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Behavior of Damaged Reinforced Concrete Beams Strengthened with Externally Bonded Steel Plate

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Abstract
Flexural strength and deformation of reinforced concrete beams strengthened with steel plates were studied in this paper. For bonding the steel plate to the beam a technique of welding steel plate to the stirrups was followed. Fifteen beams were cast and tested; nine beams were strengthened by steel plates preloaded with a fraction of the ultimate load of the control beams (three beams) and then tested to failure. Another three beams were cast and tested to failure also, strengthened and then retested to failure. The test results indicated that the process of welding is successful and can furnish the state of composite action. After strengthening, the ultimate load was increased by 1 to 17 % and by 70 to 94 % for beams strengthened with 1 mm thick and 3 mm thick steel plates, respectively. The effect of cracking due to preloading on the flexural behavior of strengthened beams was found to be not significant.
Keywords: Beam, Cracks, Ductility, Flexure, Reinforced Concrete, Steel Plate, Strengthening, Welding.

سلوك العتبات الخرسانية المسلحة المتضررة والمعززة بصفائح فولاذية مرتبطة خارجياً

الخلاصة
في هذا البحث تم دراسة مقاومة الانثناء والتشوه لعتبات خرسانية مسلحة ومعززة بصفائح حديدية. لغرض ربط الصفائح بالعتبات تم استخدام تقنية لحام الصفيحة بأطواق القص. تم صب وفحص خمسة عشر عتبة، تسعة منها عززت بصفائح فولاذية، وحملت بنسبة من الحمل الأقصى لعتبات السيطرة (البالغ عددها ثلاثة) ثم تم تحميلها إلى الفشل. كما تم صب ثلاث عتبات أخرى وفحصت إلى حد الفشل ثم تم تعزيزها بصفائح فولاذية وتم فحصها إلى حد الفشل أيضا. نتائج البحث أظهرت أن تقنية اللحام يمكن أن توفر حالة الفعل المركب بشكل جيد. بعد التعزيز بالصفائح، ازداد الحمل الأقصى بمقدار 1 إلى 17 بالمائة و 70 إلى 94 بالمائة للعتبات المعززة بصفائح بسمك 1 ملم و 3 ملم، على التوالي. كذلك وجد بان تأثير التشقق الحاصل بسبب الحمل المسبق ليس له تأثير مهم على تصرف الانثناء للعتبات المعززة بالصفائح.

Introduction
The idea of strengthening structural concrete members and rehabilitation of damaged structures is not new and turned back to the early 1960's. However, the problem is the invention of economical materials with high performance. Since the total cost of rehabilitating existing structures is usually lower than that provided to rebuild them and some structures are historical in nature, and there is a need for strengthening damaged locations for such structures. Recently there is an aspect of structural engineering that take care to strengthening technique to encourage engineers to do the process successfully. The state of the art report

of the ACI 440 Committee [1] is a useful matter for the practical applications of strengthening concrete structures and can be followed for this purpose. The noticeable property for strengthening layers is their high tensile strength and low self weight, while a successful binder epoxies is that which provides excellent bond between the sheet and concrete surface with good durability. Both bolt connections and glue epoxies have been used for bonding sheets to concrete. The strengthening layers used were steel plates as the first choice, but later due to the developments of materials technology many other types were invented. Among the widely used types are the Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) sheets.

Numerous experimental tests were conducted in order to understand the flexural and shear behaviors of reinforced concrete beams strengthened with externally bonded plates or sheets and the possible modes of failure were assessed. It is experimentally evident that the increase in flexural strength of beams is possible only when other failure modes do not interfere (like shear and bond failure). The effect of externally bonded sheets on moment capacity was found to be greater on unreinforced or lightly reinforced concrete beams with steel reinforcement [2,3]. Duthinh and Starnes[3] found that for the same (CFRP) addition the flexural strength increased two times for lightly reinforced beams (11% of the balanced reinforcement ratio), but only 19 % increase was obtained for moderately reinforced beams (46 % of (of the balanced reinforcement ratio).

Experimental tests[4] indicated that at least 120% increase in moment capacity and 40% increase in stiffness can be obtained when plain concrete strengthened with 1 mm thickness CFRP sheets.

Ramana et. al.[5] found that the maximum increase in cracking and ultimate moments of reinforced concrete beams were 150% and 230%, respectively, compared to the unplated beams. Other tests[6] carried out on full scale beams strengthened with CFRP sheets indicate that the ultimate moment was increased by 49%, while up to 58% increase was found for beams bonded with epoxy and anchored with steel bolts. The deflection at ultimate load reduced as the degree of strengthening increases and consequently the ductility of the composite beam reduced[2,5]. The lost ductility is higher when CFRP sheets are used for strengthening (due to its brittle behavior) as compared to the steel plate. However other studies[7] demonstrated that a considerable increase in load capacity can be obtained by strengthening beams with Glass Fiber Reinforced Polymer (GFRP) sheet without scarifying the ductility of the composite beam.

Some researchers[8,9] believed that if reinforced concrete beams are well designed by providing external anchorage system the lost ductility can be regained .

Since the main objective of strengthening concrete elements is to overcome the damages that usually take place due to cracking, many researches [2,7,10] took care of the behavior of cracked beams as a result of preloading and then repaired or strengthened. A large number of studies showed that there is no significant variation of ultimate load of preloaded strengthened beams and those beams without any preloading. Consequently the cracked beams can be successfully repaired by strengthening with different types of sheets of stronger materials. Test results [2] indicated that if epoxy were used for bonding the CFRP sheets better composite action is obtained as compared with steel plate. Researchers believed that there is a need for steel bolts as an anchorage. The importance of steel bolts for anchoring the steel plate to beams on both ultimate load and ductility can be found in the study carried out by Spandea et al. [9]. In contrast to this fact, other tests[8] showed that the mechanically drilled bolts create weak sections on the CFRP sheets.

In the present study, steel plates were used for strengthening the beams instead of fiber reinforced polymers sheets because yet there may be problems related to their use like the high total cost of both the sheet and bonding epoxies and the performance failure in the case of high temperature due to fire. The steel plate is welded to the stirrups to bond the steel plate to the beam. Some of the tested beams are subjected to preloading to incorporate the effect of cracking in reinforced concrete beams to be strengthened, while others were tested to failure, strengthened and then tested to failure.

Experimental Work

Materials

Ordinary constituent materials were used for preparing a normal strength concrete. Ordinary Portland Cement (Type I) (commercial name is Kurtlan / Turkey) was used. Medium size clean river sand of apparent specific gravity of 2.71 and passing 4.75 mm sieve was used. A well graded rounded gravel was used with a maximum size of 19mm and an apparent specific gravity of 2.76. The used fine and coarse aggregate are prepared from Fishkhabor / Zakho quarry and similar to that used locally in concrete works.

Two types of deformed bars were used as flexural reinforcement and one 8 mm square section as shear reinforcement. Two types of steel plates were used for strengthening the beams. Properties of the used steel bars and plates are shown in Table (1).

Beam Preparation

Twelve reinforced concrete beams were cast from three batches of concrete mix and accordingly they are classified to three groups. The first two groups are identical and the dimensions were kept to (125×160×1600 mm), (width×depth ×length) while the dimensions of the last group were 135×165×1000 mm. Fig. (1) illustrates the detail of the cross section and reinforcement of Groups (1) and (2) while that of Group (3) beams are shown in Fig. (2). All beams were cast in steel moulds which were thoroughly oiled before casting concrete. The mix proportions by weight were 1:2:3 (cement: sand: gravel) with a water cement ratio of 0.55 and were kept constant for all the beams. With each batch of concrete mix three 100 mm cubes were prepared for measuring the compressive strength. After casting the fresh concrete was vibrated by the mean of internal vibrator and the surface of concrete was well leveled and covered with a polythene sheet. After 24 hrs all the specimens were stripped from the moulds and covered with wet cloth and continuously cured for 28 days.

Strengthening Technique

The beams were left in air for 7 days after finishing the curing period. The concrete cover at the tension face beneath the stirrups locations was removed by means of ceramic saw, Fig. (3) illustrates this process.

Pieces of square section steel rods were welded to each stirrup in order to prepare a level attachment to the steel plate surface. According to the distances between each stirrup, slots of dimensions 100×5 mm were made in the steel plate, later the plate was positioned on the beam so that the slots will coincide with the square sections and then filled with weld. The length of steel plate was 1000 mm for the groups 1 and 2 and 750 mm for group 3 bonded to the central portion of the beam. Fig.(4) shows the process of welding the steel plate to the reinforced concrete beam.

Testing Technique

Before testing, all the beams were white painted to trace the cracks and testing was made under four point loading, by the mean of computerized universal testing machine (Walter + Bai AG / Switzerland). All the beams were tested by applying two central loads spaced 300 mm apart. The clear span of Group (1) and Group (2) beams was 1500 mm and that of Group (3) beams was 900 mm. The load–deflection response of the tested beams was drawn automatically by the mean of computerized plotter. Fig. (5) shows the view of the testing machine used in the present study. The given central deflection measured by the plotter is checked with the readings of a mechanical dial gage which was positioned at the bottom of some of the tested beams. The same results were obtained which indicate the accuracy of the plotter measurements. Electrical strain gauges were glued on the plate surface to measure the strain in the steel plate. One control beam in each group was first tested to failure at a loading rate of 0.5 kN/sec and the other beams then loaded by the ratios of 0, 50 %, and 75 % of the ultimate load of the control beam. The strengthening process then done using the technique discussed in the previous section. All the strengthened beams then tested for the ultimate load with a loading rate of 0.5 kN / sec. Table (2) shows the detail of the tested beams in addition to the results of the ultimate load and compressive strength of the concrete cubes.

Results and Discussion

In the following paragraphs the results of the ultimate load, load-deflection response, load-steel plate strain, and the compressive strength of concrete were presented and discussed. Table (2) shows the values of test ultimate load and the ratio of ultimate load of preloaded beams to that of the control beams. As shown, the value of ultimate load for all beams is larger than that of the control beam, or the ratio is higher than 100% for all the beams. This observation indicates the usefulness of the strengthening process using welding technique. The percentage of increase varies between 1 to 17 for Group (1) and Group(2) beams (using 1 mm thickness steel plate) with an average value of 9 and 70 to 94 for Group (3) beams (using 3 mm thickness steel plate). Fig.(6) shows the variation of load percentage with the preloading ratio for all beams. From the test results of Table (2) and Fig.(6) the following observations can be drawn:

a- The process of strengthening using welding technique is able to bond the steel plate to the reinforced concrete beam and furnishes the state of composite action.

b- The effect of preloading is too small and can be neglected and lead to the decision that cracked beams can be repaired using steel plates successfully.

c- Load increase as a result of strengthening is considerably higher for those beams strengthened with 3 mm thickness plate as compared with those beams strengthened with 1 mm thickness plate. The flexural strength of strengthened beams using 3 mm steel plate was so high that shear failure occurs for all beams as shown later from the observation of cracks in the photos taken for the tested beams.

Figs. (7-10) show the load-deflection relationship of Group (1) and Group (2) beams. It is observed that the trend of the load – deflection for strengthened beams and control beams is similar and the effect of strengthening appears near the ultimate load. It is followed that the stiffness of the plated beams is not differ from that of the control beam. It is also shown that the deflection at ultimate load and hence the ductility is not reduced due to strengthening with 1 mm steel plate. Therefore the beam can be repaired using 1 mm steel plate for the ultimate not lower than that of the control beam without scarifying the ductility. Fig. (11) shows the load-deflection relationship of Group (3) beams. The following observations can be drawn from the relationships:

a- The ultimate load was increased by about 100% due to strengthening with 3 mm thick steel plate.
b- The effect of preloading on the ultimate load and deformation is small and can be neglected.
c- The stiffness was increased by about 100% as a result of strengthening the deflection corresponding to ultimate load and hence the ductility is reduced to about one half as a result of strengthening.

Fig.(12) shows the variation of strain in steel plate with load for different preloading ratios for Group (2) beams. It is observed that the higher the preloading ratio the larger the strain in steel plate will occur. This occurs because in the cracked tension zone due to reducing the flexural stiffness, the beam material represented by the elastic concrete and steel bar will not do their role correctly and the strain later carried by strengthening plate, especially in that beam preloaded with 100% of the ultimate load of the control beam.

Cracking patterns of some of the tested beams are shown in Figs. (13-17). It is clearly shown that those beams strengthened with 1 mm thickness steel plate failed in flexure in a manner that the steel plate yielded followed by crushing of concrete in the compression zone near the central portion of the beam. Some cracks were produced due to preloading and after strengthening due to continuous strain in steel plate such cracks enlarge and increase in number and cover wide range in the central portion of the beam. In an adverse manner the number of flexural cracks in Group (3) beams is small and as a result of strong steel plate of 3 mm thickness the mode of failure changed from flexure to shear. The provided shear reinforcement spaced 75 mm was not able to resist the occurrence of shear failure due to the high flexural strength of the composite beam. Observation of the welded plates after testing indicates that debonding was occur for some beams due to the failure of weld in Groups (1) and (2) beams. Locations of debonding due to failure of the weld were larger in number for Group (3) beams. This occurs due to the fact that the yield does not occur in such types of plate and continuous deformation lead to debonding before that the crushing of concrete will occur. The strength reduction due to debonding in some locations was supported by other true weld points and make from the beam to resist further load leading the beam to fail in shear.

Conclusions

From the present experimental results, the following conclusions can be drawn:

1- The process of welding steel plate to the stirrups of reinforced concrete beams is successful and can furnish a good composite action.

2- Strengthening reinforced concrete beams with steel plate and repairing cracked beams can be done successfully for obtaining the ultimate load not lower than that of the control beam. After strengthening an increase in the ultimate load of 1 to 17 % and 70 to 94 % was obtained for 1 mm thickness plate and 3 mm thick plate , respectively .
3- The ductility of those beams strengthened with 1 mm thickness steel plate was not changed compared with that of virgin beam and reduced to about one half for those beams strengthened with 3 mm thickness plate
4- The effect of preloading is too small and can be neglected on both the ultimate load and the load-deflection response and lead to the decision that cracked beams can be repaired using steel plates successfully.

References

1- ACI 440 Committee, 1996, "State-of-the-Art Report on Fiber Reinforced Plastic (FRP) Reinforcement for Concrete Structures", ACI 440R-96, American Concrete Institutes, 68 pp.
2- Ganga Rao, H. V. S., and Vijay, P. V., 1993, "Bending Behavior of Concrete Beams Wrapped with Carbon Fabric" , J. Struct. Eng., Vol. 124, No. 1, pp. 3-10
3- Duthinh, D. and Starnes, M., 2001, "Strengthening of Reinforced Concrete Beams with Carbon FRP", Composites in Constructions, edited by Figueiras et. al., pp. 493-498
4- Balendran, R. V., Nadeem, N., Maqsood, T. and Rana, T. M., 2001, " A Parametric Study on the Flexural Behavior of Plain Concrete Beams Strengthened by Externally Bonded Plates", Proceedings of the 26th Conference on our World in Concrete and Structures, pp.173-182
5- Ramana, V. P. V., Kant, T., Morton, S. E., Dutta, P. K., Mukherjee, A. and Desai, Y. M., 2000, "Behavior of CFRPC Strengthened Reinforced Concrete Beams with Varying Degrees of Strengthening", Composites, Part B 31, pp. 461-470
6- Alagusundaramoorthy , P , Harik , I.E. , and Choo ,C.C , 2002 , " Flexural Behavior of R/C Beams Strengthened with CFRP Sheets or Fabric ," Research Report KTC -02-13/SPR 200-99-1F , 35 pp.
7- Al-Musallam, T. , 1999," Flexural Strength of Concrete Beams Externally Reinforced with GFRP Sheets ," Proceedings of the Fifth Saudi Engineering Conference, pp.117-127
8- Mukhopadhyaya, P. , Swamy , N. , and Lynsdale , C. ,1998, " Optimizing Structural Response of Beams Strengthened with GFRP Plates ," J. of Composites for Construction , Vol.2 , No. 2 , pp. 87-95.
9- Spandea, G. , Bencardino , F. , and Swamy , R.N. , 1998 ," Structural Behavior Composite RC Beams with Externally Bonded CFRP ," J. of Composites for Construction , Vol.2 , No. 3 , pp.132-137
10- Aziz, O. Q. , 1997 ," Experimental Study of Strength and Repairing of Some Fibrous Concrete Beams by Externally Steel Plate," Dirasat, Vol. 24 , No.1, pp.51-59.

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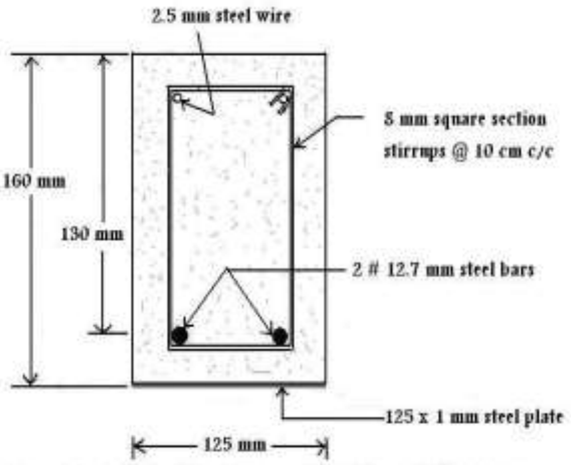

Fig. (1) Detail of Cross Section of Group (1) and Group (2) Beams

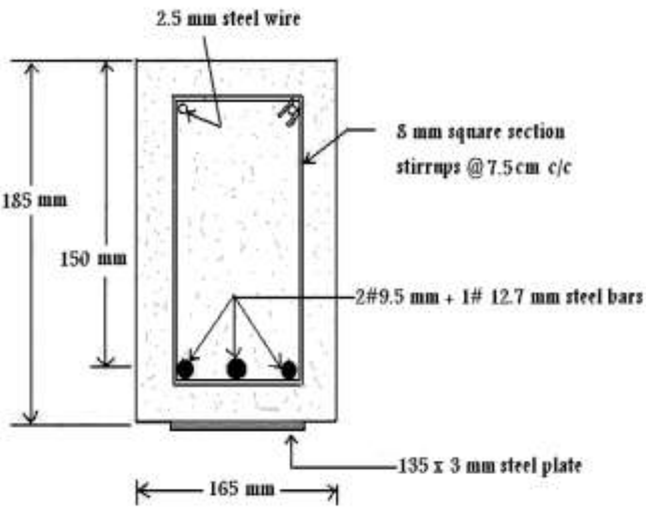

Fig. (2) Detail of Cross Section of Group (3) Beams

Figure.(3) Making grooves in the tension face of the beam by removing

Figure.(4) Welding the steel plate to the stirrups at the tension face

Figure. (5) Computerized Testing Machine with Load – Deflection Plotter

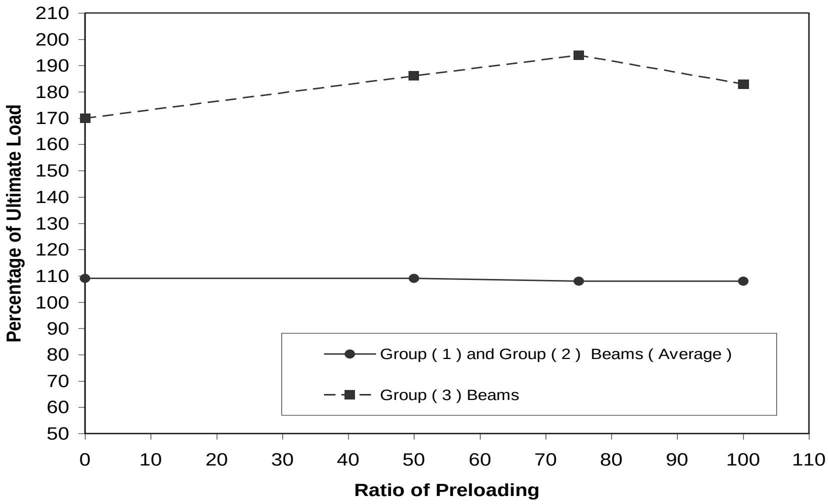

Fig.(6) Ratio of Test Ultimate Load

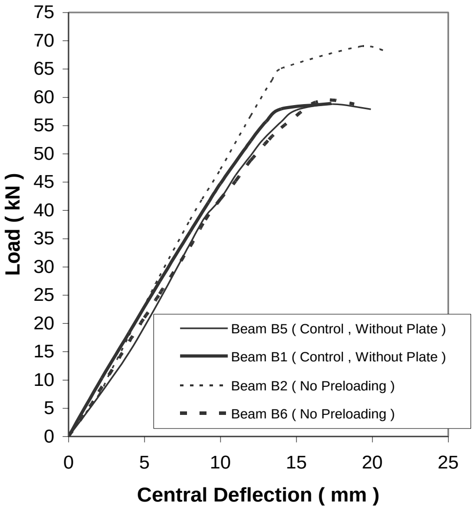

Fig. (7) Load - Deflection Relationship of Control Beams and Strengthened Beams (No Preloading)

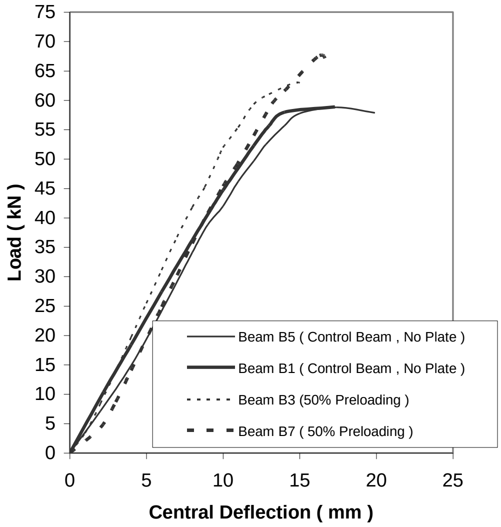

Fig.(8) Load - Deflection Relationship of Control Beams and Strengthened Beams (50% Preloading)

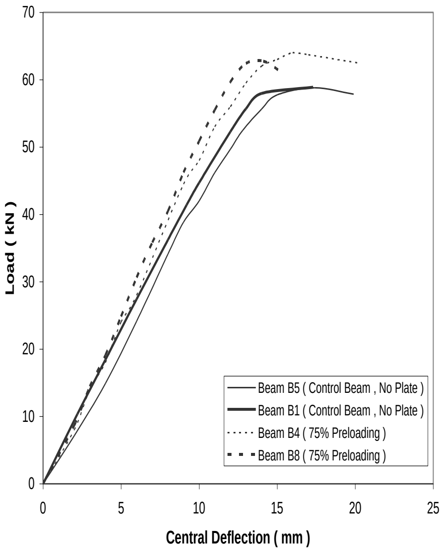

Fig.(9) Load - Deflection Relationship of Control Beams and Strengthened Beams (75% Preloading)

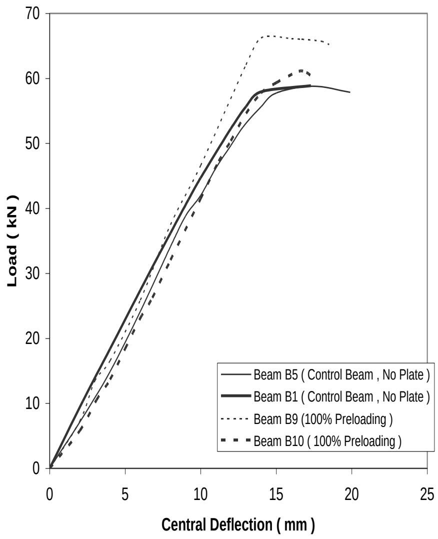

Fig.(10) Load - Deflection Relationship of Control Beams and Strengthened Beams(100% Preloading)

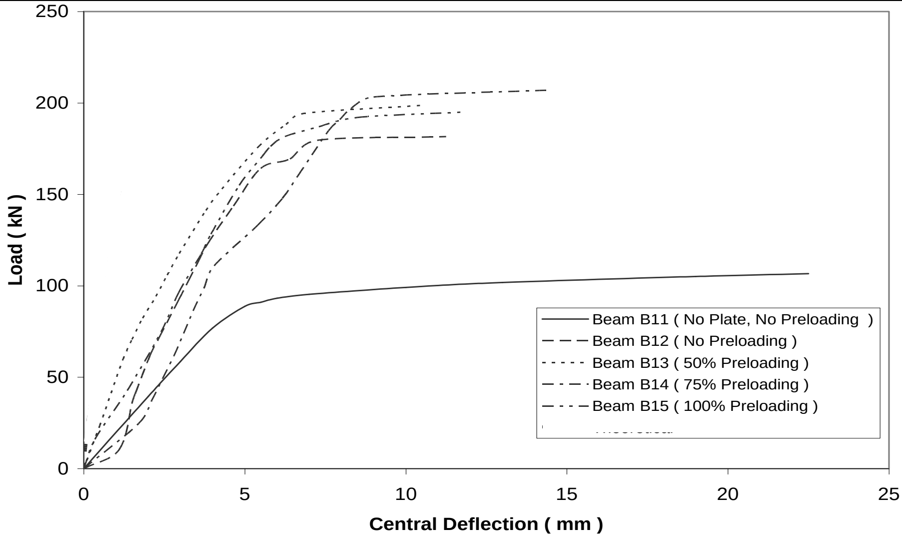

Fig. (11) Test Load – Deflection Relationship of Group (3) Beams

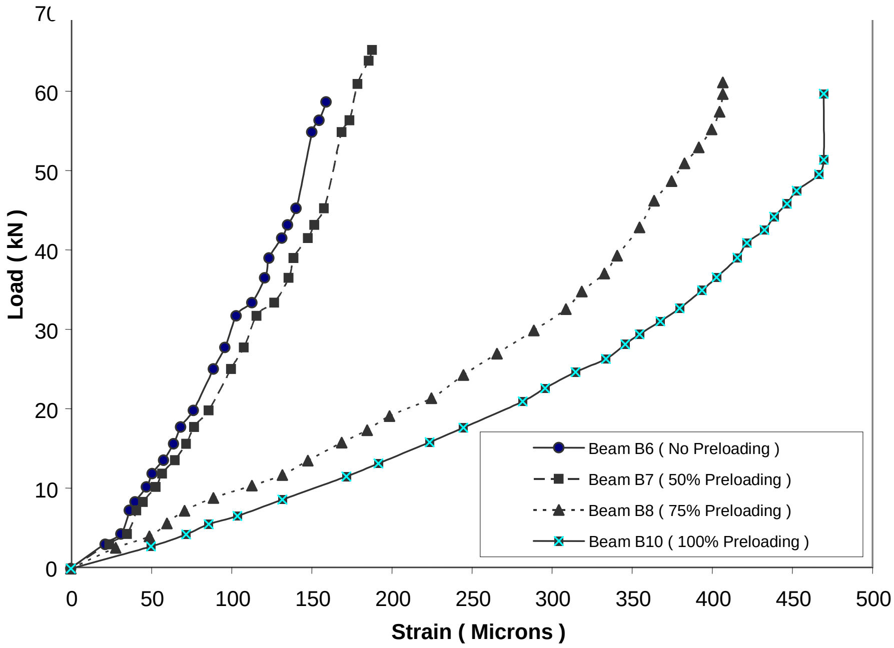

Fig.(12) Load - Steel Plate Strain Relationship

Figure. (13) View of Cracking of Beam B7 (50% Preloading, debonding in two welding point)

Figure. (14) View of Cracking of Beam B10 100%Preloading, debonding in one welding point)

Figure. (15) View of Cracking of Beam B12 (No preloading, No debonding occurs)

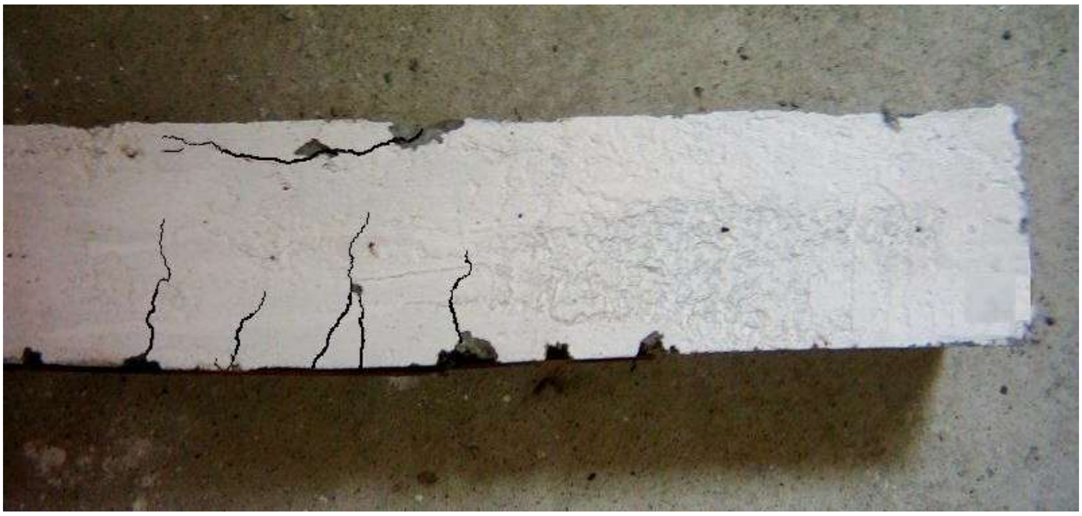

Figure. (16) View of Cracking of Beam B14 (75% preloading, debonding in one welding point)

Figure. (17) View of Cracking of Beam B15 (100% preloading, debonding in one welding point)

Table (1) Properties of the Used Steel Reinforcements and Steel Plates

Material	Shape	Type of Use	Strength (MPa)	
			Yield	Tensile
12.7 mm	Bar	Flexure	579	672
9.5 mm	Bar	Flexure	512	803
8 mm	Square	Shear	536	-----
1 mm thick	Plate	strengthening	480	-----
3 mm thick	Plate	strengthening	577	-----

Table(2) Results of Ultimate Load of Beams

Group	Beam	Percentage of Preloading Ratio	Cube Strength (MPa)	Test Ultimate Load (kN)	Ratio of Test Ultimate Load
1	B1	-----	26.7	58.89	100
	B2	0		68.99	117
	B3	25		61.02	104
	B4	50		64.00	109
	B9*	75		66.24	113
2	B5	-----	23.9	58.81	100
	B6	0		59.54	101
	B7	25		67.61	115
	B8	50		62.77	107
	B10**	75		61.11	104
3	B11	-----	24.9	106.6	100
	B12	0		181.6	170
	B13	25		198.83	186
	B14	50		207.05	194
	B15***	75		195.0	183

* Beam B1 tested and then strengthened
** Beam B5 tested and then strengthened
*** Beam B11 tested and then strengthened