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# Slab spatial composite effect in composite frame systems. I: Effective width for ultimate loading capacity

Jian-guo Nie, Mu-xuan Tao *

*Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Dept. of Civil Engineering, Tsinghua University, Beijing 100084, China*

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ABSTRACT

The slab spatial composite effect plays a significant role in the behavior of composite frame structural systems subjected to lateral forces. Since the ultimate loading capacity and stiffness are the two most basic characteristic behaviors in a design practice, this paper focuses on the influence of the slab spatial composite effect on the ultimate loading capacity, and the companion paper pays attention to the structural stiffness and internal force distribution. The extensive verifications of the proposed design methods for evaluating the ultimate loading capacity and stiffness considering the slab spatial composite effect based on various numerical examples and experimental programs are also carried out in the companion paper. In this paper, an elasto-plastic elaborate finite element model of the side joint is firstly developed in order to find the critical factors dominating the slab participation at the ultimate limit states. Furthermore, a parametric analysis is conducted to derive the simplified design formulas of the slab effective widths for calculating the ultimate positive and negative moments at the composite beam end. The predictions calculated using the proposed formulas correlate well with the numerical results. In addition, the proposed design methods are verified adapted for both side and middle joints. Finally, the proposed formulas are compared with some available formulas provided in the literature and current design codes. It is found that the proposed formulas can give the most satisfactory results for predicting the ultimate effective width and beam end moments.



## 1. Introduction

Steel–concrete composite frame structural systems have been widely used in multistory and high-rise buildings in recent years. Since the concrete slab are usually attached to the steel frames using shear connectors, the slab and the steel frame can behave compatibly subjected to lateral forces. Fig. 1a shows a typical composite frame structure and the lateral and vertical deformations of the composite frame subjected to lateral forces are respectively illustrated as Fig. 1b and c. The compatible deformation between the slab and the steel frame, and the spatial behavior of the slab can be clearly observed.

Many experimental researches have been carried out to investigate the behavior of composite frame systems [1–5]. It can be concluded from the previous researches that the slab spatial composite effect always exists in the elastic and plastic stages, and plays a significant role in the lateral resistant performance of composite frame structural systems so that (1) the lateral strength of the frame can be improved; (2) the lateral stiffness of the frame can be improved; (3) the natural periods of vibration of the frame can be shortened and the seismic effect may be amplified; and (4) the local behavior at beam–column joints can be changed. However, the slab spatial composite effect has not been intensively investigated in the previous theoretical researches on the behavior of composite frames [6–9].

Neglecting the slab spatial composite effect in the design of composite frame systems may result in: (1) the inaccurate evaluation of the structural lateral deformation, which is one of the most important indexes for the design of multistory and high-rise buildings using the performance based design method; (2) the underestimation of the proportion of the seismic shear force the frame undertakes in the frame–corewall structures, which may influence the rational evaluation of the structural dual seismic defenses; and (3) the underestimation of the ultimate loading capacity at the composite frame beam end so that plastic hinges may appear in unexpected positions and the weak-beam/strong-column design goal can not be satisfied. As a result, how to reasonably consider the slab spatial composite effect in both the elastic and elastic–plastic stages is one of the most critical issues for the design of composite frame systems.

In order to accurately simulate the slab spatial composite effect, using the elaborate shell or solid finite elements is one choice. However, such a modeling procedure may be too cumbersome and computational costing for the design of multistory and

* Corresponding author.
*E-mail address:* dmh03@mails.tsinghua.edu.cn (M.-x. Tao).

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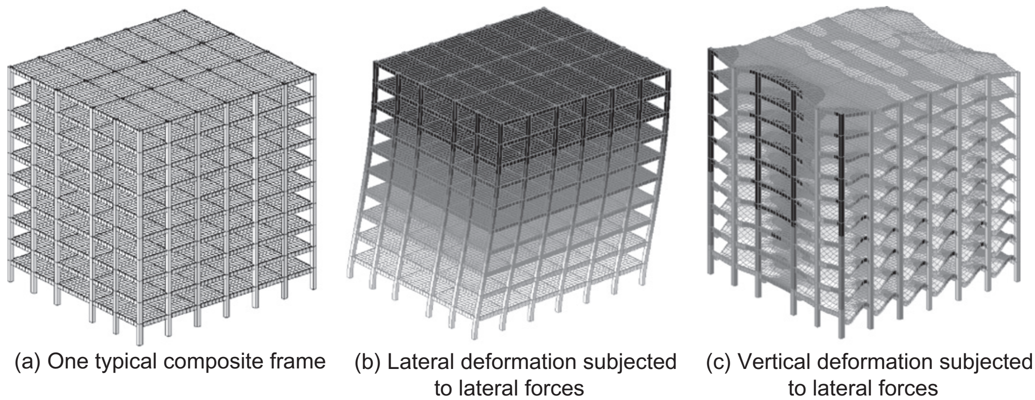


**Fig. 1.** Behavior of composite frames subjected to lateral forces.

high-rise buildings. As a result, the concept of effective flange width is usually used in a routine design practice for simplicity. Current design codes in different countries have given different recommendations for calculating the effective flange width of composite beams, but all these recommendations may be not adapted for composite frame systems which are mainly subjected to lateral loads due to the following two reasons:

### 1.1. Inappropriate load case

The methods proposed by Eurocode 4 (EC4) [10] as shown in Fig. 2a are mainly focused on continuous composite beams subjected to vertical loads. Four different equivalent span lengths are defined for four cases according to the moment distribution of the beam. However, since the composite beams in composite frame structures are mainly used to resist the lateral forces, the internal force distribution of the composite frame beams are quite different from that of the composite beams subjected to vertical loads.

### 1.2. Inappropriate equivalent rule

Fig. 2b illustrates the conventional definition of the effective flange width, which is based on the equivalence of the sectional maximum stress. As we all know, two basic steps (Fig. 3) are always required for the design of structures: the first is the global analysis of the structural internal forces and deformations, and the second is the checking of the ultimate loading capacity at all critical sections. The first step is closely related to the structural elastic stiffness. The stiffness of a structural member doesn't depend on a certain section, but the contribution of all the sections. Thus, the equivalence of the member stiffness should be used for the first step. The second step is closely related to the ultimate loading capacity of the critical sections. Since the plastic hinges should be formed at the composite frame beam ends for rational designed composite frames, the equivalence of the ultimate flexural capacity of the composite beam end section should be used for the second step. The equivalence of the ultimate flexural capacity has been used to derive the ultimate effective flange width by Nie et al. [11], but the proposed formula can only be used for the strength prediction of the composite floor under vertical loads where the plastic hinge appears at the middle span.

This research is mainly focused on the behavior of composite frame systems due to lateral forces, and how the slab spatial composite effect can be reasonably considered in the design of composite frame systems is the main topic. Fig. 3 gives the overall research framework, which can be divided into two parts: (1) the first part is to investigate the slab contribution of the beam end section at the ultimate limit states. The formulas for calculating the ultimate effective flange width of the beam end section is proposed to check the ultimate loading capacity of the critical sections; (2) the second part is to study the slab contribution to the stiffness of composite frame beams. Formulas for calculating the equivalent stiffness of composite frame beams are proposed for the global analysis of the structural internal forces and deformations.

This paper presents the first part of the research, and the companion paper [12] presents the second part. In addition, the proposed design methods both in this and the companion paper [12] are verified sufficiently by experimental programs in the final part of the companion paper [12]. Although this research mainly pays attention to the routine design practice of composite frame systems, the conclusions drawn in this research may provide a valuable support to the further research of the elastic–plastic whole-process behavior of composite frame systems.

## 2. Finite-element model and basic definitions

The behavior of the composite frame beam end at the ultimate limit state is not only influenced by the steel beam and the

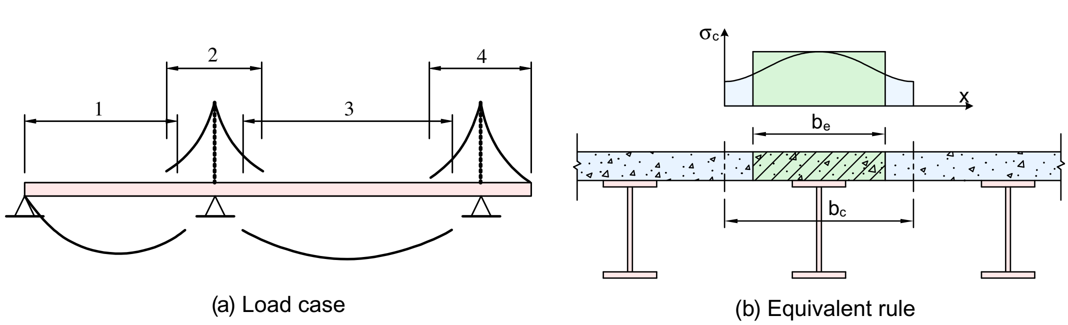


**Fig. 2.** Method for calculating the effective flange width proposed by EC4 [10].