Damaged RC beams strengthened with near surface mounted technique using fiber reinforced polymers

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ABSTRACT

Strengthening reinforced concrete (RC) structures with fiber-reinforced polymer (FRP) composites is becoming an attractive alternative for repairing of damaged structures. In the case of reinforced concrete beams, reinforcement with FRP enhances the flexural capacity and shear strength. FRP strengthening can be applied as externally bonded FRP laminates or near surface mounted (NSM) FRP rods.

The flexural behavior of damaged reinforced concrete beams repaired with NSM technique using glass fiber reinforced polymer (GFRP) bars is experimental studied in this work. Two set of beams were tested: control beams (without GFRP bars) and damaged and then repaired beams with GFRP bars by varying two parameters (damage degree and concrete strength class).

Repairing damaged RC beams with NSM technique was successful for the two different damage degrees. A recovery and a significant increase of load capacity were obtained. The compressive strength of the concrete did not have influence on the results.

INTRODUCTION

Many reinforced concrete (RC) structures are damaged. Most of them are suffering from various deteriorations: cracks, concrete spalling, and large deflection, etc. Many factors are at the origin of these deteriorations, such as ageing, corrosion of steel, earthquake, environmental effects, static overloading and accidental impacts on the structure. Under the influence of these factors, RC structures deteriorate, leading to gradual loss of performance over a period of time.

Mechanical properties degradation and structural safety loss make the rehabilitation or reinforcement necessary. In any case, composite materials or FRP are an excellent option to be used as external reinforcement because of their high tensile strength, light weight, resistance to corrosion, high durability and easy installation. The most common type of FRP in industry is made with carbon, aramid or glass fibers. The FRP can be used to improve flexural and shear capacities, provide confinement and ductility to compression structural members (Rougier and Luccioni, 2007).

FRP systems can be classified in two main categories: Externally-Bonded Reinforcement in the form of plates or sheets (EBR technique) or bars or strips applied in superficial grooves (near-surface-mounted technique, NSM). The first technique is well known and widely used in practical applications. The near surface mounted (NSM) technique using fiber reinforced polymer (FRP) reinforcement has become an attractive method for strengthening reinforced concrete (RC) members. In this methodology, the FRP reinforcement is installed into slits cut into the concrete cover using cement mortar or epoxy as bonding materials. Compared to externally bonded FRP reinforcement, the NSM system has a number of advantages: better protection from the external sources of damage, improved bond and better aesthetics (Sharaky et al., 2014, Khalifa 2016).

FRP bars can be manufactured in a virtually endless variety of shapes and surface textures. Hence, the NSM FRP reinforcement may be round; square, rectangular and oval bars, as well as strips. Their surface can be smooth, sand-blasted, sand-coated, or roughened with a peel-ply surface treatment. Round bars can also be spirally wound with a fiber tow, or ribbed. Different types of FRP bars are shown in Figure 1 (ACI 440 1R-06, 2006, De Lorenzis and Teng, 2007, El-Gamal et al., 2016).

The groove filler is the medium for the transfer of stresses between the FRP bar and the concrete. The most common and best performing groove filler is an epoxy resin. The use of cement paste or mortar in place of epoxy as a groove filler has recently been explored in an attempt to lower the material cost, reduce the hazard to workers, minimize the environmental impact, allow effective bonding to wet substrates, and achieve better resistance to high temperatures and improved thermal compatibility with the concrete substrate. However, cement mortar has inferior mechanical properties and durability, with a tensile strength an order of magnitude smaller than that of common epoxies. Results of bond tests and flexural tests have identified some significant limitations of cement mortar as groove filler (De Lorenzis and Teng, 2007, Al-Mahmoud et al., 2009, Soliman et al., 2010, Choi et al., 2011,).

Different studies investigated the effect of strengthening of reinforced concrete beams with CFRP plates or NSM bars (Badawi and Soudki, 2009, Ceroni, 2010, Sena-Cruz et al., 2012, Adam et al., 2015, Dola and Ahmed, 2015, Khalifa 2016). However, there are few studies about practical applications in which GFRP bars was used to repair damaged concrete beams (Almassri et al., 2016). Thus, this paper is concerned with the flexural behaviour of reinforced concrete beams damaged by static overloading and repaired with GFRP bars.

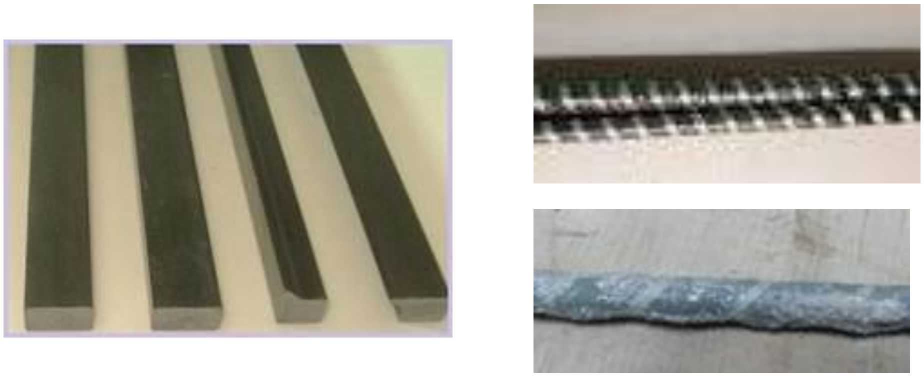


Figure 1. Types of FRP bars for NSM applications.

EXPERIMENTAL WORK

The experimental program presented in this work is part of an ongoing research in which, different types of damage, in different RC elements and the efficiency of repairing technique using FRP, are studied.

A total of twelve RC beams were manufactured and tested under four-point bending. Two parameters were investigated in this work: damage degree and strength concrete class. Damage degree is defined as the ratio between the load applied to the beam causing its pre-cracking and the load capacity of the control beam, which has been taken as 75 % and 90 %. Two types of concrete were used to cast the beams: an ordinary concrete (H30: having an average compressive strength of 30 MPa) and a low resistant concrete (H20: having an average compressive strength of 20 MPa) corresponding to a weak concrete.

Beams were divided in two groups, according to concrete strength class and damage degree and some specimens were considered as a control beam, the remaining specimens were damaged with a fixed damage degree and then repaired by bonding glass fibers bars in their tensile face by using an epoxy resin. Details of the beams tested are summarized in Table 1. Test specimens, properties of the materials, FRP repair method, test procedure and instrumentation, are detailed in the following sections.

Table 1. Details of the beams tested under flexural.

Group	Beam reference	Concrete strength f'_{c28} (MPa)	Designation	Damage degree (%)
Group I	V1C	30	Control beam	-
	V2C	30	Control beam	-
	V3R	30	Repaired	75
	V4R	30	Repaired	75
	V5C	30	Control beam	-
	V6C	30	Control beam	-
	V7R	30	Repaired	90
	V8R	30	Repaired	90
Group II	V9C	20	Control beam	-
	V10C	20	Control beam	-
	V11R	20	Repaired	75
	V12R	20	Repaired	75

Test specimens

All test beams had the same overall cross-sectional dimensions, internal longitudinal reinforcement and stirrup arrangement. The beams had a rectangular cross section of 80 x 160 mm, 1100 mm total length, and 1000 mm clear span. All beams were reinforced with two 8 mm diameter ribbed steel bars in the tension side and two 6 mm diameter ribbed steel bars in the compression side. To avoid shear failure, beams were reinforced with closed stirrups of 4.2 mm diameter ribbed steel bars spaced at 75 mm. Figure 2 shows the dimensions and reinforcement details of test specimens.

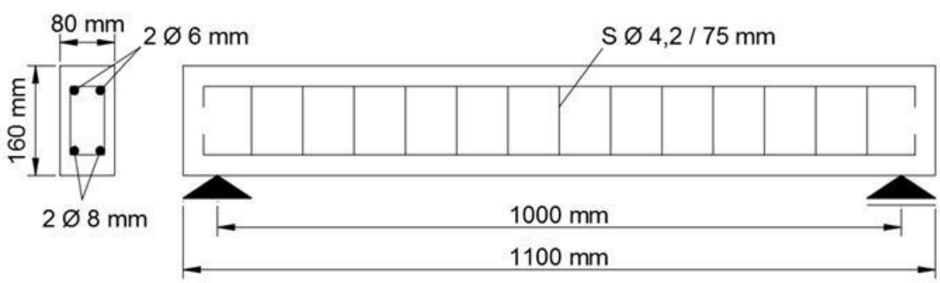


Figure 2. Dimensions and reinforcement details of test specimens

Materials used

Concrete and steel bars were used in preparation of beam specimens. GFRP bars with an epoxy adhesive were selected for repairing. The details of these materials are briefly discussed here.

Concrete

Two concrete classes were design: H30 concrete having an average compressive strength of 30 MPa and H20 concrete having an average compressive strength of 20 MPa. Concrete cylinders were taken to find compressive strength and elastic modulus of concrete, according IRAM standards. The obtained data from the laboratory tests are listed in Table 2. Test results show that the average measured concrete compressive strengths and elastic modulus for aforementioned concrete classes were 34.92 MPa and 28.2 GPa and 25.18 MPa and 21.13 GPa, respectively.

Table 2. Mechanical properties of concretes and steel.

Materials		E (GPa)	f'_m (MPa)	f_y (MPa)	f_u (MPa)
Concrete	H20	21.13	25.18	-	
	H30	28.20	34.92	-	
Steel	Bars	210	-	420	500

Steel and FRP reinforcement

Steel bars of 6 and 8 mm diameter were used for all beams as top and bottom steel reinforcement, respectively. The mechanical properties of the 6 and 8 mm diameter steel bars, were supplied by manufactures and are presented in Table 2. Steel bars of 4.2 mm diameters were also used as shear reinforcement.

For the FRP reinforcement, glass sand coated FRP bars of 12 mm nominal diameter were used as the NSM reinforcement. The FRP bars were manufactured by an Argentinian company using the pultrusion process. An epoxy resin, with high viscosity, was used for embedding the GFRP bars in the NSM technique. The mechanical properties of the FRP bars and epoxy resin were supplied by manufactures and they are shown in Table 3.

Table 3. Mechanical properties of GFRP bars and epoxy resin.

	Elastic Modulus, E (GPa)	Tension strength, σ_t (MPa)	Compresssion strength, σ_c (MPa)
GFRP bars	45	740	-
Epoxy	12.8	-	95

Specimen preparation and repairing technique

The GFRP rod was installed in the damaged beams by making a cut in the concrete cover in the longitudinal direction at the tension side. A special concrete saw with a diamond blade was used. Groove size of 20 x 20 mm^2 was cut for a GFRP bar of 12 mm diameter and then it was half-filled with epoxy resin. The GFRP bar was then lightly pressed into the resin. Finally, more resin was added and the surface leveled (Al-Mahmoud et al., 2009, Soliman et al., 2010, Choi et al., 2011, Standard ACI 440 1R-06). Figure 3 shows the steps of the reparation process.

The length of the GFRP bars was set at 1000 mm (80 times the diameter of the FRP bar) and it was defined taking into account experimental tests carried out by other authors (Sharaky et al., 2014).

Finally, the damaged beams were tested 72 hours after the installation of the GFRP rod, in order to ensure the maximum degree of adhesion between the concrete surface and the epoxy resin.

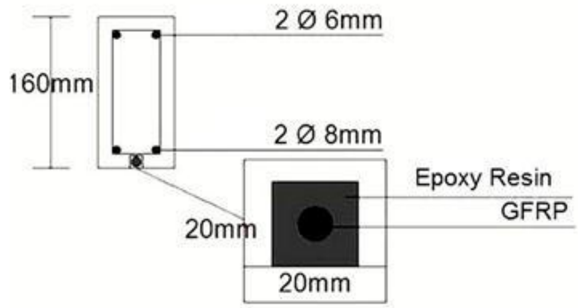


Figure 3. Details of NSM system.

Figure 4. Steps of the reparation process.

Test setup

All beams were tested in four-point bending under displacement control at the rate of 1.5 mm/min on a universal testing machine with a maximum load capacity of 1000 kN. The load data was automatically recorded through a data logger and displacements were measured through dial gauge. The beam supports consisted of a roller support at the two ends. The outer loading span was 1100 mm and the inner loading span was 1000 mm. The test setup, the various monitoring devices, and their location along the beam are presented in Figure 5. The damaged beams were precracked also by this machine. The load, necessary to attain the fixed damage degree, was applied. Then, each specimen was unloaded and the GFRP bar was bonded on the tensile face of the damaged beam. Finally, the last step was to load the repaired beams until failure.

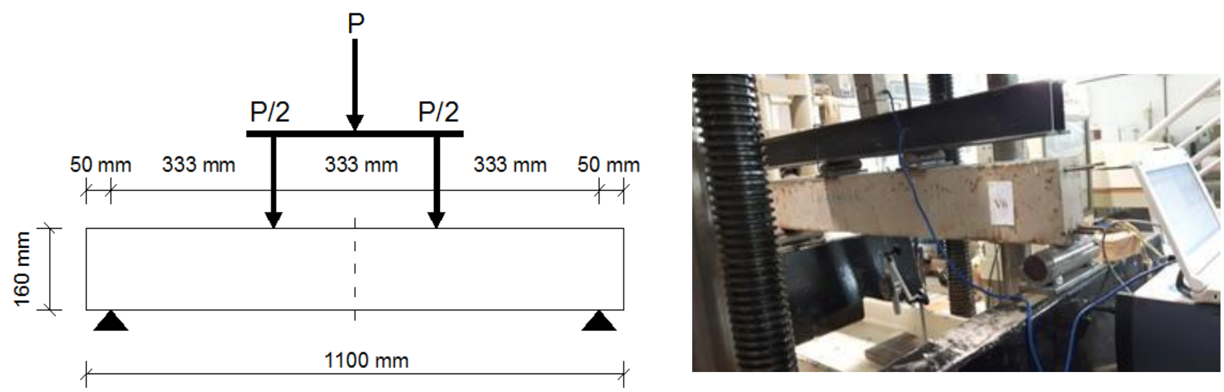


Figure 5 Test set-up. a) Four-point bending set-up (schematic drawing); b) General view of the test setup and instrumentation.

TEST RESULTS

The results of the tested beams are given in Table 4. In this table, ultimate load (Pu), damaged degree (D), load capacity contribution, rigidity coefficient (RC), rigidity contribution and failure modes, are summarized. The load capacity contribution is the ratio between the load carrying capacity of the repaired beam and that of the control beam. The rigidity coefficient is the ratio between the load at elastic limit of the beam and the corresponding deflection. The rigidity contribution is the ratio between the rigidity capacity of the repaired beam and that of the control beam.

All repaired beams have a mechanical behavior, in terms of load capacity, higher than those of control beam. For all repaired beams of group I and group II, the ultimate load was increased. This increase ranged between 7% and 48% (Table 4). GFRP bars were able to efficiently restore the load capacity of damaged RC beams, and they significantly enhanced it, in comparison with control beams. On the other hand, for the same damage degree (75 %), concrete strength class had no influence on the load capacity of repaired RC beams. In the next sections, failure modes of control beams and GFRP repaired beams, load deflections responses, effect of damage degree, effect of concrete strength class, are analyzed.

Table 4. Beams tested under flexural

Group	Beam	[a] D (%)	[b] P_u (kN)	Load capacity contribution (%)	[c] RC (kN/mm)	Rigidity contribution (%)	Failure mode
Group I H30	V1C	0	41.2	0	8.66	0	Yielding
	V2C	0	42.7	0	8.60	0	Yielding
	Average $P_{u\ V1C\ and\ V2C}$ = 41.95 kN Average $RC_{V1C\ and\ V2C}$ = 8.63 kN/mm						
	V3R	75	62.2	48	9.89	14.60	Support cracking
	V4R	75	59.4	42	9.66	12.00	Support cracking
	V5C	0	41.4	0	6.78	0	Yielding
	V6C	0	45.0	0	9.36	0	Yielding
	Average $P_{u\ V5C\ and\ V6C}$ = 43.20 kN Average $RC_{V5C\ and\ V6C}$ = 8.07 kN/mm						
	V7R	90	46.4	7	8.75	8	Concrete cover separation
	V8R	90	51.1	18	9.24	14	Concrete cover separation
Group II H20	V9C	0	45.0	0	8.56	0	Yielding
	V10C	0	42.0	0	6.97	0	Yielding
	Average $P_{u\ V9C\ and\ V10C}$ = 43.50 kN Average $RC_{V9C\ and\ V10C}$ = 7.77 kN/mm						
	V11R	75	58.9	35	9.04	16.34	Concrete cover separation
	V12R	75	58.0	33	8.73	12.35	Concrete cover separation

[a]D = damage degree; [b] P_u = ultimate load; [c] RC = rigidity coefficient

Failure modes

The failure mode of the control beams was by steel yielding giving a large deflection of the beam. This failure mode is characterized by the appearance of two first cracks localized under the two loads (Figure 6), followed by the appearance of micro-cracks between the two large cracks. Finally and by increasing the load, concrete crushing happened.

a

b

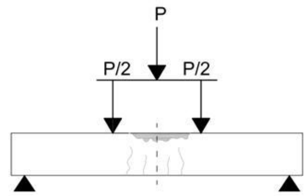


Figure 6. (a) Failure of the control beam and (b) schematic drawing.

For all repaired beams, the authors observed two failure modes: support failure and concrete cover separation. In the first case, several cracks developed in the zone of one of the support, which was damaged in reparation process, when groove was cut (Figure 7a). Concrete cover separation occurred due to high shear and normal stresses at the ends of the GFRP rods. Failure started with inclined cracks in the concrete cover, and extended along the tensile reinforcing bars (Figure 7b).

a

b

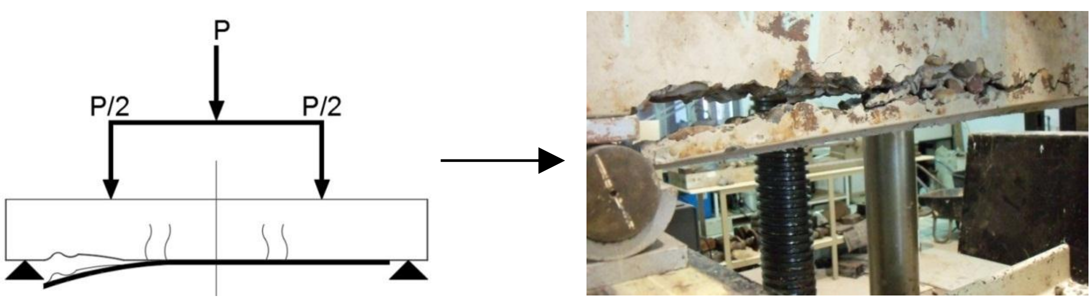


Figure 7. Failure of repaired beams. (a) Support failure (b) Concrete cover separation.

Load- deflection responses

The load–mid span deflection responses for some individual beams, with different damage degree and different concrete strength class, are plotted in this Figure 8. Control beams had a significant ductility. On the other hand, the behavior of all repaired beams was brittle due to the purely elastic behavior or GFRP bars. A slight increase in stiffness, in beam V4R (D= 75% and H20), was reached. All repaired beams recovered and improved the bearing capacity in comparison with control beams.

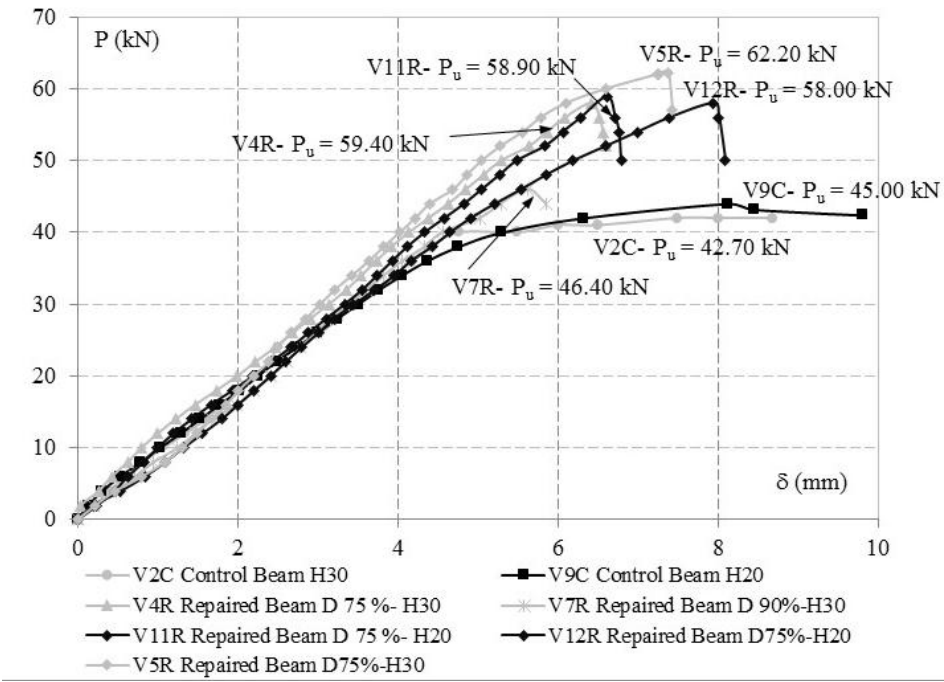


Figure 8. Load- deflection curves for beams strengthened with NSM GFRP bars.

Effects of the damage degree of beams

In this study, the authors tested the effect of the damage degree on the load capacity and the rigidity of the repaired RC beams by bonding GFRP bars. Two damage degrees were analyzed: D = 75% and D = 90%. At 75 % of damage degree, the beam is still in the elastic range. At 90% of damage degree, the beam reached the plastic range.

The load–deflection responses for the individual beams, with different damage degree and concrete strength class of 30 MPa, are plotted in Figure 9. Four control beams and four damaged beams were tested: V1C and V2C (D=75 %), V5C and V6C (D=90%), V3R and V4R (D=75 %), V7R and V8R (D=90%).

From the results presented in Table 4 and Figure 9, the authors observed that all repaired beams had a mechanical behavior, in terms of load capacity and rigidity, higher than those of control beams (the load capacity increased by 48% from average $P_{uV1CandV2C}$ to V3R and by 44% from average $P_{uV1CandV2C}$ to V4R, for D= 75 %. In case of D = 90 %, the load capacity increased by 7 % from average $P_{uV5CandV6C}$ to V7R and by 18% from average $P_{uV5CandV6C}$ to V8R. The rigidity coefficient increased about 8% to 14.60 % for D=90% and D=75 %, respectively).

Furthermore, the mechanical behavior of the repaired beams changed from elastoplastic to elastic behavior, as it can be seen in Figure 9.

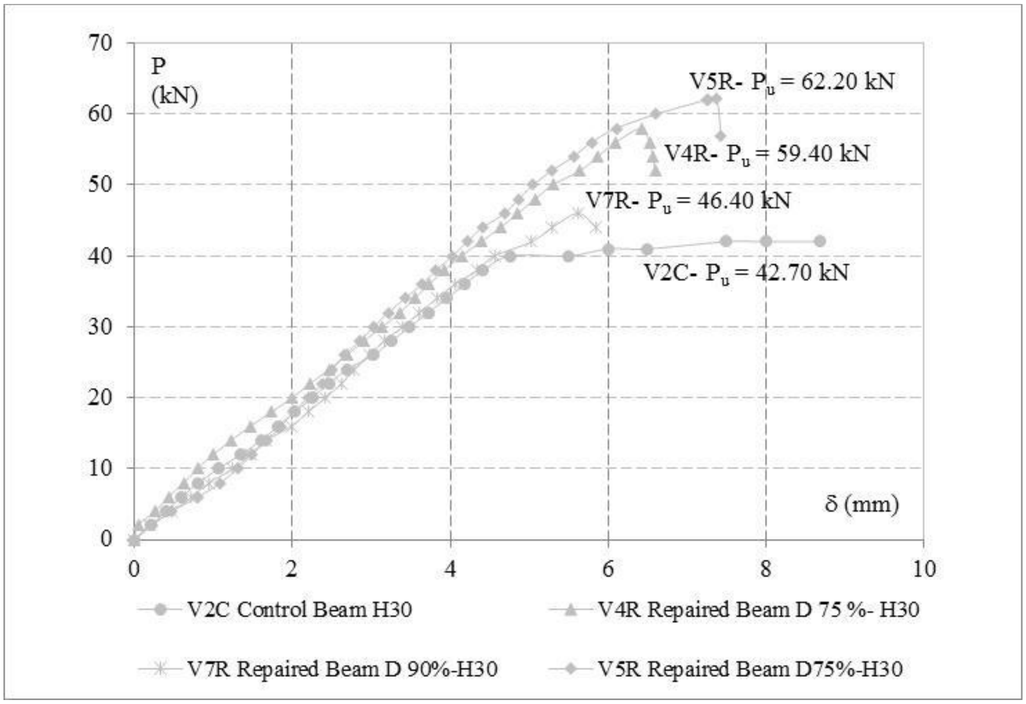
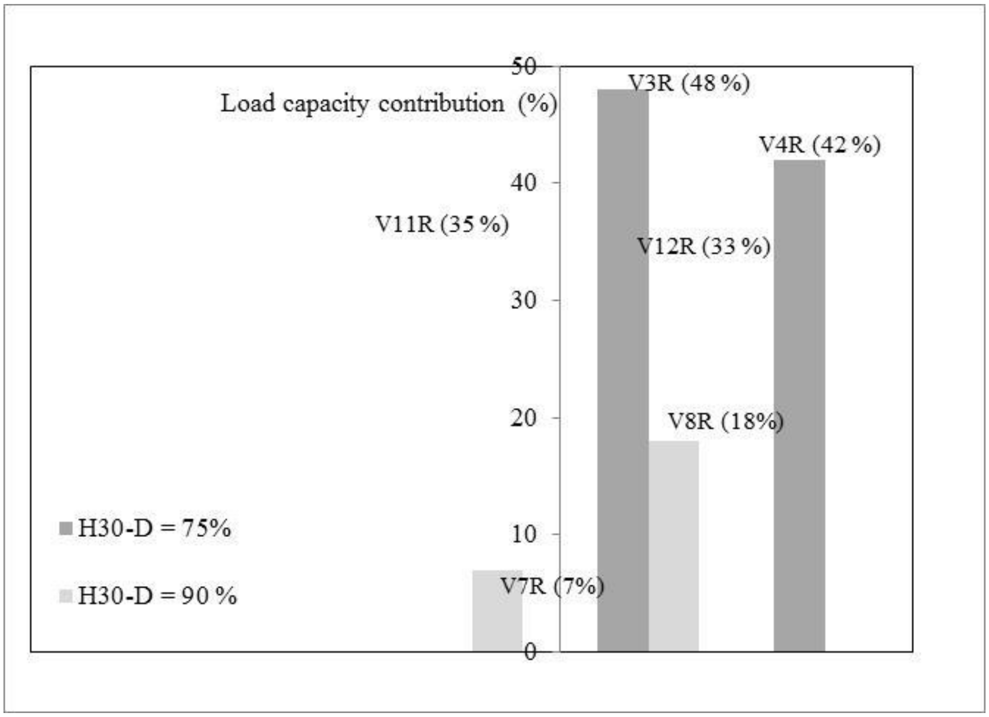


Figure 9. Load versus deflection curves for beams with different damage degree and concrete strength class of 30 MPa.

The load capacity and rigidity contribution of the NSM repaired beams, taking to account damage degree and compared to that of the control beams, are presented in Figure 10. Damage degree was an important influence on bearing capacity of GFRP repaired beams while the influence on rigidity of those specimens was less significative.

a



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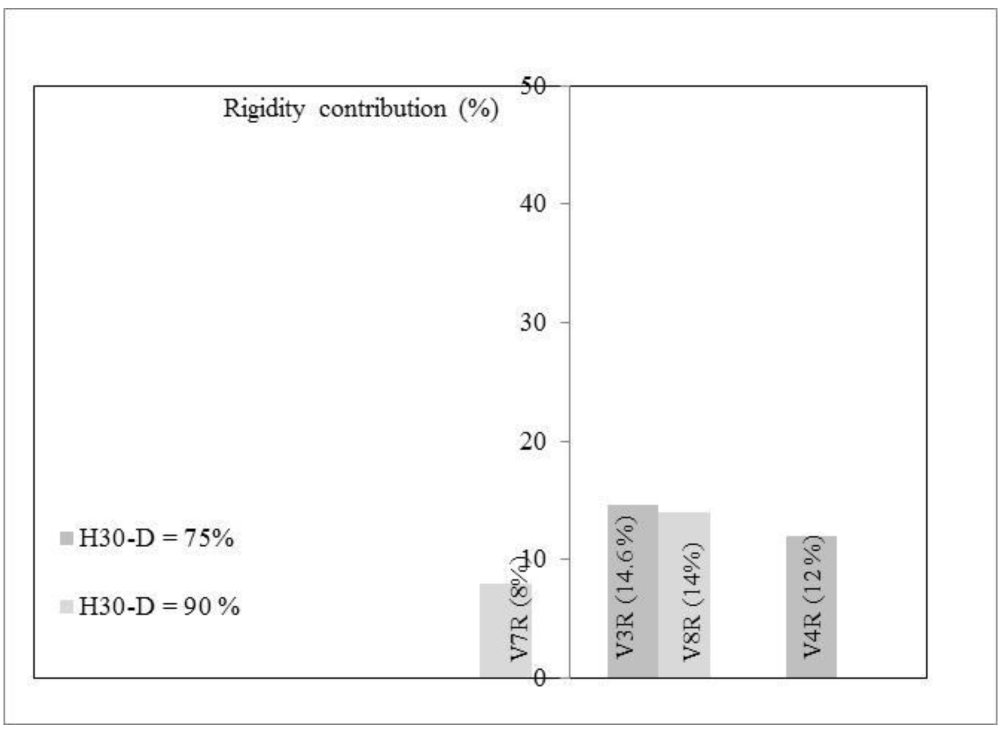

Figure 10. Load capacity contribution and rigidity contribution taking into account damage degree and concrete strength class

It can be conclude that for any damage degree the repairing of RC beams by using GFRP bars was effective and that the performance of the repaired beam is mainly attributed to the higher mechanical characteristics of the GFRP laminates. Furthermore, the 75% damage degree beams behave likely and they gave a higher performance in term of load capacity due to the additional contribution of the reinforced concrete.

Effect of the concrete strength class

In order to observe the effect of the concrete strength class on the load capacity and the rigidity of the GFRP repaired RC beams, two concrete strength types were analyzed: H20 and H30. Figure 11 presents the load versus midspan deflection curves for these two-concrete strength classes a damage degree of 75 %. It can be observed that for the two types of concrete, the mechanical behavior of repaired beams, in terms of load capacity, was higher than those of control beams and concrete strength had no influence on the ultimate load reached by repaired specimens.

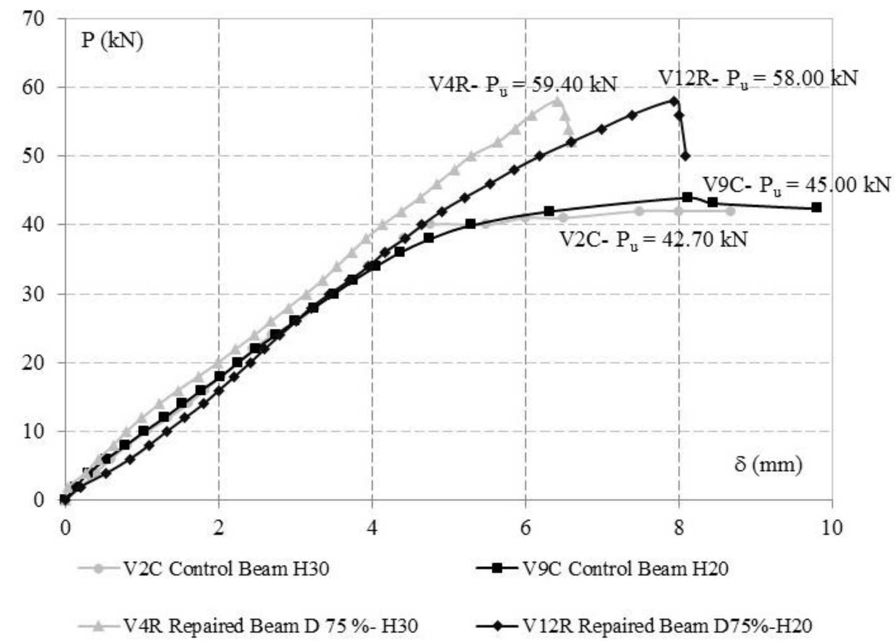

Figure 12. Effect of concrete strength class.

CONCLUSSION

Based on the test results of this study, the following conclusions can be drawn:

1. All repaired beams show an increase in the ultimate capacity compared to the references beams. This increase ranges between 7% and 48 %, according to damage degree. Therefore, this technique is effective to at least restore the mechanical performance of cracked RC beams.

2. The compressive strength of concrete has no significant influence on the load capacity and rigidity of the GFRP bars repaired beams.

3. For damage degree = 90%, it is not possible to increase the stiffness of the beams and for the value of 75%, a slight increase of that parameter can be obtained.

4. In terms of ductility, the repaired beams, show a more fragile behavior than the control beams, which is consistent with the linear elastic behavior until breaking that is characteristic of the PRF. This last property makes the beam behavior brittle.

ACKNOWLEDGMENTS

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