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Analysis of partially composite foam insulated concrete sandwich structures

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ABSTRACT

This paper presents the theoretical development that defines the small displacement behavior of foam insulated concrete sandwich panels. Composite theories presented by other researchers are first thoroughly reviewed and scrutinized in the context of their use for precast concrete beams. A more rigorous Discrete Model that incorporates the complex shear deformation behaviors and independent flexural resistance of the concrete wythes is then derived. Experimental data from full-scale precast sandwich panel tests are used to validate the developed methodology. Finally, it is demonstrated that this study provides a rigorous analysis methodology for foam insulated concrete sandwich structures.

1. Introduction and background

1.1. Historical development of composite structures

Recently, due to energy efficiency interests, foam Insulated Concrete Sandwich Panels (ICSP), as illustrated in Fig. 1, have gained popularity in civil engineering construction. ICSPs provide thermal efficiency advantages over other traditional building façade construction due to the layer of insulation sandwiched between the structural concrete wythes. Unfortunately, this layer of insulation, along with the shear connectors, results in significant behavior complexity, and an absence of versatile analysis methodology. This research focuses on developing a suitable ICSP theory after reviewing typical composite structures and associated theoretical developments. The research developments presented herein are limited to elastic small displacement behavior of sandwich panels that have symmetric wythes.

Partially composite structures of three layers and more, sometimes called sandwich or laminated structures, have been used for structural purposes for more than a half century in the aerospace engineering and nailed timber construction industries. During this time period, a number of analysis methods have been derived [2–11]. In the late 1940s, Granholm [1] published his theory and work in the field of nailed timber structures. Granholm's theory focused on the equilibrium of axial force within individual layer and overall bending moment of the whole cross-section. More than a decade later, Holmberg [2] adopted and improved Granhom's theory by considering additional transverse action and applied it to various concrete structures. Meanwhile, Allen [3] and Hartsock [4] respectively published essentially the same governing equations with each other by considering the kinematics relation between interior and exterior wythes, and overall shear or bending moment equilibrium. Later, based on very similar governing equations of Hartsock [4], Ha [5,6] and Davies [7] focused on aspects of matrix formation and finite element algorithm. Also, there are a number of studies that focus on a particular aspect of sandwich structures construction, such as design optimization, structures with thin or thick wythes [8], and development of various composite elements [9]. Therefore the list of multi-layer composite structures theories is extensive, and a comprehensive review and study of over 1300 publications is available [10].

In bridge engineering, two-layer composite structures such as composite steel concrete T beams have been widely used and studied theoretically [12–18]. In 1951, Newmark [12] published his work on composite T beams; his theory was derived from the strain compatibility of the steel concrete interface. In 1967, Goodman [11] proved that Newmark's theory is the same with Granholm's [1]. Since then, a number of studies targeting different aspects of composite T beam mechanics have been carried out. Girhammar [13] developed a second order analysis approach. Ranzi [14–16], Salari [17], and Sousa [18] published studies involving finite element formation. Fabbrocino [19] employed predefined moment curvature relation and force equilibrium to study the mechanics of composite T beams. Xu [20,21] considered the

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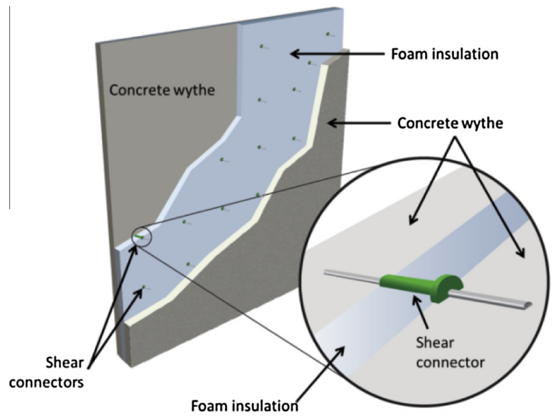

Fig. 1. Typical sandwich panel geometry.

composite cross-section in a plane stress state and derived theoretical solutions.

The mechanical behaviors of metallic sandwich panels, nailed timber systems, composite bridge beams and ICSPs are similar in some respects. For example, they all consist of a relatively deformable middle layer that results in large overall shear deformation. However, there are also significant differences. For example, metal faced sandwich structures, due to the slenderness of the face plates, are more susceptible to face buckling and other local failure modes. For nailed timber and composite bridge beams, components are connected tightly through shear connectors, leaving little room for shear deformation. Actually, those two-layer composite structures could have fairly high composite action that in some circumstances may be considered as fully composite. Whereas metallic sandwich panels and ICSPs have a thick middle insulation bearing considerable amount of shear deformation and therefore are usually partially composite.

1.2. ICSP literature

Increasing building constructions involving ICSPs call for accurate analysis theory. The majority of available literatures focus on experimental studies [22–42], although there have also been attempts to define sandwich panel behavior by force equilibrium [22,23], classical beam theory [24,25], and adapting various existing composite theories [26,27]. Most of those theories however are not appropriate for ICSP behavior and not derived rigorously nor validated by experiments. Consequently, few of them properly predict the response behavior of concrete sandwich structures to transverse loading.

ICSP analysis methodologies by others [22,24,25,28] typically consider sandwich structures to be classical Euler–Bernoulli beams involving flexural deflection only, and then attribute the additional unexpected deflection of the sandwich beam to a reduced moment of inertia through the concept of composite ratio. The present study uses a closed form solution to demonstrate that the additional unexpected deflection, along with other unexplained behaviors, is the consequence of shear deformation within the insulation layer. The moment of inertia should still be calculated without reduction until cracking. In this way, the correct stress and strain distributions can be determined.

2. Sandwich structure mechanics

Before proceeding with the theoretical development, sandwich structures' general behavior will be briefly introduced. One of the essential differences distinguishing ICSPs from conventional solid beams is the significant shear deformation. Therefore the deflection can be considered to consist of two components, shear deflection and flexural deflection, as illustrated in Fig. 2(b) and (c), respectively. These two components interact with each other through shear connectors and the insulation layer, resulting in four internal forces: two identical local bending moments around two wythes and one pair of opposite axial forces that form an overall bending moment around the entire cross section. External moment is resisted by means of summing these internal bending moments at any given cross-section.

The flexural deflection can be obtained readily by Euler–Bernoulli beam theory, but the shear deflection is complicated and can vary due to different shear connector stiffness, wythe thickness, theories employed and assumptions. The primary difference of various theories lays in this shear deflection and will also be discussed thoroughly in later sections.

3. Typical theoretical developments

Theories that could potentially be applied are mainly from three areas: thin face metal laminated plate [3–9], composite steel concrete T beam [12–21], and nailed timber structures [1,11]. Among these three areas, some theories are similar in terms of deriving governing equations and therefore are applicable to each other in the elastic range with modification. Here two major strong form theories are chosen prior to proposing a new model. Assumptions shared by both are listed as:

(1) Structural behavior is limited to elastic and small displacement, and the constitutive relation is assumed to be linear.
(2) The wythes have the same deflections.
(3) Perfect bond is achieved at the interfaces between the middle foam layer and the wythes, meaning that no relative sliding occurs at the two interfaces. However, the two wythes move relative to each other due to the shear deformation of the middle layer, and in the literature, this relative movement is referred to as "slip". Therefore, even though no sliding occurs and the use of the word "slip" may not be mechanically accurate, "slip" will be used herein to be consistent with other prominent literatures.
(4) Continuous and constant middle layer shear stiffness exists along the span.

3.1. Single cross section sandwich theories

The first category of theories [3–5] considers the two wythes connected by the middle layer as one whole unit, and only one governing equation is derived in this manner. Among these theories, Allen's [3] and Hartsock's [4] theories are most frequently referenced since their assumptions are most realistic. Also, these two are equivalent as demonstrated by Ha [5]. Therefore, Allen's theory is used to illustrate the approach herein.

From the geometry and shear deformation kinematics shown in Fig. 3, the shear deformation can be represented as follows:

$$y_s' = \gamma \frac{c}{2r} \tag{1}$$

where y_s = shear deflection; $c = 2r - d$ = middle layer thickness; d = wythe thickness; $2r$ = distance between centroids of two wythes; and γ = shear strain of middle layer. The shear stress caused by flexural deformation in the middle layer can be considered to be constant since the stiffness of the middle layer foam is much lower than that of concrete. Also, because of the existence of the shear stress and strain in the middle layer, the wythes must retain compatibility with the middle layer shear strain, resulting in additional