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New method of inelastic buckling analysis for steel frames

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Abstract

In general, the concept of bifurcation stability cannot be used to evaluate the critical load of typical steel frames that have geometric imperfections and primary bending moment due to transverse loads. These cases require a plastic zone or plastic hinge analysis based on the concept of limit-load stability instead. However, such analyses require large computation times and complicated theories that are unsuitable for practical designs. The present paper proposes a new method of inelastic buckling analysis in order to determine the critical load of steel frames. This inelastic analysis is based on the concept of modified bifurcation stability using a tangent modulus approach and the column strength curve. Criteria for an iterative eigenvalue analysis are proposed in order to consider the primary bending moment as well as the axial force by using the interaction equation for beam–column members. The validity and applicability of the proposed inelastic buckling analysis were evaluated alongside elastic buckling analysis and refined plastic hinge analysis. Simple columns with geometric imperfections and a four-story plane frame were analyzed as benchmark problems. The results show that the proposed inelastic buckling analysis suitably evaluates the critical load and failure modes of steel frames, and can be a good alternative for the evaluation of critical load in the design of steel frames.

Keywords: Elastic buckling analysis; Inelastic buckling analysis; Refined plastic hinge analysis; Critical load; Steel frame

1. Introduction

For decades, researchers have explored various approaches for assessing column and frame stability in the design of steel structures. Most approaches, known as the effective length method, deal with the effective length factor and the buckling strength of individual members. Aimed at providing sufficient simplicity for hand calculations, the effective length method is based on some assumptions that may have considerable influence on accuracy [6]. Nevertheless, it has been generally believed that the effective length method is sufficient for the design of steel frames. In addition, it is frequently used in practical design fields because many structural engineers still prefer analytical approaches, at least in the preliminary design stage.

Nonetheless, there are several drawbacks to the effective length method. Since the behavior of a large structural system is too complex to be represented by the simple effective length factor, the effective length method cannot adequately account for the interaction between the structural system and its members. Furthermore, the effective length method cannot express the inelastic redistributions of internal forces in a structural system and the failure modes of a structural system at its ultimate condition [3,13].

Nowadays, considerable attention is being devoted to the problem of steel frames in the presence of both geometric and material nonlinearities as a result of the development of computer technology and the need to adopt limit-state design principles. In general, these approaches may be categorized into two main types: plastic zone analysis and plastic hinge analysis. Although plastic zone analysis is regarded as an exact method, this approach is inappropriate to the practical design process because of its complexity and great cost [13,15,18]. On the other hand, the plastic hinge method is considered a practical approach and it has been applied many times in a variety of settings with different modifications. Liew et al. [18] introduced the refined plastic hinge method as an effective alternative for typical elastic–plastic hinge methods. Their research resulted in the development of an inelastic analysis approach based on simple refinements of the elastic–plastic hinge model for steel members. Similarly, plastic hinge analysis has been studied with semi-rigid connections [14,16], tapered members [17],

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design concepts [8,13] and different design specifications [15]. General reviews and design examples can also be found in the Refs. [7,18].

In addition, some research has been devoted to developing alternative methods to evaluate the critical loads of steel frames. Kameshki and Syngellakis [11] proposed a method using transfer matrices and verified their results by comparison with other analytical and numerical methods. Hayalioglu [9] introduced a new method of analysis for steel frames with a genetic algorithm and illustrated examples of optimum design for some types of steel frames. Nogami et al. [19] and Iwasaki et al. [10] proposed a simple alternative, the E_f method, and applied it to determine the critical load of steel cable-stayed bridges modeled by frame elements. Their research contributed to the modified bifurcation concept with column strength curves used to evaluate the critical load of steel structures. Nevertheless, the validity and applicability of their method have not yet been confirmed for the design of general steel frames.

The main purpose of this paper is to propose a new and simple alternative to evaluate the critical load of steel frames. We present a method of modified bifurcation stability using the tangent modulus theory and a column strength curve instead of the conventional plastic hinge method. In real situations, the method based on bifurcation stability is inadequate to determine the critical load of steel frames that have geometric imperfections or transverse loadings. However, inelastic buckling analysis, which is presented in this paper, can consider geometric imperfections or residual stresses in a steel frame by using the column strength curve. In addition, we suggest the criteria for inelastic buckling analysis in order to account for the effect of the primary moment as well as the axial force of members in steel frames. Simple columns with geometric imperfections and a four-story plane frame were analyzed as benchmark examples. Conventional elastic buckling analysis and refined plastic hinge analysis with these models were also performed to validate the proposed inelastic buckling analysis method.

2. Methods of analysis

2.1. Stability concepts for steel frames

A structural system loses stability due to singular points on the equilibrium path, referred to as critical points. There are two alternative concepts of overall structural stability: bifurcation stability and limit-load stability. Bifurcation stability is characterized by the fact that the system, which was originally deflected in the direction of the applied load, suddenly deflects in a different direction as the external load increases. The critical load is commonly determined from an eigenvalue analysis of an idealized elastic model of the structure. Alternatively, limit-load stability is characterized by the fact that there is only a single mode of deflection from the start of loading to the limit or maximum load. An incremental-load analysis and load–displacement curve are needed to determine the critical load of the system because the tangent stiffness of the system is indefinite at the ultimate stage.

Table 1
Comparison of the critical load factors of steel frames

Analysis method	Elastic buckling analysis	Refined plastic hinge analysis	Inelastic buckling analysis
Stability concept	Bifurcation	Limit-load	Bifurcation
Indicators for the critical load	κ (Minimum eigenvalue)	CLF (Critical load factor)	κ^{conv} (Converged eigenvalue)

Bifurcation stability that uses eigenvalue analysis is only appropriate for a geometrically perfect system. The critical load of a geometrically imperfect structure should be determined using the concept of limit-load stability instead of bifurcation stability. Since all structures have some imperfections in real situations, the actual critical load of a system is generally determined as a lower value than the elastic buckling load by eigenvalue analysis based on the concept of bifurcation stability.

In this study, we used three methods to evaluate the stability and critical load of the steel frames. First, elastic buckling analysis was performed and the critical load determined by the minimum eigenvalue of the first eigenmode. Second, refined plastic hinge analysis, proposed by Liew et al. [18], was carried out to determine the critical load of the steel frames. The load–displacement curve was made for the specific degree of freedom in a structure according to the load factor, and the critical load factor was determined at the point where the tangent stiffness of the structure was nearly zero. Lastly, inelastic buckling analysis, which is proposed in the present paper, was performed and the critical load factor of a structure was determined by the converged eigenvalue. Elastic and inelastic buckling analyses are based on the concept of bifurcation stability, whereas refined plastic hinge analysis is based on the concept of limit-load stability. Table 1 contrasts the critical load factors of steel frames calculated by these methods of analysis.

2.2. Elastic buckling analysis: Eigenvalue analysis

In the concept of bifurcation stability, a structure is assumed to be a perfect structural system and to have elastic material behavior. The critical load is determined by a conventional eigenvalue calculation. The basic equation can be expressed as

$$([K_e] + \kappa[K_g])\{\phi\} = \{0\} \quad (1)$$

where $[K_e]$, $[K_g]$ and $\{\phi\}$ are the elastic stiffness, geometric stiffness and buckling eigenmodes corresponding to the eigenvalues of κ, respectively. The stiffness matrix can be derived using the concept of general continuum mechanics and the principle of virtual work [20]. Fig. 1 presents the 3-dimensional beam–column element and corresponding degrees of freedom. In addition, Fig. 2 shows the elastic and geometric stiffness matrix for a beam–column element explicitly used in this study. In Fig. 2, the terms E, A, I and L indicate the modulus of elasticity, sectional area, second moment of area