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Estimation of web distortion effect on the elastic and plastic limiting lengths for lateral torsional buckling (LTB) through the web-strain results

Yanal burulmalı burkulma için tanımlanan elastik ve plastik sınır uzunluklarına gövde buruşmasının etkisinin gövde şekil değiştirme sonuçları ile tahmini

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Estimation of Web Distortion Effect on the Elastic and Plastic Limiting Lengths for Lateral Torsional Buckling through the Web Strain Results

Highlights

- *The elastic (L_r) and plastic (L_p) limiting lengths for LTB are determined to be greater than that obtained from the analytical formulations given in the design codes due to the influence of the web distortion.*
- *The design codes for steel structures don't consider the web distortion effects on the limiting lengths.*
- *The web distortion is predicted to lead to reducing the torsional and warping rigidity of the section.*
- *A reduction factor for the torsional and warping rigidity is recommended to determine by conducting more numerical analyses for different sections and unbraced lengths in the code.*

Graphical Abstract

Depending on the considerations for the FE modeling and the eigenvalue buckling analysis of the beam, the numerical results are summarized by plotting the ratio of the web strain to the yield ($\varepsilon_y=1.72x10^{-3}$) and to the max. strain ($\varepsilon_p=15x10^{-3}$) versus the unbraced length (L)-to-the elastic (L_r) and plastic (L_p) limiting length ratios calculated according to the formulation given in the AISC code.

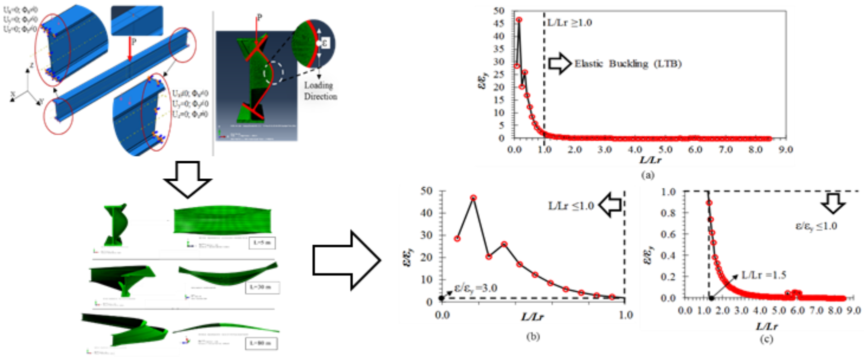

Figure 1. FEM model and the variation of the web strain with the limiting lengths for W44x335 beam

Aim

The present study is aimed to estimate the influence of the web distortion on the elastic (L_r) and plastic (L_p) limiting lengths given in the AISC code for the lateral torsional (LTB) and lateral distortional buckling (LDB) of doubly-symmetric steel I-beam.

Design & Methodology

The eigenvalue buckling analyses are performed with developing the FE models.

Originality

The influence of the web distortion on the limiting lengths for the buckling analysis of the beam is quantitavely specified in terms of the web strain results.

Findings

The web strain results are highly greater than the yield strain value when L/L_r is equal to 1.0. Hence, the elastic limiting length (L_r) is required to be considered greater than the calculated length as per the code formulation. The section is obtained to reach the max. strain value at the web before the unbraced length (L) is equal to the plastic limiting length (L_p). Therefore, the calculated L_p is estimated with the given analytical formulation to be highly shorter than the length through the FE analysis.

Conclusion

The formulations in the AISCI code for the buckling response of steel beams don't consider the influence of the web distortion. Therefore, the limiting lengths are resulted to be generally shorter than those obtained from the FE analysis. The distortion at the web is predicted to lead to reducing the torsional and warping rigidity of the section.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Estimation of Web Distortion Effect on the Elastic and Plastic Limiting Lengths for Lateral Torsional Buckling through the Web Strain Results

Araştırma Makalesi / Research Article

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ABSTRACT

The present study is aimed to estimate the influence of the web distortion on the elastic (L_r) and plastic (L_p) limiting lengths given in the American Institute of Steel Construction (AISC code) for the lateral torsional buckling behavior of steel beams. For this aim, the W44x335 beam is adopted in the buckling analyses carried out by the ABAQUS finite element (FE) program. The strain results at mid-height of the web at mid-span of the beam are taken into account as monitoring parameters. The web strain results are found highly greater than the yield strain value when L/L_r is equal to 1.0. Hence, the elastic limiting length (L_r) is required to be considered greater than the calculated length as per the code formulation. The section is obtained to reach the maximum strain value at the web before the unbraced length (L) is equal to the plastic limiting length (L_p). Therefore, the calculated L_p is estimated with the given analytical formulation to be highly shorter than the length through the FE analysis. These outcomes prove that the formulations of the limiting lengths proposed in the AISC code don't consider the influence of the web distortion that is predicted to lead to reducing the torsional and warping rigidity of the section. With the study, it is proposed to determine a reduction coefficient by performing more numerical analyzes for different cross sections and free openings in the regulation.

Keywords: Web distortion, lateral torsional buckling, elastic and plastic limiting length, finite element method.

Yanal Burulmalı Burkulma için Tanımlanan Elastik ve Plastik Sınır Uzunluklarına Gövde Buruşmasının Etkisinin Gövde Şekil Değiştirme Sonuçları ile Tahmini

ÖZ

Bu çalışmada, çelik kirişlerdeki gövde buruşmasının Amerikan çelik yapılar yönetmeliğinde yanal burulmalı burkulma için verilen elastik (L_r) ve plastik (L_p) sınır serbest boyları üzerine olan etkisinin tahmin edilmesi amaçlanmıştır. Bu amaçla, ABAQUS sonlu elemanlar (FE) programı kullanılarak yapılan burkulma analizlerinde W44x335 kirişi göz önüne alınmıştır. Kirişin orta açıklığında bulunan gövde kesitinin ortasındaki şekil değiştirme değerleri kritik kontrol parametreleri olarak dikkate alınmıştır. Kiriş serbest açıklığı (L) elastik burkulma için önerilen sınır değere (L_r) eşit olduğunda, gövde de elde edilen şekil değiştirme değerinin akma şekil değiştirmesinden oldukça büyük olduğu görülmüştür. Bu nedenle, elastik burkulma için (L_r) sınır uzunluğunun yönetmeliğin önerdiği değerden daha büyük dikkate alınmasının gerekliliği ortaya konulmuştur. Kesitin gövdede maksimum şekil değiştirme değerine kiriş serbest açıklığının (L) plastik burkulma için önerilen sınır değere (L_p) eşit olmadan önce ulaştığı sonucuna varılmıştır. Bu sebeple, yönetmeliğin plastik burkulma için önerdiği uzunluğun (L_p) sonlu elemanlar analizi ile elde edilen uzunluk değerinden çok daha küçük olacağı tahmin edilmiştir. Bu sonuçlar, yönetmeliğin yanal burulmalı burkulma için önerdiği sınır değer formüllerinde, kesitin burulma ve çarpılma rijitliklerinde azalmaya sebep vereceği tahmin edilen gövde buruşmasını dikkate almadığını göstermiştir. Yapılan çalışma ile yönetmelikte bulunan farklı kesitler ve serbest açıklıklar için daha fazla nümerik analizler yapılarak bir azaltma katsayısının belirlenmesi önerilmiştir.

Anahtar Kelimeler: Gövde buruşması, yanal burulmalı burkulma, elastik ve plastik sınır uzunluk, sonlu elemanlar yöntemi

1. INTRODUCTION

Steel beams subjected to loading in plane generally experience the characteristic modes of lateral-torsional buckling and local buckling. Lateral-torsional buckling (LTB) is pertinent to the overall slenderness of the beam, whereas the slenderness of the web and flanges directly affects local buckling (LB). In addition to the fundamental buckling modes of LTB and LB, lateral-distortional buckling (LDB) is also observed especially in the beams with intermediate length, slender web and stocky flanges. Based on the lateral-torsional buckling strength behavior of a steel beam, as shown in Fig.1, these buckling modes are identified according to the limiting unbraced lengths (L_r and L_p) or the slenderness

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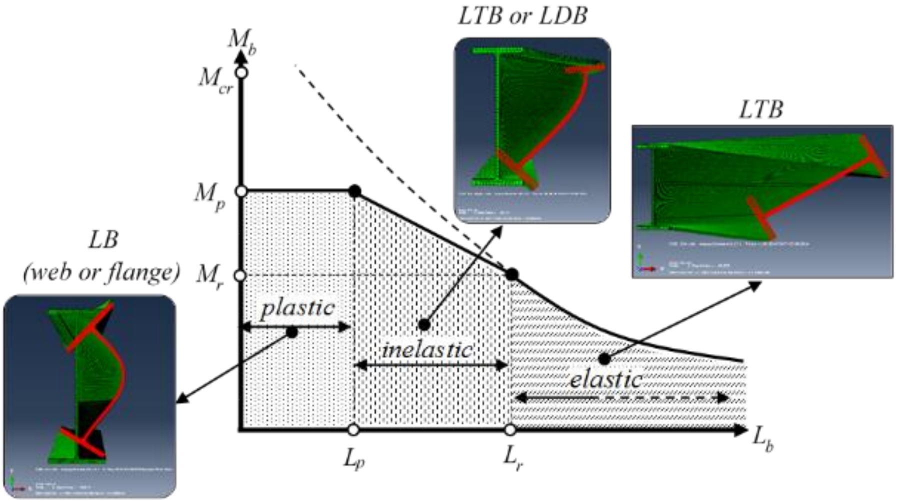


Figure 1. Buckling behavior of steel beams with I-section

parameters (λ_r and λ_p). For a short beam with the length (L_b) lower than L_p, the cross-section has full resistance, and the plastic behavior is regarded in the region where local buckling (LB) is seen, as depicted in Fig. 1. For an intermediate beam with the length of $L_p<L_b<L_r$, stability problem is seen after certain portion of the beam yielded. As revealed in Fig. 1 in the inelastic region, the beam can undergo LDB or LTB. LDB is mostly encountered in beams with slender webs, while LTB in beams with tocky webs. The last region where a beam with the length (L_b) higher than L_r shows fully flexural response is named as elastic. So, the elastic LTB problem is considered in the region. In this region, LDB is rather unlikely.

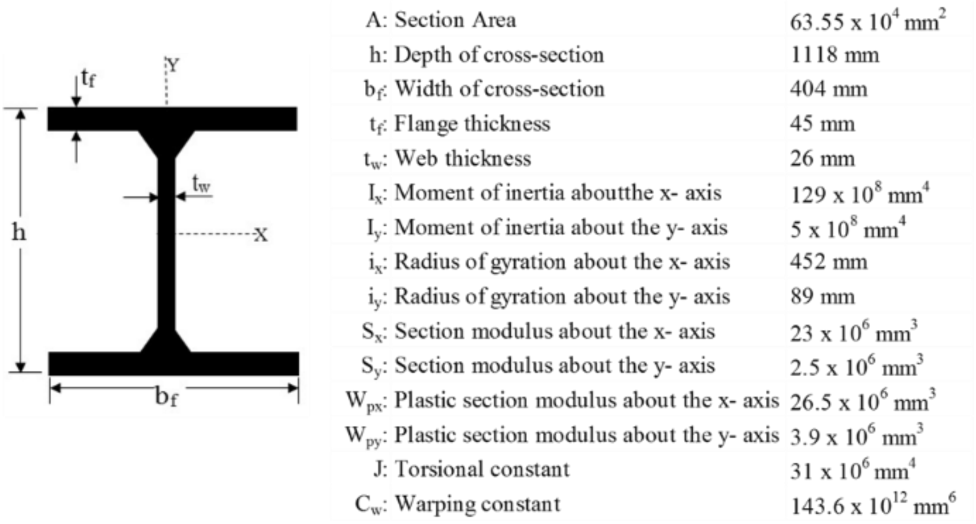
In literature of the lateral-torsional buckling behavior of steel beam, related studies seem to focus on estimation of buckling moment (M_n) separately for LB (plastic), LDB (inelastic) and LTB (elastic). In this sense, the most well-known fundamental analytical formulation was proposed in [1] for the elastic lateral-torsional buckling moment of compact steel-I beams. The formulation was originally given for uniform bending moment distribution along the span of the beam; therefore, a modification factor was defined for this formulation in [2-3]. A similar modification factor (C_b) has also been proposed and used in different versions of the AISC code. Hence, the results obtained from the formulation in [1] have still been adopted in the literature as a benchmark value to compare the accuracy of newly developed analytical solution to the elastic LTB problem.

Due to the importance of structural stability in the design stage of steel structures, various significant standards for steel structures [4-6] paid attention to developing formulations for the LTB capacities of steel beams. According to the assumptions made in these standards, the elastic LTB moment capacity of a beam varies according to the standard. For example, geometrical imperfection is considered in Eurocode-3 (EC3) [5] whilst the formulation proposed in [4] does not include this effect. Therefore, the AISC code predicts lower elastic LTB moment than the other important standards [5-6]. To understand the assumption and limitations in the standards, many detailed investigations have been carried out in literature. Among some of the previously conducted studies, general stability design criteria for steel structures were presented in [3] and [7-9], which explains fundamental parameters of LTB behavior of beams. Besides, some recommendations to be considered in future were stated in these studies. One of recent studies in the literature on LTB of steel beams was conducted by Galambos [10]. In this study, various important information was summarized for practical applications and concepts of LTB for practicing engineers. More specific detailed studies on LTB were done in [11-15]. In these studies, the effects of geometric imperfection, boundary and loading conditions were determined by using numerical and analytical methods that also considers the sensitivity analysis.

The present study is aimed to estimate the influence of the web distortion on the elastic (L_r) and plastic (L_p) limiting lengths given in the AISC code [4] for the lateral torsional buckling behavior of steel beams. For this aim, the W44x335 beam is adopted in the buckling analyses carried out by the ABAQUS [16] finite element (FE) program. The strain results at mid-height of the web at mid-span of the beam are taken into account as monitoring parameters.

2. PREFERENCES OF THE CONSODIRED BEAM

The W44x335 section is only adopted in the eigenvalue buckling analysis since it is marked as the highest and the slenderest beam in [4]. It is also thought that the influence of web-distortion on the limiting lengths (L_r and L_p) can be easily observed in the most critical section of W44x335. The general sectional view and details are given in Fig. 2. The material properties of A992F_y50 commonly-used section for structural steel elements in the US are considered in the numerical analysis and the calculation of the limiting lengths. It is a structural steel



A: Section Area	63.55×10^4 mm^2
h: Depth of cross-section	1118 mm
b_f: Width of cross-section	404 mm
t_f: Flange thickness	45 mm
t_w: Web thickness	26 mm
I_x: Moment of inertia aboutthe x- axis	129×10^8 mm^4
I_y: Moment of inertia about the y- axis	5×10^8 mm^4
i_x: Radius of gyration about the x- axis	452 mm
i_y: Radius of gyration about the y- axis	89 mm
S_x: Section modulus about the x- axis	23×10^6 mm^3
S_y: Section modulus about the y- axis	2.5×10^6 mm^3
W_{px}: Plastic section modulus about the x- axis	26.5×10^6 mm^3
W_{py}: Plastic section modulus about the y- axis	3.9×10^6 mm^3
J: Torsional constant	31×10^6 mm^4
C_w: Warping constant	143.6×10^{12} mm^6

Figure 2. Sectional parameters of W44x335 beam

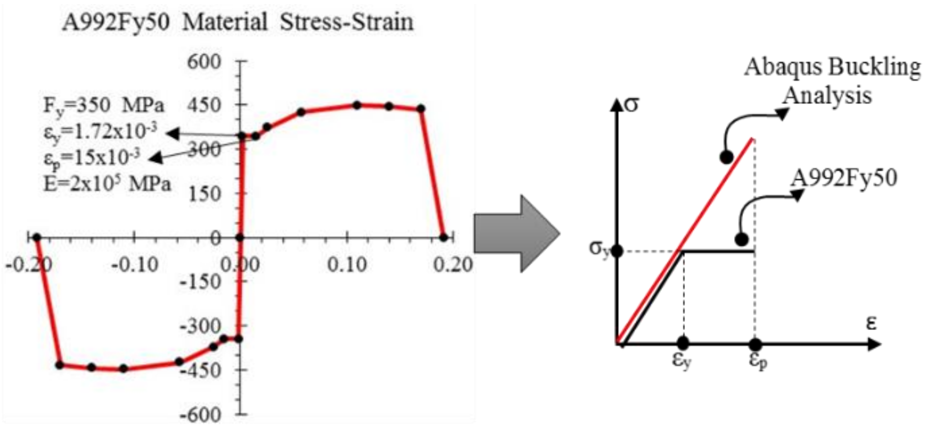


Figure 3. Material considerations

alloy, which has a high-strength, corrosion resistance and low-alloy content as well. The max. carbon percentage of the material is 0.23%, and the rest of them are small additions of vanadium or columbium, copper, nickel, chrome, and molybdenum. Details for the material are presented in Fig. 3.

Due to fact that the eigenvalue buckling analysis considering the requirements of the linear analysis is carried out, instead of the non-linear branches of the σ-ε curve, the ABAQUS [16] finite element (FE) software only requires the linear branch of the curve, as depicted in Fig. 3. To show the effect of web-distortion on the elastic (L_r) and plastic (L_p) limiting lengths, the yield strain values, ε_y=1.72x10^{-3}, and the max. strain value, ε_p=15x10^{-3}, are also utilized, as indicated in Fig. 3.

3. THE UNBRACED LENGTHS OF W44X335 BEAM

The unbraced lengths of W44x335 beam are specified according to the analytical formulations of Eq. (1) and Eq. (2), as given below for the elastic (L_r) and plastic (L_p) limiting lengths, respectively. These equations are the design provisions of the AISC code [4] for the lateral torsional buckling of flexural members in steel structures. Except for the AISC code [4], the other important codes [5-6] for the design of steel structures don't propose a limiting length for the buckling analysis of flexural members. Thus, the AISC code [4] standard is only regarded in the present study. These limiting lengths are practically useful for the estimation of the elastic and plastic behavior of steel I-beams, but they should be investigated in detail by regarding the distortion effect.

$$r_{ts} = \frac{b_f}{\sqrt{12 \cdot \left(1 + \frac{1}{6} \cdot \frac{h \cdot t_w}{b_f \cdot t_f}\right)}} \tag{1}$$

$$L_r = 1.95 \cdot r_{ts} \cdot \frac{E}{0.7 \cdot F_y} \cdot \sqrt{\frac{J \cdot c}{S_x \cdot h_o}} \cdot \sqrt{1 + \sqrt{1 + 6.76 \cdot \left(\frac{0.7 \cdot F_y}{E} \cdot \frac{S_x \cdot h_o}{J \cdot c}\right)^2}}$$

$$L_p = 1.76 \cdot r_y \cdot \sqrt{\frac{E}{F_y}} \tag{2}$$

Utilizing these equations, the elastic (L_r) and plastic (L_p) limiting lengths are calculated as L_r=11.84 m and L_p=3.76 m, respectively. Based on these results, different unbraced lengths from 1.0 m to 100 m adopted in the eigenvalue buckling analysis to sensitively observe the variation of the web strain results with them.

4. NUMERICAL MODELING CONSIDERATIONS (FEM)

The W44x335 beam is numerically modeled with solid elements through ABAQUS [16] FE software. Solid element of C3D20R type having 20-node quadratic brick and reduced integration properties are defined for the FE models. The free meshing method is utilized with the mesh geometry of quadratic. The reason of selecting this method is to have the ability to mesh arbitrary geometries with quadratic tetrahedral and triangular elements. Based on the convergence analysis that gives the optimum mesh size, the element size is obtained less than 10 mm for the buckling analysis.

Loading and support conditions at both ends are other critical issues for reliably calculating the elastic LTB moments. In the current study, simply-supported beam conditions are adopted for the beams since most of the experimental studies on the LTB moment prediction in literature [17] were conducted under these conditions. As shown in Fig. 4(a), both ends are restrained against vertical and lateral displacements; however, longitudinal displacement of one end is not allowed by assigning displacement restraint in this direction to the bottom flange at the pinned support location while the other support is considered as free in the longitudinal direction of the beam. The eigenvalue buckling analysis is also performed with the concentrated single load at mid-span of the beam at top of the section. Besides, the warping effect on the LTB moment value is prevented by assigning no rotation support conditions to both end sections. Details are schematically shown in Fig. 4(a).

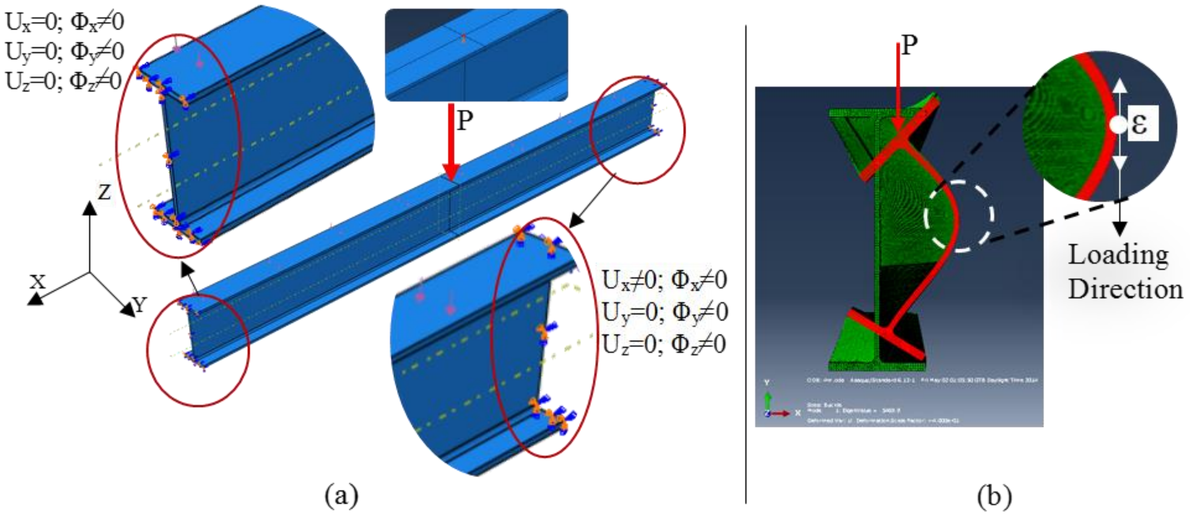


Figure 4. (a) Support and loading conditions (b) Web strain calculation

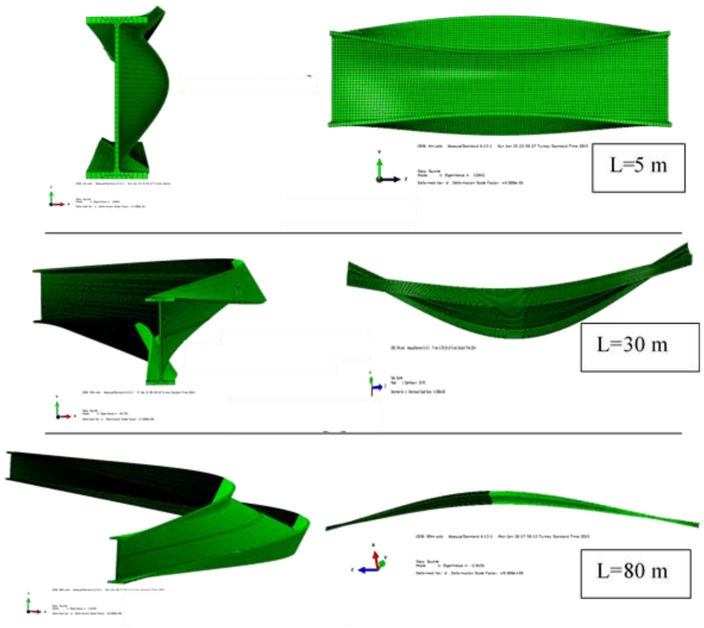


Figure 5. General views of 3D FE models for some of the beams with their 1st buckling modes

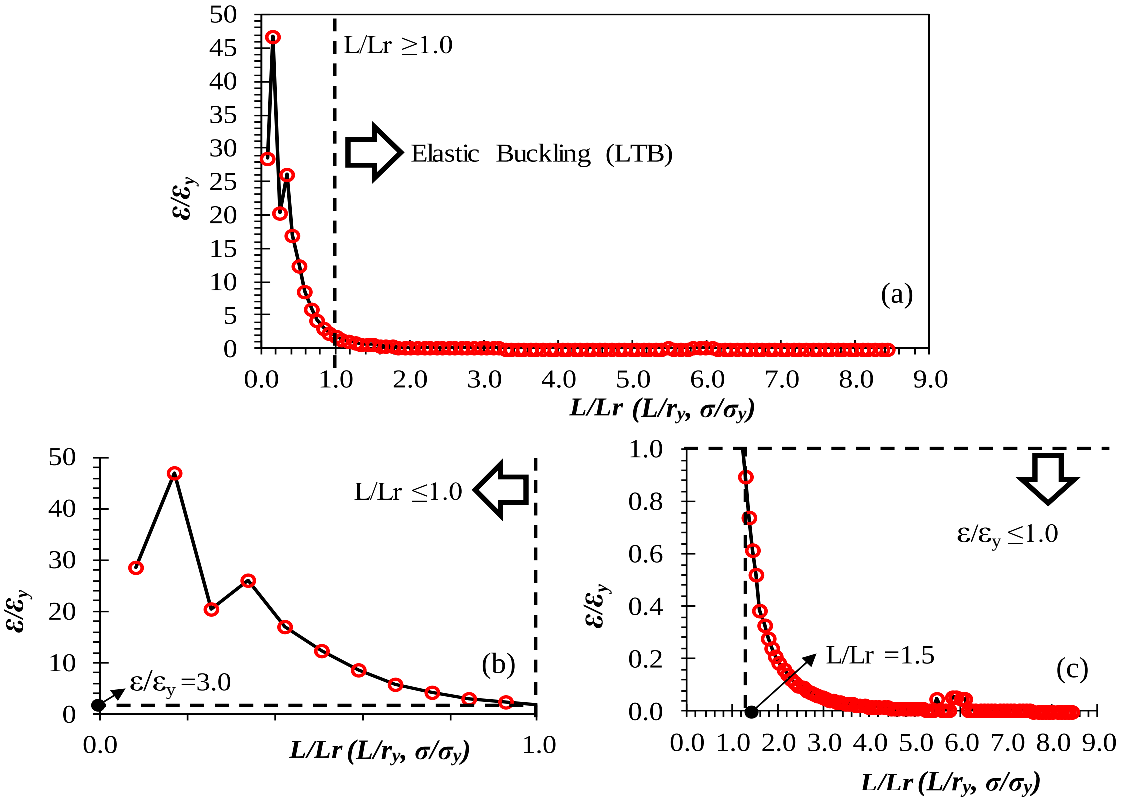


Figure 6. (a) Variation of $\varepsilon/\varepsilon_y$ with L/L_r (b) variation for $L/L_r \leq 1.0$ (c) variation for $\varepsilon/\varepsilon_y \leq 1.0$

In this study, the web strain results at mid-height of the section at mid-span of the beam are taken into account as an effective parameter to estimate the influence of the web-distortion on the L_r and L_p given in [4]. As indicated in Fig. 4(b), the web strain results where the max. curvature at the web are obtained in the loading direction (transverse) for each unbraced length. Thus, the 3D FE models of the beam are developed, as shown in Fig. 5 with the 1st buckling modes of some of the beams having the unbraced lengths of 5 m, 30 m, and 80 m.

5. ANALYSIS RESULTS

Depending on the considerations for the FE modeling and the eigenvalue buckling analysis of the beam, the numerical results are summarized by plotting the ratio of the web strain to the yield (ε_y=1.72x10^{-3}) and to the max. strain (ε_p=15x10^{-3}) versus the unbraced length (L)-to-the elastic (L_r) and plastic (L_p) limiting length ratios calculated according to the formulation given in Eqs. (1-2) [4].

As seen in Fig. 6(a), the variation of $\varepsilon/\varepsilon_y$ with L/L_r clearly reveals that the web strain results relatively exceed the yield strain value when the ratio of L/L_r is equal to 1.0. This finding is detailed more in Fig. 6(b) and Fig. 6(c) to quantitatively estimate the influence of the web distortion on the lengths of L_r and L_p. According to the variation of $\varepsilon/\varepsilon_y$ with L/L_r for $L/L_r \leq 1.0$, as indicated in Fig. 6(b), the strain web results reaches to three times of the yield strain value for the given elastic limiting length (L_r). This means that the web may be totally distorted for the length of L_r, and that inelastic buckling (LDB) governs the behavior for the length of L_r that is given for the elastic buckling (LTB) in the code. This outcome is also supported with the obtained ratio of L/L_r =1.5 when the first yielding starts ($\varepsilon/\varepsilon_y$ =1.0), as shown in Fig. 6(c). Therefore, greater elastic limiting length (L_r) should be considered due to the effect of the web distortion.

In order to determine the influence of the web distortion on the length of L_r, the variation of $\varepsilon/\varepsilon_p$ with L/L_r is also shown in Fig.7. This variation, as seen in Fig. 7(a), proves that the web distortion is highly effective on the length of L_r since the ratio of $\varepsilon/\varepsilon_p$ is obtained greatly as 0.4 for the elastic limiting length (L_r). This result, as demonstrated in Fig. 7(b), underlines clearly that the web strain results is about to reach the max. strain value (ε_p) for the elastic limiting length (L_r) instead of the plastic limiting length (L_p). The conclusion reveals again that the formulation given in [4] for elastic limiting length (L_r) does not include the web distortion. According to these results, the elastic limiting length should be taken greater than L_r to be able to observe the elastic buckling behavior, as clearly shown in Fig. 7(c).

Similar demonstration is also given in Fig. 8 for the variation of $\varepsilon/\varepsilon_p$ with L/L_p. When the unbraced length is equal to L_p, the strain results at mid-height of the web are obtained three times greater than ε_p, as depicted in Fig. 8(b). This is an evidence that the max. strain (ε_p) is first observed for the unbraced length greater than L_p that is calculated according to the ASIC code [4]. As shown in Fig. 8(c), this unbraced length (L) is obtained as 2.0L_p for the strain ratio of $\varepsilon/\varepsilon_p$ =1.0.

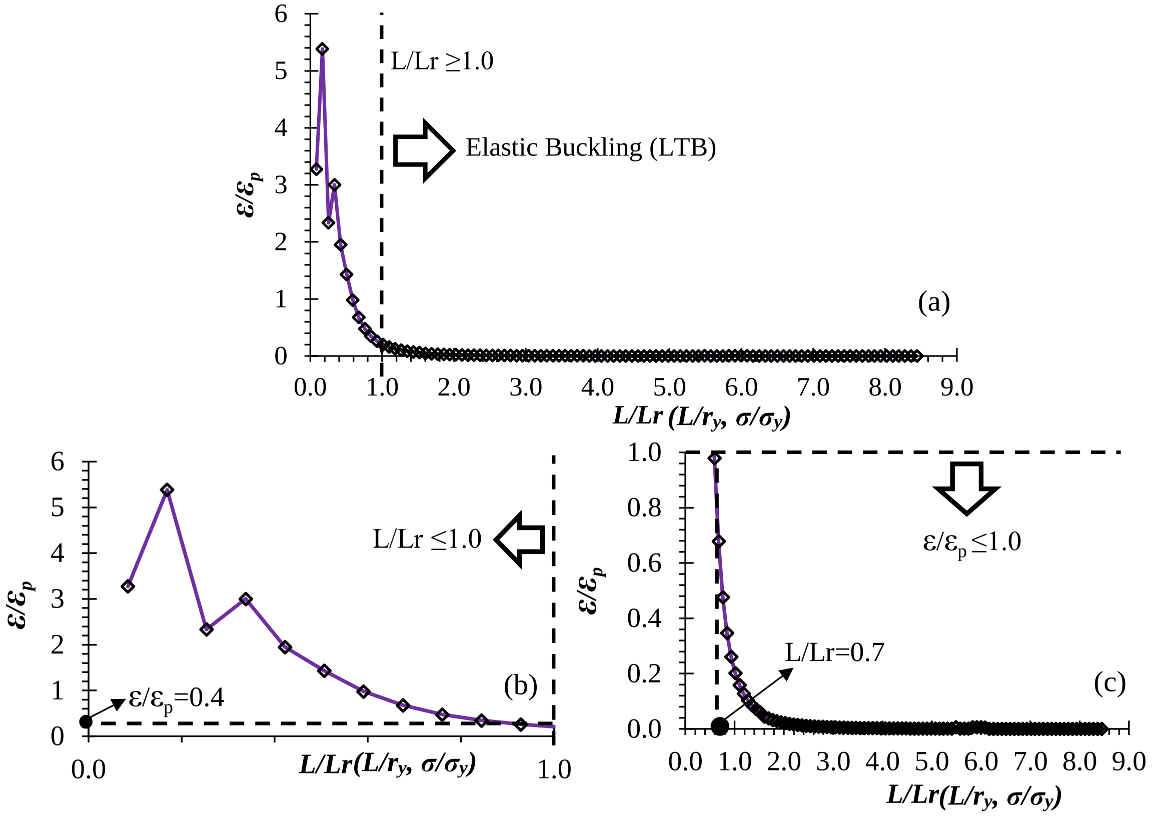


Figure 7. (a) Variation of $\varepsilon/\varepsilon_p$ with L/L_r (b) variation for $L/L_r \leq 1.0$ (c) variation for $\varepsilon/\varepsilon_p \leq 1.0$

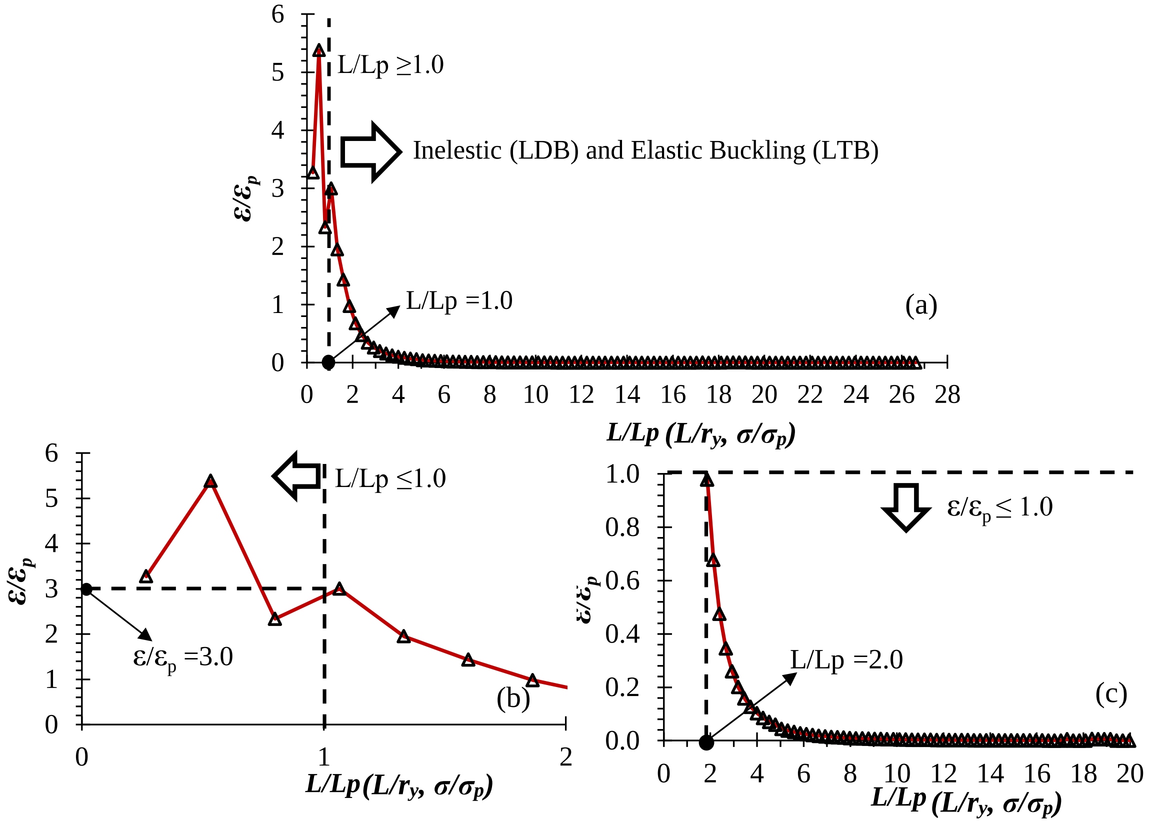


Figure 8. (a) Variation of $\varepsilon/\varepsilon_p$ with L/L_p (b) variation for $L/L_p \leq 1.0$ (c) variation for $\varepsilon/\varepsilon_p \leq 1.0$

Therefore, it is readily clear that the limiting length formulations given in the AISC code [4] don't consider the effects of the web distortion, and they should be updated based on the preliminary conclusions of the study. For example, the coefficients on the formulation (Eq.1 and Eq. 2) can be updated by doing more numerical parametric analyses. Another potential reason can also be a decrease in the torsional and warping rigidity of the section due to the web distortion.

6. CONCLUSIONS AND RECOMMENDATIONS

The present study is aimed to estimate the influence of the web distortion on the elastic (L_r) and plastic (L_p) limiting lengths given in the code of the AISC code for the lateral torsional (LTB) and lateral distortional buckling (LDB). For this aim, the W44x335 beam is adopted in the buckling analyses. The strain results at mid-height of the web at mid-span of the beam are taken into account as monitoring parameters to understand the influence of the web distortion on the length of L_r and L_p. Thus, the results are presented through the variation of the ratio of the web strain to the yield (ε_y=1.72x10^{-3}) and the max. strain (ε_p=15x10^{-3}) with the unbraced length (L)-to-the elastic (L_r) and plastic (L_p) limiting length ratios. Depending on the results, the following critical points are underlined in the study.

- The web strain results are highly greater than the yield strain value when L/L_r is equal to 1.0. This also means that the elastic limiting length (L_r) is required to be considered greater than the calculated length as per the code for the elastic buckling behavior (LTB).
- When the strain value is equal to the max. strain, the unbraced length (L) is almost obtained to be equal to the elastic limiting length (L_r). This finding also demonstrates that the formulation given in the AISC code for the elastic limiting length calculates shorter L_r length not to consider the web distortion in its current form.
- The section is obtained to reach the max. strain value at the web before the unbraced length (L) is equal to the plastic limiting length (L_p). This conclusion means that the calculated L_p is estimated with the given analytical formulation to be highly shorter than the length through the FE analysis considering the distortion of the web.
- The web strain results clearly prove that the formulations of the limiting lengths proposed in the AISCI code for the buckling response of steel beams don't consider the influence of the web distortion. Therefore, the limiting lengths are resulted to be generally shorter than those obtained from the FE analysis.
- The distortion at the web is predicted to lead to reducing the torsional and warping rigidity of the section. Therefore, a reduction factor is recommended to obtain by doing more numerical analyses for different sections and unbraced lengths in the code.

SYMBOLS AND ABBREVIATIONS

c: coefficient of sectional symmetry (c=1.0 for doubly-symmetric I-beams)
E: the modulus of elasticity of steel (200 GPa)
F_y: the yield stress (275 MPa)
h_o: the distance between the flange centroids
I_y: moment of inertia about the y (minor) axis
J: the torsional constant
r_{ts}: effective radius gyration of the section (mm)
r_y: radius gyration of the section about y axis (mm)
S_x: the elastic section modulus with respect to the horizontal principal axis

DECLARATION OF ETHICAL STANDARDS

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Selcuk Bas: Developed the concept, established numerical FEM model, performed the analyses, investigated the analysis results, prepared, wrote and edited the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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