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Shear retrofitting of reinforced concrete beams with steel fiber reinforced concrete

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HIGHLIGHTS

- RC beams strengthened and repaired with SFRC jacketing were tested under shear.
- Fibers help preventing debonding of the jacketing.
- Shear strength of RC beams with stirrups can be improved with SFRC jacketing.
- Damaged RC beams repaired with SFRC jacketing recover/increase initial shear strength.

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ABSTRACT

With the objective of evaluating the performance of steel fiber reinforced concrete (SFRC) as a retrofitting material for reinforced concrete beams the experimental study of reinforced concrete beams repaired and strengthened with a SFRC jacketing and tested under shear is presented in this paper.

The reinforced concrete beams were designed with high amount of longitudinal steel and minimum transverse reinforcement so that they present shear failure. Some of the beams were strengthened with very fluid high strength SFRC jacketing and some of them were first tested under shear to produce some damage and then they were repaired with the same technique. Plain concrete and SFRC with two different fiber dosages, 30 kg/m^3 and 60 kg/m^3, were used for the reinforcement.

The experimental program showed the possibility of performing the retrofitting at work place. The repaired beams showed excellent strength and deformation capacity restitution. The strengthened beams exhibited increase of load bearing capacity. The addition of fibers to the concrete played an important role in the prevention of the jacketing debonding from the beams.

1. Introduction

Concrete is the most used constructive material all over the world [1]. Compared with other constructive materials it has the less cost/strength ratio [2]. Reinforced concrete (RC) structures often require repairing and/or strengthening, due to a change of use, design with old normative, change of design philosophy as the case of capacity design of reinforced concrete, aging or deterioration of materials produced by environment factors, construction mistakes or material damage due to extreme loads [3]. The reduction of governmental funds for new constructions has also led to the new tendency of increasing service life of existent structures [4].

There are many different techniques to repair or strength reinforced concrete structures like steel plates, polymers or concrete. Some retrofitting methods like addition of steel or reinforced concrete present corrosion problems or failure of the retrofitting system [5]. Generally, the most important problem is adherence and durability of the retrofitting layer.

The reinforced concrete structures retrofitting technique using fiber reinforced concrete (FRC) avoids some of the problems that other systems present like the brittle failure of the interface retrofitting layer/concrete. Compared with fiber reinforced polymers, fiber reinforced cement composites present higher resistance against high temperature and ultraviolet radiation, more long term durability and fundamentally more compatibility with the substrate [6]. Moreover, the use of fibers in the retrofitting concrete layer helps controlling shrinkage cracking.

FRC is a material composed of a concrete matrix with addition of fibers that improve its behavior. Many different types of fibers can be used like steel, glass, organic polymers [7] or vegetable fibers [8]. While glass and organic polymer fibers present brittle failure under tension loads without previous plastic strain or

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yielding [7], steel fibers generally can deform plastically. The most important geometric fibers characteristics are their aspect ratio (length/diameter) that define the slenderness and the shape of the fibers axis that can be straight or including some type of anchorage, smooth or wavy, etc. Sometimes a combination of different types of fibers is also used. Short fibers are responsible of bridging thin cracks (0.2–0.3 mm), improving durability, while ductility development requires greater deformations and wider cracks that are sewn by the longer fibers [9].

The main effect of fibers is controlling cracking processes. This effect leads to important increases of material toughness as well as additional benefits related to strength mainly under tension loads. FRC presents more distributed cracking pattern, evidencing thinner cracks. As a result, the durability of the retrofitting layers is increased preventing the entrance of aggressive agents that favor the layers debonding. All these improvements are connected to the load transfer process from the matrix to the fibers. The main mechanism contributing to this process is fibers pull out that is strongly dependent on fibers shape. FRC is normally designed in a way that the fibers are pulled out before breaking [10].

Although any concrete can be reinforced with fibers the tendency nowadays is the use of fibers to improve ductility of high or ultrahigh strength concrete. In this way a material with the required strength and ductility to be used in reduced thicknesses is obtained. The use of self compacting concrete has also became popular since it requires less hand work and it has more dense internal structure, better strength and less permeability. This concrete is easy to be poured in small thicknesses and this property makes it suitable for retrofitting works.

All these properties make FRC an attractive material for retrofitting concrete structures. The effectiveness of the FRC retrofitting is strongly influenced by the adherence between fibers and concrete matrix and between matrix and the concrete substrate [6]. It has been proved both in experimental tests and field experience that the incorporation of fibers helps controlling cracking and delaying debonding initiation and its propagation [11].

2. Repairing/strengthening of reinforced concrete structures with fiber reinforced cement matrix. Brief review

Much research has been done to assess effectiveness of FRC retrofitting technique during the last years. This section presents a brief review of research done related to the use of fiber reinforced composites with cement like matrix for repairing or strengthening purposes. The research done concerning retrofitting with this type of materials has two main motivations. By one side, it is aimed at solving durability or aging problems or prolonging service life of the structure and by the other side, it is aimed at solving strength or structural problems.

The use of fiber reinforced both for the strengthening and repairing of different types concrete and reinforced concrete elements like beams, columns, panels, joints, slabs and pavements has been extensively investigated during the last years. Different types of cement based materials for the matrix like normal strength, high strength concrete or self consolidating concrete, were used and compared. Moreover different types, sizes and shapes of fibers were used.

Independently of the motivation and materials used, improvement of the mechanical behavior of the retrofitted element or structure and cracking process was usually investigated.

The use of slurry infiltrated mat concrete (SIMCOM) for repair and rehabilitation of reinforced concrete beams and columns was studied by Naaman et al. [12]. They concluded that SIMCOM can successfully interact with reinforced concrete elements substantially increasing flexural strength and energy absorption capacity.

The flexure behavior of beams repaired in the bottom concrete cover with self compacting concrete and self compacting FRC was experimentally studied by Mesbah et al. [13]. The beams repaired with FRC presented thinner cracks. The use of self compacting concrete has shown to be a good option to facilitate the pouring. The behavior of the repaired beams seemed to be not influenced by the placing and the length of the repaired zone.

A system for the stiffening of frame structures with precast engineering cement composites (ECC) plates was proposed by Li et al. [14]. They studied the performance of the system numerically. The plates contributed to energy dissipation of the structure through the early cracking of ECC. Although the ECC has strength not very different from the FRC or mortar used, structural strength and structural ductility was all much higher when ECC was used, especially when ECC composition (fiber, matrix and interface) was adequately tailored taking into account the influence of material micromechanics on composite macromechanics and structural behavior. The use of this material in a bridge deck patch repair was presented later [15]. A very high performance fiber-reinforced concrete composite combining macro and microfibers of steel was developed and applied to repair a parking garage by Banthia and Bindiganavile [16].

A repair method consisting of the replacement of damaged materials in aged structures due to the lack of maintenance was proposed by Kim et al. [17]. They used ductile fiber reinforced cementitious composite (DFRCC) as repair material for over reinforced concrete beams under flexure. Neither the strength nor the deformation capacity were significantly changed with this type of repair and the importance of the interface between the old and the new material and the debonding prevention were showed.

The use of ultra-high strength steel fiber-reinforced concrete (UFC) jacketing for the strengthening of internal nodes of reinforced concrete frames was proposed by Wang and Lee [18]. They showed that the use of UFC leaded to an increase of ductility and the formation of plastic hinges in the beams.

A new material called ultra-high performance cement-based fiber composite (CARDIFRC) was presented by Farhat et al. [19]. It is an ultra high performance composite reinforced with 8% in volume of short fibers. They used this material for the reinforcement of under reinforced concrete beams under flexure and over reinforced concrete beams under shear. The reinforcement consisted of thin plates made of CARDIFRC that were glued with epoxy cement to previously damaged beams. In all strengthening setups the strength of the beams was increased with the reinforcement.

Experimental results of two actual scale bridge piles repaired with high performance fiber reinforced concrete (HPFRC) were presented by Massicotte and Boucher-Proulx [20]. The concrete cover of one of the piles was removed and replaced by HPFRC. The piles were tested under quasistatic cyclic load. The strengthened pile presented greater load bearing capacity, increasing with load cycles, and also greater ductility.

An ultra high performance fiber reinforced concrete (UHPFRC) was used by Brühwiler and Denarié [21] to restore reinforced concrete structures that have suffered environment attacks and surface mechanical actions. Taking advantage of the low permeability, high mechanical strength combined with the self compacting property, they proposed the use of thin layers of this material that can be combined with steel bars or in precast elements. They showed some applications already done in bridge decks, highways protection barriers, bridge piles and industrial floors.

Marini et al. [22] numerically studied the behavior of a FRC diaphragm as vertical load transferring element to perimeter structure. They concluded that the use of FRC would allow the use of lower thicknesses than in the case of reinforced concrete and that the thickness could be reduced if the fiber content was increased.

Table 1
Beams tested.

Beam	Stirrups	Treat.	Fiber Content kg/m^3	N° Tests
1	Yes	Str.	–	1
2	Yes	Str.	–	1
3	No	Str.	–	1
4	Yes	Rep.	–	2
5	Yes	Rep.	–	2
6	Yes	Rep.	–	2
7	Yes	Str.	30	1
8	Yes	Str.	30	1
9	No	Str.	30	1
10	Yes	Rep.	30	2
11	Yes	Rep.	30	2
12	Yes	Rep.	30	2
13	Yes	Str.	60	1
14	Yes	Str.	60	1
15	No	Str.	60	1
16	Yes	Rep.	60	2
17	Yes	Rep.	60	2
18	No	Control	N/A	1

Rep.: Repaired; Str.: Strengthened.

The efficiency of high performance fiber-reinforced micro-concrete as a repair material when applied on concrete beam was evaluated by Skazlic et al. [23] and they concluded that the use this material for repairing purposes has both economical and technical advantages.

The behavior of rectangular concrete plates used as industrial pavements repaired with FRC was studied by Boscato and Russo [24]. They achieved excellent adherence between the materials and increase of the first crack load and the collapse load.

A self compacting FRC jacketing was used by Martinola et al. [25] to strength and repair reinforced concrete beams predominantly subjected to flexion. They obtained good adherence between the jacketing and the beams and the flexural strength and stiffness were increased.

A high performance self compacting FRC jacketing was used by Rosignoli, et al. [26] for the strengthening of an actual scale column constructed with low strength concrete. To achieve a good adherence between both materials, the column surface was sandblasted. The test showed a remarkable increase of strength and ductility without much weight increase and high performance concrete of the jacketing provided protection to the concrete core increasing durability.

Two methods, glass-fiber-reinforced polymer (GFRP) sheets and a layer of fiber-reinforced cement, for strengthening two-way reinforced concrete floor slabs subjected to out-of-plane bending were compared by Radik et al. [27]. They concluded that fiber-reinforced cement has great potential as a strengthening method, and future work was recommended to further optimize the proposed strengthening technique.

An overview of the different possible applications of HPFRC for strengthening or repairing existing RC structures was presented by Maringoni et al. [28] and the benefits in terms of bearing capacity, stiffness and durability were discussed.

Reinforced concrete beams were repaired by Iskhakov et al. [5] replacing the compression zone concrete by steel fiber reinforced high strength concrete (SFHSC) and creating two layers beams. The beams presented a classical flexure behavior. The addition of steel fibers increased ultimate deformations and provided supplementary energy dissipation to the structure.

A patch repair method that uses high performance fiber reinforced cement composites to repair reinforced concrete members damaged by chloride attack was presented by Iskhakov et al. [5]. Strength could be recovered if the amount of corrosion was less than 10%. HPFRCC layer remained impermeable due to its very small crack width.

Many authors agree that one of the reasons for failure of concrete repairs has been the lack of knowledge regarding bonding mechanism and bond properties at the interface of repair material and concrete substrate. They centered their research on the bond between reinforcing/repairing layers and old concrete that is the most important issue when considering durability [12]. Failure due to delamination in weak joints or failure due to cracking in strong joints can occur. A repairing test consisting of small plain concrete beams with the addition of a concrete, FRC or engineering cement composites (ECC) section to check the ECC aptitude was developed by Li et al. [12]. A horizontal notch was done to induce delamination. The beams were tested under four points flexure. Cracking took place without delamination and the load abruptly decreased in the case of concrete. The fibers bridged the cracks and the load decreased gradually with the cracking advance in

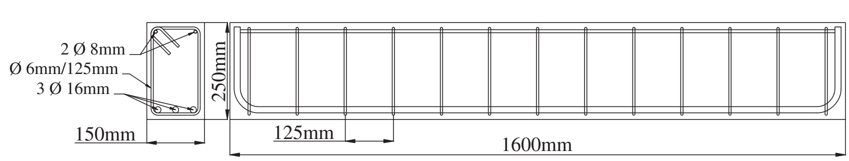

Fig. 1. Reinforced concrete beams.

Table 2
Plain concrete. Mixture proportion and properties.

Materials	Beams	Step I	Step II
Cement CPN50 (kg/m^3) [42]	–	567	567
Cement CPN40 (kg/m^3) [42]	430	–	–
Water (kg/m^3)	172	170	170
Sand (kg/m^3)	911	868	868
Coarse 5–10 mm (kg/m^3)	853	820	820
Superplasticizer (kg/m^3)	–	3.97	3.97
Properties			
Compression strength, mean σ_m; Stand dev s (MPa)	26.3; 2.6	89.7; 5.8	95.3; 3.2
Young mod., mean E; Stand dev s (GPa)	24.0;	38.8; 2.0	41.5; 1.7
Flexure strength, mean F_L; Stand dev; s (kN)	12.21;	17.3; 1.7	16.4; 1.0
Slump flow (mm)	–	76	–
J Ring (mm)	–	71	–

Table 3
FRC properties.

Step	I	II
Fiber content (kg/m^3)	30	60
Compression strength, mean σ_m; Stand dev s (MPa)	86.5;5.95	95.5;6.71
Young mod., mean E; Stand dev s (GPa)	40.7;2.0	–

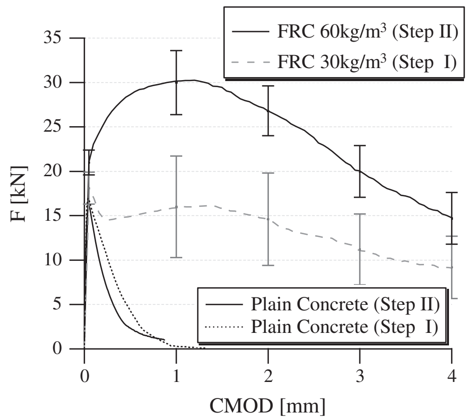

Fig. 2. RILEM test results. Comparison of plain concrete with FRC results.

the case of FRC. Both cracking and delamination between materials took place in the case of ECC, also showing the greatest strength and ductility.

The influence of surface preparation on the kink-crack trapping mechanism of engineered cementitious composite (ECC)/concrete repair system was studied by Kamada and Li [29]. They showed that kink-crack trapping which prevents the typical failure modes of delamination or spalling in repaired systems is best revealed when the substrate concrete surface is smooth prior to repair. This is in contrast to the standard approach according to which the substrate concrete is roughened to improve bonding to the repairing concrete.

The use of ECC to construct more sustainable, durable rigid pavement overlays was proposed by Lepech and Li [30]. The use of high-early-strength engineered cementitious composites (HES-ECC) developed for concrete repair application was presented by Li and Li [31,32]. HES-ECC was suggested as highly suitable for fast and durable concrete repairs with shortened downtime and improved long-term durability.

A critical review on the parameters which have to be taken into account when designing appropriate connection between concrete substrate and new repair material was presented by Luković et al. [33] together with an overview about application of ECC as a promising repairing material.

An experimental investigation to evaluate the relationship between concrete substrate roughness parameters and the bonding performance of UHPFRC used as a repair material was carried out by Tayeh et al. [34]. The significant influence of substrate surface preparation method on bonding strength between UHPFRC and the concrete substrate was shown. When the surface was sand blasted the composite behaved closely as a monolithic structure.

The improvement of tensile ductility and cracking tendency of ECC repairs with the addition of tire rubber in ECC mixtures was shown by Huang et al. [35].

Concluding, many authors have remarked the benefits of FRC as repairing/strengthening materials for concrete and reinforced concrete structures. On the other side FRC presents compatibility with the base material, that is, its physical and mechanical properties, particularly the thermal dilatational coefficient and the Young modulus, are similar to those of the substrate material [15].

There is tendency to use high strength concrete as matrix. In many works FRC has been used in reduced thicknesses and in this cases self compacting concrete as matrix facilitates pouring. Some dry systems that make this technique attractive for repairing works have been proposed. Both good adherence with substrate and less cracking width result in durability increase of the repairing/strengthening layers. Different surface treatments and mixture designs to achieve an optimal bond were proposed.

Some works have pointed out the increase in ductility and strength in FRC repaired and strengthened structures. Nevertheless, in order to improve the intervention techniques, further research is needed to understand the behavior of the resulting structure under different types of load and the transference mechanisms between the reinforcement and the substrate. In fact, there is no much research related to shear repair or strengthening of reinforced concrete elements with FRC.

3. Experimental program

3.1. Introduction

The main objective of the experimental program was the evaluation of the performance of FRC as shear repairing/strengthening system for reinforced concrete beams, specially the contribution of fibers to the behavior of the repaired/ strengthened beams.

Table 4
Steel properties.

Steel	Yield stress, mean; Stand dev σ_y; s (MPa)	Young Mod., mean; Stand dev E; s (GPa)	*First yielding strain* ε_y	*Final step yielding strain* ε_{yf}	*Rupture strain* $\varepsilon_{rupture}$
1	484.6; 2.4	201.1; 6.8	0.00241	0.00873	0.153
2	489.9; 4.4	191.2; 10.0	0.00257	0.02231	0.200

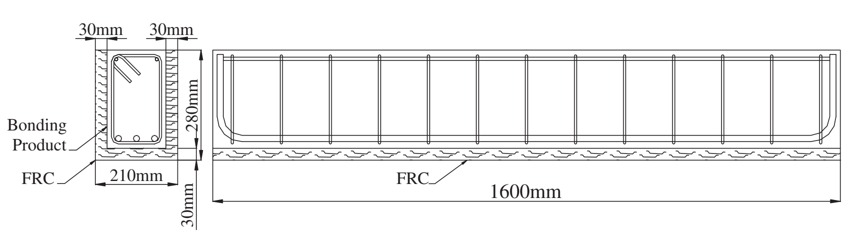

Fig. 3. Repaired/strengthened beam.

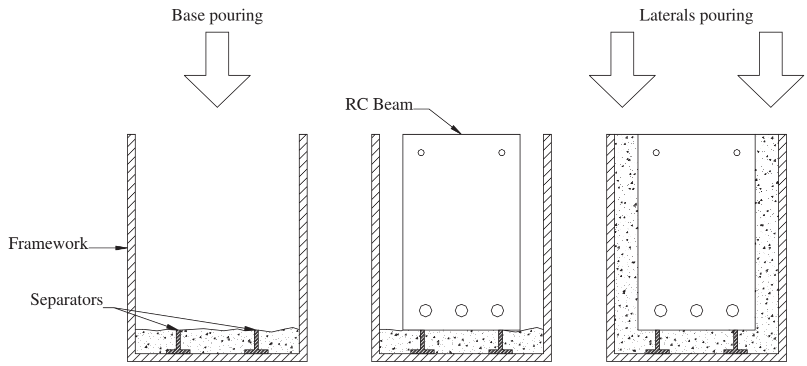

Fig. 4. Strengthening/repairing sequence.

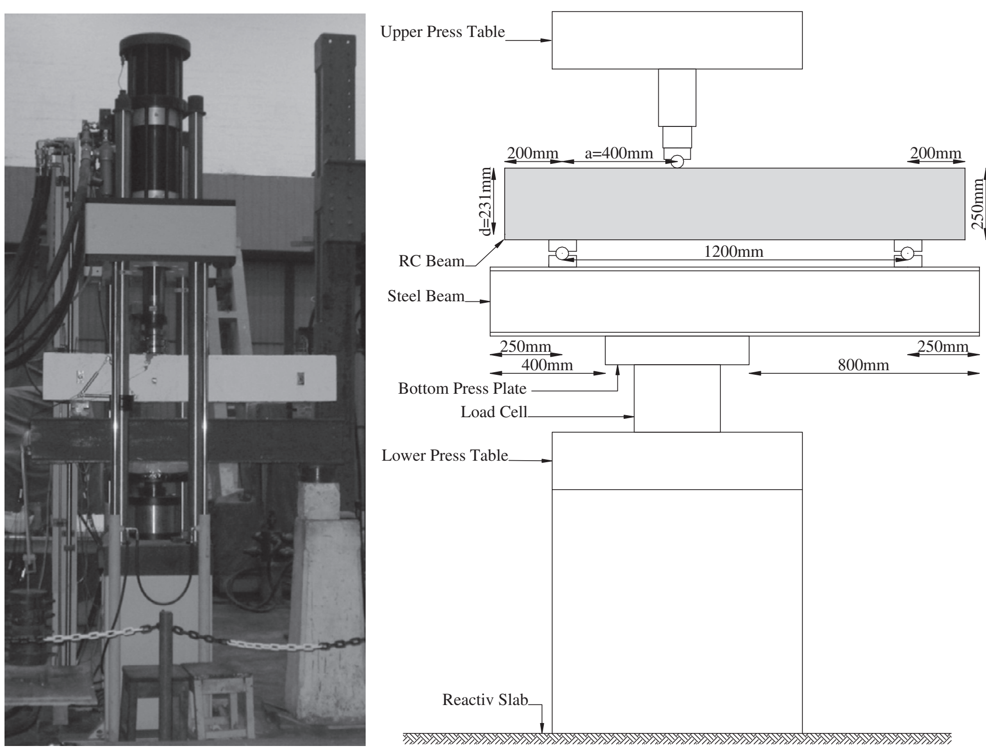

Fig. 5. Mounting device for the tests.

For this purpose, reinforced concrete beams that would present shear failure were designed. In a previous step two beams were casted, tested, repaired with normal strength FRC and retested to prove their failure and the retrofitting technique. Then, the complete experimental program was developed.

The program consisted of a total of 18 reinforced concrete beams, with and without stirrups casted together. Some of the beams with stirrups were damaged, repaired with FRC and retested. One beam without stirrups was tested as control beam. The rest, including beams with and without stirrups, were strengthened with FRC and tested. To study the effect of fibers addition, three types of high performance concrete with self compacting matrix were used as repairing/strengthening material, plain concrete (without fibers), FRC with 30 kg/m^3 of steel fibers and FRC with 60 kg/m^3 of steel fibers. Plain concrete and FRC with 30 kg/m^3 of steel fibers reinforcement were performed simultaneously in Step I while FRC with 60 kg/m^3 of steel fibers reinforcement was performed later (Step II). The main characteristics of the beams tested are presented in Table 1.

3.2. Reinforced concrete beams

The dimensions and reinforcement of the reinforced concrete beams tested are shown in Fig. 1. They were designed so that they present shear failure and not a flexure one.

The mixture proportion and the main properties of the different types of concrete used in experimental program are presented in Table 2. They were obtained from compression tests of cylindrical specimens [36,37] and flexure tests of notched beams (150 × 150 × 600 mm) [38]. The jacketing concrete in Table 2 refers to the concrete base of FRC jacketing whose properties are presented in Table 3. The flexure test results of these concretes are presented in Fig. 2.

Although the same mixtures were used for concrete matrix in Steps I and II, the resulting concrete presents slightly different mechanical properties. The differences could be attributed to ambient temperature. It is well known that high temperature during concrete mixing and curing affects mechanical properties [39]. In fact, Step I concrete was molded in summer while Step II concrete was molded in winter. In correspondence higher compressive strength was obtained for Step II concrete.

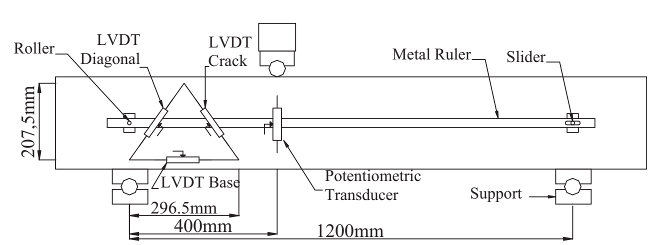

Fig. 6. Instrumentation.

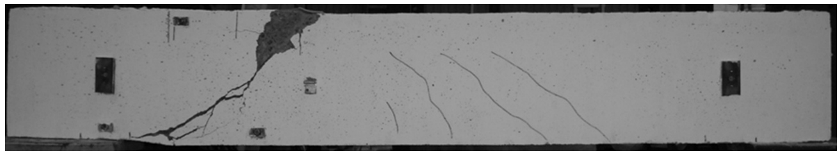

Fig. 7. Beam 5 (reinforced concrete beam with stirrups) left side crack pattern.

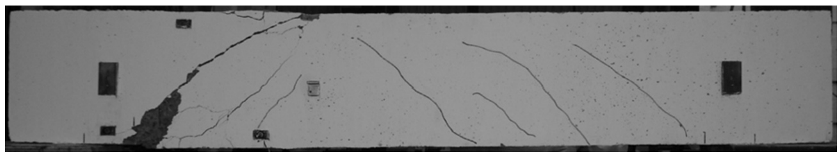

Fig. 8. Beam 11 (reinforced concrete beam with stirrups) left side crack pattern.

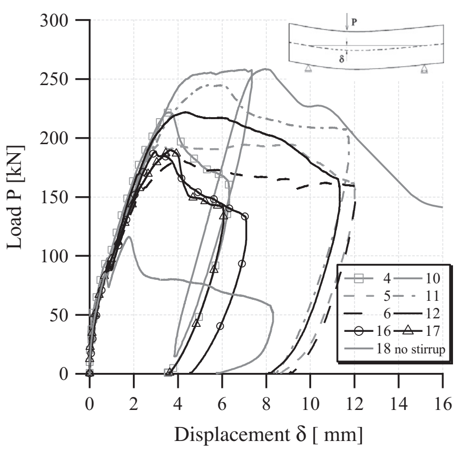

Fig. 9. Reinforced concrete beams. Load–displacement curves.

50 mm length and 1 mm diameter hooked end steel fibers with yield strength of 860 MPa were used for FRC.

FRC mechanical properties are presented in Table 2. It can be observed that the addition of fibers slightly modifies the mean compressive strength and the elasticity modulus of the corresponding concrete matrix. Statistical hypothesis tests were performed and it was shown that in both steps there is no statistical difference between FRC compressive strength and the corresponding concrete matrix compressive strength [40]. Similar conclusions were obtained for the elasticity modulus.

The results of the flexure tests performed on FRC specimens and their comparison with those of plain concrete are presented in Fig. 2. The effect of fiber addition and fiber content on flexure properties of FRC is evident. Flexure strength of beams with 60 kg/m^3 is greater than that corresponding to 30 kg/m^3. Moreover, beams with 60 kg/m^3 present strain hardening up to 1 mm of crack opening. In correspondence with others authors' previous observations, the results present lower dispersion for greater fiber contents [41]. This effect can be attributed to the greater homogeneity in fibers distribution obtained when fibers content is increased from 30 kg/m^3 to 60 kg/m^3.

Two types of reinforcing bars were used. Steel 1 was used for stirrups and hangers while Steel 2 was used for longitudinal reinforcement. The properties of both types of steel are presented in Table 4.

3.3. Repairing/strengthening method

The beams were repaired/strengthened with a jacketing on lateral and bottom sides. See Fig. 3. In all cases, the jacketing thickness was 30 mm.

The beams were previously cleaned, washed with pressurized water to remove loose material and dried with compressed air. A commercial product based on modified epoxy resins was used as bonding between the beams concrete and the jacketing.

Fig. 4 shows the FRC jacketing casting process. First short metallic separators were placed on the bottom end of the framework. Then FRC was poured up to the separator height. The beams were placed in the frameworks on the separators and the rest of the FRC was casted.

It should be observed that, due to the narrow thickness of the jacketing (30 mm) in comparison with fibers length (50 mm), fibers were mainly oriented parallel to jacketing planes.

3.4. Test set up

The beams were tested under asymmetric flexure with an INSTRON 8504 press. A steel beam was located on the bottom press plate to place the beams supports. See Fig. 5.

The displacement at the point of application of the load was recorded using a system similar to that proposed by standard [43]. Potentiometric displacement transducers were positioned on both sides of the beams so that the vertical

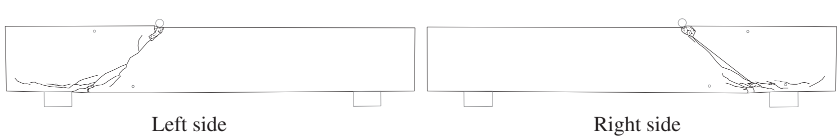

Fig. 10. Beam 18 (reinforced concrete beam without stirrups) crack pattern.

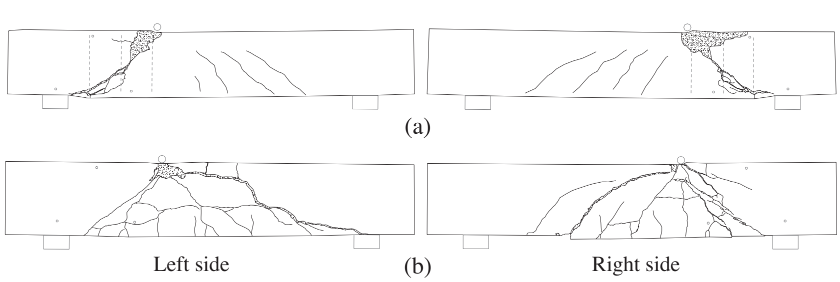

Fig. 11. Crack pattern obtained for Beam 5. (a) First test; (b) Second test, beam repaired with plain concrete.

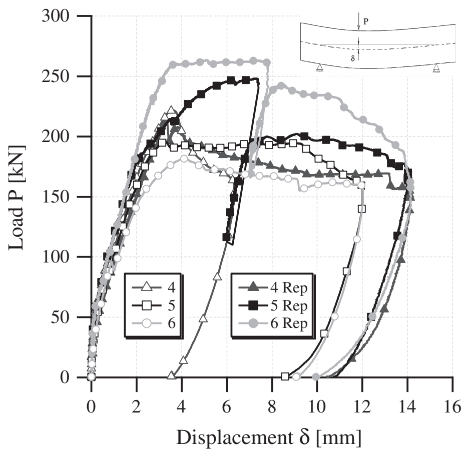

Fig. 12. Load–displacement curves for the beams repaired with plain concrete.

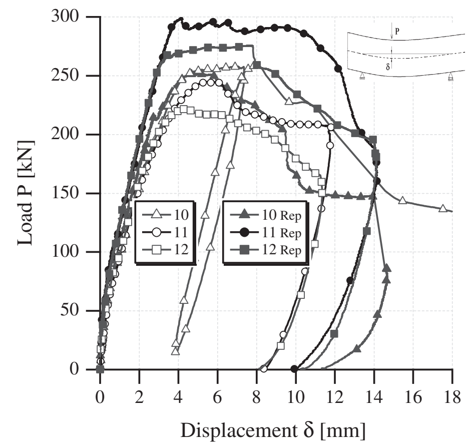

Fig. 14. Load–displacement curves for the beams repaired with FRC with 30 kg/m^3 of fibers.

displacements were measured up to the longitudinal axis of the beam. The transducers were mounted on a metal ruler with one end that can rotate and the other end with a slider. Additionally, systems of lineal variable differential transformers (LVDT) in the form of isosceles triangle on both sides were used to measure the displacement perpendicular to the direction where the majority of shear cracks form (LVDT Crack), the displacement in the direction of the longitudinal reinforcement (LVDT Base) and the displacement in the remaining direction closing the triangle (LVDT Diagonal), see Fig. 6. Similarly, vertical displacements and load were measured by the press internal LVDT and load cell respectively.

The beams were first tested under load control and then, with displacement control going through the peak load and getting part of the descending branch of the load–deflection curve. Finally, they were unloaded in a controlled way. An increasing load at a rate of 0.167 kN/s was first applied up to a load of 30 kN; then, the test was continued with displacement rate of 0.5 mm/min.

Data acquisition was performed automatically by taking two measurements per second.

Most of the unreinforced beams with stirrups were tested up to a displacement of 12 mm, which is greater than the standard limit value for flexion [44]. However, not all of these beams were tested to that shift. Some of them showed a very pronounced softening after the maximum load and the tests were stopped when the load decreased to 70% of the maximum load. The strengthened/repaired beams were tested up to a deflection of 14 mm.

4. Experimental results

4.1. Reinforced concrete beams

Two typical crack patterns corresponding to beams with stirrups are shown in Figs. 7 and 8. The cracks were more marked in the shorter side. In general, all the beams presented concrete spalling in the surrounding of the load transmission point or near the support. Some of the beams (beams 5, 6 and 11) exhibited buckling of the top longitudinal reinforcement.

The load–displacement curves registered for the reinforced concrete beams with stirrups are shown in Fig. 9. The eight beams were similar but they presented different responses. The maximum load varied from 181.7 kN to 257.9 kN. Two typical behaviors were observed. Beams 4, 16 and 17 presented a marked softening after the maximum load and they were unloaded when the load reached 70% of the peak load. The rest of the beams presented more load capacity and the tests could be continued up to greater displacements.

The crack pattern obtained for the reinforced concrete beam without stirrups is shown in Fig. 10. Cracking was localized in the shorter side of the beam. Cracks were markedly diagonal except for the bottom of the beam where cracks were horizontal following the bottom longitudinal reinforcement.

The load–displacement curve obtained for a reinforced concrete beam without stirrups (Beam 18) is included in Fig. 9. The maximum load was 116 kN, lower than for the beams with stirrups and the response was very brittle. The beam showed an abrupt load decay after the peak load and finally maintain the load through a mechanism constituted by two concrete blocks separated by a diagonal crack and linked though the bottom longitudinal reinforcement.

4.2. Repaired beams

The beams whose responses were shown in Section 4.1 were repaired with plain concrete and FRC with different fibers contents and retested.

4.2.1. Plain concrete jacketing

The debonding of the concrete encasement from the beams with the consequent loss of the reinforcement collaboration was frequently observed in these tests. Horizontal cracks separating the laterals from the bottom part of the concrete jacketing was also observed in some cases. A typical crack pattern and its comparison with that of the same beam in the first test are presented in Fig. 11.

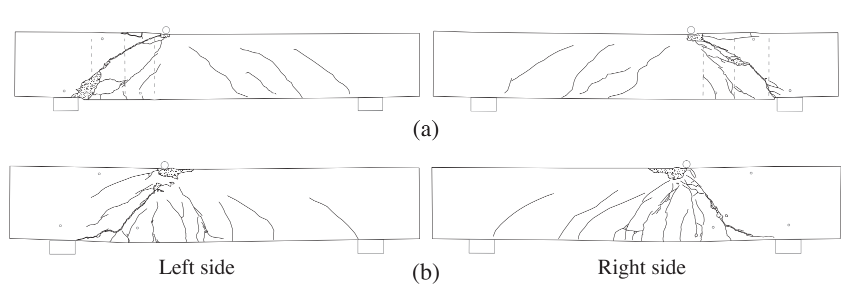

Fig. 13. Crack pattern obtained for Beam 11. (a) First test; (b) Second test, beam repaired with FRC with 30 kg/m^{3}of fibers.

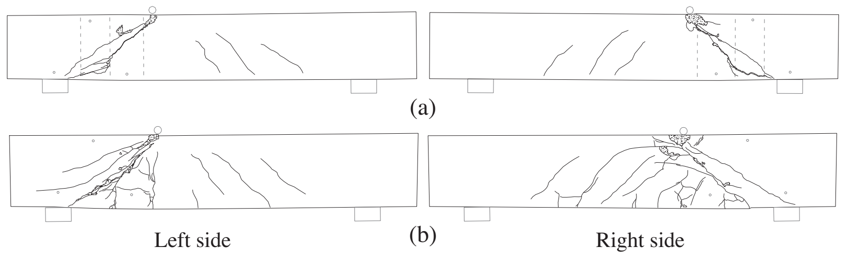

Fig. 15. Crack pattern obtained for Beam 16. (a) First test; (b) Second test, beam repaired with FRC with 60 kg/m^3 of fibers.

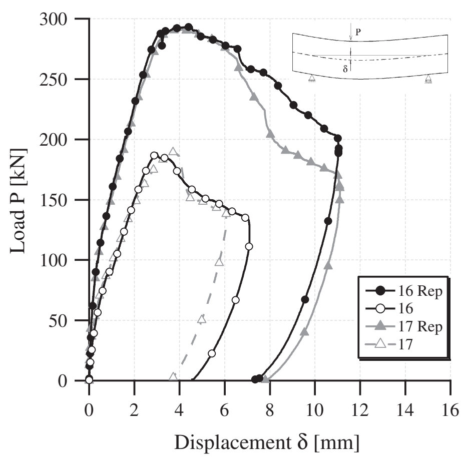

Fig. 16. Load–displacement curves for the beams repaired with FRC with 60 kg/m^3 of fibers.

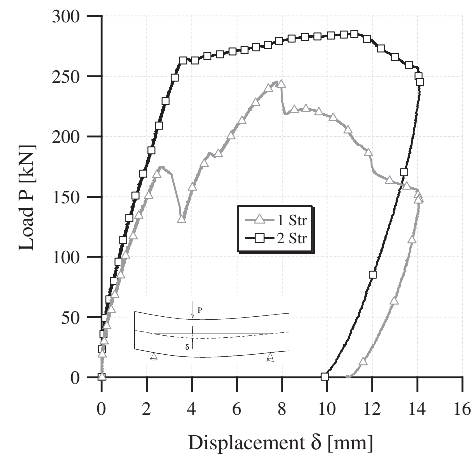

Fig. 18. Load–displacement curves for the beams with stirrups strengthened with plain concrete.

The vertical dashed lines in the first test diagram indicate the stirrups position.

The load–displacement response registered for the beams repaired with plain concrete and their comparison with those corresponding to the same beams in their first tests are presented in Fig. 12. In general the curves corresponding to the repaired beams presented load drops due to the jacketing debonding. In spite of these load drops, the repaired beams, especially Beam 6, presented a good stiffness and load bearing restitution when compared with the first tests.

4.2.2. FRC with 30 kg/m^3 of fibers jacketing

Some of the beams repaired with FRC with 30 kg/m^3 of fibers exhibited a slight debonding of the FRC jacketing from the beams and horizontal cracks separating the laterals from the bottom part of the FRC jacketing were formed in some cases. Nevertheless, cracking of the FRC was predominantly diagonal. A typical crack pattern and its comparison with that of the same beam in the first test are presented in Fig. 13.

The load–displacement response registered for the beams repaired with FRC 30 kg/m^3 and their comparison with those corresponding to the same beams in their first tests are presented in Fig. 14. All the beams presented very good stiffness restitution and initial strength was surpassed in all cases.

4.2.3. FRC with 60 kg/m^3 of fibers jacketing

In this case only one of the beams exhibited a slight debonding of the FRC jacketing from the beam. In general, cracking was predominantly diagonal. A typical crack pattern and the comparison with that corresponding to the first test of the same beam are presented in Fig. 15.

The comparison of the load–displacement curves registered for the beams repaired with FRC with 60 kg/m^3 of fibers and those corresponding to the same beams in their first tests is presented in Fig. 16. Stiffness and load bearing capacity were substantially recovered and increased with this FRC jacketing.

4.3. Strengthened beams

Nine beams were strengthened with different types of jacketing: plain concrete, FRC with 30 kg/m^3 and FRC with 60 kg/m^3 of fibers. Some of the strengthened beams had stirrups and some of them did not.

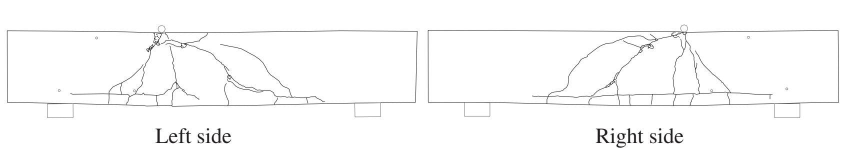

Fig. 17. Crack pattern obtained for Beam 2 (with stirrups) strengthened with plain concrete.

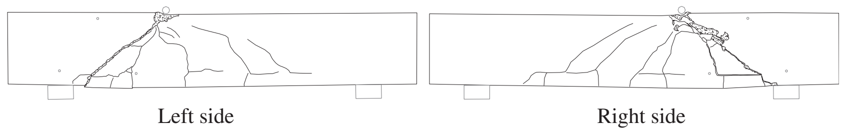

Fig. 19. Crack pattern obtained for Beam 7 (with stirrups) strengthened with FRC with 30 kg/m^3 of fibers.

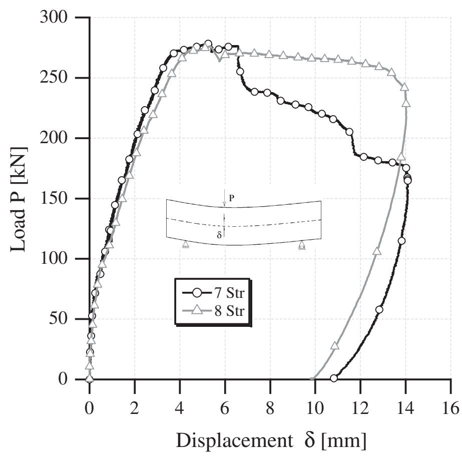

Fig. 20. Load–displacement curves for the beams with stirrups strengthened with FRC with 30 kg/m^3 of fibers.

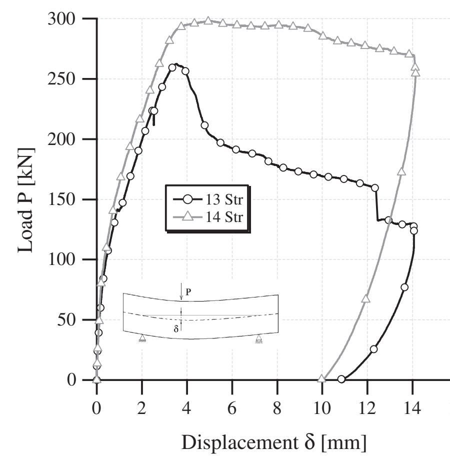

Fig. 22. Load–displacement curves for the beams with stirrups strengthened with FRC with 60 kg/m^3 of fibers.

4.3.1. Beams with stirrups

4.3.1.1. Plain concrete jacketing. Two beams with stirrups were strengthened with plain concrete. One of them (Beam 1) exhibited debonding previous to the test and the other (Beam 2) not. As a consequence, the cracks patterns and behaviors of both beams were markedly different. The crack pattern of Beam 2 is presented in Fig. 17. The load–displacement responses of both beams are presented in Fig. 18 where the different behaviors are evident.

4.3.2. FRC with 30 kg/m^3 of fibers jacketing

Some of the beams strengthened with FRC with 30 kg/m^3 of fibers presented slight debonding of the jacketing and some of them showed horizontal cracks separating the bottom part of the jacketing from the laterals. The main cracks were diagonal. A typical crack pattern obtained for a strengthened beam with stirrups (Beam 7) is shown in Fig. 19. Concrete spalling can be observed in the zone surrounding the applied load.

The load–displacement curves obtained for the beams with stirrups strengthened with FRC with 30 kg/m^3 of fibers are presented in Fig. 20.

4.3.3. FRC with 60 kg/m^3 of fibers jacketing

In this case only one of the beams presented debonding of the jacketing and it was very slight. The main cracks were predominantly diagonal. A typical crack pattern for a beam with stirrups strengthened with FRC with 60 kg/m^3 of fibers is presented in Fig. 21. The load–displacement curves are presented in Fig. 22.

4.3.4. Beams without stirrups

Independently of the type of material used for the strengthening jacketing, failure of strengthened beams without stirrups was characterized for the cracking of the longer side of the beams. Although the first cracks appeared in the shorter side of the beam, suddenly the failure pattern changed and a shear failure in the longer side appeared as dominant. This result indicates that in the case of reinforced concrete beams without stirrups, the strengthening jacketing changed the structural behavior of the resulting system.

A typical crack pattern is presented in Fig. 23. The load–displacement curves obtained for strengthened beams without stirrups are presented in Fig. 24 where a brittle response is observed in all cases.

5. Results analysis

5.1. Reinforced concrete beams

The load–displacement mean response and the standard deviation obtained for the set of reinforced concrete beams with stirrups without reinforcement tested are shown in Fig. 25. The box diagrams are also plotted in Fig. 25.

The dispersion is very low for the first part of the tests but increases for displacements greater than 4 mm. The maximum coefficient of variation is 0.23 and it is comparable with those obtained by other authors for shear tests of reinforced concrete beams [45].

5.2. Repaired beams

The maximum load obtained in the tests of reinforced concrete beams with stirrups without reinforcement (subindex 1: first test)

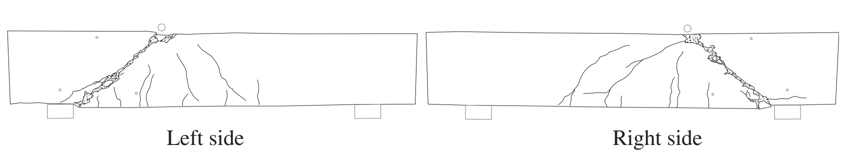

Fig. 21. Crack pattern obtained for Beam 13 (with stirrups) strengthened with FRC with 60 kg/m^3 of fibers.

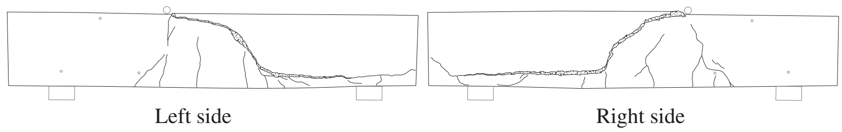

Fig. 23. Crack pattern obtained for Beam 3 (without stirrups) strengthened with plain concrete.

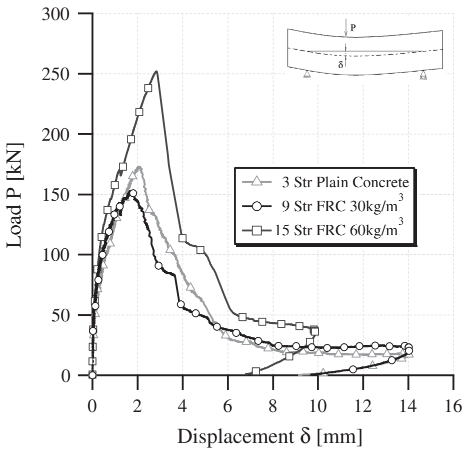

Fig. 24. Load–displacement curves for beams without stirrups strengthened with plain concrete and FRC with different fibers contain.

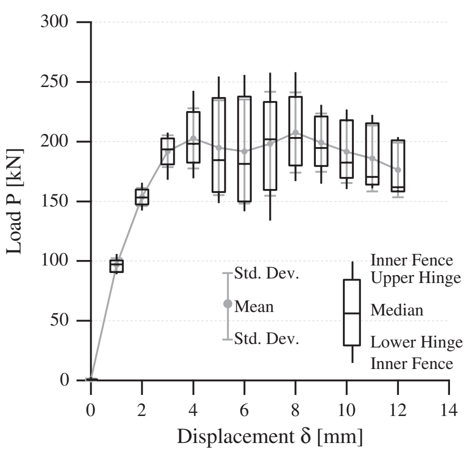

Fig. 25. Descriptive statistic for the reinforced concrete beams with stirrups.

and those reached by the same beams repaired with plain concrete and FRC with different fibers contents (subindex 2: second test) are presented in Table 5. The mean load values for each group, $\overline{F_{1max}}$ and $\overline{F_{2max}}$ are also presented in Table 5. $\overline{\overline{F_{1max}}}$ represents the mean value of $\overline{F_{1max}}$. Most of the repaired beams reached greater loads than in their first test excluding beams 4 and 10. Beam 4 was repaired with plain concrete and it exhibited debonding of the jacketing from the beam. Beam 10 was tested to a greater displacement than the others in the first test. The beams repaired with FRC with 60 kg/m^3 of fibers presented the greater F_{2max}/F_{1max} but it must be noted that these results may be partly due to the fact that they were tested to lower displacement in the first test.

The comparison of the responses of the beams repaired with plain concrete and FRC with different fibers contents is presented in Fig. 26. The mean values with the standard deviation values are shown. Considering average values it can be concluded that the repaired beams reached greater loads. The mean strength increased with the fiber content of the FRC jacketing. The beams repaired with FRC with 60 kg/m^3 of fibers presented the greatest strength differences with respect to their first test. Dispersion was low for all the repaired beams for displacement values lower than 3 mm. The lower dispersion was obtained for the beams repaired with FRC with 60 kg/m^3 of fibers.

The groups of beams without reinforcement and the beams repaired with plain concrete and FRC with different fibers contents were treated as paired observations and matched-pair tests were performed to compare their responses. A 10% significance level was considered in all cases. As result, statistic significant difference between the original and the repaired beams were only found for the case of the FRC reinforcement with 60 kg/m^3 of fibers. This result means that for this case the strength was increased while for lower fibers content and plain concrete it was recovered.

5.3. Strengthened beams with stirrups

The maximum loads reached by the beams with stirrups strengthened with plain concrete and FRC with different fibers contents are presented in Table 6. The mean maximum load values $\overline{F_{max}}$ are included in Table 6. The direct comparison of maximum loads reached shows that the strengthened beams presented greater load bearing capacity than the unstrengthened beams (Table 5) and that the strength slightly increased with the fibers content of the reinforcement.

The comparison of the mean responses obtained for the beams with stirrups strengthened with FRC with that of the unreinforced beams is presented in Fig. 27. Mean and standard deviation values of load for different displacements are plotted. In all cases the

Table 5
Beams without reinforcement and repaired with plain concrete and FRC.

Beam	Without reinforcement			Repaired			
	F_{1max} (kN)	$\overline{F_{1max}}$ (kN)	$\overline{\overline{F_{1max}}}$ (kN)	Jacketing	F_{2max} (kN)	$\overline{F_{2max}}$ (kN)	$\frac{F_{2max}}{F_{1max}}$
4	221.7	199.7	212.8	Plain concrete	215.8	242.5	0.97
5	221.7			Plain concrete	248.1		1.27
6	221.7			Plain concrete	263.5		1.45
10	257.9	241.6		FRC 30 kg/m^3	252.3	275.7	0.98
11	245.0			FRC 30 kg/m^3	299.3		1.22
12	221.9			FRC 30 kg/m^3	275.6		1.24
16	188.5	189.1		FRC 60 kg/m^3	293.5	292.3	1.56
17	189.6			FRC 60 kg/m^3	291.1		1.54

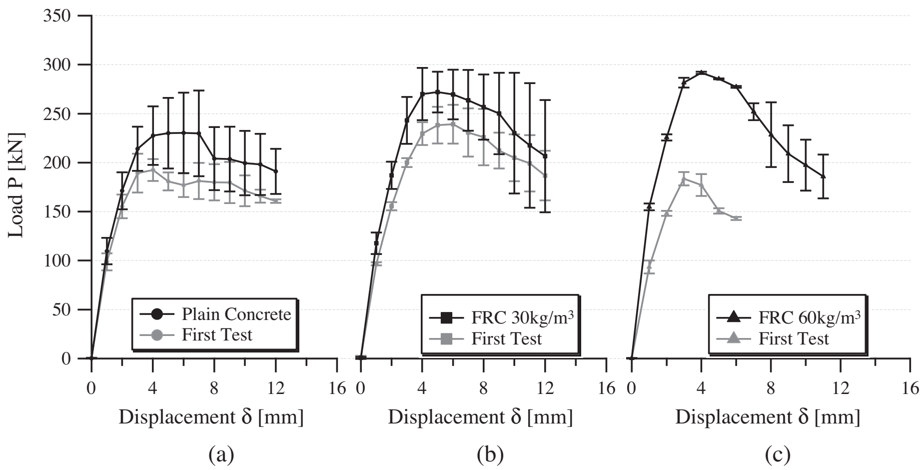

Fig. 26. Comparison of beams without reinforcement and repaired with plain concrete and FRC with different fibers contained. (a) Plain concrete; (b) FRC with 30 kg/m^3 and (c) FRC with 60 kg/m^3 of fibers.

Table 6
Beams with stirrups strengthened with plain concrete and FRC.

Beam	Jacketing	F_{max} (kN)	$\overline{F_{max}}$ (kN)
1	Plain concrete	245.4	265.2
2	Plain concrete	284.9	
7	FRC 30 kg/m^3	278.5	277.3
8	FRC 30 kg/m^3	276.2	
13	FRC 60 kg/m^3	262.4	280.2
14	FRC 60 kg/m^3	298.0	

strengthened beams presented greater load bearing capacity than the unreinforced beams. The beams strengthened with FRC with 30 kg/m^3 of fibers presented the lowest dispersion.

A one-way ANOVA test was done to compare the responses of the strengthened beams with those without strengthening. The statistic conclusion was that there was significant difference between the responses of beams strengthened with plain concrete and FRC with different fibers contents (p-value = 0.046). Taking as control group the unreinforced beams, the Dunnett test showed that there is no difference between the beams strengthened with plain concrete and the unreinforced beams but there are differences between the responses of the strengthened and unreinforced beams when fibers are added to the jacketing (30 kg/m^3 and 60 kg/m^3 of fibers).

5.4. Strengthened beams without stirrups

The maximum load reached by the beams without stirrups strengthened with plain concrete and FRC and their comparison with the maximum load obtained for the unreinforced beam without stirrups tested as control are presented in Table 7. Although the strengthened beams exhibited greater load bearing capacity than the unreinforced beam, the strengthened beams presented a brittle failure characterized by the cracking of the longer side of the beams. This type of failure differs from the failure obtained for the unreinforced beam without stirrups and also from the responses obtained for all the unreinforced beams tested, including the beams with stirrups. This fact indicates that in this case (beams without stirrup) the addition of the FRC jacketing changes the way in which the beams resist the applied load.

The comparison of the responses of the beams without stirrups strengthened with plain concrete and FRC with different fibers contents with the response of the unreinforced beam without stirrups and the mean response of the unreinforced beam with stirrups is shown in Fig. 28. The beam strengthened with FRC with 60 kg/m^3 of fibers reached the greater load. Although the reinforcement increased the strength, a brittle behavior was exhibited by all the strengthened beams. Moreover, if the responses of the strengthened beams without stirrups are compared with the mean

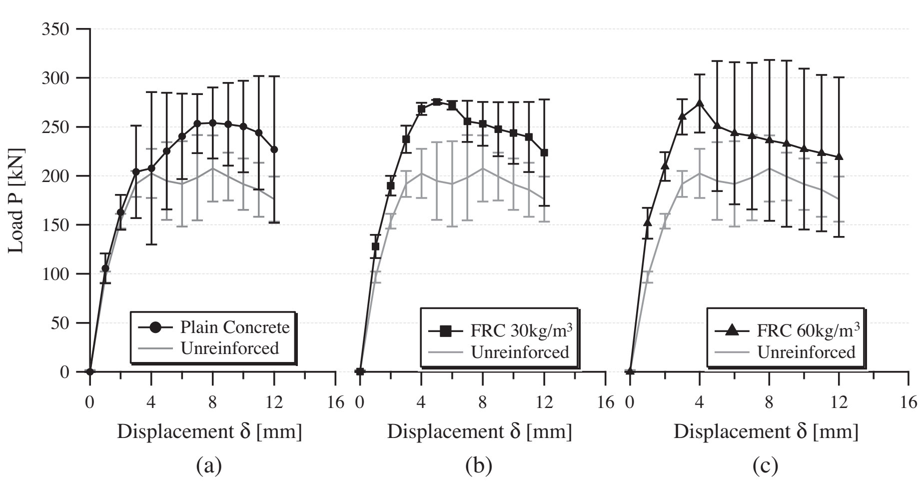

Fig. 27. Comparison of beams with stirrups retrofitted with plain concrete and FRC with different fibers contents. (a) Plain concrete; (b) FRC 30 kg/m^3 and (c) FRC 60 kg/m^3.

Table 7
Beams without stirrups strengthened with plain concrete and FRC.

Beam	Jacketing	F_{max} (kN)	$F_{max}/F_{max.unreinforced}$
18	Unreinforced	116.1	1.00
3	Plain concrete	172.9	1.49
9	FRC 30 kg/m^3	152.7	1.32
15	FRC 60 kg/m^3	252.0	2.17

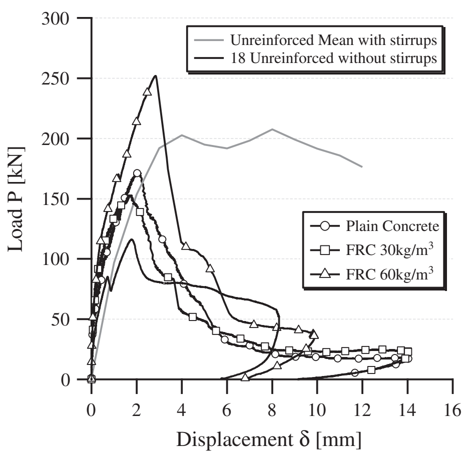

Fig. 28. Comparison of beams without stirrups strengthened with plain concrete and FRC with unreinforced beams with and without stirrups.

response of the unreinforced beam with stirrups it can be observed that the ductility obtained with the addition of stirrups is not obtained with FRC jacketing.

6. Conclusions

The strengthen/repair technique using a self compacting concrete matrix with steel fiber reinforcement is feasible to apply in building site. Fiber reinforced concrete with these characteristics is suitable to be poured in reduced thicknesses jacketing. On the other side, it provides a good surface finish so that the plaster layers can be avoided partly compensating the mass added to the structure.

Fiber reinforced concrete improves structural properties. Moreover, the compatibility between the base and the retrofitting materials and the extended but thinner cracking pattern, prevents the income of aggressive agents increasing the durability of the reinforcement. These conditions are very important taking into account that one of the main goals of repairing works is that structure exhibits integrity and provides a sense of security.

The shear tests of the reinforced concrete beams presented a high dispersion of results. This dispersion can be attributed to the brittleness of shear failure and is similar to that found by other authors for this type of tests.

The beams strengthened or repaired with plain concrete jacketing presented debonding and spalling of the reinforcement. The addition of fibers to the jacketing prevented the debonding, preserving the integrity of the beams. This fact not only results in durability increase but it is also very important from the structural point of view because if the reinforcement debonds its contribution is lost.

Generally, strengthened and repaired beams presented stiffness increase due to the transverse section enlargement. Statistically, the beams with stirrups strengthened with fiber reinforced concrete with 30 kg/m^3 and 60 kg/m^3 of fibers increased their shear strength while for the case of beams strengthened with plain concrete no strength increase was found. In conclusion, the fiber reinforced concrete jacketing looks like an efficient method for shear strengthening of reinforced concrete beams with stirrups.

All the beams without stirrups retrofitted with plain concrete and fiber reinforced concrete exhibited greater stiffness and shear strength than the unreinforced beam. Nevertheless, the failure of these beams was sudden and located in the larger side of the beams. The cracks were so wide that the fibers could not joint both sides of them. It can be concluded that this retrofitting method is not able to replace the stirrups and does not prevent longitudinal reinforcement buckling either.

Almost all the repaired beams with high strength concrete and high strength fiber reinforced concrete increased the strength and the rest recovered their initial load bearing capacity. Statistically, the beams repaired with fiber reinforced concrete presented greater strength than the original beams. When the beams had been excessively damaged in the first tests it was difficult to recover the load bearing capacity. Concluding, fiber reinforced concrete jacketing with fiber contents equal or greater to 30 kg/m^3 seems to be an efficient shear repairing method for reinforced concrete beams with stirrups being the percentage of load bearing recovery dependent on the severity of previous damage.

Acknowledgements

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