KSCE Journal of Civil Engineering (2014) 18(7):2162-2169

DOI 10.1007/s12205-014-1353-x

Structural Engineering
pISSN 1226-7988, eISSN 1976-3808
www.springer.com/12205

An Experimental Investigation on Flexural Behavior of RC Beams Strengthened with Different Techniques

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Received June 16, 2013/Revised October 12, 2013/Accepted December 8, 2013/Published Online July 7, 2014

Abstract

In in many earthquake-prone regions and countries including Mediterranean area, India, the Middle East, Southeast Asia, existing buildings with its structural elements such as Reinforced Concrete (RC) beams and columns, which show little ductility, have consistently exhibited poor performance during past earthquakes and consequently unavoidable earthquake damages on these structures led to a significant loss of world cultural heritage. Therefore, appropriate strengthening techniques have to be implemented in order to improve load carrying capacities and overall ductility. This paper summarizes experimental investigations of damaged and undamaged RC beams. In this context, twenty-seven beams were tested under combined bending and shear. Eighteen RC beams were damaged and then strengthened with four different methods while nine were kept undamaged. The behavior of damaged and undamaged RC beams is discussed with emphasis on the load deflection and strain characteristics. The results indicate that the specimens strengthened with full jacketing had slightly higher load carrying capacity than the reference beams strengthened with other techniques. The experimental results can also be used for understanding the most convenient strengthened technique for damaged beams.

Keywords: *Reinforced Concrete (RC) beams, strengthening, jacketing, Carbon Fiber Reinforced Polymer (CFRP)*

1. Introduction

Worldwide ageing infrastructure which is susceptible to seismic events has compelled the interest of many researchers to find alternative techniques to resist seismic loads. In seismic areas, many existing RC buildings have strengthened to enhance earthquake resistance. There have been various strengthening techniques in the literature. Reinforced jacketing, carbon fiber and steel plates are mostly used as strengthening techniques.

Collins *et al.* (1990) tried the repair techniques by using gum injection for the reinforcement of the concrete beams (Collins and Roper, 1990). The gum injected concrete beams were detected to be supporting the fracture after the first damage more efficiently. Hanna and Jones (1997) investigated the use of lightweight pultruded fiberglass sheets as external reinforcement/repairs for new or existing concrete beams. Reinforcement configuration, type of adhesive and environmental effects was also discussed. Arduni and Nanni (1997), mentioned that Fiber Reinforced Polimer (FRP) has showed better performance when applied to the beam's bending section with angles of 45-135°C. They initiated that design capacity has increased when a damaged beam is reinforced by using FRP. Norris *et al.* (1997), investigated concrete beams reinforced with FRP. They established that durability and rigidity of the structure has increased when CFRPs adhesed perpendicular to the fractures. Diab (1998) investigated the reinforcement of the beams empirically by using sprayed concrete and examined nine beams in three different series to evaluate the efficiency value of concrete beams with concrete layers. The results obtained from the mathematical modeling, empirical observation, and theoretical approaches were compared. Triantafillou (1998) investigated concrete beams strengthened with two different types of reinforcement. These reinforcements (plates) implemented on the sliding sections of the beams. Textiles were adhered both on all of the shear section and scattered on the section. Plates were adhered to the bending section of the U and L shaped beams in order to prevent the tilt of the composite edges. The benefits of the composites adhered perpendicular to the fractures and difference between the scattered and whole wrapping methods were investigated. Khalifa and Nanni (2000), investigated experimentally the shear capacity of the beams wrapped with CFRP. The experiments were conducted on the six t-beams. Results were discussed. Altýn and Anýl

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(2001), investigated the shear capacity of the beam strengthened with steel plates. Three different types of steel plates were used. Five t-shaped beams produced in the laboratory were tested. The efficiency of the reinforcement technique was estimated. Yang, *et al*. (2001), examined the effect of angle rounding in FRP reinforcements on the ultimate load capacity for the circular columns. It was pointed out that the angle rounding has a significant effect. Khalifa and Nanni (2002), conducted experimental tests for the 17 beam samples with three different dimensions, and CFRP with two different thicknesses. The aim of the study was to investigate the effect of FRP on the shear section. Wu *et al*. (2005), studied the behavior of FRP. They mentioned that reinforcement with FRP had many advantages and easy to apply. El-Ghandour (2010) investigated CFRP flexure and shear strengthening efficiencies of RC beams strengthened with CFRP longitudinal sheets or U-wraps. For this purpose, half-scale beams, with different flexure and shear internal steel ratios, were tested in three-point bending. Martinola *et al*. (2010) studied strengthening of RC beams with jacket made of fiber reinforced concrete with tensile hardening behavior. full-scale tests on 4.55 m long beams with a 40 mm jacket which was directly applied to the beam surface were achieved. Cho and Kwon (2011) investigated the nonlinear load path-dependent confinement model of FRP-confined concrete. In their study, the strength enhancement of concrete was determined by the failure surface of concrete in a tri-axial stress state, and its corresponding peak strain was computed by the strain-enhancement factor. Al-Rousan and Issa (2011) achieved an experimental and analytical study on nine RC beams externally strengthened with different number and configuration of CFRP sheets to investigate the fatigue performance. Jankowiak (2012) conducted experimental and FEA study of simple supported RC beams strengthened by means of the CFRP strips in order to evaluate the effectiveness of strengthening at different preloading states. As a result, preloading was an important issue of load carrying capacity of CFRP strengthened beams and the initial state of reinforced beams were not be overlooked in the analysis of the effectiveness of this kind of strengthening. Colalillo and Sheikh (2012) studied shear strength of reinforced concrete beams under reversed cyclic loading. In their study, large-scale (400 × 650 × 3600 mm) shear-critical RC beams were tested under reversed cyclic loading to simulate a seismic event. The beams contained less than design code recommended transverse steel reinforcement for shear and were retrofitted with various FRP wrap configurations. Sena-Cruz *et al*. (2012) investigated strengthening techniques for RC beams. Fot this purpose, four-point bending tests with RC beams were carried out under monotonic and cyclic loading to explore the efficiency of different techniques.

In this study, four strengthening techniques are examined experimentally Önal (2002), Önal and Tokgöz (2005), Önal *et al*. (2005), Önal and Koçak (2006), Önal (2006), Koçak *et al*. (2007); full and half jacketing, strengthening with steel plates and with CFRP composites.

2. Experimental Work: Test Beams and Instrumentation

Experimental programs were conducted at Gazi University in order to investigate load carrying capacities and deflections of undamaged and damaged RC beams. Twenty-one specimens were produced in five sets for the experimental work (Fig. 1). The eighteen specimens for the first four sets were produced as single-supported beams having rectangular cross-section and the dimensions of $100 \times 160 \times 2200$ mm (Fig. 2). Compressive strength was 16 MPa for concrete and yield strength was 420 MPa for steel reinforcements. Besides, the longitudinal reinforcement was $2\phi12$ (total area = 226 mm^2), erection reinforcement was $2\phi8$ (total area = 100 mm^2) and lateral reinforcement was $\phi8$ (bar area = 50 mm^2) with a space of 150 mm between. For the comparison purposes, six reference RC beams dimensions of $100 \times 160 \times 2200$ mm and $160 \times 260 \times 2200$ mm having the same reinforcement detail were also produced.

2.1 Damaging Case

The loading device was used as the experiment setup. Two support apparatus were present on top of a car that moves upon rails. The space between these two supports was 2000 mm and one of the supports was stable (Fig. 1). All the specimens were damaged on the experiment set to end up with a medium damage. The load was applied until failure. The process was continued until ultimate deflection of 8 mm was obtained.

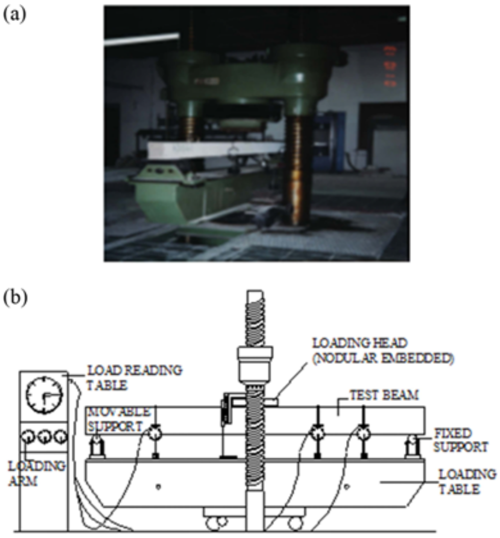

Fig. 1. Experimental Set-Up

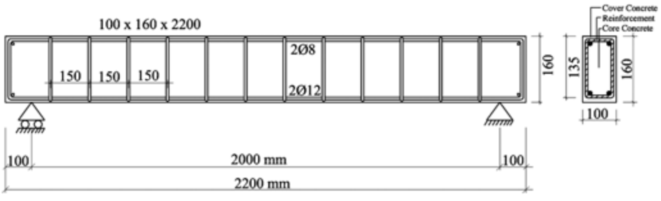

Fig. 2. Cross-section Detail of Eighteen Specimens for the First Set

2.2 Repairing Case I

Conventional strengthening techniques such as half RC jacketing, full RC jacketing and strengthening with steel plates were used in order to investigate the behavior of the fifteen test beams under pure bending.

2.2.1 RC Jacketing Wrapped with U-Shaped Stirrup: Half Jacketing

Beam surface was first roughened by notches so that the concrete width cross-section area could be deepened with the newly added concrete area and tensile reinforcements could be placed to this additional area and no mechanical problem would arise between the old and new concrete. For six RC beams (Tables 1-2: KM41, KM42, KM43, KM51, KM52, KM53), additional longitudinal reinforcement was $2\phi12$ for the first and second set of the damaged beams while $\phi8$/150 mm U-shaped stirrups were placed between old stirrups (Fig. 3). Besides, newly added concrete having 30 MPa compressive strength was used.

2.2.2 RC Jacketing Wrapped with a Stirrup: Full Jacketing

Surface of the fourth and fifth set of RC beams (Tables 1-2: KM11, KM12, KM13, KM21, KM22, KM23) were roughened by notches. $2\phi12$ longitudinal reinforcement having yield strength

Table 1. Test Beams and Strengthening Techniques

No	Serial no	Test beam	Cross section (mm)	Strengthening technique
1	1	KM 11	Before strengthening: 100×160 After strengthening: 160×260	Full jacketing
2		KM 12		
3		KM 13		
4		KM 21		
5		KM 22		
6		KM 23		
7	2	KM 31	100×160	Steel plates
8		KM 32		
9		KM 33		
10	3	KM 41	Before strengthening: 100×160 After strengthening: 160×260	Half jacketing
11		KM 42		
12		KM 43		
13		KM 51		
14		KM 52		
15		KM 53		
16	4	RKMk 1	100×160	Reference beam
17		RKMk 2		
18		RKMk 3		
19	5	RKMb 1	160×260	Reference beam
20		RKMb 2		
21		RKMb 3		
22	6	K101	150×250	Reference beam for strengthening with CFRP
23		K102		
23		K103		
24	7	KC101	150×250	Strengthening with CFRP
25		KC102		
26		KC103		

Table 2. Geometric and Material Properties for the Test Beams

No	Serial no	Test beam	Dimensions (mm)	Total bar area (mm^2)	Volumetric ratio	Concrete compressive strength (MPa)	Reinforcement	
							Yield strength (MPa)	Ultimate strength (MPa)
1	1	KM 11	100×160×2200	226	0.014	22.204	529.74	804.42
2		KM 12	100×160×2200	226	0.014	22.204	529.74	804.42
3		KM 13	100×160×2200	226	0.014	22.204	529.74	804.42
4		KM 21	100×160×2200	226	0.014	22.204	529.74	804.42
5		KM 22	100×160×2200	226	0.014	22.204	529.74	804.42
6		KM 23	100×160×2200	226	0.014	22.204	529.74	804.42
7	2	KM 31	100×160×2200	226	0.014	22.204	529.74	804.42
8		KM 32	100×160×2200	226	0.014	22.204	529.74	804.42
9		KM 33	100×160×2200	226	0.014	22.204	529.74	804.42
10	3	KM 41	100×160×2200	226	0.014	22.204	529.74	804.42
11		KM 42	100×160×2200	226	0.014	22.204	529.74	804.42
12		KM 43	100×160×2200	226	0.014	22.204	529.74	804.42
13		KM 51	100×160×2200	226	0.014	22.204	529.74	804.42
14		KM 52	100×160×2200	226	0.014	22.204	529.74	804.42
15		KM 53	100×160×2200	226	0.014	22.204	529.74	804.42
16	4	RKMk1	100×160×2200	226	0.014	22.204	529.74	804.42
17		RKMk2	100×160×2200	226	0.014	22.204	529.74	804.42
18		RKMk3	100×160×2200	226	0.014	22.204	529.74	804.42
19	5	RKMb1	160×260×2200	452	0.01	33.27	529.74	804.42
20		RKMb2	160×260×2200	452	0.01	33.27	529.74	804.42
21		RKMb3	160×260×2200	452	0.01	33.27	529.74	804.42
22	6	K101	150×250×2200	226	0.00602	36	449.3	680
23		K102	150×250×2200	226	0.00602	36	449.3	680
24		K103	150×250×2200	226	0.00602	36	449.3	680
25	7	KC101	150×250×2200	226	0.00602	36	449.3	680
26		KC102	150×250×2200	226	0.00602	36	449.3	680
27		KC103	150×250×2200	226	0.00602	36	449.3	680

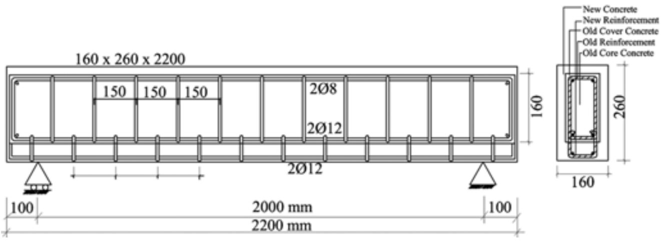

Fig. 3. Cross-Section Detail for Half Jacketing

of 420 MPa and $\phi 8$/150 mm stirrups were placed between old stirrups and the bottom area of the beams (Fig. 4). Hence, new and old reinforcements were welded together and the beam was wrapped with the lateral reinforcement. The beam was then placed in the mold and its circumference was repaired with concrete having 30 MPa compressive strength.

2.2.3 Strengthening with Steel Plates

The three RC beams (Tables 1-2: KM31, KM32, KM33) for the third set was damaged. Surfaces of steel plates having dimensions of 6 × 50 × 1200 mm, 300 MPa yield strength, 412 MPa ultimate strength and 12.7% ultimate tensile strains were cleaned with a conic stoned spiral until all the rust was removed. Plates were then fixed to the bottom and the two sides of the beam with epoxy (Fig. 5). The epoxy resin was first applied to the concrete surface, the external steel plate was then applied to the concrete surface on the epoxies resins coating, the sheet was rolled to squeeze the air that can be entrapped at the epoxy-sheet interface.

The last two sets of six specimens were produced with the dimensions of 150 × 250 × 2200 mm.

The three of these specimens were produced as reference beams and the rest were produced to be repaired. All the beams were made of concrete having 30 MPa compressive strength. Yield strength for the reinforcement was 420 MPa and, 2ϕ12 longitudinal reinforcement, 2ϕ8 erection reinforcement and ϕ8 lateral reinforcement with a space of 200 mm between (Fig. 6).

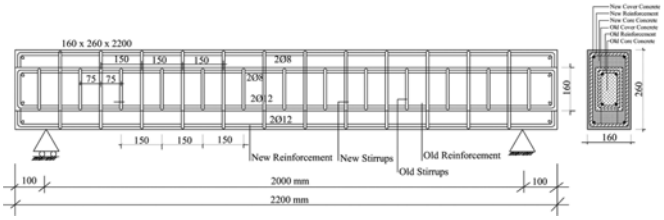

Fig. 4. Cross-Section Detail for Full Jacketing

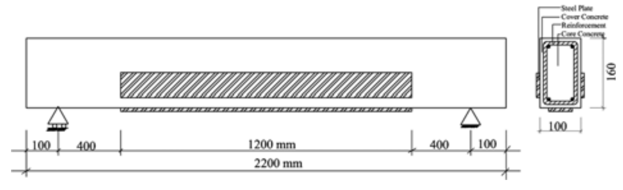

Fig. 5. Cross-Section Detail for Strengthening with Steel Plates

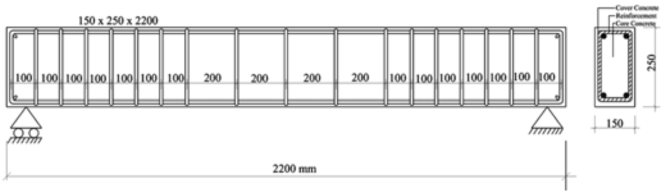

Fig. 6. Reference Beam

2.3 Repairing Case II

In this repairing case, in order to investigate the behavior of the three test beams under pure bending, CFRP composites were used for strengthening.

2.3.1 Strengthening with CFRP

CFRP, which has 2.30 N/cm^2 weight, was used for wrapping. The mechanical properties are shown in Table 3. The three specimens (Tables 1-2: K101, K102, K103) were strengthened from the bottom of the beam by wrapping with CFRP. First of all the specimens were washed with pressurized water until there were no moving particles on the surface. CFRP was then fixed at the bottom side of the beam with 1/3 ratio and 2 kg/m^2 epoxy (Fig. 7). Mechanical properties of CFRP are provided by the manufacturer.

3. Experiment Results and Evaluation

In the first set of test beams, crack width and distribution increased under incremental loading. After each load increment, cracks were started to move vertically to the compression zone (Fig. 8) up to the failure. In all strengthening techniques, the expansion and location of cracks were similar to those of reference beams. Mid-span deflections were measured as 19 mm, 18.75 mm, 22 mm for KM11, KM12 and KM13 respectively. The load-displacement curves were then plotted and compared with the reference beams (Figs. 9-14). As can be seen in Figures 9-14, the ultimate load carrying capacities and also energy dissipation capacities of the test beams depend greatly on the strengthened techniques.

The vertical displacements were measured from the center of

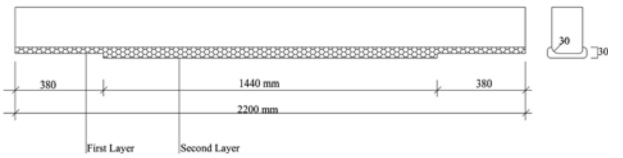

Fig. 7. RC Beam Wrapped with CFRP

Table 3. Properties of CFRP

Weight	4.3 N/m^2
Thickness	0.13 mm
Roll width	60 cm
Roll length	50m
Tensile – Failure Limit	3300 - 4500 MPa
Failure Strain	0.048

Fig. 8. Crack Distribution

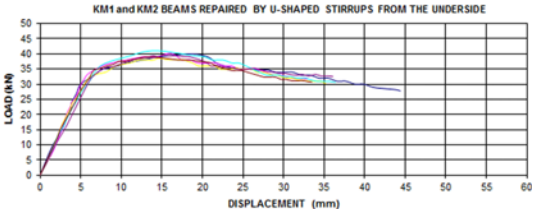

Fig. 9. Load-displacement Curves of Beams for Half Jacketing

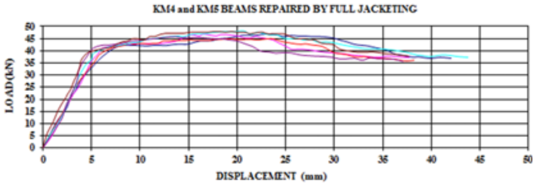

Fig. 10. Load-displacement Curves of Beams for Full Jacketing

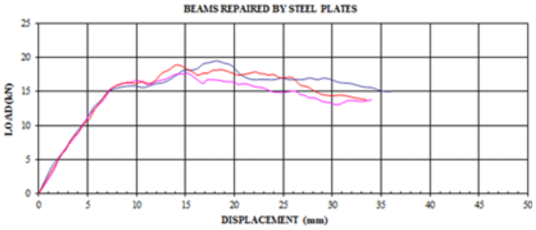

Fig. 11. Load-displacement Curves of Beams with Steel Plates

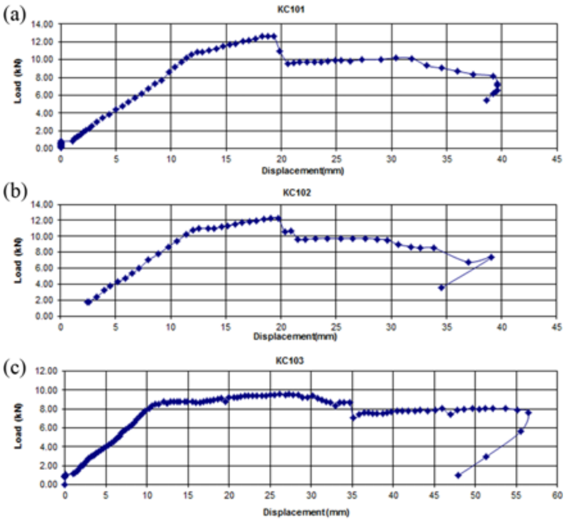

Fig. 12. Load-displacement Curves of Beams with CFRP (KC101, KC102, KC103)

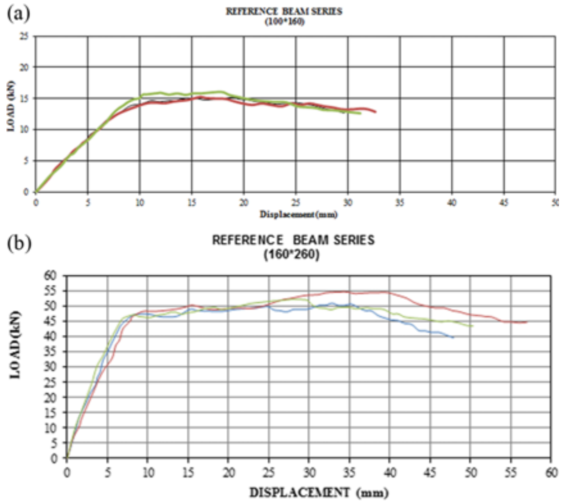

Fig. 13. Load-Displacement Curves of the Reference Beams: RKM1, RKM2, RKM3 with Dimensions of: (a) 100 (cm)×160(cm), (b) 160 (cm) × 260 (cm)

the beam using four Linear Variable Displacement Transducers (LVDTs). The loads were saved to data logger and the electronic devices were also reseted every time. Load-displacement behaviors of the beams which are damaged and then repaired by RC jacketing are similar to the reference beams (Figs. 9, 10 and 13). Same results are obtained for the strengthening with steel plates. However, the results are not as successful as those with the RC jacketing (Figs. 11and 13). In Fig. 12, the mid-span vertical displacements of the beams strengthened with CFRP are notably decreased as compared to that of reference beams (Fig. 14). Besides, significant increases in load-bearing capacities are obtained. Maximum bending moments ($M_{max.}$), load-bearing capacities (P_u) and mid-span vertical displacements (before and after strengthening case) for beam specimens are also given in Table 4 for comparison.

Ductility is considered to be a paramount safety characteristic of structures since it describes the ability of a structural element to sustain inelastic deformation prior to collapse without significant loss in resistance. The conventional methods of determining the ductility of RC beams are function of the concrete failure and yielding of the steel rebars (Oudah and El-Hacha, 2011). Generally, in order to calculate the ductility of RC beams Eqs. (1) and (2) can be used:

$$\mu = \frac{\phi_u}{\phi_y} \tag{1}$$

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{2}$$

where ϕ_u and ϕ_y bare the curvature at the ultimate and yield

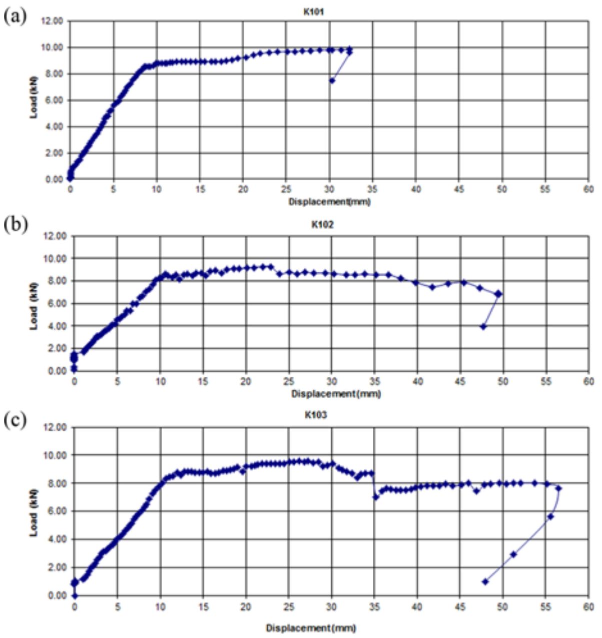

Fig. 14. Load-Displacement Curves for Reference Beams: (a) K101, (b) K102, (c) K103 with the Dimension of 150 (cm) × 250 (cm)

Table 4. Experimental Values for Test Beams

Speci-mens	Before Strengthening			After Strengthening		
	M_{max} (Nmm)	P_u (kN)	Mid-span vertical displace-ments (mm)	M_{max} (Nmm)	P_u (kN)	Mid-span vertical displace-ments (mm)
KM 11	11000×10^3	22.00	19.00	27300×10^3	34	31
KM 12	12000×10^3	24.00	18.75	27850×10^3	33.5	28
KM 13	11000×10^3	22.00	22.00	26540×10^3	32.5	29
KM 21	10000×10^3	20.00	14.00	25370×10^3	35	26.5
KM 22	10500×10^3	21.00	13.90	25500×10^3	34.5	28.4
KM 23	11000×10^3	22.00	10.70	25000×10^3	34	27
KM 41	12000×10^3	24.00	19.40	23680×10^3	40.0	35.0
KM 42	11500×10^3	23.00	15.55	23550×10^3	39.5	28.0
KM 43	11000×10^3	22.00	14.80	22700×10^3	38.0	32.0
KM 51	11500×10^3	23.00	11.20	22500×10^3	41.0	35.5
KM 52	11500×10^3	23.00	22.00	21000×10^3	38.5	24.0
KM 53	9000×10^3	18.00	15.00	22800×10^3	42.0	31.3
KM 31	12000×10^3	24.00	16.00	12350×10^3	17	30
KM 32	10500×10^3	21.00	17.80	12700×10^3	14.5	26.5
KM 33	12500×10^3	25.00	19.50	11500×10^3	16.5	26.5
RKMk 1	9500×10^3	19.00	32.10	-	-	-
RKMk 2	10500×10^3	21.00	27.60	-	-	-
RKMk 3	10000×10^3	24.00	31.25	-	-	-
RKMb 1	-	-	-	27140×10^3	42	43
RKMb 2	-	-	-	26970×10^3	46.5	50
RKMb 3	-	-	-	27018×10^3	46	43
K101	6100×10^3	99.00	32.00	-	-	-
K102	6100×10^3	92.60	49.00	-	-	-
K103	6100×10^3	95.90	55.00	-	-	-
KC101	6100×10^3	94.80	40.00	6100×10^3	133.1	31.00
KC102	6100×10^3	95.40	42.00	6100×10^3	136.5	37.0
KC103	6100×10^3	94.5	50.00	6100×10^3	128.1	44.0

Table 5. Ductility Indexes

Specimens	Δ_y (mm)	Δ_u (mm)	μ	Explanation
KM11	6.2	31.5	5.1	Half jacketing
KM12	6.2	27.8	4.5	
KM13	5.6	29.1	5.2	
KM21	6.6	26.1	4.0	
KM22	6.4	28.5	4.5	
KM23	6.4	26.5	4.1	
KM41	6.2	35.0	5.6	Full jacketing
KM42	6.1	28.4	4.7	
KM43	6.0	31.2	5.2	
KM51	5.1	35.3	6.9	
KM52	5.0	23.8	4.8	
KM53	4.6	30.7	6.7	
KM31	7.1	30.1	4.2	Steel plate
KM32	7.2	26.4	3.7	
KM33	7.0	26.4	3.8	
KC101	12.0	31.0	2.6	CFRP
KC102	11.0	37.0	3.4	
KC102	13.0	61.0	4.7	
RKM1b	6.9	43.1	6.2	Reference beams (100×160)
RKM2b	8.0	49.8	6.2	
RKM3b	7.0	48.2	6.9	
RKM1k	9.1	28.3	3.1	Reference beams (160×260)
RKM2k	8.1	32.8	4.0	
RKM3k	9.0	27.9	3.1	
K101	9.0	32.0	3.6	Reference beams (150×250)
K102	10.0	49.0	4.9	
K103	12.0	57.0	4.8	
KC101	12.0	31.0	2.6	CFRP
KC102	11.0	37.0	3.4	
KC102	13.0	61.0	4.7	

moment, Δ_u and Δ_y are deflections at ultimate and yield loads respectively.

In this study, ductility indexes for reference beams and strengthened beams with four techniques have been determined using Eq. (2) and given in Table 5.

As can be seen in Table 5, the optimum ductility has been obtained for beams strengthened with full jacketing and CFRP composites.

From Tables 4 and 5, the increment of the ultimate load for the RC beams strengthened with full jacketing as compared to the reference beams having cross section of 100×160 mm is about 200% and the ductility of 151% has been achieved and the increment of the ultimate load obtained by half jacketing compared to the reference beams is about 122% and the increment in ductility is about 68%.

Furthermore, energy dissipation capacities have also been calculated and depicted in Table 6. The optimum capacity has been obtained for beams strengthened with full jacketing and CFRP composites.

Table 6. Energy Dissipation Capacities

Specimens	Pu (kN)	Mid-span vertical displacements (mm)	Energy dissipation capacity (kNmm)
KM11	34	31	114747.74
KM12	33.5	28	109873.69
KM13	32.5	29	113207.57
KM21	35	26.5	101135.62
KM22	34.5	28.4	111074.81
KM23	34	27	101839.96
KM41	40	35	168119.79
KM42	39.5	28.0	133091.99
KM43	38.0	32.0	145486.86
KM51	41	35.5	174353.92
KM52	38.5	24	111402.98
KM53	42	31.3	154353.48
KM31	17	30	97923.54
KM32	14.5	26.5	80696.64
KM33	16.5	26.5	84870.07
RKM1b	42	43	160430.42
RKM2b	46.5	50	195658.12
RKM3b	46	43	164760.39
RKM1k	13.5	28	87021.1
RKM2k	13.6	32.5	102482.6
RKM3k	13.6	28	87251.5
K101	99.00	32.00	96921.24
K102	92.60	49.00	98246.09
K103	95.90	55.00	145434.49
KC101	133.1	31.00	133207.87
KC102	136.5	37.0	124356.06
KC102	128.1	44.0	132585.49

4. Conclusions

In this paper, twenty-seven RC beams were tested under combined bending and shear. Damaged beams were strengthened with different techniques and results were compared with those obtained from the reference beams (undamaged). The following conclusions have been reached:

1. The ultimate load for damaged RC beams has been increased by a maximum of 200% for full jacketed beams, by 156% for half jacketed beams, by 19% for steel plate-strengthened beams and by 34% for CFRP plated beams.
2. Deflection ductility values obtained from full jacketed beams were increased distinctly when compared to half jacketed ones.
3. In strengthening technique with steel plates, it was observed that increasing the thickness of the plate was not a good choice for ultimate load bearing capacity because of brittle failure of the material. Moreover, it was ineffective in terms of increasing the load carrying capacity and stiffness due to debonding failure.
4. The specimens strengthened with full jacketing had slightly higher load carrying capacity than the reference beams while the specimens strengthened with CFRP sheets showed no increase of capacity and failed by the fibers rupturing.
5. The results indicate that the beams strengthened using CFRP strips exhibited a higher first-cracking, and steel-yielding as the level of vertical force increased up to a certain point. When comparing the load–displacement diagrams of the reference (K101, K102, K103) and strengthened elements (KC101, KC102, KC103), the stiffness and the overall behavior were barely affected by loading history. Further studies are needed to consider the effect of the permanent loads.
6. Tests indicated that all techniques are feasible strengthening solutions, confirming that the retrofitting methods proposed for the field application are consistent for limiting the crack openings.
7. Increase in energy dissipation capacities are about 100%, 32%, 12% and 36% for full jacketing, half jacketing, steel plates and CFRP composites respectively.

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