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Rehabilitation of Reinforced Concrete Deep Beam by Epoxy Resin

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ABSTRACT

This investigation presents an experimental and analytical study on the behavior of reinforced concrete deep beams before and after repair. The original beams were first loaded under two points load up to failure, then, repaired by epoxy resin and tested again. Three of the test beams contains shear reinforcement and the other two beams have no shear reinforcement. The main variable in these beams was the percentage of longitudinal steel reinforcement (0, 0.707, 1.061, and 1.414%). The main objective of this research is to investigate the possibility of restoring the full load carrying capacity of the reinforced concrete deep beam with and without shear reinforcement by using epoxy resin as the material of repair. All beams were tested with shear span-depth ratio 2.2. An analytical study was made to show the behavior of a sample of test beam at higher stages of loadings before and after repair. The test results showed that the epoxy resin used for repairing was very efficient in restoring full capacity of failed beams. Moreover, epoxy resin increased the strength capacity of the original beams by about 14% to 40%. On the other hand, the increase in the longitudinal reinforcement increased significantly the ultimate capacity of deep beams before and after repair.
Keywords: Rehabilitation, Deep beam, Epoxy.

أصلاح الروافد الخرسانية المسلحة العميقة بالايبوكسي

عدنان صادق الكويتي
استاذ مساعد
قسم هندسة تقنيات البناء والانشاءات الكلية الاسلامية الجامعة/ النجف الاشرف

الخلاصة

يقدم هذا البحث دراسة عملية وتحليلية حول سلوك الروافد الخرسانية العميقة والمسلحة قبل وبعد التصليح. تم تحميل الروافد الاصلية اولا لغاية الفشل تحت تاثير نقطتي تحميل ثم اعيد تصليحها ثانية براتنجات الابوكسي وفحصت ثانية لغاية الفشل. ثلاث من نماذج من الروافد كانت بحلقات تسليح القص ورافدتان بدون حلقات القص. ان المتغير الرئيسي في هذه الروافد هو نسبة حديد التسليح الطولي (0, 0.707, 1.061, 1.414%). ان الهدف الرئيسي لهذا البحث هو دراسة امكانية استرجاع قابلية التحمل الكاملة للروافد الفاشلة بالتحميل سواءا بحلقات القص او بدونها وذلك بتصليحها براتنجات الايبوكسي. جميع الروافد فحصت بفضاء (قص–عمق) 2.2. لقد اجري تحليل بالحاسبة الالكترونية لاحد نماذج الفحص لبيان سلوك الروافد في مراحل التحميل القصوى قبل وبعد التسليح. بينت نتائج الفحص بان النموذج النظري المقترح لسلوك الروافد قبل وبعد التصليح يتوافق مع السلوك العملي. لقد اثبت الفحص بان راتنجات الايبوكسي المستخدمة كانت جدا كفوء في استرجاع قابلية التحمل للروافد الفاشلة. اضافة لذالك فان

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الراتنج الايبوكسي ادى الى ازدياد المقاومة عما كانت عليه في الروافد الاصلية بمقدار يتراوح بين 14% و 40%. من الجانب الاخر فان زيادة حديد التسليح الطولي ادى الى زيادة تحمل الروافد العميقة قبل وبعد التصليح بصورة ملموسة.
الكلمات الرئيسية : اعادة تاهيل و الروافد العميقة و الايبوكسي.

1. INTRODUCTION

The deep beam can be defined as the beam in which the concentrated loads exist within the 3h from the face of the support. In this case, the shear behavior of deep beams would be very complex since plan section before bending no longer remains plan. However, the mechanism of shear failure of the deep beam would be similar to the failure of a tied-arch.

The complexity of the shear problem in deep beam encourages research workers to carry out further tests, especially, on the effect of shear span to depth ratio and the size effect on the shear strength of the deep beam, **Kamaran, et al., 2017**. Such researches aim to improve the design procedure and to allow an evaluation of current code provisions. Further researches can also help to identify their limitations. ACI 318-2005 consider the contribution of concrete, percentage longitudinal and transverse reinforcement, the shear span-to-depth ratio for estimating the shear strength of deep beams.

In deep beams, most of the concentrated loads are transferred directly to the support by arch action. International codes, **ACI-318-2002, AASHTO, 1998,** adopt the concept of strut- and tie-model for the design of deep beam. This model is analyzed on the bases of a lower bound solution of the plasticity theory. Therefore, the principles of stress analysis developed for slender beams are neither applicable nor adequate to determine the strength of deep beams.

However, the formation of cracks in the deep beam will result in a major redistribution of strains and stresses. Therefore the beam strength must be predicted by nonlinear analysis. Because of these complexities, the study of deep beams has become a special interest. Over the years various models have been proposed by many researchers and extensive test campaigns have been carried out.

In recent years, the repair and strengthening of existing structures are rapidly emerging as a new sector in structural engineering. Sometimes strengthening and repair of partially damaging concrete structures becomes more economical than rebuilding new one especially when repairing resulted in safe and serviceable structure. Various techniques have been used for repairs and strengthening of reinforced concrete members, **Al-kuaity, 2010.** However, the success of repair will mainly depend upon the efficiency of the material of repair to recover the original strength.

Due to the importance of the problem of repair in reinforced concrete structures, many international conferences are currently been held to suggest new materials and techniques be efficient for repair. In facts, the repair involves many uncertain factors which have not yet been fully investigated.

Epoxy injection has been used recently for repairing flexural cracks to improve the behavior of the existing structure, **Ahmad, et al., 2010**. Repairing of the bond between steel and concrete has been carried out by, **Chung, 1981** which showed that the bond can be restored by adequate penetration of epoxy resin. Epoxy resin has been used effectively as adhesive for external strengthening using fiber reinforced polymer (FRP) to increase both the flexural load carrying capacity and shear load carrying capacity, **Sveinsdottir, 2012**. Epoxy and polymer have been used to strengthen cracked beams resulting in higher load carrying capacity with improved ductility, **Gunarani, and Saravanakumar, 2014**.

The degree of deterioration of concrete member takes various forms such as flexural cracks, diagonal shear cracks, crushing of concrete, anchorage failure, and bond failure. The objective of this study is to restore the full load carrying capacity of the deep beam under complete failure using epoxy resin.

2. ANALYSIS OF SHEAR IN DEEP BEAM

The mechanism of shear transfer in the deep beam is simplified by **Aoyama, 1993** to be either as a truss mechanism in slender beams or as an arch mechanism in deep beams. In beams with shear span to depth ratio less than 3, the tied arch mechanism is predominant. The major part of the load in the tied arch is transferred directly from the load point to the supports.

The shear resistance in deep beam generally depends on the amount and distribution of reinforcement in the beam as well as the compressive strength of the concrete. The critical part of the tied arch would be the strut connecting point load with the supports. Several simplified models of strut-and-tie were considered for analysis and design of deep beam, **Rogowsky and Mac Gregor 1983, CEB-FlP, 1990 and Foster and Gilbert 1998**.

The strength of strut-and-tie is based on the lower bound theory of plasticity. Therefore, the actual capacity of the deep beam is considered to be equal to or greater than that of the idealized truss.

ACI Committee 318, 2005 recommends the strut-and-tie model shown in **Fig. 1**. The compressive strength of the strut shown in **Fig.2** is calculated as:

a. For singly reinforced deep beam, the nominal compressive strength of strut Fns:

$$Fns = fce\ Acs \quad (1)$$

$$Acs = Wst\ b \quad (2)$$

$$fce = 0{,}85\beta s\ fc' \quad (3)$$

$$Wst = lb \sin\beta + ha \cos\beta \quad (4)$$

$$\tan\beta = d/a \quad (5)$$

b. For doubly reinforced deep beam the nominal compressive strength of strut Fns:

$$Fns = fcu\ Ac + As'fs' \quad (6)$$

c. Nominal strength of tie Fnt is calculated:

$$Fnt = Ast\ fy \quad (7)$$

$$fs' = fy \quad (8)$$

d. The equilibrium of internal and external forces should be satisfied, **Fig.2**:

$$P(a) = C\ (jd) \quad (9)$$

$$Fnt = C \quad (10)$$

$$P = Fns\ (\sin\beta) \quad (11)$$

Where,
Ac = cross-sectional area at one end of the strut in mm^2.
As' = cross-sectional area of compression steel in mm^2
Ast = area of reinforcing steel in mm^2

f_s' = stress at compression steel in N/ mm²
C = compressive force at compression zone, **Fig.2**.
Fns = the nominal compressive strength of strut in N/ mm²
fce = effective compressive strength of strut of the concrete
fcu = effective compressive strength of the concrete in the strut or a nodal zone MPa
fy = yield stress of steel reinforcement in N/ mm²
P = applied concentrated load
a = shear span
b = width of beam
d = effective depth of the beam
h*a* = is twice the distance between the centroid of the main reinforcement and the bottom of the beam.
Jd = lever arm, **Fig.2**.
lb = width of base plate
Wst = width of the strut, **Fig.1**.
βs = factor that accounts for the effects of cracking and confining of reinforcement in strut (βs =1 for normal weight concrete).

2.1 Strength of test beams

The maximum applied load (p) which causes failure of the beam can be estimated according to the above-mentioned equations. Referring to **Fig. 2** the test beam has no bearing plate at the supports, therefore, equation (4) was modified here using lb = ha because there were no bearing plates under point loads. This modification can take into consideration the stress distribution in concrete near the point load and the supports. On this basis, the strength of strut was calculated and it is found to be critical for B5, whereas, the strength of ties was critical for other beams. This is because the amount of longitudinal steel reinforcement in B5 is higher than the other beams. The calculated values of failure loads of original beams are given in **Table 1**.

3. EXPERIMENTAL INVESTIGATION

3.1 T Test Program

The test program reported in this study is intended to investigate the possibility of restoring the ultimate strength of reinforced concrete rectangular deep beams failed by different types of failure. Five reinforced concrete rectangular specimens were subjected to two points load up to failure. In this test, the shear span-depth ratio is kept constant (a / d = 2.2).
The failure load and cracking patterns were recorded for test beams. The beams were tested first up to failure, then, they were repaired using two types of epoxy. Epoxy paste (2200 concretive) is used at the cracked surface externally then, epoxy resin (leyco-pox 103) is injected inside cracks.
The repaired beams were tested again in the same procedure as that used before repair. The main variables considered in this test are the effect of percentage of longitudinal reinforcement (0, 0.707, 1.061, and 1.414%). This program would cover the effect of epoxy repair on unreinforced beam and reinforced beam with and without shear reinforcement. The test program is given in **Table 2**.

3.2 Test Beams

Five beams were tested in this study. One of them was unreinforced beams (B1). Beam (B2) was reinforced with 2Ø6mm diameter plan bars but without shear reinforcement. The other three beams (B2, B3, B4) were reinforced with shear reinforcement. The steel reinforcement used in this test was 6mm diameter plain bars having yield tensile stress of about 275N/mm. The beam with stirrups has 2Ø6mm at the top for fixing the stirrups. The typical detail of reinforced concrete beam is shown in **Fig. 3**.

3.3 Concrete Mix

The concrete mix was designed to get 22N/mm²cube compressive strength at 28 days. The mix proportion by weight was (1: 2.23: 1.92) with w/c ratio = 0.56
The weight of materials per one cubic meter is as follows:
Cement 400 kg/m³
Water 225 kg/m³
Sand 892 kg/m³
Gravel 768 kg/m³

3.4 Epoxy Resin

Two types of epoxy are used for repairing the cracks and replacing the crushed concrete of beams. The first type (CONCRESIVE® 2200) is recommended to be used externally as a paste to replace the crushed concrete and to close the surface cracks. It is a high strength, non-flow, epoxy bedding, and repair mortar. The mortar is prepared by mixing epoxy-based mortar with selected fine aggregate. The mechanical properties of (ONCRESIVE ® 2200) is given in **Table 3.**
The second type (LEYCO® -POX103) of epoxy resin is a liquid type which is prepared by mixing two materials. It is injected inside cracks as a liquid for filling cracks and cavities. The properties of epoxy are given in **Table 3**.

3.5 Method of Repair

All the original beams were loaded up to failure. The failures of beams observed in the tests were due to the following types:
a. crushing of concrete in compression zone either in shear span or through middle third.
b flexural cracks and diagonal shear crack which split the beam into two parts.
c. the crushing of concrete strut joining the support with a point load.
The procedure of repair can be summarized as:-
1. Remove all the crushed concrete and loose materials along the failure surfaces.
2. Retrofit the two parts of the failed beam.
3. Grind the edges of the failure surfaces of two parts of the beam to be as (v –shape). The depth of groove should not exceed 10 mm.
4. Clean the failure surfaces and existing cracks by water.
5. Close the major crack along three sides of the beam by epoxy paste (ONCRESIVE ® 2200). This paste is prepared by mixing equal volumes of two materials as recommended by the manufacturer.
6. The epoxy paste requires 24 hours to be hardened.
7. Inject the crack through the fourth side of the beam with liquid of epoxy injection resin (LEYCO® -POX103) which is prepared by mixing equal volumes of two materials A& B as recommended by manufacturer.
8. The epoxy resin requires 24 hours to be hardened.
9. For the other faces, drill holes through repaired cracks of 6mm diameter and 5mm depth and inject the liquid of epoxy (LEYCO® -POX103) through those holes.
10. The curing time for both types of epoxy is 7 days.

4. TEST RESULTS

4.1 Compressive strength

The compressive strength of concrete used in this test was found by testing six cubes (100 x 100 x100) mm. Three cubes were tested at age 7-days and another three at age 28-days. The test was carried out according to BS EN 12390-3:2009. The cube compressive strength of concrete at 28 days was found to be about 22 N/mm².

4.2 Strength of test beams

The original beams were tested under two point loads by a universal machine used for standard flexural test of the prism. Deflections were measured at mid-span using mechanical dial gauge at stages of loading. Load-deflection curves are shown in **Figs**. **4, 5 and 6**. Cracks are also observed during the loading and marked on the beams. When the load reached the maximum capacity of the beam, failure of beams occurred in different modes. The ultimate strength of beams and modes of failures are given in **Table 4.**

Single crack penetrated suddenly within the mid-span of the beam (B1) which led to fracture the beam into two parts as shown in **Fig. 7**. The failure is very brittle because the beam has no steel reinforcement. A similar type of failure was observed for beam after repair as shown in **Fig. 8.**

More ductile mode of flexural failure was obtained for the beam (B2) with higher load capacity. The increase in load capacity is due to the presence of 2Ø6 longitudinal reinforcement in this beam compared to (B1). The reinforcement in B2 prevented sudden failure. Major crack initiated under the point load and penetrated upward to the compression zone resulting in failure of the beam. The mode of failure is shown in **Fig. 9.** Beam B2 after repair showed the similar mode of failure to the original beam as shown in **Fig.10.**

Beam (B3) failed in shear due to the formation of inclined diagonal shear cracks. The increase in the steel reinforcement in this beam increases the flexural capacity of the beam but the minimum shear reinforcement provided was not adequate to resist applied shear. Therefore, shear cracks formed in the shear span. The main diagonal crack penetrates towards the point load resulting in crushing the compression zone under point load as shown in **Fig.11**. The repairing material in the beam (B3) strengthened the failure plane which shifted the failure plane to the left support as shown in **Fig. 12**.

(B4) has a similar mode of failure as B3 but it carries a higher load than B3. This is because of higher steel percentage in tension zone. The mode of failure of beam B4 is shown in **Fig.13**. After repair, (B4) showed a similar failure mode as the original beam as shown in **Fig. 14**.

(B5) showed a different mode of failure than other beams. The presence of higher longitudinal steel in (B5) relative to others changed the behavior of the beam into similar to tied arch and then load transferred through concrete strut connecting point load with support. The mode of failure of (B5) is due to the crushing of concrete strut. The mode of failure is shown in **Fig. 15**. This means that the deep beam would not act like tied arch unless sufficient amount of longitudinal steel reinforcement is provided. Test beams showed the increase in longitudinal reinforcement significantly increases the ultimate capacity of the deep beam. The ultimate load and the made of the failure of all tested beams are given in **Table 4**. Analysis of shear strength by, **ACI-318, 2005** agreed well with the test results of the original beams as shown in **Table 5**.

All repaired beams were tested by a similar procedure as the original beams. The repaired beams showed higher load carrying capacity than the original beams as shown in **Table 5**. This may be due to the very high compressive strength of the material of repaired (85-100 N/mm²) compared to that of the original beams (22N/mm²). The percentage of increase in load carrying capacity of repaired of reinforced beams is ranging between 13% and 40%, **Table 5**.

On the other hand, all planes of failures of repaired beams were shifted away from the original strengthened plane of failure as shown in **Figs. 8, 10, 12, 14 and 16**. This means that the epoxy resin is effectively acting restoring the full integrity of the failed beam with higher strength than the original concrete. The repaired beams show similar behavior under loading as those for original beams but with improved ductility.

4.3 Discussion and Comparison

STAAD/PRO-V8i-2015 was used to analyze the beam (B5) before and after repair using the finite element method. The beam is considered to be simply supported over knife edge at one end and roller type at the other end. The beam is subdivided into 470 plate elements. Each element is o.01x0.01m size having 0.10m thickness.
The plate finite element is based on the hybrid element formulation. The element is 4-noded quadrilaterals. These elements are available quadrilaterals, with corner nodes only. Each node has six degrees of freedom. The quadratic stress distribution assumed for bending is shown in **Figs 17**.
The plate bending portion of this program can handle thick and thin plate thus extending the usefulness of the plate elements into a multiplicity of problems.
The computer model was modified to take in consideration the effect of strength of repairing material (epoxy), Therefore, the plate elements located along the failure plane in the original beam is transformed to elements with a thickness equal to the thickness of original plate multiply by (n). Where (n) is the ratio between the modulus of elasticity of epoxy repair to the modulus of elasticity of the concrete material.
Beam (B5) is selected here for comparison since this beam is failed by tied rib-bearing before and after repair. The computer analysis showed the minimum principal stresses distribution in the beam (B5) before and after repair as shown in **Figs. 18, 19.** The shape of stress distribution indicates clearly the arch action as suggested by**, Rogowsky and Mac Gregor, 1983, CEB-FlP, 1990 and Foster and Gilbert, 1998**.
Computer model in **Fig. 20** shows that the stress distribution of repaired beam B5 is shifted from the repaired side to the other side of the beam. In this case, crushing of concrete along the failure, plane took place at another side as shown in **Figs. 20.** However, the computer analysis agrees well with test results. Therefore, the epoxy resin used here for repairing the failed beams is very effective in restoring the full capacity of the failed beams with an increase in the strength capacity.
Table 5 showed that the calculated values are slightly less than that observed in the tests. The ratio between observed value and those calculated according to the ACI Committee 318, 2005 is ranging from 1.08 to 1.35. This may be attributed to a factor of safety for compressive strength of concrete (0.85) used in equation 3.
Fig. 21 shows the relationship between longitudinal steel ratio and load carrying capacity of deep beams. The increase in the steel ratio significantly increases the load carrying capacity of the beams irrespective of the mode of failure.

5. CONCLUSIONS

For the limited tests carried out in this study, some conclusions may be drawn as:-
1- The use of adequate material of repair with an appropriate technique for repairing of failed deep beams could be very effective in restoring their ultimate carrying capacity.
2- The ultimate capacity of repaired beams failing in shear and flexure can be fully recovered. The load carrying capacity of repaired beams is higher than those of the original beams by an amount ranging between 114% and 140%.
3- Epoxy resin used here restored higher flexural strength than the original strength of unreinforced.
4- The increase of longitudinal reinforcement increases significantly shear strength of the deep

beam.
5-the behavior of test beam failing by tied rib-bearing agreed well with the computer model analyzed in this study.
6- Epoxy resin used in this study is very adequate to repair shear cracks, flexural crack and the crushed of concrete at failure.
7- Flexure shear cracks are the most dominant type at deep the beams tested here. Shear compression failure is observed at beams with low and moderate steel ratio. Diagonal cracks were observed in beams with high steel ratio which failed by the tied rib-bearing.

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7. NOMENCLATURE

Ac = cross-sectional area at one end of the strut in mm².
As' = cross-sectional area of compression steel in mm²
Ast = area of reinforcing steel in mm²
Fs' = stress at compression steel in N/ mm²

Fns = the nominal compressive strength of strut in N/ mm²
fce = effective compressive strength of strut of the concrete
Fy = yield stress of steel reinforcement in N/ mm²
a = shear span
b = width of beam
d = effective depth of the beam
h*a* = is twice the distance between the centroid of the main reinforcement and the bottom of the beam.
lb = width of base plate
βs = factor that accounts for the effects of cracking and confining of reinforcement in strut (βs =1 for normal weight concrete).

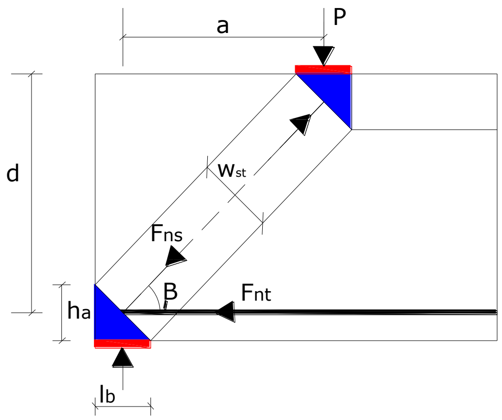


Figure 1. The strut-and-tie model of the deep beam

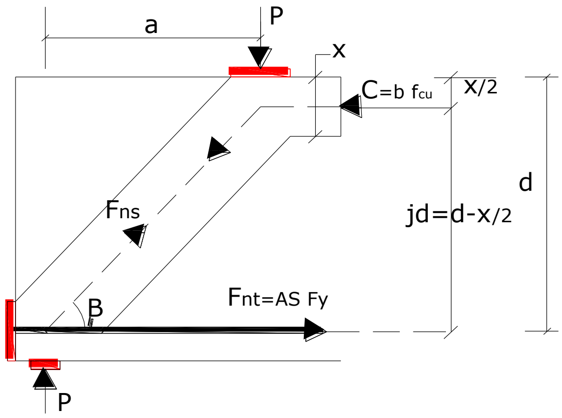
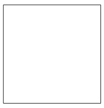
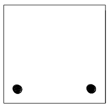
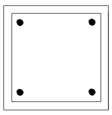
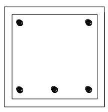
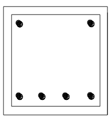


Figure 2. Equilibrium of internal forces

Table 1. The calculated strength of test beams.

Beam	Steel %			Calculated Ultimate strength (kN) of test beams by ACI
	Bottom	Top	Stirrups	
B1	0	0	none	3.15
B2	0.707	0	none	4.66
B3	0.707	0.707	ϕ 6@ 40	13.3
B4	1.059	0.707	ϕ 6@ 40	19.2
B5	1.413	0.707	ϕ 6@ 40	24.7

Table 2. Test Beams.

Beam Mark	Beam cross section	REINFORCEMENT			
		Bottom reinforcement		Top reinforcement.	Stirrups
		Steel percentage	No. of bars		
B1		0	None	None	None
B2		0.707	2Ø6	None	None
B3		0.707	2Ø6	2Ø6	Ø6@40mm c/c
B4		1.061	3Ø6	2Ø6mm	Ø6@40mm c/c
B5		1.414	4Ø6	2Ø6mm	Ø6@40mm c/c

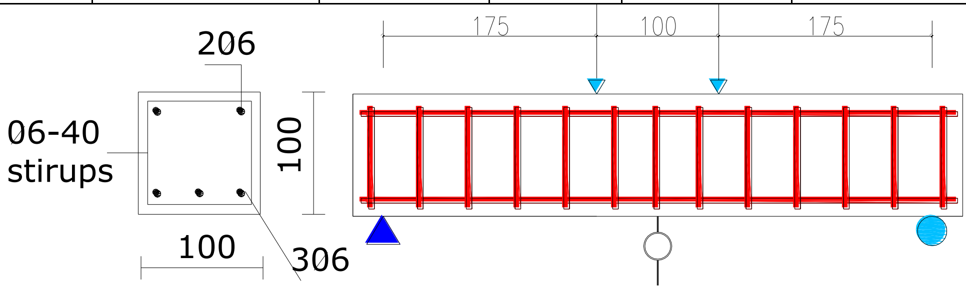


Figure 3. Details of reinforced concrete beam under test.

Table 3. Properties of Epoxy resin.

property	Cocreeive-2200	Leyco-pox103	
Compressive strength	60 N/mm² at 7 days	85-100 N/mm	
Tensile Strength (BS 6319 Part 7)	10 N/mm² @ 7 days		
Flexural strength (ASTM C 580 part 7)	20 N/mm² @ 7 days		
Young's modulus	2400 N/mm2	2800 N/mm2	
Pot life	70 minutes at 25°C	40 min at 23 °C –40°C	
Specific gravity	1.7g/cm³ (approx.) at 5°C:	1.05 g/cm3 (at 23 °C	

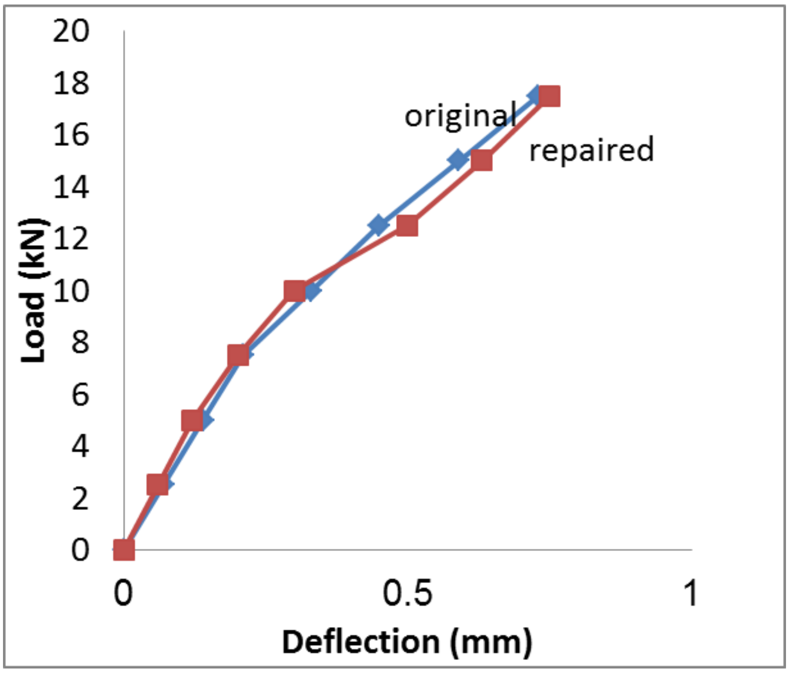


Figure 4. Load- deflection curve for B3 before and after repair.

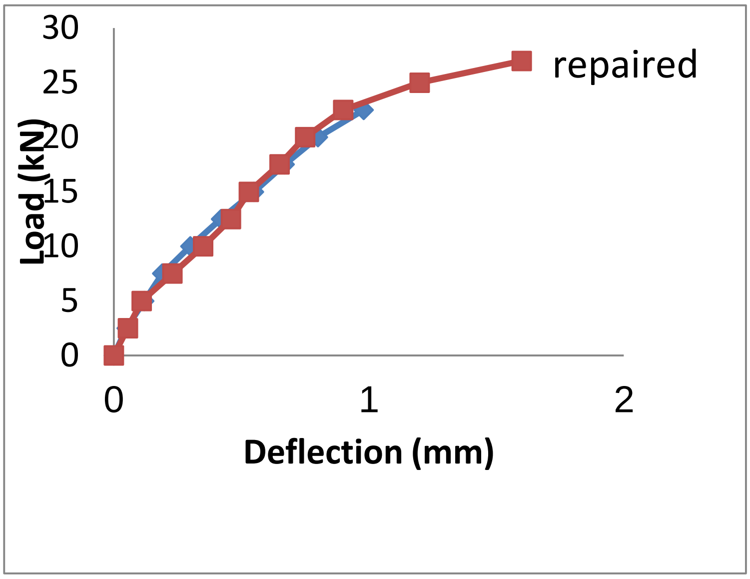


Figure 5. Load- deflection curve for B4.

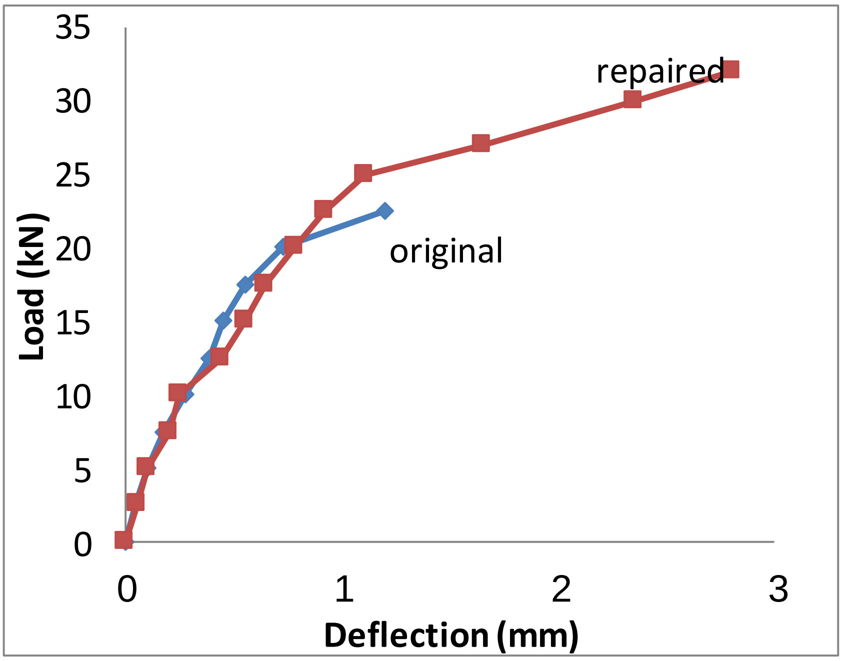


Figure 6. Load- deflection curve for B5.

Table 4. Failure load.

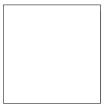
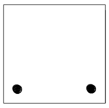
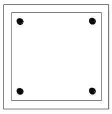
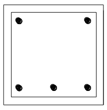
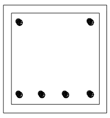
Beam Mark	Beam cross section	Failure Load (kN)				
		Original Beam		Repaired Beam		Vr/ Vo
		Failure Load Vo	Type of failure	Failure Load Vr	Type of failure	
B1		3.4	Flexural	5.52	Flexure	1..62
B2		5.31	Flexure	6.06	Flexure	1.14
B3		18.8	Shear Tension	21.3	Shear Compression	1.13
B4		22.63	Flexure	27.87	Shear Compression	1.23
B5		23.91	Arch – Rib Ten.	33.92	Tied –Rib Bearing	1.42

Table 5. Effect of steel reinforcement on the strength of repaired beams.

Beam	Steel %			Ultimate strength (kN) Original beam			Ultimate strength (kN) of Repaired beam
	Bottom	Top	Stirrups	Exp. (E)	ACI (A)	(A)/(E)	
B1	0	0	none	3.40	3.15	1.08	5.52
B2	0.707	0	none	5.31	4.66	1.08	6.06
B3	0.707	0.707	ϕ 6@ 40	18.8	13.3	1.35	21.38
B4	1.059	0.707	ϕ 6@ 40	22.6	19.2	1.18	27.87
B5	1.413	0.707	ϕ 6@ 40	23.9	24.7	0.97	33.92

Figure 7. Failure of original beam B1.

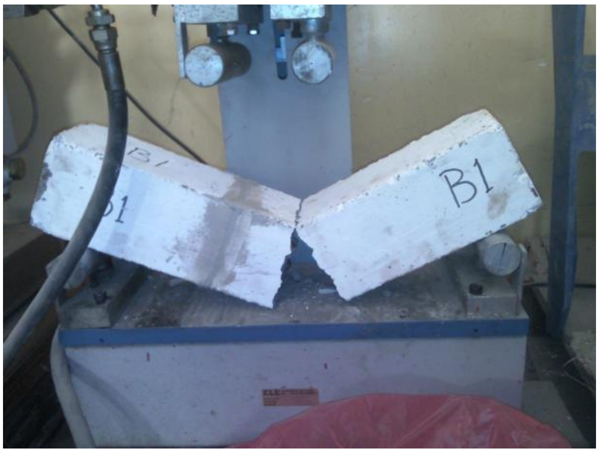


Figure 8. Failure of beam B1 after repair.

Figure 9. Failure of original B9.

Figure 10. Failure of beam B2 after repair.

Figure 11. Failure of original B3.

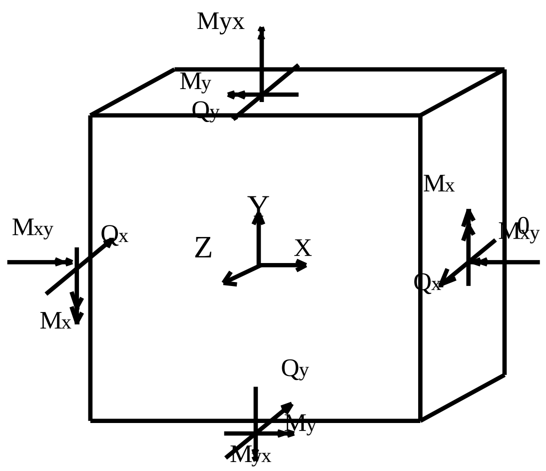
Figure 12. Failure of B3 after repair.

Figure 13. Failure of original B4.

Figure 14. Failure of B4 after repair.

Figure 15. Failure of original B5.

Figure 16. Failure of B5 after repair.



$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \\ Q_x \\ Q_y \end{bmatrix} = \begin{bmatrix} 1 & x & y & 0 & 0 & 0 & 0 & 0 & 0 & x^2 & xy & 0 & 0 \\ 0 & 0 & 0 & 1 & x & y & 0 & 0 & 0 & 0 & 0 & xy & y^2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & x & y & -xy & 0 & 0 & -xy \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & x & y & 0 & -xy \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & x & y & 0 & -xy \end{bmatrix}$$

Figure 17. Quadratic stress distribution assumed for bending.

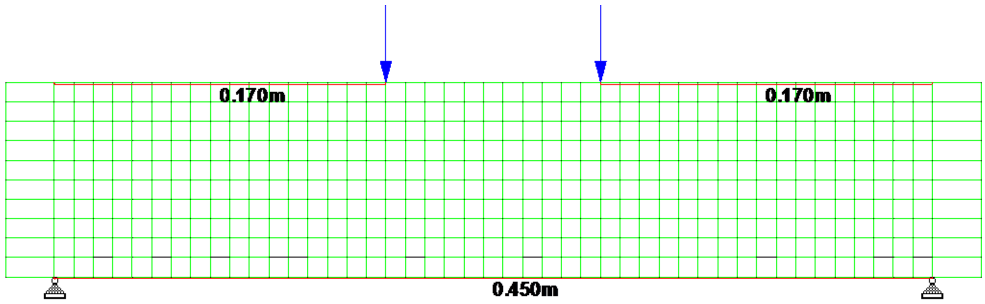


Figure 18. Typical element mesh of test beam.

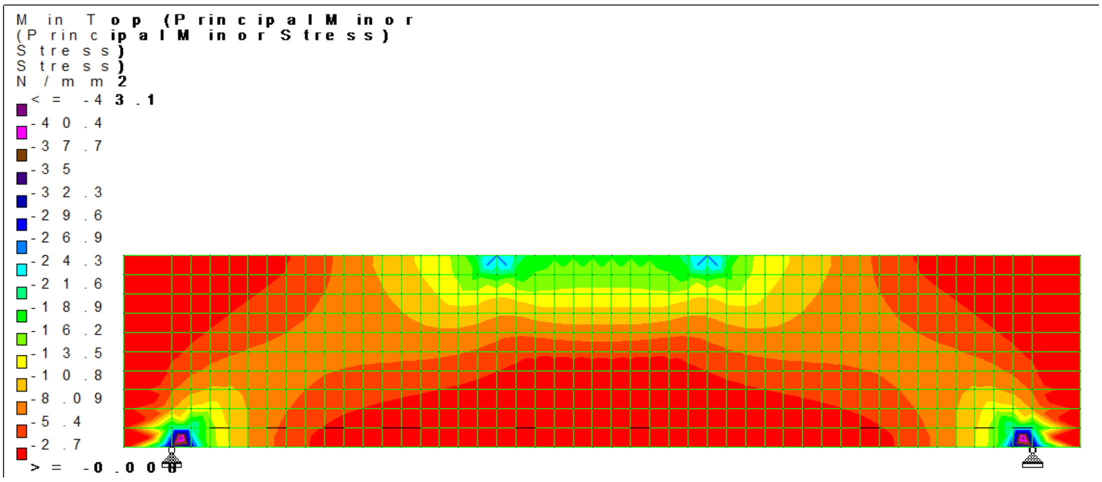


Figure 19. Typical stress distribution along the original beam.

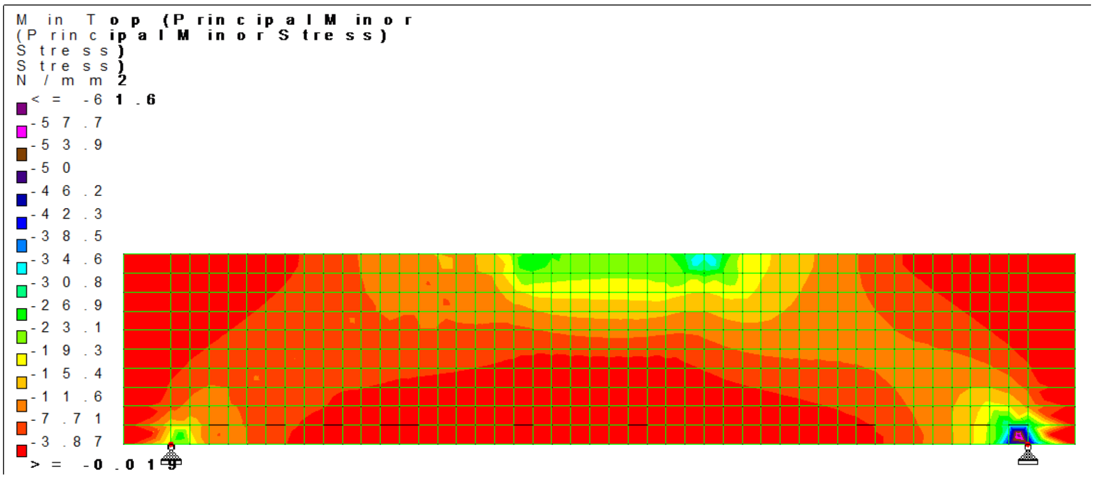


Figure 20. Typical stress distribution along the beam after repair.

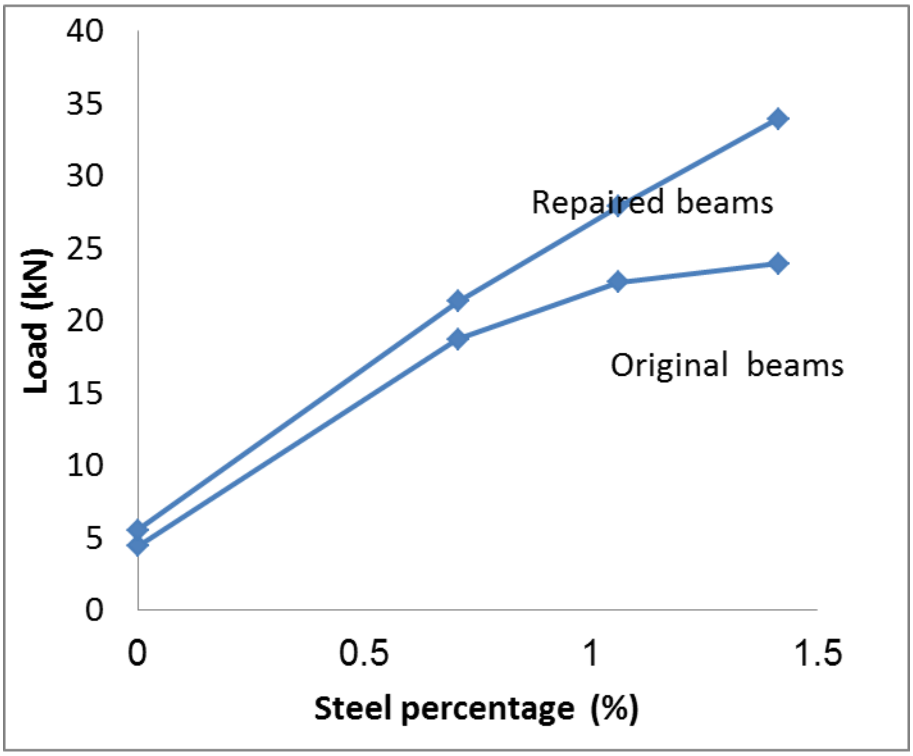


Figure 21. Effect or steel reinforcement on an ultimate load of repaired beams.