Effect of Reducing Deflection of Steel I-Beams Strengthened While Loading

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Abstract— **Extensive parametric study of the behavior of steel beam strengthened while under load, the steel cover plate is welded after the deflection of the beam was reduced. The finite element model was verified using test results presented by the author in part I, the verified model was applied to investigate the effect of several influential parameters. The parameters studied include: 1) cover plate length, 2) strengthening pattern, 3) span to depth ratio of the strengthened beam, 4) magnitude of reduced deflection, 5) lateral restraint and initial lateral displacement, and 6) steel grade of the I-section and back plates. The numerical results were used to deduce the technical recommendations needed for enhancing the behavior of strengthening steel beams under study.**

Keywords— Strengthening; Steel Beams; Cover Plate; F. E. Model; Numerical Analysis; Influential Parameters.

I. INTRODUCTION

Using traditional way to strengthening steel beams, Newman [1] presented a web seminar discussing many issues concerning strengthening structural steel beams. Newman discussed code provisions for the renovation of steel structures, investigating existing conditions and strengthening methods. Newman showed many strengthening methods like replacement, passive vs. active methods, shortening span, adding members, external prestressing and enlarging section. He states that strengthening steel beams by welding (enlarging section) may need special procedures, and strengthening rafter by laying welds or weld a plate at flange help with torsion and flexure performance.

A review of previous researches [2-20] on strengthening existing structural systems has been provided in part one of the paper with title “strengthening steel I-beams by welding steel plates before or while loading”. The experimental study of Liu [2] showed that welding cover steel plate to the steel beam while under load causes an increment in deflection during strengthening. At our researches, the author produces a reduction in deflection while the beam is strengthened. Part of this target is achieved through experimental study, which described in part one of this research. Numerical modeling will be used to extend the experimental study. Results from the numerical modeling and testing are expected to provide an understanding of the behavior of these beams in general; load–deflection behavior and ultimate load-carrying capacity are considered in the investigation beside the effects of reducing deflection before strengthening on the ultimate strength.

This paper describes a modeling technique using ANSYS^{TM} software [21]. Subsequently, the finite element model is validated with test results. It is shown that the FE (Finite Element) model is able to simulate the test results with considerable accuracy. The validation model is then used in the subsequent parametric study to further influential parameters. These parameters have been identified through the experimental study, like the effect of strengthening pattern, span to depth ratio of the strengthened beam, Magnitude of reduced deflection, lateral restraint, initial lateral displacement and steel grade of the I-section and cover plates. Technical recommendations, based on the finite element study are presented.

II. FINITE ELEMENT MODELING

A. Model description

All specimens are discretized using the commercial software ANSYS^{TM}. The beam flanges, web, stiffeners, cover plate and welds are modeled using four node structural shell element 181. SHELL181 is suitable for analyzing thin to moderately-thick shell structures[2]. The four stiffeners are fully connected at the load points. Contact element 174 and target 170 are used to model surface between the cover plate and specimen’s flange. All nodes of the strengthened flange and cover plate are coupled at a distance equal to the average of their thickness. The thickness of weld elements is varied to maintain a cross-sectional equal to that of the 6 mm fillet weld.

B. Model setup

Rotations are permitted at one support, while rotations and axial translation are permitted at the other support. An initial imperfection with maximum deflection of L/500 at the mid-length is implemented. This maximum imperfection is greater than L/1000 (the maximum allowable out of straightness). The imperfection is to indirectly account for residual stresses, which are not included in the simulation. Fig. 1 shows an example of the proposed model with imposed boundary conditions.

A displacement controlled load is used to determine the capacity of the strengthened beams; the displacement controlled load is applied at the rate of 0.5 mm/time, 0.167 mm/time in vertical and lateral direction respectively. The loading rate is selected through a trial and error process as a compromise to reduce computational run time while minimizing the difference between experimental and F.E analysis.

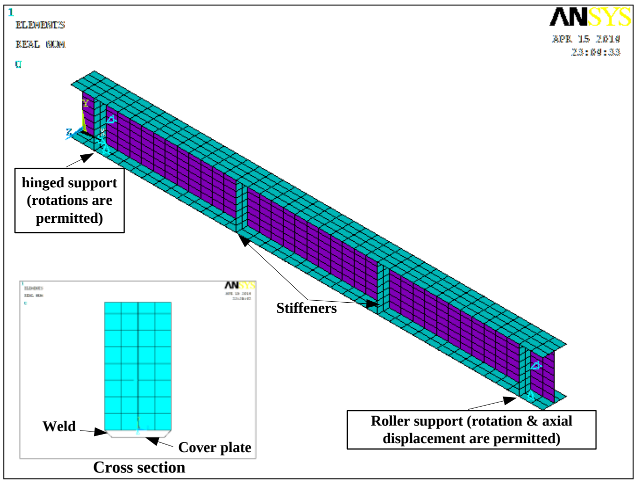
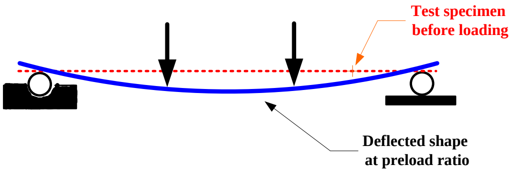
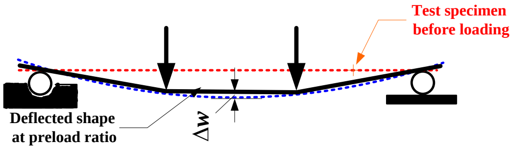


Fig. 1 Finite element model for strengthening beam

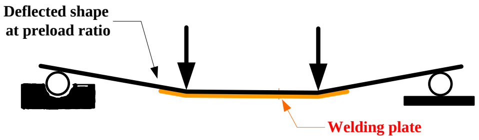
The displacement controlled load is applied at loading point till failure. For beam strengthened while under load shown in Fig. 2, loading process need five steps: 1) modeling of beam section, cover plate and welds are created, and initial imperfection is incorporated into the model. 2) All elements of the cover plate and welds are deactivated using element birth and death feature, then 3) the nonlinear analysis is performed in the model using the displacement controlled load till preloaded level. 4) At preloaded level, deflection of the nodes of lower flange (at mid panel) is controlled. 5) All deactivate elements are then reactivated and the loading process is resumed till failure.



Step 1: loading till preload ratio



Step 2: reducing deflection during welding



Step 3: welding plate

Fig. 2 Strengthening technique during loading

C. *Mesh sensitivity*

A mesh sensitivity study is first performed to ensure that the mesh being used leads to reasonable results. The mesh used by Lui et al. (2009b) was initially considered, Lui used the maximum width of element 20 mm. The final mesh seen in Fig. 1 is selected because there are insignificant changes in the results upon furthering mesh refinement. Elements with maximum width 50 mm and aspect ratio 0.5 are used herein.

D. *Verification of model*

The finite element model is verified using the results of the experimental tests described in Part I. The experimental ultimate loads of the specimens (P_{exp}) are compared with the corresponding finite element model ultimate loads ($P_{F.E.}$) as shown in table 1. The comparison shows that, the difference between the experimental and F.E. results is within reasonable limit, the difference between ultimate loads are maximum 2.3%. Deformations of experimental specimens together with finite element results are shown in Fig.s 3 - 4 in case of BL-90-50 and BL-65 respectively. The experimental and numerical curves appear to match, and the deformations presented by the numerical model are a reasonable approximation of the test results as shown in Fig. 5. A comparison between the experimental and numerical results highlights the good accuracy of the model.

TABLE 1 COMPARISON OF EXPERIMENTAL AND F.E. RESULTS

Tested beams	Experimental ultimate load P_{exp} (kN)	F.E. ultimate load $P_{F.E.}$ (kN)	P_{exp}/ $P_{F.E.}$	Percent of Increase in load capacity *%
BC	218.15	215.15	1.01	1.3
BL-65	220.62	219.54	1.00	0.5
BL-90	229.17	231.06	0.99	-0.8
BLU-45	226.02	222.68	1.01	1.5
BL-90-25	235.76	232.23	1.02	1.5
BL-90-50	242.34	236.78	1.02	2.3

**Percentage of the Increase in ultimate load capacity equal* $\frac{P_{exp}-P_{F.E.}}{P_{exp}}$%

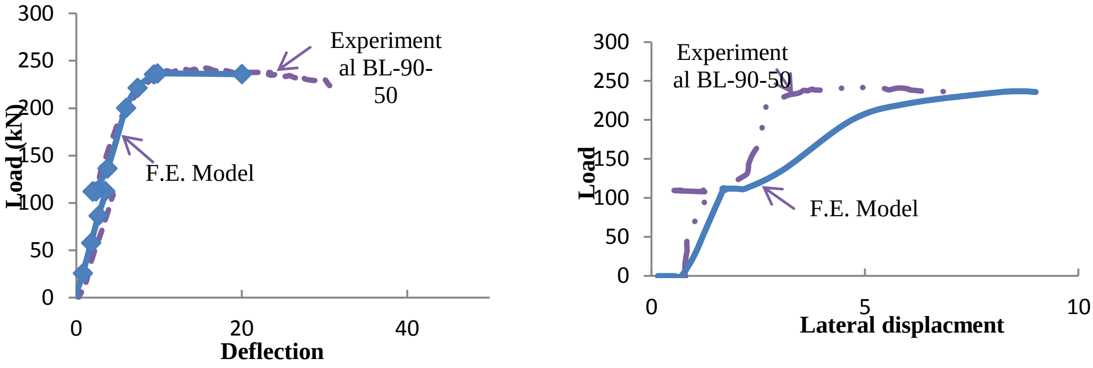
III. PARAMETRIC STUDY

Testing of full scale beams is the most direct and reliable approach to examine the strength and behavior of the strengthened steel beams. However, because of the lake of the test results presented in Part I, the finite element model used to expand the limited database of test results.

A. *Selection of parameters*

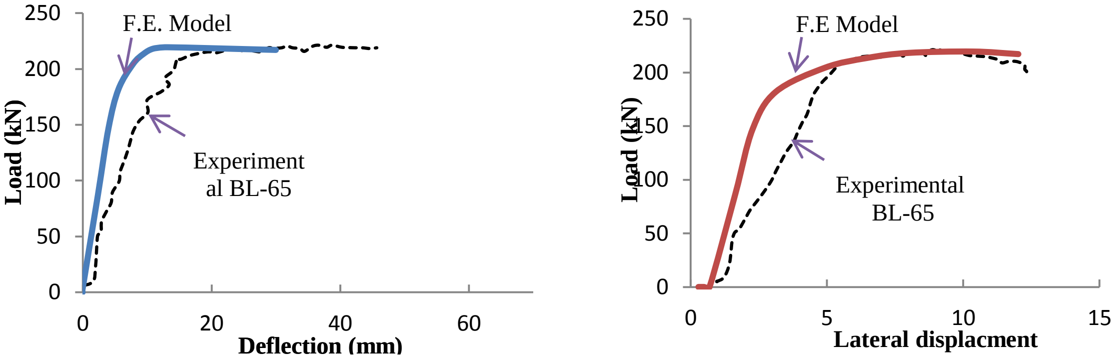
Extensive simulations were conducted to explore the effect of various influential parameters on the strengthened beam response. Many parameters are expected to influence the strength and the behavior of the strengthened steel beam using the mentioned techniques. The parameters considered include: 1) cover plate length, 2) Strengthened pattern, 3) span to depth ratio of the strengthened beam, 4) Magnitude of reduced deflection, 5) lateral restraint and initial lateral displacement and 6) Steel grade of the I-section and cover plates.

One hundred fifty eight steel beams were analyzed numerically to fully investigate the effect of these variables. Table 2 shows a list of the selected variables.



(a) Load deflection curve (b) Load lateral displacement curve

Fig. 3 Comparison of experimental and F.E. deflection and lateral displacement of BL-90-50



(a) Load deflection curve (b) Load lateral displacement curve

Fig. 4 Comparison of experimental and F.E. deflection and lateral displacement of BL-65.

TABLE 2 LIST OF THE SELECTED VARIABLES AND THEIR RANGES FOR THE PARAMETRIC STUDY

No. of analyzed beams	**Strengthen pattern**	**Span/depth ratio**	**Span (mm)**	**(w_i)**	**(v_i)**	**Lateral restraint**	**P_{str}/ P_{unstr}**	**(Δw)**	**f_y (MPa)**	
									beam	**Plate**
25	A, B, C &D	9	1800	L/500	zero	Partial (w/v = 3)	Unstrengthed,0, 0.25, 0.41, 0.57, 0.73, 0.84	w0*	275	275
25		13.5	2700				Unstrengthed, 0, 0.26, 0.42, 0.59, 0.76, 0.85			
25		18	3600				Unstrengthed, 0, 0.26, 0.42, 0.60, 0.76, 0.87			
60	A, B, C & D	18	3600	7.2 mm	zero	Partial (w/v = 3)	0.26, 0.6 and 0.87	0, w0, (0.3 w_{max}), (0.6 w_{max}), w_{max}	275	275
15	C	18	3600	7.2 mm	zero, 1, 3, 5 and 8 mm -	No lateral restraint Partial (w/v = 3) Full restraint	0.6	w0*	275	275
8	A, B, C & D	18	3600	7.2 mm	zero	Partial (w/v = 3)	0.6	w0*	235 235	235 275
Total:158										

**w0 = deflection at mid span wmax – deflection at loading point wLoad (as shown in figure 2)*

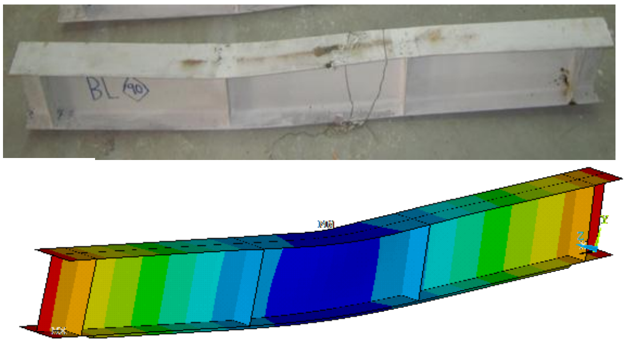


Fig. 5 Experimental and numerical deformation of BL-90

IV. NUMERICAL RESULTS

A. *Effect of cover plate length and area*

The experimental results with the data in Liu et al. [2, 3] showed that: 1) Increase welded cover plate length causes an increase in the ultimate capacity P_u, for analyzing beam BL with beam length 180 cm the ultimate capacity increase by 1.1 %, 5 % and 23 % when the plate length increase from 60 cm, 90 cm and 170 cm respectively. 2) The effect of the cover plate length decreases when the area of the cover plate is smaller than the flange area. These points suggest that, for the next analyzed beam, the welded cover plate length and area are adapted in this work to be equal to strengthened beam span and flange area respectively.

B. *Effect of strengthening pattern with different preload ratio*

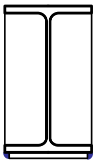
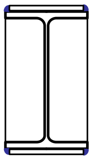
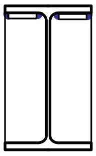
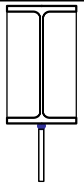
I-Beam can be strengthened with steel plate welded to upper flange or lower flange with different orientations. Table 3 indicates the strengthening patterns suggested in this study, the suggested patterns based on practicing the same area of cover plate with different orientations to enhance beam behavior.

Fig. 6 represents the load deflection curves for different patterns of the strengthening beams with two spans / depth ratio. The strengthening of steel beams under load increases the capacity of the control beam for all strengthening patterns. It can be noted that pattern B is the most effective pattern, although pattern B is less inertia than pattern D. The strengthening of upper and lower flange for pattern B enhances the behavior of the beam, moreover pattern D has difficulties with welding technique, as the initial deflect of cover plate about its major axis (to take the deflected shape of the strengthening beam under load) causes additional stress in the plate.

Another important effect of strengthening pattern is related to yield deflection w_y. The deflection of the mid-span point at yield for two different spans was listed in table 4. At a certain preload ratio, strengthening pattern A and D reduce the yield deflection of control beam, a slight reduction in deflection of nearly 3% and 8% for pattern A and D respectively was observed. On the contrary, an incremental in yield deflection of nearly 5% and 15% for pattern C and B respectively was observed.

Examination of table 5 reveals that the change of preloaded ratio has minor effect on the increment of ultimate load (the amount of incremental in ultimate capacity as a percentage ranging from -1.96 % to 0.79 %). Even so, the increase in the preloaded ratio near the end of the elastic zone reduces the increment of ultimate load for strengthening pattern A.

TABLE 3 STRENGTHENING PATTERNS

Patterns*	A	B	C	D
Cross section				
Calculated moment of inertia about major axis	2665.5 cm4	2836.2 cm4	2433.06 cm4	3467.32 cm4
Description/Name	Strengthening lower flange / BL	Strengthening lower & upper flange / BLU	Strengthening upper flange /BU	Strengthening lower flange vertically /BLV

** For all strengthening pattern: area of cover plate = area of flange plate, & Length of cover plate = span of beam*

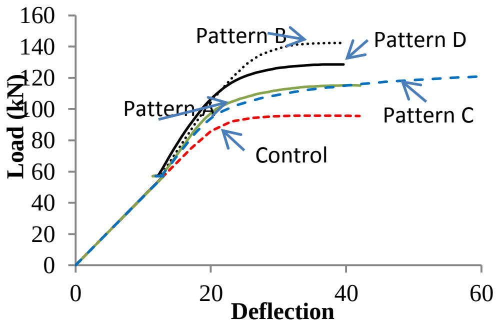


Fig. 6 Effect of strengthening pattern on the ultimate capacity of Strengthened beam (L = 3600mm, Lpl = 3500mm & preload ratio = 0.60)

TABLE 4 EFFECT OF STRENGTHENING PATTERN ON THE YIELD DEFLECTION OF STRENGTHENING BEAMS

Strengthening pattern	Span length = 360 cm		Span length = 270 cm	
	w_y yield deflection (mm)	Incremental* %	w_y yield deflection (mm)	Incremental* %
Control (BC)	12.6	-	22	-
A	12.2	-3.2	21.2	-3.6
B	14.5	15.1	24.86	13.0
C	12	4.8	20.19	8.2
D	11.7	-7.1	20.22	-8.1

*Incremental of ultimate yield deflection at mid-point = $\frac{w_y - w_{y\,(for\,BC)}}{w_{y\,(for\,BC)}} * 100\%$

TABLE 5 ULTIMATE LOADS FOR BEAM WITH DIFFERENT PRELOAD RATIO AND FOUR PATTERNS

L (beam span in mm)	Preload ratio	Strengthen pattern A		Strengthen pattern B		Strengthen pattern C		Strengthen pattern D	
		P_u (kN)	Incr.(2)%	P_u (kN)	Incr.(2)%	P_u (kN)	Incr. (2)%	P_u (kN)	Incr .(2)%
2700(1)	0.00	162.41	0.00	195.66	0	184.07	0	183.75	0
	0.26	163.60	0.73	196.50	0.43	184.47	0.22	183.14	-0.33
	0.42	163.69	0.79	196.53	0.44	184.60	0.29	182.48	-0.69
	0.59	162.46	0.03	196.60	0.48	184.98	0.49	181.58	-1.18
	0.76	161.77	-0.39	196.70	0.53	185.18	0.60	180.74	-1.64
	0.85	161.41	-0.62	196.81	0.59	185.43	0.74	180.20	-1.93

(1) Ultimate load for unstrengthen beam BC-260 = 132.85 kN

(2) Incremental of ultimate load $\frac{P_u - P_{u\,(for\,Preload\,ratio=0)}}{P_{u\,(for\,Preload\,ratio=0)}} * 100\%$

C. *Effect of span to depth ratio*

In order to study the effect of span to depth ratio on steel beams strengthened while under load, short, intermediate and long beams were analyzed. The span to depth ratio 9, 13.5 and 18 of the strengthening beams are investigated. A set of runs were conducted for the three different ratios with different pattern and preloaded ratio, the results were listed in table 6.

It is commonly understood that span/depth ratio effect on failure mode of the studied beams, it resulted in different ultimate capacity. Table 6 shows that, the effect of the span / depth ratio is negligible. The change of the ultimate load increment is about 1% to 3% with the change of span / depth ratio. That can be explained, since the lateral displacement is controlled and the failure was due to excessive yield in the middle of the beam, the ratio between deflection and lateral displacement at loading points $w/v = 3$.

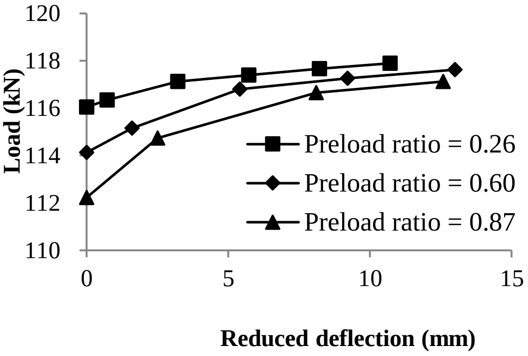
D. *Effect of the reduced deflection Δw*

The effect of reduced deflection Δw (imposed to studied beams before the welding of cover plate) is studied for 60 analyzed beams. All studied beams have a span / depth ratio equal to 18 with three preloaded ratios 0.26, 0.60 and 0.87 as listed in table 2.

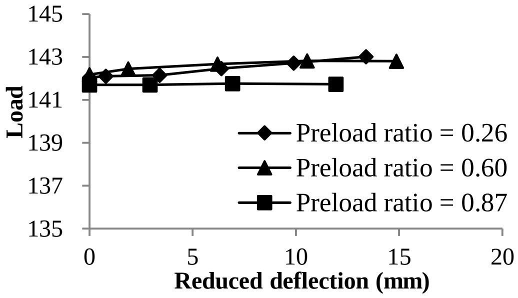
The results presented in Fig. 7 show that increasing the amount of reduced deflection increase the ultimate capacity of strengthening beam. For pattern A, the ultimate capacity of beam BL-350-87 increase from 112.23 kN (Δw = 0) to be 117.12 kN (Δw = 12.58 mm) with an incremental ratio equal 4.3 %. For pattern B and C, the reduced deflection has minor effect on the ultimate capacity of the strengthened beam at different preload ratios as shown in Fig. 7. Especially for pattern B, at a higher preloaded ratio (P_{str}/P_{unstr} = 0.87), the general trend of the ultimate capacity versus the amount of reduced deflection remains the same. For pattern D, the finite element results show that the reduced deflection is not a desirable technique for strengthening that type of beam. Since, it is difficult to weld the plate to the lower flange with the increase of deflection, moreover, to take the deflected shape of the beam.

TABLE 6 ULTIMATE LOAD INCREMENT OF BEAMS WITH DIFFERENT SPAN/DEPTH RATIO

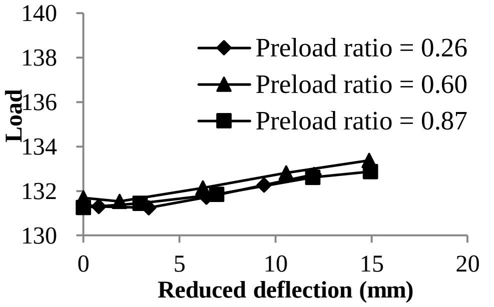
Span/depth ratio	Preload ratio	Pattern	Ultimate load increment %	Pattern	Ultimate load increment %	Pattern	Ultimate load increment %	Pattern	Ultimate load increment %
9	0	A	23.12	B	46.13	C	39.11	D	36.30
13.5			22.25		47.28		38.55		38.61
18			22.32		49.09		36.85		36.71
9	0.41: 0.42		23.34		46.38		39.59		36.19
13.5			23.21		47.93		38.95		37.66
18			21.79		48.67		37.15		35.01
9	0.73: 0.76		23.02		46.70		40.41		36.10
13.5			21.77		48.06		39.39		36.35
18			21.95		49.13		39.05		32.34



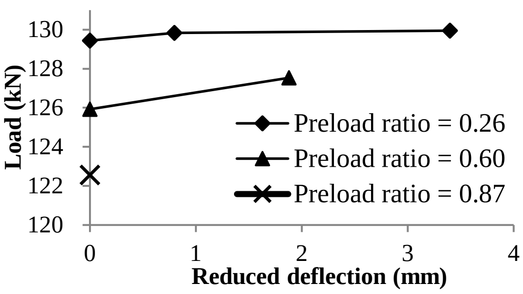
Pattern A



Pattern B



Pattern C



Pattern D

Fig. 7 Relationships between ultimate load and the amount of recovered deflection at different preload ratio

E. *Effect of lateral restraint and initial lateral displacement*

The response of the studied beam to lateral buckling is of interest to determine its ultimate capacity, lateral buckling is affected by the beam lateral restraint of compression flange. To study the effect of lateral restraint, three cases of lateral restraint for the compression flange were considered: 1) partial restraint with ratio (w/v = 3), 2) full lateral restraint, and 3) no lateral restraint.

From the experimental study presented by the author in the accompanying paper, the effect of loading mechanism can be simulated by introducing controlled vertical displacement w and horizontal displacement v that simulate the partial restraint at loading points of the compression flange.

In case of free lateral restraint, the initial lateral displacement must be introduced to the perfect geometry to analyze the post buckling behavior, where initial lateral displacement (v_i) is the lateral displacement at mid length. Table 7 shows that initial lateral displacement has a significant effect on ultimate capacity of the free lateral restraint beams, since 1 mm, 3 mm, 5 mm and 8 mm initial lateral displacement imposed to mid length cause reduction about 3.85, 5.53, 6.74 and 8.31% of the ultimate capacity of the free lateral restraint beam with prefect geometry (no initial deformation) respectively.

In cases of partial and full restraint, shown in table 7, the initial lateral displacement has negligible effect on the ultimate capacity of the studied beams, since the maximum reduction of the ultimate load of beam with partial restraint was 0.9% due to initial lateral displacement (v_i) equal 8 mm.

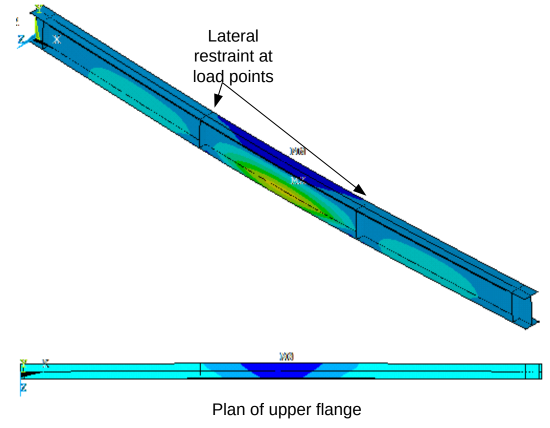
TABLE 7 ULTIMATE LOADS OF BU-350-0.6 WITH DIFFERENT INITIAL LATERAL DISPLACEMENT

L (mm)	Preload ratio	* (v_i) in mm	No lateral restraint		With partial lateral restraint w/v = 3		With lateral restraint	
			P_u (kN)	Reduction **	P_u (kN)	Reduction* *	P_u (kN)	Reduction* *
3600	0.6	0	137.60	-	131.54	-	137.62	-
		1	132.50	3.71%	131.45	0.07%	137.59	0.02%
		3	129.99	5.53%	131.15	0.30%	137.49	0.09%
		5	128.33	6.74%	130.86	0.52%	137.36	0.19%
		8	126.16	8.31%	130.36	0.90%	137.30	0.23%

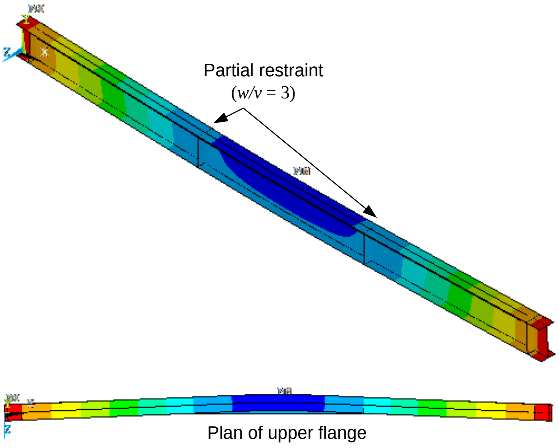
**Maximum imposed lateral displacement at mid length before loading*

***Reduction of ultimate load* $\frac{P_{u\,(for\ vi=0)}-P_u}{P_{u\,(for\ vi=0)}} * 100\%$

Finite element results for beam BU-350-60 with different lateral restraint imposed at load points presented in Fig.s 8 - 9. The results show that partial lateral restraint imposed at load points causes higher lateral displacement at the beginning of loading if compared with free lateral restrain case. In particular, there is a high incremental in lateral displacement at the step of reducing deflection, while the lateral displacement still under control even on failure. Moreover, the lateral displacement incremental of the unrestraint beam is uncontrolled within yield of the compression flange causing extensive increase in lateral displacement and failure.



(a) Beam with lateral restraint



(b) Beam with partial restraint

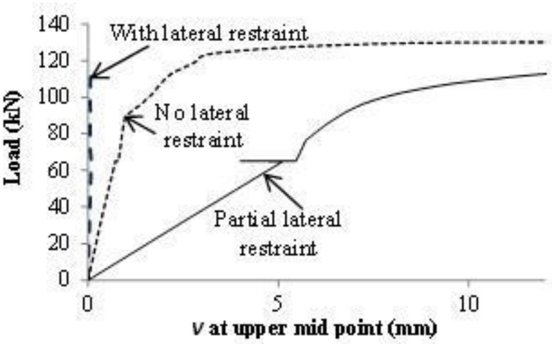


Fig. 9 Relationship between load and lateral displacement (v) at mid-point of the upper flange for beams with different lateral restraint (Pattern C, L =3600 mm, Pstr./ Punstr =0.60 and vi = 5mm)

F. *Effect of steel grade*

For older structures, beams may be of steel grade with low nominal yield strength if compared with modern structures that would be used for strengthen plates. So strengthen beams may be composed of different two grades. Beams with two different combinations of steel grades were investigated: 1) beams strengthened with the same steel grade for the plate and the rolled section (fy = 235 MPa or fy = 275 MPa), 2) strengthens beams with fy = 235 MPa for the section and fy = 275 MPa for the plates, as shown in table 2

Table 8 and Fig. 10 indicate that, when the grade of strengthen steel plate increased from fy =235 MPa to fy =275 MPa, the steel grades neither significantly affect the strength of the strengthened beam, max increment was about 5.05% of the ultimate capacity for BUL-350-60 with span length 360, nor reduce the deflection as shown in Fig. 10.

TABLE 8 ULTIMATE LOADS FOR BEAM WITH DIFFERENT STEEL GRADE AND FOUR PATTERNS

L (mm)	fy for beam (MPa)	fy for Pl (MPa)	Strengthen pattern A		Strengthen pattern B		Strengthen pattern C		Strengthen pattern D	
			Pu (kN)	Incr.%	Pu (kN)	Incr.%	Pu (kN)	Incr.%	Pu (kN)	Incr.%
3600	235	235	100.92	0.5	123.73	5.05	115.75	2.68	112.01	1.97
	235	275	101.43		129.99		118.85		114.22	

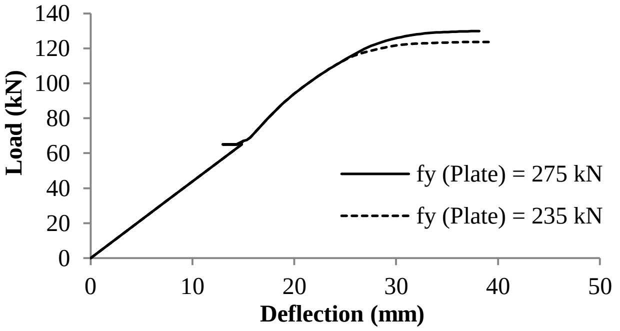


Fig. 10 Load-deflection relationship for BLU-350-60 with change of steel grades of cover plate (Pattern B, L =3600 mm, Pstr. / Punstr =0.60 and vi = 5mm fy for beam section = 235 kN)

V. CONCLUSIONS AND RECOMMENDATIONS

A study of steel beams strengthened by welding steel plates with reducing of deflection while under load has been presented in this research.

The finite element models were developed and their results were compared to data from detailed experimental tests. A maximum error of 2.3% between the experimental and the finite element model was obtained, indicating that the finite element model provides a reasonable approximation of the behavior of beams studied.

Numerous parameters may affect the strength of rolled I section strengthened were studied numerically. A total of 158 finite element models of steel I beams strengthened after reducing deflection while under load were developed.

From the results of the parametric study the following technical notes were presented:

- The cover plate length and cross-section area is the most important parameter affecting strength of strengthened beam, ultimate capacity increase by 1.1 %, 5 % and 23 % when the plate length increased to 0.33, 0.5 and 0.95 of the span respectively. So using a cover plate with full span length and has an area equal or greater than the area of the flange is recommended.
- The welding pattern affects the behavior and strength of the strengthened beam. So strengthening of upper and lower flanges (Pattern B) is recommended if possible, since the ultimate capacity and yield deflection of the control beam BC-270 were increased by 47% and 14% respectively. Contrariwise, strengthening lower flange vertically (Pattern D) is not recommended.
- Strengthening steel beams while under loading shows that the preloaded ratio has minor effect on the ultimate strength of the strengthened beam (the amount of incremental in ultimate capacity as a percentage ranging from -1.96 % to 0.79 %), even so the welding of the steel plate prior to yield enhances the beam behavior put the increment of the ultimate capacity decreases.
- Reducing beam deflection before welding has minor effect on the beam strength (the ultimate capacity of beam BL-350-87 increase from 112.23 kN at $\Delta w = 0$ to be 117.12 kN at $\Delta w = 12.58$ mm with an incremental ratio equal 4.3 %). But, it’s recommended since it overcomes the increase of deflection causes by welding.
- The initial lateral displacement must be limited. 1 mm to 8 mm initial lateral displacement imposed to mid length cause reduction about 3.85 to 8.31% of the ultimate capacity of the free lateral restraint, furthermore partial and full restraint have negligible effect on the ultimate capacity of the studied beams.
- The use of different grades in strengthening beams was found to have a minor effect on the strength of the strengthened beam.

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REFERENCES

[1] A. Newman. Strengthening Structural Steel Beams [Online].

[2] Y. Liu and L. Gannon, "Experimental Behavior and Strength of Steel Beams Reinforced while Under Load.," *Journal of construction steel research,* vol. 65, pp. 1346-1354, 2009a.

[3] Y. Liu and L. Gannon, "Finite Element Study of Steel Beams Reinforced while Under Load.," *Engineering Structures,* vol. 31, pp. 2630-2642, 2009b.

[4] K. Narmshiri and M. Z. Jumaat, "Reinforced Steel I-Beams: A Comparison between 2D and 3D Simulation," *Simulation Modeling Practice and Theory,* vol. 19, pp. 564-585, 2011.

[5] L. Tall, "The Reinforcement of Steel Columns," *Engineering Journal,* vol. 26, pp. 33-37, 1989.

[6] Z. Wu and G. Y. Grondin, "Behavior of Steel Columns Reinforced with Welded Steel Plates.," *Structural Engineering Report no. 250. Department of Civil and Environmental Engineering, University of Alberta.,* 2002.

[7] M. Elchalakani, "CFRP strengthening and rehabilitation of degraded steel welded RHS beams under combined bending and bearing," *Thin-Walled Structures,* vol. 77, pp. 86-108, 2014.

[8] A. Hmidan, Y. Kim, and S. Yazdani, "Effect of Sustained Load Combined with Cold Temperature on Flexure of Damaged Steel Beams Repaired with CFRP Sheets.," *Engineering Structures,* vol. 56, pp. 1957-1966, 2013.

[9] L. C. Hollaway, L. Zhang, N. K. Photiou, J. G. Teng, and S. S. Zhang, "Advances in adhesive joining of carbon fibre/polymer composites to steel members for repair and rehabilitation of bridge structures," *Adv Struct Eng,* vol. 9, pp. 791–803, 2006.

[10] M. Z. Jumaat and M. A. Alam, "Strengthening of R.C. Beams Using Externally Bonded Plates and Anchorages.," *Australian Journal of Basic and Applied Sciences,* vol. 3, 2008.

[11] M. M. A. Kadhim, "Effect of CFRP plate length strengthening continuous steel beam," *Construction and Building Materials,* vol. 28, pp. 649-652, March 2012 2012.

[12] Y. J. Kim and K. A. Harries, "Fatigue behavior of damaged steel beams repaired with CFRP strips," *Engineering Structures,* vol. 33, pp. 1491-1502, 2011.

[13] *Steel Beams Strengthened with ultra hight modulus CFRP laminates,* U. o. Kentucky, 2011.

[14] A. Sweedan, K. El-Sawy, and M. Alhadid, "Interfacial behavior of mechanically anchored FRP laminates for strengthening steel beams," *Journal of Constructional Steel Research,* vol. 80, pp. 332-345, 2013.

[15] A. Sweedan, H. Rojob, and K. El-Sawy, "Mechanically-fastened hybrid composites for flexural strengthening of steel beams," *Thin-Walled Structures,* vol. 85, pp. 250-261, 2014.

[16] K. Tani, M. Matsumura, T. Kitada, and H. Hayashi, "Experimental study on seismic retrofitting method of steel bridge piers by using carbon fiber sheets," in *The Sixth Korea-Japan Joint Seminar on Steel Bridges*, Tokyo, Japan 2000, pp. pp. 437–445.

[17] J. G. Teng and Y. M. Hu, "Suppression of local buckling in steel tubes by FRP jacketing," in *the Second International Conference on FRP Composites in Civil Engineering*, Adelaide, Australia 2004, pp. pp. 749–753.

[18] J. G. Teng, T. Yu, and D. Fernando, "Strengthening of steel structures with fiber-reinforced polymer composites " *Journal of Constructional Steel Research,* vol. 78, pp. 131-143, 2012.

[19] L. Z. X.L. Zhao, "State-of-the-art review on FRP strengthened steel structures," *Engineering Structures,* vol. 29, pp. 1807–1823, 2007.

[20] N. M. Yossef, "Strengthening Thin-Web Panel with and without Opining Using (CFRP) Laminate.," *STRUCTURAL FAULTS & REPAIR-2012, 3rd – 5th July 2012, Edinburgh, UK.,* 2012.

[21] ANSYS®, " Release 15.0," vol. Release 15.0, Version 3 ed: ANSYS, Inc., 2007.