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Behavior of Repaired Reinforced Normal and High Strength Concrete Beams Failed in Shear

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Abstract

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

Eight simply supported reinforced concrete beams without shear reinforcement are tested, four of which are made with normal-strength concrete (NSC) and four with high-strength concrete (HSC). The span of the simply supported beams is 1.28 m with 100 mm wide by 200 mm deep cross section. All are tested under two-point loads.

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

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

الخلاصـــــــة

يقدم هذا العمل بحثاً عن خصائص مقاومة و تشوه العتبات الخرسانية المسلحة مستطيلة المقطع المصنوعة من الخرسانة الاعتيادية وعالية المقاومة الفاشلة مسبقا بالقص و المصلحة بوساطة حقن التشققات بالايبوكسي.

تم استخدام ثمان عتبات خرسانية مسلحة بسيطة الإسناد بدون تسليح القص، أربع منها مصنوعة من خرسانة اعتيادية وأربع من خرسانة عالية المقاومة. الفضاء الصافي للعتبة بسيطة الإسناد كان ١.٢٨ م و بأبعاد مقطع ١٠٠ ملم عرضا و ٢٠٠ ملم 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: نجاح طريقة الإصلاح في زيادة أو على الأقل استعادة مقاومة القص للعتبات حيث كانت الزيادة ملحوظة و بقيمة اعلي في العتبات اعتيادية المقاومة، التشققات القصية القطرية لم يعاد فتحها(عموما) بعد الإصلاح بينما ظهرت تشققات قصية قطرية جديدة قريبة. و بصورة عامة، فان السلوك الإنشائي للعتبات المصلحة كان مشابها لسلوك العتبات الأصلية مع صلادة 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 of reinforcement, and improve the durability performance of the structure [1,2].

Reinforced concrete beams can be deficient in 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 carryout 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 causes, extent, and consequences of deterioration, the repair techniques, repair procedures, and repair materials can be selected [1,3]. Epoxy adhesives have been used extensively in the repair and rehabilitation of reinforced concrete structures damaged by several causes. In this work, investigation is carried out to study the behavior of repaired (by epoxy injection) beams 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 out for shear. Failure occurs when tensile stresses induced by shear, along with 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 a 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

The 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 a large ratio of shear span to depth [9].

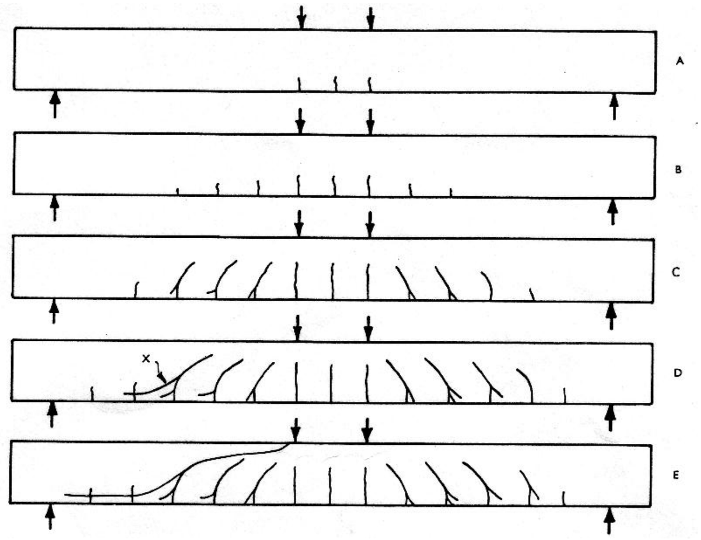

Figure (1) The formation of cracks under increasing load [9]

2-2 Variables Affecting Shear Strength

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

Subsequent to these findings, other variables such as 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'), the shear span to depth ratio (a/d), and the 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 or less are most effectively filled with a pourable or pumpable epoxy compound, whereas any 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 the injection of epoxy compounds under pressure. The technique generally consists of establishing entry and renting ports at close intervals along the cracks, sealing the crack on exposed surfaces, and injecting the epoxy [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 cycles of reversed loading designed to simulate earthquake load in 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, loose concrete was 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 that are repaired by epoxy injection do not reopen at ultimate load.
2. The presence of hair line cracks in the repaired beams is responsible for reduced stiffness, hence higher deflection.

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 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 develops 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) with access limited to one side of the specimens.

4. Experimental Work

The experimental work of this study consists of casting, testing up to failure in shear, repairing and retesting eight rectangular reinforced concrete beams without shear reinforcement. Four of these beams are made with normal-strength concrete (NSC) and four with high-strength concrete (HSC). 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 to 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 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 the crushed river gravel with maximum sizes of 20mm and 14mm for NSC and HSC respectively. The gradation of these coarse aggregates conforms to the Iraqi standard specification No.45/1984 [74], as shown in **Table (4)**.

Table (4) Grading of coarse aggregate *

Sieve size (mm)	% Passing			
	Coarse aggregate (for NSC)	Limits of Iraqi spec. No.45/1984 for size 5-20 mm	Coarse aggregate (for HSC)	Limits of Iraqi spec. No.45/1984 for size 5-14 mm
20.0	100	95-100	100	100
14.0	84.53	—	100	90 - 100
10.0	51.59	30 - 60	61.03	50 – 85
5.0	5.6	0 - 10	6.62	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 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 editions) 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 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*

4-1-6 Superplasticizer

The Superplasticizer used in this study is Daracem SP3, which is a water reducing and retarding admixture. It is in the form of liquid and instantly dispersable in water.

4-2 Concrete Mix Proportions

Mix proportions are selected depending on several trial mixes. The NSC beams are designated as B1, B2, B3 and B4 while HSC beams designated as B5, B6, B7 and B8. Mix proportions and cylinder compressive strengths obtained at 28 days for all beams are listed in **Table (6)**.

Table (6) Concrete mix proportions

Beam designation	C:FA:CA (by weight)	w/c (by weight)	SP3%*	Avg. 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	1:1.37:1.74	0.28	2	67
B6	1:1.37:1.74	0.28	2	74
B7	1:1.37:1.74	0.28	2	71
B8	1:1.37:1.74	0.28	2	72

** By weight of cement*

4-3 Details of the Beams

All beams are tested under two point loading with shear span to the effective depth ratio (a/d) of 2.83.10mm 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 beams are greater than those cause shear failure. Deflections are measured at mid-span of the beams using a dial gage having a minimum gradation of 0.01mm. **Figure (2)** shows the general details of the beams.

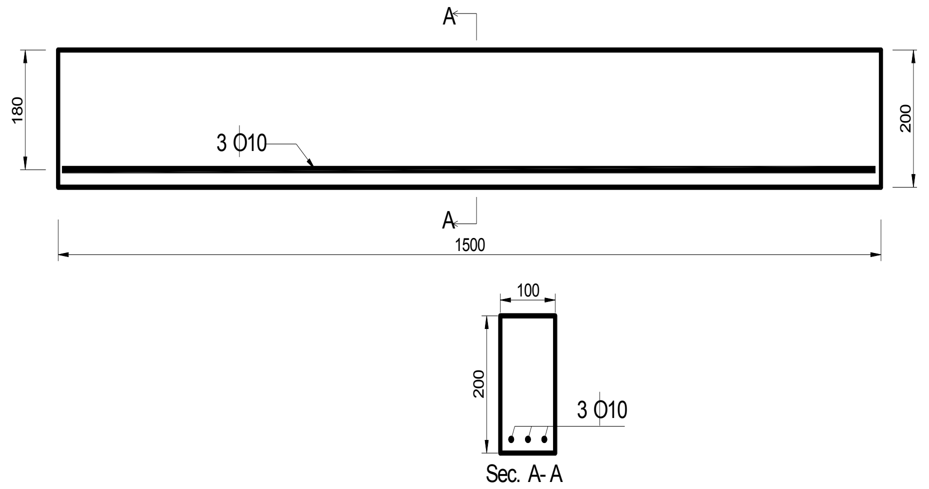

Figure (2) Beams reinforcement details (All dimensions are in millimeter)

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.

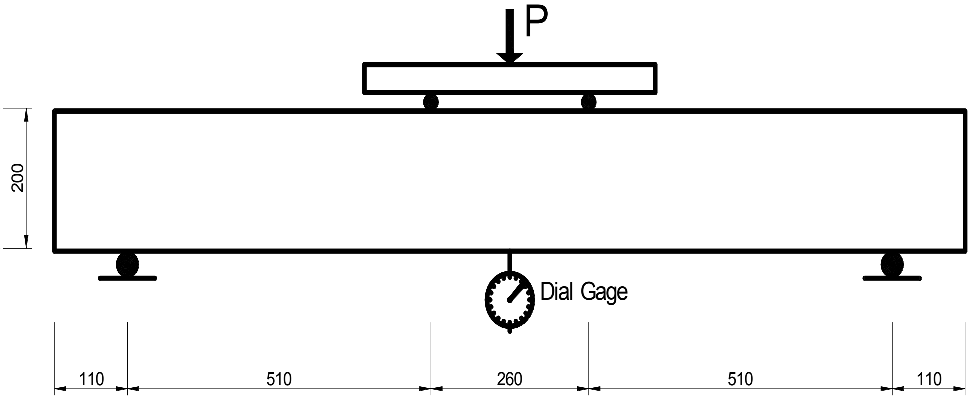

Figure (3) Loading arrangement of the tested beams (All dimensions are in millimeter)

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 crack in the shear span of the beam. 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 failure, cracks and their neighbour areas are cleaned from dust, debris and other contaminants by applying a 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 that is bonded to the concrete. The ports are placed 100-150mm 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 hole, and then tacking it in place.
3. Epoxy paste is then used to seal over the surface ports and 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 left after this stage 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 starts. The injection process begins by pumping epoxy into the lowest port until the epoxy begins to flow from the port above it. The first port is then plugged with a cap, and the process is repeated until the crack has been completely filled and all ports have been capped. Low pressure is used in injecting epoxy into cracks. A curing period of about 24 hours is provided to the injected epoxy.
6. After the injected epoxy has cured, the ports are removed by striking with a hammer and the surface seal is chipped. **Figure (4)** shows the injection process.

Figure (4) Epoxy injection process

4-6 Retesting after Repair

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

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 occur in areas where the shear force is approximately zero.

The load, at which diagonal shear cracks first formed in the original and the repaired beams, is defined as the shear cracking load (Vc). The ratios of the shear cracking load for the repaired beams (Vcr) to the shear cracking load for the original beams (Vco) are found to vary between 0.944 to 1.200 for all beams.

The load, at which failure occurs in the beam, is defined as the shear ultimate load (Vu).The shear ultimate load ratio (Vur/Vuo) of the beams varies between (0.894 to 1.152) for all beams. **Table (7)** presents the shear cracking and ultimate loads for both 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 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”, others are called “minor diagonal cracks”.

The eight beams designated as B1, B2, B3, B4, B5, B6, B7 and B8 having cylinder compressive strengths of 21, 26, 27, 29 , 67, 74, 71 and 72 MPa respectively. The results of the tests of the beams are discussed in the following sections.

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#	67	76	82	74	86	0.973	1.048
B6#	74	72	79	68	80	0.944	1.012
B7#	71	62	76	66	68	1.064	0.894
B8#	72	56	64	56	64	1.000	1.000

** NSC , # HSC*

5-2 Behavior of Original Beams

Generally, in the original beam, the first shear crack starts at one shear span at the beam bottom, near the support, propagated toward the nearest loading point as an inclined crack (diagonal crack). Some fine flexural cracks are observed before and at the appearance of the first diagonal crack. In some beams (such as B1 and B8), and by increasing the applied load, another diagonal crack is developed at the other shear span of the beam. With more applied load, the first (major) diagonal crack rapidly propagates to the nearest loading point, and then the collapse happens by splitting the beam along this crack.

The major diagonal crack is developed at the right shear span for beams B1 and B2, B6, B7 and B8 while it is developed at the left shear span for beams B3, B4 and B5 as shown in **Figs.(5)** to **(12)**. The maximum crack widths measured at the failure for the major diagonal cracks are 1.4, 0.6, 0.4, 0.95, 2.25, 0.35, 0.5 and 1.9mm for beams B1, B2, B3, B4, B5, B6, B7 and B8 respectively.

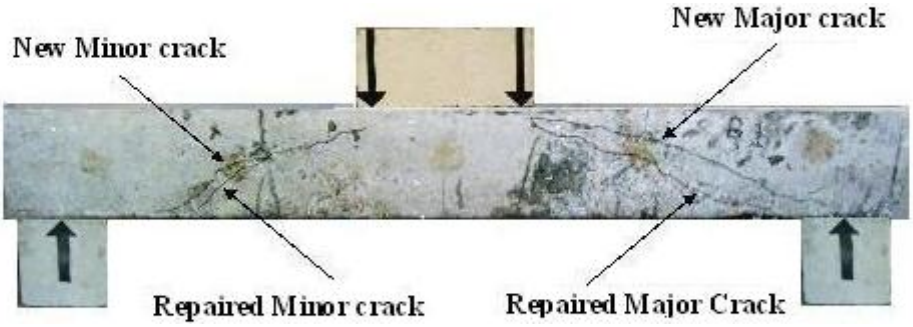

Figure (5) Beam B1 after repairing and retesting

Figure (6) Beam B2 after repairing and retesting

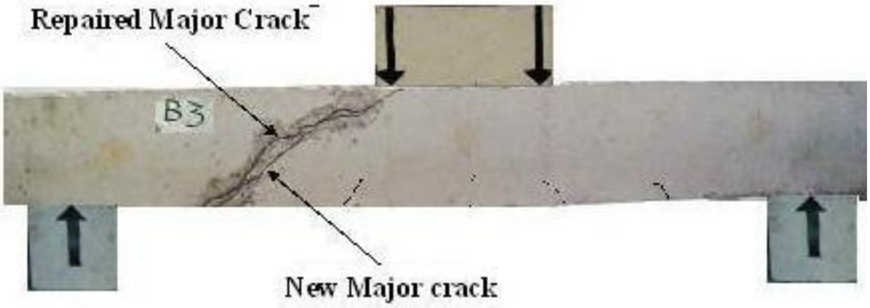

Figure (7) Beam B3 after repairing and retesting

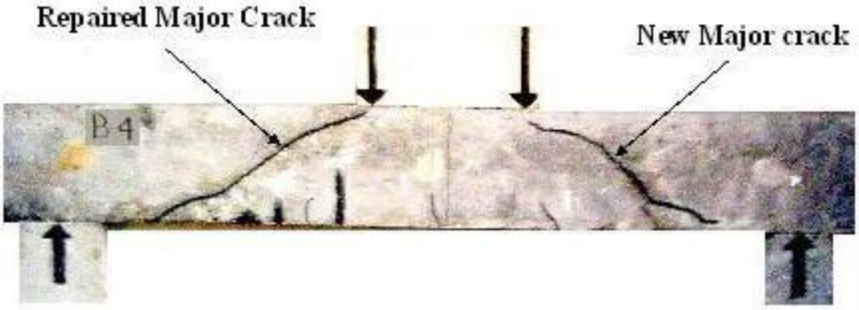

Figure (8) Beam B4 after repairing and retesting

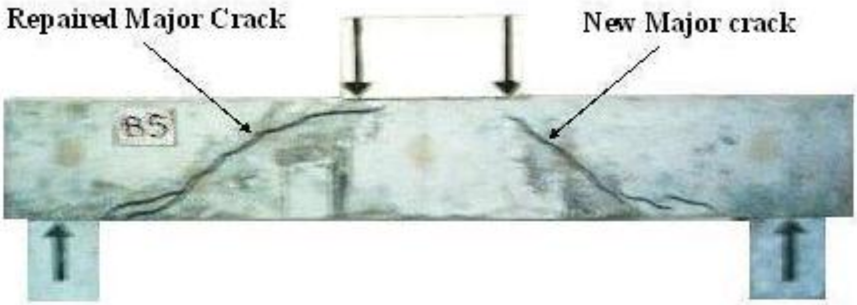

Figure (9) Beam B5 after repairing and retesting

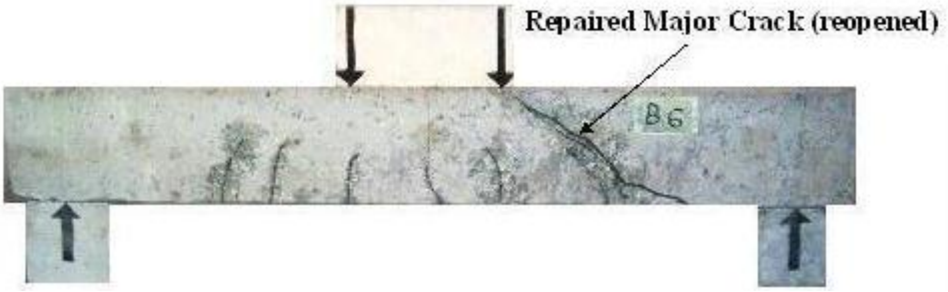

Figure (10) Beam B6 after repairing and retesting

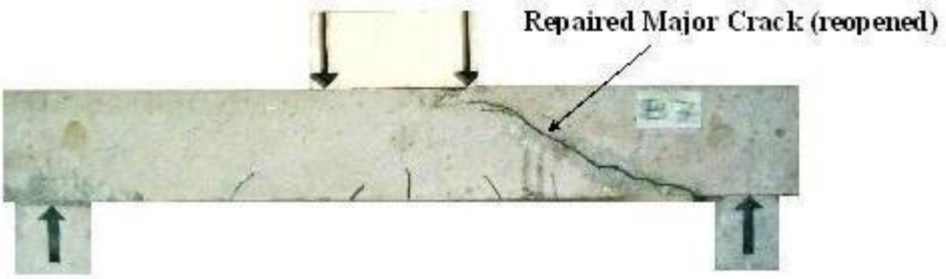

Figure (11) Beam B7 after repairing and retesting

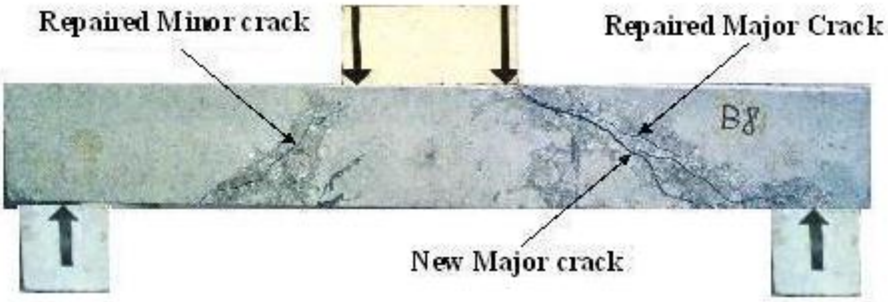

Figure (12) Beam B8 after repairing and retesting

5-3 Repairing Process

After failure of the beams, the repairing process is followed for each beam. The injection process is done successfully and easily for the beams B1, B2, B4, B5 and B8 because these cracks are wide enough to allow easy penetration of the injected resin, while for beams B3, B6 and B7, the injection process is done with a difficulty in which the process takes relatively longer time because of the relatively small widths of the diagonal cracks which limit easy penetration of the epoxy resin into the cracks.

5-4 Behavior of Repaired Beams

After testing the repaired beams, the repaired major and minor diagonal cracks in the beams do not reopen (except in beams B6 andB7) and the beams fail 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 B8) the repaired major crack, or at the other shear span (in beams B2, B4 and B5) away from the repaired major crack. A new minor diagonal cracks are developed near the repaired minor diagonal cracks in beam B1.The repaired major diagonal cracks in the repaired beams B6 and B7 are reopened, see **Figs.(5)** to **(12)**.

5-5 Shear Strength Results

The shear cracking loads for the repaired beams are greater than (or approximately equal to) 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, 0.973, 0.944, 1.064 and 1.000 respectively.

The shear ultimate loads for the repaired beams (except for beam B7) 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, 1.048, 1.012, 0.894 and 1.000 respectively. This indicates that the adopted repair processes are successful in restoring and increasing the shear capacity of the beams.

For beam B8, the shear ultimate load for the repaired beam is lower than that for the original beam. The ratio (V_{ur}/V_{uo}) is 0.894. This is the result of reopening the diagonal crack, as mentioned above.

This investigation indicates that for HSC beams, the major diagonal cracks may reopen and cause failure which differs from the case of NSC beams. This may be due to the fact that the compressive strength of epoxy is approximately similar to that of HSC beams and accordingly reopening of cracks may occur.

The above results indicate that the increase in shear capacity of the HSC beams after repair is relatively lower than that for NSC beams, see **Fig.(22)** and **Table (7)**.

5-6 Deformation Results

In general, the load-deflection behavior of the repaired beams is nearly similar to that of the original beams, **Figs.(13)** to **(20)**. The deflections at shear cracking loads and maximum deflections of the repaired beams are (in general) greater than the corresponding deflections of the original beams, **Table (8)**.

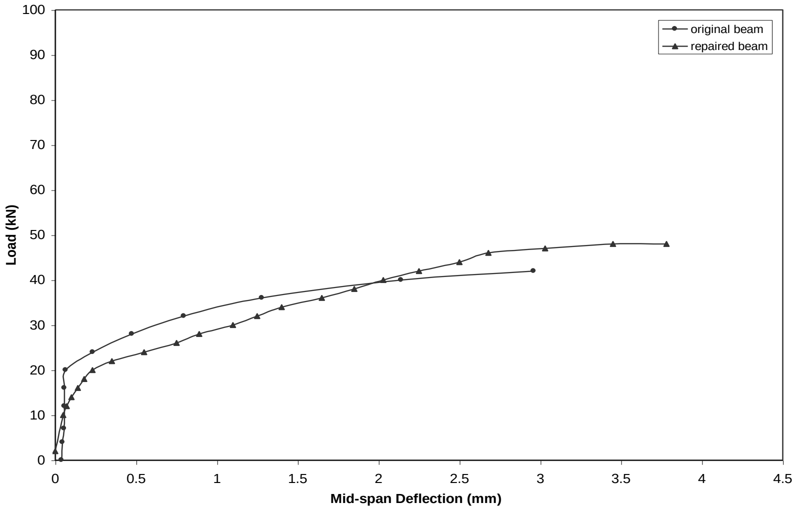

Figure (13) Load-deflection curve for beam B1

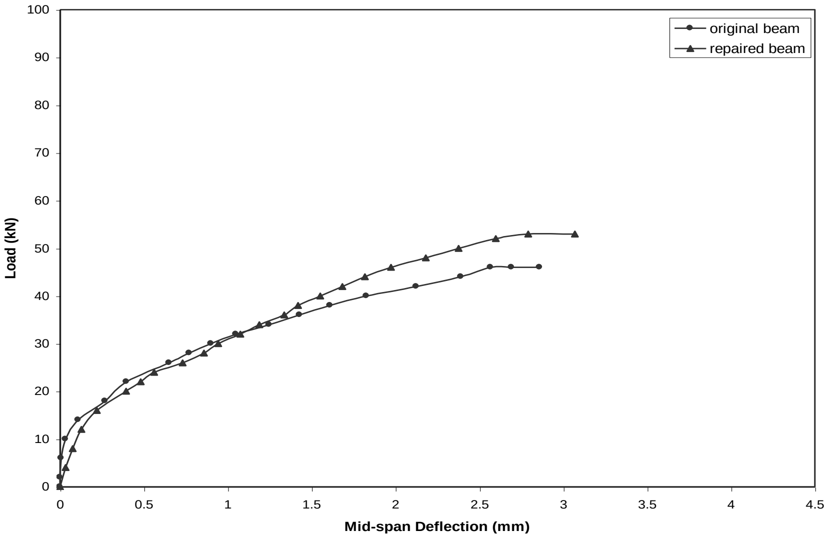

Figure (14) Load-deflection curve for beam B2

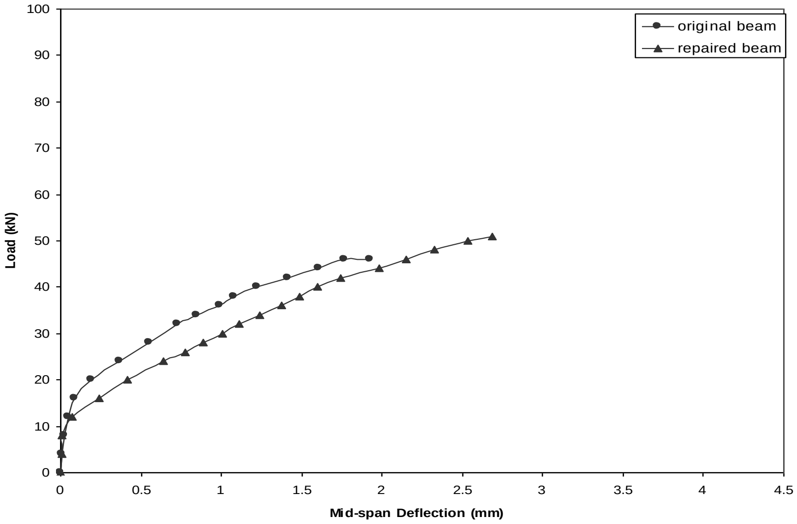

Figure (15) Load-deflection curve for beam B3

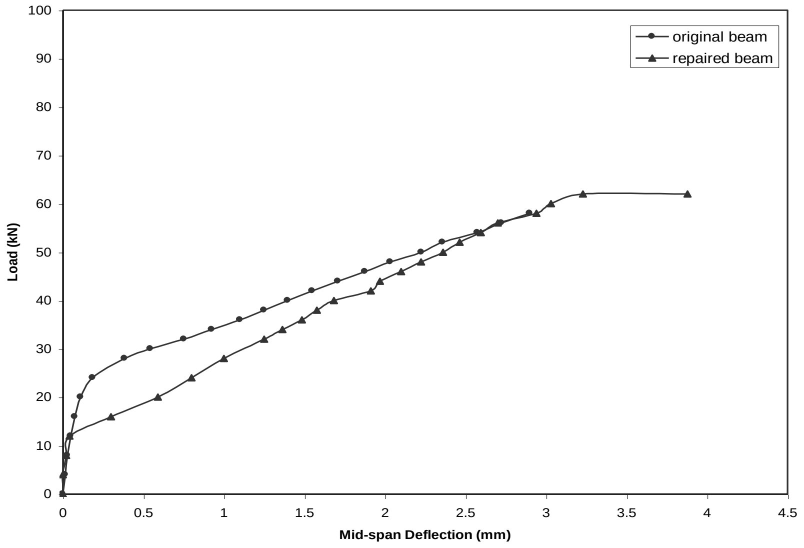

Figure (16) Load-deflection curve for beam B4

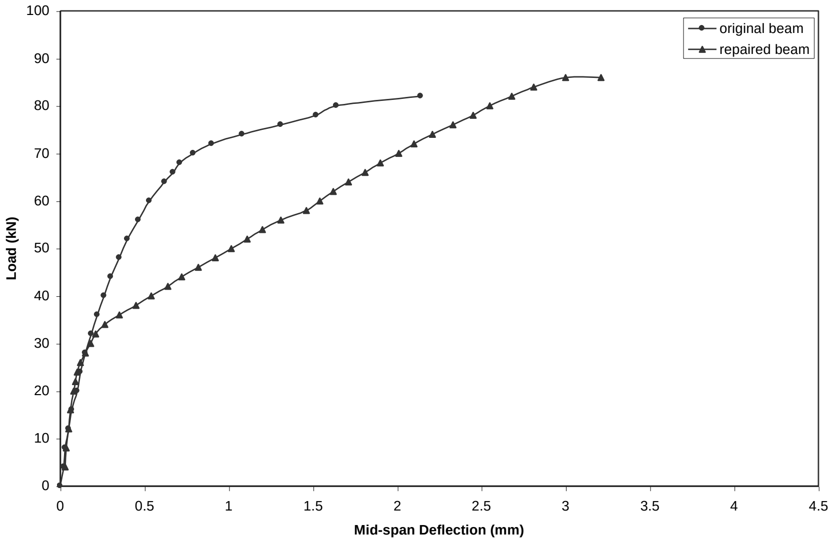

Figure (17) Load-deflection curve for beam B5

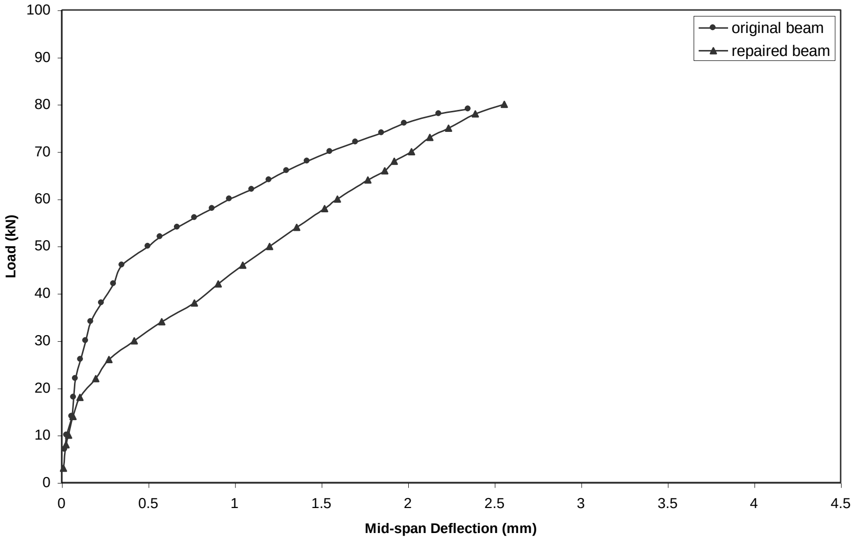

Figure (18) Load-deflection curve for beam B6

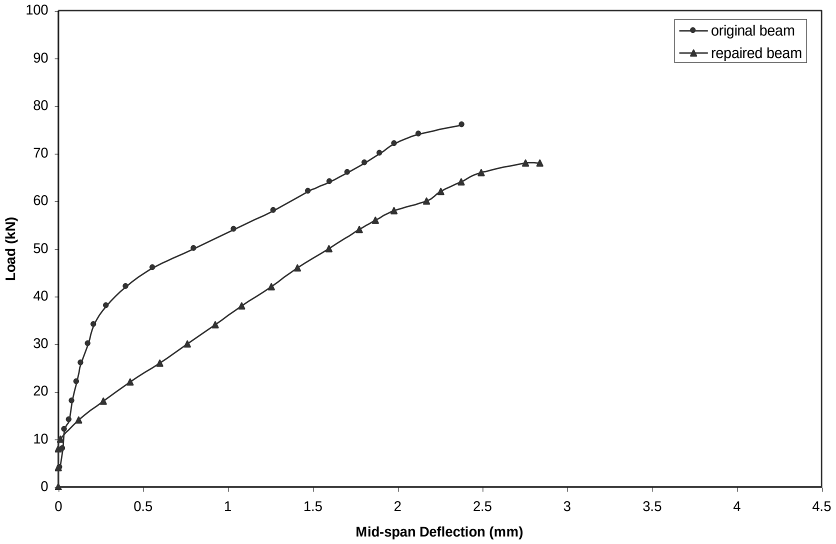

Figure (19) Load-deflection curve for beam B7

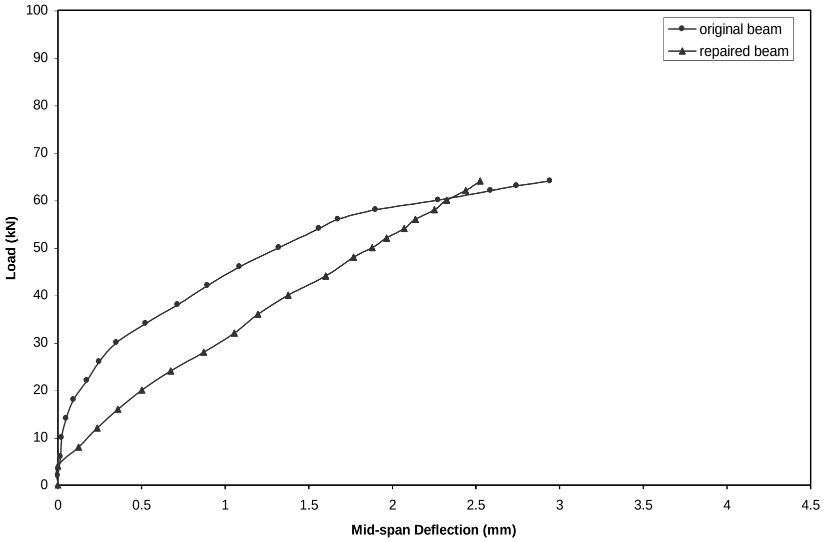

Figure (20) Load-deflection curve for beam B8

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

Beam	f'_c (MPa)	Original beam		Repaired beam	
		$D_{c,o}$ (mm)	$D_{max,o}$ (mm)	$D_{c,r}$ (mm)	$D_{max,r}$ (mm)
B1*	21	1.278	2.960	2.030	3.780
B2*	26	1.828	2.860	2.180	3.070
B3*	27	1.076	1.928	1.740	2.688
B4*	29	2.725	2.900	3.030	3.880
B5#	67	1.310	2.140	2.210	3.210
B6#	74	1.700	2.350	1.922	2.558
B7#	71	1.475	2.382	2.494	2.840
B8#	72	1.675	2.942	2.138	2.524

** NSC, # HSC*

The load-deflection curves, Figs.(13) to (20), show, as may be expected, a lower stiffness and greater ductility of the repaired beams compared with 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 beam.

The load-deflection curves for the original and repaired HSC beams show that the reduction in stiffness and the increase in ductility (up to pre-failure stage) are more noticeable than those for NSC beams, while at failure the increase in maximum deflections in the repaired beams is greater for NSC beams than that for HSC beams. This may be due to the result of a more brittle failure of HSC beams compared with NSC beams.

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.(21)**.

Figure (21) shows also 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 a 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.(21)**.

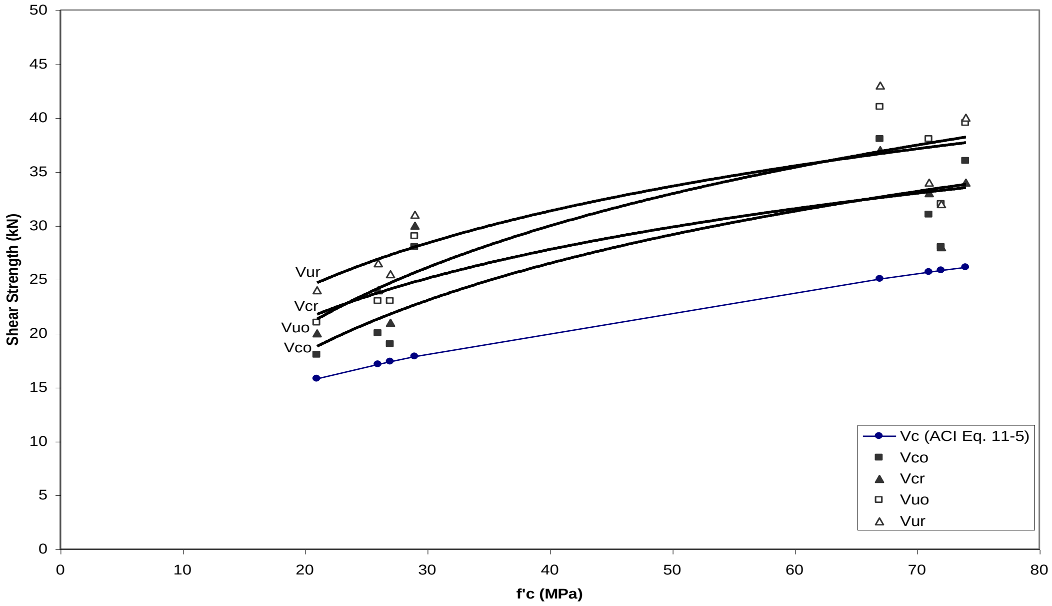

Figure (21) Effect of compressive strength on shear strength of the tested beams

The experimental results show that the improvement in shear ultimate loads of the repaired beams is relatively higher for normal-strength beams, as shown in **Fig.(22)**. This indicates effectiveness of repair process on shear strength of normal-strength beams.

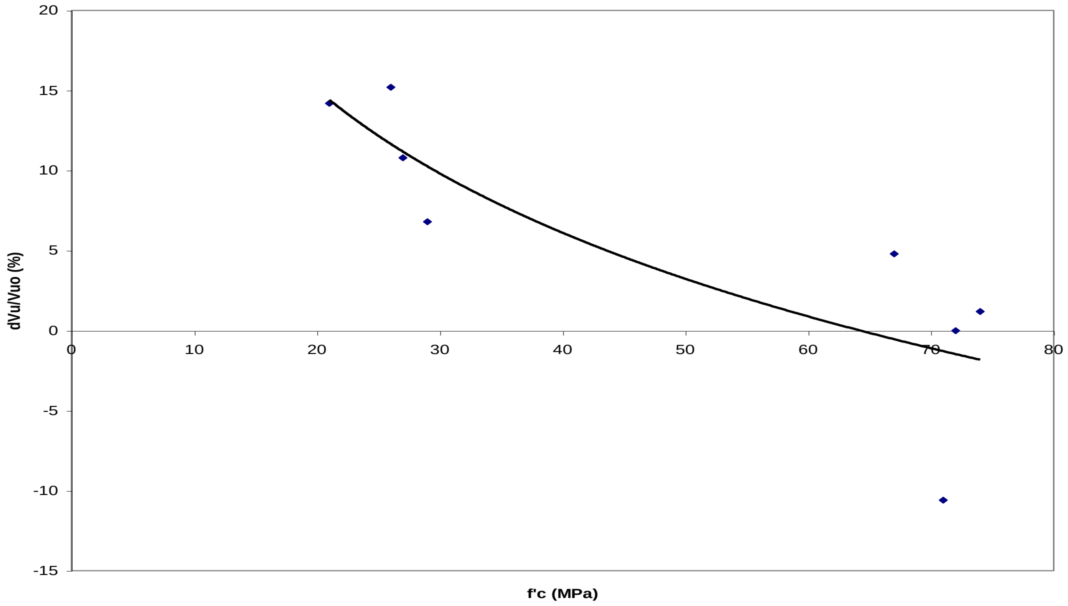

Figure (22) Effect of compressive strength on improvement in shear strength of the tested beams

5-8 Effect of Compressive Strength on Deflection of the Tested Beams

Experimental results show that both original and repaired beams of normal-strength concrete exhibit a relatively larger shear cracking and maximum deflections than high-strength concrete beams, as shown in **Fig.(23)** and **Table (8)**. This is the result of the fact that high-strength concrete is stiffer than normal-strength concrete.

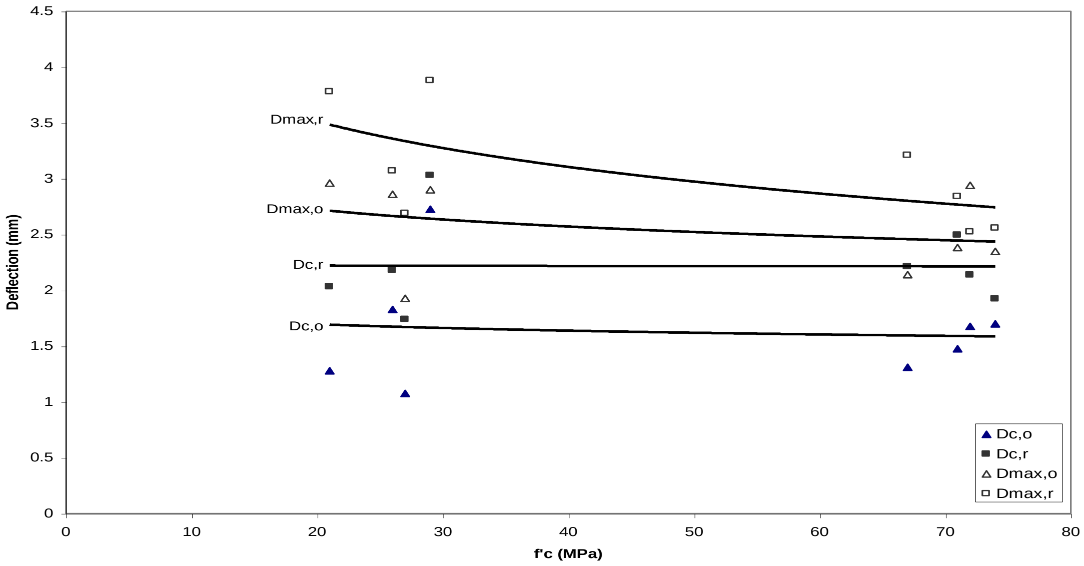

Figure (23) Effect of compressive strength on deflections of the tested beams

Figure (23) shows that the increase in shear cracking deflections after repair is higher for high-strength beams, while the increase in maximum deflections after repair is higher for normal-strength beams. This may be due to the fact that the repaired high-strength beams have a less brittle behavior up to pre-failure stage (including shear cracking moment) than behavior at failure.

6. Conclusions

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

1. 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.
2. Repair of reinforced normal and high-strength concrete beams without shear reinforcement failed in shear using epoxy resin injection method is successful in increasing (or at least restoring) shear capacity of the beams after repair. The increase in shear capacity reaches 15.2 % of the original shear capacity in Beam B1.
3. The increase in shear capacity of the repaired beams is relatively higher for normal-strength concrete beams than high-strength concrete beams.
4. The repaired beams show a lower stiffness and greater ductility compared with the original beams.
5. The reduction in stiffness and the increase in ductility (up to pre-failure stage) after repair are more noticeable for high-strength concrete beams than those for normal-strength concrete beams, while at failure, the increase in maximum deflections in the repaired beams is greater for normal-strength concrete beams than that for high-strength concrete beams.
6. The repaired major diagonal cracks in normal-strength concrete beams do not reopen while in some high-strength concrete beams, the repaired major diagonal crack reopens may be because that the injected resin has approximately similar compressive strength to adjacent concrete. Furthermore, it might be that the plane of failure in HSC beams is smoother than that in NSC beams which may facilitate reopening of repaired cracks.
7. 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 (more than 1.0 mm in width). For crack widths less than 0.5 mm, the process is done with some difficulty because these small widths of the diagonal cracks limit easy penetration of the epoxy resin into the cracks.
8. The experimental shear cracking loads for both original and repaired beams are greater than those predicted by ACI building code Equation (11-5). This equation gives relatively more conservative values for higher-strength concrete beams.

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