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LATERAL TORSIONAL BUCKLING FOR STEEL I-BEAMS STIFFENED WITH DOUBLE SIDED BATTEN PLATES.

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الملخص

تستخدم الكمرات الحديدية في المنشات في تطبيقات متعددة. تهتم هذه الدراسة بفحص سلوك الكمرات الحديدية بسيطة الارتكاز غير المدعومة جانبيا والمدعمة بالواح جانبية تحت تأثير عزوم انحناء منتظمة. مقاومة الانحناء للكمرات الحديدية تتوقف علي الالتواء الجانبي لهذه الكمرات. يقدم هذا البحث دراسة بارامترية باستخدام طريقة العناصر المحددة غير الخطية لدراسة سلوك هذه الكمرات. تم فحص العديد من العوامل المؤثرة وتتمثل في عدد وعرض وتخانة ومكان الواح التدعي الجانبية. تم عمل الدراسة للعديد من الاطوال لتغطية السلوك المرن وغير المرن للانبعاج الجانبي لهذه الكمرات. تم عرض النتائج في صورة منحنيات بيانية توضح تأثير العوامل المختلفة علي قدرة تحمل الكمرات للانبعاج الجانبي. توضح نتائج الدراسة ان وجود الواح التدعيم الجانبية يؤدي لزيادة ملحوظة في مقاومة الكمرات للانبعاج الجانبي.

ABSTRACT

Steel beams are usually used in all types of structures with various applications. This paper investigates the behavior of laterally unsupported simply supported steel I-beams stiffened with double batten plates under uniform bending. Lateral torsional buckling (LTB) failure mode always controls the flexural capacity of such beams. A parametric study is performed using nonlinear finite element analysis to simulate the behavior of these beams. Different parameters are investigated such as batten plates number, width, thickness and location of batten plates. The study is conducted for various spans to cover both elastic and inelastic lateral torsional buckling behavior. The results of this study is presented in the form of graphs showing the effect of different parameters on the LTB capacity for the studied cases. This study indicates that the presence of batten plates increases the LTB capacity for the steel I-beams.

Key words: Lateral torsional buckling, Batten plates, Simply supported beams Finite element analysis.

1. INTRODUCTION

Steel beams are the backbone of all steel structures such as floor beams for multistory buildings or as rafters for portal frames. Steel beams are also used for some special applications such as monorail beams or crane track girders. The load-carrying capacity of steel beams is controlled by the unsupported length of the compression flange. If a laterally unsupported beam is loaded vertically, it deflects about its main axis while the compression portion 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). Beams with full lateral restraint of the compression flange reach the full flexural capacity without any lateral deformations. However, the flexural capacity of laterally unsupported beams is decreased as the unsupported length of the compression flange is increased. The main failure mode of steel beams with open I-sections is LTB accompanied with vertical displacement.

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 reduces the unsupported buckling length for the compression flange by preventing its lateral movement at the braced points.

Stiffeners are often used to increase web shear capacity for plate girders with big depths 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 to prevent local stresses. Also stiffeners are used at the coped region position in the beams to strengthen the web.

Previous researches were performed to determine the effect of stiffeners with different configurations on the flexural strength of steel beams. Takabatake (1988) studied theoretically and experimentally the effect of stiffeners and batten plates on LTB behavior of I-beams. Hassanien (2004) studied the effect of stiffeners on LTB capacity of cantilever beams. Yang and Lui (2012) studied the effect of inclined stiffeners on the LTB capacity of I-beams. However, this effect is not yet included in the design codes. The research area on the effect of batten plates on the flexural capacity of beams is very limited.

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

2. THEORETICAL BACKGROUND

The critical elastic lateral torsional buckling moment was introduced by Timoshenko and Gere (1961). This critical moment was first deduced for the case of uniform bending moment only. 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 (360-2010) is represented by:

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

The actual flexural capacity of laterally unsupported I-beams may be lower than value obtained from Eq. (1) if inelastic LTB or full plastification of the cross section is the dominate failure mode. Inelastic LTB occurs when some parts of the section reach the yield stress with the beam experiencing lateral movements and twisting. As the unsupported length of the beam exceeds a certain limit value, the failure mode for the steel beam is considered to be pure elastic lateral torsional buckling (LTB). The plastic moment capacity is obtained by applying a full lateral restrain for the compression flange (i.e $L_b = 0$).

Takabatake (1988) proposed a mathematical solution for the LTB capacity of steel doubly symmetric I-beams stiffened with stiffeners or batten plates. His mathematical solution was made 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

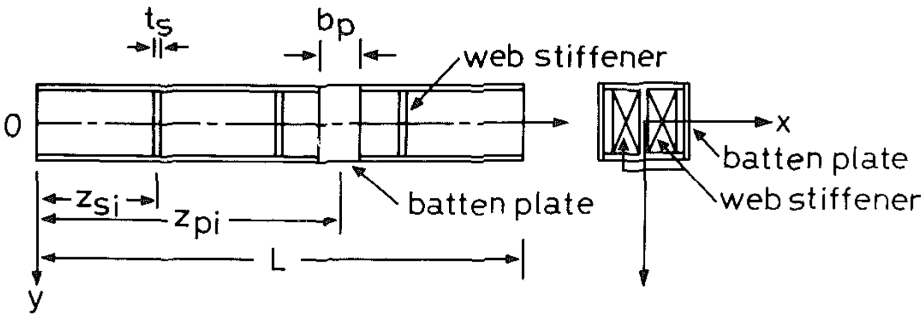


Figure (1) Takbatake (1988) stiffened steel beam definitions

Takabatake (1988) concluded that the stiffeners and batten plates have a significant effect on the LTB capacity of laterally unsupported I-beams due to the increase in torsional resistance of the beam.

Takabatake et.al (1991) 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 stiffeners are located near the supports. They also found that the presence of batten plates has a better effect on the critical moment than vertical web stiffeners.

Hassanien (2004) investigated the effect of vertical web stiffeners on the LTB capacity of cantilever steel I-beams. He suggested that web stiffeners connect 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 (2012) investigated the effect of inclined stiffeners on the LTB capacity of doubly symmetric steel I-beams. 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 beams supports.

3. NUMERICAL MODELING

3.1 CONSTRUCTION OF FINITE ELEMENT MODEL

A numerical finite element model 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 (2000) has proved to be very efficient to simulate such cases. The program used in modeling is ANSYS MECHANICAL APDL v14.5. The model includes all beam components which are the flanges, the web, beam 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 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 (U_x and U_y). The Upper node of the web at the conjunction with the upper flange was prevented from lateral movement only (U_x). Only one of the lower nodes of the beams was prevented from longitudinal movement (U_z) to achieve beam stability condition. The uniform moment loading condition is modeled using a couple of two end moments with opposite directions. The finite element model with the aforementioned criteria is shown in Figure (2).

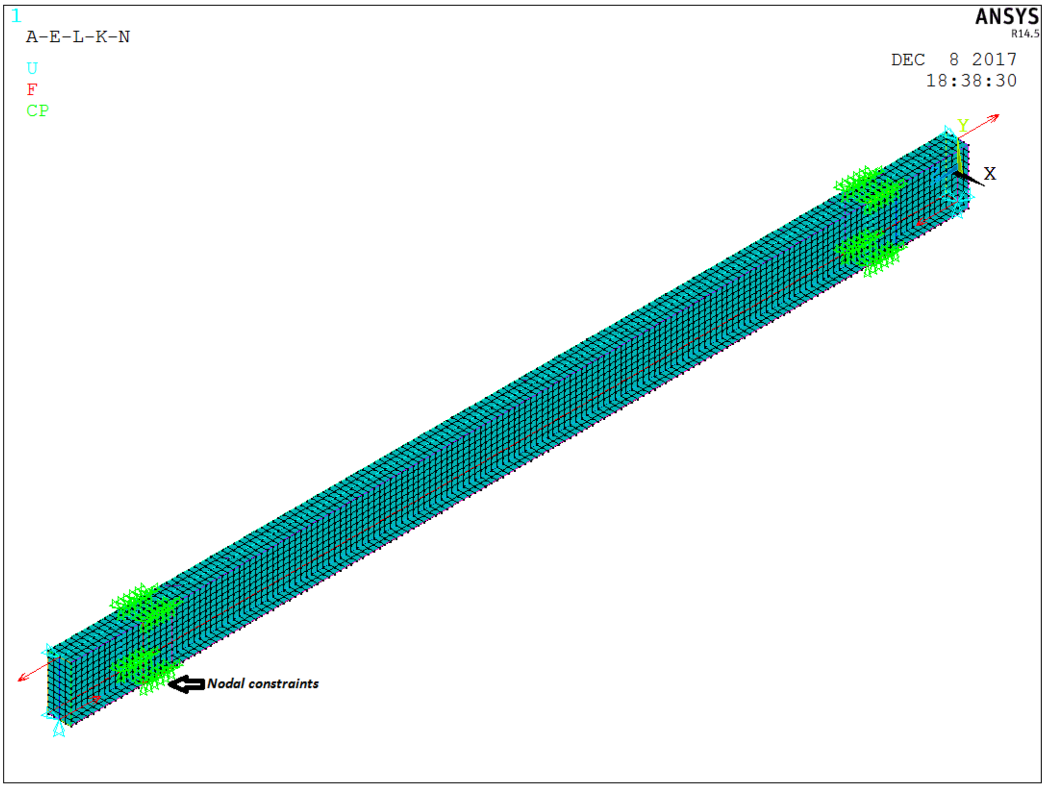


Figure (2) Sample for modeling of the beam stiffened with double sided batten plates under uniform bending.

The initial geometric imperfections are considered in the modeling procedure. According to ASTM A6/A6M-11 (2011), 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 (303-10). This initial imperfections 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 37 with elastic modulus of elasticity (E=2100 ton/cm^2), yield strength (F_y=2.4 ton/cm^2) 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). Figure (3) represents the used material properties for all cases.

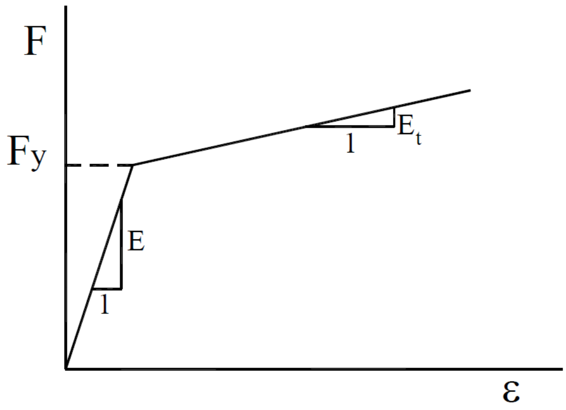


Figure (3) Idealized bilinear stress strain curve

The used size for the elements is approximately 50mm in both directions which provided reliable results 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

This part presents verification of the proposed finite element model 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 (2012). Yang and Lui (2012) checked their finite element models with design code equations for elastic and final 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. Yang and Lui (2012) studied six different spans for the studied beam varying from 120 to 420 inches in 60 inches increment and obtained their critical moments by linear and nonlinear analyses.The material properties for this study were (Yield stress F_y=345 MPa,Young's modulus E=2.1x105 MPa, 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 (2012). The verification results for the six cases showed a good agreement with the same results that were presented by Yang and Lui (2012). The detailed verification results are presented in Figures (4) and (5) for both linear and nonlinear analyses.

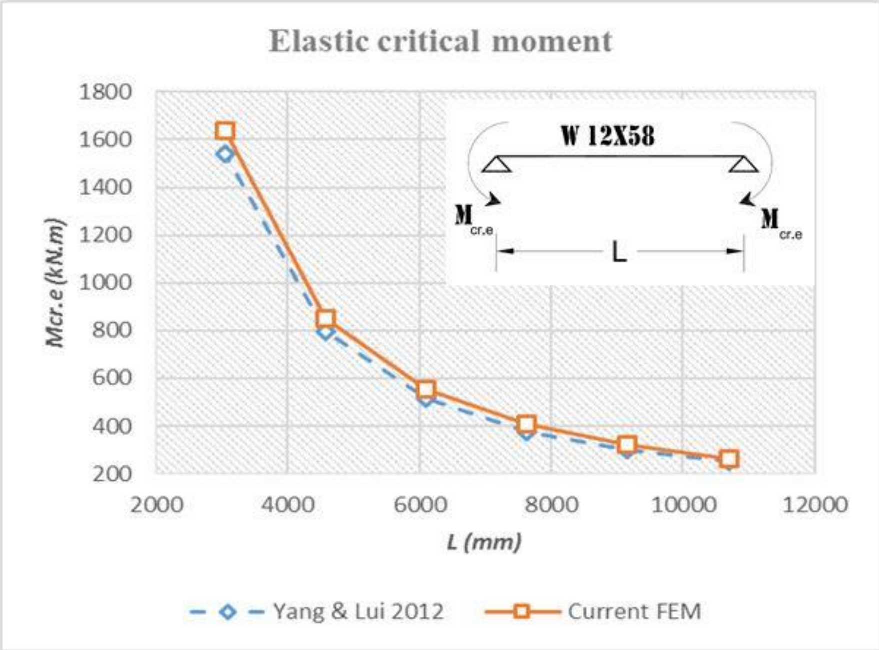


Figure (4) Verification of elastic analysis.

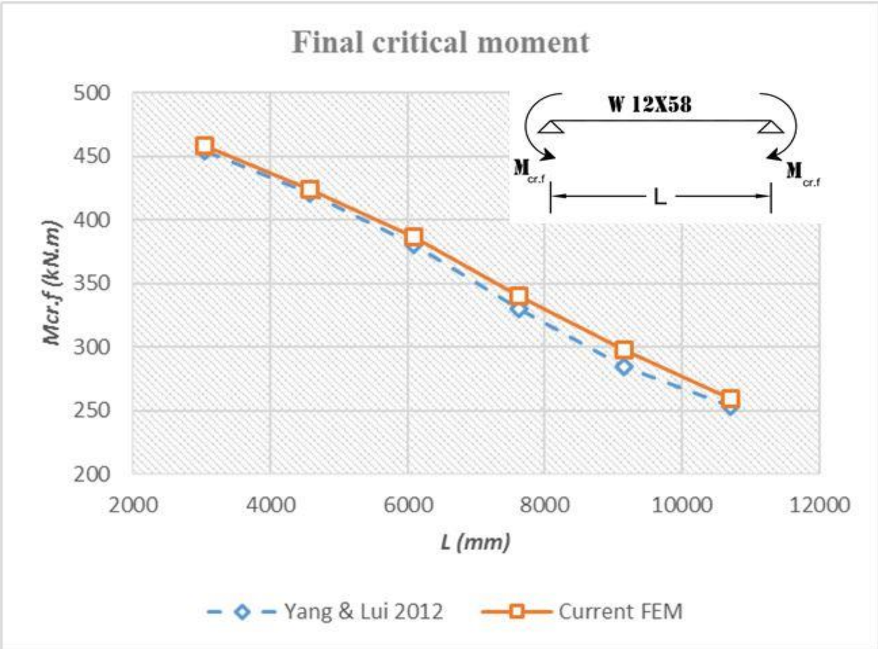


Figure (5) Verification of nonlinear analysis.

4. NUMERICAL SOLUTION RESULTS AND DISCUSSION

A Steel beam with various spans is studied to determine the effect of double sided batten plates on the LTB capacity of this beam. The steel cross sections used for this study are standard hot rolled sections (IPE 500). The used steel cross section is classified as compact section 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. r_{ts} is approximately the radius of gyration of the compression part of the cross section (compression flange and 1/6 of the web). The r_{ts} exact value could be calculated as provided in AISC (360-2010) from the following equation:

$$r_{ts}^2 = \frac{\sqrt{I_y C_w}}{S_x} \qquad (2)$$

The increase in flexural capacity due to the presence of the batten plate is represented by the ratio ($M_{cr\text{-}f}$ / M_{cr0}). Where $M_{cr\text{-}f}$ 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 model obtained also from nonlinear analysis. Different parameters for the batten plate configuration are considered. Figure (6) represents the layout for beam stiffened with double sided batten plates. The batten plate centerline location 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 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.

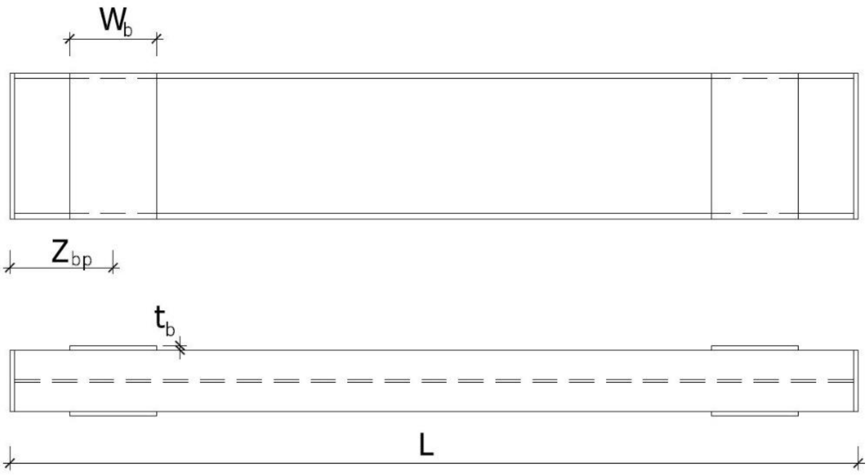


Figure (6) Beam stiffened with double sided batten plates.

4.1 EFFECT OF BATTEN PLATE LOCATION (Z_{bp})

The effect of double sided batten plates located at 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. The double sided batten plate location (Z_{bp}) varies from 0.1L to 0.5L from both beam ends. The batten plates have the dimensions 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 Figure (7).

The results for the effect of the location of double sided batten plates are presented in Figure (8). From the results, the effect of batten plates is more pronounced for the case of batten plates 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 were introduced before in the literature review as the best location for any stiffening plates is near the supports. For IPE 500 specimens with (L/rts =227, 303), it is noticed that both specimens have almost the same increase in flexural strength due to the presence of stiffening batten plates.

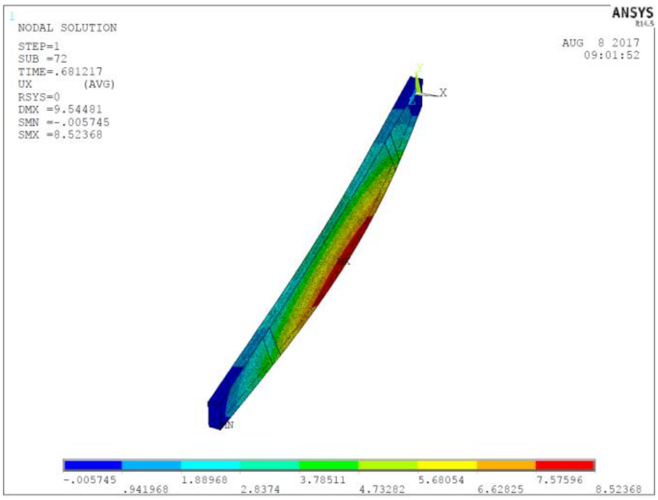


Figure (7) LTB failure mode for beam stiffened with double sided batten plates.

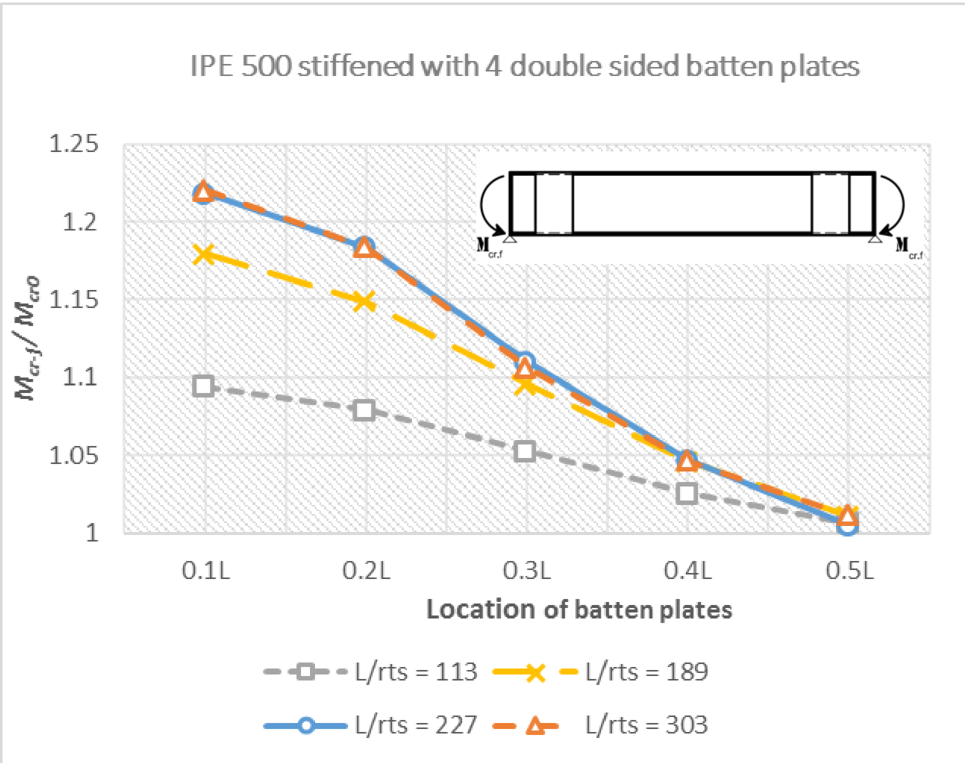


Figure (8) Effect of batten plates location on steel beam flexural strength. (W_p= L/30, t_p= 10 mm).

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 the ideal case of four batten plates as shown in Figure (6) to eighteen batten plates with an increment of 0.1L between each plate pair as shown in Figure (9). For all cases, the width and thickness of plate are kept constant with values of W_p= L/30 and t_p=10 mm.

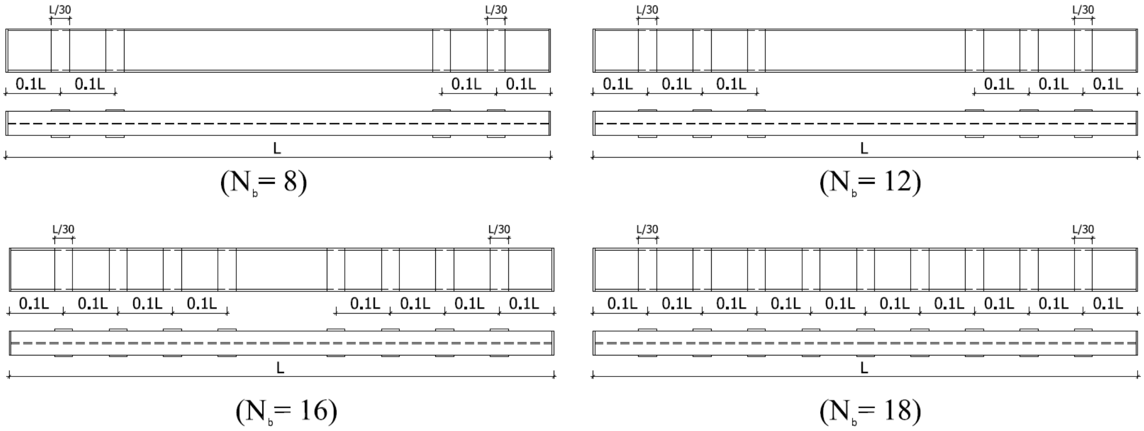


Figure (9) Variation of batten plates number along beam length

The results for the effect of varying the total number of batten plates are shown in Figure (10). It is evident from this figure that there is a significant increase of the beam flexural capacity which could reach 68% for the case of 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 shorter beam with L/r_{ts} =113.

This results prove that the batten plates are more effective for long-span beams when the elastic LTB behavior is dominant.

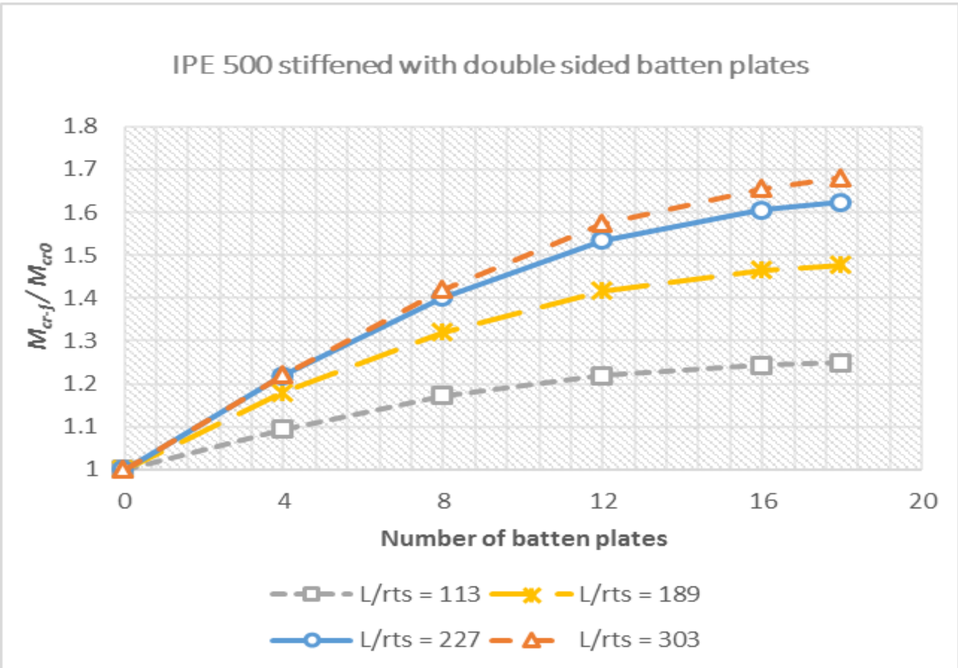
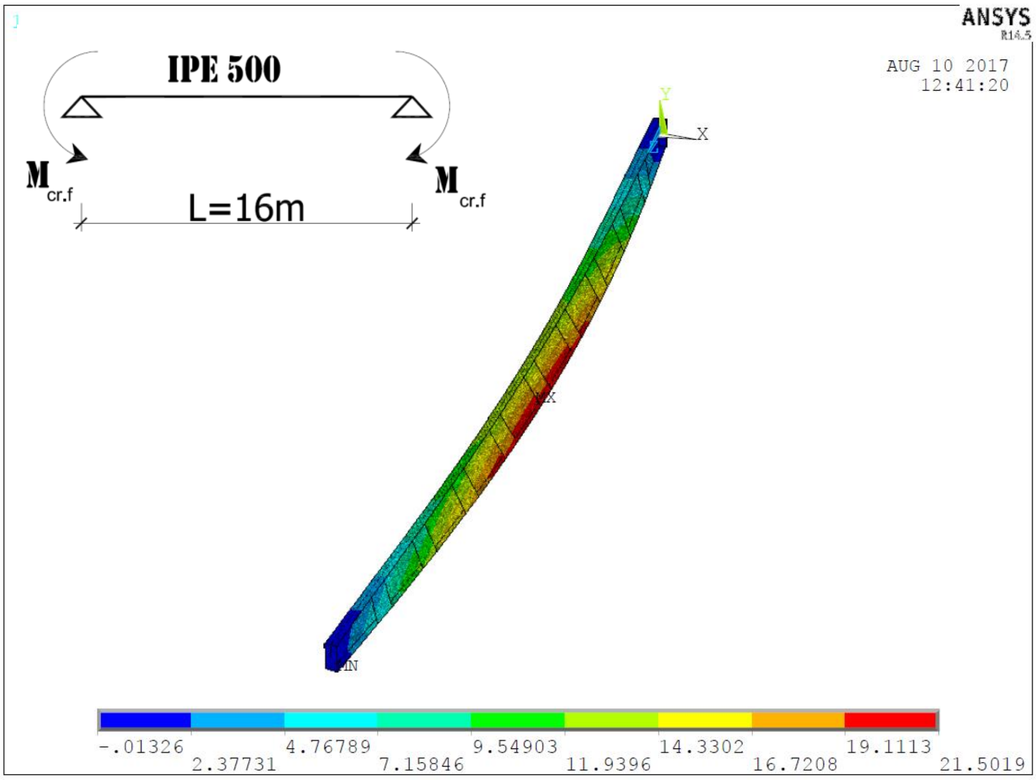


Figure (10) Effect of number of batten plates on steel beam flexural strength.



(W_p= L/30, t_p= 10 mm)

Figure (11) represents the failure mode shape for the long-span IPE500 beam stiffened with 18 double sided batten plates. This beam with the shown configuration has a flexural strength higher than the beam without batten plates by 68%. This higher value suggests that this configuration is very effective for using lighter section for the long unsupported steel beams. It is to be mentioned that despite the big strength gain for this beam However, the final flexural capacity which is 184.9 kN.m is much lesser than the yielding moment capacity of the studied beam (M_y=F_y.S_x=443.6 kN.m).

Figure (11) L.T.B failure mode for beam stiffened with
18 batten plates.
(W_p= L/30, t_p= 10 mm, L/I_y = 0.7487)

4.3 EFFECT OF WIDTH OF BATTEN PLATES (W_p)

The effect of increasing the width of the batten plates is studied in this section. This study is conducted on beam 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)..

Figure (12) shows the ratio of increase of the flexural strength against various batten plate widths. From this 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 a 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.

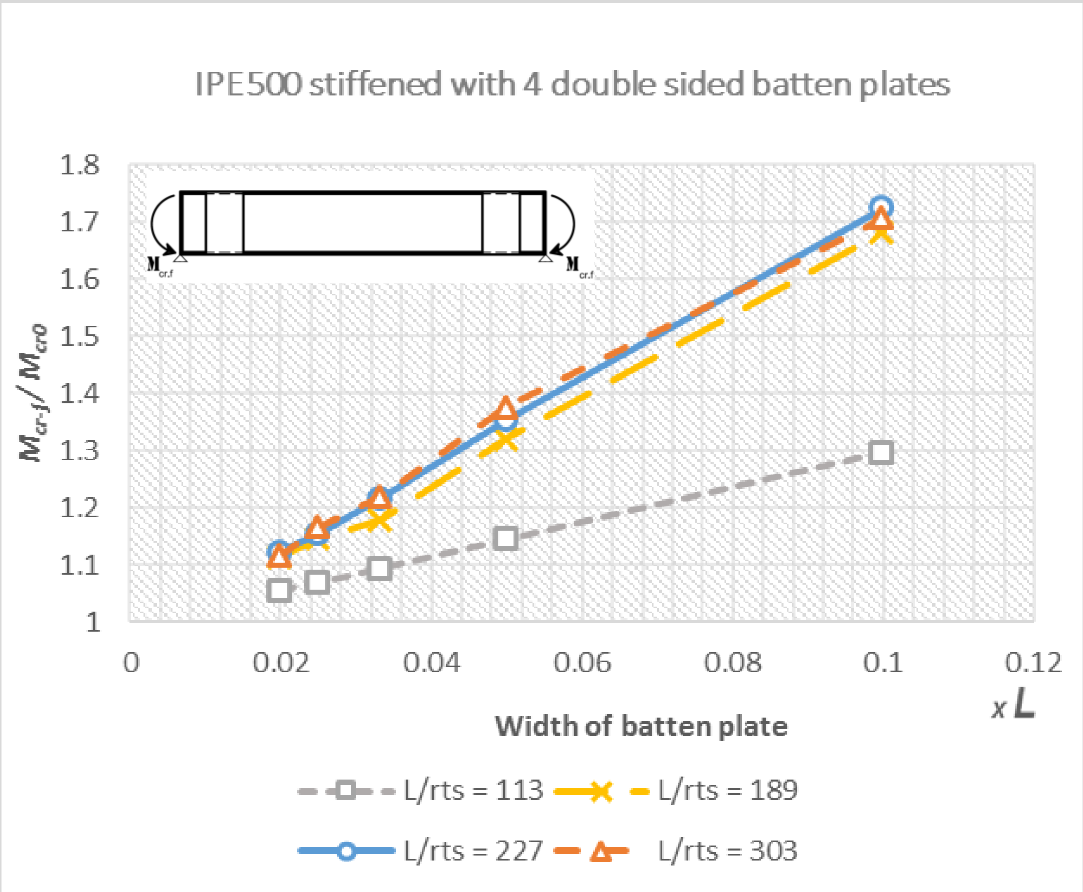


Figure (12) Effect of batten plate width on steel beam flexural strength.
(Z_{bp}=0.1L, t_p= 10 mm)

4.4 EFFECT OF THICKNESS OF BATTEN PLATES (t_p)

A practical range for batten plate thickness is investigated to study the effect of batten plate thickness. The thicknesses of batten plates investigated are from 8 mm to 16 mm with increment of 2mm. The batten plates have width of W_p= L/30 and are located at 0.1L from both beam ends.

The results for the effect of batten plate thickness are shown in Figure (13). The results for this study show that the flexural strength for the beam is slightly increased with the increase of batten plate thickness. Therefore, it is suggested to use a batten plate with minimum thickness which prevents local buckling in the batten plate itself.

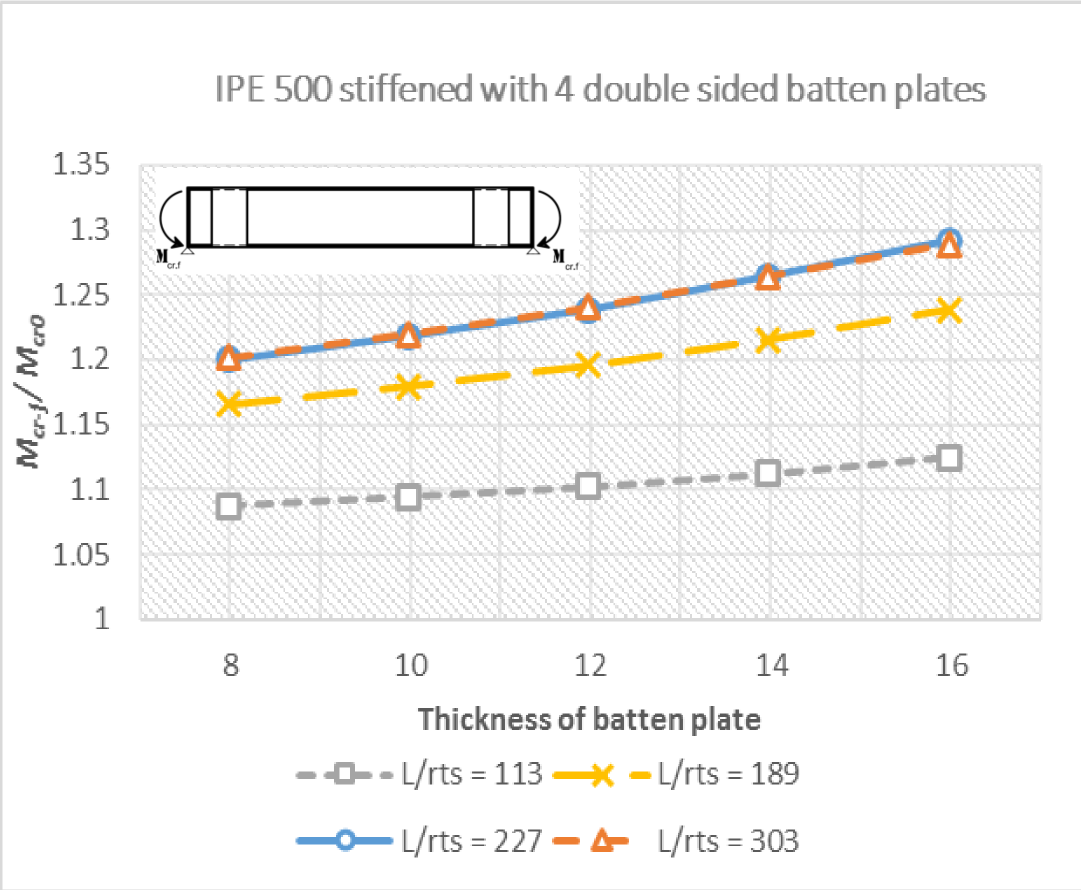


Figure (13) Effect of batten plate thickness on steel beam flexural strength.
(W_p= L/30, Z_{bp}= 0.1L)

5. 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 effect of batten plates location, number, width and thickness on the LTB strength was studied. The main conclusions of this paper can be summarized as follows:

1-The double sided batten plates have a significant effect on the lateral torsional buckling capacity of simply supported laterally unsupported steel I-beams.

2-The effect of batten plates on the flexural strength is more pronounced in the long span beams (i.e. elastic LTB).

3-The location of batten plates has a significant effect on the flexural strength and it is noticed 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 total 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 flexural strength is slightly increased with the increase of batten plate thickness. Therefore, the effect of batten plate thickness could be neglected.

6- Increasing the batten plate width leads to a significant increase in beam flexural strength.

7- The effect of batten plate width is more efficient and more effective than increasing the batten plates’ number.

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