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STRUCTURAL ASSESSMENT OF REINFORCED CONCRETE BEAMS RETROFITTED WITH CARBON FIBRES AND STEEL PLANKS SUBJECTED TO BENDING

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Abstract

This paper presents and discusses the structural behaviour of reinforced concrete beams subjected to bending with two retrofit systems, namely: (i) carbon fibre reinforcement and (ii) epoxy-bonded steel sheets. First, the beams were tested under four-point bending before repairing. In order to achieve a monolithic action, epoxy resin was used for adhering the retrofitting plates at the cracked zones and in the compression areas where the original concrete was replaced with construction grout. A total of 12 full-scale beam specimens were tested, 3 reinforced with carbon fibre and 3 reinforced with steel plates. The retrofitted results were compared against those of the 6 beams tested without reinforcement. All beams were tested in the Structural Laboratory of the Faculty of Civil Engineering at the UNSA (San Agustin National University from Arequipa) by applying 2 symmetric concentrated loads at mid-span. The structural retrofitting techniques examined herein were found to perform well and failure was not observed at the same repaired location due to adequate adhesion between grout and concrete. The experimental results of the reinforcement system with steel plates and a steel quantity of 0.3048% demonstrate an adequate structural behaviour, having increased the beam's bending capacity by 60% in comparison with the original design. Significant improvements in ductility were also documented even in those cases where the failure mode involved the detachment of the reinforcing steel plate before yielding. On the other hand, the experimental tests of the carbon fibre reinforcement system experienced a fragile failure typical of this reinforcement given its strain capacity. An overall increase of 30% in the final flexural strength was observed.

Keywords: Steel plate, carbon, fibre, reinforced concrete, epoxy resin, cracks and bending.

1. Introduction

Structural retrofitting and reinforcement is usually carried out in order to to meet the demands imposed by a change in the functional use of existing buildings, or to reinforce and/or repair existing structures affected by material deterioration or structural damage [4]. Two common retrofitting techniques are recommended for reinforced concrete (RC) buildings: (1) enlargement of the cross-sectional area by the addition of new reinforcement, or (2) bonding of steel plates or fiber reinforced polymer (FRP) sheets to improve the cross-sectional strength. However, the use of the first method is hampered by construction difficulties and the extensive demand of labor and requirement. In this context, the bonding of steel plates has been established as a simple and convenient repair alternative. For example, FRP sheeting has been widely employed given its advantage of structural strengthening without obstructing the building's function in service, however, the FRP system presents an elastic linear stress-strain behavior up to failure, without ductility. This characteristic imposes serious limitations to its application in seismic resistant structures, where seismic energy is expected to be dissipated by means of inelastic behavior [5].

An alternative technique is to use steel plates externally bonded to the soffit of the epoxy reinforced concrete (RC) beam. This adaptive approach was first used to strengthen defective concrete structures in South Africa in 1967 [6]. Later Swamy [7] and Hussain [8] investigated the influences of steel plate thickness, concrete strength, and final anchorage on the structural performance of RC beams. Swamy et al. [9,10] also studied the durability and shear behaviours of RC beams with externally bonded steel plates, and found that this method is effective in strengthening damaged structural components. By contrast, other researchers [8,11,12] have indicated that RC beams externally bonded with steel plates are more likely to present crack-induced detachment (bending crack failure) between concrete and steel prior to the development of their full capacity. This is caused by cracking of the concrete during the initial stage of loading [12]. The present paper studies the bending behavior of externally reinforced RC beams with two different methods: (i) steel plates reinforcement and (ii) carbon fibers reinforcement. The experimental results of 6 full-scale retrofitted specimens are presented and discussed. Particular attention is to the evaluation of the difference of these two methods and their corresponding advantages in the reinforcement of RC beams.

2. Experimental program

2.1. Materials Properties

Carbon Fiber is a unidirectional fabric (*SikaWrad-600C).* The material is laminated on site using Sikadur -301 (epoxy adhesive) in order to form the Fiber Reinforced Polymer. The Steel Planks (*ASTM A36)* employed have a thickness (t_{sp}) of 3 mm and a width (w_{sp}) of 100 mm. The corresponding properties are presented in Table 01.The main cracks were repaired with an injection technique using epoxy Sikadur -35 Hi-Mod LV. This epoxy is a high strength adhesive of very low viscosity, insensitive to moisture, with two fully rigid components. Severely damaged areas by compression and traction stresses in the beam, were removed and replaced with grout *(Sikagrout 110)* of compressive strength $f'c = 40\ Mpa$.

For the original beams, concrete with a compressive strength $f'c = 28\ Mpa$ in accordance with the ASTM C39 was used.The longitudinal reinforcement had a yield strength $= 420\ Mpa$, an ultimate tensile strength of $fy' = 550\ Mpa$ and a minimum ultimate strain of $u_{r\,min} = 0.14$.

Table 1: Properties of reinforcement materials

Material	Design Thickness (mm)	Elastic Modulus (MPa)	Tensile strength (MPa)	Ultimate Strain (%)
Plancha de acero ASTM A-36	3.00	250000.00	400.00	20.00
Fibra de carbono-Sika Wrap -600c	1.00	73.20	960.00	1.33

2.2. Test specimens and testing matrix

A total of six large-scale RC beams were manufactured and tested. The beams had a rectangular cross section of 250mm x 400mm with an effective length of 330mm. All the beams were provided with steel reinforcement of 2-5/8" diameter at bottom, 2-1/2" at the top and used 3/8" diameter stirrups along the beam lenght (See. Fig. 1). The beams were tested in a previous study and they attained loads from 9.52 ton to 15.61 ton and permanent plastic deflections in the range of 19.88mm to 80.93mm at midspan (See Table 2 and Fig. 2). Three beams were retrofitted using the externally bonded steel plate method and the other the three using the carbon fiber sheet bonding method. Additionally, two (2) U-shaped carbon fiber anchors were placed at each end of the beam in order to prevent rolling or premature take-off at the ends of the supplied reinforcement by bending.

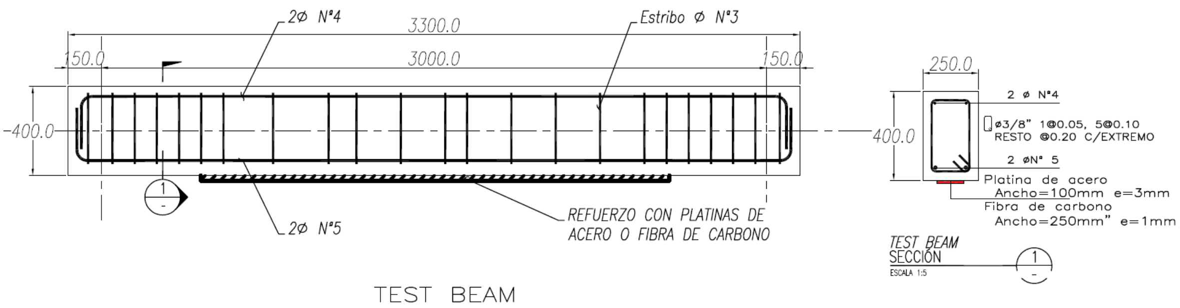

Fig. 1. Design detail of experimental beam

Fig. 2. Previously damaged beams

The test matrices are summarized in Table 2. VRFC stands for carbon fibre reinforced beam, VRPA for steel plate reinforced beam and V1 - V2 correspond to the original beams.

Tabla 2. *Tag of experimental beams*

Reinforced Beams Tag	Originals Beams			Objective test
	Beam tag	P. Ultimate (ton)	ρ deflection (mm)	
VRFC 01	V11	15.61	79.39	Increase flexural strength using carbon fiber
VRFC 02	V23	9.52	29.88	
VRFC 03	V13	12.24	56.83	
VRPA 01	V21	14.82	80.93	Increase flexural strength using steel plate
VRPA 02	V12	12.6	70.23	
VRPA 03	V22	10.06	33.15	

2.3. Repair and reinforcement methodology

2.3.1. Retrofitted beam

A typical retrofitted specimen is shown in Fig. 3. The following steps were undertaken:

a) The original position of the specimen was recovered by means of a hydraulic jack.

b) Cracks were cleaned with compressed air and sealed. Packers were placed with a fast curing epoxy adhesive (Sika Anchorfix -2).

c) Main cracks were injected and filled using Sikadur 35- hi-Mod LV, a high strength, and low viscosity adhesive epoxy. The epoxy is injected using the specific pressure pump through the packers into the surface of the specimens.

d) Th heavily damaged concrete was removed

e) Cleaning of the specimen surface to be filled in using a metal brush and compressed air

and application of bonding agent.

f) Filling in with Sika 110 grout and curing.

(a)

(b)

(c)

Fig. 3 (a) Beam geometry recovery, (b) crack repair procedure, (c) concrete repair procedure.

2.3.2. Beam reinforcement

2.3.2.1. Beam reinforcement with steel plate procedure

a) Sandblasting or steel plate cleaning and texturing (See. Fig. 04 -a).

b) Cleaning and texturing of concrete surface to be adhered to the steel plate (See. Fig. 4 -b).

c) Apply the adhesive on both sides with a thickness of approximately 2mm. Apply uniform and sufficient pressure to leave a final adhesive thickness of 1mm.

d) Keep pressure for 24 hours. Make sure the resulting adhesive thickness is as uniform as possible.

(a)	(b)	(c)

Fig. 4: Reinforcement procedure with steel plate

2.3.2.2. Beam reinforcement with carbon fiber procedure

a) The surface must be clean, free of oil, grease, dust, grout, paint, etc.

b) The surface must be uniform (i.e. with irregularities of less than 15mm per 1mm length). If retrofitting is needed, the mortar or resins used for the repair must be completely cured before the application of the carbon fibre.

c) Round off the corners to avoid stress concentration on the lower sharp edges of the beams.

d) Cut the tissue with scissors or other cutting tools.

e) Apply Sika-301 to the surface with a roller paint brush and carefully attach the carbon fibre tissue directly to

f) The fibre is pressed with a special impregnation roller, only in one direction of the fibres. The overlap will be > 100mm (depending on the type of fabric) or whatever is specified in the project.

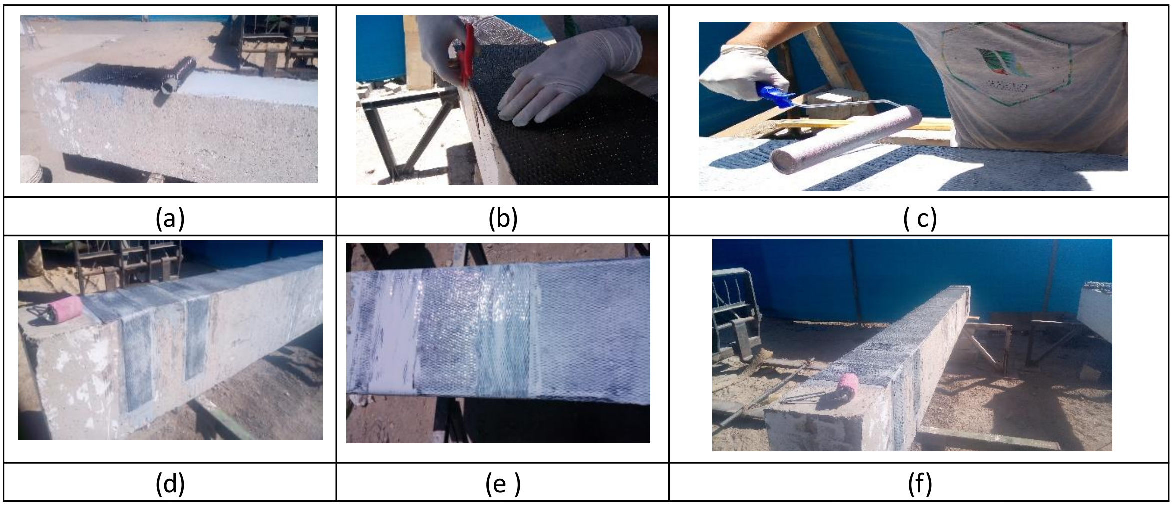

Fig. 5:(a) Placing carbon fiber fabric, (b) careful cutting of fabric, (c) pressure with roller, (d) placement of resin on fabric, (e) pressure with special roller, (f) finished specimen

2.4. Test set-up and instrumentation

The experimental tests were performed under displacement-control conditions. The loading system had a capacity of 50 tonnes. The reinforced RC beams were simply supported in a 3000mm span and subjected to monotonous three points loads using a separate beam (See Fig. 6). The loads were apply using the 50 tonnes capacity beam testing machine with two loading system of 300 mm. An internal loading distance from each other to create a constant moment region. Deflections at the midspan and supports were measured by means of displacement transducers (LVDT). Instrumentation was also placed in the tensile and compression zones at midspan.

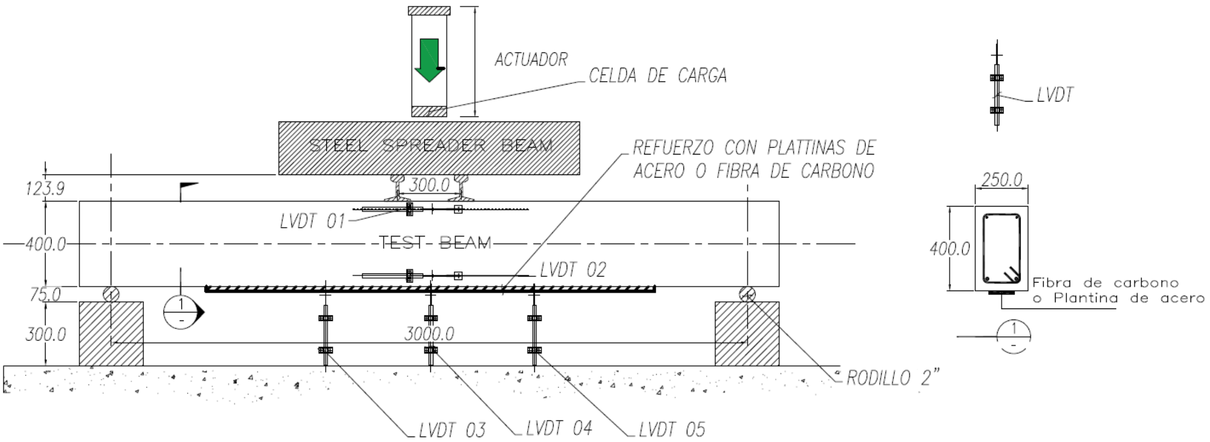

Fig. 6: Configuración e instrumentación del ensayo (todas las medidas en mm)

3. Experimental results

3.1. Force - deformation, failure modes

The total load versus midspan deflection curves of the repaired and original reinforced concrete beams are shown in Fig. 7. It can be appreciated from this figure that the repair and strengthening of the damaged beams increased their initial stiffness and strength. The carbon fibre reinforced beams showed a fragile behaviour and the steel plate reinforced beams showed a ductile response.

The failure mode identified was delamination or reinforcement failure The Control Beams experienced pure bending and related failure with severe vertical cracks propagating symmetrically from the soffit of the beam until crushing occurred between the load points.

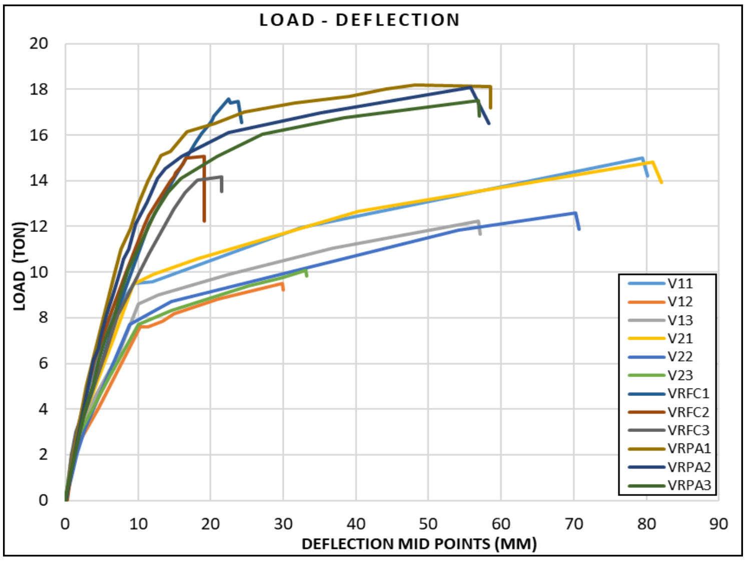

Fig. 7. Grafic Load- Deflection mid points

3.1.1. Carbon fiber reinforced beams.

Carbon fiber reinforced beam (VRFC1). The observed failure was yielding of the internal reinforcement followed by the detachment of the carbon fibber band at one end due to bending stresses (anchorage U break, followed by detachment of the longitudinal band). Flexural cracks were observed in the middle section with crack widths in the order of 0.35 to 0.6 mm. The load capacity was 17.46 ton and the associated deformation was 23.8 mm. Subsequently, the fibers of the system failed due to delamination at one end. The load achieved was 78% more than the beam without external reinforcement.

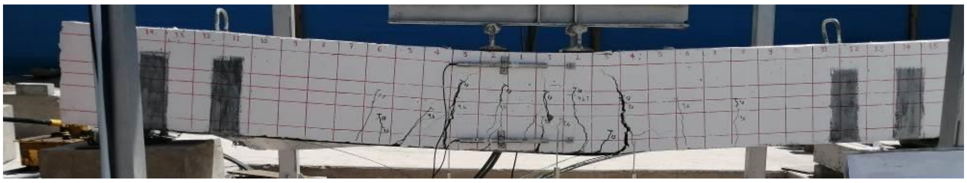

Fig. 8 Beam VRFC1

Beam reinforced with carbon fibre (VRFC2). The failure produced is by yielding of the internal reinforcement followed by fracture of the carbon fibre band due to bending stresses. Flexural cracks developed at midspan with widths in the order of 0.2 to 0.35mm. The load capacity was 15.12 ton and the ultimate midspan deformation was 19.12mm after which the carbon fibres fractured. The load achieved was 54% higher than the beam without external reinforcement.

Fig. 9 BeamVRFC2

Carbon fibre reinforced beam (VRFC3). The failure mode observed in this beams was yielding of the internal reinforcement followed by fracture of the carbon fibre band due to bending stresses. The flexural cracks in the centre had widths of 0.20 to 0.30 mm. The peak load capacity was 14.17 ton at a midspan deformation of 21.48 mm. After which the carbon fibres fracture. The load achieved was 16% higher than the beam without external reinforcement.

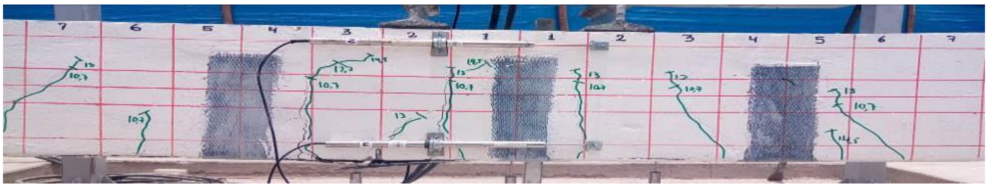

Fig. 10 Beam VRFC3

3.1.2. Beams reinforced with steel plates

Beam reinforced with steel plates (VRPA1). The failure produced was yielding of the internal reinforcement followed by an incipient detachment of the steel plate at one end of the specimen due to bending stresses. Crack associated with bending were observed in the centre of the span, being in the order of 0.35 to 0.5 mm. The load capacity was 18.02 tons and deformation at midspan was 58.6 mm. After that, the steel plate at one end of the beam detached. The load achieved was 22% larger than the associated load of the beam without external reinforcement.

Fig. 11 Beam VRPA1

Beam reinforced with steel plate (VRPA2). The failure produced is by yielding of the internal reinforcement followed by an incipient detachment of the steel plate at one end of the specimen by bending stress. The bending cracks were exhibited at midspan, being in the order of 0.35 to 0.50 mm. The load capacity was 18.08 ton and deformation in the middle section was 55.81mm. The load achieved was 50% higher than the beam without external reinforcement.

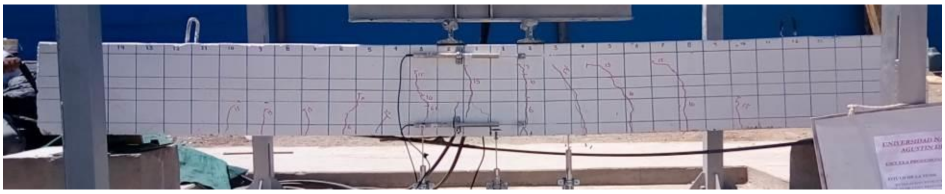

Fig. 12 Beam VRPA2

Beam reinforced with steel plate (VRPA3), the failure produced is by yield of the internal reinforcement followed by an incipient crushing of the concrete in the compression zone of the specimen by bending stress, the steel plate did not detach from the specimen. Bending cracks developed at midspan beam, which was in the order of 0.35 to 0.65 mm. The load capacity was 17.51 ton and deformation in the middle section was 56.68 mm. The load achieved was 84% larger than that of the beam without external reinforcement.

Fig. 13 Beam VRPA3

3.2. Load deflection curves

The recorded experimental results are presented in Fig. 14 in terms of load vs. deflection at midspan for all beams. Curves for beams with and without external reinforcement are represented.

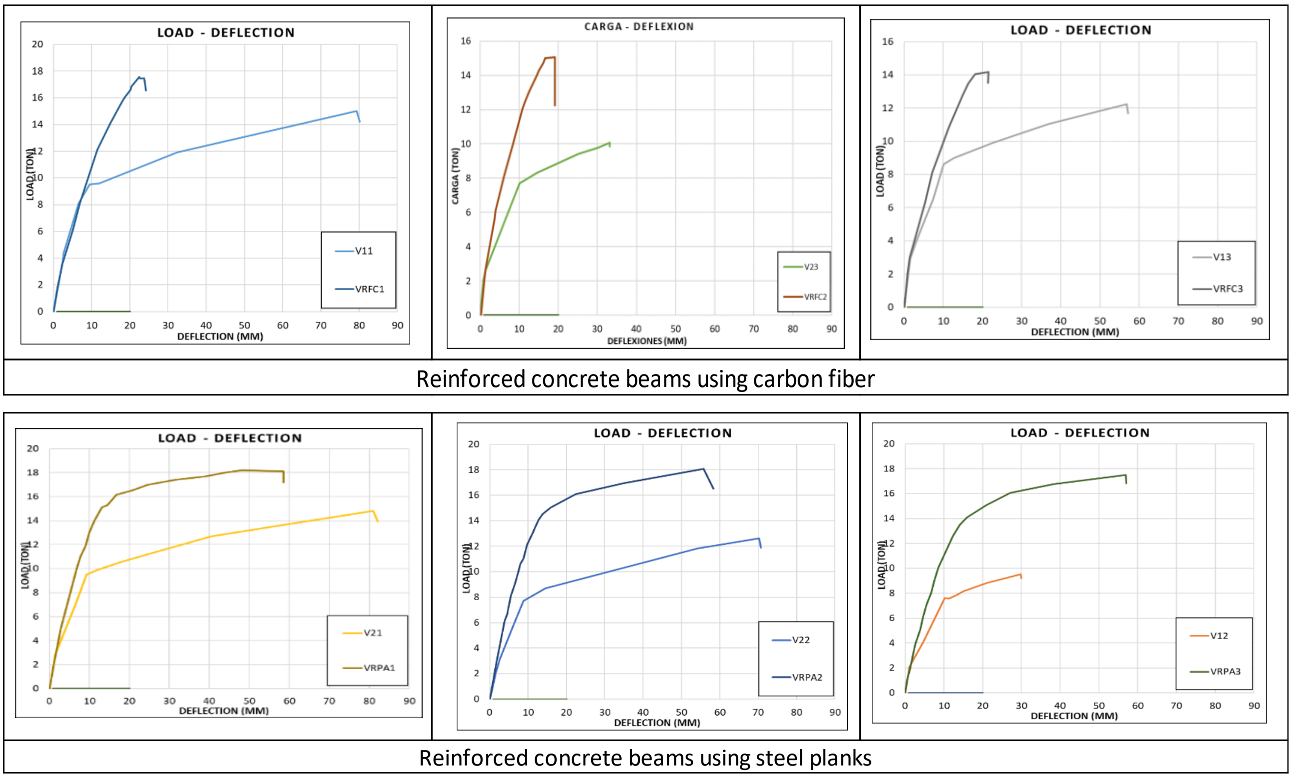

Fig. 14 Load-midspan deflection relationships for beams VRFC, VRPA and beams without reinforcement

3.3. Bending behaviour

The original reinforced concrete beam detail corresponds to a ductile system (i.e. the reinforcement steel quantity is less than the balanced amount, Ps<Pb according to the considerations of ACI 318-08). When being reinforced with carbon fibre to overcome any resistance deficit, the failure mode of the designed configuration changes. To evaluate the behaviour and expected failure mode of the externally reinforced element, some expressions from the ACI-318-11 and ACI.440.2R-08 guide for bending can be employed to characterize the contribution of stress to bending in the RC beams.

- The flexural strength of the carbon fibre system can be defined from:

Internal Steel contribution

$$M_n = A_s \cdot f_s \cdot \left[d - \frac{\beta_1 \cdot c}{2}\right] \quad (1)$$

Carbon fibre contribution

$$M_{nf} = A_f \cdot f_{fe} \cdot \left(d_f - \frac{\beta_1 \cdot c}{2}\right) \quad (2)$$

Calculation of nominal moment, where ϕ=0.9, Ψ=0.85

$$\emptyset M_n = \emptyset_1 \cdot \left(M_{ns} + \Psi_f \cdot M_{nf}\right)$$
(3)

- The resistance in bending of the steel plate system can be defined from:

Internal steel and steel plate contribution, where ϕ=0.9, Ψ=1.0

$$\emptyset M_n = \emptyset \cdot A_s \cdot f_y \cdot \left(d - \frac{a}{2}\right) + \Psi_f \cdot A_f \cdot f_{fe} \cdot \left(d_f - \frac{a}{2}\right) \quad (4)$$

Tabla 03: Summary oh the results ad capacities.

Original beam tag	P'y. Fluence (ton)	My' (Test) ton-m	Reinforced beam tag	Py. fluence (ton)	δy (mm)	My (Test) ton-m	φMn (ACI 440.2R 08) Ton-m (3)	My/φMn %	My/My' %	Description of the failure observed during the test
V11	9.52	6.43	**VRFC 01**	17.46	23.80	11.79	9.17	129%	183%	FD
V23	8.31	5.61	**VRFC 02**	15.12	19.12	10.21	9.17	111%	182%	FR
V13	8.62	5.82	**VRFC 03**	14.17	21.48	9.56	9.17	104%	164%	FR
							φMn PA ton-m (4)			
V21	9.48	6.40	**VRPA 01**	15.02	14.50	10.14	9.47	107%	158%	FDP
V12	7.60	5.13	**VRPA 02**	15.05	15.97	10.16	9.47	107%	198%	FDP
V22	8.70	5.87	**VRPA 03**	15.12	21.20	10.21	9.47	108%	174%	FC

FD: Yield of the inner reinforcement, followed by delamination of the carbon fiber sheet.
FR: Yield of the inner reinforcement, followed by breakage of the carbon fiber band.
FDP: Yield of the inner reinforcement, followed by an incipient detachment of the steel plate.
FC: Yield of inner reinforcement, followed by crushing of concrete.
PA: Steel plate

4. . Conclusions

The following conclusions can be offered:

- The carbon fibre system is associated with an increase in bending strength ranging from 64% to 83% when compared to the original beam resistance. Similarly, a 58% to 98% strength enhancement is associated with the steel plate system compared to the beam without external reinforcement.
- The increase in bending strength with respect to the nominal moment varied from 4% to 29% in the case of fibre reinforcement and between 7% to 8% in the case of the steel plate system showing less dispersion in the latter case.
- The theoretical contribution of bending strength with carbon fibres calculated using the ACI.440.2R-08 expressions leads to an overestimation.
- The application of carbon fibre at the ends (U-shape) is necessary to prevent premature failure.
- Concrete surface treatment is essential to improve the bond to the steel plate.
- The steel plate reinforcement system provides greater ductility compared with carbon fibre reinforcement which has a brittle failure.
- The injection of epoxy, not only restored the beam, but also improved significantly their bending capacity.

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