論文 Experimental and Analytical Studies of Plated T-Beams Subjected to Negative Bending

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ABSTRACT: This paper presents the results of an experimental and theoretical analysis of the behaviour of reinforced concrete T-beams strengthened with external bonded steel plates when subject to negative bending. Ten T-beams were tested. The main parameter investigated were width and thickness of bonded plates (the plates have the same cross sectional areas), position of glued plates (i.e. either at the middle or sides of the flange), shear span to effective depth ratio (a/d), and longitudinal reinforcement partially replaced by glued steel plates. A numerical analysis to predict the flexural behaviour of both strengthened and repaired beams was done using a nonlinear finite element approach
KEYWORD: strengthened T-beam , glued plate by epoxy resin.

1.INTRODUCTION

In recent years, the development of a wide variety of epoxy adhesives, has given rise to new techniques for repairing and strengthening concrete structures. These techniques include gluing steel plates to the surface of the concrete. The overall aim of the present experimental work was to study strength and deformation characteristics of R/C T-beams strengthened with steel plates glued to their tension faces when subjected to negative bending moment. The tests therefore, simulate the hogging moment region of the continuous beam or inverted T-beam. The main parameters investigated were as mention above. A theoretical analysis to predict the flexural (deflection, cracking load and ultimate load) of both strengthened and conventional R/C beams was performed, using a nonlinear finite element program based on the isoparametric timoshenko beam element [7]. In order to allow for development of cracks through the depth of the beam and to represent the properties of the different materials through this depth a layer approach was adopted. Nonlinear effects due to yielding of steel, cracking and crushing of concrete were taken into account.

2. EXPERIMENTAL WORK

2.1 OUT LINE OF PROGRAM

Ten beams were tested, full details of their dimensions, arrangement of reinforcing steel and loading set up are shown in Fig. 1 and variables studied are given in table 1. For all strengthened beams, the glue layer thickness was constant at 1.5 mm and the steel plates were stopped 5 cm short of the supports.

2.2 MATERIAL PROPERTIES

Concrete mix used was produced from ordinary Portland cement, local natural sand and local gravel. The mix proportions by weight were 1.0: 2.13: 4.26: 0.55 (cement :sand :gravel :water/cement) with cement content of 300 kgf/m³. Three diameters of mild steel bars of 6, 10 and 13 mm with yield

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strengths of 2.6, 2.41 and 2.86 tf/cm^2 respectively were used as conventional reinforcement. Four thickness 1, 2, 3 and 4 mm of mild steel plates with yield strengths 2.6, 3.1, 2.08 and 2.46 tf/cm^2 respectively were used as strengthening reinforcement. Epoxy compound was used as adhesive material in this work. Compressive, bending and adhesive strength on concrete of Epoxy adhesive as given by the manufacturers are 600, 250 and 25 kgf/cm^2 respectively.

2.3 BONDING PROCEDURE

After 21 days of casting, the beams and steel plates were prepared for bonding. Bonding procedure was carried out as described in Ref. [3] and [5]. It can be briefly explained as follow: the concrete surface was roughened by using electrical disk grinder to remove a thin layer having a higher water/cement ratio and a lower strength compared with under concrete and wire brushed. The steel plate was also roughened and cleaned by Aston. The epoxy adhesive was applied to both surface and held in position by uniformly distributed pressure obtained by a thick wooden plate clamped to the tested beams and maintained for 24 hours until the adhesive had cured

2.4 TEST METHOD AND MEASUREMENT

All beams were tested under simply supported condition over a span 2.0 m with their tension faces uppermost as shown in Fig.1. For all beams, the first crack load, deflection under loading point, steel plate strains and ultimate load were measured.

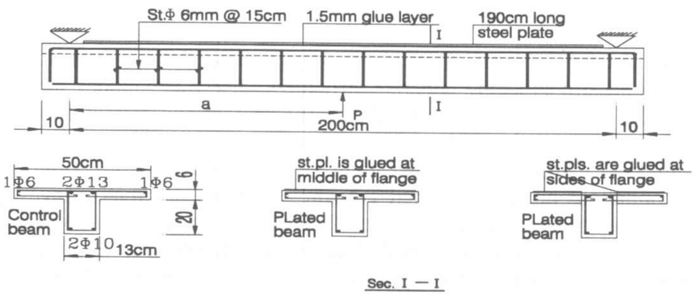


Figure 1 Details of Tested Beams

Table 1 Details of Tested Beams

Beam No.	Longitudinal reinforcing bars	Dimension of steel plat (mm)	*1a/d ratio	*2A_s bar (cm^2)	*2A_s plate (cm^2)	*2A_s total (cm^2)	*3F_{cu} (kg f/cm^2)	Position of plate
BC-1	2.13 +2.6	Without	4.33	3.22	-	3.22	210	Without
BC-2	6.13 +2.6	Without	4.33	8.52	-	8.52	230	Without
BA-1	2.13 +2.6	1×500	4.33	3.22	5.00	8.22	220	
BA-2	2.13 +2.6	2×265	4.33	3.22	5.30	8.52	215	
BA-3	2.13 +2.6	3×175	4.33	3.22	5.25	8.47	218	
BA-4	2.13 +2.6	4×135		3.22	5.40	8.62	225	
BB-1	2.13 +2.6	2(2×130)	4.33	3.22	5.30	8.52	218	
BB-2	2.13 +2.6	2(3×87.5)	4.33	3.22	5.25	8.47	226	
BD-1	2.13 +2.6	2×265	3.00	3.22	5.30	8.52	220	
BD-2	2.13 +2.6	2×265	2.00	3.22	5.30	8.52	210	

*1a/d Shear span to effective depth ratio *2A_s Sectional area of steel bars or plates 3F_{cu}

3F_{cu} Concrete compression strength measured by using cube 15 15* 15 cm

3. EXPERIMENTAL RESULTS

3.1 MODE OF FAILURE

Table 2 lists the mode of failure of each beam. Three modes of failure were identified during the tests and which are defined as follows:
Flexural failure: this type of failure was characterized by yielding of reinforcement before failure occurred, followed by crushing of concrete in the compression zone. This mode of failure was reported by many researchers [1, 3, 4]. **Shear/bond (plate debonding):** this was initiated at one end of the plate accompanied by the formation of shear cracks near this end at a load slightly less than the failure load. As the load increased these cracks propagated diagonally towards the loading point and horizontally in the concrete at tension steel level toward the plate end causing partial separation of the plate end. This type of failure was observed by other [1, 3, 4]. **Shear failure:** beam BD-2 having a/d of 2 failed suddenly in shear. A large diagonal tension crack took place in the midway between point of load application and the nearest support. At failure no sign of plate separation or yielding was observed.

3.2 FIRST CRACK LOAD

Table 2 lists the experimental value of first crack load obtained visually using a magnifying glass. These results show that the restraining effect of the glued plate on the appearance of first crack load is clear. Using two plates glued at both sides of the flange is better in increasing cracking load than using only one plate with the same dimension at the middle of the beam, this might be due to the increase of the stiffness of the flange, which cracked first. Results show also that as a/d decreased the cracking load increased

3.3 ULTIMATE LOAD

The experimental ultimate loads and theoretical values calculated according the ultimate limit state simplified method of CP 110 [8] for all beams are given in table 2. The results show that generally the addition of the plates to the tested beams increased their ultimate loads. The maximum increase obtained was 157% for beams strengthened with plate of b/t ratio132.5. While the maximum increase in the ultimate load of rectangular beams (12 ×20× 200 cm dim.) and (15× 25×230 cm dim) researched by Abdel Hafez [3] and Swamy et. al. [1] were 33% and 16% respectively. The results also show that for the same dimensions of bonded plate, gluing two plates at the sides of the flange instead of one plate at the middle of the flange, reduced the ultimate capacity of the beam by about 13%. It can be noticed that as the a/d ratio decreased the effect of the bonded steel plates in improving the ultimate load of strengthened beams decreased. Beams BA-1 and BA-2 in which 62% of the longitudinal

Table 2 Results of Tested Beams

Beam No.	Dimension of steel plate (mm)	*b/t ratio	**a/d ratio	Exp. first crack load(tf)	(1)Exp. ultimate load (tf)	(2)Theo. ultimate. Load(tf)	(1) . (2)	Mode of failure
BC-1	Without	-	4.33	1.0	4.9	3.97	1.23	flexure
BC-2	Without	-	4.33	3.5	9.0	8.84	1.02	flexure
BA-1	1×500	500	4.33	3.5	12.6	9.67	1.3	flexure
BA-2	2×265	132.5	4.33	3.5	12.6	10.15	1.24	flexure
BA-3	3×175	58.33	4.33	3.5	9.8	10.12	0.97	flexure
BA-4	4×135	31.75	4.33	4.2	8.4	9.10	0.92	shear/bond
BB-1	2(2×130)	130	4.33	4.2	11.2	10.15	1.10	flexure
BB-2	2(3×87.5)	58.33	4.33	4.2	8.4	10.12	0.83	shear/bond
BD-1	2×265	132.5	3.00	4.9	9.8	11.16	0.88	shear/bond
BD-2	2×265	132.5	2.00	5.6	7.7	15.46	0.50	shear

* b/t- plate width to thickness ratio **a/d- Shear span to effective depth

reinforcement was replaced by glued plates of b/t ratio equal or greater than 132.5 showed a significant increase about 40% in ultimate load over the control beam BC-2. This may be due to increase of the lever arm of the glued plated beams. However, beams BA-3 and BA-4 in which also 62% of longitudinal reinforcement was replaced by plates having b/t ratio equal or less than 58.3 showed a slight increase or decrease compared with that of the control BC-2

From the values of the ultimate load, calculated according to method of CP110 [8] given in table 2,.it can be seen that this method was under- estimate the ultimate load of most beams failed in flexure, while over- estimate of those failed in shear/bond or shear only.

3.4 LOAD DEFLECTION RELATIONSHIPS

Figures 2 to 4 show the typical load-deflection characteristics curves for most of the tested beams. Figure 2 shows that the stiffness of all plated beams have been increased compared to those of the unplated BC-1 and BC-2, and the increase is considerable compared to BC-1. Beam BA-2 shows the best stiffened especially near failure. Figure 3 illustrates that beam strengthened with steel plate glued at the middle of the flange showed lager stiffness than that with the steel plates glued at both sides of the flange. Beams strengthened with similar plates and tested under different a/d ratios showed increase in stiffness as a/d ratio increased as shown in Fg.4. This maybe due to the change of the mode of failure from flexural to shear/bond and shear failure respectively

3.5 STEEL PLATE STRAINS

The relations of load and strain of the center of steel plate for some chosen beams are shown in Fig. 5. It can be seen from Fig. 5 that, if beams are strengthened with the steel

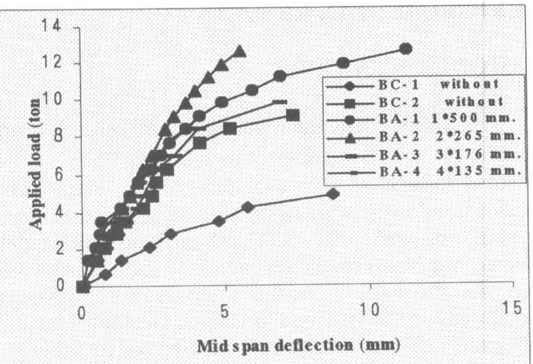


Figure 2 Effect of plate dimensions on load deflection curve

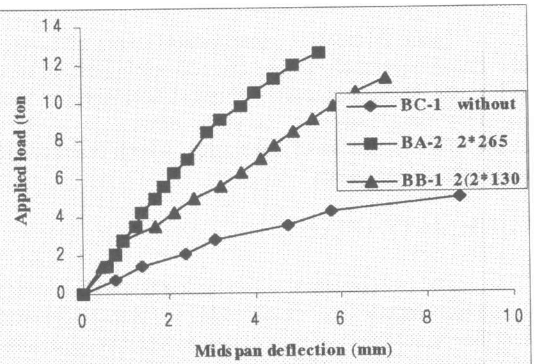


Figure 3 Effect of position of plates on load-deflection curve

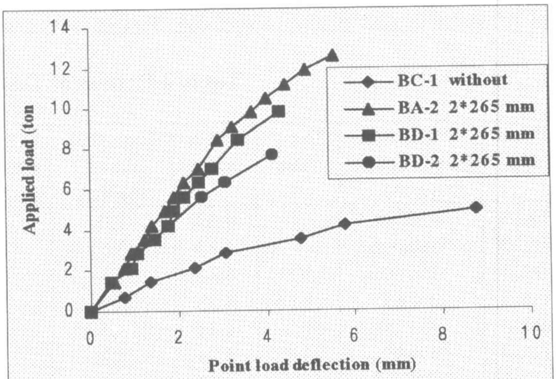


Figure 4 Effect of a/d ratio on load deflection curve

plates of the same cross section area, as the thickness of the plate increased, the general level of strain decreased. It has to be mentioned that the tensile strain of plate at ultimate load for beams BA-1 and BA-2 was larger than the plate yield strain, while it was less than that of the plate of beams BA-3 and BA-4 due to sudden shear/bond failure of those two beams.

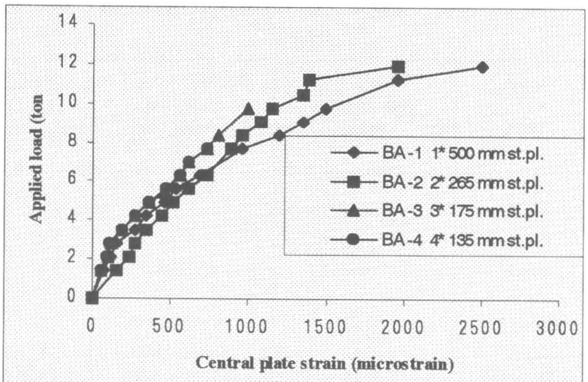
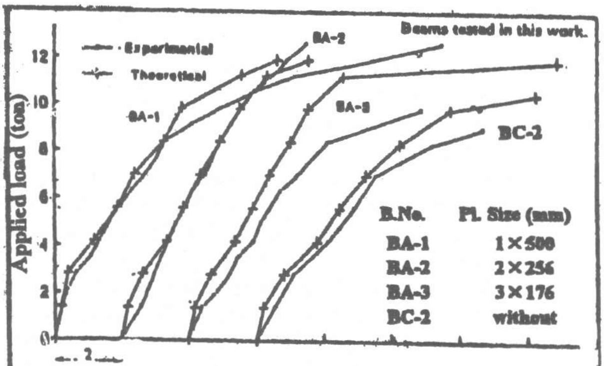


Figure 5 Effect of plate dimension on central plate strain

4.THEORTICAL ANALYSIS

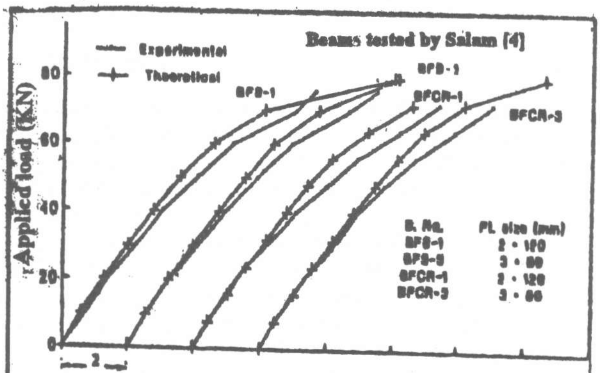
In order to predict the flexural behavior of reinforced concrete beams, strengthened or repaired, a nonlinear finite element program based on the layer approach was developed. In this approach the depth of the beam is divided into a number of layer parallel to the neutral plane. Each layer is assumed to resist both axial and transverse stresses. This approach enables the penetration of the cracks through the depth of the beam to be taken into account. Concrete was assumed to follow the stress-strain relationship proposed by Liu et al [6]. Steel was modeled as an elastic perfectly plastic smeared layer capable of carrying forces in original bar direction only. The behavior of the epoxy was assumed to be as that of concrete in tension. Typical results for load -mid span deflection curves for beams tested in this work and the beams (strengthened or repaired) tested by Salam [4] are shown in Fig 6 and Fig 7 respectively. Acomparison between the measured and calculated loads are given in Table 3.

It is concluded that the proposed layered model can predict the behavior of both strengthened or repaired reinforced concrete beams failing in flexure.



Mid span deflection

Figure 6- Comparisons of load-deflection curve



Mid span deflection

Figure7 -Comparisons of load-deflection curve

Table 3 Comparison between Calculated and Measured Loads

Beam No.	Longitudinal reinforcing Bars	Dimension . of steel plat (mm)	First Crack Load (tf) .			Ultimate load (tf)		
			(1) Test	(2) Cal.	(1) . (2)	(1) Test	(2) Cal.	(1). . (2)
BC-2*	6.13 +2.6	Without	3.5	2.8	1.25	9.0	10.5	0.85
BA-1*	2.13 +2.6	1×500	3.5	2.8	1.25	12.6	11.9	1.06
BA-2*	2.13 +2.6	2×265	3.5	2.8	1.25	12.6	11.9	1.06
BA-3*	2.13 +2.6	3×175	3.5	2.8	1.23	9.8	11.2	0.88
			KNf	KNf				
BFS-1**	2.12	2×120×1800	18	20	0.90	75.8	75	1.01
BFS-3**	2.12	3×80× 1800	18	20	0.90	79.5	80	0.99
BFCR-1**	2.12	2×120×1800	8.5	8.0	1.06	74.4	74	1.01
BFCR-3**	2.12	3×80× 1800	8.0	8.0	1.00	74.8	76	0.98

* Beams tested in this work **Beams (12×20×200 cm dimension.) tested by Salam [4]

5. CONCLUSIONS

Based on the experimental and theoretical results, the following conclusions are drawn:

1. The addition of glued steel plates to the T-beams delays the appearance of the first visible crack, increases both the ultimate load and the flexural stiffness, and improves the structural deformations of the beams at all load levels
2. The maximum increases in the ultimate load over that of unplated beam were 71%, 100%, 157% and 157% for beams strengthened with steel plates having the same cross-sectional area and with b/t ratios equal 33.75, 58.33, 132.5 and 500 respectively.
3. For the same dimensions of bonded plate, gluing two plates at the sides of the flange instead of one plate at the middle of the flange reduced the ultimate strength of the beam by about 13% and caused an increase in both mid span deflection and central plate strain.
4. Up to 62% of the main steel of the T-beam can be replaced by external bonded steel plate and the composite section still reached its full flexural strength.
5. For T-beams strengthened with similar plates as the a/d ratio increased the ultimate load increased, and the deflection under loading point reduced.
6. The proposed layered modal can be confidently used to predict the flexural behavior (deflection, cracking load and ultimate load) of either plated or conventional reinforced concrete beams.

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