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Second-order analysis and design of imperfect composite beam–columns

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ABSTRACT

In current practice, the design of composite columns such as concrete-filled and concrete-encased steel columns is a member-based procedure which is based on linear analysis in conjunction with the effective length method, rather than a system-based approach utilizing the concept of advanced analysis. In principle, the advanced analysis can be used for any structural forms when imperfections are considered and proper plastic functions for cross-sections are used. The new method considering these issues needs to be calibrated with design codes and experimental tests. Surprisingly, the application of advanced analysis to composite structures is relatively rare in the literature and the advantages have not been exploited fully. In this paper, an "advanced analysis" design method for composite columns is proposed, and the results predicted by the proposed method are compared with the results calculated by Eurocode 4 and from laboratory tests. With the verification and calibration carried out in this study, without loss of generality, the proposed method can be applied to the design of composite structures beyond the scope of the conventional design method and without the assumption of an uncertain effective length factor, which implies an improved accuracy and convenience, as frame classification for the use of the effective length method or alignment charts is no longer needed.

1. Introduction

In recent years, the use of steel–concrete composite columns has been popular. Generally speaking, composite columns can be classified into either a hollow section filled with concrete or a steel section encased by concrete. The use of composite columns combines the advantages of steel and reinforced concrete such as provision of fire protection on steel by the surrounding concrete, elimination of permanent formwork and the production of high-strength and stiff columns. Due to the fast development in the technology of composite structures, several design codes such as AISC [1], Eurocode 4 [2], BS5400 [3] and CoPHK [4] provide different design methods for several common types of composite column. Some methods consider the composite columns as a steel column with equivalent and modified cross-sectional properties whereas other methods consider the composite columns as a concrete column with modified cross-sectional properties. So far these design methods commonly use the linear elastic analysis approach to find the axial force and bending moment in the members and check with the modified resistance of each member individually with allowance for the second-order effects. This method simplifies the analysis process at the expense of complicating the design process.

Rapid development of technology in desk-top computing has made the second-order analysis more popular, as summarized by Chen [5] and Kim and Chen [6], with extensive research focused on refining this method for practical applications. Many design codes such as AISC [1], Eurocode 4 [2], and CoPHK [4] also allow the use of the second-order analysis method as a more accurate computational tool, and it should be used when the elastic critical load factor is small. In the second-order analysis, important nonlinear effects such as the P–Δ (Equilibrium in the deformed position of the structure) and P–δ (Member bowing deflection and stiffness change) effects, and member and geometric imperfections are required for inclusion in analysis process. As a result, this analysis method not only increases the accuracy of estimation of the failure load, but also saves time and effort for the design. The advantages of using the second-order analysis and design method and advanced analysis method have been presented by many researches, such as Chen [7] and Kim and Chen [8] who avoid the assumption of effective length factor, with the P–Δ and P–δ effects being considered reliably and automatically.

Different expressions for the tangent and secant stiffness matrices and the method of calculating the element displacements and the rotations for second-order analysis have been proposed by many researchers; these include the cubic Hermite function [9], stability function [10] and [11] and pointwise equilibrium polynomial (PEP) function [12]. The pointwise equilibrium polynomial (PEP) element has been used in most of the authors' previous work because of its simplicity and computational stability and efficiency which allows modeling by one element per member. It not only

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simplifies the modeling process, but also greatly reduces the computational time. Besides, PEP element method also eliminates the need for separating the compressive and the tensile load cases with the matrix being valid for positive, negative and zero axial force, which is required in the stability function method. Chan and Zhou [13] included an equivalent initial imperfection, which simulates the effect of geometric imperfection and residual stress, into the PEP element formulations to complete the modeling for real and imperfect members. The PEP element was further modified by Zhou and Chan [14] to include the semi-rigid joint at the ends of the member. Use of the PEP element for second-order analysis in various types of steel structure with different buckling modes such as snap-through and snap-back buckling has been demonstrated [13,14]. The behavior of slender structures with complex geometry such as space domes [15,16] and the angle truss [17–19] can also be modeled and analyzed well by the second-order analysis method.

In spite of many achievements in the topic, the use of the second-order analysis and design method with a PEP element on composite columns is not yet adequately studied. Many researchers use the finite element method to simulate the behavior and to predict the failure load of the composite columns. Fairly speaking, accurate results can be obtained by using the finite element method, which, however, requires a huge amount of computational effort and time that makes the method unacceptable for practical design involving hundreds of members and load cases. As a result, the rigorous finite element method is seldom used in engineering practice. In this paper, the use of the second-order analysis and design method with a PEP element on composite columns for both concrete-filled steel tube columns and concrete-encased steel columns is proposed. The PEP element allowing for modeling by one element per member is important for successful application in real structures, not only because it saves computer time, but also because it permits the use of a simple modeling approach of every member modeled as an entity rather than as an assembly of elements. Thus, the structural model here is the same as in the linear analysis model which has a beauty of simplicity of every member simulated as an element. In this study, the failure loads under axial force with and without end moments are analyzed and compared with the results based on the design method in Eurocode 4 [2] and experimental tests. The efficiency and accuracy of the proposed method make the proposed method a potential candidate for replacement of the currently used linear analysis or second-order analysis considering only the P–Δ effect which still requires the use of the effective length for a buckling strength check.

2. Codified design method — Eurocode 4

Many design codes, such as Eurocode 4 [2], BS5400 [3] and CoPHK [4], provide a conventional design method for composite columns, which allows engineers to use the first-order analysis and effective length method to check the strength and stability of each member separately. The member forces and moments are first calculated on the basis of the first-order analysis, and the design formulae in the codes are then applied to check the buckling strength of each member individually by assuming an effective length factor or K-factor. The first-order moment will then be amplified to account for the second-order sway effect. The accuracy of this design method depends highly on the error of the effective length factor, which it is not quite possible to eliminate, as the idealized assumption for simple end conditions like a pin and a rigid end are unrealistic in most practical structures. Further, the effects of buckling of a member on the deterioration of the member and frame stiffness are not accounted for in the analysis part, so the computed axial forces and moments can be overestimated or underestimated.

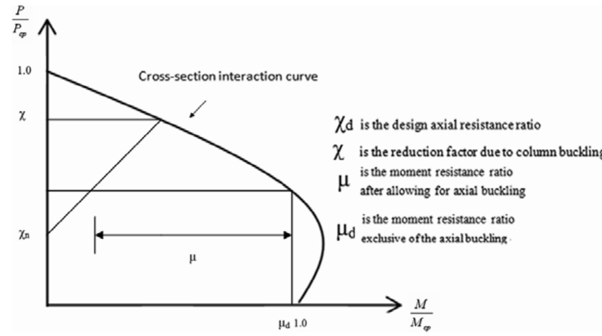

Fig. 1. Interaction curve for compression and uniaxial bending.

Eurocode 4 [2] proposes two methods for the design of composite columns and beam–columns. The first method is applicable to all sections by taking into account the second-order effects directly in the analysis. It ensures that instability does not occur, so the resistance of an individual cross-section allowing for reduction due to buckling is not exceeded by the external loads. The second, more popular, method used in practice is a simplified approach which is used to predict the failure load of doubly symmetrical and uniform cross-section composite columns. This method requires the use of modification factors and the effective length method to consider the second-order and buckling effects.

In Eurocode 4 [2], the axial resistance of composite columns without consideration of buckling is determined simply by adding the resistances of all components, which includes concrete, steel and reinforcement, as

$$P_{cp} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd} \tag{1}$$

in which A_a, A_c and A_s, and f_{yd}, f_{cd} and f_{sd} are the cross-sectional area and the design strength of the steel, concrete and reinforcement, respectively.

For a concrete-filled rectangular and square hollow section, the coefficient of 0.85 in Eq. (1) is replaced by 1.0. For a concrete-filled circular hollow section, the strength of concrete would be further increased under specific conditions by considering the confinement effect of the external steel tube surrounding the concrete.

To allow for the buckling effect, a reduction factor χ, which is based on the effective slenderness ratio and section types, is used in the axial capacity of the columns, and then the compressive resistance is given by

$$P_{cp} = \chi (A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd}). \tag{2}$$

For beam–columns, the non-dimensional interaction curve for compression and uniaxial bending for composite columns is used, as shown in Fig. 1.

To take into account the second-order effect, the first-order design moment M should be multiplied by a factor k defined by

$$k = \frac{\beta}{1 - P/P_E} \tag{3}$$

in which P_E is the Euler buckling load and β is an equivalent moment factor which depends on the distribution of moment along the member.

The term χ_n in Fig. 1 is used to represent the influence of the imperfection on different bending moment distributions and it depends on the end moments ratio as

$$\chi_n = \frac{(1 - r)\chi}{4} \tag{4}$$

where r is the ratio of the end moments and a positive value of r means that the column bends in the single curvature, so the