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In-plane shear behavior of insulated precast concrete sandwich panels reinforced with corrugated GFRP shear connectors

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A B S T R A C T

Precast concrete sandwich panels often are used for the exterior cladding of residential and commercial buildings due to their thermal efficiency. Precast concrete sandwich panel systems consist of two precast reinforced concrete walls that are separated by a layer of insulation and joined by connectors that penetrate the insulation layer and are anchored to two precast concrete wythes. This paper presents push-out test results of concrete sandwich panels with and without corrugated shear connectors to investigate in-plane shear performance. The variables in this study are two types of insulation materials and the width, pitch, and embedment length of shear connectors. The test results indicate that the type of insulation material that is used in the system considerably affects the bond strength between the concrete walls and the insulation layer. A design equation adopted in ICC-ES is revised to determine the shear design capacity of precast concrete sandwich panels with various configurations of shear connectors.

1. Introduction

Insulated precast concrete sandwich panel (PCSP) systems are widely used commercially due to their economic advantages and superior thermal and structural efficiency [1]. As shown in Fig. 1, the PCSP system discussed in this study consists of exterior and interior precast concrete panels, called *wythes*, separated by a layer of rigid foam insulation. The presence of the insulating layer enhances the thermal efficiency of the PCSP system. The two discrete thin concrete wythes help resist applied loads by changing the shear transfer mechanism of a conventional concrete wall panel.

According to the degree of the composite action of the interior and exterior concrete panels, insulated sandwich panels are classified in terms of design as fully composite, non-composite, or partially composite, as shown in Fig. 2 [2].

The degree of composite action depends on the adhesion between the insulation and the concrete and the type of shear connector used in the system. Connections between the concrete panels (and thus through the insulating layer) can be made by using a steel truss, various specially-designed steel, and solid zones of concrete [3–5]. Such connectors, however, interrupt the continuity of the insulation layer and are known as 'thermal bridges'. These thermal bridges result in the severe reduction of the R-values of the PCSP system [6].

Recently, fiber-reinforced polymer (FRP) connectors have been employed to help solve the problem of thermal bridging because they have a higher ratio of strength-to-mass density and a lower level of thermal conductivity than concrete and steel [3–5]. Several researches have been conducted experimental tests and numerical analysis to understand the bond-slip behavior of FRP in concrete and delamination behavior of FRP on concrete surface as rehabilitation materials [7–12].

However, it is difficult to determine the level of composite action using FRP shear connectors. It is also hard to predict the structural performance of the panel, including the moment capacity and thermal deflections (or thermal bowing) caused by the temperature differences between the two concrete wythes. Soriano [5] conducted a comprehensive testing program of 66 panels that were subjected to direct shear testing to determine the effects of different combinations of parameters, including the type of foam, thickness of the foam, and spacing between the rows of grids, on the shear flow strength of the panels. Soriano proposed a design

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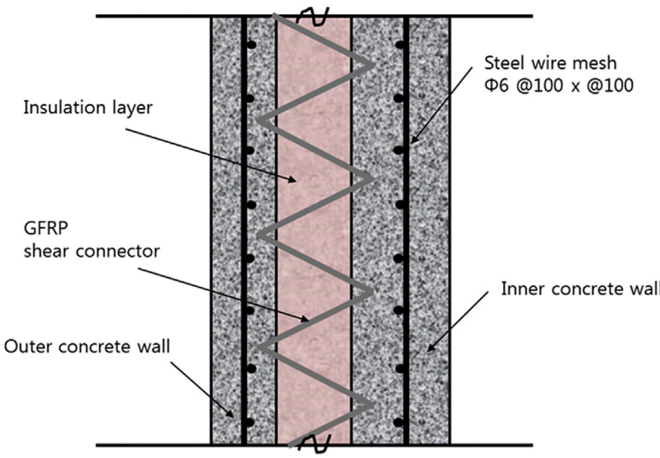

Fig. 1. Typical PCSP system reinforced with GFRP shear connectors.

equation to determine the shear flow capacity of the combined glass fiber-reinforced polymer (GFRP) grid and rigid foam insulation mechanism.

Similar to the related research conducted by Soriano [5], the main objective of this experimental program is to characterize the in-plane shear behavior that results from the combination of a GFRP grid and the rigid foam insulation in a PCSP system. Various parameters were considered for this study, including the type and thickness of the rigid insulating foam and the spacing between the individual rows of the grid. Research results from other recent studies [13–15] conducted by the author indicate that the shear flow strength is reduced due to failure of the embedded area when the embedment length is insufficient. In these earlier studies, this deficiency in the length of the embedment led to brittle failure after reaching the maximum load [13–15]. Therefore, for the current study, various embedment lengths were considered to investigate the in-plane shear behavior of an insulated PCSP system. Small-scale specimens of typical sandwich wall panels were used to determine the shear flow strength of the PCSP system with regard to the effects of various parameters. The experimental results were used to propose a recommended design equation and a robust database of shear flow values for various panel configurations.

The flexural behavior of PCSP with steel truss shear connectors under axial loading was investigated experimentally and analytically by Benayoune et al. [16] and Carbonari et al. [17].

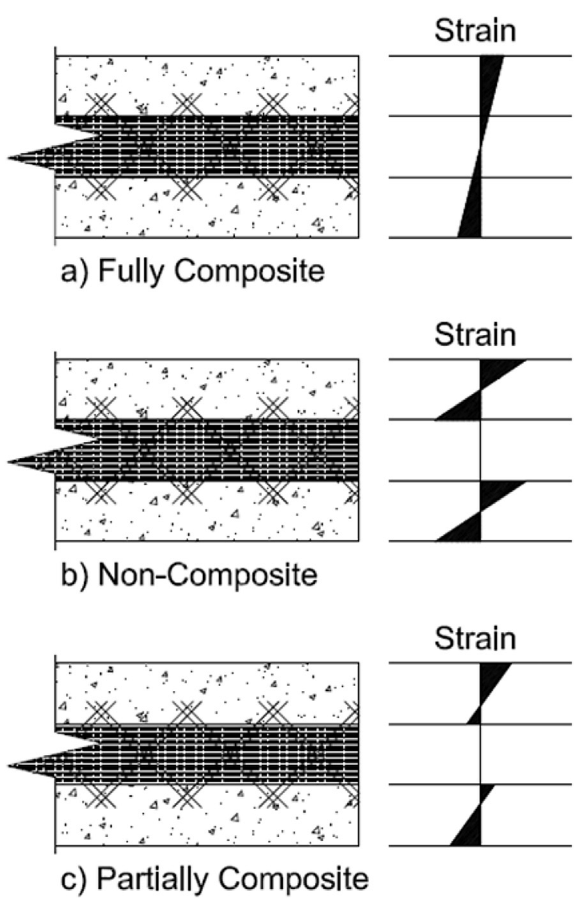

Fig. 2. Strain profiles of insulated sandwich panels for various degrees of composite action [2].

2. Experimental program

2.1. Test plan

The experimental design used in this study considers two types of insulation material and various installation methods for the use of corrugated GFRP shear connectors. Fig. 3 shows two types of insulation material considered in this study: expanded polystyrene (EPS) and extruded polystyrene (XPS), which are both commonly used in Korea.

You [18] reported that XPS insulation debonded when formwork was demolded and transported due to the weak adhesion capacity between the insulation and concrete wythe. Therefore, in a later study by Oh et al. [19], the researchers used a 10-mm wide groove and rough surface treatment of the XPS to enhance the insulation's adhesive capacity. This surface treatment increased the bond strength and composite behavior of the PCSP system [19].

Fig. 4 shows a corrugated GFRP shear connector that is commercially available in Korea. The shear connector incorporates a 45-degree angle to the shear plane and is 5 mm thick. Table 1 presents the section and material properties of three different types of this shear connector. The three variables used in this study to investigate the toughness of the GFRP shear connector are its pitch, height, and width.

2.2. Details of specimens

Direct shear specimens were employed in this study according to ICC-ES [20] to determine the shear resistance of the rigid insulation in a concrete sandwich panel using corrugated GFRP shear connectors.

Fig. 5 shows the design of a 'push-out' specimen that is composed of three concrete wythes and two insulation foam wythes. For this study, the thickness of the inner (middle) concrete wythe was 130 mm for all specimens, and the thicknesses of the outer concrete wythes were 60 mm and 80 mm with respect to the embedment length of the shear connector. The thickness of the inner insulation foam was 100 mm. The middle concrete wythe was reinforced with reinforcement yield strength of 400 MPa (SD400) and rebar diameter of 13 mm (D13) with 100 mm spacing in the longitudinal and transverse directions. The inner and outer wythes were reinforced with welded wire reinforcement (100 mm × 100 mm) with yield strength of 400 MPa (SD400). A shear connector was placed every 300 mm. Four locations were reinforced with the corrugated GFRP shear connectors.

Table 2 provides the specimen designations that represent the type of insulation and the width of the GFRP shear connector used