The Influence of Web Distortion of Doubly-Symmetric Steel I-Beam on Elastic and Plastic Slenderness Limits

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Abstract Lateral buckling of steel girders with slender webs and stocky flanges are accompanied by distortions in the web, known as lateral distortional buckling (LDB). These distortions result in reductions in the torsional and warping rigidities of the girders and cause them to buckle at moments below that calculated from lateral torsional buckling (LTB) formulations, neglecting the web distortions. Based on these considerations for estimating the LDB moments of doubly-symmetric steel I-beam in both elastic and inelastic ranges of buckling, the present study aims at developing elastic and plastic slenderness limits for the beam. These limits provide to use the right formula among the elastic and inelastic LDB equations. For this purpose, a numerical study was conducted to determine LDB moments of doubly-symmetric steel I-beam for varying unbraced lengths. For all these works, the ABAQUS finite element program was utilized. In the finite element analysis, distributed loads were acted on flange of the beam, and roller supports was assigned to one end of the beam providing simple support conditions in and out of plane while for the other end pinned boundary conditions were defined. The present analyses indicated that the web distortions, which are usually accounted for in the inelastic range of lateral torsional buckling, also affect the buckling behavior of steel I-beams in the elastic range. The elastic and inelastic limiting unbraced lengths of steel beams were found not to comply with the buckling behavior in the presence of web distortions.

1 Introduction

Structural stability is one of the most important issue for slender structures. Steel structures are more prone to stability problem than concretes structures due to thin

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dimensions. Stability problems are related to not only overall slenderness but also sectional slenderness of a component of steel structure. As shown in Fig.1, steel I-beams loaded in plane are faced with lateral torsional (LTB), distortional buckling (DB) and lateral distortional buckling (LDB), which is the combination of LTB and DB. In LTB, the beam shows flexural behavior along its span, and rigid body

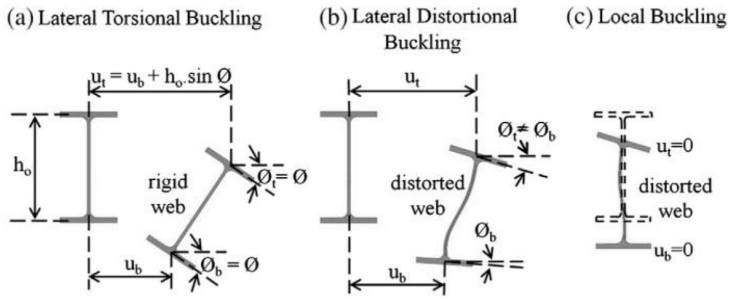

Fig.1. Typical buckling modes of I beam [13]

motion, in which translation and rotation are same, is seen at the cross-sections of the beam. Distortional buckling stems from the local buckling of the web that is more slender than the flanges in almost all I-beams. Due to larger deformation of the web, the flanges have different twist angle and lateral translation. Therefore, the presence of DB in the beam leads to reducing torsional rigidity, the resistance to buckling and thus loading capacity of the beam [1]. In literature, various experimental and numerical studies were conducted for buckling of steel I-beams [2-7]. The stress level in elastic DB was obtained considerably lower than that in elastic LTB [2]. Considering different loading cases, elastic buckling modes of I-beams were determined by proposing theoretical approach [3]. The derived equations in that study enabled to predict lateral distortional buckling modes. The effects of distortion on buckling behavior were also investigated in [4, 5] performing finite element-FE analysis. The developed FE models in those studies showed a good performance on estimating distortion effects. The FE analyses results from [5] were compared with the test data considering the plotting concepts proposed in [6, 7].

In addition to research studies, design codes [8-12] also proposed the provisions for LTB and DB. Although torsional and warping rigidity were stated to be reduced by DB, certain formulations were not presented in the codes. In some of the recently published studies [13, 14], a formulation was developed to predict the reduced moment capacity of I-beam considering the reduction in torsional and warping rigidity.

In the present study, the effects of web distortion on slenderness limit of doubly symmetric I-beam were investigated depending on the results from the numerical analysis. For this objective, W44x335 I-beam more prone to buckling than the other sections was considered. For all these works, the finite element program ABAQUS [15] was utilized. Transverse strain values at mid-span of the beam at mid-height of the web were obtained to understand the distortional of the web. The variation of the strain values with the different unbraced lengths of the beam were presented.

2 General description of W44x335 I beam

The W44x335 steel I-beam is more susceptible to LTB, LB and LDB than the other W sections. The beam with stock flanges and slender web is one of the critical sections given in AISC-LRFD [10] for buckling. Considering these specifications of the beam, W44x335 was selected to be utilized in the finite element analysis. General views from the beam are indicated in Fig. 2.

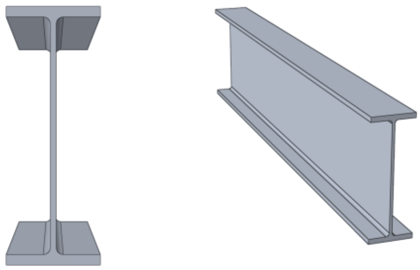

Fig. 2. General views from W44x335

3 Finite element modeling of the beam

For the finite element analysis, 3-D solid element with 8-nodes was assigned to the beam as indicated in Fig. 3a. Meshing size was determined after a set of analysis. In order to perform lateral torsional buckling analysis, uniform distributed load was defined and was acted on the top flange of the beam. Roller support condition was assign to one end of the beam whereas the other end was restrained with pinned boundary conditions. In addition, twisting rotation was not allowed for both ends to readily observe distortion of the web. These considerations are illustrated in Fig. 3b. So as to obtain the elastic and plastic slenderness limits, different unbraced lengths of the beam ranging from 1.0 m to 100.0 m with the same increment of 1.0 m. were taken into account. In all analyses, A992Fy50 structural steel model with yielding stress of 50 ksi (345 MPa) was used.

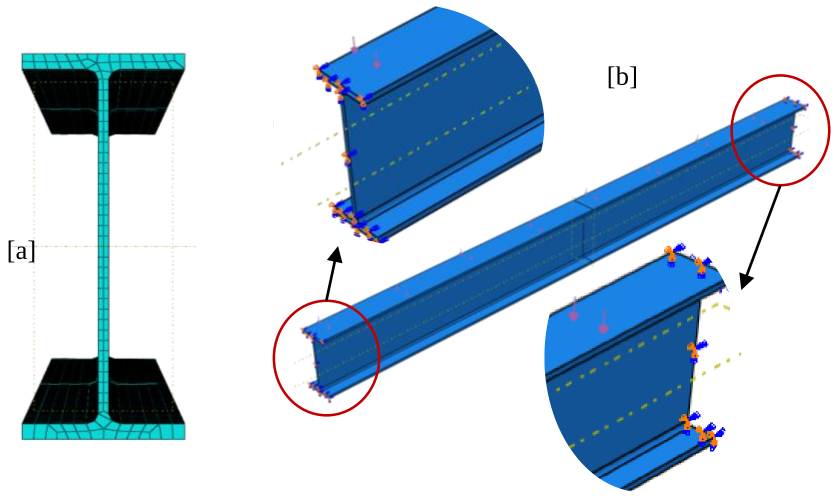

Fig. 3 FE modeling considerations

4 Analysis results

Considering the efforts for FE modeling, buckling analysis was conducted for various lengths of the beam. The eigen values and associated mode shapes were determined. The beams were then loaded with their corresponding eigen values representing uniformly distributed load on the top flange of the beam. The representative outcomes are depicted in Fig. 4 for the length of 5 m, 30 m and 80 m of the beam.

In order to identify the influences of the web distortion, transverse strain at mid-span of the beam at mid-height of the web were also obtained. The variation of the strain values normalized by yield strain (ε_y) with length of the beam normalized by elastic and plastic buckling limits (L_r and L_p) calculated from Eq.1 and Eq. 2 given in AISC-LRFD [10] are revealed in Fig. 5 and Fig. 6. As shown in the figures, certain peaks were obtained for the beams with the length below 5 m. These outcomes stem from buckling mode shifting from local to distortional over a short distance.

$$L_p = 1.76 r_y \sqrt{\frac{E}{fy}} \tag{1}$$

$$L_r = 1.95 \times r_{ts} \times \frac{E}{0.7 \times f_y} \times \sqrt{\frac{J \times c}{S_x \times h_0}} \times \sqrt{1 + \sqrt{1 + 6.76 \times \left(\frac{0.7 \times f_y}{E} \times \frac{S_x \times h_0}{J \times c} \right)^2}} \tag{2}$$

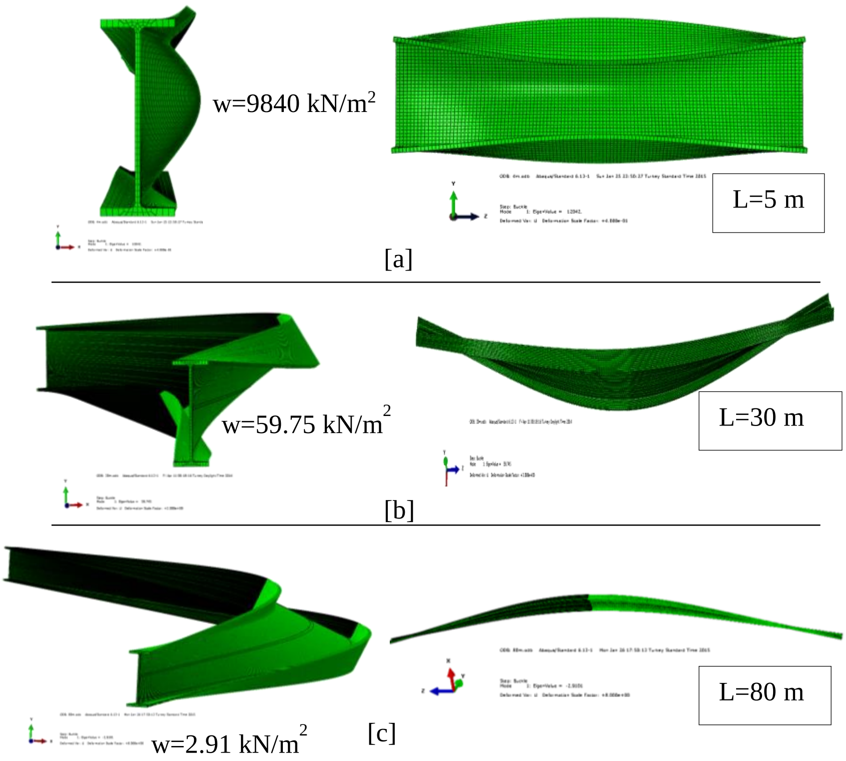

Fig. 4 Buckling analysis results of W44x335.

5 Results and conclusions

The lateral distortional buckling behavior of doubly-symmetrical steel I-beams were investigated numerically in the present study. For this purpose, the American wide-flange section W44x335 was adopted in the analyses, since this section was stated to have a slender web in the code when the beam is of grade 50 ksi (345 MPa). The transverse strain values at mid-span of the beam at mid-height of the web were compared for different unbraced beam lengths. The transverse strain in the web is an indicator of web distortions during lateral buckling since these distortions result in the bending of the web about the longitudinal beam axis.

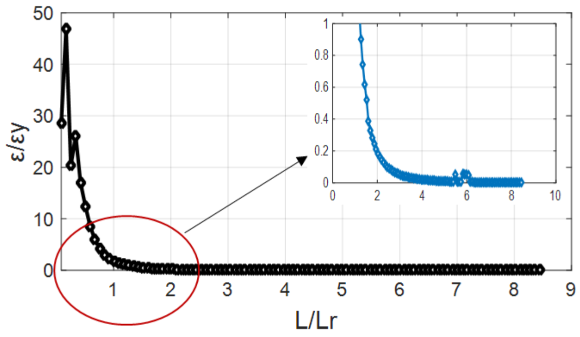

Fig. 5 The variation of $\varepsilon/\varepsilon_y$ with L/L_r

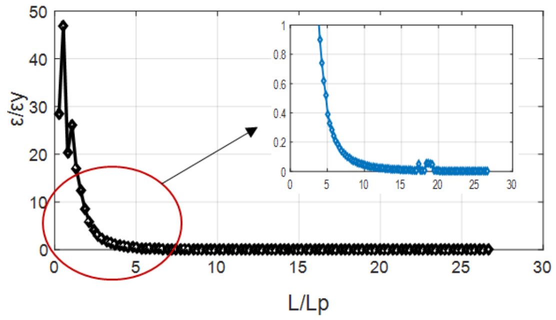

Fig. 6 The variation of $\varepsilon/\varepsilon_y$ with L/L_p

The analysis results indicated that the transverse strains in the web influence the buckling behavior of the beam up to four times the elastic limiting unbraced length of the section, calculated according to the AISC-LRFD [10] code. Beyond four times the elastic unbraced length, the transverse strains in the web, i.e. the web distortions, become negligible and the buckling behavior turns into pure lateral torsional buckling. The web distortions are generally considered to be influential in the inelastic range of buckling. Nevertheless, the results of the present analyses showed that the distortions cannot be ignored in the elastic range of lateral buckling unless the unbraced length is substantially greater than the elastic limiting value. The transverse strain in the web was found to be as great as the yielding strain of steel when the unbraced length of the beam is in the order of the elastic limiting length and about five times the plastic limiting length. The web distortions, which are associated with the local web buckling and lateral distortional buckling modes of failure of a beam, can only be ignored when the unbraced length is more than four and ten times the elastic and plastic limiting length values of the section, respectively. The plastic and elastic limiting unbraced lengths of the codes were found to ignore the web distortions. These limits need to be revised in further studies based on distortional buckling, since a steel beam expected to undergo elastic lateral torsional buckling can reach yielding under the effect of web distortions. However, it should be noted that the section analyzed in the present study already holds a web slenderness according to the AISC manual. Repeating these analyses for different sections, whose webs are not given as slender or non-compact in the manual, will be beneficial to derive further conclusions.

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