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Seismic rehabilitation of reinforced concrete beam-column connections by FRP material

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Summary

The seismic behaviour of reinforced concrete beam-column connections with a variety of stirrup reinforcement configuration and volumetric ratio is presented. The specimens were subjected to a cyclic displacement path until their failure and then repaired by Fiber Reinforced Polymer (FRP) sheets and tested again applying the same displacement history. The performance of rehabilitation of columns by FRP sheet is evaluated in terms of load – displacement response of the specimens as well as their ability to absorb energy.

Introduction

The behaviour of beam-column (BC) connections is of great research interest as they are critical in aseismic design. Experimental investigation has been conducted on the behaviour of BC connections including lap spliced steel reinforcements [1], as well as shear strengthening by FRP sheets [2], [3]. Analytical work using finite element method, has revealed some important aspects of the behaviour of reinforced concrete BC joints [4], as well as of FRP sheet strengthened BC joints so as to receive higher load [5]. In this paper an experimental investigation is made on the viability of the use of FRP sheets in effective repair of BC connections that have been subjected to increasing displacement cycles until their severe damage.

Experimental Program

Internal BC connections of reinforced concrete (RC) frame building were constructed in scale 1/3. The joints were subjected to displacement steps causing large inelastic deformation of columns. After initial loading (phase I) the same specimens were repaired and tested again to evaluate the potential of different repairing techniques using external wrapping by FRP sheets (phase II).

Phase I – As built specimens and initial loading

Six specimens of cross shape with 100 x 200 mm cross-section, were constructed, simulating an internal BC connection of RC frame building in scale 1/3. As built specimens had dimensions and steel reinforcement configuration as shown at the top of

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figure 1. The reinforcement description of as built BC connections is presented on the left side of table 1.

The initial specimens were subjected to cycles of increasing displacement steps, imposed by loading axially the beams of the connection according to the testing arrangement in figure 2. Two displacement transducers (DTs) were placed from both sides of the connection to measure its vertical displacement. The displacement steps were successively increased according to figure 2. The corresponding maximum relative storey drift was 5.3%. In this paper, due to limited space, the behaviour of specimens R50B2 and R100B2 is further discussed.

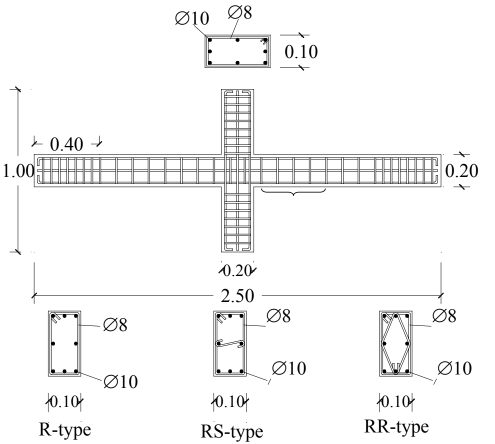
Extensive damage of the tested BC joints was caused from both sides of the joint in the critical zone (left side of fig. 3). In specimen R50B2, severe cracking of concrete core led to complete disintegration near the joint. Specimen R100B2 presented spalling of concrete cover and minor cracking. Yielding of longitudinal reinforcement was evidenced in all specimens, while minor local buckling of main reinforcement took place in specimen R100B2 with 100 mm spacing of stirrups during endmost displacement steps. The localization of damage was not related to the side that included the lap splice of bars. Load – displacement behaviour of as built specimens is discussed in relation to repaired specimens.

Phase II – Rehabilitation procedure

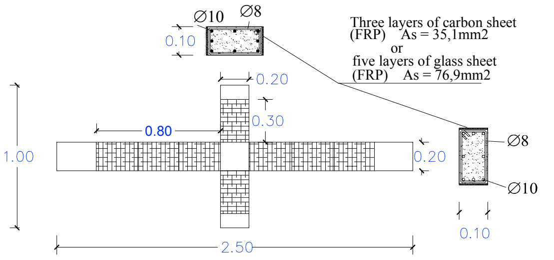
After initial testing the rehabilitation procedure followed, with special treatment of damaged specimens. The disintegrated concrete core was removed. Main reinforcement was straightened eliminating local buckling. In the case of extensive disintegration of concrete core (left side of R50B2), high-strength concrete (HSC) of EMACO S55 [6] type was cast to substitute the concrete core (case 1 in the middle of table 1). In the case of minor or capillary cracks as well as spalling of concrete, an epoxy paste of P103 S&P type was used while the cracks were filled with an injectable resin of J12 S&P type (case 2 in the middle of table 1). The succeeded corner radius of the rectangular cross-section of the specimens was around 10 mm. Repaired specimens are presented in figure 3.

To enhance moment bearing capacity of columns as the reinforcement had yielded, carbon and glass FRP sheet reinforcement providing equivalent moment at failure was applied on both top and bottom surfaces of the members (beam and columns). Three layers of 100 mm width carbon FRP sheet or five layers of 100 mm width glass FRP sheet were found to be equal with the three steel bars of 10 mm diameter. The mechanical characteristics of the repair materials are presented in table 2.

A variety of wrapping configurations of FRP sheets were applied as confinement, mainly to support the anchorage of longitudinal FRP reinforcement and further to investigate the effect of confinement on the behaviour of the columns. For the presented specimens the confinement configuration B2 was used as demonstrated in figure 1.

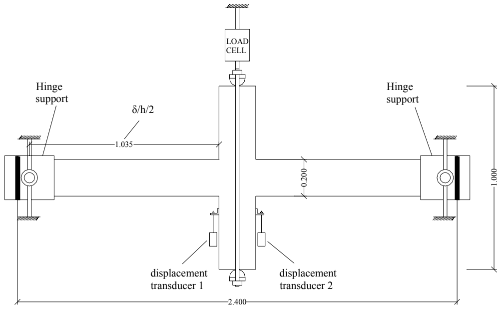


Types of as built specimens



Layout of specimens R100B2c or R50B2g

Figure 1. Layout of steel as well as FRP sheet



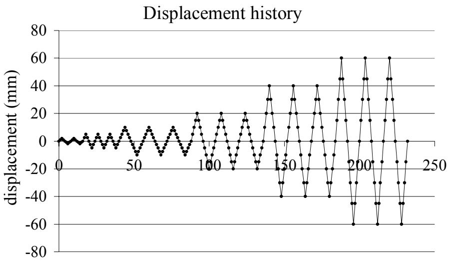


Figure 2. Testing scheme and displacement steps.

Figure 3. Specimens before and after rehabilitation

Table 2. FRP materials.

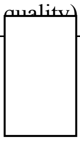
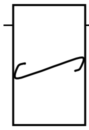
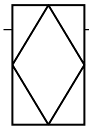
Label	Tensile Modulus, GPa	Elonga-tion, ‰	Type	Thick-ness, mm
c	240	15.5	Unidirectional Carbon S&P C-Sheet 240	0.117
g	65	28	Unidirectional Glass S&P G-SheetE 90/10	0.1384

Data given by the manufacturer [7].

R100B2c R50B2g

Figure 5. Characteristic mode of failure of specimens.

Table 1. Specimen layout as built and rehabilitated.

Labels	As built specimens				Rehabilitation					
					Repair of concrete core		Reinforcement			
	Main steel reinforcement		Steel stirrups (S220 quality)		Left side of the joint	Right side of the joint	Material	Longitudinal		Trans-verse
	Dia-meter (mm)	Type (S500 quality)	Reinfor-cement	Mechanical confinement volumetric ratio, ω_w				Cross-sectional area (mm^2)	Type	Layers
R100B2c	10		Ø8/100	0.0104	1*	1	Carbon FRP sheet	35.1	B	2
R50B2g			Ø8/50	0.0208	2*	1	Glass FRP sheet	76.9	B	2
RS100C3c			Ø8/100	0.0126	2	1	Carbon FRP sheet	35.1	C	3
RS50C3g			Ø8/50	0.0251	2	1	Glass FRP sheet	76.9	C	3
RR100B1C3c			Ø8/100	0.0178	1	2	Carbon FRP sheet	35.1	BC	1+3
RR50B1C3g			Ø8/50	0.0356	1	2	Glass FRP sheet	76.9	BC	1+3

1* concrete core disintegration – use of HSC
2* minor cracking – use of injectable resin

It included wrapping of FRP sheets with 300 mm width, perpendicular to column axis, in two layers with 200 mm overlap. The overlap among adjacent sheet rings was 50 mm. A total length of 800 mm was confined from both sides of the column. Confinement of three layers was provided in the beams of the specimens to avoid anchorage failure. FRP confinement characteristics of the specimens are cited in table 1.

The evaluation of the presented repairing technique effectiveness was conducted by subjecting the rehabilitated specimens to the same displacement history with the initial specimens (fig. 2).

Discussion of results

The behaviour of the selected specimens is evaluated through their load-displacement response (fig.4).

Table 3. Test results for repaired specimens

Labels	Load, KN				Displa-cement, mm	Stiffness, KN/mm			Energy absorption, KNmm			
	5th cycle	11th cycle	14th cycle	At maxi-mum, P_{max}	At P_{max}, δ_{max}	5th cycle	11th cycle	14th cycle	5th cycle	11th cycle	14th cycle	17th cycle
R100B2c	24.84	63.88	62.87	70.98	41.24	4.67	3.41	1.77	100	2025	11522	20981
	(1.26)	(1.26)	(1.22)	(1.26)	(40.69)	(1.44)	(1.40)	(1.17)	(0.77)	(1.38)	(1.27)	(1.52)
R50B2g	20.03	57.29	36	60.84	19.40	4.05	2.82	1.08	100	1741	7506	12521
	(0.60)	(1.06)	(0.68)	(1.06)	(41.52)	(1.09)	(1.07)	(0.61)	(0.51)	(0.22)	(0.34)	(0.48)

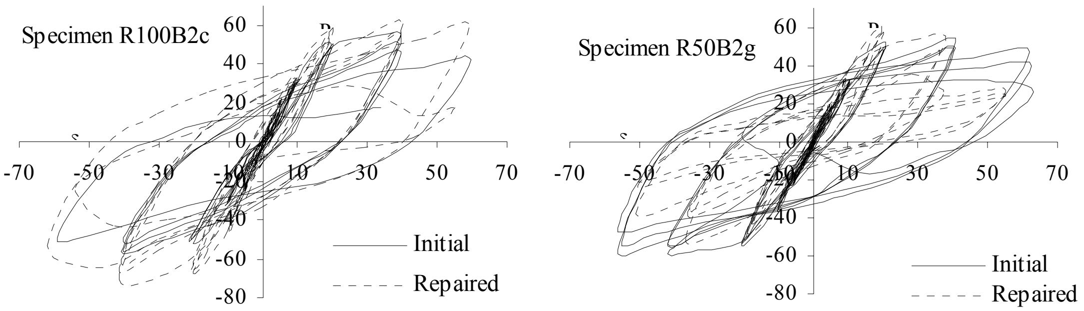


Figure 4. Load – displacement behaviour of specimens.

In specimen R100B2c cracks were formed from both sides of the joint in the inter-surface between epoxy paste and concrete core (fig. 5). The carbon FRP sheet was cut at 60 mm cycle. As presented in figure 4, the hysteresis loops of the repaired specimen were envelope-like and demonstrated an overall enhanced behaviour. The undertaken load, the stiffness as well as the absorbed energy were relatively increased per cycle of displacement (table 3). Load per cycle presented a steady increase from 22% to 26% of the initial specimens' capacity (maximum load of 70.98 KN). Stiffness per cycle respectively presented an increase from 44% (5th cycle) to 17% (14th cycle). Total absorbed energy of repaired specimen was increased by 52%.

In specimen R50B2g cracks were formed only in the side of the joint where HSC was applied, and in the inter-surface between HSC and concrete core. The other side rehabilitated with epoxy paste was intact (fig. 5). In cycles higher than 40 mm the main glass FRP reinforcement failed and pinching of the hysteresis loops occurred. Then the hysteretic behaviour of repaired specimens became inferior (fig.4). The undertaken load of repaired specimen was increased by 6% (maximum load of 60.84 KN). The stiffness was increased for the first cycles of displacement. Total absorbed energy of repaired specimen was less than 48% of the initial specimen (table 3).

Concluding remarks

BC joints that have failed by severe disintegration of concrete core in the critical zone of columns and yielding of main steel reinforcement, can be effectively repaired by application of FRP sheets as longitudinal and confining reinforcement. Failure of longitudinal carbon or glass FRP reinforcement occurred in high cycles of 60 mm displacement. In similar displacement levels the main steel reinforcement was considered to have failed during initial loading. The R100B2c specimen that presented minor cracking at initial loading and after repair revealed damage distribution in both sides of the joint, had a remarkably steady and enhanced behaviour. Despite the relatively low confinement provided by the steel stirrups, the load capacity, stiffness and energy absorption were enhanced. In specimen R50B2g with severely damaged concrete core it seems that this type of repair restores the bearing capacity of the column but lower ductility levels are achieved. The stiffer carbon FRP material in wrapping repairing technique, restores load, stiffness and energy absorption of initial specimen more effectively than glass FRP material.

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