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Discussion on the applicability of the M-N interaction curve for the fire resistance design of CFT members

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ABSTRACT

When subjected to combined axial force and bending moments at ambient temperature, concrete filled tubes (CFTs) show a marginal increase in bending resistance at low level of axial compression, but the bending resistance reduces when the compression force is high. To evaluate the buckling resistance of CFT member subject to axial compression (N) and moment (M), a second order analysis approach is proposed by EC 4: EN 1994-1-1 in which the cross section check can be carried out using the N-M interaction curve which is derived based on the plastic design principle. When the CFTs are further subjected to high temperature due to fire, the design method is however not available in EC 4: EN 1994-1-2. This paper proposes a modified M-N interaction curve based on plastic stress distribution as in EC 4: 1994-1-1 for fire resistance design of CFT members. The superiority of the M-N interaction curve is the universality to both axially loaded members and members subjected to combined axial force and bending moments, regardless of the moments being induced by load eccentricities or initial bow imperfections. Backgrounds of the existing simple calculation model in EC 4 using buckling curves and the proposed M-N interaction curve were first discussed. Then the validity of the said M-N interaction curve was established by comparisons with test results. The proposed M-N interaction curve was found to provide better predictions of the fire resistance than the simple calculation model. Hence, it could be safely extended to EC 4: 1994-1-2 for the design of CFT members under fire.

1. Introduction

Concrete filled tubes (CFTs), comprising hollow steel tubes infilled with concrete, have been used in many structural applications, especially for columns in high-rise buildings. Other applications include structural uses in civil infrastructural work, industrial construction, offshore oil and gas installations, and protective structures. CFTs exhibit better ductility compared with reinforced concrete members owing to the confinement of the tubes to the core concrete, and better fire performance compared with steel members since the infilled concrete absorbs the heat and delays the temperature rise of the steel sections when subjected to fire [1]. The CFT beam-column is defined as being subjected to combined axial force and bending moments. The bending moments can be induced by transverse loads, end moments, axial load eccentricities, and thermal bowing due to non-uniform heating under fire, etc. In fact, all CFT columns can be classified as beam-columns, even for axially loaded CFTs as there are additional moments resulting from initial imperfections. Basically, the initial imperfections are considered for the existence of out-of-straightness and residual stresses during hot rolling or welding, etc. For ambient-temperature design of the CFT beam-columns according to Eurocode EN 1994-1-1 [2], a simple calculation model using a buckling reduction factor and buckling curves (only applicable for beam-columns with moments induced by the initial imperfections) and a design calculation model using a simplified M-N interaction curve can be adopted. For the fire resistance design of CFT beam-columns, Eurocode EN 1994-1-2 [3] gives a simple calculation model for beam-columns with bending moments resulting from either the initial imperfections or the load eccentricities, which are limited in a small range. This means that the Eurocode model is only applicable for beam-columns subject to the moment distributions shown in Fig. 1(a). It is not applicable for beam-columns subjected to end moments or transverse loads with moment diagrams such as those shown in Fig. 1(b)-(d). When such cases are encountered, the M-N interaction curves, varying with the fire exposure time, may be adopted. The American Code ASCE/SFPE 29-05 [4] provides a design method for an even narrower application. This method

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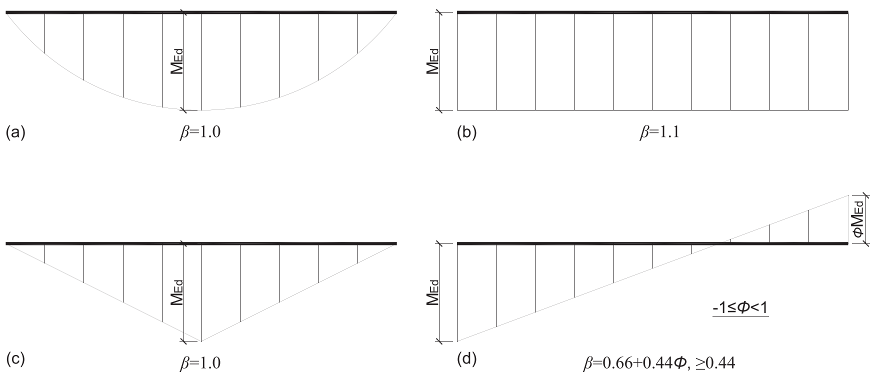

Fig. 1. Moment diagrams of beam-columns.

uses a parametric equation, developed by Lie et al. [5,6] based on a series of loaded fire resistance tests, to directly determine the fire resistance time of axially loaded CFT columns; the initial imperfections are not explicitly considered, and the deteriorated axial and moment resistance with temperature cannot be calculated. With regard to the moment distributions, the ASCE/SFPE model is limited to CFT beam-columns with moments induced by the initial imperfections, as in Fig. 1(a). It is also not applicable for the other moment distributions shown in Fig. 1(b)-(d).

In the early work of Liew [7], plastic M-N interaction curves were introduced to investigate the inelastic behaviour of beam-columns in steel frames subjected to fire. The M-N interaction curves were allowed to contract with the degradation of stiffness and strength according to Eurocode 3. Garlock and Quiel [8] studied the effects of thermal gradients on the M-N interactive resistance of steel beam-columns and compared the resistance with those based on uniform temperature profiles. The prototype beam-columns used were wide-flange steel sections. Similarly, Dwaikat and Kodur [9] proposed a simplified approach to evaluate the plastic axial-moment interaction curves for steel beam-columns with non-uniform thermal gradients. The simplification was done by adjusting the M-N interaction curves of a beam-column with a uniform but averaged temperature on the cross-section. The objects of the abovementioned research studies were steel beam-columns exposed to fire, and thus the developed M-N curves are not applicable for the CFT members. Choi et al. [10] proposed a new approach to design square CFT beam–columns based on an existing AISC/LRFD method that was known to provide an over-conservative estimation of the resistance for ambient-temperature design. The new approach assumed full composite action and idealized the M–N interaction curve with two lines. The proposed M-N interaction curve was validated by comparisons with a wide range of experimental data, and the comparisons showed greatly improved predictions when compared with the existing AISC/LRFD design method. After that, Choi et al. [11] proposed a simplified M-N interaction curve for square CFT beam-columns with high-strength concrete. The strength was as high as 100 N/mm^2. The interaction curve in Ref. [10] was based on and modified for the influence of high-strength concrete by calibrating two variables, i.e., the normalized maximum moment α and axial load ratio at the maximum moment β, through comparisons with test data. Although the objects of research by Choi et al. were CFT beam-columns, the M-N interaction curves were proposed only for ambient-temperature design and thus were not applicable for the fire resistance design of CFT beam-columns. There were also numerical work on the M-N interaction curves based on the conventional fibre element method or finite element method [12]. These methods may be more accurate; however, they are not easy to be implemented and not exactly following the principles of design codes, such as the plastic stress blocks at ultimate limit state, etc.

The above literature review indicates a lack of design model for CFT members subjected to combined axial force and bending moments. Set against this background, this study extended the simplified M-N interaction curve from ambient temperature design in EN 1994-1-1 [2] to the fire resistance design, maintaining the consistency with ambient temperature design. To establish the validity of this extension, the fire resistance time predicted by the proposed M-N interaction curves were compared with test results in the available literature. It should be addressed that the proposed M-N interaction curves are limited to CFT members using normal-strength concrete and steel strength no more than 460 MPa as limited in EC 4 [2], since the plastic cross-sectional resistance is assumed.

2. Design methodologies

2.1. Existing design method based on the buckling curve

EN 1994-1-2 provides a simple calculation model for designing an axially loaded CFT column with all surfaces exposed to a standard fire. The additional moments by initial imperfections are considered by selecting proper buckling curves. For a perfectly straight column under compression as shown in Fig. 2(a), the failure load is the Euler buckling load $N_{\mathrm{fi,cr}}$ given in Eq. (1), where $(EI)_{fi,eff}$ is the effective flexural stiffness of the CFT column under fire as given in Eq. (2).

$$N_{fi,cr} = \pi^2 (EI)_{fi,eff} / l_\theta^2 \tag{1}$$

$$(EI)_{fi,eff} = \sum_j (\varphi_{a,\theta} E_{a,\theta,j} I_{a,j}) + \sum_k (\varphi_{c,\theta} E_{c,\theta,k} I_{c,k}) \tag{2}$$

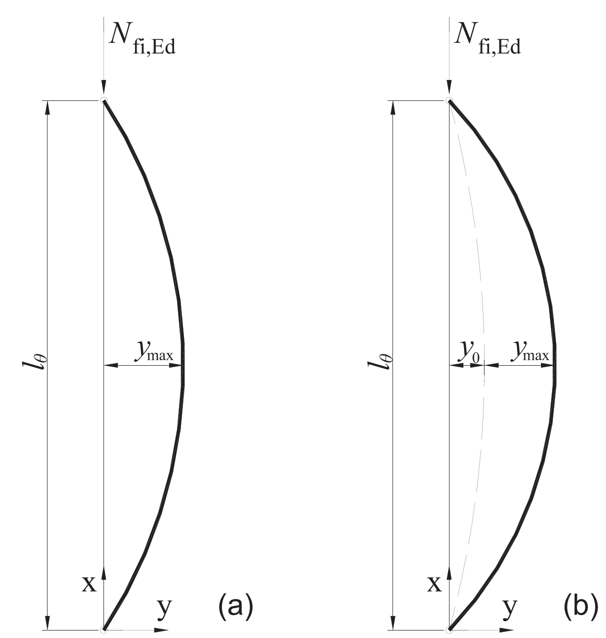

Fig. 2. Deflected shapes of CFT columns (a) straight; (b) initial imperfection.