

Shear Strengthening of R/C Beams with FRP Strips and Novel Anchoring

G. C. Manos*, K. Katakalos, G. Koidis, C. G. Papakonstantinou

Laboratory of Strength of Materials and Structures Department of Civil Engineering, Aristotle University of Thessaloniki, 54006, Thessaloniki, Greece

Abstract The shear strengthening behaviour of R/C beams, when applying FRP strips externally with or without anchoring, is studied. This is done by subjecting six specimens of prototype dimensions with or without such strengthening to four-point bending. Specimens strengthened with either carbon or steel FRP strips without the use of anchors exhibited a modest increase in shear capacity, when compared to the non-strengthened control specimen, due to the debonding mode of failure of these FRP strips. The patented anchoring device was utilized together with either carbon or steel FRP strips for shear strengthening. In this case, the FRP strips debonding failure was prevented and the increase of the shear capacity was much larger than in identical specimens without anchors. An expert system developed for this purpose is quite efficient in producing successful shear capacity predictions based on the provisions of various codes. The Greek Code for retrofitting existing R/C structures yields shear capacity predictions in good agreement with measured values.

Keywords Strengthening R/C beams, Upgrading shear capacity, FRP sheets, Novel anchoring devices, monotonic loading conditions

1. Introduction

Many reinforced concrete (R/C) structural members of old buildings need strengthening. This is either because they were built according to old code provisions and do not meet the current design requirements, or because they are damaged after a strong earthquake sequence. Strips made of fiber reinforcing polymers (FRP) behave in tension almost elastically till their ultimate state; this for the material itself is the breaking of the fibers in tension. The value of the Young's modulus is approximately 240Gpa for carbon fibers, 200Gpa for steel fibers and 80Gpa for glass fibers ([1] to[4]). Their design ultimate axial strain values are in the range of 1%. Consequently, strips made from these materials, despite their relatively small thickness which is usually below 0.2mm for one layer, can develop substantial tensile forces in the direction of their fibers. This property accompanied by their low weight and their very easy external attachment results in their being used as effective transverse reinforcement for structural elements in need of shear capacity upgrading (figure 1 and[1] to[6]). A wide range of fiber reinforced composite materials have been successfully used in the past for the repair and strengthening of existing R/C structures[1]. Strengthening

with externally bonded FRPs is particularly common, due to the speed and ease of installation, their low weight and high tensile strength[3].

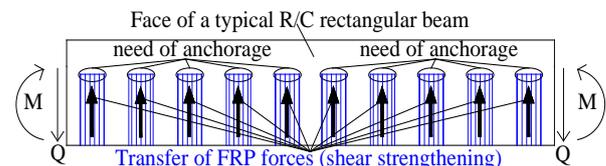


Figure 1. Shear FRP reinforcement for a rectangular beam

Such strengthening schemes utilize glass or carbon fiber reinforced polymer (FRP) composite materials ([4] to[6]). Lately, new steel fiber reinforced polymer (SFRP) sheets were introduced as an alternative employing high strength steel fibers that also exhibit a small domain of inelastic deformations[7]. The application of all these various types of FRP sheets is limited by the way the tensile forces which develop on these FRP sheets can be transferred. When the transfer of these forces relies solely on the interface between the FRP sheet and the external surface of the reinforced concrete structural elements the delamination (debonding) mode of failure of these sheets occurs. This interface is composed of the used organic or inorganic matrix for the attachment. The delamination is due to the relatively low value of either the ultimate bond stress at this interface or the relatively low value of the tensile strength of the underlying concrete volume. Consequently, there is a need for anchoring of these FRP sheets, in addition to the simple attachment, in order to transfer their tensile forces.

* Corresponding author:

gmanos@civil.auth.gr (G. C. Manos)

Published online at <http://journal.sapub.org/jce>

Copyright © 2012 Scientific & Academic Publishing. All Rights Reserved

In this way, the exploitation of the FRP material will be enhanced. The satisfactory behaviour of such anchoring, without its premature failure, becomes in this case critical. Successful FRP anchoring results in the development of high levels of tensile forces at the FRP layers, thus meeting the strengthening design requirements for the structural members under consideration[1].

The shear capacity of reinforced concrete (R/C) structural elements, with low ratio value of the steel transverse reinforcement (stirrups), can be enhanced by applying such FRP strips as transverse external reinforcement[1],[8]. This paper presents results from an experimental investigation aiming to develop such a shear strengthening technique based on anchored open hoop CFRP or SFRP strips in the form of external transverse reinforcement (Figure 2). As already mentioned, when these strips are simply attached, the exploitation of the FRP high tensile strength 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 member with these strips can inhibit their debonding and lead to the fiber fracture mode of failure. In this case, much higher forces develop at these external shear reinforcement strips than the forces prior to their debonding ([1],[9],[10]). However, there are many practical applications when full wrapping cannot be implemented (T-beams).

As an alternative to full wrapping, an innovative open hoop FRP transverse reinforcement with an anchoring device was developed in order to upgrade the shear capacity of full scale R/C beams. Use was made of 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 beam specimens in need of shear strength upgrade were constructed and tested, being subjected to shear and flexure by a four-point bending loading arrangement (Figure 9). This investigation included the use of an anchoring device developed for this purpose and patented by the Laboratory of Strength of Materials and Structures, of Aristotle University, Greece under the patent number WO2011073696[11]. Finally, an analytical approach, developed for predicting the shear strength of such R/C beams that include FRP transverse reinforcement, is applied and its predictions are validated by the obtained measurements.

2. Initial Tests Assessing the Effectiveness of Anchoring

Initially, the effectiveness of anchoring devices for an FRP strip was investigated by utilising a number of concrete prismatic specimens representing a part of an R/C beam of prototype dimensions. These specimens can house one such open hoop FRP strip with sufficient width and length (Figure

2, part a-a and part b-b). In all, ten such specimens were fabricated and tested being subjected to the loading arrangement depicted in figure 3. Five of these specimens had CFRP strips, whereas SFRP strips were attached to the remaining five. The use of the anchoring device was also utilised selectively with a number of these specimens as follows.

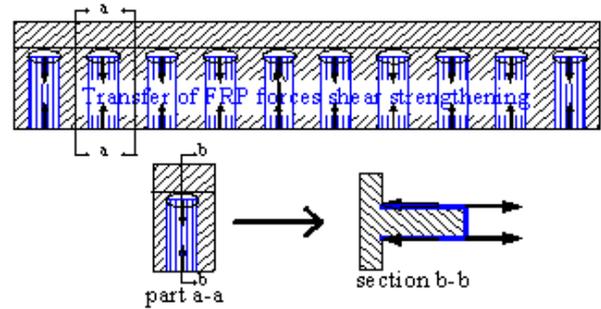


Figure 2. RC beam strengthened with FRP strips as transverse reinforcement

2.1. Experimental Set-up

All concrete prisms were fabricated using the same concrete mix and the same internal reinforcement, which was used to prohibit any accidental failure (figure 3). The measured cylinder strength of the concrete was equal to 22 MPa. The properties of the used FRP's are listed in Table 1, as given by the manufacturers.

Table 1. Material properties of the used FRP strips

Material	Type / Name	Modulus of Elasticity (GPa)	Thickness of Layer (mm)	Ultimate nominal axial FRP strain
CFRP	SikaWrap 230C	234	0.131	0.018
SFRP	Bekaert BW01	210	0.1184	0.015

In the loading arrangement of figure 3 the tensile force is directly applied in the axis of symmetry at the right part of the FRP strip that forms a continuous open U-hoop; the other two sides of the FRP strip are bonded in a symmetric way on the top and bottom side of the concrete prism, as shown in this figure. Despite the symmetry of this test set-up, instrumentation was provided in order to record symmetric as well as asymmetric response of the specimen, especially during the initiation and propagation of the FRP debonding.

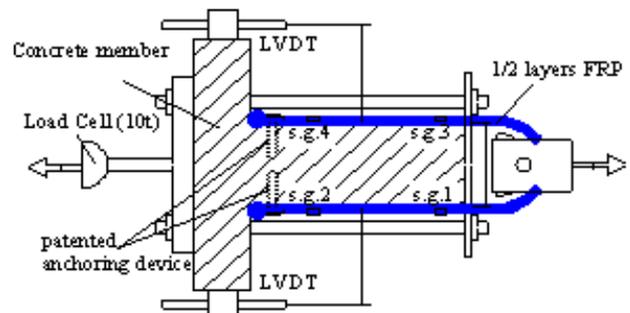


Figure 3. Experimental set-up used in the initial tests

The applied load is measured during testing together with the longitudinal (axial) strains at four different locations of the external surface of the FRP strip, as indicated in figure 3 (s.g.1 to s.g.4). This is done in order to obtain the stress field that develops at the FRP layers before and during the debonding. Moreover, the relative longitudinal displacement between the concrete prism and the FRP surface is also monitored using two displacement transducers that are properly attached on the specimen, as indicated in this figure. This is done in order to record the initiation and propagation of the debonding of the FRP strip from the specimen.

Two different types of anchoring devices were investigated. The first utilizes an L-shape steel angle and bolts for transmitting the forces to the concrete prism representing a part of a T-beam (figure 4). The second type, which is developed by the Laboratory of Strength of Materials and Structures of Aristotle University of Thessaloniki in Greece and is patented with patent number WO2011073696[11], is also depicted in figure 5. Type 2 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 5). 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 of either a T-beam or a rectangular beam.

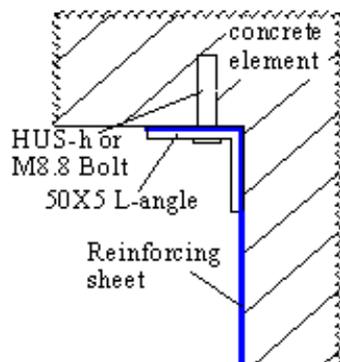


Figure 4. Type 1 Anchor

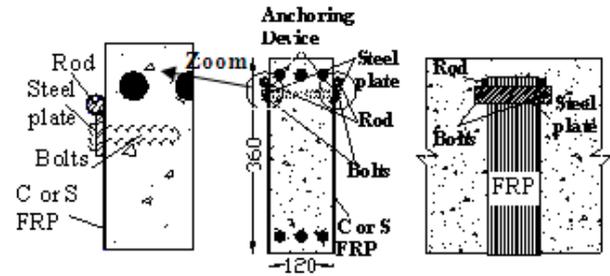


Figure 5. Type 2 Anchor (Patented under WO2011073696[11])

The tested specimens with their details are listed in table 2 together with their code names. The first letter C in the code name denotes a carbon fiber reinforcing polymer strip (CFRP); alternatively, letter S denotes a steel reinforcing polymer strip. The type of anchor is denoted by the second letter of the code name (L for anchor type 1, P for anchor type 2 and N when no anchoring device is utilized). Moreover, the number of layers of FRP strips is denoted by the third character of the code name (1 or 2 for one or for two layers, respectively). Finally, when using an anchoring device this is indicated by a fourth character in the code name denoting the type of bolt that is employed (h for bolts provided by HILTI and b for regular M8.8 bolts). The tests were conducted using a 1000 kN capacity hydraulic piston. The measurements of load, displacements and strains were recorded using an automatic data acquisition system.

2.2. Experimental results and discussion

The summary of the experimental results is shown in table 3. In this table, the observed failure mechanism is also listed together with the corresponding value of the ultimate measured load as well as the value of the load recorded at the initiation of debonding. Moreover, the maximum strain values measured by the strain gauges at locations 1 and 3 on the FRP strip surface are also listed. The average value of these maximum FRP strains was utilised to calculate indirectly the load sustained by the FRP strips taking into account their total cross-sectional area and the value of the Young's modulus, listed in table 1. Finally, the material exploitation indicator (M_e) is given at the same table as the ratio of the maximum measured strain by the ultimate strain value provided by the manufacturer (Table 1).

Table 2. Details of specimen used in the initial tests

Specimen Name	Material Type	Number of Layers	Anchor Type	Bolt Type
CN1	CFRP	1	no	no
CL2h ₁	CFRP	2	L-shape	1XHUS by Hilti
CL2b	CFRP	2	L-shape	1Xbolt M8 through floor
CL2h ₂	CFRP	2	L-shape	2XHUS by Hilti
CP2h	CFRP	2	pin-anchor	2XHUS by Hilti
SN1	SRP	1	no	no
SL2h ₁	SRP	2	L-shape	1XHUS by Hilti
SL2b	SRP	2	L-shape	1Xbolt M8 through floor
SL2h ₂	SRP	2	L-shape	2XHUS by Hilti
SP2h	SRP	2	pin-anchor	2XHUS by Hilti

Table 3. Experimental results obtained from the initial tests

Spec. Name	Max Load (kN)	Failure Mechanism	Load at Debonding (kN)	Measured Average** Max Strain (μ Strain)	Material Exploitation*** M_e	Load from Strain (kN)
CN1	27.9	debonding	27.9	5400	0.3*	32.5
CL2h ₁	42.1	pull out of HUS Hilti	28	3680	0.20	44.4
CL2b	54.9	premature CFRP fracture	32	4680	0.26	56.4
CL2h ₂	40.1	pull out of HUS Hilti	32	4347	0.24	52.4
CP2h	112.8	CFRP fracture	30	9065	0.51	109.2
SN1	29.9	debonding	29.9	5700	0.38*	28.3
SL2h ₁	40.4	pull out of HUS Hilti	30	4950	0.19	49.2
SL2b	64.7	M8 fracture	30	4623	0.31	46.0
SL2h ₂	44.1	pull out of HUS Hilti	32	5125	0.34	51.0
SP2h	105.3	SRP fracture	43	7980	0.53	79.4

*These specimens were strengthened utilizing one layer of FRP.

**Average value from measured strain at strain-gauges No 1 and No 3

***Maximum nominal axial FRP strain

For specimens CN1 and SN1, an average ultimate load was found equal to 28.9 kN. When an anchoring device is employed, the ultimate load, for all specimens, is greater than the load at debonding. The load at debonding for those specimens where an anchoring device was utilized had a value approximately equal to 32 kN with small deviations. The aforementioned observation is valid for either CFRP or SFRP strips. This investigation uses non-commercial steel fibers which are being tested in prototype experimental applications at the Laboratory of Strength of Materials and Structures of Aristotle University. The results so far demonstrate that this novel material is equivalent to CFRP and other Fiber Reinforced Polymers (FRPs) and can be used as an alternative strengthening material. Carbon fibers and epoxy resins were provided by Sika (Sikarap 230-C).

When an anchoring device is employed the ultimate load increases from 28 kN to 112.8 kN for a number of specimens strengthened with CFRP strips, and from 30 kN to 105 kN for a number of specimens strengthened with SFRP strips. This represents a four-fold increase in the value of the ultimate load for the continuous open U-hoop FRP strip.

Table 3 links this observed ultimate load increase to the type of used anchoring device and the corresponding mode of failure. For specimens CL2h, SL2h, the observed mode of failure was that of the pull-out of the employed Hilti bolts. When bolts M8.8 were applied through the concrete volume, the ultimate load was significantly increased (CL2b and SL2b); however, when the load reached the value of 63 kN, the ultimate capacity of these bolts was exceeded, thus limiting any further increase (Figure 6). This observation demonstrates the importance of properly detailing the anchoring device in order to drive the mode of failure to the fracture of the FRP strip rather than the failure of the anchor (Figure 7). In this way, the desired exploitation of the high tensile strength FRP potential could be achieved.



Figure 6. Failure of anchor Type1



Figure 7. Fracture of SFRP (Type2)

Finally, when the patented anchoring device was applied for specimens CP2h and SP2h a further increase in the ultimate load was observed. This time the performance of the anchoring device was very satisfactory and the observed failure was that of the fracture of the FRP strips for all these specimens. Figure 7 depicts such a failure mode for specimen SP2h (see also table 3).

In order to discuss the observed behaviour in terms of exploitation of the high strength of the FRP materials the following procedure was used. As already mentioned, a material exploitation indicator was defined (M_e) as the ratio of the maximum measured strain values for each specimen over the ultimate strain value as specified for each of the used FRP materials by the manufacturers (see table 1). The maximum measured strain was found from the average of

the measured strains of the FRP strip at two opposite sides of the specimen (Table 3a). These material exploitation indicator values (M_e) are also listed in Table 3, having ideally as an upper limit the value of 1. As can be seen in this table, the highest M_e value during the present experimental sequence is approaching the value of 0.53. This was achieved by the specimen that utilizes the patented anchoring device together with two layers of SFRP strips. When, CFRP strips are employed with the patented anchoring device the M_e value is equal to 0.51. As expected, debonding of FRP strips or premature failure of the anchoring device results in relatively low values of the material exploitation indicator M_e . In conclusion, it is important to properly detail the anchoring device in order to drive the mode of failure to the fracture of FRP strips rather than the failure of the anchoring thus exploiting the high tensile strength FRP potential. The measured behaviour of the anchoring schemes tested during this initial experimental sequence was utilised by applying such anchoring schemes in the strengthening of R/C beams with prototype dimension; this is presented in the next section.

3. Application of anchored open-hoop FRP strips to R/C beam specimens

In this section, the shear behavior of reinforced concrete (R/C) rectangular beams with or without open-hoop FRP transverse reinforcement is presented and discussed. They were tested in four-point bending (Figure 9) up to failure either in their virgin state or being strengthened with open-hoop FRP transverse reinforcement, in the form of FRP strips with or without anchoring. Alternatively, this FRP shear strengthening scheme was applied after the virgin specimens reached failure in the framework of repair and strengthening of such damaged R/C structural elements.

3.1. Experimental Set-up

In this section, results from a total number of six reinforced concrete (R/C) rectangular beam specimens will be presented. Their cross-section was 120mm wide and 360mm deep (Figure 8). Their overall span was 2700mm whereas the shear span was equal to 900mm (1/3 of the total length). These rectangular section beam specimens were simply supported and loaded up to failure.

Instrumentation was provided to monitor the applied load as well as the deformation of these specimens (Figure 9). Strain gauges were placed on every FRP strip in order to record the developed strains on them. The strain gauges 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 the shear cracks are difficult to predict. The cross-sections and conventional steel reinforcement details were identical for all specimens (Figure 8). 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. Table 1 presents the properties of the strengthening materials. These sheets were attached externally on the specimens as transverse (shear) reinforcement (Figures 1 and 2). The width of the sheets was kept constant and equal to 100mm, whereas the axial distance between these sheets was also constant and equal to 200mm. Type 2 anchoring device (Figure 5) was used for the FRP strips in two specimens. Table 4 summarizes the specimens' properties.

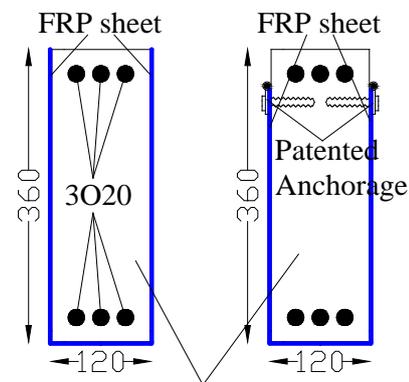


Figure 8. Cross section of the rectangular beam specimens with reinforcement details (dimensions in mm)

Average 28-day compressive strengths of concrete were obtained from uniaxial compressive tests of 150 by 300 mm cylinders that were cast with the same concrete mix used for all beams. Three cylinders were tested for each beam. The average compressive strength of the concrete was approximately 22 MPa. The axial distance of all FRP sheets was kept constant and equal to 200mm. Specimens RB and RBs were used as control beams. The first letter R indicates that the specimens have a rectangular cross section. RBs is the only specimen with internal shear reinforcement ($\varnothing 8/250$), all other specimens were constructed without any steel transverse reinforcement. RB200C and RB200S are beams strengthened with either Carbon or Steel FRP sheets without any anchoring of FRP strips. On the other hand, RB200Ca and RB200Sa are specimens strengthened with either Carbon or Steel FRP sheets combined with the anchoring device developed and patented by the Laboratory of Strength of Materials and Structures (type 2, figure 5).

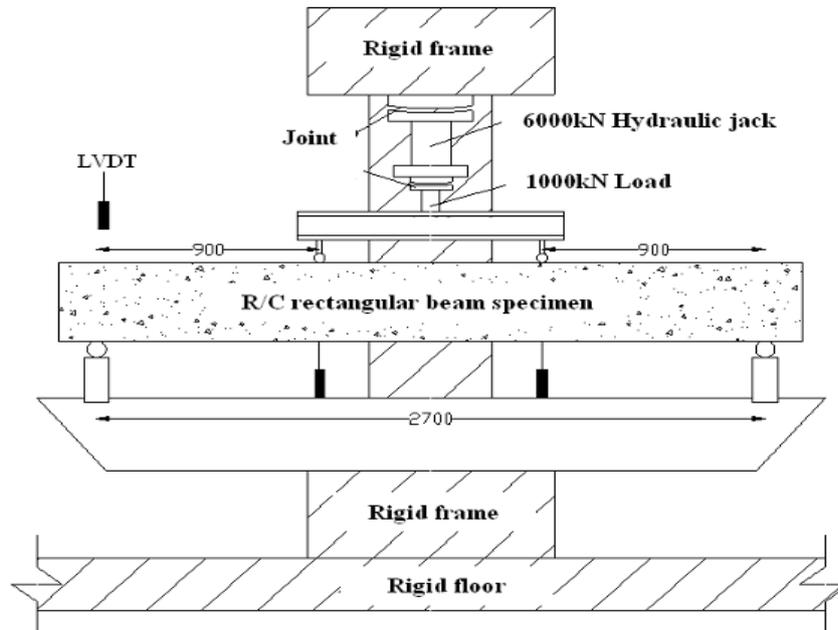


Figure 9. Experimental set-up for the four-point bending of the rectangular cross-section specimens (dimensions in mm)

Table 4. Specimen details and summary of experimental results for rectangular beams subjected to four-point bending

Name of specimen	Shear reinforcement	FRP / anchors	Measured shear force V_{max} (kN)	Strain (μ strain) of 1 st sheet	Strain (μ strain) of 2 nd sheet	Average strain (μ strain)	Calculated shear force V_{fcal} (kN)	Mode of failure
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
RB Rectangular	NO	-	39.4	-	-	-	-	Brittle shear crack
RBs Rectangular	Ø8/ 250 (intenal)	-	90.9	-	-	-	-	Yield of stirrups
RB200C Rectangular	1 layer CFRP	NO	97.8	7390	610	4000	88.45	Debonding
RB200Ca Rectangular	1 layer CFRP	YES	115.1	4580	6590	5585	107.88	CFRP fracture
RB200S Rectangular	1 layer SFRP	NO	94.0	5935	4620	5278	91.89	Debonding
RB200Sa Rectangular	1 layer SFRP	YES	122.0	6115	6415	6265	101.71	Anchoring failure

Table 5. 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

3.2. Increase of Strength – Modes of failure

For all specimens, the applied load and the vertical displacements were recorded as well as the strains at each FRP sheet. Table 4 lists the measured values from this experimental investigation. The measured shear capacity is listed in column 4 of Table 4 whereas the measured maximum strain values of the attached FRP sheets that the shear crack intersects are listed in 5th and 6th columns of the same table.

The shear strength of the control rectangular beam (RB) without any stirrups or CFRP/SFRP strips was recorded equal to 39.4kN, whereas the shear capacity of specimen

RBs with stirrups Ø8/250mm as transverse reinforcement was increased to 90.9kN. From the results shown in Table 4, it is evident that the maximum recorded shear capacity for all strengthened rectangular beams with CFRP/SFRP strips was significantly greater than that of either the RB or the RBs shear capacity (see also Table 5). Without anchors, the shear capacity increase was limited to 138%, due to the debonding mode of failure of the CFRP strips (figure 10). The specimen strengthened with SFRP strips exhibited an increase in the shear capacity of up to 210% when anchors were utilized. For this specimen, the mode of failure was the pull-out of the anchoring system (figure 11).

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 5). The beneficial effect of anchoring the U-shape open-hoop FRP strips in order to inhibit the debonding mode of failure is thus demonstrated.



Figure 10. CFRP debonding



Figure 11. CFRP failure of the anchoring

3.3. Shear Force – beam Deflection Response

Shear force – beam deflection response envelope curves are depicted in figure 12. 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 beam deflection.

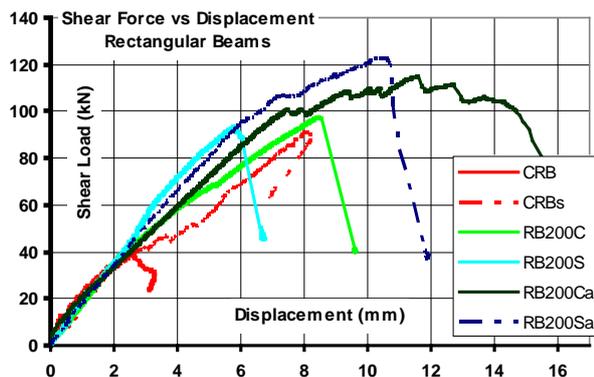


Figure 12. Shear force – vertical displacement response envelope curves for the rectangular beam specimens

The beam deflection increase due to the presence of FRP strips with anchors is of the order of 65%. The non-anchored FRP strips were delaminated and led to the brittle failure of the specimens. On the contrary, the

anchored FRP strips led to a relatively less brittle behaviour than the behaviour of specimens without anchors. 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 behaviour of the strengthened beams from a rather elastic-brittle to a more ductile-seismic efficient behaviour. This is achieved when the shear strengthening scheme is designed in such a way that the flexural mode of failure finally prevails.

3.4. CFRP-SFRP strains

In order to evaluate the shear resistance contribution offered by either the CFRP or the SFRP sheets, strain gauges were attached at mid-height and mid-width of each FRP 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 gauges corresponding to those FRP sheets that were intersected by the main shear crack which developed during the loading sequence. These measured maximum FRP strip strain values are listed in table 4 (columns 5 and 6) together with the serial number of the corresponding FRP strip. Those recorded maximum strain values are next employed as maximum average strain values (Table 4 col. 7) in order 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 RB200Sa (122KN, Table 4) where the used SFRP developed maximum average strain value equal to $6265\mu\epsilon$ (Table 4 col. 7). The use of anchoring prevented the premature delamination mode of failure of the FRP strip; instead, the failure of the anchoring occurred in this specimen (see Table 4). Through proper detailing of the patented anchor this anchoring failure could be prohibited, thus further enhancing the shear capacity of this specimen. In contrast, for specimens strengthened with FRP strips without the use of anchors, the maximum FRP strains and the corresponding shear force values were kept to significantly lower levels (average of $4644\mu\epsilon$). 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[19] or FIB[18], the maximum effective FRP strain that can be utilized should be limited to 0.004 mm/mm (see section 4.1). Eurocode[17] 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 values 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. Finally, it is 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 V_{cal} was obtained (Table 4 col. 8). This is compared to the experimental maximum shear force V_{max} (Table 4 col. 4). Values of V_{cal} were found through equation (1):

$$V_{cal} = V_{c,exp} + V_{f,cal} \quad (1)$$

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

$$V_{f,cal} = 4A_f E_f e_{fav,exp} = 4t_f b_f E_f e_{fav,exp} \quad (2)$$

where:

$$e_{fav,exp} = \frac{e_{f1,exp} + e_{f2,exp}}{2} \quad (3)$$

and $\varepsilon_{f1,exp}$, $\varepsilon_{f2,exp}$ are the maximum recorded strains in two consecutive FRP strips intersected by a shear crack (see Table 4 cols. 5, 6, 7). The width and thickness of each U-FRP strip are t_f and b_f , respectively. By employing the strain value resulting from Eq. 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 4 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 quite close to the one measured during the experimental sequence. More specifically, the ratio of measured vs. calculated shear capacity values ($V_{max}/V_{f,cal}$) varies from 1.023 up to 1.199 with an average value of 1.111 (Table 6). As already mentioned, the FRP strains were measured using only one strain gauge per FRP strip, which was located approximately in the centre 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 the observed discrepancy between measured and predicted shear capacity values (Table 6). For specimen RB200Sa the calculated shear capacity was 20% lower than the measured value, which represents the higher

value for the $V_{max}/V_{f,cal}$ ratio. 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 6. Measured vs. calculated shear capacity

	RB200C	RB200S	RB200Ca	RB200Sa
$V_{max}/V_{f,cal}$	1,106	1,023	1,067	1,199

4.1. Brief Description of an Expert System

The calculated shear capacity values listed in table 4 are based on the FRP shear contribution obtained from the measured FRP strip strain values. In this section, the measured shear capacity will be compared with predictions 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 calculation of such code predictions, an expert system was developed. The main features of this expert system are as follows. The section geometry and the longitudinal and transverse reinforcing details are given by the user through the appropriate user-friendly interface. Rectangular as well as T-beam reinforced concrete sections are alternative options of this expert system (see figure 13). The details of a strengthening scheme, utilizing externally attached FRP strips, can also be input through the same interface. The given options for such a strengthening scheme of an R/C cross-section is for enhancing either the flexural capacity or the shear capacity. The former is done by placing FRP sheets at the bottom of the R/C section and the latter by placing transverse shear reinforcing FRP strips. For the latter case, the strips can be either closed hoops or open-hoop U-strips (Figure 13). The actual properties of the concrete, the steel and the FRP strips 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 user 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 [16] as well as those of the EuroCode-EC8 [17], FIB [18] and ACI [19]. The shear contribution of the FRP strips in table 7 was obtained assuming a nominal ultimate strain value equal to 0.018 and 0.015 for CFRP or SFRP strips, respectively (see table 1). The Greek Code provisions assume a maximum FRP strain value equal to 1/2 of this nominal ultimate strain value. Specimens RB200C and RB200Ca are of rectangular cross-section with U-shape CFRP strips. More specifically, specimen RB200C has U-shape FRP strips without anchoring whereas specimen RB200Ca has U-shape FRP strips with anchoring. Table 7 lists the predicted by the expert system shear capacity values of the tested rectangular specimens, strengthened with FRP strips with or without anchoring. Moreover, these predicted values are compared with the measured shear capacity values by finding the ratio

of the measured vs. predicted shear capacity values (V_{max} / V_{pre}). The values of this ratio are listed at the far right columns of table 7. As can be seen in this table, the Greek Code for retrofitting existing R/C structures [16] yields shear capacity predictions that are closer to the measured

values than the corresponding predictions made by the rest of the codes. The measured shear capacity is 11% to 34% larger than the corresponding Greek Code predictions whereas they are 22% to 87% larger than shear capacity predictions made by the rest of the Codes ([17],[18],[19]).

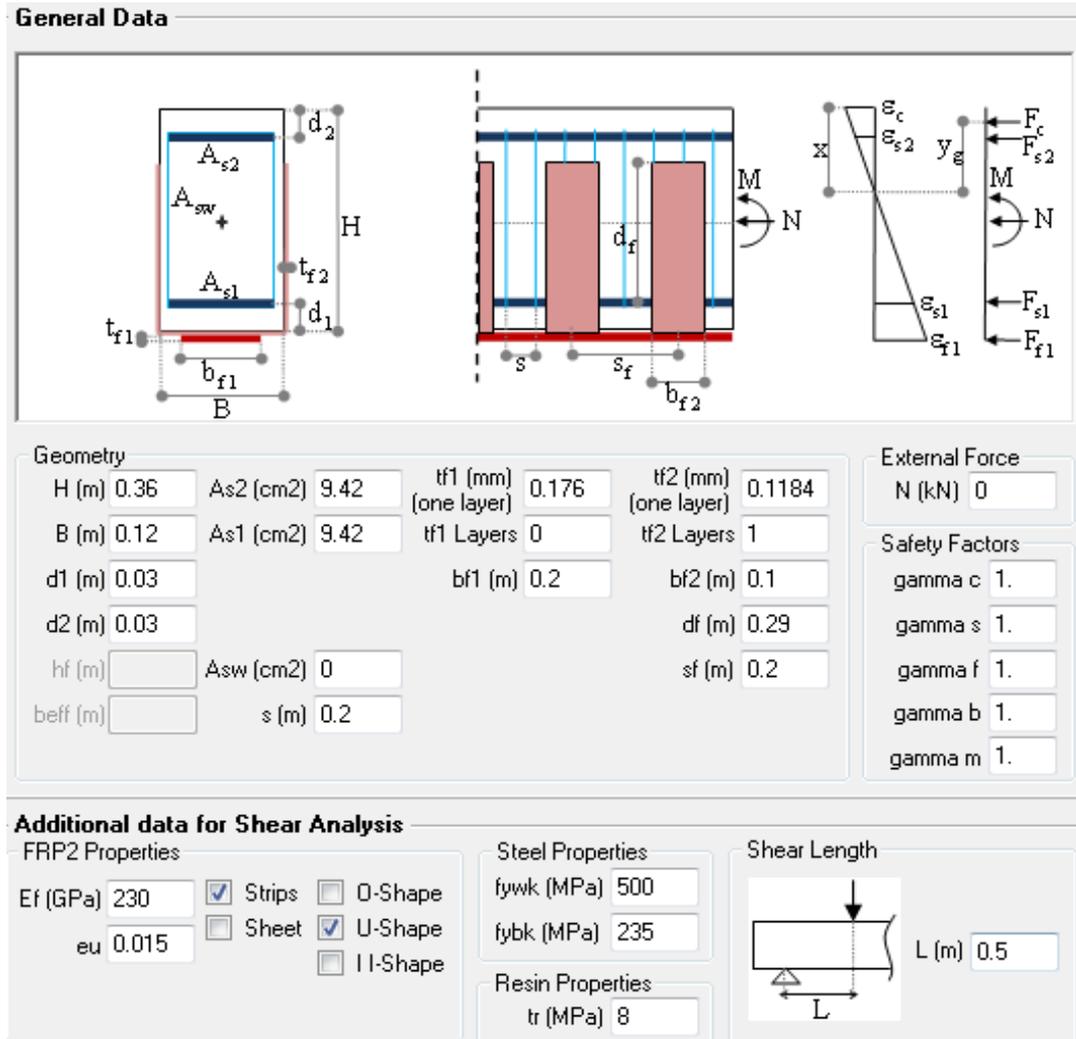


Figure 13. Expert system utilized for specimens RB200C and RB200Ca

Table 7. Measured and Calculated by various Codes shear capacity for the tested rectangular beam specimens strengthened with FRP strips

Name of specimen	V _{cd} concrete (KN)	V _{fd} FRP strips shear contribution predicted by the following Codes (KN)				Predicted shear capacity by the following Codes V _{pre} = V _{cd} + V _{fd} (KN)				Measured V _{max} (KN)	Ratio V _{max} / V _{pre} (KN)			
		FIB	EC2	Greek Code	ACI	FIB	EC2	Greek Code	ACI		FIB	EC2	Greek Code	ACI
RB200C *	38.91	29.95	22.91	41.23	23.15	68.86	61.82	80.14	62.06	97.8	1.42	1.58	1.22	1.58
RB200Ca **		55.47	24.54	64.37	32.62	94.38	63.45	103.28	71.53	115.1	1.22	1.81	1.11	1.61
RB200S *		27.31	20.92	37.13	20.48	66.22	59.83	76.04	59.39	94.0	1.42	1.57	1.24	1.58
RB200Sa **		39.93	22.24	52.21	26.46	78.84	61.15	91.12	65.37	122.0	1.55	1.54	1.34	1.87

* relevant provisions based on the debonding mode of failure
 ** relevant provisions based on the FRP fracture mode of failure
 The suffix a signifies the presence of anchoring

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 either CFRP or SFRP strips without the use of the anchors exhibited a modest increase of the shear capacity, when compared to the non-strengthened control specimen. This is due to the debonding mode of failure of the FRP strips.

- When the patented anchoring device was utilized together with either CFRP or SFRP reinforcing strips for shear strengthening, the increase of the shear capacity was much larger than in identical specimens without anchors. This shear capacity increase attained a maximum value of 220% when compared to the shear capacity of the control beam without any transverse reinforcement (either steel stirrups or FRP strips).

- Both measured maximum displacement values and maximum FRP strain values are significantly higher for specimens with anchored FRP strips than without anchors. 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 use of FRP strips with anchoring devices transforms the overall behavior of the strengthened beams from a rather elastic-brittle to a relatively less brittle behaviour.

This is achieved when the shear strengthening scheme is designed in such a way that the flexural mode of failure finally prevails for the specific structural member.

- 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.

- The Greek Code for retrofitting existing R/C structures yields shear capacity predictions for the tested specimens with FRP strips as transverse reinforcement that are closer to the measured values than the corresponding predictions made by the rest of the codes. The measured shear capacity is 11% to 34% larger than the corresponding Greek Code predictions whereas the measured capacity is 22% to 87% larger than shear capacity predictions made by the rest of the Codes.

ACKNOWLEDGEMENTS

Carbon fibers and epoxy resins were provided by Sika

Hellas.

Steel fibers are not commercially available and were provided for the present study by Bekaert Industries.

Partial financial support for this investigation was provided by the Hellenic Earthquake Planning and Protection Organization (EPPO).

The anchoring device employed in this study, is patented under patent no. WO2011073696 which is managed by the Research Committee of Aristotle University.

REFERENCES

- [1] Manos G..C., Katakalos K., Kourtidis V. (2011) "The influence of concrete surface preparation when fiber reinforced polymers with different anchoring devices are being applied for strengthening R/C structural members", *Applied Mechanics and Materials*, Vol, 82, Pages 600-605.
- [2] Manos, G.C., Katakalos, K., Papakonstantinou, C.G. (2011) "Shear behavior of rectangular beams strengthened with either carbon or steel fiber reinforced polymers", *Applied Mechanics and Materials*, Vol, 82, Pages 571-576.
- [3] Katakalos K., Papakonstantinou C.G. (2009) "Fatigue of reinforced concrete beams strengthened with steel-reinforced inorganic polymers", *Journal of Composites for Construction*, Vol. 13, Issue 2, Pages 103-112.
- [4] Casadei, P., Nanni, A., Alkhrdaji, T. (2005) "Steel-reinforced polymer: An innovative and promising material for strengthening infrastructures", *Concrete Engineering International*, Vol. 9, No. 1, pp. 54-56.
- [5] Ceroni F., Pecce M., (2007) "Cracking behaviour of RC beams externally strengthened with emerging materials." *Construction & Building Materials*, 21(4): pp. 736-45.
- [6] Pecce, M., F. Ceroni, A. Prota, AND G. Manfredi, (2006) "Response prediction of RC beams externally bonded with steel-reinforced polymers." *Journal of Composites for Construction*, 10(3):pp. 195-203.
- [7] Prota, A., T. Kah Yong, A. Nanni, M. Pecce, G. Manfredi, (2006) "Performance of shallow reinforced concrete beams with externally bonded steel-reinforced polymer." *ACI Structural Journal*, 103(2): pp. 163-70.
- [8] Papakonstantinou, C.G., Katakalos, K. (2009) "Flexural behavior of reinforced concrete beams strengthened with a hybrid inorganic matrix-Steel fiber retrofit system", *Structural Engineering and Mechanics*, Vol. 31, Issue 5, Pages 567-585.
- [9] Plevris N., Triantafillou, T.C., (1994) "Time-dependent behavior of RC members strengthened with FRP laminates", *Journal of Structural Engineering*, Vol. 120, No. 3, pp. 1016-1042.
- [10] Saadatmanesh, H., A.M. Malek, (1998) "Design guidelines for flexural strengthening of RC beams with FRP plates." *Journal of Composites for Construction*, 2(4):pp. 158-164.
- [11] Manos G..C., Katakalos K., Kourtidis V. (2011) "Construction structure with strengthening device and method", *European Patent Office*, Patent Number

WO2011073696 (A1) — 2011-06-23.

- [12] Anil, O., (2008) "Strengthening of RC T-section beams with low strength concrete using CFRP composites subjected to cyclic load." *Construction and Building Materials*, 2008. 22(12): pp. 2355-2368.
- [13] Anil, O., (2006) "Improving shear capacity of RC T-beams using CFRP composites subjected to cyclic load." *Cement & Concrete Composites*, 2006. 28(7): pp. 638-649.
- [14] Tanarslan, H.M., Y. Ertutar, S. Altin, (2008) "The effects of CFRP strips for improving shear capacity of RC beams." *Journal of Reinforced Plastics and Composites*, 27(12): pp. 1287-1308.
- [15] Tanarslan, H.M., S. Altin., (2010) "Behavior of RC T-section beams strengthened with CFRP strips, subjected to cyclic load." *J. Materials and Structures*, 43(4): pp. 529-542.
- [16] Organization of Earthquake Planning and Protection of Greece (OASP), (2011) "Guidelines for Retrofitting in Reinforced Concrete Buildings" Athens, Greece.
- [17] Eurocode 8 (2004) - Design of structures for earthquake resistance - Part 2: Bridges, DRAFT No 3. European Committee for Standardization.
- [18] FIB, I.F.f.S.C., (2001) "Externally Bonded FRP Reinforcement for RC Structures", in *Bulletin 14, f.T.G. 9.3*, Editor. p. 165.
- [19] ACI, (2008) "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures (ACI 440.2R-08)", in *ACI 440.2R-08*. American Concrete Institute: Farmington Hills. p. 45