Strengthening Steel I-Beams by Welding Steel Plates before or While Loading

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***Abstract*— In this paper, the behavior of strengthening steel beams is investigated experimentally. Full scale tests on six specimens strengthened with steel cover plates are present. All tested beams have IPE sections. They were tested under four point loads with one end hinged and the other end roller. Four specimens were strengthened before loading. Nevertheless, two specimens were strengthened while under load using a new welding technique. The new welding technique is based on reducing deflection before welding of cover plate. Test parameters include changing the length of strengthening cover plate, two strengthening patterns, and three levels of preloading. The experimental results showed that the cover plate length affects the ultimate carrying capacity of the tested specimens. In addition; the ultimate carrying capacity was affected by the area of the welded plate. The proposed welding technique (used to weld cover plate while under load) was found to be effective in increasing the load capacity by up to 5.7% and reducing the maximum deflection by 30.7%.**

Keywords*— *Strengthening; Steel Beams; Cover Plate; Experimental; Reducing of Deflection, Welding

I. INTRODUCTION

Strengthening the existing structures is a common way to avoid failure due to change in function or construction error [1]. Two different techniques are currently used to increase or restore the load capacity of steel structures: 1) Bonding FRP sheets [2]; and 2) welding steel plates. Using of FRP sheets overcome several difficulties such as corrosion resistance and bigger value of the resistance / weight ratio [3] & [4]. There are many factors affecting the capacity of strengthened structure, like type of FRP, number of layers, type of adhesive and special considerations must be applied at the place of bonding [5, 6].

The use of fiber reinforced polymer FRP is well established [2, 7, 8], many research on the application of FRP composites to steel structures have been published [2, 9-13]. Even the use of FRP material for strengthening and rehabilitation of steel members hold numerous benefits, but applications involving wide flange beams have been limited due to the negligible increases in elastic stiffness [14].

Strengthening by steel plate is a popular method due to its availability, cheapness, uniform materials properties (isotropic), easy to work, high ductility and high fatigue strength. However, several disadvantages of steel plate including the transportation, handling and installation of heavy plates, corrosion of the plates, and limited delivery lengths of plates which necessitates the work and difficulty of forming joints, the need for massive and expensive false work to hold plates in position during adhesive cure, and the need to prepare for steel surface for bonding are very apparent [15].

Strengthening of existing structures may be carried out while under load or with the load temporarily relieved. For beams carrying loads, strengthening is possible and safe [16]. Few researches have been focused on the behavior of the steel structures strengthened while loaded by welding steel plates.

Early research of Tall [17], studied the strengthening of loaded steel columns. He stated that columns can be strengthened by welding of steel cover plates, or by changing the residual stress distribution with laying of a weld. Tall changed the orientation of welded cover plates with discussion of residual stresses magnitudes and distributions. He proposed that the strengthening of steel columns by cover plates welded to the flanges improves column strength than laying the weld alone.

Wu et al. analyzed 317 finite element models to verify the behavior of strengthening wide flange steel columns with welded cover plates [18]. The study showed that column slenderness and initial out of straightness remain the important factors for reinforced columns. The interactions of the orientation of the cover plates and the buckling direction were observed to affect the strength of strengthened columns.

Liu et al. [16] conducted an experimental study on W-shaped beams strengthened while under load. The W-shaped beams were tested under four point loads. The results stated that the effect of preload level, at the time of strengthening, on the ultimate loads of the beams associated with the beams failure modes. In a follow-up study, Liu et al. [16, 19] extended their research to investigate several influential parameters. Deflection charts of tested specimens [16] showed an increment of deflections during the welding process, while the load was held.

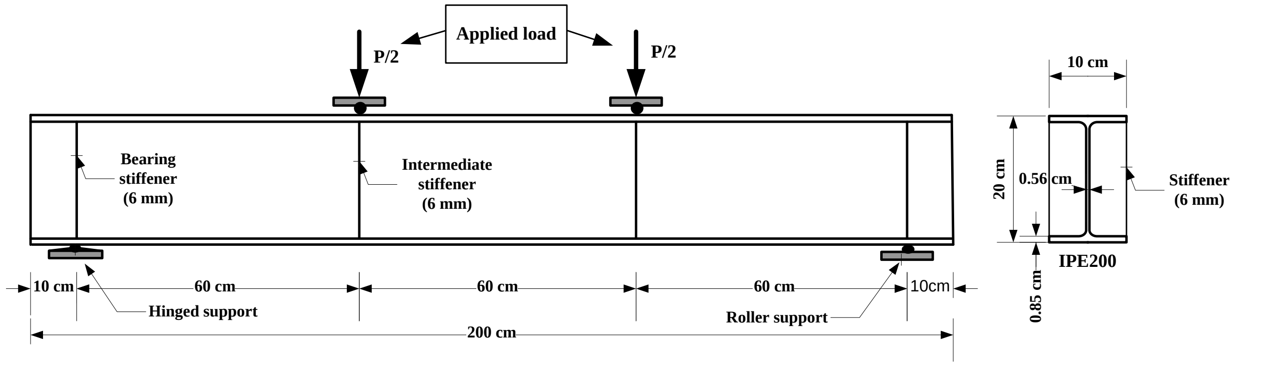


Fig. 1 Test setup for Beam BC

The increment of deflection during welding is unacceptable action, since structural elements must be designed to satisfy requirements that prevent excessive movement or deflection. Due to that fact, the author produces the reduction of deflection before the beam is strengthened. This is achieved through experimental study described herein.

This study was therefore carried out to investigate the behavior and ultimate load carrying capacity of beam strengthened with steel cover plates. It is on an experimental study of the behavior of six strengthened IPE beams. Two specimens were strengthened while loaded after reducing the beam deflection, and their performance was compared with that of testing specimens strengthened before loading. The adopted strengthening patterns use the welded cover plate whose area is less than that of the flange area.

II. EXPERIMENTAL PROGRAM

A. The Scope

An experimental program was conducted to investigate the behavior and ultimate capacity of flexural I-beams reinforced with welded plates. The following subtitles provide a detailed description of the tested beams, experimental procedure and instrumentation.

B. Description of the Tested Beams

Details of test specimens are listed in table 1. All six beams used in the experimental study are IPE 200 with total length L_t= 200 cm such that the length between supports is L= 180 cm. Four vertical stiffeners at four point load (two bearing & two intermediate) were welded to the tested beams before loading. The dimensions of tested beams and the test setup are shown in Fig. 1. The tested beams were strengthened by a cover steel plate (8 x0. 6 cm) with weld size 6mm, the two strengthen patterns (labeled as A and B) are shown in Fig. 2. Pattern A was to weld the cover plate to lower flange of the test specimen, where pattern B was to weld the plate to the upper and lower flanges.

The tested beam is referred, throughout the paper, as:

BX-Y-Z

Where:

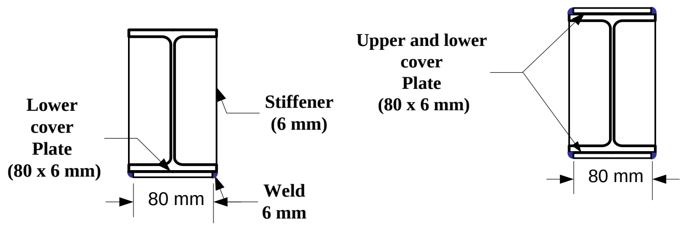
X describes strengthening patterns such that (C) for the control beam, (L) for plate welded to lower flange and (U) for plate welded to upper flange. Y indicates the length of cover plate in cm. Z is the ratio of preload (load applied while the beam was strengthened P_{str}/ ultimate load capacity P_u).

Four tensile coupons were obtained to determine the mechanical properties of steel. The average value of the yield stress (F_y) for beams and plates are 284 MPa and 279 MPa respectively.

TABLE 1 TESTED BEAMS DESCRIPTION

Tested beams	Strengthening pattern	Cover plate length (cm)	Preload ratio* %
BC	-	-	-
BL-65	A	65	0
BL-90	A	90	0
BLU-45	B	45	0
BL-90-30	A	90	30
BL-90-50	A	90	50

* *Preload ratio is calculated as ratio between load during welding of cover plate / ultimate Load of control beam BC.*



(a) Pattern A (b) Pattern B

Fig. 2 Strengthening pattern

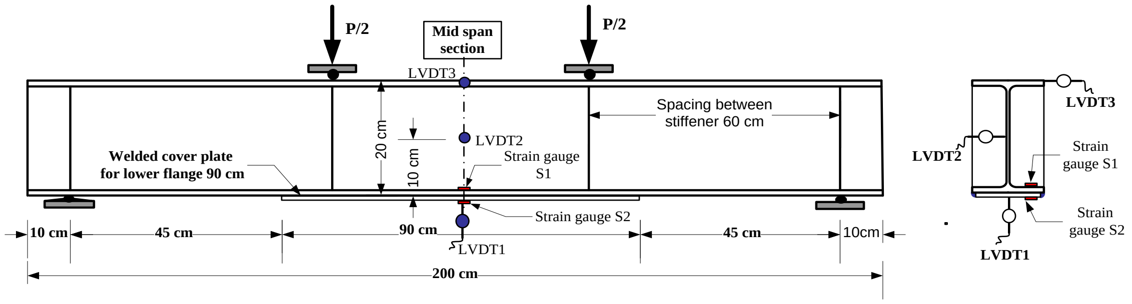


Fig. 3 Instrument locations for tested beam BL-90

C. *The Test Instruments and Setup*

Three LVDTs (linear variable differential transformer) were installed to monitor the behavior of test specimens at the mid-span section, as shown in Fig. 3, which is an illustrated figure of test specimen BL-90. LVDTs were used to record deflection and lateral displacements of the test specimens. In addition, two strain gauges were used to measure the strain of lower flange.

The test specimens were loaded on steel loading frame under four point loads with hinge-roller supports. The load cell capacity is 900 kN. Load distributed beam and 20 mm bearing plates were used to distribute load at two points as shown in photo1.

The specimens are placed and centered on the loading frame. The test procedure begins by Appling a load of approximately 10% of experimental ultimate load (P_u) and then removed. For beam strengthened before loading, the main load is applied and increased till failure. While, loading procedure and welded technique used for beam strengthened while loaded is as follows: 1) The load is applied to certain load value P_{str} then the loading process is paused, 2) part of the beam deflection is reduced manually and measured, 3) the strengthening cover plate is welded. 4) After that the load was continued until failure happened as shown in Fig. 4 and photo 2. Fig. 5 shows the welding sequences for strengthening patterns. Similar sequences have been used by Lui et al. [16].

An automatic testing technique is used to allow computerized control of the displacement of the testing machine head. The reading data for all instruments is recorded with a personal computer using a data logger system.

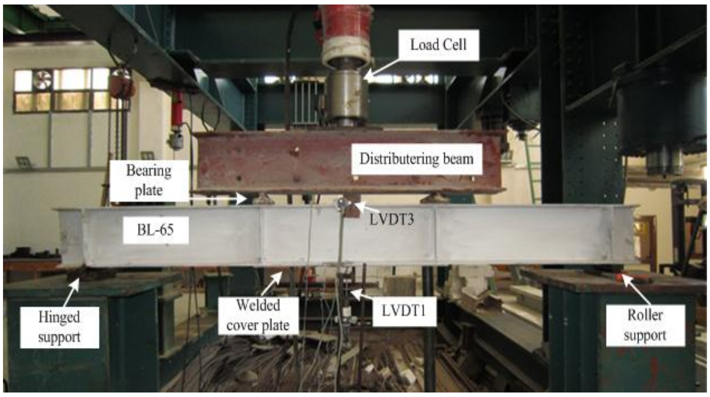


Photo1 Test setup for tested beam BL-65

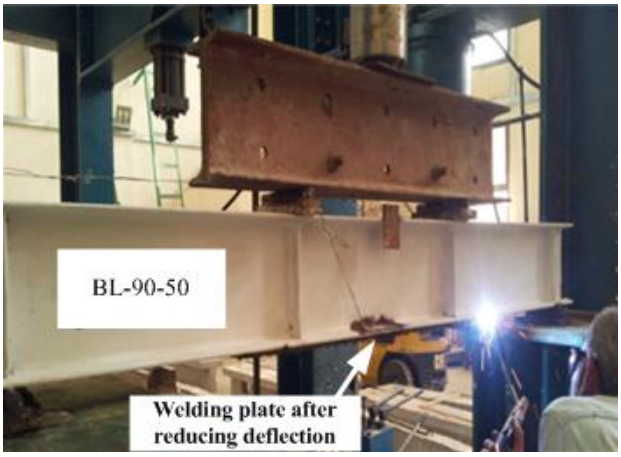


Photo2 Welding process during loading of specimen BL-90-50

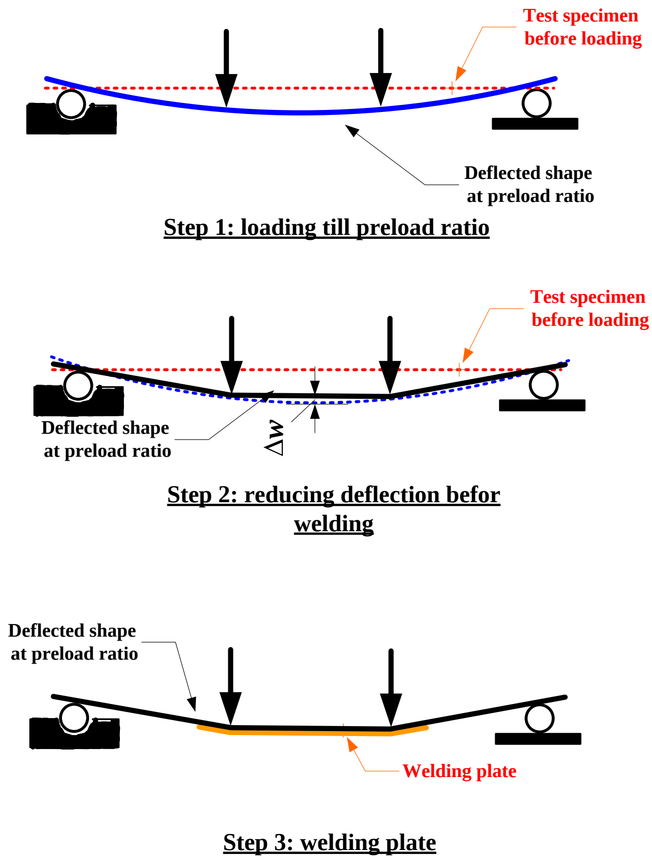


Fig. 4 Strengthening technique during loading

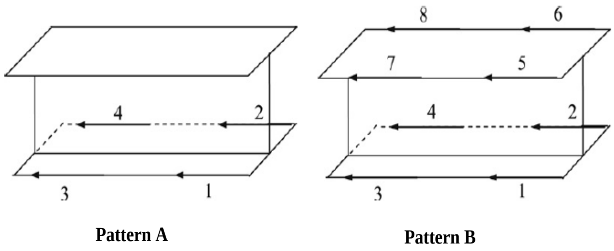


Fig. 5 Welding sequence for pattern A & B

III. THE TESTS RESULTS

In this section, detailed experimental results of the six steel beams are presented. The test results were analyzed according to three influential parameters: 1) welded cover plate length, 2) strengthening pattern; and 3) preload ratio. For each parameter the experimental ultimate load (P_u), the mid span deflection (*w*) and lateral displacement (*v*) are discussed.

A. Effect of Welded Cover Plate Length

The effect of welded cover plate length on load-displacement relationships (deflection and lateral displacement) of the strengthened specimens is shown in Figs. 6 - 7.

The three test specimens BC, BL-65 and BL-90 are referred to as group (1). Specimens BL-65 and BL-90 were strengthened with pattern (A) before loading (preload ratio equal zero). The ultimate loads of the strengthened and un-strengthened specimens are given in table 2.

TABLE 2 TEST RESULTS OF GROUP 1

Tested beams	Ultimate load P_u (kN)	Deflection at P_y (1) w_y (mm)	Lateral deformation at P_u (mm)	Percent increase in load capacity (2) %	Percent increase in max deflection(2) %
BC	218.15	10.89	7.71	-	-
BL-65	220.62	11.91	8.35	1.1	9.3
BL-90	229.17	9.85	N.A.	5.0	-9.5

(1) Py is the load at yield, it was calculated theoretically

(2) Percentage of the Increase in ultimate load capacity and max. deflection equal $\frac{P_u - P_u(BC)}{P_u(BC)}\%$, $\frac{w_y - w_y(BC)}{w_y(BC)}\%$ *respectively.*

For group (1) specimens, the increase in the ultimate load carrying capacity is directly proportional to the increase in cover plate length. The increment in strength relative to the un-strengthened specimen, when the bottom flange was strengthened, was 1% and 5% for cover plate length of 65 cm (0.36 L) and 90 cm (0.50 L) respectively, where L is the span length (180 cm).

The effect of cover plate length, for strengthening pattern A, is less significant than strengthening patterns presented by Lui et al. [19]. As the area of strengthening cover plate used by Lui is bigger than the flange area presented herein.

The increment of the elastic stiffness of specimens (BL-65) is negligible (the same as un-strengthened steel beam (BC), as shown in Figs. 6 - 7. The increment of the elastic stiffness of the strengthened specimen (BL-90) is noticeable. Also, a small increment of the post-yield stiffness was finally attained as clearly indicated by the slope of the load–displacement curve in the post-yielding region.

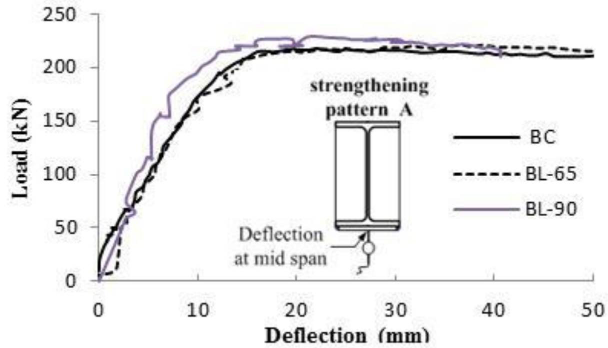


Fig. 6 Load deflection curves for group (1)

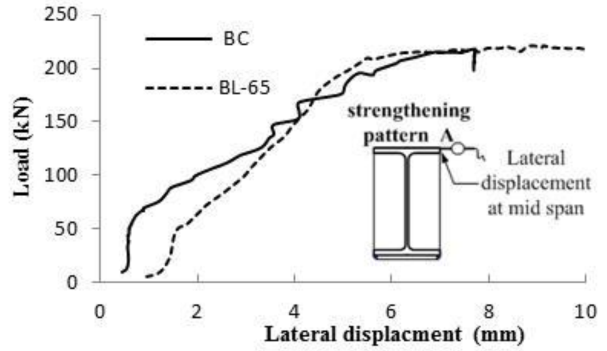


Fig. 7 Load lateral displacement curves for group (1)

B. The Effect of Strengthening Pattern

The tested specimens have two strengthening patterns: A and B, as presented in Fig. 2. Specimens BL-90 and BLU-45 are referred to as group (2). The change in the ultimate capacity of the strengthened specimen with respect to strengthening pattern is presented in table 3.

The increment in the ultimate load carrying capacity for BLU-45 (upper and lower flange were strengthened) is nearly of BL-90 (lower flange was only strengthened). It is clearly known that the strengthening of compression flange has a clear influence on the ultimate load of the specimens, but reducing the length of the welded cover plate causes the plastic hinge formation at load point.

TABLE 3 TEST RESULTS OF GROUP3

Tested beams	Ultimate load P_u (kN)	Deflection at P_y w_y (mm)	Lateral deformation at P_u (mm)	Percent of Increase in load capacity *%	Percent of Increase in max deflection *%
BL-90	229.17	9.85	N.A.	-	-
BLU-45	226.02	6.92	6.43	-1.4	-29.74

**Percentage of the Increase in ultimate load capacity and max. deflection equal* $\frac{P_u - P_u(BL-90)}{P_u(BL-90)}\%$, $\frac{w_y - w_y(BL-90)}{w_y(BL-90)}\%$ *respectively.*

The elastic stiffness of the strengthened specimen (BLU-45) was quite higher than the strengthened specimen (BL-90), as shown in Fig. 8. It can also be seen that, a negligible increment of the plastic stiffness was attained as clearly indicated by the slope of the load–displacement curve in the post-yielding region.

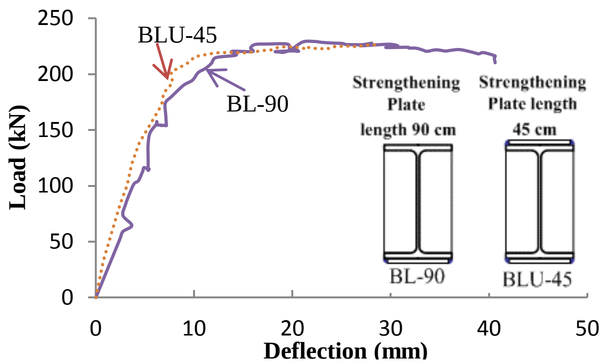


Fig. 8 Load deflection curves for group (2)

The effect of strengthening pattern in the increment of ultimate capacity is unclear, only from these two experimental results, thus no certain conclusions can be drawn at this stage. Further research is presented in part 2 of this research to address different conditions than those considered in this work.

C. *Effect of Preload Ratio*

Three levels of preload ratio (0%, 30% and 50% of un-strengthened beam capacity) were investigated for the pattern A specimens, with cover plate length 90 cm (0.5 L). The test specimens BL-90, BL-90-30, and BL-90-50 are referred to as group (3). The ultimate capacity of un-strengthened specimen was experimentally determined, and the values preload level and ultimate load are listed for each specimen in table 4.

TABLE 4 TEST RESULTS OF GROUP 3.

Tested beams	Amount of reduced deflection $-\Delta w$ (mm)	Ultimate load P_u (kN)	Preload P_{str} (kN)	Preload ratio(1) $\left(\frac{P_{str}}{P_{uc}}\right)$	Deflection at P_y w_y (mm)	Percent increase in load capacity (2)	Percent increase in max deflection (2)
BL-90	0	229.17	0	0	9.85	-	-
BL-90-30	1.20	235.76	67.1	30%	6.83	2.8%	-30.6%
BL-90-50	2.11	242.34	109.7	50%	5.68	5.7%	-42.3%

(1) P_{uc} was taken experimentally as (Pu= 218.15 kN) and the preload was chosen to be ratio from it
(2)Percentage of the Increase in ultimate load capacity and max. deflection calculated as
$\frac{P_u-P_u(BL-90)}{P_u(BL-90)}$% , $\frac{w_y-w_y(BL-90)}{w_y(BL-90)}$% *respectively.*

An increase in the preload ratio resulted in an increase in the ultimate capacity of the strengthened specimens, since the increase in preload ratio causes increase in the reducing deflection. The increment in the ultimate capacity of the strengthened specimen (when the bottom flange was strengthened) was 2.8% and 5.6% for preload ratios of 30% and 50%, respectively. As shown in Fig. 9, at the preload level, when a reduction in deflection of the strengthened specimens acts, the higher elastic stiffness of the strengthened specimens was observed. From table 4 and Fig. 9, the decrease in deflection at yield point was from 30.6% to 42.3% when the preload ratio increases from 30% to 50% respectively.

On the contrary, Lui et al. [16] stated that an increase in the preload ratios decreases the capacity of the specimen strengthened while loaded, that may be explained, since the welded technique used by Lui (steel plates are welded without reducing deflection) causes increase in deflection of tested specimens while strengthening, as shown in Fig. 10. The welded technique used by the author (steel plates are welded after reducing deflection) helps in restoring the load capacity and enhances specimen behavior.

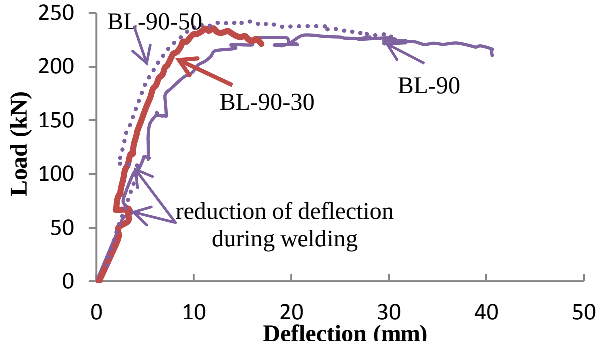


Fig. 9 Load deflection curves for group (3)

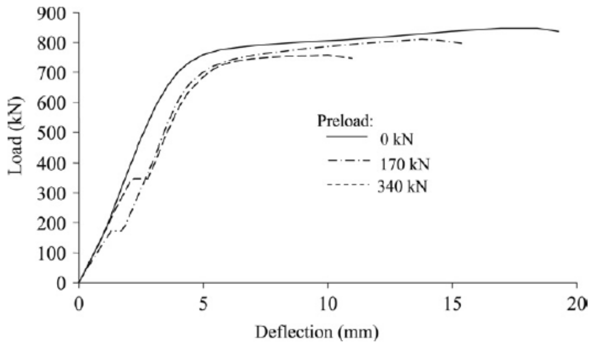


Fig. 10 Load deflection curves of Liu's tested specimens (2009a)

D. *Failure Modes*

The failure modes of the tested specimens were observed as shown in photo 3. Three modes of failure were observed. The strengthened specimens (BLU-45 and BL-90) had large deflection accompanied by lateral deflection for upper compression flange. This lateral deflection caused yield of compression flange and instability of specimen leading to failure. Photo 4 depicts failure mode of the test specimen BLU-45. For preload strengthened specimens BL-90-30 and BL-90-50, reductions in deformations were observed (such as mid span deflection and lateral displacement of compression flange). The un-strengthened specimen (BC) and the strengthened specimen (BL-65) induce local deformation accompanying by large deflection, the local deformation causes formation of plastic hinge at load points.

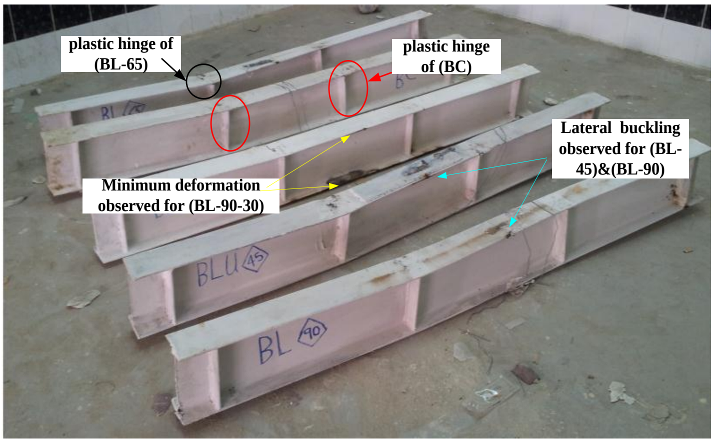


Photo 3 Failure modes of test specimens

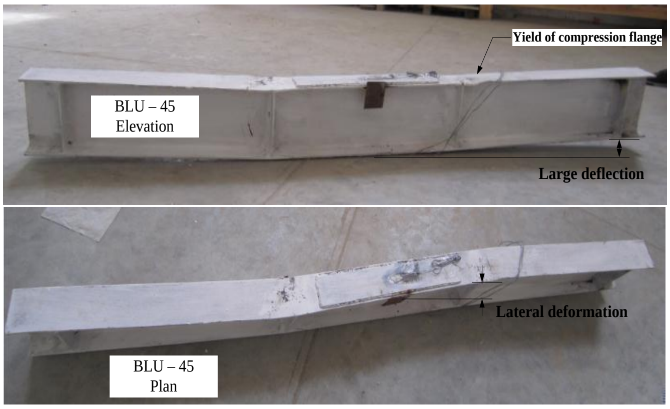


Photo 4 Failure mode of test specimen BLU-45

IV. CONCLUSIONS

The behavior of six strengthened IPE beam specimens was experimentally investigated under four point loads. The results of the tests shed light on the influence of the welding technique on structural performance of strengthened beams. The results indicated that Reducing deflection before welding the cover plate (the welding technique) increases load capacity from 2.58% to 5.6%. This increase in load capacity is insignificant, and further numerical study is presented in part 2 of this research to address different conditions than those considered in this work.

It can be also noted that from load deflection curves, decreases the deflection (at yield) by about 30.6% to 42.3% were recorded, when the preload ratio increases from 30% to 50%. In anther mean, the deflection at ultimate load decreases when the reducing deflection increases (Δw increase). That means that the technique used to weld cover plate during loading enhances the behavior of the strengthened beam.

Many influential parameters were investigated, these parameters included changing the length of strengthening cover plate, two strengthening pattern and the effect of preload ratio. The results of the experimental tests indicate that the ultimate load capacities of the beams considered in this work are affected by the cover plate length. The effect of the cover plate length is less significant when the area of the cover plate is smaller than the flange area. An increase in the ultimate capacity Pu from 1% to 5% by increase welded cover plate length from 36% to 50%. No change in ultimate capacity was observed using same cover plate length with different pattern.

In part II of this research, the author is expanding the simulation studies using the developed finite element models to investigate factors affecting strengthening of beams.

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