also be prevented.

3.2. Shear force – vertical displacement response

Shear force – vertical displacement response envelope curves are depicted in figure 7a for the rectangular specimens and in figure 7b for the T-beam specimens, respectively. When anchors are used together with the FRP strips the increase in the shear capacity is also accompanied by an increase in the measured maximum displacements for the specimens. For T-beam specimens the displacement increase due to the anchors is of the order of 35%, whereas for the rectangular section specimens the

corresponding increase is of the order of 65%. The non-anchored FRP strips were delaminated and led the specimens to a brittle failure. On the contrary, the anchored FRP strips led the specimens to a relatively ductile behavior. These anchored FRP strip specimens were able to absorb considerable amounts of energy up to failure. The utilization of the anchoring device transforms the overall behavior of the strengthened beams from a rather elastic-brittle to a more ductile-seismic efficient behavior.

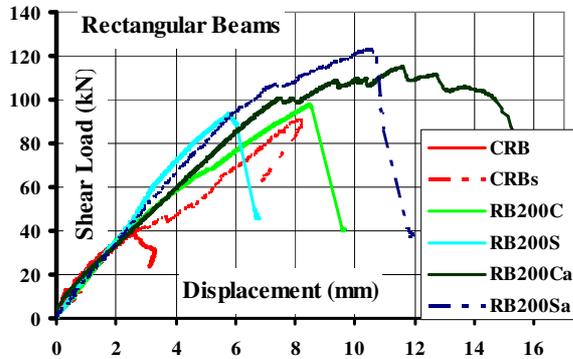


Figure 7a. Shear force – vertical displacement response curves for rectangular beam specimens (monotonic load)

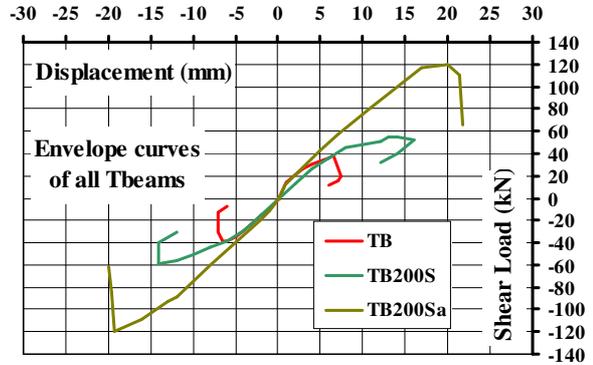


Figure 7b. Shear force – vertical displacement response envelope curves for the T-beam specimens (Cyclic load)

3.3. CFRP-SFRP strains

In order to evaluate the shear resistance contribution offered by either the CFRP or the SFRP sheets, strain gages were attached at midheight and mid-width of each sheet along the direction of the fibers. It should be mentioned that the strain values for each specimen reported here are the measured maximum strain values from strain gages corresponding to those FRP sheets that were intersected by the shear crack that developed during the loading sequence. These measured maximum FRP strip strain values are listed in table 1 (columns 5 and 6) together with the serial number of the corresponding FRP strip. Those average recorded maximum strain values are next employed to obtain the shear force that is contributed by the FRP sheets. As already mentioned, the existence of an anchoring device allows the development of greater strains on FRP sheets compared to the cases where no anchoring device is in place. The highest measured shear capacity value was obtained for specimen TB200Sa (120KN, Table 1) whereby the used 2 layers of SFRP developed maximum strain value of $4960\mu\epsilon$. The use of anchoring prevented the delamination mode of failure; instead, the failure of the anchoring occurred in this specimen (see Table 1). By proper design of the patented anchor this failure could also be inhibited. In contrast, for specimens strengthened with FRP strips without the use of anchors, the maximum FRP strains and the corresponding force values were kept to significantly lower levels (average of $4000\mu\epsilon$). This observation indicates that the use of anchors results in better utilization and performance of the FRP material for shear strengthening.

According to the recommendations of either ACI 440-08 or FIB, the maximum effective FRP strain that can be utilized should be limited to 0.004 mm/mm. Eurocode does not provide a specific FRP strain limit; the effective strain is calculated using formulas that depend upon the strengthening scheme. These recommended relatively small strain value are based on the assumption that typical composite materials do not cope well with stress concentrations that occur at the corners of the FRP strips as they are wrapped around the beam. This precaution is not necessarily applicable when using steel fiber strips for shear reinforcement as they are tougher than strips made by either carbon or glass fibers. During the experimental sequence, none of the SFRP strips attached as shear reinforcement developed any type of failure at its steel fibers at the bottom corners of the strengthened specimens.

From past research, it was demonstrated that specimens strengthened with carbon fibers and subjected to seismic type cyclic loads developed maximum strains that were less than $4500\mu\epsilon$, when CFRP strips were placed at 45 degrees (Anil, 2008) or in a U-shape configuration with anchors, while the maximum recorded strains were less than $3500\mu\epsilon$ when the CFRP strips were not anchored (Anil, 2006, Tanarlsan, et al. 2008, 2010). It is therefore evident that SFRP strips, with modulus of elasticity

similar to that of CFRP strips, can develop much higher stresses and therefore perform better than the corresponding CFRP strips for shear strengthening applications of R/C beams.

4. ANALYTICAL PREDICTIONS

Based on these strain recordings the maximum shear capacity was obtained (V_{cal} , Table 1 column 7) which is compared to the experimental maximum shear force V_{max} . Values V_{cal} were calculated using the equation:

$$V_{cal} = V_{c,exp} + V_{f,cal} \quad (4.1)$$

Where, $V_{c,exp}$ is the experimental shear force of the control specimen (RB or TB), while the $V_{f,cal}$ is calculated as:

$$V_{f,cal} = 2A_f E_f \varepsilon_{f,exp} = 2t_f b_f E_f \varepsilon_{f,exp} \quad (4.2)$$

where:

$$\varepsilon_{f,exp} = \varepsilon_{f1,exp} + \varepsilon_{f2,exp} \quad (4.3)$$

and $\varepsilon_{f1,exp}$, $\varepsilon_{f2,exp}$ are the maximum recorded strains in two consecutive FRP strips intersected by a shear crack (see Table 1). By employing the strain value resulting from Eq. 4.3 it is assumed that the FRP contribution utilizes the force that develops at these two consecutive FRP strips intersected by the major shear crack (in our case strip No. 1 and 2, listed in table 1 columns 5 and 6). In this way, this contribution of the FRP shear resistance replaces the term commonly used that employs the ratio d_f/S_f (where d_f is the width of the FRP strip and S_f is the distance between subsequent FRP strips)

In almost all cases the calculated shear capacity value is lower, by a relatively small margin, than the one measured during the experimental sequence. More specifically, the ratio of measured vs. calculated shear capacity values (V_{meas}/V_{cal}) varies from 1% up to 16% with an average value of 5,7%. (Table 3). As already mentioned, the FRP strains were measured using only one strain gage per FRP strip, which was located approximately in the center of FRP sheets in terms of width and height; therefore any variation of the strain field along the width of the strip could not be captured. This may partially explain why in some cases the ratio of measured vs. calculated shear capacity values (V_{meas}/V_{cal}) indicates relatively larger discrepancy between measured and predicted shear capacity than in other cases, where there is an almost perfect match. For specimen RB200Sa the calculated shear capacity was 16% lower than the measured value. Despite these discrepancies it can be concluded that the shear capacity values calculated in this way agree quite well with the corresponding measured values.

Table 3. Measured vs. calculated shear capacity

	RB200C	RB200S	RB200Ca	RB200Sa	TB200S	TB200Sa
V_{meas}/V_{cal}	0,997	0,94	1,07	1,16	1,02	1,03

4.1. Brief Description of an Expert System.

The comparison of measured versus calculated shear capacity values listed in table 3 is based on the FRP shear contribution obtained from the measured FRP strip strain values for both the measured as well as the calculated shear capacity. In this section, the comparison of the measured shear capacity will be made with predictions of the shear capacity based on relevant code provisions, assuming the value of all the safety factors for the materials is equal to 1.0. In order to facilitate the comparison of the measured experimental results of the shear capacity of the tested specimens with predictions obtained through the relevant code provisions, an expert system was developed. The main features of this expert system are as follows. The section geometry and the longitudinal and transverse reinforcing detailing is given by the user through the appropriate user-friendly interface. Rectangular as well as a T-beam sections are alternative options of this expert system (see figures 8a, 8b). The detailing of an externally attached FRP strengthening scheme can also be input through the same interface. The given options for such a strengthening scheme is either for enhancing the flexural capacity by placing FRP layers at the bottom of the section or for enhancing the shear capacity by placing FRP transverse shear reinforcing strips. For the latter case, the strips can be either closed hoops or open U-strips. The actual

properties of the concrete, the steel and the FRP are easily input by the user. The safety factors, commonly used in design for all these materials, have their default values that can be subsequently changed by the users to alternative desired values. The results are given in terms of ultimate flexural and shear capacity. For evaluating the shear contribution of the FRP strips, use is made of the relevant provisions of the Greek Code for the repair of R/C structures as well as those of the EuroCode (EC2), FIB and ACI. The shear contribution of the FRP strips in table 4 was obtained assuming an ultimate strain value for these strips equal to 0.015. The Greek Code provisions assume a maximum FRP strain value equal to 1/2 of this ultimate strain value. Specimens RB200C and RB200Ca are of rectangular cross section with U-shape CFRP strips whereas specimens TB200S and TB200Sa are of T-section with U-shape SFRP strips. Specimens RB200C and TB200S are with U-shape FRP strips without anchoring whereas specimens RB200Ca and TB200Sa are with U-shape FRP strips with anchoring.

Table 4. Measured and Predicted shear capacity

Specimens (Table 1)	Vcd (KN) concrete	Vfd (KN) FRP strips shear contribution predicted by				Predicted Vcd+Vfd (KN)	Measured Vcd+Vfd (KN)
		FIB	EC2	Greek Code	ACI		
RB200C RB200Ca	38.91	29.44	22.65	32.70* / 59.23**	22.61	71.61* / 98.14**	97.8* / 115.1**
TB200S TB200Sa	38.91	28.29	21.76	31.25* / 54.08**	21.44	70.16* / 92.99**	58.3* / 120.0**

* applying the relevant provisions based on the debonding mode of failure

** applying the relevant provisions based on the FRP fracture mode of failure

General Data

Geometry: H (m) 0.36, B (m) 0.12, d1 (m) 0.03, d2 (m) 0.03, hf (m) [], beff (m) [], As2 (cm2) 9.42, As1 (cm2) 9.42, Asw (cm2) 0, s (m) 0.2, tf1 (mm) 0.176, tf1 Layers 0, bf1 (m) 0.2, tf2 (mm) 0.1184, tf2 Layers 1, df (m) 0.29, sf (m) 0.2

External Force: N (kN) 0

Safety Factors: gamma c 1., gamma s 1., gamma f 1., gamma b 1., gamma m 1.

Additional data for Shear Analysis

FRP2 Properties: Ef (GPa) 230, eu 0.015, Strips [checked], Sheet [unchecked], O-Shape [unchecked], U-Shape [checked], I-Shape [unchecked]

Steel Properties: fywk (MPa) 500, fybk (MPa) 235

Resin Properties: tr (MPa) 8

Shear Length: L (m) 0.5

Figure 8a. Expert system utilized for specimens RB200C and RB200Ca

General Data

Geometry: H (m) 0.36, B (m) 0.12, d1 (m) 0.03, d2 (m) 0.03, hf (m) 0.075, beff (m) 0.36, As2 (cm2) 9.42, As1 (cm2) 9.42, Asw (cm2) 0, s (m) 0.2, tf1 (mm) 0.176, tf1 Layers 0, bf1 (m) 0.2, tf2 (mm) 0.1184, tf2 Layers 1, df (m) 0.29, sf (m) 0.2

External Force: N (kN) 0

Safety Factors: gamma c 1., gamma s 1., gamma f 1., gamma b 1., gamma m 1.

Additional data for Shear Analysis

FRP2 Properties: Ef (GPa) 210, eu 0.015, Strips [checked], Sheet [unchecked], O-Shape [unchecked], U-Shape [checked], I-Shape [unchecked]

Steel Properties: fywk (MPa) 500, fybk (MPa) 235

Resin Properties: tr (MPa) 8

Shear Length: L (m) 0.5

Figure 8b. Expert system utilized for specimens TB200S and TB200Sa

5. CONCLUSIONS

- Steel Fiber Reinforced Polymers (SFRP) that were specially fabricated for this specific research program could be successfully used as an alternative material for shear strengthening of R/C beams.
- Reinforced Concrete beams that were strengthened with FRP strips without the use of the anchors exhibited a modest increase of the shear capacity, when compared to the non-strengthened control specimen due to the debonding of the FRP sheet.
- When the patented anchoring device was utilized together with either CFRP or SFRP shear reinforcing strips for strengthening the same R/C specimens, the increase of the shear capacity was much larger than in the case without anchors. This shear capacity increase attained a maximum value of 220% when compared to the shear capacity of the control beam without stirrups.

- In the absence of anchors and with the debonding mode of failure prevailing, the cyclic load conditions result in a decrease of the ultimate shear strength when compared to similar specimens loaded in a monotonic way. However, when the anchoring device is utilized, the influence of the type of loading is not conclusive.
- Both measured maximum displacement values and maximum FRP strain values are significantly increased for specimens with anchored FRP strips. For similar specimens the measured maximum FRP strain values in the case of SFRP strips were higher than in the case of CFRP strips, thus resulting in a much better performance.
- The utilization of FRP strips with anchoring devices transforms the overall behavior of the strengthened beams from a rather elastic-brittle to a relatively ductile behavior.
- An increase of the post cracking stiffness was observed for all strengthened specimens. This was more pronounced for specimens with FRP strips utilizing anchors.
- The analytical predictions of the shear capacity agree quite well with the corresponding measured values.
- The developed expert system is quite efficient in producing shear capacity predictions based on the provisions of various codes. In all examined cases, the measured shear capacity values are larger than the corresponding values obtained by applying the various code provisions, which are based on rather low limits of allowable FRP strains even in the presence of anchors.

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