EFFECT OF BATTEN PLATES ON STEEL I-BEAMS FLEXURAL STRENGTH

Ahmed Hassan, Sherif M. Ibrahim, Abdelrahim K. Dessouki

ABSTRACT—This paper investigates the effect of batten plates on the flexural capacity of laterally unsupported simply supported steel I-beams. Lateral torsional buckling (LTB) failure mode always controls the flexural capacity of such beams. A Nonlinear finite element model for the doubly symmetric I-beams stiffened with batten plates is presented. The proposed model accounts for initial geometric imperfections and material non-linearity. Firstly, the finite element model is applied on unstiffened steel I-beams to obtain a reference value of the flexural capacity. Subsequently, a parametric study is performed to illustrate the increase in flexural strength of the same beams that are stiffened with batten plates of various configurations. The parameters in the research includes the location of batten plates along the beam span, the number and the dimensions of the batten plates. Moreover, the study is performed on both double sided and single sided for batten plates. Design charts are presented to predict the increase in flexural capacity of steel I-beams with various batten plates configurations. A simplified design procedure is proposed to predict the flexural strength of beams with batten plates. The research results indicate that batten plates are very efficient in increasing LTB capacity of steel I-beams when it is challenging to add lateral bracing.

Index Terms—Lateral torsional buckling, Batten plates, T-stiffeners, simply supported beams, Finite element analysis.

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1 INTRODUCTION

Steel beams are usually used in all types of steel structures with various applications. They are used as floor beams for multistory buildings or as main girders for portal frames. Steel beams are also used for some special applications such as monorail beams or crane track girders. Moreover, they are used in bridge main supporting elements. The load-carrying capacity of steel I-beams is controlled by the unsupported length of compression flange of the steel cross section. If a laterally unsupported beam is loaded vertically, it deflects about its main axis while the compression part of the beam tends to deflect laterally about the weak axis and twist about the longitudinal axis of the beam. This behavior is called lateral torsional buckling (LTB). Lateral bracing for the compression flange is used to increase the flexural capacity of the steel elements subjected to pure flexural stresses or flexural stresses accompanied with axial stresses. Lateral bracing reduce the unsupported buckling length for the compression flange by preventing its lateral movement at braced points. Stiffeners are often used to increase web shear capacity for plate girders with big depth and to support the girder web against local buckling. For hot rolled sections, stiffeners are used at the connections locations to strengthen the web capacity and prevent local stresses. Also stiffeners are used at the coped region position in the beams to strengthen the web.

The main aim of this research is to investigate the behavior of laterally unsupported simply supported steel I-beams stiffened with single or double-sided batten plates. A parametric study is conducted using non-linear finite element model to evaluate the effect of different batten plate configurations on the flexural strength of laterally unsupported simply supported steel I-beams.

2 LITERATURE REVIEW

Timoshenko and Gere [1] presented a closed form solution for the critical bending moment of a simply supported beam subjected to uniform moment across the beam length.

The critical moment equation was modified using a factor C_b to take into account different loading conditions. The final elastic critical lateral torsional buckling moment used by most design specifications such as AISC [2] and SSRC Guide [3] is represented by:

$$M_{cr.e} = C_b \sqrt{\frac{\pi^2.E.I_y.G.J}{(L_b)^2} + \frac{\pi^4.E.I_y.E.C_w}{(L_b)^4}} \quad (1)$$

Where L_b is the unsupported length of the beam, E is Young's modulus, I_y is the minor moment of inertia of the cross section, G is the shear modulus, J is the shear constant and C_w is the warping constant. The actual flexural capacity of laterally unsupported I-beam may be lower than value obtained from (1) if inelastic LTB or full plastification of the cross section are the dominate failure modes. The upper limit for the member flexural capacity is the plastic moment capacity of the beam (for beam with compact cross sections). As the unsupported length decreases, the failure mode of the beam is considered inelastic lateral torsional buckling. Inelastic lateral torsional buckling is achieved when some parts of the section reach the yield stress with the beam experiencing lateral movements with twisting. As the unsupported length of the beam exceeds a certain value the failure mode for the steel beam is considered pure elastic lateral torsional buckling (LTB).

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Szewczak et al [4] investigated the behavior of beams stiffened with different stiffener configurations under torsional loading. They suggested that transverse stiffeners (i.e. web stiffeners) are not effective in reducing warping normal stresses and displacements. However, longitudinal stiffeners (i.e. batten plates) are moderately effective in resisting torsional stresses.

Takabatake [5] attempted to develop a mathematical solution for the LTB capacity of steel doubly symmetric I-beams stiffened with stiffeners or batten plates. His mathematical solution was derived by energy method based on the following assumptions :1) the beam is doubly symmetric, 2) the initial imperfections and residual stresses are neglected, and 3) only elastic lateral buckling is considered. He suggested that the increase in beam flexural capacity stiffened with stiffeners and/or batten plates is due to local increase of both torsional constant and weak axis inertia at the stiffeners locations. He suggested that stiffeners or batten plates had no effect on the beam warping resistance. He attributed this to the fact that stiffeners or batten plates do not exist continuously along the beam length. According to that, the warping constant for the unstiffened-beam was used. Takabatake [5] compared his theoretical results of the stiffened beam to unstiffened beam. The maximum increase noticed was 260% over the unstiffened beam (for the beam stiffened with batten plate located near the support location).

Takabatake et.al [6] followed the aforementioned theoretical research with experimental work for beam stiffened with stiffeners or batten plates. Their results showed that the beam stiffened with batten plates or stiffeners has a bigger critical moment compared to the original unstiffened beam. The increase in beam elastic flexural capacity is bigger if the stiffener is located near the support. They also found that the presence of batten plates has a better effect on critical moment than vertical web stiffeners. However, their experimental results did not agree with their previous theoretical work.

Hassanien [7] investigated the effect of vertical web stiffeners on the LTB capacity for cantilever steel I-beam. He suggested that the web stiffeners are connecting the compression flange with the tension flange which reduces the lateral movement of the compression flange. He indicated that the presence of 6 vertical stiffeners results in average of 25% increase in cantilever beam elastic critical LTB moment.

Yang and Lui [8] investigated the effect of inclined stiffeners on the LTB capacity of doubly symmetric steel I-beam. They investigated the effect of inclined stiffeners on the flexural capacity of doubly symmetric steel I-beams. Double sided inclined stiffeners with inclination angle θ were welded to the beam flanges. The study was conducted using nonlinear finite element method. The material nonlinearity and initial geometric imperfections were considered in their study. Various parameters were considered regarding the inclined stiffeners configuration. Their study showed that the inclined stiffeners have a significant effect of the LTB capacity for steel I-beams. The best location for inclined stiffeners is near the beam supports.

Sorensen and Rasmussen [9] investigated the effect of vertical stiffeners and vertical stiffeners combined with short longitudinal stiffeners (i.e. Box stiffener) on the warping resistance of simply supported beams. The stiffeners were installed at mid-span of the beam. An experimental study was conducted to investigate the stiffener effect on the capacity of simply supported beams. A point load was applied at mid-span. The used section was IPE 80 with length of 5m.

3 NUMERICAL MODELING

3.1 Construction of Finite Element Model

A numerical finite element analysis is conducted to study the effect of batten plates on the LTB capacity of laterally unsupported simply supported steel I-beams. The finite element method as described by Zienkiewicz and Taylor [10] has been proven to be very efficient to simulate such cases. The program used in modeling is ANSYS MECHANICAL APDL v14.5 [11]. The model includes all beam components which are flanges, web, end plates and batten plates. These beam components are modeled using four-node thin shell element (SHELL181) with six degrees of freedom at each node. This element is formulated to be suitable for thin to moderately-thick shell structures for both linear and nonlinear analyses. An end plate with thickness of 16 mm is used at the beam ends to avoid any stress concentration at the steel beam ends (i.e supports location). The beam supports are represented to simulate true hinged support condition that is free to warp and prevented from torsion. The lower node of the web at the conjunction with the lower flange was prevented from vertical movement and lateral movement (Ux and Uy). The Upper node of the web at the conjunction with the upper flange was prevented from lateral movement only (Ux). Only one of the lower nodes of the beams was prevented from longitudinal movement (Uz) to achieve beam stability condition. The uniform moment loading condition is modeled using a couple of two concentrated loads with opposite directions. The finite element model with the aforementioned criteria is shown in Fig. 1.

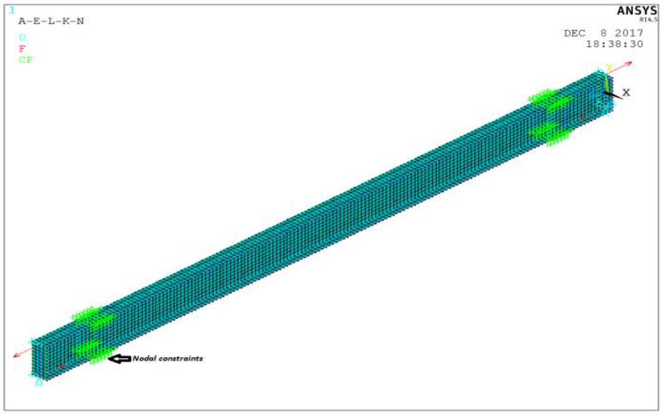


Fig. 1. Sample for modeling of the beam stiffened with double sided batten plates under uniform bending.

The initial geometric imperfections are considered in the modeling procedure. According to ASTM A6/A6M-11 [12], the maximum allowable value for lateral deformations (sweep) for I-shapes beams is defined by L/960. In this study, a value of L/1000 is used as initial geometric imperfections. It is to be mentioned that L/1000 is the maximum out of straightness value for compression members defined in the code of standard practice AISC [13]. This initial imperfection is implemented in the nonlinear finite element model by conducting a linear buckling analysis on the studied beam to obtain the critical LTB failure mode shape. This critical buckled shape obtained from linear buckling analysis is normalized by setting the maximum lateral deformation at mid-span to a value of L/1000. Using "update geometry" command in ANSYS program, the normalized buckled shape is considered to be the initial shape of the studied steel beam in the nonlinear final finite element model. For all the specimens, a nonlinear material properties are considered. The stress strain curve is assumed to be a bilinear curve. The material used is steel S235 with elastic modulus of elasticity (E=210 GPa), yield strength (F_y=235 MPa) and Poisson's ratio (υ=0.3). The tangent modulus (E_t) is used with an approximate value of 10% of the used steel elastic modulus (E_t=0.1E). Fig. 2 represents the used material properties for all cases.

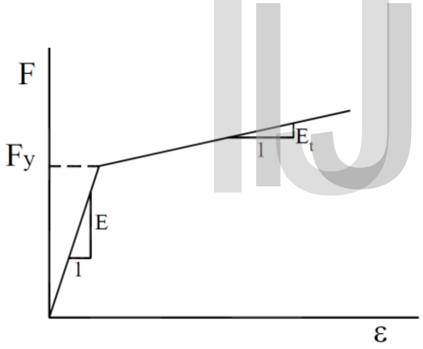


Fig. 2. Idealized bilinear stress strain curve

The used size for the elements is approximately 50mm in both directions which provided a reliable result with verification cases that will be described in the following section. The model is meshed for beam without any stiffening batten plates. Batten plates are added to the model after meshing the beam and then meshed. Nodal constraints (i.e. coincident nodes) are used to join the batten plate to the beam model.

3.2 Model Verification

The proposed finite element model is verified with previous research works. The verification process is an important step to prove the capabilities of the proposed model to simulate the studied cases of steel beams stiffened with batten plates. The model verification is conducted with the finite element work done by Yang and Lui [8] and with the experimental and finite element work done by B. Yang [14]. Yang and Lui [8] checked their finite element models with design code equations for elastic and final (nonlinear) critical moment value for simply supported beam under uniform bending. The studied beam was W12x58 with different lengths to cover the full behavior of the studied beam. They studied six different spans for the studied beam varying from 120 to 420 inches in 60 inches increment and obtained the critical moments by linear and nonlinear analyses. The material properties for this study were (Yield stress F_y=345 MPa, Young's modulus E=210 GPa, Tangent modulus E_t = 5%E and Poisson ratio υ=0.3).

A set of finite element models are constructed to verify the proposed model with the finite element results that were given by Yang and Lui [8]. The verification results for the six cases showed a good agreement with the same results that were presented by Yang and Lui [8]. The detailed verification results are presented in Fig. 3 and 4 for both linear and nonlinear analyses.

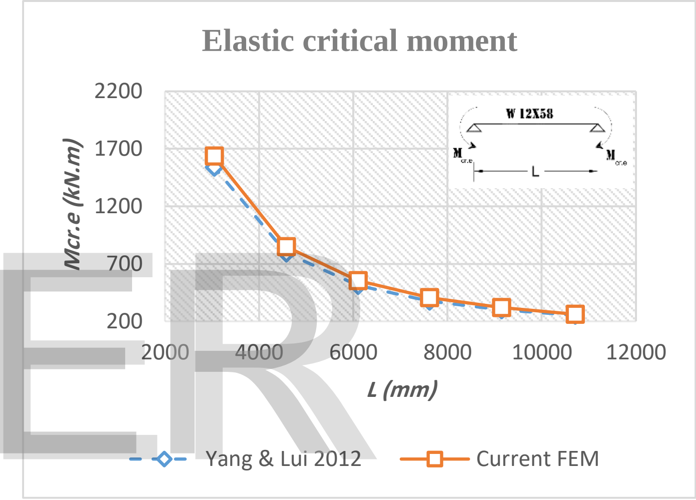


Fig. 3. Verification of elastic analysis

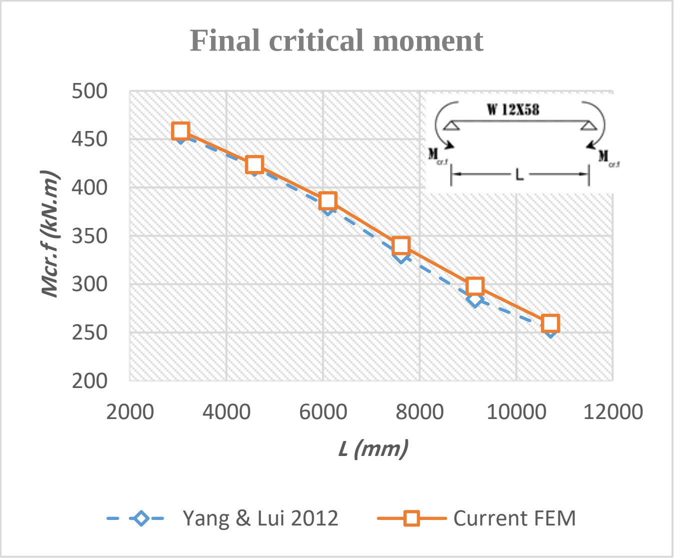


Fig. 4. Verification of elastic analysis

B. Yang [14] investigated the lateral torsional buckling behavior of structural steel beams under concentrated load. He investigated this behavior using both experimental work and finite element analysis. The material properties were obtained from a tensile test and could be summarized as (Yield stress F_y= 410 MPa, Ultimate strength F_u=570 MPa, Young's modulus E=211 GPa and Poisson ratio υ=0.3). For finite element modeling, a bilinear stress strain curve was used with tangent modulus E_t = 0.1E. The initial imperfections were taken as span/1000 for finite element modeling. Comparison between the B. Yang [14] results and the current finite element model is shown in Table (1). As evident in Table (1), the verification results for the used specimens show good agreement for specimens DTS 2 and DTS 3 for both numerical and experimental work. However, for specimen DTS 1, the experimental results were not close to the finite element results of original work and the current proposed finite element model used in the verification study.

TABLE 1

DETAILED VERIFICATION RESULTS WITH B. YANG [14] WORK

Specimen ID	B.Yang results [14]		Current finite element model	$\frac{M_{FEM}}{M_{exp}}$	$\frac{M_{FEM}}{M_{num}}$
	Exp.	Num.			
	M_{exp}	M_{num}	M_{FEM}		
DTS 1	52.6	47.3	45.5	0.87	0.96
DTS 2	179	166.5	167.7	0.94	1.01
DTS 3	268	277.2	278.3	1.04	1.00

Units for moments are kN.m

4 PARAMETRIC STUDY AND DISCUSSION

A set of steel beams with various spans is studied to determine the effect of double and single-sided batten plates on the LTB capacity. The steel cross sections used for this study are standard hot rolled sections (IPE 500 and HEB 260). The used steel cross section is classified as compact sections with respect to local buckling conditions. The studied spans are 6, 10, 12 and 16 meters to cover both elastic and inelastic LTB failure modes.

The flexural capacity is highly dependent on the cross section factor of L/r_{ts}. Therefore, all results are presented with respect to this factor. Where L is the beam length and also represents the unsupported length for the simply supported loading condition and r_{ts} is approximately the radius of gyration of the compression part of the cross section (compression flange and 1/6 of the web) or it can by calculated exactly as provided by AISC [2].

The increase in flexural capacity due to the presence of the batten plate is represented by the ratio (M_{cr-f} / M_{cr0}). Where M_{cr-f} is the critical moment obtained from the nonlinear finite element model for the beam stiffened with batten plates and M_{cr0} is the critical moment for the control unstiffened beam obtained also from nonlinear analysis. Different parameters for the batten plate configuration are considered. Fig. 5 represents the layout for beam stiffened with double sided batten plates. The batten plate centerline location (Z_{bp}) is varied from 0.1L to 0.5L with increment of 0.1L. The batten plate number is investigated with increase of 4 batten plates for each step with increment of 0.1L. The width of the plate (W_p) is considered equal to L/50, L/40, L/30, L/20 or L/10. The thickness of the batten plate is investigated for plate thickness from 8mm to 16mm with increment of 2mm.

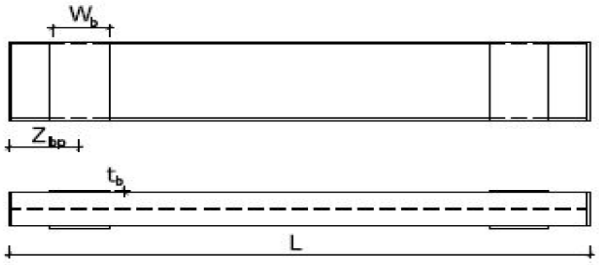


Fig. 5. Beam stiffened with double sided batten plates.

4.1 Effect of Batten Plate Location (Z_{bp})

The effect of double and single sided batten plates located at distance Z_{bp} from both beam ends is investigated in this section. Every specimen has four welded batten plates except at distance 0.5L where only two batten plates are located at beam mid-span. All beams are investigated under the effect of uniform moment. The double sided batten plate location (Z_{bp}) varies from 0.1L to 0.5L from both beam ends. The batten plates have the dimension of W_p= L/30 and t_p=10 mm. Where W_p and t_p are the width and thickness of the batten plate respectively.

The final failure mode obtained from nonlinear finite element analysis for all specimens stiffened with batten plates is lateral torsional buckling accompanied with small vertical displacements. A sample for the LTB failure mode is shown in Fig. 6. The results for the effect of the location of double sided batten plates is presented in Fig. 7 and 8. From the results, the effect of batten plates is more pronounced for the case of batten plates are located near the beam supports. For the batten plates located at mid-span, minimal increase in the beam flexural strength is noticed. The batten plates are more effective for the beams with long spans where elastic lateral torsional buckling is dominant. The maximum increase in flexural strength is about 22% for the case of double sided batten plates with dimensions of W_p= L/30 and t_p=10 mm located at location 0.1L from both beam ends. These results show good agreement with the previous researches that was introduced before in the literature review which suggested that the best location for any stiffening plates is near the supports. For IPE 500 specimens with (L/r_{ts} =227, 303), it is noticed that both specimens have almost the same increase in flexural strength due to presence of stiffening batten plates. Although the yield moment for the HEB 260 is lower than IPE 500, HEB 260 has a better resistance to LTB failure mode due to the wide flange configuration. The HEB 260 specimens showed a combined failure mode between LTB and yielding (inelastic LTB). Therefore, the effect of batten plates on the flexural capacity of HEB 260 is less than that for IPE 500 cases for the same spans and same L/r_{ts} values.

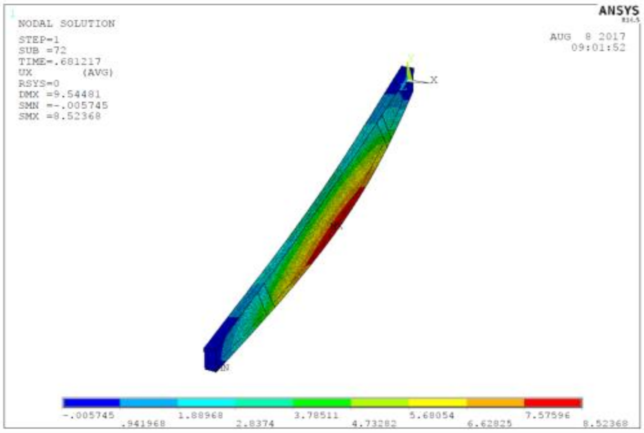


Fig. 6. LTB failure mode for beam stiffened with double sided batten plates.

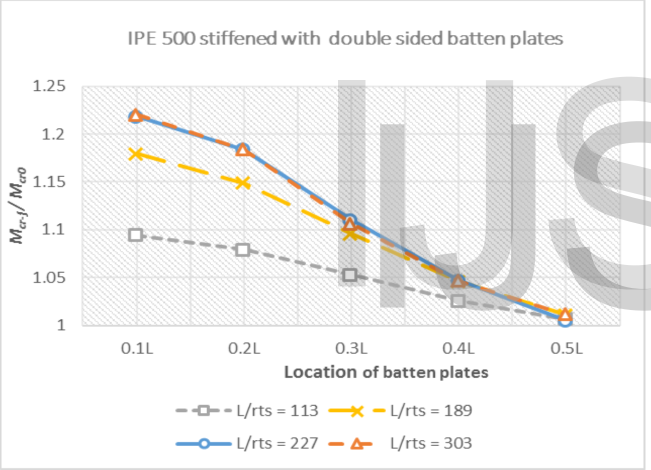


Fig.7. Effect of double-sided batten plates location on steel beam flexural strength (IPE 500), (W_p= L/30, t_p= 10 mm)

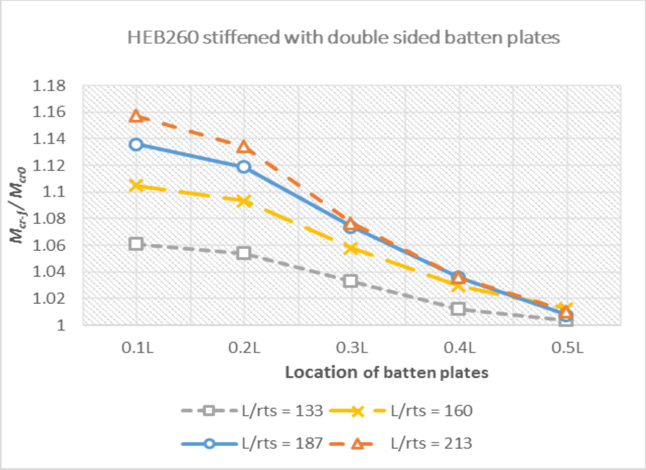


Fig.8. Effect of double-sided batten plates location on steel beam flexural strength (HEB 260), (W_p= L/30, t_p= 10 mm)

For the cases of beams stiffened with single sided batten plates, similar behavior is noticed as the cases of beams stiffened with double sided batten plates but with less increase in the flexural capacity of the beam compared to the cases of double-sided batten plates as shown in Fig. 9 and 10. The increase of flexural capacity for single-sided batten is almost 88% of the increase of flexural capacity of double-sided batten plates for the same span and cross section.

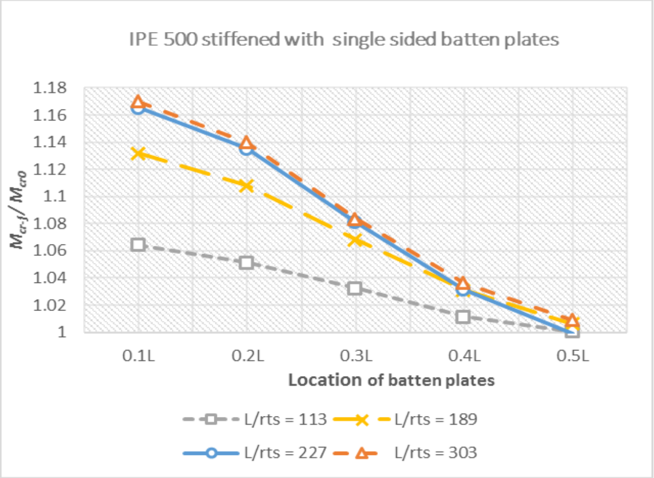


Fig.9. Effect of single-sided batten plates location on steel beam flexural strength (IPE 500), (W_p= L/30, t_p= 10 mm)

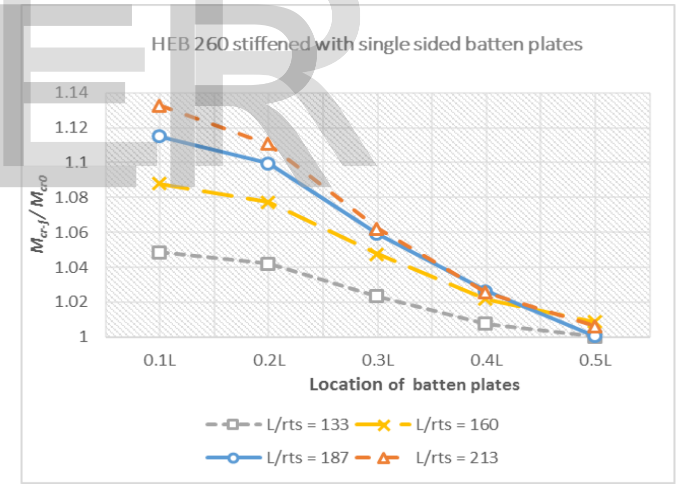


Fig.10. Effect of single-sided batten plates location on steel beam flexural strength (HEB 260), (W_p= L/30, t_p= 10 mm)

4.2 Effect of Number of Batten Plates (N_p)

The effect of increasing the total number of batten plates along the beam length is investigated in this section. The total number of batten plates along the beam span varied from ideal case of four to eighteen batten plates with an increment of 0.1L between each batten plate pair as shown in Fig. 11. For single sided batten plates cases, half the number of batten plates is used. For all cases, the width and thickness of plate are kept constant with values of W_p= L/30 and t_p=10 mm. All beams are investigated under the effect of uniform moment.

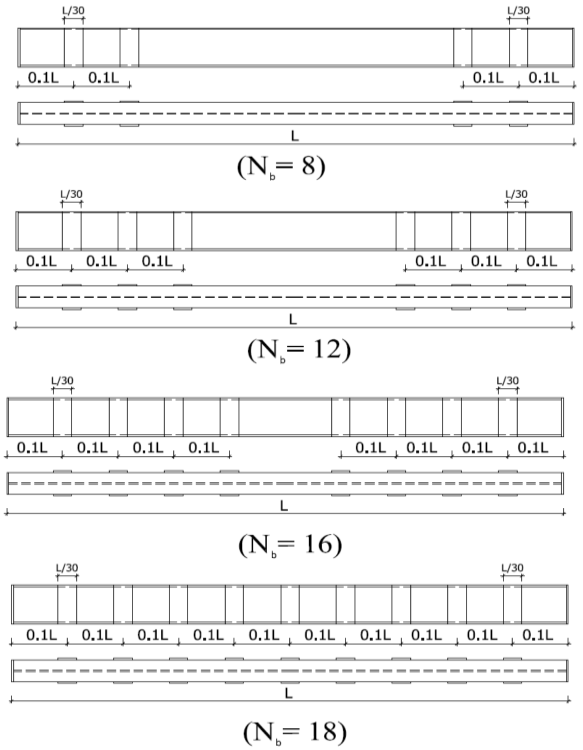
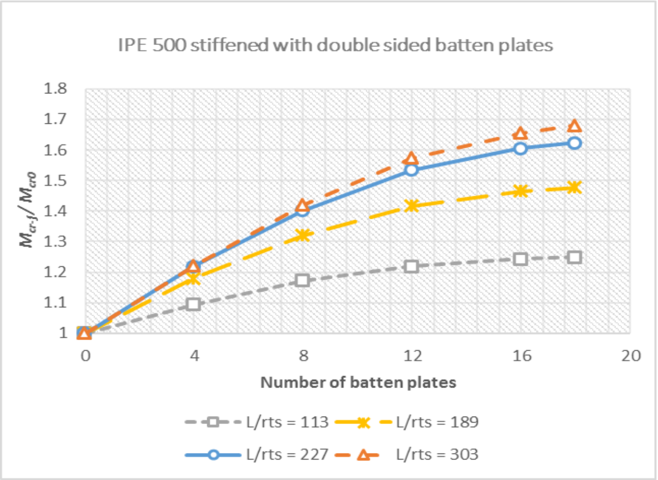
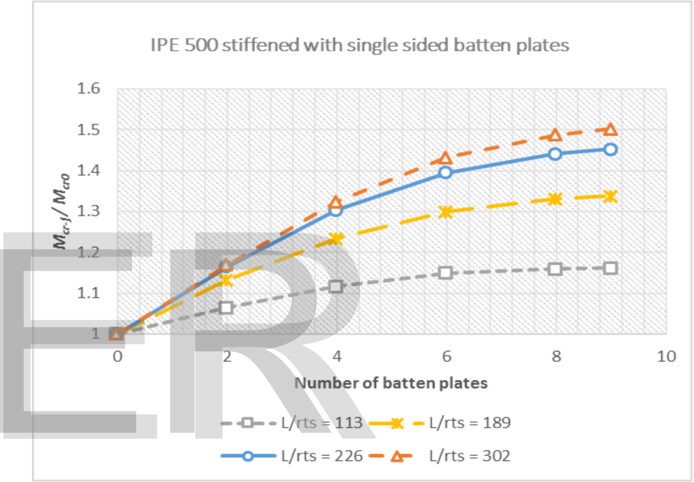


Fig.11. Variation of double-sided batten plates number along beam length

The results for the effect of varying the total number of batten plates are shown in Fig. 12 and 13. It is evident from these figures that there is a significant increase of the beam flexural capacity which could reach 68% for the case of IPE 500 stiffened with total 18 batten plates for beam with L/r_{ts} =303. However, for the same number of batten plates this increase ratio is only 23% for the same shorter beam with L/r_{ts} =113. The large number of batten plates leads to a higher major and minor moment of inertia for the beam at the positions of these batten plates. These plates also enhance both torsional and warping resistance of the beam. For HEB 260 specimens, the maximum increase in flexural strength obtained for the beam with (L/r_{ts}= 213) stiffened with 18 double sided batten plates is 33.2%. For beams stiffened with single sided batten plates, the maximum increase in flexural strengths are 50 % and 27.9 % for IPE 500 and HEB 260 specimens stiffened with total 9 single-sided batten plates distributed along the beam span each with width (W_p= L/30) respectively. This maximum increase in flexural strength is noticed for the long span beams for the studied cases. For most cases, the increase of flexural strength for beams stiffened with 18 double-sided batten plates is almost equal to that for beams stiffened with 16 batten plates. This indicates that using batten plates at mid-span of the beam is not beneficial as it has almost minimal effect on increasing the flexural strength. These results prove that the batten plates are more effective for long-span beams when the elastic LTB behavior is dominant.

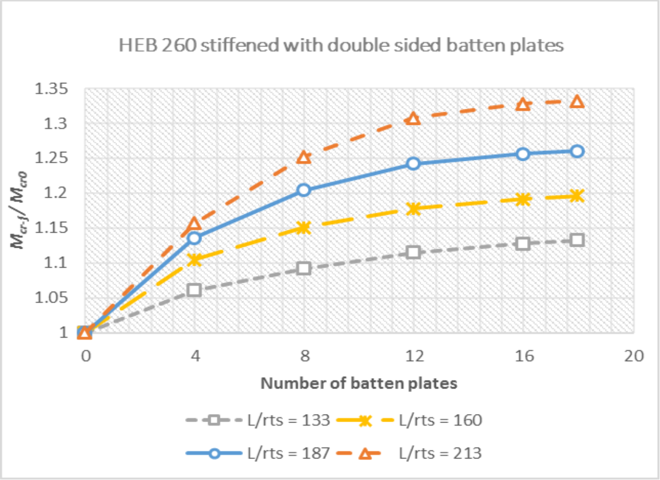


a- Double-sided batten plates

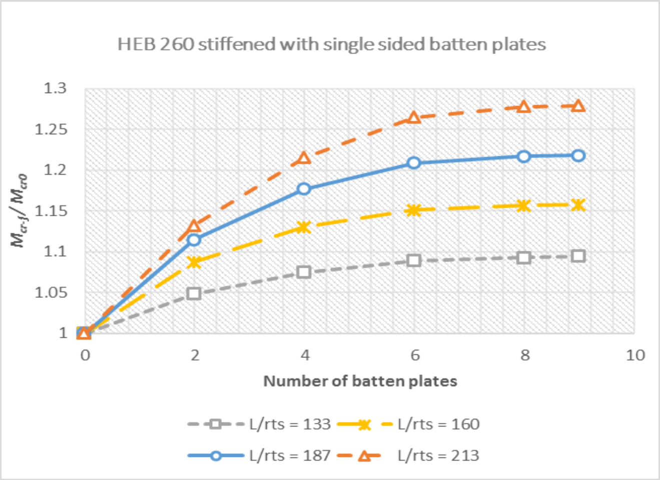


b- Single-sided batten plates

Fig.12. Effect of number of batten plates on steel beam flexural strength (IPE 500), (W_p= L/30, t_p= 10 mm)



a- Double-sided batten plates



b- Single-sided batten plates

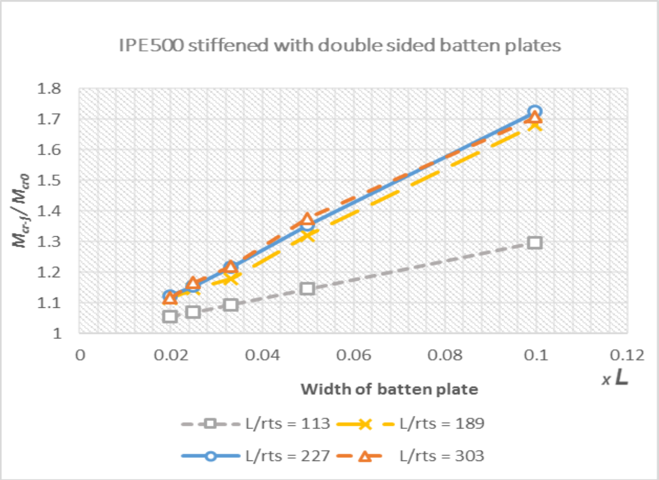
Fig.13: Effect of number of batten plates on steel beam flexural strength (HEB 260), (W_p= L/30, t_p= 10 mm)

4.3 Effect of Width of Batten Plate (W_p)

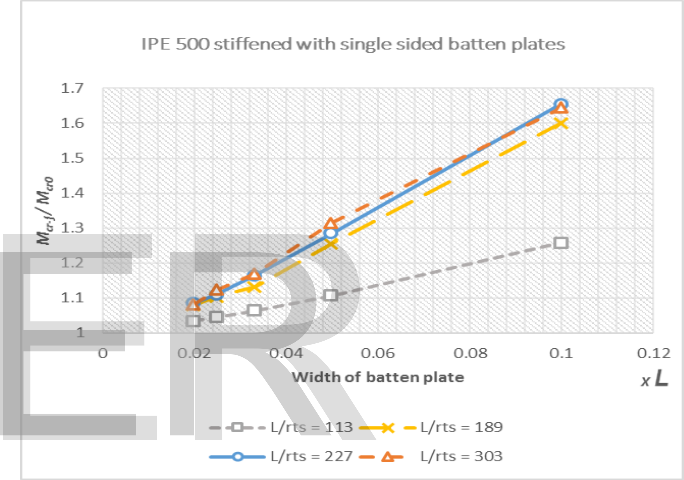
The effect of increasing the width of the batten plates is studied in this section. This study is conducted on beams with four batten plates of thickness (t_p=10mm) and located at distance 0.1L from both beam ends. The width of the batten plates is defined relative to the beam span (L). The studied ratios for the width are (L/50, L/40, L/30, L/20, L/10). The maximum suggested batten plate width (L/10) does not reach the ends of the beam.

Fig. 14 and 15 show the ratio of increase of the flexural strength against various batten plate widths. From these figure, it is evident that the effect of batten plate width is more significant than all other parameters. This effect is also more pronounced for long spans. For the studied steel beams with cross section IPE 500, the increase in flexural strength is directly proportion to batten plate width with almost linear trend. For IPE 500 specimens with (L/r_{ts} =227 and 303), the results are very close. The maximum increase in flexural strength almost reaches 70% for a beam with L/r_{ts} = 303 stiffened with four batten plates each of width 0.1L. For HEB 260 specimens, the maximum increase in flexural strength obtained is 27.6% for the beam with (L/r_{ts} =213) stiffened with double sided batten plates with width L/10 located at 0.1L from both beam ends.

The effect of batten plate width is extremely significant on the flexural strength of laterally unsupported simply supported I-beams. The wide batten plates change the behavior of open I-beam to become closer to the closed box beam which has a better resistance to torsional deformations. The effect is also more pronounced in long spans, where elastic LTB is dominant. The shorter beams and wide flange beams show inelastic LTB behavior so that the effect of batten plates is less effective for these cases.

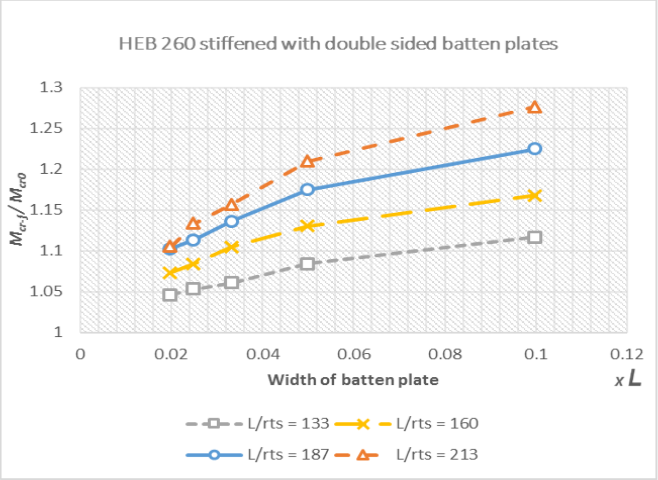


a- Double-sided batten plates

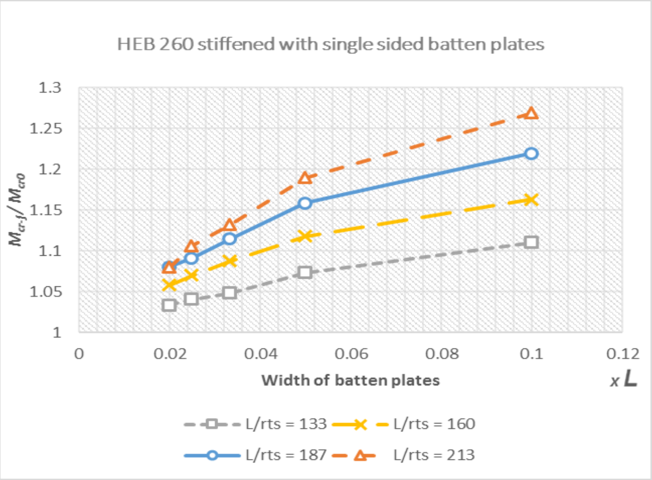


b- Single-sided batten plates

Fig. 14: Effect of batten plate width on steel beam flexural strength (IPE 500),(Z_{bp}=0.1L, t_p= 10 mm)



a- Double-sided batten plates



b- Single-sided batten plates

Fig. 15. Effect of batten plate width on steel beam flexural strength (HEB 260),(Z_{bp}=0.1L, t_p= 10 mm)

4.4 Effect of Loading condition for Beams Stiffened with double-sided batten plates

The effect of loading condition for simply supported I-beam stiffened with double sided batten plates is investigated in this section. The loading conditions studied are uniform moment loading and a single concentrated load at the beam mid-span. The batten plates are located at 0.1L from both beam ends with thickness of 10 mm. The studied width for batten plate is L/30. The study is performed for the same ratios of L/r_{ts} that were used before for uniform moment loading condition. The used section profile is IPE 500.

Fig. 16 shows a comparison between the two different loading conditions of uniform bending and mid-span single concentrated load. It is evident from this figure that the increase in flexural capacity due to the presence of double sided batten plates in a beam subjected to single concentrated load at mid-span is lower than the case for uniform moment with less than 3 %. Therefore, the effect of changing the loading condition is minimal regarding the increase in flexural capacity for the beams stiffened with batten plates.

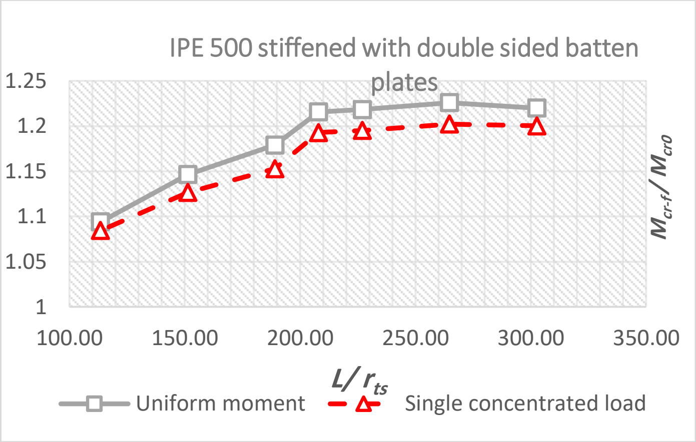


Fig. 16: Flexural strength for steel beams stiffened with double-sided batten plates under different loading condition

5 PROPOSED DESIGN PROCEDURE

The parametric study results showed that the batten plates have a significant effect on flexural strength of laterally unsupported simply supported I-beams. This effect is noticed for both single and double sided batten plates configurations. The main parameters affecting flexural strength are found to be the batten plate width and number of batten plates along the beam span. The main concept of this design procedure is to introduce proposed magnification factors for width and number of batten plates to be applied to the elastic critical LTB moment defined in (1). Another separate factor for the case of single-sided batten plates is applied also to the same equation. Thus, three modification factors C_1, C_2 and C_3 are applied to the elastic critical moment equation for the case of beam subject to uniform moment which can be written as follows:

$$M_{cr.bp} = C_1.C_2.C_3.\left(\sqrt{\frac{\pi^2.E.I_y.G.J}{L^2}+\frac{\pi^4.E.I_y.E.C_w}{L^4}}\right) \quad (2)$$

The modification factors are formulated based on the results from linear buckling analysis of cases studied in the parametric study. Polynomial equations are obtained to define the values for these factors based on best fitting techniques. The factor C_1 is the magnification factor to include the effect of the width (W_b) of double-sided batten plates located at distance 0.1L from beam ends. The factor C_2 is the magnification factor to account for the total number of double sided batten plates (N_p) which are spaced at 0.1L intervals. The factor C_3 is introduced to consider the effect of single-sided batten plates cases. The modification factors C_1, C_2 and C_3 are defined by the following equations:

For 110 < L/r_{ts} ≤ 185

$$C_1 = 22.1.\left(\frac{W_b}{L}\right)^2 + 2.927.\left(\frac{W_b}{L}\right) + 0.8793 \quad (3)$$

$$C_2 = -0.0011.N_p{}^2 + 0.0438.N_p + 0.99 \quad (4)$$

For 185 < L/r_{ts} ≤ 225

$$C_1 = 20.82.\left(\frac{W_b}{L}\right)^2 + 5.25.\left(\frac{W_b}{L}\right) + 0.8 \quad (5)$$

$$C_2 = -0.0016.N_p{}^2 + 0.059.N_p + 0.99 \quad (6)$$

For 225 < L/r_{ts} ≤ 310

$$C_1 = 6.98.\left(\frac{W_b}{L}\right) + 0.769 \quad (7)$$

$$C_2 = -0.0019.N_p{}^2 + 0.073.N_p + 0.99$$

For all L/r_{ts} values and single-sided batten plates

$$C_3 = 0.88 \quad (8)$$

For all L/r_{ts} values and double-sided batten plates

$$C_3 = 1 \tag{9}$$

Based on the modified elastic critical moment, the nominal moment strength of beam with batten plates ($M_{bp,Rd}$) can be calculated based on equations of EuroCode 3 [15] defined as follows:

$$M_{bp,Rd} = \chi_{LT}.W_y.F_y \tag{10}$$

Where, χ_{LT} is the lateral torsional buckling reduction factor and W_y is the plastic section modulus about major axis for compact sections.

$$\chi_{LT} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \beta\lambda_{LT}^2}} \leq \begin{cases} 1 \\ 1/\lambda_{LT}^2 \end{cases} \tag{11}$$

Where,

$$\phi_{LT} = 0.5\left[1 + \alpha_{LT}(\lambda_{LT} - \lambda_{LT,0}) + \beta\lambda_{LT}^2\right] \tag{12}$$

$$\lambda_{LT} = \sqrt{\frac{W_y.F_y}{M_{cr.bp}}} \tag{13}$$

α_{LT} is the imperfection factor which takes the cross section aspect ratio of depth-to-width (h/b) into consideration.

$$\alpha_{LT} = \begin{cases} 0.34 & \text{for rolled sections with } h/b \leq 2 \\ 0.49 & \text{for rolled sections with } h/b > 2 \end{cases} \tag{14}$$

The recommended values for β and $\lambda_{LT,0}$ in EuroCode 3 [15] are β = 0.75 and $\lambda_{LT,0} = 0.75$.

Table (2) shows a comparison between the proposed equations results and the finite element results for IPE 500 section strengthened with double-sided batten plates under uniform bending moment, where $M_{bp,Rd}$ is the final nominal critical flexural strength obtained from the design equation of Eurocode 3 [15] based on the modified elastic critical moment given by equation (2), and $M_{cr.f}$ is the final flexural strength obtained from nonlinear finite element analysis. The results of the proposed design procedure show an excellent agreement with the finite element results with average ratio for ($M_{bp,Rd}$ / $M_{cr\,f}$) equals to 1.01 and standard deviation of 2 %.

Table (3) shows a comparison between the proposed equations results and the finite element results for HEB 260 section stiffened with single-sided batten plates under uniform bending moment. Results show a very good agreement and most of the results obtained by the proposed equations are on the conservative side with average ratio for ($M_{bp,Rd}$ / $M_{cr\,f}$) equals to 0.95 and standard deviation of 4.6 %.

The previous results indicate that the proposed design procedure is efficient for both double and single-sided batten plates. The same design procedure can be applied for other cases of beams subjected to moment gradient by considering non-uniform moment factor in equation (10) as defined in EuroCode 3 [15].

TABLE 2
COMPARISON OF FLEXURAL STRENGTH FOR IPE 500 STIFFENED WITH DOUBLE-SIDED BATTEN PLATES

L/r_{ts}	N_p	W_b/L	Proposed procedure (kN.m) $M_{bp,Rd}$	Finite element (kN.m) $M_{cr.f}$	$\frac{M_{bp,Rd}}{M_{cr.f}}$
303	4	0.02	123.4	122.8	1.005
303	4	0.025	128.1	128.3	0.998
303	4	0.033	136	134.2	1.013
303	8	0.033	157.8	156.2	1.010
303	12	0.033	173.0	173.1	0.999
303	16	0.033	181.6	182.1	0.997
303	18	0.033	183.5	184.9	0.992
189	4	0.02	206.5	198	1.043
189	4	0.025	211.8	203.5	1.041
189	4	0.033	220.9	209.4	1.055
189	8	0.033	242.0	234.5	1.032
189	12	0.033	255.3	251.5	1.015
189	16	0.033	262.0	260.1	1.007
189	18	0.033	263.0	262.3	1.003
113	4	0.02	330.8	322.3	1.026
113	4	0.025	334.2	326.5	1.024
113	4	0.033	339.9	333.9	1.018
113	8	0.033	356.2	357.6	0.996
113	12	0.033	366.4	372	0.985
113	16	0.033	372.0	379.3	0.981
113	18	0.033	373.3	381.1	0.980

TABLE 3
COMPARISON OF FLEXURAL STRENGTH FOR HEB 260 STIFFENED WITH SINGLE-SIDED BATTEN PLATES

L/r_{ts}	N_p	W_b/L	Proposed procedure (kN.m) $M_{bp,Rd}$	Finite element (kN.m) $M_{cr.f}$	$\frac{M_{bp,Rd}}{M_{cr.f}}$
213	4	0.02	190.8	211.9	0.900
213	4	0.025	190.8	217.1	0.879
213	4	0.033	201	222.2	0.905
213	8	0.033	217.6	238.5	0.912
213	12	0.033	226.4	248.2	0.912
213	16	0.033	230.5	250.8	0.919
213	18	0.033	231.2	251	0.921
160	4	0.02	232.9	243.7	0.956
160	4	0.025	232.9	246.4	0.945
160	4	0.033	233.9	250.4	0.934
160	8	0.033	243.8	260.2	0.937
160	12	0.033	249.6	265	0.942
160	16	0.033	252.6	266.3	0.949
160	18	0.033	253.3	266.5	0.950
133	4	0.02	252	256.2	0.984
133	4	0.025	252	257.9	0.977
133	4	0.033	252.8	259.8	0.973
133	8	0.033	260.2	250.9	1.037
133	12	0.033	264.4	257.8	1.026
133	16	0.033	266.6	259.5	1.027
133	18	0.033	267.1	259.7	1.028

6 SUMMARY AND CONCLUSIONS

A non-linear finite element model was utilized to investigate the gain in LTB strength of steel beams stiffened with batten plates. The proposed finite element model is verified with previous experimental and analytical research works. The effect of batten plates location, number, width and thickness on the LTB strength was studied. A simplified design procedure is proposed to determine nominal flexural strength of beams with batten plates of various configurations. The main conclusions of this paper can be summarized as follows:

1- The double and single sided batten plates has a significant effect on the flexural strength of simply supported laterally unsupported I-beams
2- The effect of batten plates on the flexural strength is more pronounced in the long span beams (i.e. elastic LTB) with increase of LTB flexural capacity up to 70%.
3- The location of batten plates has a major effect on the flexural strength and it is found that the best location for batten plates is near the beam supports. On the other hand, installing batten plates at mid-span of the beam is not effective.
4- Increasing the number of batten plates leads to a higher flexural strength. However, it is recommended to keep the mid-span with no batten plates as it has minimal effect.
5- The effect of batten plate width is very significant and leads to a higher increase in the flexural strength than increasing the batten plates number with less increase in beam weight.
6- Beams stiffened with single-sided batten plates show a similar behavior to the beams stiffened with double-sided plates but with a lower increase in the flexural strength. Beams with single-sided batten plates have approximately 88% of the increase in flexural capacity of the same beam with double-sided batten plates.
7- The wide flange shapes have a better ability to resist LTB. Therefore, the effect of batten plates for wide flange beams is lower than the ordinary beams for the same L/r_{ts}
8- The loading condition has a slight effect on the increase of flexural strength for the beams stiffened with batten plates with minimal difference of 3% between the uniform bending and single concentrated load condition.
9- The proposed design procedure of beams with batten plates proved to be efficient and in very good agreement with nonlinear finite element results.

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