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Effect of cyclic loading on composite behavior of insulated concrete sandwich wall panels with GFRP shear connectors

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ABSTRACT

A full-scale experiment was conducted to investigate the composite behavior of insulated concrete sandwich wall panels (ICSWPs) under monotonic loads and wind-induced cyclic loads. The experimental program consists of two groups, according to the applied loading type and the type of insulation, with the same configurations of glass-fiber-reinforced polymer (GFRP) grids. The degree of composite action in terms of the initial stiffness and ultimate strength were compared at the global level, and the degree of composite action in terms of the shear flow were compared at the local level (in accordance with the variables). The test results showed that the adhesive bonds based on the insulation absorptiveness and the mechanical bonds based on the insulation surface roughness and groove treatment were effective for inducing the desired composite behavior of ICSWPs in both monotonic loading and cyclic loading tests. The cyclic test group showed a lower degree of composite action compared to the monotonic test group at a constant rate. This is the case because cumulative fatigue loading damaged the GFRP strands and debonded the interface between the concrete and insulation. These results indicated that the adhesive and mechanical bonds between the insulation and concrete wythes can be used to estimate the design strength of ICSWPs with GFRP shear grids. Additionally, the reduction factor for the design strength by the fatigue effect should be considered in estimation of design strength.

1. Introduction

Due to the ongoing worldwide depletion of energy sources and natural resources, reducing the amount of energy consumed while constructing or using buildings has become an increasingly salient issue. Heat loss through building envelopes accounts for the largest amount of energy consumption by buildings; this heat loss accounts for 33% of energy consumption worldwide. This heat loss is especially high (60%) in the case of residential buildings in areas with cold climates [1]. Therefore, insulated concrete sandwich wall panels (ICSWPs) are systems that can be used to reduce the energy consumption of buildings because they provide insulation by including an extremely low thermal conductivity material that is inserted between their internal and external concrete wythes. In addition, they can help reduce the construction period if ICSWPs are used as curtain walls. However, ICSWPs must satisfy the existing structural performance requirements for curtain walls. Because the influence of the wind load increases as the height of a building grows, the verification of safety and serviceability for ICSWPs can be needed with regard to the specific circumstance.

ICSWPs are generally comprised of internal and external concrete wythes with insulation in between. The internal and external concrete wythes are connected by connecting elements in order to enhance their composite behavior. The connecting elements include the shear connectors (which connect the internal and external concrete wythes using concrete, steel, and fiber-reinforced polymer (FRP) materials) and the insulation inserted between the internal and external concrete wythes. In addition, the bond between the insulation and concrete wythes can be viewed as a connecting element. Choi et al. [2] and Jang et al. [3] experimentally showed that the shear flow capacity between the insulation and concrete wythes is affected by the width and the embedded length of the shear connector and the type of insulation. The degree of composite action of ICSWP is determined by the shear flow capacity of the connecting elements; these can be classified as full-

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composite, partial-composite, or non-composite according to the degree of composite action.

According to Bush and Stine [4], although steel continuous truss connectors showed buckling of compressed truss diagonals and yielding of tensile truss diagonals, ICSWPs reinforced with steel continuous truss connectors have a high degree of composite action in terms of strength. While a sufficient shear flow capacity can be secured by using a steel material as the shear connector, this lowers the energy efficiency of the building because of the high thermal conductivity of the steel material. Research involving the use of FRP materials (with a lower thermal conductivity) as a substitute for steel began in the mid 1990's. Recently, glass-fiber-reinforced polymer (GFRP) was used for reinforcement of thin concrete panel and I-section beam as an alternative of steel material in order to decrease the heat loss [5,6]. Einea et al. [7] observed ductile behavior in specimens that used FRP bent bars as shear connectors, despite the fact that there was no yielding in the FRP material itself. Salmon et al. [8] showed that ICSWPs reinforced with FRP bent bars as shear connectors exhibited approximately full-composite behavior in terms of the strength, and the thermal performance of these components was improved significantly as compared to other ICSWPs reinforced with steel or concrete ribs as the shear connectors. Frankl et al. [9] showed that ICSWPs reinforced with carbon-fiber-reinforced polymer (CFRP) grid shear connectors had full-composite action in terms of stiffness. In an experiment using GFRP NU-ties (similar to truss-shaped connectors) as shear connectors, Morcous et al. [10] obtained a result where the degree of composite action in terms of the ultimate strength was near 100%. Multiple researchers [11–13] reported that the continuous shear connector have a higher shear flow capacity compared to discrete shear connectors. In addition, Kang [14] experimentally and numerically showed that installing the shear connectors at the ends is effective on increasing the ultimate strength of ICSWPs subjected to uniform load.

Although the shear connector had the largest impact on the composite behavior of ICSWPs, and the Precast/Prestressed Concrete Institute (PCI) Committee [15] does not consider connecting elements other than shear connectors, multiple researchers have reported that the bond between the insulation and concrete wythes affects the composite behavior of ICSWPs [16–18]. The shear flow capacity of the bond between the insulation and concrete wythes cannot be calculated accurately, but it can be determined from the physical properties of the insulation that is used. In a flexural test using the same shear connectors for expanded polystyrene (EPS) and extruded polystyrene (XPS) foams, Frankl et al. [19] found that even though XPS foam shows higher flexural and shear strength than EPS foam (in terms of the intrinsic material properties), the specimen with EPS foam showed a higher degree of composite action in terms of stiffness as compared to the specimens using XPS foam. This is due to the high adhesive bond between the EPS foam and the concrete wythes. However, there is other research that has achieved an increase in the composite behavior of ICSWPs by increasing the mechanical bond quality between the insulation and the concrete wythes by roughening the surface of XPS foam [20–22]. In these experiments, specimens using XPS foam with a roughened surface showed equivalent or higher composite behavior compared with specimens using EPS foam. In addition, Choi et al. [23] showed that the mechanical bond of XPS foam with a roughened surface has a greater impact on the composite behavior than the adhesive bond of EPS foam in a flexural test utilizes a negative load with idealized wind suction. Because curtain walls are exposed to repeated wind pressure and suction every day, there are differences between the experimental behavior and the real behavior of ICSWPs. Therefore, studies investigating the composite behavior of ICSWPs that are subjected to repeated wind pressure and suction are necessary in order to determine the viability of using ICSWPs for curtain wall systems.

In this study, a total of four full-scale specimens were tested to investigate the flexural behavior under wind-induced cyclic loading. Two types of loads were applied to the specimen: a monotonic load applied only in the direction of positive pressure and a cyclic load repeatedly applied in both the direction of positive pressure and the direction of negative pressure to implement wind pressure and suction. All specimens were confirmed to meet the required safety and serviceability dictated by current standards. The degree of composite action in terms of initial stiffness, ultimate strength, and shear flow were calculated for each applied loading type and for each type of insulation. In addition, the fatigue effect on the specimens caused by repeated cyclic loading was analyzed by comparing the degree of composite action with the results of the monotonic loading test.

2. Experimental programs

2.1. Full-scale test specimens

In this experiment, a total of four full-scale specimens were used to investigate the flexural behavior caused by wind-induced cyclic loads. As shown in Table 1, the specimens were divided into three groups according to the applied loading type and the insulation type; each group had the same layout of GFRP shear grids. The dimensions of the specimens are 2100 mm (width) × 4500 mm (length) × 220 mm (thick). The thickness of each concrete wythe is 60 mm, and the thickness of the insulation inserted between the internal and external concrete wythes is 100 mm (see Fig. 1). To account for the fact that the specimens are installed into actual buildings, two internal pilasters were made in the lower concrete wythe of the specimen. Then, the specimen was installed through the beam or slab with an anchor. The internal pilasters were designed in accordance with ACI318-14 [24] and measure 300 mm (width) × 100 mm (thick) in the longitudinal direction of the specimen. The type of insulation used is either EPS or XPSST (XPS foam with a roughened surface and groove treatment). XPSST refers to the insulation with the improved mechanical bond performance enabled by increased friction with the concrete surface. This friction is caused by making the surface of the XPS insulation rougher and by cutting a groove in it. GFRP shear grids were used to improve the composite behavior of the specimen by connecting the internal and external concrete wythes. All specimens were assumed to be installed at a height of 60 m; thus, the minimum number of required GFRP shear grids was determined to be four.

The most important variable is the applied loading type. The applied loading types used in our experiment included a monotonic load (applied only in the positive direction to represent the wind pressure) and a cyclic load (applied in both the positive and negative directions to represent the wind pressure and suction, respectively). In the monotonic load test group, the GEL01_M and GXL01_M specimens, which have the same conditions as the GEL01_C and GXL01_C specimens of the cyclic load test group, were designed in order to investigate the flexural behavior according to the applied load type. These samples can also be used to identify

Table 1
Test specimen matrix.

No.	Label	Load type	Insulation type	Shear grid layout
1	GEL01_M	Monotonic	EPS	Layout 1
2	GXL01_M		XPSST	Layout 1
3	GEL01_C	Cyclic	EPS	Layout 1
4	GXL01_C		XPSST	Layout 1