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Behavior of pre-cracked deep beams with composite materials repairs

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Abstract. The study covers the behavior of reinforced concrete deep beams loaded under 4-point bending, failed by shear and repaired using bonding glass fiber reinforced plastics fabrics (GFRP) patches. Two rehabilitation methods have been used to highlight the influence of the composite on the ultimate strength of the beams and their failure modes. In the first series of trials the work has been focused on the reinforcement/rehabilitation of the beam by following the continuous configuration of the FRP fabric. The patch with a U-shape did not provide satisfactory results because this reinforcement strategy does not allow to increase the ultimate strength or to avoid the abrupt shear failure mode. A second methodology of rehabilitation/reinforcement has been developed in the form of SCR (Strips of Critical Region), in which the composite materials reinforcements are positioned to band the inclined cracks (shear) caused by the shear force. The results obtained by using this method lead a superior out come in terms of ultimate strength and change of the failure mode from abrupt shearing to ductile bending.

Keywords: glass fiber; shear reinforcement; reinforced concrete; beams; repair; failure modes; cracking

1. Introduction

The maintenance and repair of civil engineering structures involves problems both in terms of structural integrity and performance, as well as cost effectiveness and durability of these structures. In this context, the development of suitable repair techniques constitutes a major challenge for the building industry. The deterioration of the structures due to the decrease of the material mechanical properties requires the development of new rehabilitation techniques and a good control of the behavior of the material constituents. Many reasons can justify the use of reinforcements or repairs. Between the various technical causes that justify the adoption of rehabilitation techniques one can cite examples such as structural alterations and changes of use or even repairs after earthquakes. Initially, steel plates bonded to the concrete elements were used as reinforcing components, but they have been gradually replaced by the use of composite materials. Composites constitute a very attractive solution to answer the need for reinforcement in buildings and civil engineering structures.

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As the cost of the structural repair by using composite materials based on carbon fibers is not negligible, the industrial application of the repair technique by including glass fibers or hybrids could be a viable alternative to be considered from a design perspective (Attari *et al*. 2012).

In recent years many research activities and practical realizations of external reinforcements using composite materials have been developed. The behavior of reinforced concrete deep beams (a/d=1.3 -where a is the beam spam and d the depth), which fail by shear and are then strengthened or repaired has been the subject of a limited number of research papers. It must be noted that the shear behavior of steel reinforced concrete beams is an already complex topic, because a multitude of parameters often interdependent influence the mechanical behavior of the structural elements. An example of the set of these interrelated parameters is the geometry of the type of the structural component considered (deep or slender beam type, longitudinal steel ratio, beams size and the rate of transverse reinforcement etc...). Moreover, different failure modes are observed for reinforced concrete beams by (Chajes *et al*. 1994, Chaallal *et al*. 2002, Diagana *et al*. 2003, Zhang and Hsu 2004). Recently, Ramadass and Thomas (2015) have identified the major influential parameters related to the shear reinforcement using FRP, which are the concrete compressive strength and the longitudinal reinforcement ratio.

Several reinforcement methods using composite materials have been used so far, in particular the external bonding (EB) of the FRP fabrics (Ta¨ljstena and Elfgrena 2000, Mofidi and Chaalal 2011, Dong *et al*. 2013, Manos

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Table 1 Identification of the strengthening configurations

		Specimen Type	strengthening
Series A	No preloaded	DB_control	--
		DB_NP_(0/90)_STV1	1 ply with GFRP
		DB_NP_(20/70)_STV1	1 ply with GFRP
		DB_NP_(30/60)_STV1	1 ply with GFRP
		DB_NP_(+45/-45)_STV1	1 ply with GFRP
		DB_NP_2c_STV1	2plies with GFRP
		DB_NP_3c_STV1	3 plies with GFRP
	preloaded at 40%	DB_40%_2c_STV1	2 plies with GFRP
		DB_40%_3c_STV1	3 plies with GFRP
Series B	preloaded at 40%	DB_40%_STV2	Strips of Critical Region (SCR)

DB: Deep beams (a/d=1.3)

et al. 2014, Panigrahi *et al.* 2014, Baggio *et al.* 2014) and the method Near Surface Mounted Rebar (NSMR) by (Lorenzis and Teng 2007, Rizzo and Lorenzis 2009), which consists in bonding bars of FRP near the surface. The method Embedded Through Section (ETS) developed by (Chaalal *et al.* 2011b, Breveglieri *et al.* 2014) involves the use of an adhesive for bonding the FRP bars with concrete, and has showed quite satisfactory results in terms of shear strength, especially when no transverse reinforcement was present.

However, a limited set of data related to the behavior of pre-cracked beams repaired with composite materials and subjected to static 4-point bending loading is available in open literature, and this is the main rationale behind the scope of this work. The problem of deep beams failed by shear is at the core of the research activities presented in this paper, together with the repair or rehabilitation of the shear damaged structure by compensating the loss of rigidity and strength, which ultimately leads to extend the life and durability of the structure.

A current important challenge is to find approaches that mitigate the catastrophic failure mode by shear existing in reinforced concrete deep beams. In order to solve this problem, a new method based on the use of bands in critical regions SCR (Strips of Critical Region) is being proposed in this work.

This proposed rehabilitation technique is feasible, efficient and shows that the performance of the repaired beams is significantly higher compared to other shear repair approaches based on EB classical methods. The proposed method constitutes an innovative alternative, potentially more effective and leads to the desired failure mode by bending, rather than shearing.

2. Experimental protocol

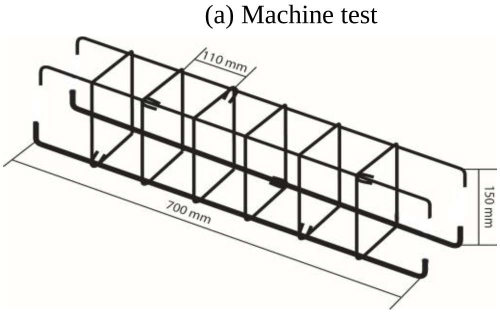
2.1 Preparation of the test specimensand test conditions

The experimental tests have been carried out on deep beams whose ratio between the distance of between the application of the point loads and the support at the height of the beam is small (only 1.3) so that shear failure is predominantly.

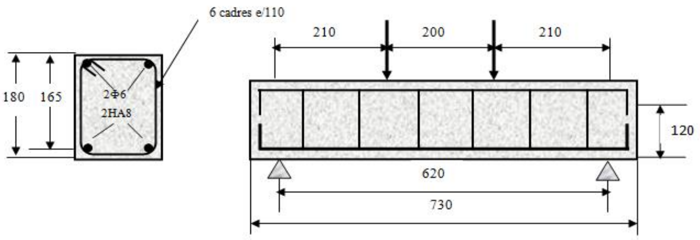
These investigations are useful to identify the contribution of the GFRP in terms of strength gain and failure modes. The tests were conducted in accordance with the ASTM C78-00 (2004) using a four-point bending device with a capacity of 150 kN (Fig. 1(a)).The manufacturing of the beams was performed at the

(a) Machine test

(b) Pouring of concrete



(c) Strengthening with armatures



(d) Detail of the beam

Fig. 1 characteristics of the beams tested

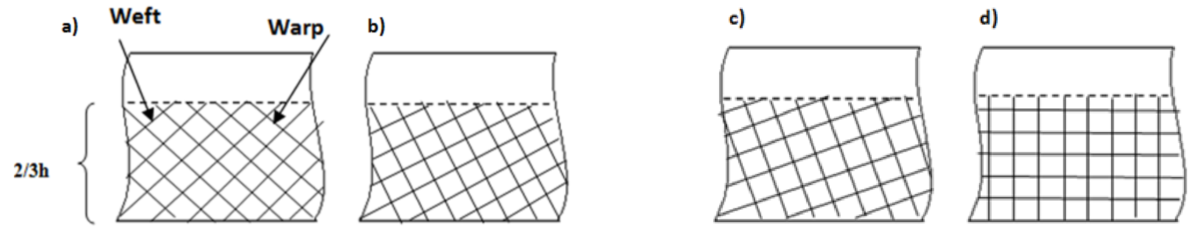
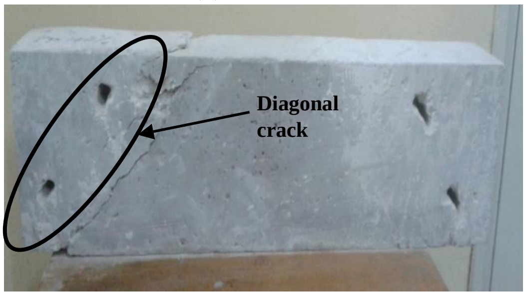


Fig. 2 Reinforcement with U shape patch following orientations (a) +45/-45 (b) 30/60 (c) 20/70 (d) 0/90

(a) Pristine (undamaged)

(b) Preloaded

(c) Drilled



(d) Repaired by mortar

(e) Repaired (bandage with the composite)

Fig. 3 Evolution of the state of the beam with the SCR methodology

Laboratory of Civil Engineering and Hydraulics (LGCH) of Guelma University. In order to characterize the concrete, six cylindrical and cubic specimens having dimensions of 160×320 and 150×150 mm^2 respectively were also produced. After 24 hours the specimens are removed from the mould and stored in tanks of water at ambient temperature up to 28 days. The beams have 730 mm long and width and height of 100 mm and 180 mm respectively, they are reinforced by two HA8 bars in the tensioned zone and by two HA6 bars in the compressed one. For vertical steel (steel frames), 6 mm of diameter rods in mild steel and spaced by 110 mm have been used (Fig. 1 (b)-(d)).

Table 1 shows the configurations adopted for this study, with the codes of the twelve reinforced concrete beams fabricated under the same conditions. The first three are control beams, six are sane (not preloaded) and strengthened by two and three plies of GFRP with U shape. The last three beams are preloaded at 40% of their ultimate strength; two are repaired by two and three plies of U-shaped GFRP, while the last one with the proposed new SCR method by bonding on the beam failure region.

To better understand the behavior of the reinforced concrete beams preloaded and repaired by glass bidirectional fiber fabrics (GFRP), a testing program was established by using two specific rehabilitation methods. The activities related to the first series of tests have focused on strengthening or repairing by using a continuous configuration of the reinforcement consisting in GFRP with a U-shaped recovery system following orientations (0/90, 20/70, 30/60 and +45/-45) (Fig. 2).

The second series of tests consists in placing reinforcements made from composite materials according to the new proposed procedure.

The composite patches are placed as to intersect the cracks produced by the shear force in order to improve the

Table 2 Characteristics of the materials used

Material	Young's modulus (GPa)	Limit tensile failure (MPa)
Concrete	23.9±0.95	28±2.2
Steel HA	200	400
Steel soft	200	235
Resin (flexural)	3.33±0.25	81.74 ±11.08
Resin (tension)	12.13±2.04	29.36 ±2.87
Glass fiber (Series A)	8.5	171
Glass fiber (Series B) 33%	26.3	1141

brittle failure mode of the reinforced concrete. In this way the glass fibers of the composite are loaded along their longitudinal direction (tensile) and therefore maximizing the strength of the system. This method uses a composite constituted by strands of unidirectional glass fibers impregnated in polyester resin and applied as a wrapping system on the beam by bonding.

After drilling the holes the damaged beams have been repaired using mortar concrete. This repair was performed in order to improve the aesthetics and the surface finish before the bonding of the composites (see Fig. 3 (d) and (e)). The various reinforcements were arranged to intercept the diagonal cracks as accurately as possible. To facilitate the setting of the unidirectional fabric with the resin in the holes, the fibers are interlaced and centered in each hole. It is necessary that the holes are very clean before the resin filling. As the load is symmetric, it is important to note that the non-cracked parts of the beam are also repaired in the same manner to avoid the appearance of new diagonal cracks.

2.2 Characteristics of thematerials

2.2.1 Glass fiber

The composite materials used in this study belong to two series:

• Series A: the composite patch STV1 is made from bidirectional glass fiber having a surface density of 500 $g/m^2$with a U-shaped reinforcement system according to different orientations (0/90, 20/70, 30/60 and +45/-45).The total mass of the fiber reinforcement is 102 g all manually impregnated into a polyester resin with rollers (low pressure) to ensure complete bonding between the concrete and the GFRP and avoid trapped air bubbles. The configuration of the composite STV1 is U-shaped reinforcement continuously applied for a length of 580 mm and a height of 120 mm (2 / 3h).

• Series B: the STV2 patches consist of 15 strands of glass fibers in the shear zone of the cross section of the reinforced concrete beam taken from the same fabric STV1.The total mass of the reinforcement is 40 g, and a polyester resin has been used as a matrix.

The repaired/reinforced beams were left to cure at room temperature for at least two weeks before being tested, in order to obtain a polymerization of the resin.

2.2.2 Concrete and steel

The average compressive strength of 28 MPa of the concrete is determined from using three cylindrical specimens after 28 days. These specimens were made from the same cast as used for the fabrication in accordance with the ASTM C39-96 standard. The yield strengths of the steel bars and steel stirrups are 400 and 240 MPa, respectively. The main characteristics of the materials (concrete, steel, resin, fabric Series A and Series B) are summarized in Table 2.

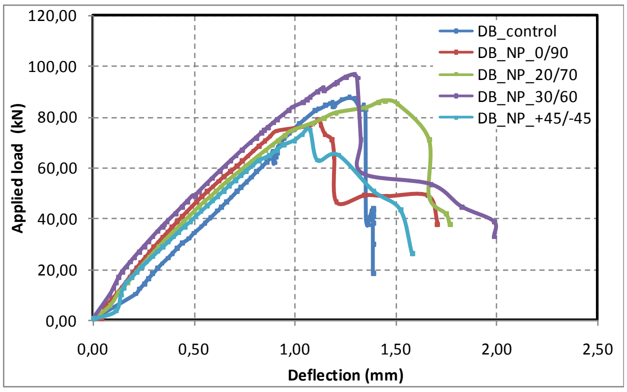


Fig. 4 Force-deflection curves of non preloaded beams obtained for the orientations (0/90,20/70,30/60 and +45/-45)

3. Results and discussions

The experimental results are presented in the following sections in terms of failure load, ductility of the beams and the observed failure modes.

3.1 Influence of the compositeSTV1 orientations

The results obtained show that the stiffness of the beams is increased by the bonding of the composite patch. The best performance is obtained for the beam reinforced with the stacking of (+30/-60) (see Fig. 4).The ultimate strength of the control beam is 87.6kN with a deflection equal to 1.27 mm. Based on the orientation of the reinforcement, the ultimate load of the beam (DB_NP_30 / 60) is increased by 10.5% compared to the reference beam (DB_control). This gain at the ultimate load is accompanied by a reduction in ductility, resulting in a decrease of the deflection by approximately 12.4% compared to the beam (DB_NP_20 / 70).This value is in good agreement with the results obtained by Bouchelaghem *et al.* (2011 a, b) for cylindrical specimens. The beams have diagonal cracks with an average orientation of 34°. The orientation of the composite fibers should be perpendicular to the cracks in order to close them. The stress field in the composite of the beam (DB_NP_30/60) shows a lower shear effect compared to the one of the beam DB_NP_20/70; this is due to the difference of the crack directions (4° and 14° respectively to the direction of the 34° crack). This is the reason why the beam DB_NP_30/60 has a higher ultimate strength compared to the beam DB_NP_20/70.

The orientation of the fibers has a great influence on

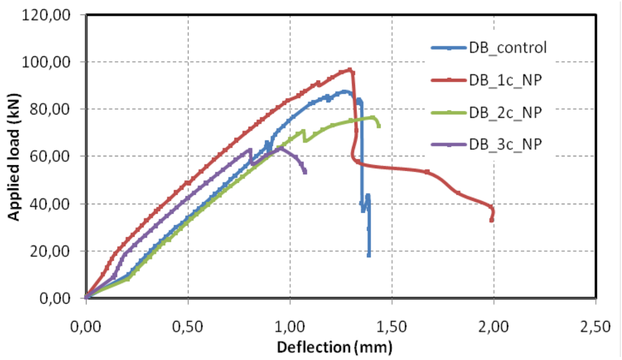


Fig. 5 Force/deflection curves of STV1 reinforced non-preloaded beams

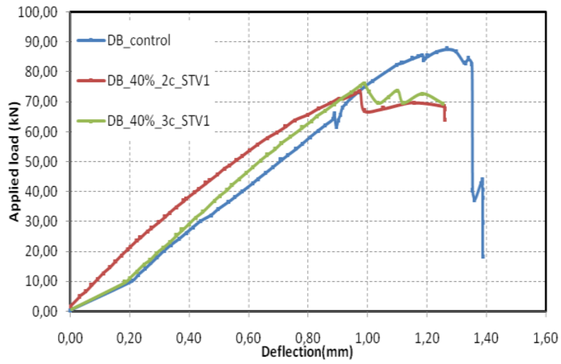


Fig. 6 Force/displacement curves charge / deflection of the beams preloaded at 40% of the ultimate load and then repaired by the STV1 patch

the behavior of test beams due to the difference in rigidity during the first phase of the curves. Because of this reason, the (+30/-60) orientation is adopted in the following steps of this work, i.e., all other beams of the series A were repaired using the external bonding with two or three plies of GFRP and only using the (+30/-60) orientation.

3.2 Influence on stiffness and strength provided by the number of plies in the composite U-shaped STV1 patches

The beams considered in this case belong to the non-preloaded and preloaded cases reinforced with the composite STV1 patches with different thicknesses. Fig. 5 shows the load history of the non-preloaded reinforced beams with one, two and three composite plies compared to the analogous behavior of the control beam.

The load drop observed in the curves of Fig. 3. 9 indicates a sudden decrease in resistance due to delamination of the composite. The analysis of the results shows that the rate of improvement of the ultimate strength of the beams reinforced by one ply is in the order of 10.5% compared to a control beam, whereas the application of one or two plies of the fabric PRFG leads to decreases in strength in the order of 12.5 and 27.6% respectively. The strengthening of deep beams appears therefore to be governed by the first ply only, and this is in good agreement with previous works from (Bousselham and Chaallal 2006, Contamine *et al*. 2013).

It was also noticed that the beams bonded by three layers of STV1 show a more stable deflection behavior compared to the case of beams strengthened by one and two layers. The beams reinforced by one and three plies showed however a greater stiffness than the control beam (Sundarrajaand Ganesh Prabhu 2011). In addition, it has been noticed that the beam reinforced by a STV1 ply showed a greater rigidity than the control beam itself, as well as the beams reinforced by two and three plies. This phenomenon confirms the observations present in the works of (Kreit 2012). The absence of bearings in the test setup explains the brittle behavior of the deep beams.

The load corresponding to the appearance of diagonal cracks is in the vicinity of 40% of the ultimate load, and therefore it appears reasonable to use this value for the preloading of the beams. The responses of the beams at this level of preloading and then repaired by two or three plies of composite with U shape are shown in Fig. 6. The preloaded and then repaired beams using one or two plies showed a less brittle behavior, with a reduction of the resistance respectively in the order of 15.3 and 12.3%, 76% and 78% respectively for the deflection of the test pieces repaired with two and three plies, and also a stiffness increase compared to the control beam. These beams still show some residual compliance that provides lower brittleness compared to the control beam. The composite repairs do not appear however to provide a significant influence to the resistance of the beams. The resistance of the beam DB-40% -3c-STV1 is greater than the one of the beam DB - 3c-NP due to the deformations of the most remote compressed zones of the concrete, which have reached their limits near the loading zones after the crushing of the concrete under compression (Figs. 4, 5 and 6). Preloaded beams that have been repaired by the U-shaped composite STV1 showed a higher rigidity than the control beam. The STV1 reinforcement with the U-shape does not prevent the appearance of diagonal cracks.

3.3 Effect of the SCR method on the strength and stiffness of the beams when using the STV2 patch

The analysis of the results obtained on the beam preloaded at 40% of its ultimate load and then repaired following the new SCR method (wrapping in the cracked zone) using the composite STV2 (DB_40%_STV2) allowed an increase of the load capacity of 7.1% and a more ductile behavior with an increase in the deflection of the order of 26% compared to the control concrete beam as shown in (Fig. 7). The load deflection behavior of this beam is quite different from the others and can be divided into four phases. During the first part of the curve it is possible to notice a nonlinear behavior dominated by the concrete until a load of 25 kN. Phase 1 represents the behavior of the concrete, in which the rigidity has decreased significantly due to the cracked concrete for the preloaded beam (EP_40%_STV2) compared to the other tested beams. This load-deformation behavior is then followed by a very significant increase of the stiffness

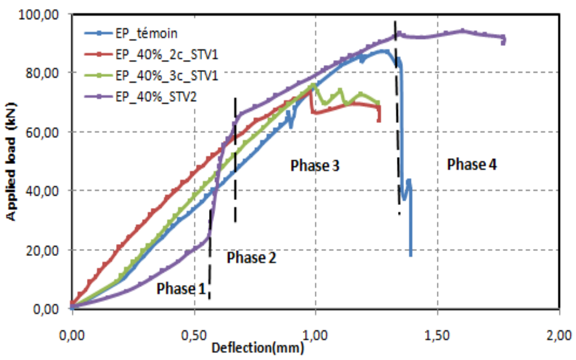


Fig. 7 Force/deflection curves of the beams preloaded at 40% and repaired with U-shaped and SCR

Table 3 Load capacity and failure mode types for the tested beams

Beam types	(U/SCR) *	Ultimate load (kN)	Gain or loss of ultimate load (%)	Deflection (mm)	Gain or loss of deflection (%)	Failure mode
DB_control	----	87.6	----	1.27	----	Shear
DB_40%_2_STV1	1.74	73,52	-16.1	0.98	-23	Shear+debonding
DB_40%_3_STV1	2.43	76,17	-13.1	0.99	-22	Debonding+crushing of concrete compressive
DB_STV2	1	94,33	+7.1	1.60	+26	Bending

* Quantity of the used composite / composite SCR.

(increase in the slope) in the second phase until a value of 67 kN. The stiffness increase is due to the contribution of the composite patch that possesses very good tensile properties. During the third phase the curve segment is equivalent to the other curves with a slight higher increase due to the significant contribution of the composite to the resistance to shearing forces, which is characterized by a drop in stiffness followed by a quasi-plateau in the fourth phase. The latter behavior can be explained by the appearance of vertical cracks leading to a change of the failure mode from abrupt due to shear, to a ductile one due to bending.

Table 3 lists the loads attained at failure for the two repair types, namely the U-shaped one (with2 and 3plies) and the SCR approach. The table lists the type of composite, the gain or loss of load capacity, defined as [1-(load after repair / load of control concrete)] × 100%, and a summary of the final failure type for each beam. Beams rehabilitated with composites having a U-shape with two and three plies use 74% and 143% more composite material respectively, compared to the new SCR method proposed.

The results of the tests are very positive with an increase of 7.1% and 26% of the ultimate load and deflection of the rehabilitated SCR beams compared to the beam control, while the rehabilitated beams by the patches (two and three plies) with U-shape bring reductions of 16.1% and 13.1% .for the ultimate load, and 23% and 22% for the deflection.

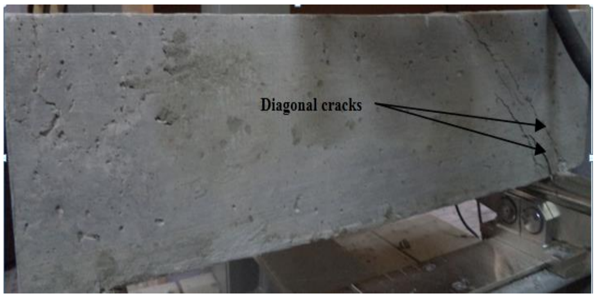


Fig. 8 Failure mode of the control beam

3.4 Cracking and failure modes of the beams reinforced/repaired using the STV1 patch

Fig. 8 shows that the control beam subjected to 4-point bending underwent shear failure. The reasons behind the particular failure type are two folds:

→ The average ultimate strength of the beam obtained experimentally is 86.7 kN. This value is very close to the 84.5 kN estimated by using the BAEL 91 code. The failure of the control beam due to oblique principal stress was planned because the estimated ultimate strength due to bending is 27% higher than the estimated one with shear force (61.7 kN). In addition, the slenderness ratio of the beam is equal to (a/d=1.3), which is an appropriate geometry for a beam with the type of failure experimentally found.

The ultimate strength V_{Ed} of the shear force with the reinforced elements and calculated by using Eurocode 2 ($V_{Ed}=V_{Rd,\ c}+V_{Rd,\ s}$) is in the order of 61 kN, whereas the calculated value of the maximum shear force calculated ($V_{Rd,\max}$) is of the order of 83 kN. This level of force can be taken up by the element before the crushing of the compression rods (Hamrat *et al.* 2012). Because $V_{Ed}<V_{Rd,\max}$ we can safely state that the failure is due to transverse reinforcement (shear), and it is not caused by the compression rods.

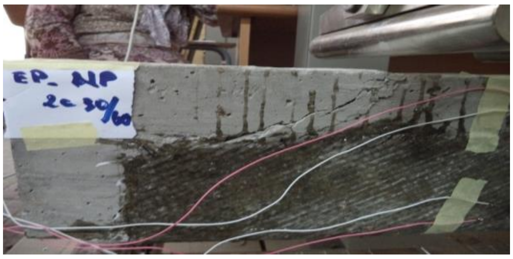
The parallel diagonal cracks created in the vicinity of the supports are located around the position of the application of the point load, and may appear on both sides and propagate with increasing load values at an angle of approximately 40°. Only the large and dominant crack progresses to reach the application point of the concentrated load where the failure of the beam is obtained only in one side.

This behavior is typical of deep beams and also in good agreement with previous works carried out on beams with different and large sizes (Sayed 2014, Baggio *et al.* 2014, Bousselham *et al.* 2006).

The failure mode observed in the case of the beams non-preloaded and reinforced with one, two or three composites plies of U-shaped patches was shear failure, similar to the one found in the control beam.

During the tests one crack was heard followed by the delamination of the composite. In beams reinforced by one and two plies two cracks thereafter appeared, however only a single crack was evident for the beam reinforced by three plies due to the large amount of composites used (Figs. 9 (a)-(c)). Shear cracks could be

(a) Beam reinforced by one ply



(b) Beam reinforced by two plies

(c) Beam reinforced by three plies

Fig. 9 Failure modes of non preloaded beams and reinforced bytheSTV1 patch

(a) Repaired by two plies

(b) Repaired by three plies

(c) Vertical and horizontal debonding

(d) Crushing of the concrete under compression

Fig. 10 Failure modes of preloaded beams at 40% and repaired by STV1

observed in the part of the beam covered by the composite with the U-shape.

The failure mode of the beams preloaded at 40% and then repaired by two and three plies is similar to the one present in the control beam and the non preloaded STV1-reinforced one as shown in Fig. 10(a). However, for the beam preloaded at 40% and then repaired by three plies with large composite mass a delamination between the composite and the concrete in the horizontal and vertical direction was obtained(Figs.10(b)-(c)), followed by the deformations on the concrete in highly compressed zones that have reached their limits near to the loading point (Fig. 10 (d)).

3.5 Cracking and failure mode of the beam repaired using the STV2 patch

The beam belonging to the B series preloaded and then repaired using the STV2 composite failed by bending due to the appearance of vertical cracks followed by the formation of a bearing, which prevented the shear crack to appear and to develop. The experimental results of the SCR-rehabilitated beam have therefore showed the desired type of failure mode, which is the bending one (Fig. 11). Similar results were also observed by other researchers in previous investigations of reinforced concrete beams strengthened with composite materials using the ETS method by inserting FRP rods into the shear zone of the beam (Chaallal *et al*. 2011b, Breveglieri *et al.* 2014, Mofidi and Chaallal 2014). Therefore, the repair of the beams by bonding with a U-shaped continuous fabric does not allow “sewing”, or closing the cracks. This beams belonging to the series B have the composite material loaded until failure; the beams belonging to the series A show a delamination between the composite and the concrete that does not permit to

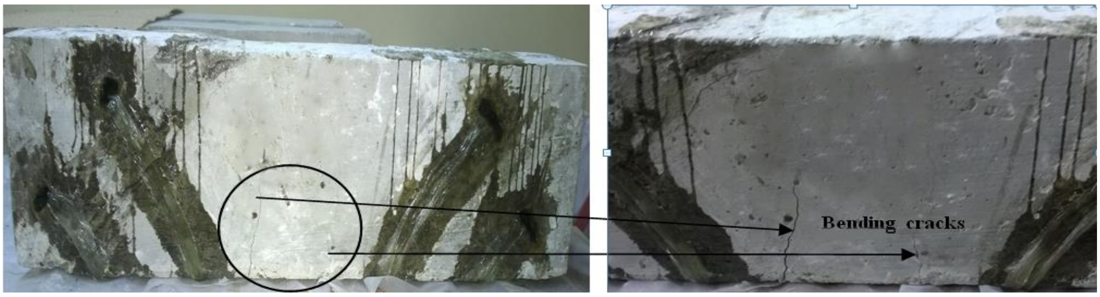


Fig. 11 Failure mode of the beam repaired using the STV2 patch

reach the ultimate strength of the composite. The SCR method minimizes the likelihood of cracks with the use of fibers oriented perpendicularly to the shear cracks. The fibers therefore provide a uniaxial tensile loading that provides a maximum resistance and a functional use of the composite until its ultimate strength is reached. Strengthening or repairing the beams using the new method leads to changes of the failure modes, from a fragile failure by shear to a ductile one by bending.

4. Conclusions

The main objective of this research consisted in developing and improving the knowledge surrounding the alleviation of shear-induced failure by using GFRP to strengthen or repair beams following the newly proposed SCR method. Special focus was dedicated to reinforced concrete deep beams. Composite materials are used to restore and increase the ultimate shear capacity of the beams. The main conclusions are summarized as follows:

• The reinforced concrete deep beams subjected to 4-points bending loading fail by shear;

• The repair or reinforcement of beams by one or two plies of composite STVI patches with a U-shape led to a shear failure mode like the one already observed in the case of the control beams;

• The reinforcement by using one ply of composite U-shaped patch results in an increase of about 10.5% of the ultimate strength. When using two and three plies the ultimate strength decreased by12.5% and 27.6% respectively.

• Repair of preloaded beams withSTV1 U-shaped composite patches using two and three plies showed reductions of the strength in the order of 16.1% and 13.1%, respectively. The failure mode was modified from shear to a concrete compression crushing one when the beam was repaired using three plies;

• The beam repaired following the proposed new SCR methodology uses less composite (i.e., lower costs), allows to a diagonal bandage of the crack and leads to increases in the load capacity and deflection of 7.1% and 26% respectively when compared against to the pristine control concrete beam. In addition, this method has changed the final failure mode of the beam from a shear to a ductile one by bending.

Acknowledgments

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