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Distortional lateral torsional buckling of beam-columns including pre-buckling deformation effects

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ABSTRACT

The present study develops a unified distortional lateral torsional buckling finite element formulation for the elastic analysis of beam-columns with wide flange doubly symmetric cross-sections. The solution captures several non-conventional features including the softening effect due to web distortion, the stiffening effect induced by pre-buckling deformations, the pre-buckling nonlinear interaction between strong-axis moments and axial forces, the contribution of pre-buckling shear deformation effects, the destabilizing effects due to loads being offset from the shear centre, and the presence of transverse stiffeners on web distortion. In the present theory, it is possible to evoke/suppress any combination of features and thus isolate the individual contribution of each effect or quantify the combined contributions of multiple effects. The effects of beam span-to-depth, flange width-to-thickness, web height-to-thickness, and flange width-to-web height ratios on the critical moments are investigated. Comparisons with conventional lateral torsional buckling solutions that omit distortional and pre-buckling effects quantify the influence of distortional and/or pre-buckling deformation effects. The theory is also used to investigate the influence of P-delta effects of beam-columns subjected to transverse and axial forces on their lateral torsional buckling. The solution is adopted to quantify the beneficial effects of transverse stiffeners in controlling/suppressing web distortion in beams.

1. Introduction and motivation

Lateral torsional buckling (LTB) solutions for beams with wide-flange cross-sections are commonly based on the Vlasov thin-walled beam kinematic assumption that, throughout buckling, a given cross-section moves within its own plane laterally and undergoes twisting rotation as a rigid disk (Fig. 1a) as it displaces from the position of buckling onset to the buckled configuration. The Vlasov assumption neglects possible distortional deformations of the web within the plane of the cross-section (Fig. 1b) and thus over-predicts the lateral torsional buckling capacity. While distortional effects may be small in some cases, past studies (Section 2.1) have shown that distortional effects gain significance in beams with slender webs, stocky flanges, and/or shorter spans. In such situations, the omission of web distortion leads to grossly over-estimating the lateral torsional buckling capacity of the member.

Also, while all conventional lateral torsional buckling solutions and commercial finite element software account for the pre-buckling stresses induced in the member in going from the un-deformed configuration to the position of buckling onset, most solutions omit the associated pre-buckling deformation (PBD) and curvature, by assuming that the member is approximately straight at the onset of buckling. Past studies (Section 2.2) have shown that pre-buckling deformations induce a beneficial stiffening effect, i.e., the omission of pre-buckling deformation leads to under-predicting the lateral torsional buckling capacity of members.

As will be discussed in Section 2.1, some lateral torsional buckling solutions have captured the web distortion effects alone while others (Section 2.2) have accounted for pre-buckling deformation effects alone. To the authors' knowledge, no solutions have captured the combined effect of web distortion and pre-buckling deformation. The subject is thus the focus of the present study. The present study thus develops a unified lateral torsional buckling solution that captures multiple effects including (1) web distortion, (2) pre-buckling deformation, (3) pre-buckling interaction effects between axial loads and strong-axis bending including P-delta effects through a geometric non-linear analysis, (4) pre-buckling shear-deformation effects, and (5) the destabilizing effects due to load offset from the shear centre. While, by default, the present solution captures all effects combined, methodologies were developed to suppress/evoke any combination of features as needed.

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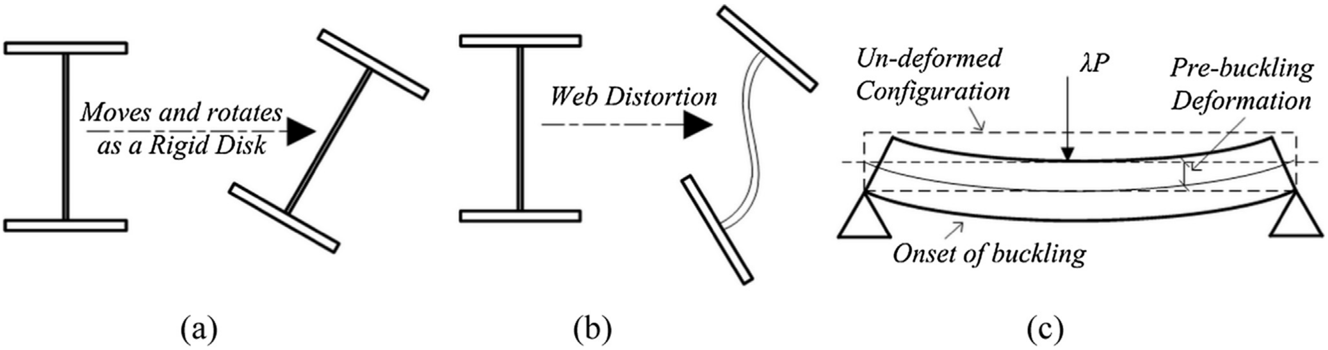

Fig. 1. (a) Classical LTB kinematics, (b) distortion lateral torsional buckling and (c) beam configuration onset of buckling incorporating PBD effect.

2. Literature review

A distinctive feature of the present study is that it combines the effect of distortion and pre-buckling deformation effects. Thus, within the large number of lateral torsional buckling studies, the present review places emphasis on those that incorporate distortional effects, followed by those that incorporate pre-buckling deformation effects.

2.1. Distortional buckling effect

This section provides an overview of past distortional buckling formulations. It is noted that in all cases, pre-buckling deformation effects were not captured. Distortional buckling solutions for I-sections were developed using the finite strip method [1,2]. Distortional solutions include a 12 degrees of freedom (DOFs) element [3] and a 16 DOFs element [4]. Other distortional buckling solutions focused on mono-symmetric beams [5], inelastic buckling of I-beams [6], and mono-symmetric I-beams with continuous elastic lateral restrains [7]. Distortional buckling solutions investigated tee sections using finite strips and plate finite element analysis [8], mono-symmetric beam-columns [9], and doubly-symmetric cantilevers [10].

The effect of rotational and translational restraints on web distortion of I-beams was investigated in [11,12], cantilevers with tee sections [13], and I-beam columns with continuous elastic restraints [14]. The influence of single flange lateral restraint on distortional buckling was investigate in [15]. Local instability of I-beams was investigated in [16] and energy solutions were developed to capture web distortion. A parametric study [17] investigated the effect of web distortion on the buckling of simply supported members with mono-symmetric I-sections subjected to uniform moment and axial forces. A super-element with 16 DOFs that captures web distortion was developed in [18]. The distortional buckling of beams with mono-symmetric sections was investigated under point loads [19] and under uniformly distributed loads [20]. In both studies, the web lateral displacement was approximated by quintic polynomials along the height. A simplified distortional model was devised based on continuous springs [21] to model the stiffness of the web and the flanges. An approximate distortional buckling solution [22] was devised based on torsional and warping rigidities that characterize web distortion. A finite element [23] was developed based on Fourier series in the longitudinal direction and cubic functions along the height. A shell finite element model in Abaqus was used to investigate the web distortional effect on the lateral torsional buckling moments of simply supported beams [24] and cantilevers [25].

Experimental investigations of distortional buckling were conducted for castellated I-beams [26] and for I-beams subjected to mid-span loading with lateral bracing at the compression flange [27]. The effect of lateral braces was investigated on the distortional buckling of I-beam cantilevers [28]. The distortional buckling of monorails was numerically investigated [29] under loads applied at the bottom flange. The study characterized the effect of web stiffeners and flange torsional stiffeners on the critical moments. Using the Ritz method [30] a distortional lateral buckling solution was developed for simply supported beams under transverse distributed load. Ref. [31] characterized the reduction in torsional and warping rigidities of beams due to web distortion. A distortional theory [32] was developed for the analysis of beams with mono-symmetric sections and finite element formulations were developed based on the theory [33]. A shell based distortional buckling analysis [34] was conducted for beams with cleat end connections. Among the above studies, only the work in Refs. [2–4,9,14] incorporated the effect of axial loads. A Generalized Beam Theory (GBT) solution was developed [35] to investigate the local and global buckling of steel open thin-walled beams under transverse load and the work was extended to closed sections under general loadings [36]. Both solutions in [35,36] capture the load position effect.

2.2. Pre-buckling deformation effect

A limited number of studies investigated the effect of pre-buckling deformations on the buckling capacity of thin-walled beams. Such studies are first reviewed, followed by the few studies that investigate the effect of pre-buckling deformations in plates.

The effect of pre-buckling deformation on the lateral buckling strength of beam columns was investigated in [37]. An energy-based solution [38] was developed for simply supported beams and cantilevers. The differential equations of lateral torsional neutral stability conditions were derived [39] and numerical solutions were developed for various boundary conditions and loading cases. A finite element solution that captures the PBD effects on the buckling load of planar structural elements was developed in [40]. The formulation resulted in a quadratic eigenvalue problem. A finite element with 14 degrees of freedom was developed in [41] for the flexural torsional and lateral buckling analysis of beams with open thin-walled cross sections. The element captures pre-buckling deformation effects. A critical moment expression that captures the magnifying influence of axial forces on pre-buckling deflections and curvatures was derived [16] for simply supported beams. Energy expressions including PBD effects were developed for the lateral buckling of doubly symmetric thin-walled beams [42] and comparisons were conducted with the classical solution. Based on a variational approach, the LTB governing equations were derived [43] for I beam-columns including PBD effects and a finite element formulation was developed for the problem. In a compan-

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