REPAIR OF DAMAGED REINFORCED CONCRETE BEAMS BY EPOXY INJECTION

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The presented study investigates the efficiency of repairing damaged reinforced concrete beams by a novel technique, which is the injection of epoxy resin to the cracks. The two main test parameters were the amount of flexural reinforcement (low, medium, and high) and the level of seismic damage before repair (light, moderate, and heavy). Nine cantilever beams were tested under reversed cyclic transverse loading in the undamaged (original) and repaired (after damaging) states. The test results were examined and discussed in terms of the initial flexural rigidity and ultimate load capacity. The technique was shown to be the most effective in damaged beams with mid-sized cracks. The minor cracks particularly in lightly-reinforced beams were not suitable for proper injection of resin, while the major cracks resulted in the epoxy to govern the flexural behavior of the beam after repair. The experimental load capacities were shown to be in close agreement with the analytical flexural capacities of the respective beams. The sizes of the cracks before repair and the longitudinal reinforcement did not affect the repaired beam to reach the load capacity of the original counterpart but affected the extent of deformations before reaching this load level.

Keywords: *Repair; Crack width; Flexural reinforcement; Seismic retrofit; Concrete structures.*

1. Introduction

The reinforced concrete (RC) frames can withstand seismic movements as long as the vertical load-bearing members, i.e. columns in frame structures, are not subjected to major earthquake damage. The earthquake resistant structural design requires the presence of strong column-weak beam connections according to the structural earthquake codes around the globe. Accordingly, the beams rather than the columns are expected to dissipate earthquake-induced energy through the formation of plastic hinges at prescribed locations on the beam. These locations are distant from the connection region so that the beam-column connections and the columns are not affected from the seismic damage. The damage in the beams due to plastic hinging are in the form of flexural cracks close to both upper and lower faces as a result of the reversal of bending moments during an earthquake. The performance-based assessment of earthquake safety of existing structures, which is recommended by various structural earthquake codes, allows significant or minimum damage in a certain percentage of the beams in a frame even if the structure is expected to satisfy the “ready for use” or “life safety” performance levels under weak and moderate earthquakes. In other words, the damaged beams are in a repairable condition after an earthquake so that the structure can be safely used in the future.

RC beams have been strengthened or repaired by steel or Fiber Reinforced Polymer (FRP) jacketing, reinforced shotcrete or concrete overlays, bonding external steel plates, near-surface mounted FRP or steel rebars in the literature. As well as being costly and requiring significant time and skilled labor, these methods have not gained wide popularity in practice due to the brittle stress-strain characteristics of FRP, low fire resistance of FRP and steel, the additional measures required to safeguard steel against corrosion and the difficulties related to satisfy adequate interfacial shear strength between the existing beam and the overlay. The presented study adopts a more novel and conventional method, i.e. injecting low-viscosity epoxy resin into the cracks, which significantly reduces the amount of time and workmanship for the repair process. Considering that there may be a significant number of beams to be repaired in a structure, the reduction in the time and labor of the repair works is rather crucial in the practice.

There are numerous studies in the literature on epoxy repair of RC members. The ones with the most significant outcomes are discussed herein. French et al. [1] tried two different methods for the application of epoxy repair, namely pressure injection and vacuum impregnation. The tests on interior RC specimens indicated that both methods were effective in restoring the strength, stiffness, energy-dissipation capacity, and bond of the specimens with an emphasis on the vacuum impregnation technique to be applicable to larger regions of damage and offshoot cracks. Karayannis et al. [2] tested 17 exterior beam-column connection specimens, representing different practices commonly used for reinforcing RC joints, with an

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emphasis on the effect of shear reinforcement in the connection region to the repair efficiency. The damaged specimens were repaired by infusion of epoxy resin under pressure. The original (virgin) and repaired specimens were subjected to cyclic deformations until the maximum load of the cycle was about 40% of the yield load, reached in the first cycle. All of the repaired specimens had load capacity and stiffness values comparable to or above the virgin specimens and could resist a greater number of load cycles without a major loss in strength. Yousri and companions [3, 4] tested 14 cantilever RC beams under monotonic transverse loading and quasi-static cyclic loading, simulating seismic excitation, to investigate the effects of the damage level, applied loading history and presence of load during the injection process on the behavior of repaired beams. The specimens subject to different levels of damage before repair reached the strength values of the respective original specimens and stiffness values even higher than the respective values of the reference beams. This implies that the damage level has little influence on the efficiency of the repair process. Furthermore, the presence of applied load on the beam during repair, which corresponds to the dead weight of the structure, was shown to have no considerable influence on the efficiency of the repair application. The loading history was the only parameter with a major influence on the load-deflection behavior of the repaired beam. Kaya et al. [5] applied the epoxy injection crack repair technique to a T-shaped beam-column joint with significant seismic design deficiencies, i.e. smooth reinforcing bars, inadequate transverse reinforcement, and low concrete compressive strength, simulating the old construction practices. Both the virgin and repaired specimens underwent significant shear cracking in the joint region and shear failure under reversed cyclic lateral loading and constant axial load on the column. Nevertheless, the repair method helped the specimen to regain its lateral load and shear capacity. Nikopour and Nehdi [6] investigated the effects of strengthening shear-deficient RC beams with side-bonded FRP sheets and repairing damaged RC beams with epoxy injection and unidirectional carbon fiber polymer (CFRP) sheets. The experiments on a total of six original, including two control, and three repaired specimens indicated that the FRP type and the wrapping scheme has an important effect on the retrofitted beam behavior and the simultaneous application of epoxy injection and FRP wrapping was much more effective in repairing the damaged beams instead of the sole application of epoxy. The tests of Ahmad et al. [7] on simply-supported RC beams with and without shear reinforcement depicted that the strength and stiffness values of cracked RC beams can be restored and even enhanced with the application of the epoxy resin injection technique. Up to a maximum crack width of 1 mm before repair, the repair method was found to be more effective in RC beams with shear reinforcement, while the method had higher contributions to the energy and load capacities of beams without shear reinforcement if the maximum crack width before repair exceeds 1 mm. Gunarani and Saravanakumar [8] adopted two different types of materials, namely epoxy and polymer grouting, for repairing RC beams. Six RC beams were tested under monotonic transverse six-point bending. Both of the repair materials provided the beams with load capacities even higher than the original beams and similar crack patterns. Rashid and Ahmad [9] tested a cantilever RC beam under quasi-static cyclic loading with increasing amplitude of displacement cycles before and after repair. The original specimen underwent spalling of the cover concrete and significant cracking in the plastic hinging region and at the beam-column interface due to fixed-end rotation. The cracks were treated with low-viscosity epoxy, while the spalled concrete was repaired with early-strength grout. The repair procedure did not help the repaired beam to regain its strength and stiffness due the bar slip at the beam-column interface and the inelastic extension of the longitudinal bars. Al-Rifaie et al. [10] conducted tests on a total of 12 RC beams under three-point bending. The original beams were tested to failure and repaired afterwards. Different repair applications, namely repair with ferrocement composite, steel plate, fiber carbon reinforced polymer (FCRP), nano cement composite, and by injection of nano cement mortar, were investigated in the study. Injection of the nano materials, including micro cement and nano fumed silica, helped the failed beam to regain 80 % of its ultimate load capacity under monotonic loading. Based on previous studies in the literature on repair of fire-damaged RC structures, Mohd Zahid et al. [11] concluded that injection of epoxy resin does not effectively improve the behavior of a fire-damaged RC member, although epoxy resin has a good bonding performance with concrete.

Albeit there are numerous studies on the efficiency of this novel technique in RC beams and joints, none of the studies in the literature focused on the effects of the longitudinal reinforcement in the beam and the damage level prior to repair on the repaired beam behavior. The present study mainly aimed at investigated the enhancement in the strength and stiffness of damaged RC beams with different longitudinal reinforcement ratios. The flexural reinforcement in the beam plays a crucial role in the presence and extent of flexural and shear cracks prior to the repair process, and hence, the efficiency of epoxy injection. In this respect, the tests on nine original undamaged and nine repaired RC specimens under reversed cyclic loading provided the researchers with valuable conclusions on the effects of different levels of damage on the epoxy injection repair process for lightly-, moderately-, and heavily-damaged RC beams.

Table 1
Test specimens

Specimen Group	Specimen Notation	Flexural Reinforcement		Shear Reinforcement	Damage Level
		Strong	Weak		
Original	SS1	3Ø8	2Ø8	Ø4/10	Light
	SS2	3Ø8	2Ø8	Ø4/10	Moderate
	SS3	3Ø8	2Ø8	Ø4/10	Heavy
	SM1	3Ø14	2Ø14	Ø4/10	Light
	SM2	3Ø14	2Ø14	Ø4/10	Moderate
	SM3	3Ø14	2Ø14	Ø4/10	Heavy
	SB1	5Ø14	3Ø14	Ø6/14	Light
	SB2	5Ø14	3Ø14	Ø6/14	Moderate
	SB3	5Ø14	3Ø14	Ø6/14	Heavy
Repaired	RSS1 RSS2 RSS3 RSM1 RSM2 RSM3 RSB2 RSB3	Identical to the Original Counterpart			

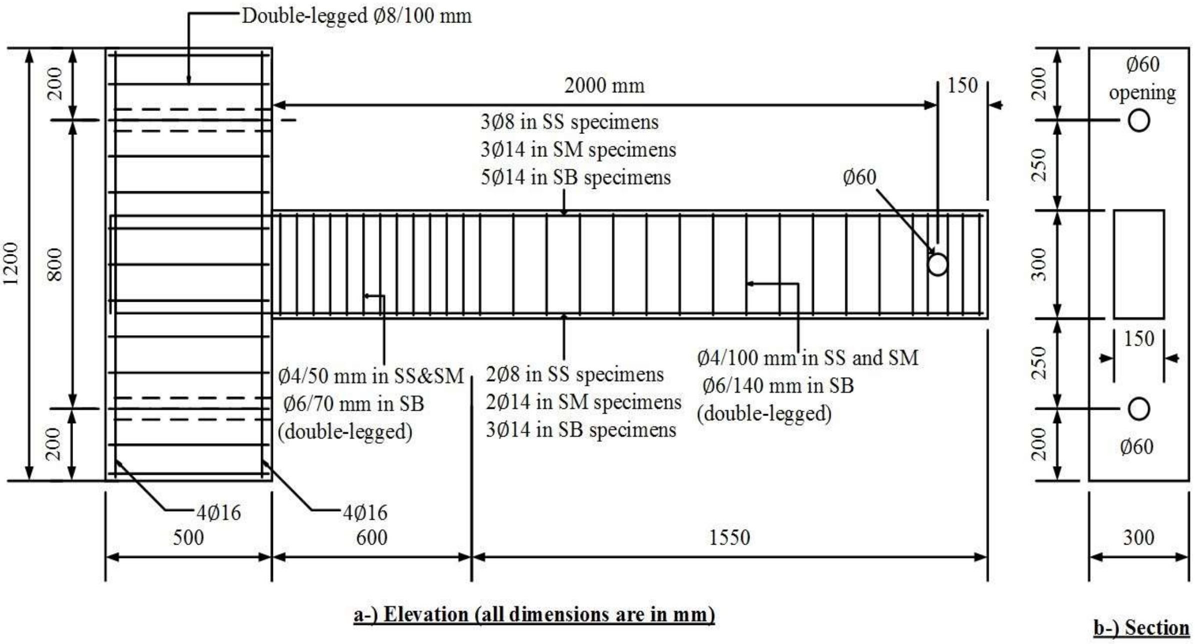

Fig. 1 - Test specimen details

2. Experimental Study

2.1. Specimens

In the experimental stage of the present study, a total of 18 tests were conducted. First, each original (virgin) beam was tested under reversed cyclic transverse loading. After reaching the predetermined damage level, the beam was repaired by means of the proposed repair technique. Later, each repaired beam was tested under the same experimental conditions as its respective virgin counterpart.

The notations of the specimens were developed in such a way that each notation reflects all test parameters corresponding to this very specimen. The specimen notation is composed of two or three capital letters and a number. The names of the original specimens started with the capital letter "S", while the ones of the repaired specimens started with the letter group "RS". The second capital letter in the original specimens and the third letter in the repaired specimen names corresponds to the longitudinal reinforcement ratio. Accordingly, the letters "S", "M" and "B" imply that the beam contains low, medium and high reinforcement ratio, respectively. Finally, the number corresponds to the level of damage before repair. In this respect, the numbers "1", "2" and "3" correspond to the light, moderate and heavy damage. To exemplify, the notation “SM2” corresponds to the moderately-reinforced virgin specimen liable to medium damage in the test, while the notation “RSM2” corresponds to the same specimen after repair. The list of all specimens is given in Table 1.

The size and number of test beams have been chosen in such a way that they can be carried out in laboratory conditions and reflect the usual situations. To provide fixed support conditions at one end of the specimen, the beam was cast simultaneously with a concrete block and the longitudinal reinforcing bars in the beam were extended adequately inside the block (Fig. 1). The beam and block have cross-sectional dimensions of 150x300 mm and 300x500 mm, respectively. The beam has a total length of 2150 mm and the block has a height of 1200 mm. The longitudinal reinforcing bars had a clear concrete cover of 15 mm. Sufficient shear reinforcement was provided to each beam (Table 1) to ensure flexural cracking and failure in all specimens. The reinforcement and dimensions of the specimens are presented in Table 1 and Fig. 1. Steel plate formworks which are completely modularly designed with a thickness of 4 mm were used to produce specimens.

The lightly-reinforced beams had a tensile reinforcement ratio in the weakest (reverse) direction of loading equal to the minimum tension reinforcement ratio limit of the Turkish Concrete Code TS500 [12]. This limit (ρ_{min}), which assures that an RC beam does not fail suddenly and maintains its flexural capacity for certain deformations after reaching the cracking moment, is calculated from the following formula:

$$\rho_{\min} = 0.8 \cdot \frac{f_{ctd}}{f_{yd}} \quad (1)$$

where f_{ctd} and f_{yd} are the design direct tensile strength of concrete and the design yield stress of reinforcement, respectively. The heavily-reinforced concrete beams, on the other hand, were reinforced in a way that the tension reinforcement in the strongest (forward) direction of loading is about equal to the upper flexural reinforcement limit of TS 500 [12], i.e. 85 % of the balanced reinforcement ratio. Finally, the moderately-reinforced beams were designed to have a tension reinforcement ratio equal to the arithmetic average of the respective ratios of the heavily- and lightly-reinforced beams.

The top and bottom longitudinal reinforcement were selected based on the limitations of the experimental setup, i.e. stroke of the hydraulic jack. The term “forward direction of loading” refers to downward displacement of the free end, i.e. the loading end, of the beam, while the term “reverse direction of loading” corresponds to upward displacement of the free end. In other words, forward and reverse directions of loading induce negative (tension at the top) and positive (tension at the bottom) bending moments in the beam. The hydraulic jack used in the tests has a stroke of 200 mm and it was installed to allow an overall displacement of 120 mm in the forward and 80 mm in the reverse loading directions. The tension reinforcement in the forward and reverse directions of loading were selected to be compatible with the displacements in the two directions. Accordingly, the top reinforcement was about 1.5 times the bottom reinforcement (Fig. 1) identical to forward-to-reverse stroke limit (120/80=1.5). Hence, the negative bending moment capacity of each beam was 1.5 times its positive moment capacity.

The loading point was displaced up to the full stroke (120 mm in the forward and 80 mm in the reverse directions) in original beams subject to heavy damage. Similarly, the maximum displacements of the specimens with moderate damage were half of the stroke limits (120/2=60 in the forward and 80/2=40 mm in the reverse directions) and one-third of the stroke limits in specimens with light damage (120/3=40 in forward and 80/3=27 mm in reverse directions of loading). In some specimens, however, these intended displacement values could not be reached due to concrete crushing, compression bar buckling or tension bar rupture.

2.2. Materials

Concrete C20/25 with the concrete mix calculation was produced in laboratory conditions and poured into the prepared modular steel plate formworks by compacting with a vibrator. Three standard 150x300 mm concrete cylinders were prepared for each beam specimen and these cylinders were tested under axial compression at the test day of the original (virgin) beam. The cylinders were kept in the curing room until the test day. The average concrete compressive strength was measured as 26 MPa for beams SS1, SS2, RSS1 and RSS2; 24 MPa for SS3 and RSS3; 23 MPa for SM1, SM3, RSM1 and RSM3; 28 MPa for SM2 and RSM2; 20 MPa for SB1; 25 MPa for SB2 and RSB2; and 30 MPa for SB3 and RSB3. The Ø8 and Ø14 bars had measured yield stress values of 480 and 450 MPa, respectively.

Sikadur® 31 epoxy, a ticroscopic two-component epoxy adhesive, was used for repairing the damaged surfaces, while Sikadur® 52, a two-component low-viscosity epoxy resin, was injected into the cracks. The mechanical properties of these two adhesives are given in Table 2.

2.3. Method of Epoxy Injection

The recommendations of the ACI committee reports ACI 224.1R-93 [13] and ACI 503R-93 [14] were implemented in the epoxy injection repair process. The dust in the flexural

Table 2. Material properties of the epoxy

Material	Property		Time (days)	Temperature (°C)	Value (MPa)
Sikadur® 31	Compressive Strength		1	+20	40-45
	Compressive Strength		10	+20	60-70
	Tensile Strength		10	+10-20	15-20
	Bond Strength	to Concrete	10	+10-20	3.0-3.5
		to Steel			15
	Bending Strength		10	+10-20	30-40
	Modulus of Elasticity		-	-	4300
Sikadur® 52	Compressive Strength		10	+20	53
	Tensile Strength		10	+20	25
	Bond Strength	to Concrete	7	+23	4
		to Steel			10

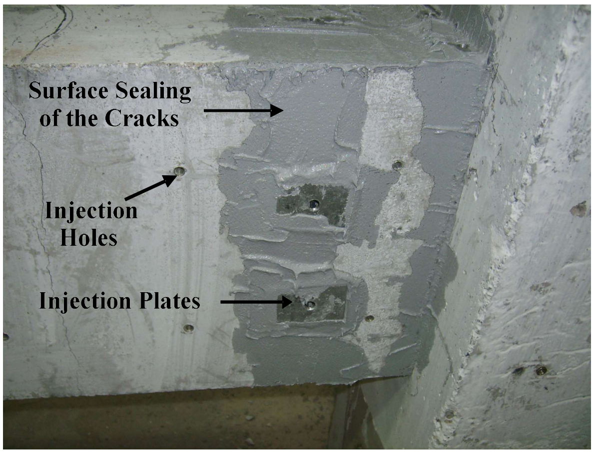

Fig. 2 - Sealing of the exposed surfaces of the cracks and injection plates

Fig. 3- Epoxy injection

cracks of the original beams were removed with the help of pressurized air so that the epoxy resin can completely fill the cracks. After sealing the exposed surfaces and bonding the injection plates to the specimen with epoxy (Fig. 2), epoxy was applied to the cracks through ports in the injection plates by using a special injection gun and an air pump (Fig. 3). Injection was terminated as soon as the epoxy pressure in the cracks was equal to the pump pressure (50 bar = 725 psi).

2.4. Test Setup and Instrumentation

The concrete block, cast monolithically with the beam, was fixed to the strong wall with the help of post-tensioned rods (Figs. 4 and 5) in order to provide fixed support conditions. A double-action hydraulic cylinder was used to apply concentrated load at a distance of 2000 mm from the face of the support (concrete block). The hydraulic cylinder was connected to the strong floor via a hinge. Furthermore, the load was conveyed to the beam with the help of a loading cage, which was connected to the hydraulic cylinder through a hinge. An electronic load cell, located between the hydraulic cylinder and the loading cage, was used to measure the applied load.

The displacement at the loading end of the beam was measured with the help of an LVDT (denoted as D1). However, this measured displacement might not be the net displacement in the beam due to the applied load. The net displacement can be determined by subtracting the rigid-body translation of the entire specimen and the effect of the rigid-body rotation of the beam at the free end from the measured absolute displacement. For this purpose, the rigid-body translations of the specimen were measured by an additional LVDT (D14) and rigid-body rotations by two LVDT's (D10 and D11). The shear deformations of the connection region were determined from the readings of four LVDT's (D6, D7, D8 and D9). Finally, six more LVDT's (D2, D3, D4, D5, D12 and D13) were used to measure the crack widths at three different locations along the beam (Fig. 6). D1, D10, D11 and D14 (measuring the end displacement, rigid-body rotation and translation) were not directly installed on the beam, while the

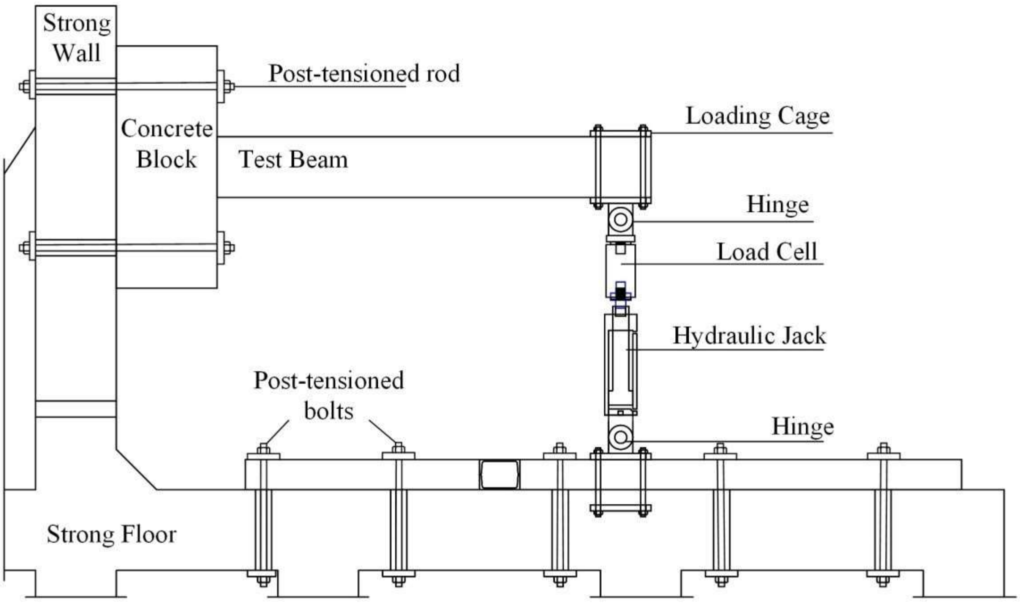

Fig. 4 - Test setup

Fig. 5 - General view of the test setup

remaining LVDT's (measuring shear deformations and crack widths)were installed directly on the specimen. The difference between the readings of D10 and D11 was divided by the vertical distance between these two transducers to obtain the rigid-body rotation of the beam. The effect of this rotation on the vertical displacement at free end was calculated by multiplying this rotation with the distance of the load from the support face.

3. Evaluation of the Test Results

The original and repaired specimens experienced flexural failure and the shear reinforcement in the beams prevented the beams to undergo shear failure. Since the beams were subjected to greater deformations in the forward direction of loading (downward deformations), the

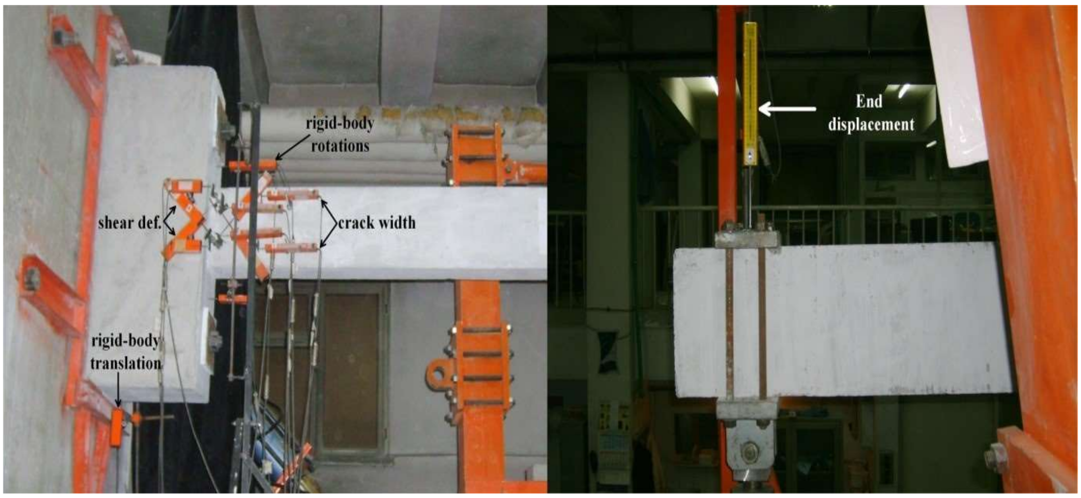

Fig. 6 - LVDT's in the tests

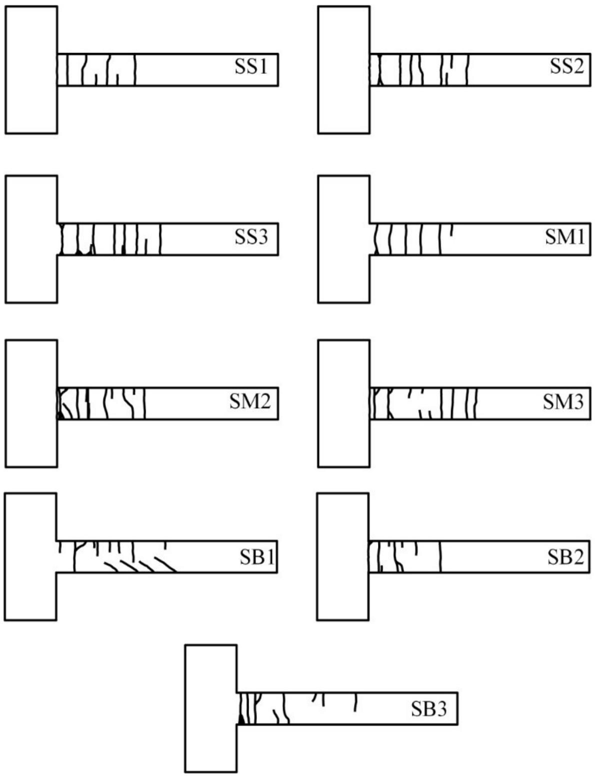

Fig. 7 - Final crack patterns of the virgin specimens

Fig. 8 - Extensive cracking in specimen with medium and high reinforcement ratio

Fig. 9 - Disintegration of the epoxy layer and nozzles (ports)

number and degree of flexural cracking in the upper portion of each beam exceeded the flexural cracking in the lower portion (Fig. 7). Failure of the moderately- and heavily-reinforced beams was characterized by concrete crushing and compression bar buckling in addition to the extensive flexural cracking, particularly in the forward direction (Fig. 8).

In the same specimens, the epoxy layers and the nozzles were observed to disintegrate from the beam after repair (Fig. 9). Different from the other specimens, the test of RSM1 was terminated in the second cycle and the tests of RSM2 and RSB2 after the second cycle due to the excessive damage in these specimens, which prevented the specimens to maintain their integrity.

The significant diagonal cracking in specimen SB1 urged the researchers to provide additional external stirrups for the other reference beams with heavy longitudinal reinforcement (SB2 and SB3). These external stirrups were in the form of shear cages, composed of two tubular steel profiles on top and bottom of the beam and two threaded rods connecting these profiles. The threaded rods were post-tensioned. The extent and amount of shear cracks were much less in SB2 and SB3 as compared to SB1, implying that this additional measure was quite beneficial.

The test results of the present study were mainly evaluated and discussed in terms of flexural rigidity and bending moment capacity. The ratio of the flexural rigidity of each repaired specimen in each cycle to the respective rigidity of the original specimen in the same cycle is given in Table 3 for the sake of comparison. The flexural rigidity of a repaired beam in the first cycle is the most important indicator of the efficiency of repair. In the first cycle, a beam behaves as a solid body and the entire body contributes to the flexural rigidity, while in the further cycles the longitudinal and transverse reinforcement starts controlling the flexural behavior as a result of extent and propagation of cracks in the beam. Hence, the contribution of repair and integrity of a beam as a result of this repair can be best evaluated based on the flexural behavior and rigidity at the initiation of the test under small deformations. Accordingly, the tabulated values clearly indicate that the flexural rigidities of the repaired beams with low reinforcement ratio (RSS1, RSS2 and RSS3) are much smaller than the rigidities of the original beams (SS1, SS2 and SS3) in the first cycle. In the further cycles, however, these differences vanished and the repaired beam stiffness approached or even exceeded (RSS3) the respective value of the virgin beam.

Table 3

Repaired-to-original flexural rigidity ratio

Reinforcement	Specimen	Direction and Cycle of Loading					
		Forward			Reverse		
		1	2	3	1	2	3
Lightly-Reinforced	RSS1/SS1	0.35	0.9	1.28	0.60	0.96	1.05
	RSS2/SS2	0.24	1.24	1.22	0.86	1.06	1.00
	RSS3/SS3	0.27	1.00	1.00	0.54	1.21	1.00
Moderately-Reinforced	RSM1/SM1	0.55	-	-	0.92	-	-
	RSM2/SM2	0.70	1.00	-	1.00	0.96	-
	RSM3/SM3	0.88	1.00	1.00	0.86	0.84	0.77
Heavily-Reinforced	RSB2/SB2	0.86	0.95	-	0.98	0.97	-
	RSB3/SB3	0.53	0.94	0.97	0.94	0.96	1.09

Table 4

Ultimate load values of the specimens

Specimen		Experimental Ultim. Load (kN)		Analytical Ultim. Load (kN)		Load Ratio			
						Repaired-to-original		Experimental-to-analytical	
		Forw.	Rev.	Forw.	Rev.	Forw.	Rev.	Forw.	Rev.
Lightly-reinforced original	SS1	10.64	5.58	9.76	6.61	-		1.09	0.84
	SS2	11.28	6.48	9.76	6.61			1.16	0.98
	SS3	12.23	6.98	9.73	6.58			1.26	1.06
Lightly-reinforced repaired	RSS1	10.11	6.38	9.76	6.61	0.95	1.14	1.04	0.97
	RSS2	10.96	6.68	9.76	6.61	0.97	1.03	1.12	1.01
	RSS3	12.02	7.18	9.73	6.58	0.98	1.03	1.24	1.09
Moderately-reinforced original	SM1	30.00	18.95	26.93	18.14	-		1.11	1.04
	SM2	29.48	17.85	27.04	18.21			1.09	0.98
	SM3	29.17	19.45	26.93	18.14			1.08	1.07
Moderately-reinforced repaired	RSM1	30.67	18.65	26.93	18.14	1.02	0.98	1.14	1.03
	RSM2	29.69	18.55	27.04	18.21	1.01	1.04	1.10	1.02
	RSM3	28.02	19.25	26.93	18.14	0.96	0.99	1.04	1.06
Heavily-reinforced original	SB1	40.11	28.43	44.00	27.03	-		0.91	1.05
	SB2	42.49	28.44	44.47	27.10			0.96	1.05
	SB3	49.23	25.33	44.67	27.17			1.10	0.93
Heavily-reinforced repaired	RSB2	41.39	28.44	44.47	27.10	0.97	1.00	0.93	1.05
	RSB3	46.81	27.43	44.67	27.17	0.95	1.08	1.05	1.01

In moderately- and heavily-reinforced concrete beams, on the other hand, the flexural rigidity of the repaired beam (RSM1, RSM2, RSM3, RSB2 and RSB3) was closer to the rigidity of the original beam (SM1, SM2, SM3, SB2 and SB3) in the first cycle. In this respect, the epoxy resin injection technique can be said to become less efficient with decreasing longitudinal reinforcement ratio. This conclusion can be primarily attributed to the formation of numerous capillary cracks in lightly-reinforced concrete beams. These capillary cracks cannot be repaired by epoxy injection and the flexural rigidity of the repaired specimen does not reach the desired level.

The formation of flexural cracks beyond cracking moment results in a significant reduction in the flexural rigidity. This reduction is much more drastic in lightly-reinforced beams. As a result, the major difference between the flexural rigidities of the original and repaired beams in the first cycle vanishes and becomes insignificant in the further cycles even in the presence of low reinforcement ratio. The values in Table 3 also indicate that the flexural rigidities of the repaired specimens were higher in the first cycle in the reverse direction of loading. As stated before, the beams were subjected to smaller deformations in reverse direction, and therefore, less capillary cracks formed in the beam soffit, causing a greater rigidity in this direction.

The experimental ultimate load values of the repaired specimens are in rather close agreement with the respective values of the original specimens (Table 4). This conclusion is valid for all specimens with different reinforcement ratios. The repaired-to-original ultimate load ratio ranged between 0.95 and 1.14 in the present experimental program, indicating that the repaired specimens were able to reach the bending capacities of their original counterparts irrespective of the damage level before repair and the amount of flexural reinforcement. Similarly, all of the original and repaired specimens reached ultimate load values in close agreement with the theoretically calculated values both in the forward and reverse directions of loading. The experimental-to-analytical ultimate load ratio varied between 0.84 and 1.26 in the present experimental program with the most of values in the 0.96-1.05 interval. The analytical flexural capacities were calculated by using the concrete and steel strength values from the material tests and the Todeschini et al. [15] concrete stress-strain model. Although all of the repaired specimens reached the experimental ultimate load values of their original counterparts and the calculated bending capacity values, this ultimate load was attained after excessive deformations generally in the second or third cycles (Fig. 10), particularly in the forward direction of loading. In heavily-reinforced repaired beams, the transition between the elastic and inelastic portions of the load-deflection curve can be seen to be much milder due to the elastic nature of epoxy and abundance of this material in the beam.

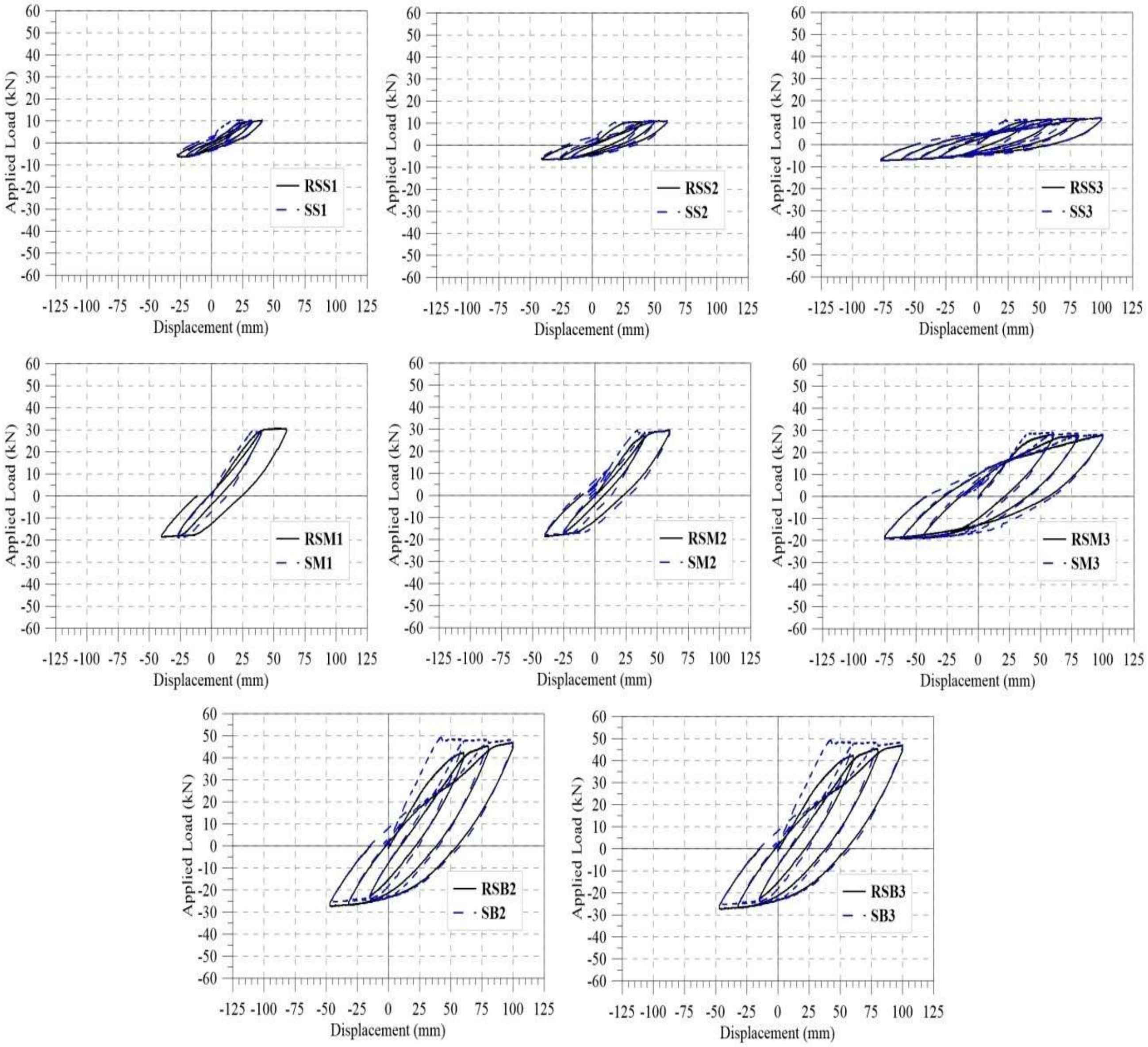

Fig. 10 - Load-deflection curves of specimens

4. Conclusions

The efficiency of the epoxy resin injection repair technique in RC beams with different longitudinal reinforcement ratio and subject to different levels of damage before repair was investigated experimentally and analytically in the present study. Nine undamaged original and nine damaged and repaired RC beams were tested under reversed cyclic transverse loading, simulating the presence of reversal of moments in RC beam-column connections during an earthquake. The original reference and repaired beams were tested under identical experimental conditions to provide a healthy comparison between the test results and to accurately evaluate the efficiency of repair.

The results of the present study were carefully interpreted owing to the importance of this novel repair technique, which can facilitate the repair of damaged RC beams after an earthquake due to many advantages and superiorities over the remaining repair methods. The most important conclusions of the study are summarized as follows:

- The most important factor for the efficiency of epoxy injection repair is the crack width of the beam to be repaired. If the flexural cracks in the beam are too narrow, the epoxy resin cannot be properly injected to the cracks and the repair does not provide adequate improvement in the repaired beam behavior. If the flexural cracks are too wide, the epoxy resin in the cracks controls the flexural behavior of the beam. In other words, the flexural rigidity of the beam is reduced and the deflections increase due to the over presence of epoxy. For all these reasons, the epoxy resin injection technique is most efficient in RC beams with medium-width cracks, i.e. subject to moderate damage before repair.
- The flexural rigidities of the repaired specimens were observed to be lower than the rigidities of the respective original beams at the initiation of loading. The difference between the flexural rigidity of a repaired beam and its virgin counterpart decreases in the further cycles of loading. This finding can be attributed to the fact that the flexural rigidity of an RC beam is mainly provided by the flexural reinforcement, not concrete itself, in the further stages of loading, as the number and extent of flexural cracks increase. The repaired beams with identical longitudinal reinforcement ratio but different damage level were determined to have close flexural rigidities.
- The repaired specimens were able to reach the flexural capacities of their virgin counterparts irrespective of the damage level and flexural reinforcement ratio. Nonetheless, the repaired specimens reached the ultimate load values at greater deflections as compared to the original beams. The experimental ultimate bending moment values of the original and repaired specimens were in close agreement with the calculated flexural capacity values.
- In repaired specimens, the reduction in the flexural rigidity with the initiation of cracking increased with increasing longitudinal reinforcement. However, the presence of epoxy provided a milder transition between the elastic and inelastic portions of the load-deflection curve. The flexible nature of epoxy provided the transition zone of the curve to resemble the shape of a bow.

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