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Simplified analysis method accounting for shear-lag effect of steel–concrete composite decks

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ABSTRACT

Due to the influence of steel beam web, the concrete slab and steel box-beam flange would undergo significant warping in steel–concrete composite decks with wide slab. Such mechanical behavior is referred as the shear-lag effect and often calculated by adopting effective width. There arises a necessity to propose a simplified analysis method based on effective width to account for the shear-lag effect of composite decks, which would greatly assist in design analysis as it is easy to use in a general beam element model. In this paper, the static tests are carried out on a composite twin I-girder deck and a composite box-girder deck specimens. These two specimens are subjected to vertically flexural and axially compressive loads in the tests. An elaborate element model is later built and utilized to analyze the shear-lag effect of composite decks. Through elaborate element model analysis on composite decks subjected to vertically flexural and axially compressive loads, respectively, the longitudinal distribution characteristic of effective width are determined. Furthermore, the prediction formulae of effective width are proposed. Finally, based on a general beam element model, the simplified analysis method of a composite continuous I-girder deck for the design process is performed taking into consideration three load cases, which include gravity load, traffic load envelope and prestressing load.

1. Introduction

Steel–concrete composite decks are widely used because of their high stiffness, superior strength, and lower self-weight, which result in great economical performance compared to other types of deck. In composite decks with wide slab, the usual assumption of cross-section to remain plane before and after loading is not realistic. In fact, the influence of steel beam web on the concrete slab or steel box-beam flange would cause significant warping in composite decks with wide slab. This mechanical behavior is referred as the shear-lag effect.

Studies dedicated to shear-lag effect of steel–concrete composite decks are divided into the following three stages:

Stage 1 is to develop the analytical model accounting for the shear-lag effect and to define the effective width. Von Karman first proposed the use of effective width method for aeronautical applications [1]. Reissner also recognized the significance of taking into account the shear-lag effect in the discipline of civil engineering, and presented an analytical model introducing a predefined warping function [2]. Adekola extended the partial interaction composite model of Newmark et al. to account for the shear-lag effect in the slab [3].

Stage 2 is to propose the prediction formula of effective width. Allen and Severn deduced the analytical solutions for the shear-lag effect of composite decks [4]. Adekola used the analytical solutions derived by Allen and Severn to calculate effective width for simple supported decks by considering the variation of geometric parameters [5]. It was found that the effective width was closely related to slab dimension and load type. Several years later, Ansourian applied the finite element method to perform the elastic analysis of composite fixed decks [6]. Those results concluded that reasonable slab stress is obtained when the effective width is taken as one quarter of the span length. This formulated the foundation for calculating the effective width of composite decks in EC4 [7] and AASHTO [8]. Later, Heins and Fan presented an analytical method for predicting the elasto-plastic behavior of composite simple supported decks and evaluated the effective width distribution at the ultimate load [9]. Amadio et al. discussed the correctness and applicability of the effective width formula suggested by EC4 through utilization of experimental and numerical methods [10,11]. It was established that the formula suggested by EC4 was conservative for predicting the plastic behavior of

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composite decks. In reality, the effective width increases continuously with the development of plastic behavior and finally achieves the geometrical slab width. Nie et al. conducted the experimental and numerical studies on the effective width of concrete slab at the ultimate strength limit state and proposed the corresponding prediction formula [12]. Chiewanichakorn et al. considered comprehensively the difference of slab stress distribution of composite decks at the elastic stage, the normal service stage (crack and uncrack of concrete slab) and the strength limit state [13–15]. The corresponding definitions and formulae of effective widths for three states were proposed. In recent years, Dezi and Gara have investigated in-depth the shear-lag effect of composite decks. Dezi et al. proposed the analytical solution on the shear-lag effect of composite decks based on the virtual work principle [16]. In the analytical solution, the linear elastic and linear viscoelastic behaviors were assumed for steel and concrete components, respectively. Gara et al. [17] and Ranzi et al. [18] compared four available numerical structural analysis formulations for composite decks with partial shear interaction at the slab–girder interface, which included the finite difference method, the finite element method, the direct stiffness method and the analytical method. Rationality and accuracy of the finite difference and finite element methods were further verified. Based on the foregoing studies, Gara et al. developed a beam finite element for the long-term analysis of composite decks, which can take into account the shear-lag effect in the slab and the shear interaction at the slab–girder interface [19]. This beam finite element model provided an available research tool to account for the shear-lag effect and the shear interaction for the analysis of composite decks.

Stage 3 is to propose the simplified analysis method based on the effective width. The implementation of simplified analysis method requires not only the adoption of effective width formula but also the determination of effective width distribution along the deck span. To determine the effective width distribution along the span, the whole span is usually separated as a series of equivalence spans and the effective width distribution in the range of whole span is obtained approximately by combining the distribution of all the equivalence spans. According to EC4's regulation, the equivalence span is only related to the geometrical span but not load type, as shown in Fig. 1. From the mechanical viewpoint, the length of equivalence span is, nevertheless, exactly equal to the distance between zero moment points. To solve this problem, Gara et al. utilized their proposed beam element model to redefine the methodology for determining equivalence span [20]. This methodology is suitable for three kinds of loading conditions, including constant uniformly distributed load, envelopes of traffic load specified by Italian guidelines [21] and supported settlements. Gara et al. finally implemented their analysis based on the use of effective width and equivalence span. Long-term and systematic studies conducted by Dezi and Gara et al. on shear-lag effect of composite decks are praiseworthy. However, a simplified analysis method appropriate to other types of traffic load, besides that suggested by Italian guidelines, is lacking and need to be addressed. In addition, stretching the prestressing tendon is a common technology to prevent cracking of concrete slab in hogging moment region. According to the study conducted by Dezi et al. [22], the value and longitudinal distribution of effective width of composite decks under compressive load are different from those under vertically flexural load. However, the methodologies of common codes of practice are usually only suitable for condition in which the vertically flexural load is applied to composite decks. Huge error may result when these methodologies are employed to calculate the effective width value and distribution of composite decks subjected to axially compressive load. Therefore, the study on shear-lag effect of composite decks under axially compressive load will also be conducted in this paper.

In routine practice of bridge engineering, structural stresses are generally controlled in a range far lower than yield strength, with the exception of the tensile stress of concrete slab that may exceed the tensile strength, resulting in crack of concrete. Hence, prestressing tendons are generally utilized in the slab to avoid such occurrence. On these premises, the main aim of this study is focused on the elastic mechanical range of composite decks. The shear-lag effect in the elastic mechanical range is suitably reflected by adopting these stress-based definitions:

$$b_{\mathrm{eff}} = \frac{\int_{A_c} \sigma(x,y,z)dydz}{\int_{h_c} \sigma_{\max}(x,z)dz} \tag{1}$$

$$b_{\mathrm{eff}} = \frac{\int_{b_c} \sigma(x,y,z_{\mathrm{mid}})dy}{\sigma_{\max}(x,z_{\mathrm{mid}})} \tag{2}$$

$$b_{\mathrm{eff}} = \frac{\int_{A_c} \sigma(x,y,z)dydz}{\sigma_{\max}(x)h_{\mathrm{c}}} \tag{3}$$

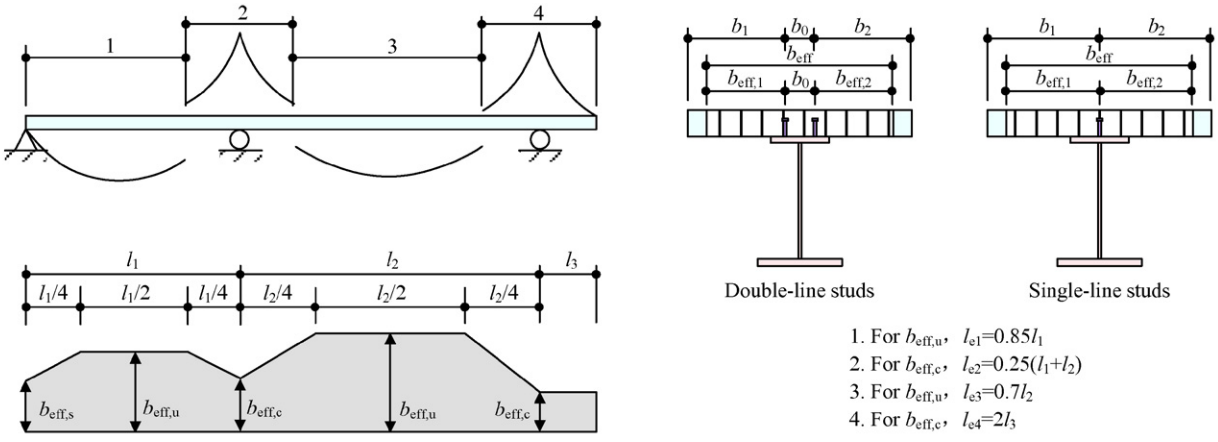

Fig. 1. Regulation of effective width and equivalent span in EC4.