Journal of Engineering and Development, Vol. 10, No. 3, September (2006) ISSN 1813-7822

Behavior of Repaired Reinforced Concrete Beams Failed in Shear

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Abstract

This paper presents an investigation of the strength and deformation characteristics of reinforced concrete rectangular beams failed in shear and repaired by epoxy injection.

Five simply supported reinforced normal-strength concrete (NSC) beams without shear reinforcement are used. The span of the simply supported beams is 1.28 m with 100 mm wide by 200 mm deep cross section. All beams are tested under two-point loads.

A method of epoxy injection is used to repair cracks in the failed-in-shear beams. Careful repair process is adopted and proved successful.

The Main conclusions are: a successful repair method is used to increase or at least restore the shear capacity of beams; repaired diagonal shear cracks do not reopen after retesting, instead, new nearby diagonal shear cracks are developed and the repaired beams show a lower stiffness and greater ductility than the original beams.

الخلاصـــــــة

يقدم هذا العمل بحثاً عن خواص مقاومة و تشوه العتبات الخرسانية المسلحة مستطيلة المقطع المصنوعة من الخرسانة الفاشلة مسبقا بالقص و المصلحة بوساطة حقن التشققات (بالايبوكسي).

تم استخدام خمس عتبات خرسانية مسلحة بسيطة الإسناد بدون تسليح القص. الفضاء الصافي للعتبة بسيطة الإسناد كان (1.28 m) و ذات مقطع بأبعاد (100 mm) عرضا و(200 mm) عمقا و قد أجريت الفحوص على العتبات بأحمال ثنائية مركزة.

استخدمت طريقة الحقن بالايبوكسي لإصلاح التشققات في العتبات الفاشلة بالقص و قد تم تنفيذها بعناية لملء التشققات بالايبوكسي و قد أثبتت الطريقة نجاحها.

إن أهم الاستنتاجات الرئيسية هي: نجاح طريقة الإصلاح في زيادة أو على الأقل استعادة مقاومة القص للعتبات، إن التشققات القصية القطرية لم يعاد فتحها بعد الإصلاح بينما تشكلت تشققات قصية قطرية جديدة قريبة. وبصورة عامة، فان السلوك الإنشائي للعتبات المصلحة كان مشابها لسلوك العتبات الأصلية مع جساءة اقل ومطيليه أعلى.

1. Introduction

The purpose of repair is to improve the function and performance of the structure, restore and increase the strength and stiffness, improve appearance of the concrete surface, provide water tightness, prevent access of corrosive materials to the reinforcement, and improve the durability performance of the structure [1,2].

Reinforced concrete beams can be deficient in their shear capacity due to a variety of factors. They require immediate repair to prevent further degradation and to restore their structural integrity.

The proper repair of deteriorated concrete structures depends on the precise diagnosis and evaluation of the cause of deterioration. Consequently, the first step in a successful repair program is to carry out a systematic field investigation to diagnose and evaluate the cause and factors contributing to the deterioration. Based on the conclusion of the careful evaluation of the causes, extent, and consequences of deterioration, the repair techniques and repair materials can be selected [1,3].Epoxy adhesives have been used extensively in the repair and rehabilitation of damaged reinforced concrete structures. This investigation is carried out to study the behavior of repaired (by epoxy injection) beams that failed in shear.

2. Shear Failure of Reinforced Concrete Beams

Shear failure in reinforced concrete members is sudden and catastrophic in nature and should be avoided in the design process. That is why reinforced concrete members are first dimensioned in flexure and then checked for shear. Failure occurs when the tensile stresses induced by shear, along with the horizontal stresses due to bending, exceed the diagonal tensile strength of the material [4,5,6]. Therefore, shear failures in concrete members are diagonal tension phenomena. The failures occur in an inclined plane due to the combined shear and flexural stresses. There are basically two definitions for the nominal shear strength; the cracking shear strength, Vc/bd (the shear strength at the occurrence of first major diagonal crack) and the ultimate shear strength, Vu/bd (the shear strength when complete and total failure occurs) [7].

2-1 Mechanisms of Shear Failure

Various modes of diagonal failure exhibited by reinforced concrete beams under increasing load are connected with the multiaxial stress condition that exists in the region of the path along which the compressive force is transmitted from support to support (compressive force path) [8]. Diagonal failure is usually investigated by testing reinforced concrete beams under two-point load. The sequence of cracks formation shown in **Fig.(1)** is observed to be a common one for beams with large shear span to depth ratio [9].

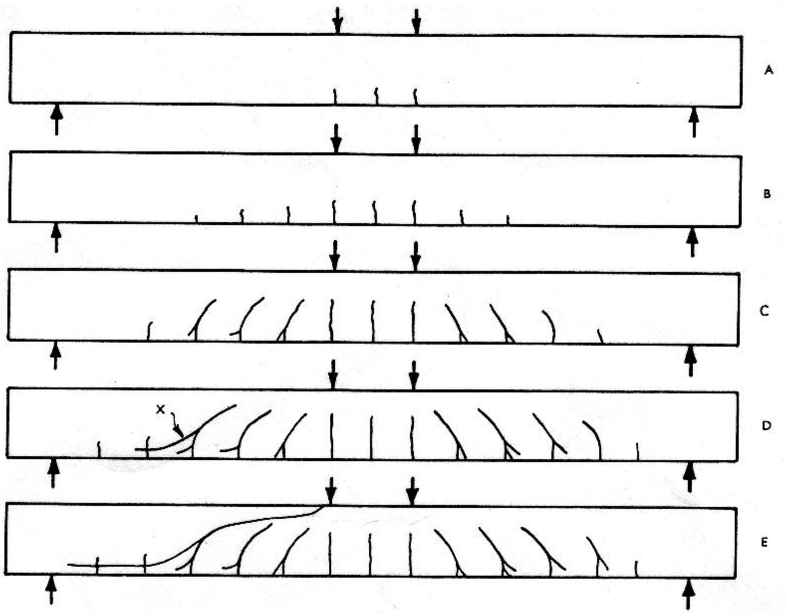

Figure (1) The formation of cracks under increasing load [9]

2-2 Variables Affecting Shear Strength

In the early 1950s, Clark introduced a mathematical expression for the nominal shear strength prediction that included the following three variables: shear span to depth ratio, longitudinal tensile reinforcement ratio, and concrete compressive strength [7].

Subsequent to these findings, other variables such as the maximum aggregate size; spacing of the flexural cracks and diameter of tensile reinforcing bars have also been found to influence the shear strength of concrete members. Nevertheless, it is now widely accepted that the three main variables affecting the shear strength of concrete members without shear reinforcement are the concrete compressive strength (f_c'), shear span to depth ratio (a/d), and tensile reinforcement ratio (ρ) [10].

3. Repair of Cracks in Concrete Structures

Cracks need to be repaired if they reduce the strength, stiffness, or durability of the structure to an unacceptable level, or if the function of the structure is seriously impaired.

3-1 The Use of Epoxy with Concrete

Epoxy resins find wide application as grouting materials. The filling of cracks, either to seal them from the entrance of moisture or to restore the integrity of a structural member is one of the most frequent applications. Cracks of 6mm width or less are most effectively filled with a pourable or pumpable epoxy compound, whereas epoxy resin mortar should be used for wider cracks. Epoxy resins are useful as grouts for setting machine base plates and for grouting metal dowels, bolts and posts into position in concrete [11,12].

3-2 Epoxy Injection

Cracks in concrete as narrow as 0.05mm can be bonded by injection of epoxy compounds under pressure [2,13]. Epoxy injection has been successfully used in the repair of cracks in buildings, dams, and other types of concrete structures [14].However, unless the crack is dormant (or the cause of cracking is removed, thereby making the crack dormant), it will probably recur near actively leaking and cannot be dried out [2,13,15].

In 1975, Chung [16] tested three reinforced concrete beams up to flexural failure. The beams were then repaired with an epoxy injection. His conclusions are:

1. The flexural strength of the repaired beam is not less than that of the original beam.
2. The repaired beam may be slightly stiffer than the original beam, but the loss of ductility is not significant.
3. The repaired cracks do not reopen even at failure of the beam.

Popov and Bertero [17] subjected some reinforced cantilever beams repaired by resin injection to a number of reversed loading cycles designed to simulate earthquake load to a structure. It was found that the repaired beams are capable of resisting numerous applications of cyclic loading. In the repaired beams, new cracks are usually formed at different locations. The repaired beams are seen to be somewhat less stiff than in the undamaged condition.

In 1985, Mansur and Ong [18] tested six reinforced concrete beams, each with a large rectangular opening, and severely damaged during a test program. These beams were then repaired, with loose concrete removed and replaced with epoxy mortar then the cracks were filled by epoxy injection.

From the testing of repaired beams, they concluded:

1. All cracks repaired by epoxy injection do not reopen at ultimate load.
2. The presence of hairline cracks in the repaired beams is responsible for the reduced stiffness, and hence higher deflection results.

In 1986, Plecnik et. al. [19] studied the behavior of epoxy repaired beams under fire. About 200 beams were tested. Shear reinforcement was not provided and both rectangular and T-sections were considered. They concluded that the behavior of epoxy repaired beams under uniform temperature of fire exposure is greatly determined by the type of crack formation and the extent of epoxy repair. For shear type epoxy repaired cracks, the strength and stiffness of the beams are primarily determined by epoxy strength which is negligible above 400^{o}F (204^{o}C).

In 1989, Aziz et. al. [20] studied the effectiveness of epoxy resin injection and resin bond anchors and steel plates to restore strength and stiffness of reinforced concrete beams which fail primarily due to the formation of major diagonal cracks. Their conclusions are:

1. The strength of reinforced concrete beams can be restored with epoxy resin injection coupled with or without resin bonded anchors and steel plates.
2. The repaired or repaired and strengthened beams are less stiff than corresponding undamaged beams because very fine cracks are not easily accessible to resin injection.

3. Failure of the repaired or strengthened beams is mainly due to the formation of new diagonal cracks. Old repaired cracks do not seem to be affected.

In 1990, French et. al. [21] conducted two test series to determine the effectiveness of epoxy techniques to repair moderate earthquake damage. Two interior reinforced concrete subassemblages were subjected to a series of cyclic lateral loads to simulate moderate earthquake damage. The specimens were then repaired with one of two epoxy repair techniques: pressure injection or vacuum impregnation. The repaired specimens were then subjected to the same load history as the original specimens. They concluded that both techniques work well in restoring the strength, stiffness, energy dissipation capacity, and bond of the specimens.

Collins and Reper [22] tested a series of beams unreinforced in shear. The beams were loaded until a major diagonal tension crack developed on both shear spans. Individual beams were then repaired and retested. Four techniques of repair were used: resin injection, post-tensioning, bar bonding, and stitching.

In 2002, a study was conducted by NAHB research center [23] to evaluate the performance of epoxy injection crack repair of unreinforced concrete stem walls and slabs on grade for different loading conditions, crack widths, and epoxy repair strategies (e.g. epoxy mix viscosity and injection method). The major conclusions from this study are:

1. Crack repairs are completely effective for less than 1.58mm and 6.35mm crack widths, because the epoxy viscosity selection appears straight-forward.
2. A variety of viscosities and methods is used for repair of the 3.17 mm wide cracks, several of which are successful. Unsuccessful repairs are the result of epoxy seeping out of the cracks into the sand bedding.

4. Experimental Work

The experimental work of this study consists of casting, testing up to failure in shear, repairing and retesting five rectangular reinforced normal-strength concrete beams without shear reinforcement. Details of the work stages mentioned above are presented in this section.

4-1 Materials

4-1-1 Cement

Ciplin ordinary cement, manufactured in Lebanon, complying with Iraqi standard specification No.5/1984 [24] is used throughout this study. The chemical analysis and physical test results of the used cement are shown in **Tables (1)** and **(2)**, respectively.

4-1-2 Fine Aggregate

Al-Ukhaidher natural sand is used for concrete mixes in this study. The grading of the fine aggregate which conforms to the Iraqi standard specification No.45/1984 [25] is shown in **Table (3)**.

Table (1) Chemical composition of cement #

Chemical composition	percent	Limits of Iraqi spec. No.5/1985
CaO	62.33	
SiO_2	22.01	
Al_2O_3	5.49	
Fe_2O_3	3.93	
MgO	2.54	5*
SO_3	1.92	2.8*
L.O.I	0.83	4.0*
Insoluble residue	1.2	1.5*
L.S.F	0.86	0.66-1.02
C_3S	35.66	
C_2S	36.2	
C_3A	7.91	
C_4AF	11.95	

 # All tests are made in Falloja Cement Factory.
** Maximum limit.*

Table (2) Physical properties of the cement #

Physical properties	Test result	Limits of Iraqi spec. No.5/1985
Fineness using Blain air permeability apparatus (m^2/kg)	288.9	230**
Soundness using Autoclave method	0.4	0.8%*
Setting time using Vicat's instruments Initial (min) Final (hr)	 160 4	 45** 10*
Compressive strength for cement paste cube (70.7mm) at 3 days (MPa) 7 days (MPa) 28 days (MPa) 56 days (MPa)	 26 37 46 60	 15** 23** … …

 # All tests are made in Falloja Cement Factory.
** Maximum Limit.*
*** Minimum Limit.*

Table (3) Grading of fine aggregate *

Sieve size (mm)	% Passing	
	Fine aggregate	Limits of Iraqi spec. No.45/1984 for zone(2)
4.75	100	90-100
2.36	87.55	75-100
1.18	73.97	55-90
0.600	36.3	35-59
0.300	8.34	8-30
0.150	0.77	0-10

** The test is carried out in the laboratory of constructional materials in College of Engineering /Al-Mustansiriya University.*

4-1-3 Coarse Aggregate

The coarse aggregate used is crushed river gravel with maximum size of 20mm.The gradation of this coarse aggregate conforms to the Iraqi Standard Specification No.45/1984 [25], as shown in **Table (4)**.

Table (4) Grading of coarse aggregate *

Sieve size (mm)	% Passing	
	Coarse aggregate	Limits of Iraqi spec. No.45/1984 for size 5-20
20	100	95-100
14	84.53	—
10	51.59	30 - 60
5	5.6	0 - 10

** The test is carried out in the laboratory of constructional materials in College of Engineering /Al-Mustansiriya University.*

4-1-4 Steel Reinforcement

Hot rolled deformed steel bars of 10mm diameter are used as longitudinal reinforcement in all beams, while no shear reinforcement is used. Three 400mm long specimens from this steel are tested at the laboratory of constructional materials in the College of Engineering/ Al-Mustansiriya University to determine the average yield stress (f_y) and the ultimate strength (f_u). The test results are, as follows:

$f_y = 483\ MPa$, $f_u = 720\ MPa$

4-1-5 Epoxy Resin

A two part, solvent-free, low viscosity, named Conbextra EP10 epoxy injection resin is used for the repair of the beams. It has many advantages such as suitability for hot climates, excellent bond to concrete, and no-shrinkage. The properties of Conbextra EP10 (according to the manufacturer) are listed in **Table (5)**.

Table (5) Properties of Conbextra EP10

Property	Typical results
Compressive strength*	70.0 MPa @20°C 93.0 MPa @35°C
Tensile strength*	26.0 MPa @35°C
Flexural strength*	63.0 MPa @35°C
Young's modulus in compression	16.0 GPa
Pot life	90 minutes @20°C 40 minutes @35°C
Specific gravity	1.04
Mixed viscosity	1.0 poise @35°C

**At 7 days*

4-2 Concrete Mix Proportions

Mix proportions are selected depending on several trial mixes. The beams are designated as B1, B2, B3, B4 and B5. Mix proportions of reference beam (B1) are 1:1.5:3 (cement: fine aggregate: coarse aggregate) by weight, which is a common proportion for normal strength concrete (NSC) with water-cement ratio of 0.6. Beams B2 and B3 are made with the same proportions as B1, but with water-cement ratio of 0.5. B4 and B5 have mix proportions of 1:1.6:2.5 and water-cement ratio of 0.45 to obtain a higher concrete strength than that obtained by previous concrete mix. Maximum size of coarse aggregate used for NSC beams is 20mm. The cylinder compressive strengths obtained at 28 days are 21, 26, 27, 29, and 34 MPa respectively, **Table (6)**.

Table (6) Concrete mix proportions

Beam designation	C:FA:CA (by weight)	w/c (by weight)	Ave. f'_c (MPa) (28 days)
B1	1:1.5:3	0.6	21
B2	1:1.5:3	0.5	26
B3	1:1.5:3	0.5	27
B4	1:1.6:2.5	0.45	29
B5	1:1.6:2.5	0.45	34

4-3 Details of Beams Testing

All beams are tested under two point loading with shear span to effective depth ratio (a/d) of 2.83.10-mm diameter steel bars are used as the tensile reinforcement. Stirrups are not provided in the shear spans in order to ensure shear failure in the beams where the calculated loads which cause flexural failure for all the beams are greater than those causing shear failure. Deflections are measured at midspan of the beams using a dial gage having a minimum gradation of 0.01mm. **Figure (2)** shows general details of the beams.

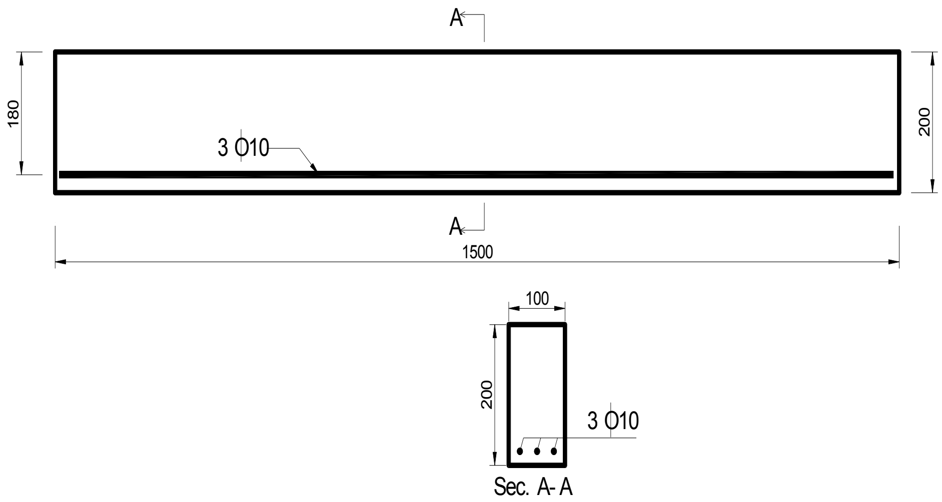

Figure (2) Details of beams reinforcement (All dimensions are in millimeter)

4-4 Test Procedure

The load is applied in small increments and the dial gage readings are taken every 4kN until failure occurs. The deflections are recorded at each level of loading. Cracks are detected and their widths are recorded at several levels of loading. **Figure (3)** shows the loading arrangement used throughout the tests.

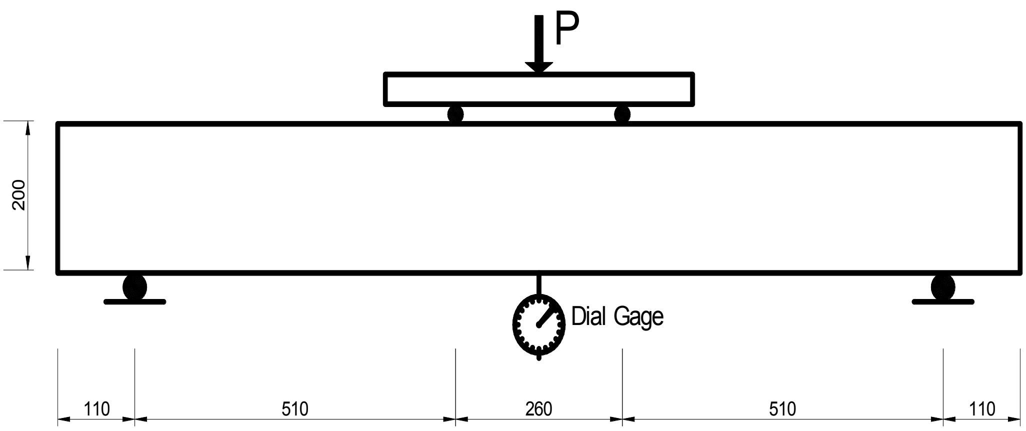

Figure (3) Loading arrangement of the tested beams (All dimensions are in millimeter)

4-5 Repairs of Cracks in Failed Beams

The method of epoxy injection is used in this study to repair cracks in the failed beams. Since the beams are designed to fail in shear, the major cause of failure is the formation of diagonal tension cracks in the shear span. Thus, repair work is focused on applying the injection technique to the major diagonal cracks and other (minor) cracks formed along the beam, while hairline cracks are ignored because of their insignificant effect and the practical difficulty in treating them.

4-5-1 Repair Procedure

The following steps are followed in the epoxy injection repair process for each failed beam:

1. After shear failure, the cracks and their neighboring areas are cleaned from dust, debris and other contaminants by applying compressed air using electrical blower to ensure good penetration of the resin and proper bond of the crack paste.

2. Surface ports are then fixed along the considered crack. The port has an opening at the top for the epoxy to enter and a flange at the bottom bonded to the concrete. The ports are placed 10-15cm apart. The port is fixed in its proper position by applying an epoxy paste to the flange portion of the port taking care not to cover the hole, and then tacking it in place.

3. Epoxy paste is then used to seal over the surface ports and the exposed cracks. The paste is extended 20-30mm on either sides of the crack with 2-3mm thickness to prevent resin seepage. The beam is then left for 30-45 minutes to ensure complete curing of the paste.

4. The two components of epoxy resin are then mixed in a metal batch using a mechanical stirrer at a proportion of 1(base): 3(hardener) by volume, according to the manufacturer's instructions.

5. A mechanical injection gun is fed with the mixed epoxy and the injection process started. The injection process began by pumping epoxy into the lowest port until the epoxy began to flow from the port above it. The first port was then plugged with a cap, and the process was repeated until the crack has been completely filled and all ports have been capped. Low pressure was used in injecting epoxy into the cracks. A curing period of about 24 hours was provided to the injected epoxy.

6. After the injected epoxy has cured, the ports were removed by striking with a hammer and the surface seal was chipped. **Figure (4)** shows the injection process.

4-6 Retesting after Beam's Repair

After the repair process is completed, the repaired beams are retested to evaluate the efficiency of the repair work. Loading arrangement and test procedures of the repaired beams are the same as those described for the original beams.

Figure (4) Epoxy injection process

5. Results and Discussion

5-1 Shear Cracking and Ultimate Loads

In general, the structural behavior of the repaired beams is similar to that of the original beams. Failures in both cases are characterized by diagonal cracking in the shear spans. At the same time, some flexural cracking occurs in areas where the shear force is low.

The load, at which diagonal shear cracks first formed in the original and the repaired beams, is defined as the shear cracking load (V_c).The ratios of the shear cracking load for the repaired beams (V_{cr}) to the shear cracking load for the original beams (V_{co}) are found to vary between 1.038 to 1.200 for all beams.

Table (7) Shear cracking and ultimate loads for the tested beams

Beam	f'_c (MPa)	Original beam		Repaired beam		Ratio V_{cr}/V_{co}	Ratio V_{ur}/V_{uo}
		V_{co} (kN)	V_{uo} (kN)	V_{cr} (kN)	V_{ur}(kN)		
B1	21	36	42	40	48	1.111	1.142
B2	26	40	46	48	53	1.200	1.152
B3	27	38	46	42	51	1.105	1.108
B4	29	56	58	60	62	1.071	1.068
B5	34	52	58	54	58	1.038	1.000

The load, at which failure occurs in the beam, is defined as the ultimate shear load (V_u). The beams ultimate shear load ratio (V_{ur}/V_{uo}) varies between 1.000 to 1.152 for all beams. **Table (7)** presents the shear cracking and ultimate loads for both the original and repaired beams and their corresponding ratios. The results generally indicate that the repaired beams have at least restored their original shear strength.

In general, more than one diagonal crack has developed in both the original and repaired beams, but one of them will cause failure. In this study, the diagonal crack which causes failure in the original beams is called "major diagonal crack", while the others are called "minor diagonal cracks".

The five beams designated as B1, B2, B3, B4 and B5 having cylinder compressive strengths of 21, 26, 27, 29 and 34 MPa, respectively. The test results of the beams are discussed in the following sections.

5-2 Behavior of Original Beams

Generally, in the original beam, the first shear crack started at one shear span at the beam bottom, near the support, and it propagated towards the nearest loading point as an inclined crack (diagonal crack). Some fine flexural cracks were observed before and at the appearance of the first diagonal crack. In some beams (such as B1), after increasing the applied load, another diagonal crack was developed at the other shear span of the beam. With more applied load, the first (major) diagonal crack rapidly propagated to the nearest loading point, and then collapse happened by splitting the beam along this crack.

The major diagonal cracks were developed at the right shear span for beams B1, B2 and B5, while they were developed at the left shear span for beams B3 and B4, as shown in **Figs.(5 to 9)**. The maximum crack widths measured at failure for the major diagonal cracks are 1.4, 0.6, 0.4, 0.95 and 0.6mm for beams B1, B2, B3, B4 and B5, respectively.

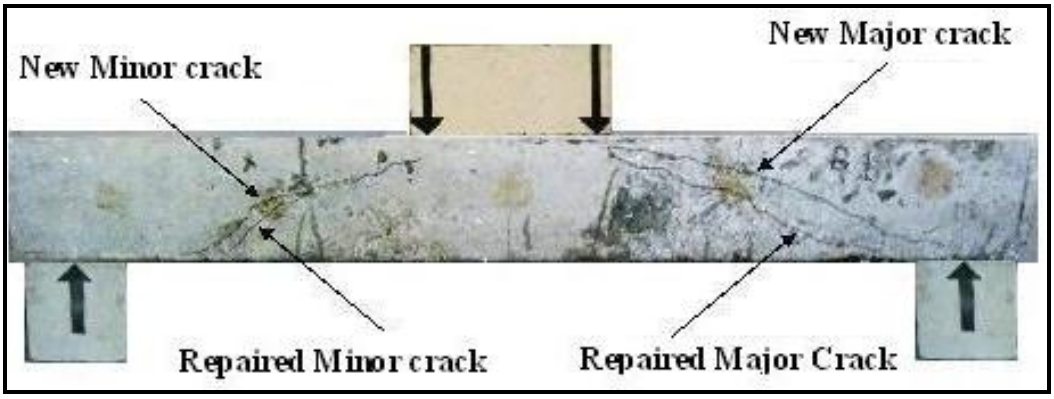

Figure (5) Beam B1 after repairing and retesting

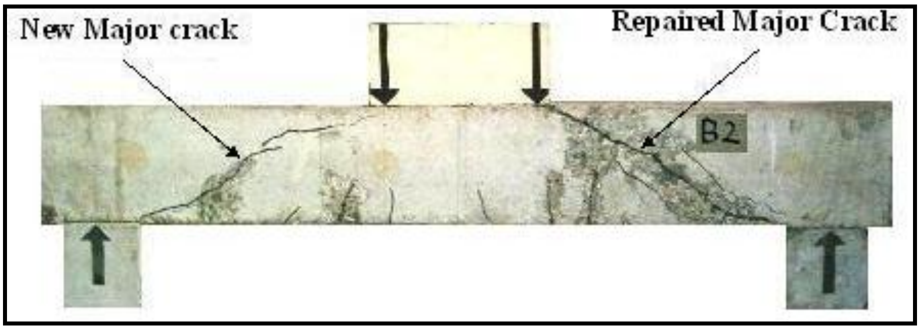

Figure (6) Beam B2 after repairing and retesting

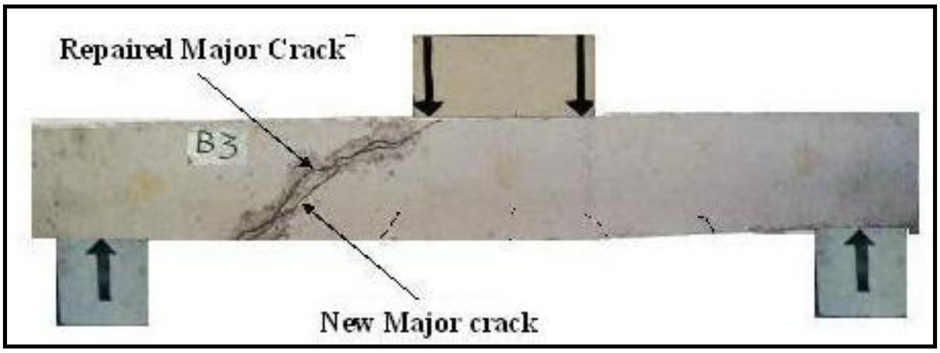

Figure (7) Beam B3 after repairing and retesting

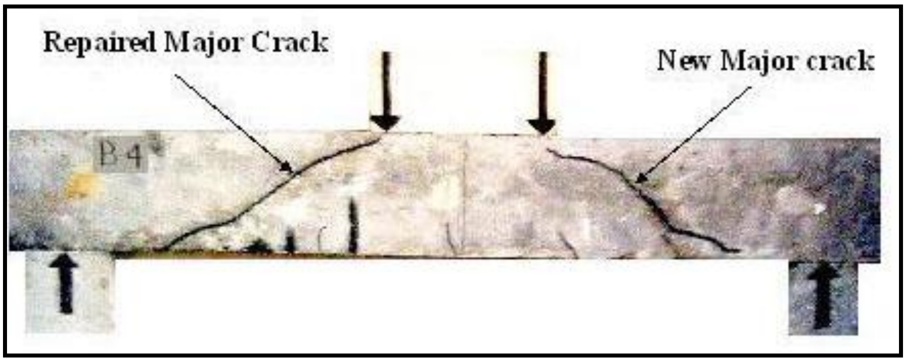

Figure (8) Beam B4 after repairing and retesting

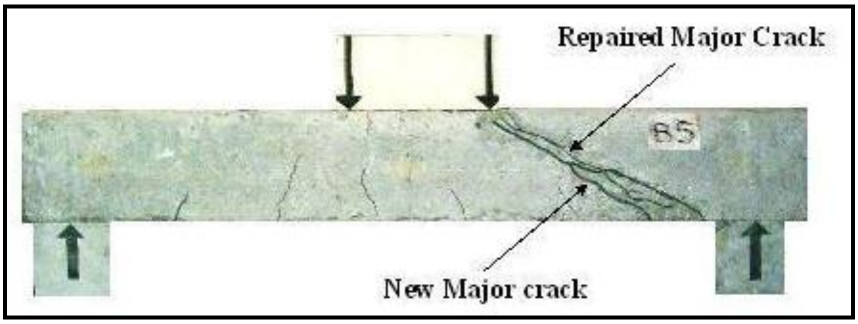

Figure (9) Beam B5 after repairing and retesting

5-3 Repairing Process

After failure of the beams, the repairing process was followed for each beam. The injection process was done successfully for all beams and easily for beams B2, B4 and B5 because the cracks in these beams are wide enough to allow easy penetration of the injected resin. For beam B1, the injection process was easier for the major diagonal crack because of the relatively large width which allowed easier penetration of the epoxy resin. On the other hand, the injection process for beam B3 was done with some difficulty in which the process took relatively longer time because of the relatively small width of the diagonal crack.

5-4 Behavior of Repaired Beams

After testing the repaired beams, the repaired major and minor diagonal cracks in all the beams did not reopen and the beams failed due to new diagonal cracks developed with approximately the same formation sequence as the major diagonal cracks in the original beams. The new diagonal crack is developed adjacent to (in beam B3) or near (in beams B1 and B5) the repaired major crack, or at the other shear span (in beams B2 and B4) away from the repaired major crack. A new minor diagonal crack is developed near the repaired minor diagonal crack in beam B1, **Figs.(5 to 9)**.

5-5 Shear Strength Results

The shear cracking loads for the repaired beams are greater than those for the original beams. The ratios of the shear cracking loads for the repaired beams to the shear cracking loads for the original beams (V_{cr}/V_{co}) are 1.111, 1.200, 1.105, 1.071 and 1.038 respectively.

The shear ultimate loads for the repaired beams are greater than (or equal to) those for the original beams. The ratios of the shear ultimate loads for the repaired beams to the shear ultimate loads for the original beams (V_{ur}/V_{uo}) are 1.142, 1.152, 1.108, 1.068 and 1.000 respectively. This indicates that the adopted repair processes are successful in restoring and increasing the shear capacity of the beams.

5-6 Deformation Results

In general, the load-deflection behavior of the repaired beams is nearly similar to that of the original beam, **Figs.(10 to 14)**.The deflections at shear cracking loads D_c and maximum deflections D_{max} of the repaired beams are greater than the corresponding deflections of the original beams, **Table (8)**.

The load-deflection curves of the repaired beams, **Figs.(10 to 14)**, show, as may be expected, a lower stiffness and greater ductility than those in the original beams. This may be attributed to the difference in stiffness between an integrated (original) beam and a bonded (repaired) beam, and to the presence of hair line cracks in the repaired beams.

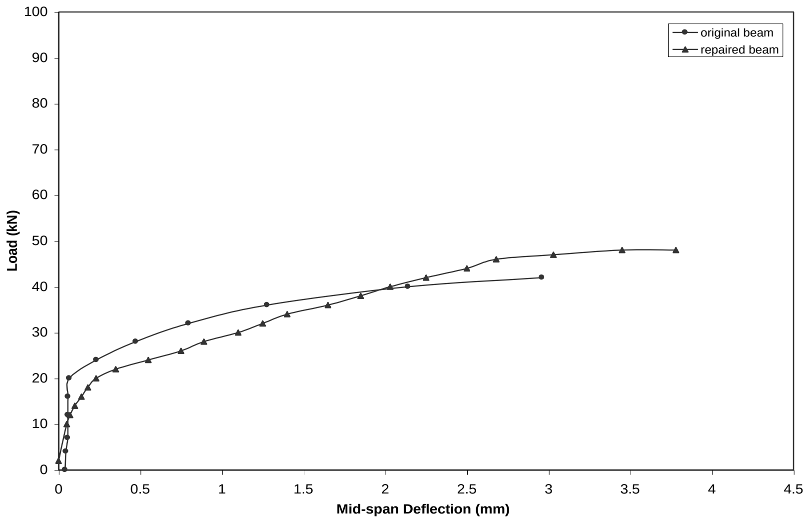

Figure (10) Load-deflection curve for beam B1

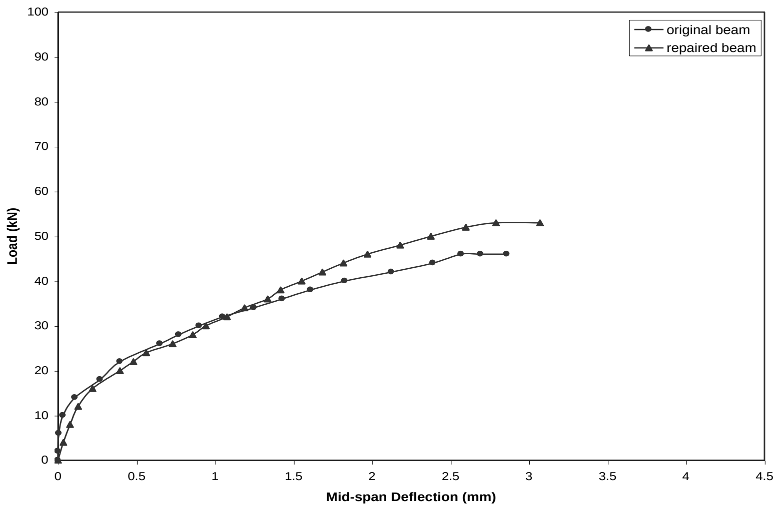

Figure (11) Load-deflection curve for beam B2

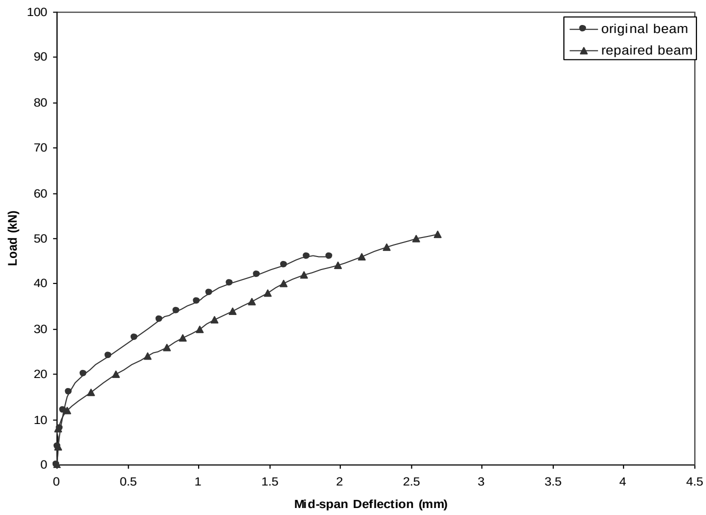

Figure (12) Load-deflection curve for beam B3

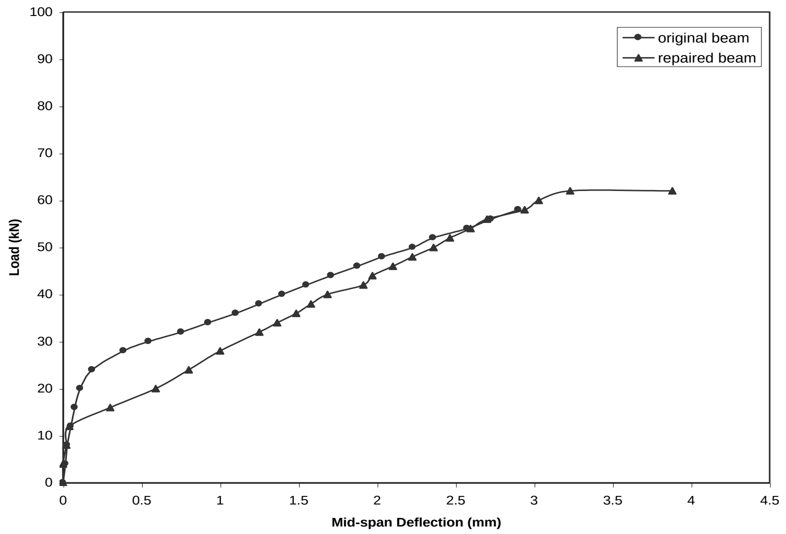

Figure (13) Load-deflection curve for beam B4

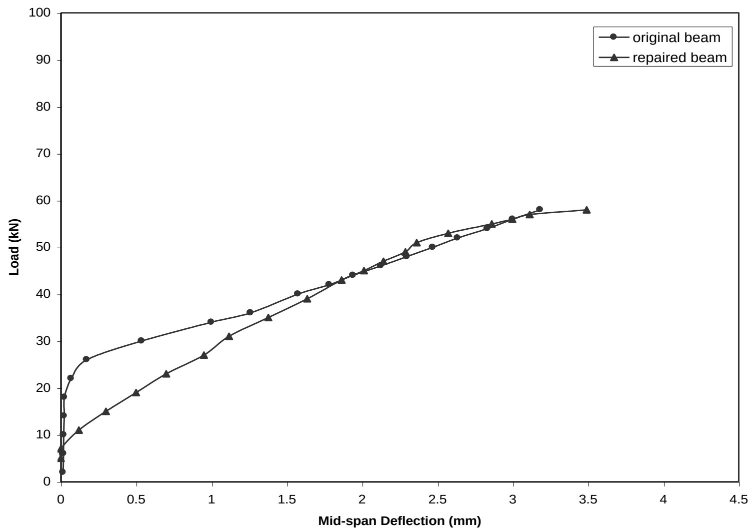

Figure (14) Load-deflection curve for beam B5

Table (8) Shear cracking and maximum deflections for the tested beams

Beam	f'_c (MPa)	Original beam		Repaired beam		Ratio $D_{c,r}/D_{c,o}$	Ratio $D_{max,r}/D_{max,o}$
		$D_{c,o}$ (mm)	$D_{max,o}$ (mm)	$D_{c,r}$ (mm)	$D_{max,r}$ (mm)		
B1	21	1.278	2.960	2.030	3.780	1.588	1.277
B2	26	1.828	2.860	2.180	3.070	1.192	1.073
B3	27	1.076	1.928	1.740	2.688	1.617	1.394
B4	29	2.725	2.900	3.030	3.880	1.111	1.337
B5	34	2.635	3.182	2.716	3.490	1.030	1.096

5-7 Effect of Compressive Strength on Shear Strength of the Tested Beams

The experimentally obtained shear cracking and ultimate loads show an increase with the increase of compressive strength (f'_c) for both original and repaired beams, as shown in **Fig.(15)**.

Figure (15) shows that the experimental results give values of shear cracking loads for both original and repaired beams higher than those predicted by ACI Building Code Equation (11-5) [26]. This equation ($V_c=[\sqrt{f'_c}+120\rho(V_u d/M_u)](bd/7)$) seems to give relatively more conservative values for higher strength beams.

In general, the trend of relation between shear cracking and ultimate loads for the repaired beams and compressive strength is similar to that for the original beams, see **Fig.(15)**.

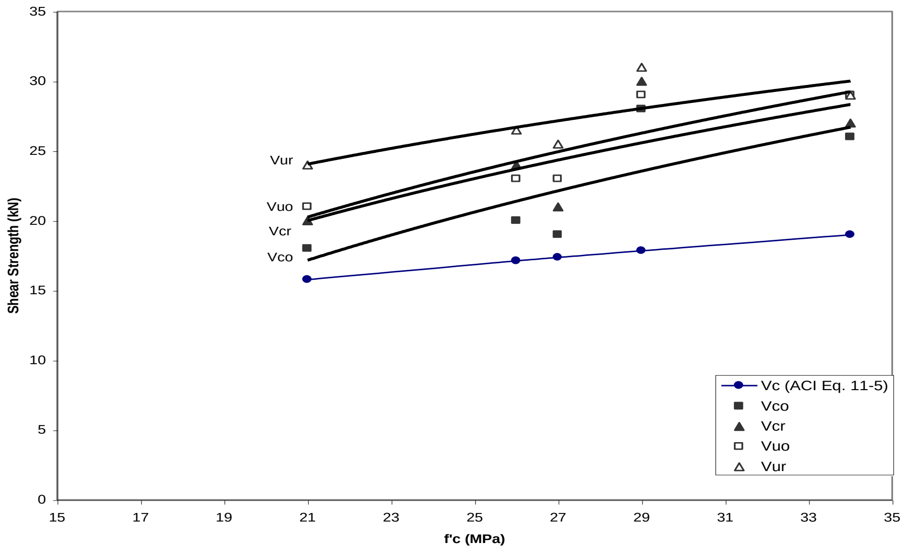

Figure (15) Effect of compressive strength on shear strength of the tested beams

6. Conclusions

Based on the results of this study, the following conclusions can be drawn:

1. The structural behaviors of the five repaired beams by epoxy injection are similar to those of the original beams. Failures in both cases are characterized by diagonal cracking in the shear spans.

2. Repair of reinforced normal-strength concrete beams, without shear reinforcement that failed in shear using epoxy resin injection method is successful in increasing (or at least restoring) the shear capacity of the beams after repair. The increase in shear capacity reached 15.2% of the original shear capacity in Beam B2.

3. The repaired beams showed a lower stiffness and greater ductility compared with the original beams.

4. The repaired major diagonal cracks did not reopen and the repaired beams failed due to formation of new major diagonal cracks.

5. The crack injection process using a manual injection gun is done successfully and easily for cracks whose widths range from 0.5 to 1.0 mm and easier for wider cracks. For crack widths less than 0.5 mm, the process is done with some difficulty because these small widths of diagonal cracks limit easy penetration of the epoxy resin into the cracks.

6. The experimental shear cracking loads for both original and repaired beams are greater than those predicted by ACI Building Code Equation (11-5).

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