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Simplified Beam Design for Semi-Rigid Composite Frames at the Serviceability Limit State*

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Abstract: This paper presents a simplified beam design method for semi-rigid composite frames with vertical loading at the serviceability limit state. Equations were developed to determine the deflections of the composite beam allowing for both joint flexibility and beam sectional properties, along with a formula for the connection secant stiffness. The equations for the connection stiffness are more accurate than previous equations used because it considers the beam-to-column stiffness ratio and the beam-to-connection stiffness ratio. The equations were validated by the experimental results for two semi-rigid composite frames. The equations agree well with the experimental data because they take into account the actual beam-to-column connections and the composite action between the steel beam and the concrete slab.

Key words: semi-rigid; composite frame; composite action; deflection; connection stiffness; serviceability

Introduction

Traditionally, composite beam-to-column joints are designed either as perfectly pinned or rigid connections. However, the actual behavior of the composite joints is semi-rigid with a range of moment-rotation characteristics. The benefits of adopting the semi-rigid joint design have become more obvious in recent years. Most recently built steel buildings have used concrete floor slabs designed to act as composites with steel beams by means of shear connectors[1]. There are also economic and structural benefits to utilize the partially restrained composite connections with some degree of continuity and without the disadvantages associated with the fully rigid approach. Thus, the semi-rigid composite frames are very useful and the effects of the semi-rigid connections and composite action of the slab should be properly considered in the design of steel frames.

When building frames are subjected to vertical and lateral loads, the distribution of the bending moment in the composite beams varies along the member length. In the negative moment region, the concrete is in tension and may crack and the steel reinforcement in the slab may be yielded. In the positive moment region, a large bending moment may cause yielding of the steel section and crushing of the concrete. Thus, the effects of the location vary as the moment varies along the beam.

Over the past thirty years, extensive studies[2-4] have been carried out to understand the actual behavior of semi-rigid connections. Many studies[1] have used the nonlinear numerical analyses of frame systems with semi-rigid connections. However, little effort has been devoted to developing simplified methods to calculate the deflection of semi-rigid composite frames. Although Wong et al.[5] proposed a set of equations and design charts to calculate the deflections of the composite beams according to the beam line theory, they

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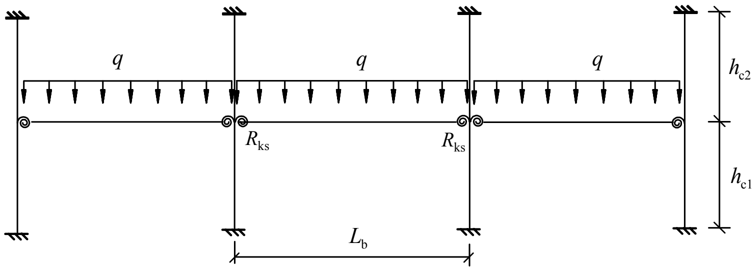
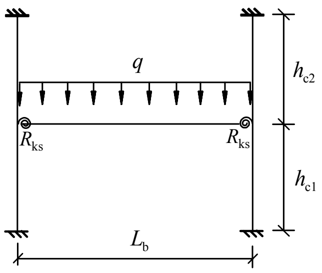
did not give an equation to determine the connection rotational stiffness at the serviceability limit state (SLS). This paper presents a simplified practical beam design method for semi-rigid composite frames at the serviceability limit state with vertical loading which takes into account both the joint flexibility and the beam sectional properties. An equation is given for the appropriate formula of connection secant stiffness and the design procedure is developed.

1 Simplified Deflection Equation

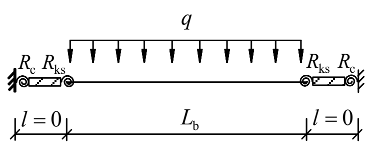
The internal forces and deformations in each individual beam of a multistory frame with vertical loads are usually evaluated by considering a plane frame (Fig. 1a). The column ends far from the beam under investigation can be assumed to be fixed. Each beam is assumed to have an effective value of the second moment of area, I_b, which approximately simulates the sectional properties of the composite beam. Due to the flexible natural of semi-rigid connections, the contributions to the end restraint from the beams on either side of the beam under consideration are generally insignificant. Consequently, a simplified subframe may be used to determine the moments and deflections of the composite beam with semi-rigid connections as shown in Fig. 1b. The simplified subframe can then be transformed to a beam line model shown as in Fig. 1c where R_{ks} and R_c are the rotational stiffnesses of the semi-rigid beam-to-column connections and the columns.



(a) Frame model



(b) Simplified subframe model



(c) Beam line model

Fig. 1 Calculation model

The rotation of beam-to-column connection, θ_r, based on the slope deflection method and the symmetrical properties of the beam line model, can be expressed as

$$\theta_r=\theta_b-\theta_c=\frac{qL_b^3}{24EI_b}-\frac{ML_b}{2EI_b}-\frac{M}{R_c} \tag{1}$$

where θ_b and θ_c are the support rotation of the beam and the column rotation at the joints, q is the uniformly distributed load, E is Young modulus of elasticity, M is the support moment of the beam, I_b is the effective second moment of area of the composite beam and

$$R_c=\frac{a_1EI_{c1}}{h_{c1}}+\frac{a_2EI_{c2}}{h_{c2}} \tag{2}$$

where I_{ci} is the second moment of area of the column at level i, h_{ci} is the story height for level i, and a_i is the column stiffness coefficient at level i. For the first story, $a_i=3$ for columns fixed and equally for columns pinned at their remote ends, while $a_i=4$ for other stories.

In Eq. (1), when the support moment of the beam is equal to zero, the support rotation of the beam is θ_{pin}, i.e., the support rotation of the beam with pinned connections; when the support rotation of the beam is zero, the support moment of the beam is M_{rigid}, i.e., the support moment of the beam with rigid connections. M_{rigid} and θ_{pin} are expressed as

$$M_{rigid}=\frac{qL_b^3}{24EI_b}\Big/\left(\frac{L_b}{2EI_b}+\frac{1}{R_c}\right) \tag{3}$$