Engineering Structures 160 (2018) 293–303

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Elastic flexural rigidity of steel-concrete composite columns

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ARTICLE INFO

Keywords:
Steel-concrete composite
Columns
Elastic analysis
Flexural rigidity
Design

ABSTRACT

The use of elastic analysis is prevalent in the design of building structures even under loading conditions where inelasticity would be expected. Accordingly, geometric and material properties used in the elastic analyses must be carefully selected to maintain accuracy. Steel-concrete composite columns experience different forms of inelasticity. Concrete cracking is the source of much of the inelasticity and occurs at relatively low levels of load, but partial yielding of the steel, slip between concrete and steel, and concrete crushing also contribute to losses in stiffness. In this paper, the behavior of composite columns is characterized at the cross section and member levels through comparisons between inelastic and elastic analyses. Then, through a broad parametric study, specific practical design recommendations are developed for the elastic flexural rigidity of composite columns for the determination of lateral drifts under service loads. The recommendations in this paper provide simple and robust values for the stiffness of composite columns to be used for drift computations involving lateral loads.

1. Introduction

Building structures are typically designed with the expectation that they will experience inelasticity during their design life. Different forms of inelastic behavior will occur at different levels of loading. In steel-concrete composite members, concrete cracking may occur under relatively low loads, slip may occur at moderate loads, and steel yielding and concrete crushing may occur relatively high loads. Despite the increasing use of inelastic analysis, which can track this behavior explicitly, elastic analysis remains prevalent in design. Thus, the expected inelasticity must be accounted for implicitly in the elastic analysis. One way of accomplishing this is through appropriate modifications of the geometric and material properties assumed in the analysis.

In elastic analyses with frame elements, the behavior of cross sections is represented by elastic rigidities which define the stiffness of cross sections in various modes of deformation, for example the axial stiffness, EA, the flexural stiffness, EI, the shear stiffness, GA, and the torsional stiffness, GJ. For moment frame systems, the dominant mode of deformation is typically bending, thus EI is of prime importance.

Elastic analyses are used for many different purposes in the design of building structures, and the appropriate elastic geometric and material section properties may differ depending on the purpose of the analysis. For strength design, appropriate elastic section properties typically reflect the level of inelasticity at the "ultimate" limit state. Alternatively, when computing deflections due to wind loading for story drift checks, appropriate elastic section properties typically reflect the level of inelasticity at a "service loading" level. The elastic section properties used for service loading level design checks are often greater than those for the determination of required strengths. For example, in the ACI *Code*, the moment of inertia is permitted to be increased by a factor of 1.4 for service load analysis [2] and in the AISC *Specification*, the stiffness reductions associated with the direct analysis method are not intended for determining deflections [3].

While a variety of potential uses for elastic flexural rigidity exist, they are not all equally common in practice. All structures are evaluated for strength which typically includes using an elastic flexural rigidity within design equations to determine the compressive strength of columns and within a second-order analysis to determine required strengths. The appropriate effective flexural rigidity for these uses was the subject of recent research and changes to code provisions [3,8]. The evaluation of serviceability drift limits is equally important, especially for moment frames where drift limitations may control the design. However, less attention has been paid to the appropriate effective flexural rigidity for this use. Another common use of the elastic flexural rigidity is within an Eigenvalue analysis to compute fundamental periods for the determination of seismic loads as was investigated by Perea et al. [20]. An example of a less common use of the elastic flexural rigidity is to define the elastic component of a concentrated plasticity

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https://doi.org/10.1016/j.engstruct.2018.01.044
Received 23 June 2017; Received in revised form 29 December 2017; Accepted 15 January 2018

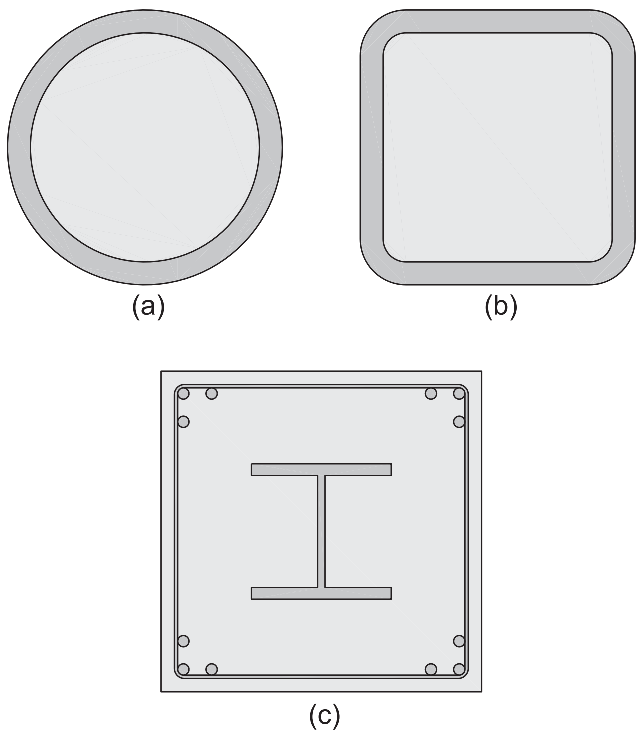

Fig. 1. Composite cross sections.

beam element or other beam element where geometric and material nonlinearity are handled distinctly [22].

In this paper, the stiffness of steel-concrete composite columns is tracked first at the cross-section level then at the member level to provide accurate and practical guidance on the elastic flexural rigidity of such members for the specific purpose of determination of lateral drifts under service loads. Both concrete-filled steel tube (CFT, Fig. 1a and b) and encased or steel-reinforced concrete (SRC, Fig. 1c) columns are investigated. This research focuses on short-term behavior, such as deformations caused by wind loading, and thus the effects of creep and shrinkage are not included.

2. Literature review

Structural steel has a relatively high proportional limit, thus, the use of the gross section properties and modulus of elasticity is widely considered safe and accurate for analysis at service loads. For determination of required strengths per the direct analysis method, a reduction of 0.8 is applied to all stiffness of all members that contribute to the lateral stability of the structure with a further reduction of τ_b on EI (τ_b is a factor that varies between 0 and 1 and depends on the axial compression within the member) [3]. These reductions account for the partial yielding (accentuated by residual stresses) that occurs in members under combined bending and axial load.

Concrete cracks in tension and has a relatively low proportional limit in compression. Several different recommendations and options for the flexural rigidity are given in the ACI *Code* [2] depending on the use of the value. A relatively low flexural rigidity is used to determine the moment magnification of nonsway frames. Relatively higher flexural rigidities are permitted for use in elastic analyses to determine required strengths or lateral deflections at ultimate loads. Two primary options are given. For the simple option, the flexural rigidity for columns is recommended as 70% of the product of the modulus of elasticity of the concrete and the gross moment of inertia (Eq. (1)) based on the work of MacGregor and Hage [15]. The more complex expression for the flexural rigidity takes into account the effects of load and steel ratio (Eq. (2)). These equations were developed by Khuntia and Ghosh [11,12] based on parametric computational studies on reinforced concrete cross sections. To determine lateral deflections at service loads, the ACI *Code* [2] permits the use of Eq. (1) or (2) multiplied by 1.4. Other studies have also focused on the flexural rigidity of reinforced concrete members [16,9,4,13].

$$EI = 0.7E_c I_g \tag{1}$$

$$EI = E_c I \tag{2a}$$

$$I = \left(0.80 + 25\frac{A_{sr}}{A_g}\right)\left(1 - \frac{M_u}{P_u H} - 0.5\frac{P_u}{P_{no}}\right) \leqslant 0.875 I_g \tag{2b}$$

where E_c = modulus of elasticity of concrete, I_g = gross moment of inertia of the cross section, A_{sr} = area of steel reinforcing, A_g = gross area of the cross section, M_u = required bending moment, P_u = required axial compression, H = section depth, and P_{no} = cross-sectional axial capacity.

A variety of approaches and relations have been proposed to evaluate the elastic rigidity of composite members. The different recommendations are not necessarily comparable since they were often developed with different objectives and for different purposes (e.g., determination of axial strength, assessment of deformations, and use in nonlinear finite element formulations).

The effective flexural rigidity, EI_{eff}, given in the AISC *Specification* [3] is intended for use within a column curve approach to compute the axial compressive strength of composite columns. Different expressions are provided for this rigidity for SRC (Eq. (3)) and CFT (Eq. (4)) members. The effective flexural rigidity is also used, with reductions, for determining required strengths within the direct analysis method (EI_{DA}, Eq. (5)). These expressions are based on computation analyses of small frames as well as an evaluation of column and beam-column experimental results [8]. The expressions are new to the 2016 AISC *Specification*; previous expressions were similar in form and based solely on evaluations of experimental results [14].

$$EI_{eff} = E_s I_s + E_s I_{sr} + C_1 E_c I_c \qquad \text{(SRC)} \tag{3a}$$

$$C_1 = 0.25 + 3\left(\frac{A_s + A_{sr}}{A_g}\right) \leqslant 0.7 \tag{3b}$$

$$EI_{eff} = E_s I_s + E_s I_{sr} + C_3 E_c I_c \qquad \text{(CFT)} \tag{4a}$$

$$C_3 = 0.45 + 3\left(\frac{A_s + A_{sr}}{A_g}\right) \leqslant 0.9 \tag{4b}$$

$$EI_{DA} = 0.64 EI_{eff} \tag{5}$$

where E_s = modulus of elasticity of steel, I_s = moment of inertia of the steel shape, I_{sr} = moment of inertia of the reinforcing, I_c = moment of inertia of the concrete, and A_s = area of the steel shape.

In the ACI *Code* [2], composite columns are treated much the same as reinforced concrete columns. A slightly different formula is recommended for the determination of the moment magnification for nonsway frames, but, otherwise no special formulas are given.

In Eurocode 4 [5], two equations for the effective flexural rigidity are provided. The first, $(EI)_{eff}$ (Eq. (6)), is for the determination of the member slenderness to be used within a column curve to determine axial strength. The second, $(EI)_{eff,II}$ (Eq. (7)), is to be used within an elastic analysis to determine required strengths. For both equations, the effective rigidity is taken as the sum of the individual components with factors reducing the concrete contribution. For $(EI)_{eff,II}$, an additional reduction factor is applied to the summation.

$$(EI)_{eff} = E_s I_s + E_s I_{sr} + 0.6 E_c I_c \tag{6}$$

$$(EI)_{eff,II} = 0.9(E_s I_s + E_s I_{sr} + 0.5 E_c I_c) \tag{7}$$

Other recommendations can be found in the literature. Schiller et al. [22] summarized published elastic rigidity recommendations for