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Precast concrete sandwich one-way slabs under flexural loading

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ABSTRACT

The behavior of precast concrete sandwich panels consisting of two thin R/C layers (wythes) separated by an expanded polystyrene core is examined through experiments on prototype panels subjected to four-point bending, for different values of panel thickness and mesh size, with/without either shear-resistant ribs or conventional steel rebars (besides the wire mesh) in the bottom wythe. The test results indicate that all the panels behave as composite member until failure, and the panel behavior is similar to conventional R/C one-way slabs under flexural load. Due to the presence of wire mesh, cracking behavior in terms of number of cracks and crack spacing of concrete sandwich panels is similar to that of ferrocement cracking behavior. Volume ratio and specific surface of reinforcement affect the cracking behavior of concrete sandwich panels similar to that of ferrocement panels. The crack spacing based on predictive models for concrete slab reinforced with wire mesh agrees with the experimental results. Presence/absence of shear-resistant ribs and/or rebars in the bottom wythe significantly affects the flexural behavior of the panels. Presence of conventional rebars in the bottom wythe together with the wire mesh increases the ultimate flexural load capacity of the panels. The load-deflection response of the concrete sandwich panels exhibits trilinear behavior, and is similar to ferrocement behavior under flexural loading. Analytical study includes strength predictions based on conventional R/C beam analysis.

1. Introduction

Use of precast technology and lightweight structural members has gained wide acceptance in construction industry. Precast concrete sandwich slabs/panels have combined advantages of precast technology and lightweight structural members. These types of panels may consist of two concrete R/C layers (wythes) separated by a core made of less dense material that often provides significant thermal and sound insulation. Welded wire mesh or rebars may be used as reinforcements in the wythes. The degree of composite action achieved by concrete sandwich panels primarily depends on type of shear connectors used to connect the wythes. Shear connectors may be discrete or continuous (truss-shaped) that are spanwise-distributed.

State-of-the-Art report by PCI committee [1] provides detail description of panel types, design and detailing, insulation performance calculation procedures and manufacturing methods of precast/prestressed concrete sandwich panels. Yee [2,3] reports that the use of precast concrete technology, besides being structurally and economically efficient, also have social and environmental benefits. Pfeifer and Hanson [4] carried out experiments on small-scale concrete sandwich panels to study their flexural behavior. Different types of wythe reinforcement, shear connectors, and core thickness were used in their experiments. They concluded that the presence of edge ribs and type of shear connectors significantly affect the failure load and the flexural behavior, respectively, of the panels. Einea et al. [5] found that full-scale concrete sandwich specimens exhibit more composite action than small-scale specimens, and this shows the necessity of testing prototype concrete sandwich panels in order to understand their flexural behavior. Bush and Stine [6] found that truss girder connectors provide high degree of composite action of the panels. In order to improve thermal efficiency, Fiber Reinforced Polymer (FRP) connectors were used as shear connectors by Salmon et al. [7]. Tomlinsons and Fam [8] studied the effect of sizes and spacing of Glass Fiber Reinforced Polymer (GFRP) connectors on the flexural behavior of precast concrete panels. They also examined the effect of adhesion and friction between the concrete and insulation. They found that increase in the percentage of area of shear connectors increases the ultimate load of the panels. They also found that adhesion and friction contributed 44–59% of the ultimate load. Pantelides et al. [9] studied the flexural behavior of precast concrete panels with shell connectors as horizontal shear transfer

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mechanism. They found that panels with shell connectors can withstand out-of-plane loads at the same time resisting horizontal shear between the concrete wythes.

Flexural behavior of concrete sandwich panels under one-way action and two-way action was studied by Benayoune et al. [10]. Their study indicates that the panels behaved similar to conventional R/C slabs. Gara et al. [11] studied the effect of no-shear connectors on the flexural behavior of concrete sandwich panels. They found that the panels exhibited semi-composite action. Amran et al. [12] carried out experimental and analytical studies on the behavior of concrete sandwich panels with foam as the core. Six specimens were tested and they found that the behavior is similar to conventional R/C solid slabs. Pessiki and Mlynarczyk [13] carried out experimental and analytical studies on concrete sandwich panels to study the effect on composite action of the panels by different shear transfer elements such as solid concrete region, metal wythe connectors (M-tie) and bond between concrete wythe and insulation. They reported that solid concrete region significantly affects the composite action and ultimate load of the panels. Hassan and Rizkalla [14] proposed design guidelines for sandwich wall panels with Carbon Fiber Reinforced Polymer (CFRP) shear connectors. They concluded that the percent of composite action is superior when Extended Polystyrene (EPS) is used as an insulation material when compared to Extruded Polystyrene (XPS).

Experimental and analytical studies with respect to the behavior of insulated concrete panels under in-plane and eccentric compression were carried out by Gara et al. [15], Benayoune et al. [16,17] and Frankl et al. [18]. The behavior of precast concrete insulated panels under combined flexural and axial loading was reported by Tomlinsons and Fam [19]. They used basalt Fiber-reinforced polymer for the shear connectors and longitudinal rebars. They report that when compared to stiffness strength reduction is higher when axial compression was increased. Load-moment interaction diagram based on the experimental results was also reported by the authors. Experimental and analytical studies to investigate the effect of connectors (made of materials such as GFRP, CFRP, Carbon steel, Basalt FRP bars etc.) on the behavior of precast concrete insulated sandwich panels were carried out by Woltman et. al. [20] and Naito et al. [21]. They found that there is considerable variation in strength, stiffness and deformability of shear ties used in sandwich panels.

Ferrocement is a form of reinforced concrete that is different from conventional reinforced concrete primarily in the manner in which the reinforcing elements are dispersed and arranged [22]. Ferrocement normally consists of one or more layers of closely spaced wire mesh as reinforcement embedded in mortar. Ferrocement panels may have thickness equal to or even less than 25-mm. Ferrocement, a composite material, behaves differently from conventional reinforced concrete. More importantly, ferrocement has superior cracking behavior when compared to conventional reinforced concrete [22]. Cracking behavior of ferrocement is influenced primarily by the factors such as volume fraction of reinforcement (V_r) and specific surface of reinforcement (S_r) [23]. Volume fraction of reinforcement (V_r) is the ratio of volume of reinforcement embedded in composite (say, mortar) to volume of the composite. Lighter mesh and more layers of wire mesh increase the volume fraction of reinforcement. Specific surface of reinforcement (S_r) is the ratio of total lateral surface area of the bonded reinforcement to volume of the composite. Normally ferrocement panels have high specific surface of reinforcement, and it may be one to two orders of magnitude as that of conventional reinforced concrete [23]. Ferrocement has high reinforcement ratio with volume fraction of reinforcement in the range of 2–8%. However, distinct characteristics of ferrocement are evident only at higher values of specific surface of reinforcement [23]. It is logical to expect cracking behavior of concrete sandwich panels with wythe thickness of 25-mm and using wire mesh as reinforcement in tensile wythe (i.e., bottom wythe in flexure) to be similar to that of ferrocement. However studies to investigate this aspect of concrete sandwich panels are not found in the literature. Also, in the literature studies with respect to behavior of concrete sandwich panels under flexural loading are available but studies with respect to behavior of concrete sandwich panels reinforced with both wire mesh and conventional rebars are not found. The flexural behavior of concrete sandwich panels using both wire mesh and conventional rebars as reinforcement in bottom wythe may thus include (i) load–deflection response, and (ii) cracking behavior. If the composite action is achieved in these panels, the load–deflection response may be comparable to that of conventional R/C solid slabs, and factors such as volume fraction of reinforcement (V_r) and specific surface of reinforcement (S_r) may affect cracking behavior of concrete sandwich panels similar to ferrocement.

It is also important to note that, providing additional conventional rebars together with the wire mesh in the bottom wythe increases the reinforcement percentage, and therefore may trigger shear failure of concrete sandwich panels. This aspect is also investigated in the present study. Experimental program also includes panels with shear-resistant ribs provided along the longitudinal edges of the panels to preclude shear-controlled failure.

This paper presents results of flexural tests carried out on prototype precast lightweight concrete sandwich one-way panels. In the experimental investigation wire mesh size, panel thickness, presence/absence of shear-resistant ribs and presence/absence of rebars in bottom wythe together with wire mesh are the major variables considered. Effect of these variables on the failure mode, failure load, load-deflection behavior, load-strain behavior and cracking behavior of the panels are studied and discussed. Also, the predictability of model to predict flexural crack spacing and flexural strength prediction based on conventional R/C beam analysis are presented in this paper.

2. Concrete sandwich panel behavior

The flexural behavior of precast lightweight concrete sandwich panels under one-way bending may be expected to behave similar to sandwich beams. In design of sandwich beams for flexural load, it is common to assume wythes to resist bending moment and core to resist shear. The only difference between ordinary beams that obey elastic bending theory and sandwich beams is that the deflection due to shear deformation of the core is not neglected in the latter. Based on the interaction between the wythes and the core, sandwich beams may be classified into three types such as fully composite, semi-composite and non-composite [1]. The bending stress distributions across the depth of the cross-section based on linear elastic bending theory for the three types of sandwich beams are shown in Fig. 1. In order to achieve fully composite action, the shear transferring capacity between the top and bottom wythe should be ensured.

3. Experimental campaign

The experimental program consists of 10 prototype precast lightweight concrete sandwich one-way panels tested under four-point bending. The parameters examined in this project concern the mesh size, the panel thickness, the shear-resistant ribs and conventional rebars added to the wire mesh in the bottom wythe. Expanded Polystyrene (EPS) is used as the core. Wires of the mesh and shear connectors are made of high strength steel with average yield strength of 651-MPa. Conventional rebars used