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Practical advanced analysis of steel frames considering lateral-torsional buckling

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Abstract

In this paper, the advanced analysis of 3D steel frames accounting for lateral-torsional buckling is presented. This analysis accounts for material and geometric nonlinearities of the structural system and its component members. Moreover, the problem associated with conventional advanced analysis, which do not consider lateral-torsional buckling, is overcome. An efficient way of assessing steel frame behavior including gradual yielding associated with residual stresses and flexure and second-order effect is presented. A case study shows that lateral-torsional buckling is a very crucial element to be considered in advanced analysis. The proposed analysis is shown to be an efficient and reliable tool ready to be implemented into design practice.

Keywords: Advanced analysis; Lateral-torsional buckling; Material and geometric nonlinearities; Steel frame

1. Introduction

In current engineering practice, the interaction between a structural system and its component members is represented by the effective length factor. The effective length method generally provides a good design of framed structures. However, despite its popular use as a basis for design, the approach has major limitations. First, it does not give an accurate indication of the factor against failure because it does not consider the interaction of strength and stability between the member and structural system in a direct manner. It is well-recognized that the actual failure mode of the structural system often does not have any resemblance whatsoever to the elastic buckling mode of the structural system, which is the basis for the determination of the effective length factor, K. The second and perhaps the most serious limitation is probably the rationale of the current two-stage process in design: elastic analysis is used to determine the forces acting on each member of a structural system, whereas inelastic analysis is used to determine the strength of each member treated as an isolated member. There is no verification of the compatibility between the isolated member and the member as part of a frame. The individual member strength equations as specified in specifications are unconcerned with system compatibility. As a result, there is no explicit guarantee that all members will sustain their design loads under the geometric configuration imposed by the framework.

In order to overcome the difficulties of the conventional approach, advanced analysis should be directly performed. With the current available computing technology with advancement in computer hardware and software, it is feasible to employ second-order plastic-hinge analysis techniques for direct frame design. Most of the second-order plastic analyses can be categorized into one of the two types: (1) Plastic-zone; or (2) Plastic-hinge based on the degree of refinements used to represent yielding. The plastic-zone method uses the highest refinements while the elastic–plastic hinge method allows for significant simplifications. The typical load–displacements of the plastic analyses are illustrated in Fig. 1. One of the second-order plastic-hinge analyses called the "plastic-zone method" discretizes framed members into several finite elements.

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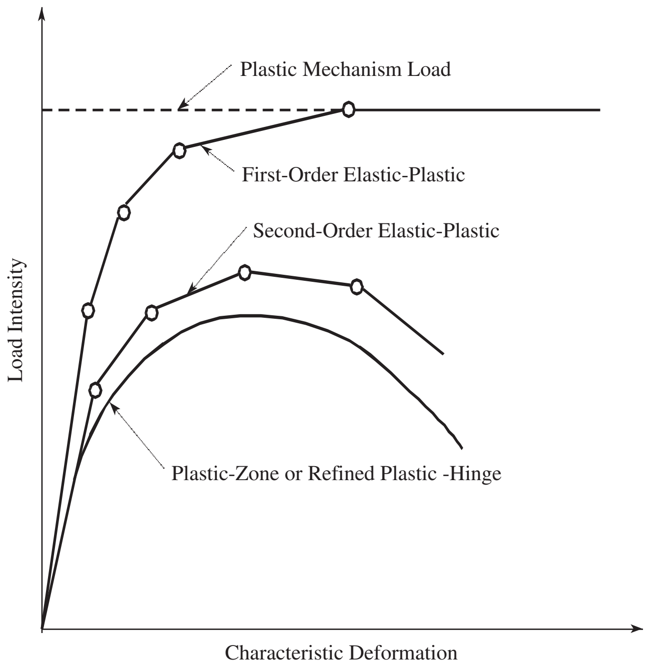

Fig. 1. Load–displacement of plastic analyses.

Also the cross-section of each finite element is further subdivided into many fibers [1–3]. Although the plastic-zone solution is known as an "exact solution", it is yet to be used for practical design purposes. The applicability of the method is limited by its complexity requiring intensive computational time and cost. The real challenge in our endeavor is to make this type of analysis competitive in present construction engineering practices. A more simple and efficient way to represent inelasticity in frames is the second-order plastic-hinge method. Until now, several second-order plastic-hinge analyses for space structures were developed by Prakash and Powell [4], Liew et al. [5], and Kim et al. [6], among others. The benefit of the second-order plastic-hinge analyses is that they are efficient and sufficiently accurate for the assessment of strength and stability of structural systems and their component members. But these conventional 3D second-order plastic-hinge analyses cannot consider lateral-torsional buckling. Therefore, advanced analysis needs to consider that effect to enhance its capacity in predicting the behavior of structure accurately.

Early attempts to study the behavior of thin-walled structures include Bleich [7], Barsoum and Gallagher [8], Trahair and Kitipornchai [9], and Allen and Bulson [10]. But these studies focused on the numerical methods that permitted to treat only linear elastic lateral-torsional buckling. After that, geometric nonlinear elastic studies about thin-walled element considering lateral-torsional buckling were conducted by Bazant and El Nimeiri [11], Yang and McGuire [12], Chan and Kitipornchai [13], Conci and Gattass [14], Chen and Blandford [15], and Kwak et al. [16]. Nonlinear inelastic analyses of lateral-torsional buckling were performed by Pi and Trahair [17], Gruttmann et al. [18], Battini and Pacoste [19]. However, the drawback of these methods is that they must use many elements to obtain the accurate result of complex structures. Recently, Kim et al. [20] developed a nonlinear analysis method that can consider lateral-torsional buckling effect. But this method cannot predict the real behavior of member accurately because it only considered lateral-torsional buckling strength using AISC-LRFD equation.

The purpose of this paper is to propose a practical advanced analysis method that can conduct nonlinear inelastic analysis considering lateral-torsional buckling. The stability functions and the refined plastic-hinge approach are reasonably applied into the beam–column formulation to take the advantage of computational efficiency. The local buckling effects are ignored. The shear, torsional, and warping effects on the cross-sectional plastic strength are not considered.

2. Stiffness matrix formulation

2.1. Virtual work equation

In the conventional beam–column approach, some coupling terms between the flexural and torsional displacements are excluded due to the simple expansion from 2D element to 3D element, so the lateral-torsional buckling cannot be predicted there. To overcome this obstacle, a virtual work equation including lateral torsional buckling effect is used. The linearized form of incremental virtual work equation of beam–column element having doubly symmetric cross-section with 14 degrees-of-freedom may be expressed as [21]

$$
\begin{aligned}
&\frac{1}{2}\int_0^L \Big[EA\delta\left(u'^2\right) + EI_y\delta\left(v''^2\right) + EI_z\delta\left(w''^2\right) \\
&\quad + EC_\omega\delta\left(\theta''^2_x\right) + GJ\delta\left(\theta'^2_x\right)\Big]\,\mathrm{d}x \\
&\quad + \int_0^L \frac{F_x}{2}\delta\left(v'^2 + w'^2\right)dx + \int_0^L \frac{\overline{K}}{2}\delta\left(\theta'^2_x\right)\mathrm{d}x \\
&\quad - \int_0^L F_y\delta(u'v' - w'\theta_x)dx - \int_0^L F_z\delta(u'w' - v'\theta_x)\,\mathrm{d}x \\
&\quad - \int_0^L M_y\delta\left(v'\theta'_x\right)dx - \int_0^L M_z\delta\left(w'\theta'_x\right)\mathrm{d}x \\
&\quad - \int_0^L \frac{M_x}{2}[\delta(v'w'') - \delta(v''w')]\,\mathrm{d}x \\
&\quad = \{\delta u\}^{\mathrm{T}}\left(\{{}^2f\} - \{{}^1f\}\right) \qquad (1)
\end{aligned}
$$

in which E is the modulus of elasticity; G is the shear modulus; A and L are the area and length of element; I_y and I_z are the moment of inertia with respect to y and z axes; C_ω is the warping constant; J is the torsional constant; $\bar{K} = F_{xB}(I_y + I_z)/A$ is the Wagner coefficient; and $\{f\}$ and $\{u\}$ are element force and displacement vectors.