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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF RECTANGULAR R/C BEAMS RETROFITTED AGAINST SHEAR UTILIZING FRP STRIPS

G.C. Manosr[1], K. Katakalos[1*], M. Theofanous[1], E. Kozikopoulos[1]

[1]Laboratory of Strength of Materials and Structures
Dept. Civil Engineering. Aristotle University of Thessaloniki
University Campus, Egnatia street, Thessaloniki, 54006
gcmanos@civil.auth.gr

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Abstract. *Reinforced concrete structures, designed and constructed according to old earthquake resistant design provisions are in need of retrofitting. This paper presents results from an investigation aiming to examine the behaviour of rectangular R/C beams in need of being retrofitted against shear. Towards this objective, ten (10) R/C beam specimens of prototype dimensions were constructed and tested under four point flexure. The retrofitted scheme which was investigated was based on fiber polymer sheets, either made of carbon (CFRP) or steel (SFRP); strips of such FRP sheets were attached externally on the R/C beam specimens as transverse reinforcement in order to upgrade their bearing capacity in shear. One potentially weak point of such a retrofitting scheme was investigated in depth; that is the debonding mode of failure of the FRP strips from the concrete surface, when these strips develop considerable stresses that cannot be transferred to the main volume of the structural element solely by the bonding surface. This mode of failure limits the potential of the high tensile strength capability of these FRP strips and inhibits the aimed increase of the shear capacity of the R/C beams. In order to confront with this limitation the effectiveness of an innovative type of anchoring device that can be incorporated together with such FRP strips was specially examined. The obtained experimental results are discussed in order to demonstrate the capability of such a retrofitting scheme, when proper anchoring of the FRP strips is utilized, to efficiently upgrade the shear capacity of such R/C beams. The experimental results were validated through a numerical simulation of the experimental set-up employing the ABAQUS finite element software. This numerical simulation took into consideration the non-linear behaviour of the concrete and steel as well as the cohesive surface zone between concrete and FRP strips in their contact area. Moreover, the presence or not of an anchoring device was also simulated numerically. From the comparison between the observed behavior, in terms of either load-displacement response or mode of failure, with the results of the numerical simulation the reliability of such a numerical simulation is demonstrated. This research was 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.*

1 INTRODUCTION

A wide range of fiber reinforced composite materials have been successfully used for the repair and strengthening of existing reinforced concrete (R/C) structures [1]. Strengthening with externally bonded FRPs is particularly common, due to the numerous advantages related with their use. These advantages include the speed and ease of installation, the low weight and their high tensile strength [4]. The most commonly used strengthening systems are glass or carbon fiber reinforced polymer (FRP) composite materials [1-5]. Lately, a new strengthening system based on high strength steel fibers known as steel reinforced polymers (SRP) [3] was introduced as an alternative having high strength and ability 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 [1, 3, 4].

However, the exploitation of the high tensile strength of such FRP's or SFRP's is usually rather low due to the debonding type of failure. In the case that these strips can be fully wrapped around the structural member, the degree of exploitation of these materials increases and the mode of failure can then result due to fiber fracture of the external reinforcement [2,6]. However, there are many practical applications that full wrapping cannot be practically materialized. This paper presents results from an experimental investigation that focuses on the upgrade of the shear capacity of 3m span R/C beams strengthened with either CFRP or SRP 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. This specific anchoring device is developed at the Laboratory of Strength of Materials and Structures, in Thessaloniki, Greece under the patent number WO2011073696 [6]. Finally the experimental results are validated through a numerical simulation employing the ABAQUS finite element software. This numerical simulation takes into consideration the non-linear behaviour of the concrete and steel as well as the cohesive surface zone between concrete and FRP strips in their contact area. Moreover, the presence or not of an anchoring device is also simulated numerically.

2 EXPERIMENTAL SETUP

2.1 Materials

Totally ten reinforced concrete beams were fabricated and tested at the Laboratory of Experimental Strength of Materials and Structures of Aristotle University of Thessaloniki. The compressive strength of concrete was measured equal to 22.4 MPa. The internal reinforcement yielded at f_y=527MPa and failed at a stress equal to f_{ul}=645MPa. The rectangular beams were strengthened with either CFRP or SFRP. CFRP sheets and epoxy resins were provided by SIKA Hellas. The type of CFRP is SikaWrap 230C and the two substitute epoxy is named SikaDur 330. SFRP sheets were fabricated, specifically for this project. Unidirectional tension tests were conducted on resin rich CFRP and SFRP sheets up to failure to obtain the Young's modulus (E_1) and strength (f_u) in their fibre orientation and the Poisson's ratio ($\nu_{12}=(E_1/E_2)\ \nu_{21}$). The remaining two material properties pertaining to the orthotropic nature of the material under the plane stress assumption, namely the transverse Young's modulus E_2 and the shear modulus G_{12}, were derived by applying the conventional rule of mixture for composites (Hashin 1983), taking into account the manufacturer's specifications for the resin (citation SIKA) and the FRP (citation SIKA) sheets and the experimentally determined volume fraction of resin and FRP sheets.

Material property	E_1 (MPa)	ν_{12}	f_{u1} (MPa)	E_2 (MPa)	G_{12} (MPa)
CFRP	41784	0.305	376	4476	1935
SRP	36350	0.312	330	4400	1900

Table 1. Material properties of CFRP and SFRP

2.2 Geometry and loading of specimens

The present research program includes the investigation of ten rectangular R/C beams under monotonic loading conditions. The cross section of the beams was 120X360 (mm). All specimens were longitudinally reinforced with 3Ø20mm bars at the top and 3Ø20mm at the bottom of the beam. (see figure1)

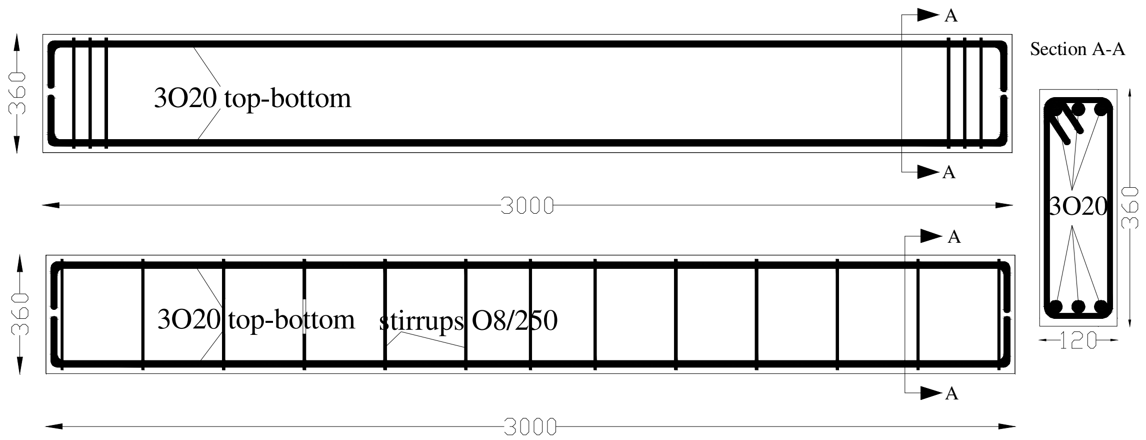

Figure 1. Mean dimensions and reinforcement details of specimens

Two control beams were tested. The first one, named as RB, had no internal shear reinforcement whereas the second, named as RBs, had Ø8/250mm as transverse reinforcement. The remaining eight beams did not have any internal transverse reinforcement, thus were strengthened with externally bonded open hoop CFRP or SFRP sheets, with or without an anchorage device. The strengthened beams were designed in such way that would be able to upgrade their shear capacity at least to the point of the RBs' strength. Table 2 that follows depicts the variables that were taken under consideration for each specimen.

BEAM NAME	SHEAR REINF/MENT	ANC HOR AGE	FRP WIDTH (mm)	FRP axial DISTANCE (mm)
RB	NO	-	-	-
RBs	Ø8/ 250	-	-	-
RB200C	CFRP	NO	100	200
RB200Ca	CFRP	YES	100	200
RB200S	SFRP	NO	100	200
RB200Sa	SFRP	YES	100	200
RB150C	CFRP	NO	100	150
RB150Ca	CFRP	YES	100	150
RB150S	SFRP	NO	100	150
RB150Sa	SFRP	YES	100	150

Table 2. Experimental variables of specimens

All beams were subjected under four point monotonic loading conditions. The overall beam span was 2700mm whereas the shear span was equal to the 1/3 of the total length, thus 900mm. Figure 2 represents the experimental setup. The loads as well as the vertical displacements at two points, under the application of the load, were recorded. Strain gauges were placed to every FRP sheet in order to record the developed strains on them. Figure 2 also shows a photographic demonstration of the experimental setup.

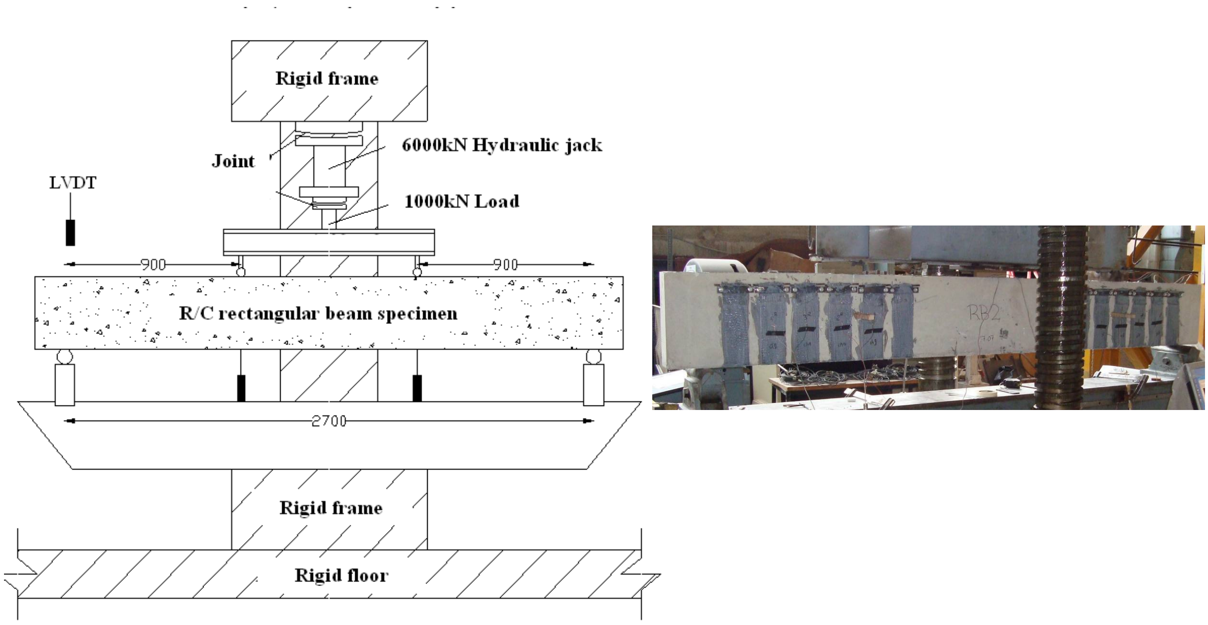

Figure 2. Experimental Setup (sketch and photo)

The present investigation also focuses on the application of a novel anchoring device which was developed and patented at the Laboratory of Experimental Strength of Materials and Structures of Aristotle University of Thessaloniki. The developed anchoring device is transforming the axial tensile forces, applied on the FRP sheet, to shear forces imposed through the bolts into the concrete mass of the beam. Figure 3 shows a front face and a section of the novel anchoring device.

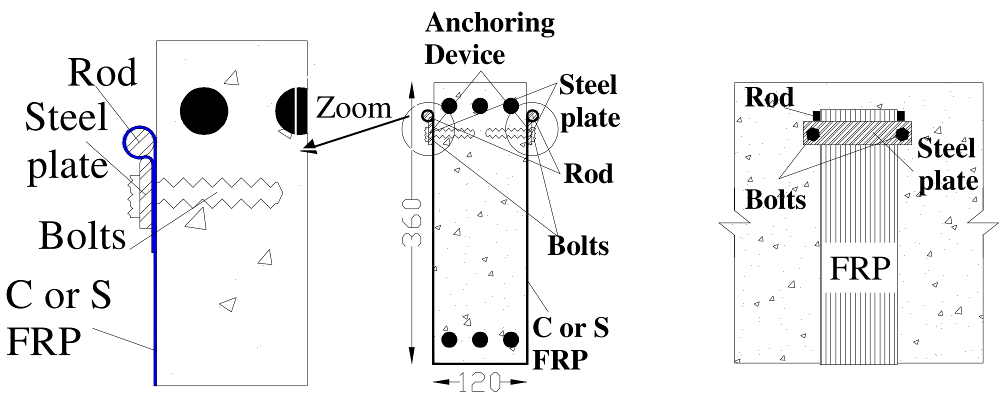

Figure 3. Patented Anchoring Device (WO2011073696) [6]

3 EXPERIMENTAL RESULTS

Totally ten R/C rectangular beams were investigated. For all beams not only load and vertical deflection were recorded but strains at each FRP sheet as well. Table 3 depicts the obtained data from the experimental investigation. The experimental measured shear force is depicted at fourth column of Table 3 whereas the measured strains of the FRP sheets that the shear crack is intersecting are mentioned at fifth and sixth columns of the same table.

BEAM NAME	ANCHORAGE	EXP. SHEAR FORCE (kN)	STRAIN of 1st STRIP (μstrain)	STRAIN of 2nd STRIP (μstrain)	CALC. SHEAR FORCE (kN)	MODE OF FAILURE
CRB	-	39.4	-	-	-	Brittle shear crack
CRBs	-	90.9	-	-	-	Yield of stirrups
RB200C	NO	97.8	7390	610	98.05	Debonding
RB200Ca	YES	115.1	4580	6590	107.77	CFRP fracture
RB200S	NO	94	5935	4620	99.77	Debonding
RB200Sa	YES	122	6115	6415	104.68	Anchorage failure
RB150C	NO	101	3820	5580	108.88	Debonding
RB150Ca	YES	123	7145	6080	120.61	CFRP fracture
RB150S	NO	103	4530	4905	103.53	Debonding
RB150Sa	YES	119	7855	6245	115.13	Anchorage failure

Table 3. Experimental results

The shear strength of the control beam (CRB) without any stirrups was recorder equal to 39.4kN, whereas the specimen CRBs with Ø8/250mm as transverse reinforcement was increased to 90.9kN. The strengthening scheme that took place to the remaining of the beams had an objective to increase the shear strength at a lower limit equal to CRBs. From the results shown in Table 3, it is evident that the maximum recorded shear load for all strengthened beams was significantly greater than that of the CRB. In Table 4 the percentage of the increase of the shear load is presented.

	CRB	CRBs	RB200C	RB200Ca	RB200S	RB200Sa	RB150C	RB150Ca	RB150S	RB150Sa
% INCREASE compared to CRB	0	130.7	148.2	192.1	138.6	209.6	156.3	212.2	161.4	202.0
% INCREASE compared to CRBs	-	0	7.6	26.6	3.4	34.2	11.1	35.3	13.3	30.9

Table 4. Experimental results

The shear load of the strengthened beams, compared to CRB, met an increase of more than 200%, but not less than 130%. The largest percentages of that increase were observed, as it was expected, for the strengthened beams that the novel anchoring device was used in combination with FRP sheet. The biggest increase of the shear load was observed for specimen RB150Ca and was equal to 212,2%. For this strengthened beam the mode of failure was located at the fracture of the CFRP sheet which demonstrates that the novel anchoring device anchored the CFRP sheet properly on the concrete beam. Specimen RB150Sa exhibit a maximum shear load equal to 119kN that resulted to a 202% increase compared to CRB. For this specimen the anchoring devised posed an upper limitation to the shear load of the beam due to the fact that the device failed it self, before the failure of SFRP sheet. Nevertheless the strains that were recorded reached 7000μstrain which is close to the maximum strain at failure of SFRP sheet (9000μstrain). This specimen reached the maximum recorded average displacement for the maximum load, fact that results to an increase of an inelastic behavior.

By comparing the beams that were strengthened with CFRP vs. SFRP it could be noted that the overall behavior was similar. SFRP sheets could be utilized as an alternative material for strengthening applications. More specifically, focusing on strengthened beams without the use of the anchoring device, RB150S exhibit the biggest shear load (103kN) which is very close to RB150C's (101kN). Figure 4 presents the shear load vs. the average displacement of all beams in two graphs. The first one shows the behavior of the strengthened beams without an anchoring device, compared with the control beams CRB and CRBs, whereas the second graph deals with those that the anchoring device was utilized for the proper attachment of FRP sheets.

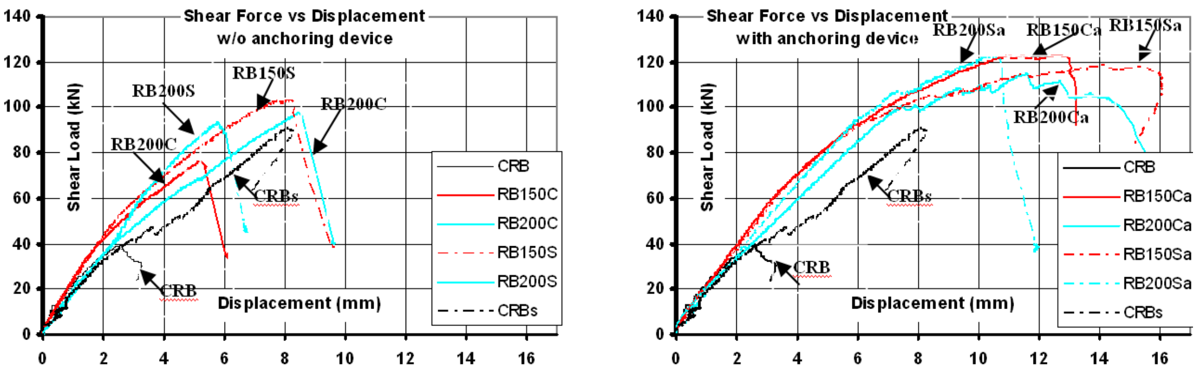

Figure 4. Shear Force vs. Displacement graphs w/o and with the novel anchoring device

Specimens, where the novel anchoring device was utilized, exhibit a clear increase of the shear load as well as of the developed average displacement. The premature mode of failure, the debonding of FRP sheet, changed to either fracture of FRPs or failure of the anchoring device, when the sheets were properly anchored. The prevention of the premature delamination resulted to an increase of the specimen's strength. However, the initial stiffness remains the same for all specimens. On the other hand after the first cracking the stiffness of the strengthened beams is greater than the stiffness of the control beams. This phenomenon is stronger for the specimens that FRP sheets were anchored. The behavior of the control beam with stirrups (CRBs) was sufficiently reached by the strengthened beams without the anchoring device, despite the fact that the premature debonding of the sheets, either CFRP or SFRP, posed an upper limitation. The rest of the strengthened beams, where the FRP sheets were properly anchored, presented a better behavior than CRBs', concerning not only the shear force but the average displacement as well. Finally, as far as the measured strains are concerned it could be said that the existence of the anchoring device is allowing the development of greater strains on FRP sheets compared to the cases that the anchoring device was not utilized, where a limitation was posed due to the debonding.

4 NUMERICAL VERIFICATION

4.1 Assumptions of modeling

The general purpose FE software ABAQUS [7] was employed to generate FE models to simulate numerically the structural response of the previously described concrete beams strengthened with externally attached FRP sheets. The generated models were validated against all respective experimental results. The aim of this part of the study is to generate reliable FE models that can be utilized to enhance the understanding of the fundamental structural response of the FRP shear strengthening scheme of R/C beams with and without anchorage devices and hence optimize the anchorage device design. In order to reduce the computational cost, the symmetry of the structure with respect to the x-y and z-y mid-planes was exploited, by numerically simulating one quarter of the physical model and applying the appropriate boundary conditions at each of the two planes of symmetry as shown in Figure 5.

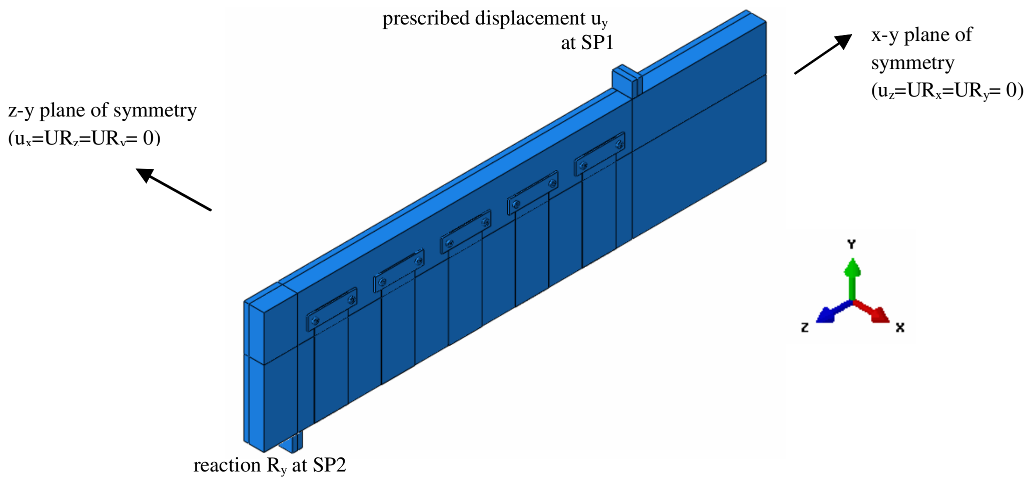

Figure 5. Modeled geometry and applied boundary conditions.

The contact between the various parts of the model (steel bolts, steel plates and concrete volume) was explicitly modeled and a friction coefficient equal to 0.3 was assumed for tangential contact behaviour except for the contact between the concrete beam and the loading reaction plates which was assumed frictionless.

Variation of the friction coefficient applied to the bolt-concrete interface between the idealized frictionless and rough contact extreme cases was attempted, but no significant effect on the overall solution was observed. Moreover, in order to reduce computational cost, the actual detail of the cylindrical rod of the anchoring device through which load is transferred from the FRP strips to the concrete beam through the steel plate was somewhat simplified (see figures 3 and 6); towards this end, the displacements of the FRP's edge were constrained to be equal to the respective displacements of the steel plate's mid plane for the numerical representation of the anchoring device. The interface between the FRP and the concrete was simulated as a cohesive zone endowed with a suitable traction separation response.

Material properties for all components were obtained from experimental measurements, as they were described previously, and used as input to model the structure.

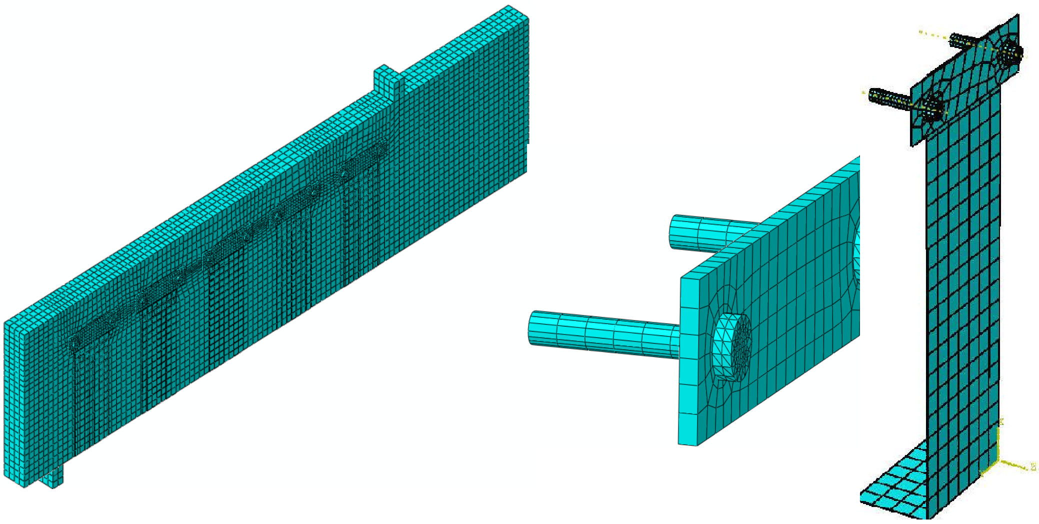

Figure 6. FE discretisation of the rectangular beam and close-ups of the discretization of the anchoring device

Linear 8-noded brick elements were adopted for the discretisation of the concrete beam, steel bolts, steel plates and loading plates, whilst the longitudinal reinforcing bars and the steel stirrups were discretised with linear truss elements embedded in the concrete region (i.e. no relative displacement between reinforcement and concrete was allowed for). Linear 4-noded shell elements were used to discretise the FRP sheets, the degrees of freedom (DOF) of which were tied to the respective DOFs of the underlying 8-noded 3D cohesive elements. The mesh size was dictated by the attempt to minimize computational time whilst maintaining accuracy and, upon extensive mesh convergence studies, a uniform mesh size of 15mm was adopted for the concrete beam, cohesive zone and FRP sheets, whilst smaller mesh sizes were adopted for the steel plates, bolts and concrete regions surrounding the bolts as shown in Figure 6.

4.2 Numerical results - Discussion

The F.E. numerical predictions regarding the ultimate shear capacity ($^{num}V_{max}$) and failure modes with the ones observed during testing (see Table 2) are summarized in Table 5.

The ratio of numerically predicted over measured ultimate shear capacity is listed in column 3 of table 4 with values very close to 1.0, which signifies a very good agreement of the numerically predicted ultimate shear capacity values with the respective experimental ones included in Table 1. Moreover, the numerically predicted modes of failure are also in very good agreement with the ones observed during testing, with the exception of specimen RB200Ca. This discrepancy can be attributed to the premature failure of the CFRP strip due to the non-ideal preparation of the concrete surface at the bottom fiber of this specimen prior to gluing this CFRP strip. Detailed discussion for each of the three types of rectangular beams considered in the present study follows.

The observed behaviour of the two control beam specimens, which were initially tested to obtain the basic structural response of the reinforced concrete rectangular beam specimens without the added complexity of the attached FRP sheets, was, in general, well-predicted by the FE numerical models with $^{num}V_{max}$ / $^{exp}V_{max}$ ratios equal to 1,0 and 0,97 respectively

BEAM NAME (1)	Numerical ultimate shear capacity ${}^{num}V_{max}$ (kN) (2)	${}^{num}V_{max}$ / ${}^{exp}V_{max}$ (3)	Numerical failure mode (4)	Observed failure mode (5)
CRB	39.44	1.00	Shear cracking	Shear cracking
CRBs	87.89	0.97	Yielding of stirrups	Yielding of stirrups
RB200C	97.99	1.00	Debonding	Debonding
RB200Ca	118.79	1.03	Anchorage failure	Premature FRP rupture
RB200S	87.54	0.93	Debonding	Debonding
RB200Sa	112.47	0.92	Anchorage failure	Anchorage failure
RB150C	99.65	0.99	Debonding	Debonding
RB150Ca	120.58	0.98	FRP rupture	FRP rupture
RB150S	96.95	0.94	Debonding	Debonding
RB150Sa	123.52	1.04	Anchorage failure	Anchorage failure
		Mean Value 0.98		
		Coef. Of Variation 0.05		

Table 5. Summary of Numerical results

The experimental vs numerical comparison the concrete beam specimens strengthened with FRP sheets without the provision of additional anchoring devices resulted to an excellent agreement between the experimental and the numerical results in terms of ultimate load and mode of failure. (see table 5) The debonding of the FRP sheets commenced and propagated rapidly, leading to the formation of critical diagonal cracks and thus to failure. This observed behaviour was also accurately reproduced by the previously described numerical simulations.

The provision of additional anchorage by means of the device shown in Figure 3 allows for additional forces to be carried by the FRPs once debonding has occurred; these forces are transferred by the anchoring device finally through the bolts into the concrete thus resulting in an increased ultimate shear capacity and thus in a more efficient utilisation of the FRP material. The anchorage zone is stressed from the onset of loading but deformations and stresses remain small as long as the resin remains effective. Upon debonding, the anchorage zone experiences high localised stresses. The failure is no longer due to FRP debonding but rather localised above the anchorage zone, due to the high stresses transmitted by the bolts in the vicinity of the bolt holes. The failure mode is complex and involves a combination of local concrete cracking and crushing near the bolt holes, flexure of the compressive reinforcement due to the forces exerted by the bolts and possibly pullout of the anchoring bolts. In some cases, FRP rupture may occur prior to the failure of the anchorage device or anchorage zone.

The generated FE models were in general able to capture the sequence of failure as described above. From the input of table 5 $^{num}V_{max}$ / $^{exp}V_{max}$ ratios vary from 0,92 to 1,04 but the modes of failure are in perfect agreement.

5 CONCLUSIONS

- The present study examined both experimentally and numerically the behaviour of ten (10) full scale rectangular R/C beams in need of being retrofitted against shear, by utilizing anchored or non-anchored Carbon or Steel FRP strips.
- Steel Fiber Reinforced Polymers (SFRP) that were specially fabricated for this research program could be equally used as an alternative strengthening material.
- Reinforced Concrete beams (R/C) that were strengthened without the use of the anchoring device exhibit a limitation to the maximum shear load and displacement due to the debonding mode of failure occurred on FRP sheet. Despite that fact the limited developed shear load was greater than the control's beam with stirrups (CRBs).
- When the novel anchoring device is utilized for the proper attachment of the FRP sheets, either carbon or steel, to the R/C beams a further increase of the shear capacity of the beams is observed. At some case this increase is greater that 210% compared to the control beam without stirrups and 35% greater compared with CRBs.
- The successful numerical simulation of the application of a novel anchoring device together with open hoop FRP strips, which enhances the efficiency of these FRP sheets applied as shear reinforcement for reinforced concrete rectangular beams, was demonstrated by this study.
- The validation of the numerical simulation is based on the measured behaviour of two (2) full-scale reinforced concrete rectangular beams without or with nominal shear reinforcement as well as with eight (8) full-scale reinforced concrete rectangular beams that employed open hoop FRP strips, with or without novel anchoring devices, as a means of upgrading their shear capacity.
- The success of the deployed numerical simulation is fully demonstrated by comparing first the observed and numerically predicted ultimate shear capacity and second by comparing next the observed and numerically predicted mode of failure, for each one of the ten (10) tested specimens. The achieved accuracy of the predicted ultimate shear capacity and mode of failure is excellent.
- Based on the validated FE numerical models presented here, further research is underway to identify the key features affecting overall structural response and thus to optimise the structural arrangement of the proposed novel anchoring device in terms of strength and ductility.

ACKNOWLEDGEMENTS

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- The employed, in this study, anchoring device is patented under the no. WO2011073696

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