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A solution considering partial degree of composite action for insulated sandwich panels with general configuration flexible shear connectors

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ABSTRACT

Insulated sandwich panels consist of two wythes separated by a non-structural insulation layer. These two wythes are connected using shear connectors. In recent years, Fiber-Reinforced Polymer (FRP) shear connectors have been increasingly used due to their low thermal conductivity. However, they have lower stiffness compared to other rigid shear connectors, resulting in partial degree of composite action (DCA) for the sandwich panels. Until now, insulated sandwich panels are designed based on the assumption that the longitudinal stress is uniform across the wythe, which is not reasonable since the in-plane shear flexibility of the wythe causes non-uniform distributions of the stress, which is called shear lag effect. This paper presents an analytical solution to study the behavior of insulated sandwich panels with flexible shear connecotors. To this end, a solution based on the shear lag model is firstly developed, where the partial DCA and boundary conditions from various configuations of the flexible shear connectors are considered. The effective width, an important parameter to describe the shear lag effect, is defined. The analytical model is then verified through close correlations among experimental, Finite Element (FE) and analytical resutls for multi-cell box girders; and FE and analytical results for an insulated concrete sandwich panel with FRP shear connectors. A parametric study is finally conducted using the analytical model to study the effects of deck stiffness and aspect ratio on the effective width. The results from this study can be used for the design of insulated sandwich panels.

1. Introduction

1.1. Insulated sandwich panels

Insulated sandwich panels are typically composed of two wythes separated by a layer of insulation. They can be used in different structures, including residential and commercial buildings, schools, warehouses, etc., as walls, roofs, and floors due to their many advantages, such as energy efficiency, acoustic and vibration control, fire and blast resistance, etc. As shown in Fig. 1, the insulated sandwich panels can be connected using various types of shear connectors, including steel ties, wire trusses, bent wires, truss-shaped connectors, and solid zones [1–4]. Although these connectors can establish effective connections, they can cause thermal bridging between the wythes, which impairs the advantage of the sandwich panels as insulating elements. Recently, these connectors are being replaced by Fiber-Reinforced Polymer (FRP) shear connectors [5,6], since FRP has a thermal conductivity about 14% that of steel, which can significantly reduce the thermal bridging. In addition, the non-corrosive FRP can increase the durability and decrease the maintenance cost [7,8].

1.2. Shear-lag effect

The importance of the sandwich panels demands the need for accurate description of their structural behavior. Until now, sandwich panels are designed as rectangular beams, where constant stress is assumed across the width of the cross-section. However, stress distribution for sandwich panels is non-uniform due to the in-plane shear flexibility of the wythe, which is called shear lag effect, as shown in Fig. 2 [10].

Reissner introduced the concept of the shear lag effect for isotropic sections [11]. Later, Reissner developed a shear lag model using the minimum potential energy for box beams [12]. Kemmochi et al. [13] followed Reissner's concept to obtain the shear lag for FRP sandwich panels with aluminum channel shear connectors. The authors were able to formulate the strain and deflection of the sandwich panel in terms of its flexural rigidity. However, the shear connectors were assumed to be rigid.

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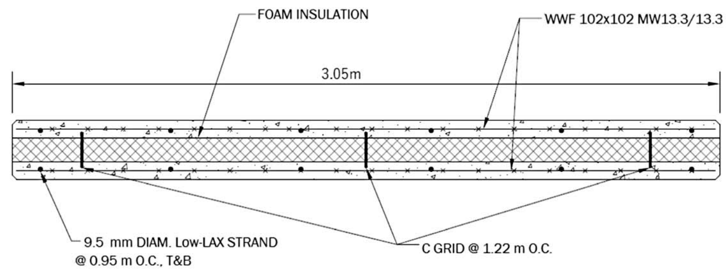
(a)



(b)

Fig. 1. Sandwich panels with FRP connectors. (a) Tested panel with FRP shear grid [1]. (b) Cross section of test panel [9].

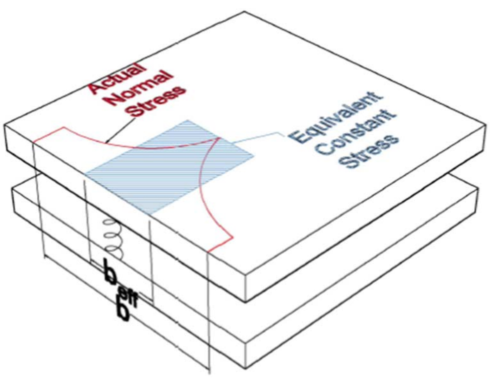


Fig. 2. Effective width.

Evans and Taherian [14] proposed a bar method to predict the shear lag in box girders. In this method, the web and flanges of the box girder are converted into equivalent axial load carrying bars where the forces can be calculated at each bar. The bar simulation was then expanded to study multi-cell and continuous box girders [15]. Upadyay and Kalyanaraman [16] used the bar simulation method to study box girders undergoing distortion and buckling. Although this method is simplified, however, it still assumes perfect interaction between the webs and flanges of the box girders.

Evans and Shanmugam extended the bar method to grillage method to analyze the shear lag effect for multi-cellular structures [17]. The grillage system is ideal for two-dimensional continuous bridge deck where it can be idealized into two perpendicular beam elements. Since then, the grillage method has been used for bridge design and analysis [18–20]. However, this paper is focused on one-way sandwich panel.

Cheung and Chan [21] used finite strip method to evaluate the effective width of a slab-on-multi-cellular box girders. The slab and girders were idealized into folded plates, which were divided into strips. However, this method was complicated and difficult to implement.

Kristek et al. [22] proposed a shear lag model based on harmonic analysis. The method was applied to steel and steel-concrete composite box girders. This paper represents the keystone for the shear lag analysis due to its simplicity and fairly accurate results. The shear lag model was then generalized to include multi-cellular structures [23]. Kristek [24] expanded the harmonic analysis model to account for the partial interaction between the concrete slab and steel box girder. However, the interaction was based on the friction between the overlapping area of concrete slab and steel flange and not the location of shear connectors, which limits this model to structures with one shear connector only.

Salim and Davalos [25] extended the harmonic method to model the shear lag for thin-walled composite beams. The model was based on the mechanics of laminated beams model proposed by Barbero et al. [26]. Explicit formulas were derived for single box, multi-box and wide-flange sections. Later, Zou et al. [27] evaluated Salim's model for orthotropic FRP bridge decks, where good correlation was achieved between the analytical model and experimental results. However, these models did not consider partial Degree of Composite Action (DCA).

In all these studies, effective flange width was used to describe the shear lag effect, reducing the three-dimensional behavior of the structural system to the analysis of a two-dimensional section with a reduced width of flange. Fig. 2 shows that a uniform stress can be assumed along the reduced width b_{eff}. The area of this stress block is equivalent to the area of the actual stress distributed along the width b. This reduced width b_{eff} is called effective flange width. This paper will extend the concept of effective flange width to insulated concrete sandwich panels based on the shear lag model. In particular, partial DCA will be considered, as described next.

1.3. Degree of composite action (DCA)

Headed steel studs are typically used to connect the deck and girder for a deck-on-girder composite beam system. These connections are rigid and the slip between the deck and girder is minimum. This slip is usually neglected in the calculation of effective flange width. Unlike rigid headed steel studs, FRP connectors are flexible. Therefore, the slip between the two wythes cannot be neglected for sandwich panels with FRP shear connectors. Degree of Composite Action (DCA) can be used to interpret this slip.

DCA depends on the shear force transferred through shear connectors between the two wythes. As shown in Fig. 3, Lorenz and Stockwell [10] pointed out that 100% and zero shear forces can be transferred for full-composite and non-composite cases, respectively. Partial DCA is from the limited amount of slip due to the inadequacy of the shear connectors to maintain strain compatibility.

Several studies have studied DCA for sandwich panels. Benayoune et al. [28] calculated the DCA for sandwich panels based on the stress distribution as follows:

$$DCA = \frac{I_e}{I_g}, I_e = \frac{M \times h}{\sigma_b - \sigma_t} \quad (1)$$

where σ_b, σ_t are the stresses at the bottom and top faces of the panel, respectively, M is the applied bending moment, h is the depth of the panel, I_g is the moment inertia of the sandwich panel with 100% DCA and I_e is the effective moment of inertia. The ratio between I_e and I_g can be defined as DCA.

The earliest investigation of GFRP as a shear connector for insulated sandwich panels was conducted at Iowa State University in 1988 [29], where the authors proposed a method to determine the DCA based on the percentage of the existing moment (M_{ext}) at the mid-span resisted by the internal non-composite moment of the top wythe (M_{tw}) and bottom wythe (M_{bw}):