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Thermal response of precast concrete sandwich walls with various steel connectors for architectural buildings in cold regions

Yail J. Kim[a,*], Austin Allard[b]

[a] Department of Civil Engineering, University of Colorado Denver, Denver, CO 80217, United States
[b] Department of Civil Engineering, North Dakota State University, Fargo, ND 58108, United States

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ABSTRACT

This paper presents the thermal response of a precast concrete sandwich wall system subjected to a typical cold region environment, including an exposure temperature of −30 °C for 12 h. Three types of thermal bridges are used for mechanically connecting two concrete layers and an embedded insulation layer. Each test category encompasses single or multiple connectors and their thermal transmittance characteristics are measured. Three-dimensional finite element models are developed to predict the heat transfer of the connectors across the insulation (i.e., thermal response rate and heat flux). Three existing design approaches are evaluated for applicability and limitation. The geometric configuration of the connectors and their interaction are important parameters affecting the thermal efficiency of the sandwich system. Connector types may be determined based on the thickness of an insulation layer. The effect of heat flux concentrations should explicitly be taken into consideration for practice and the existing design methods should be refined accordingly.

1. Introduction

Sandwich wall panels are widely used for residential and office buildings. Such a system is comprised of two outer layers of precast concrete and an inner layer of insulation material, as shown in Fig. 1(a) and (b). The thickness of the concrete layer typically ranges from 50 mm to 150 mm and an insulation thickness is determined depending upon the level of thermal protection required (i.e., thermal properties of the insulation being used and the thermal load the structure is exposed to). Some responsibilities of the sandwich wall panel include insulation, supporting gravity loads, resisting wind load, and esthetics [1]. Rapid construction and reduced long-term maintenance costs are the advantage of precast sandwich wall systems. Use of sandwich wall panels is energy-efficient because the built-in insulation layer precludes heat flow from interior to exterior environments, thereby improving thermal performance of the building. The wall panel system is held together using steel connectors for structural integrity: the insulation layer does not shift due to a combination of the friction of the concrete and the connectors penetrating the insulation (Fig. 1(c) and (d)). Thermal efficiency of such a sandwich wall system is, however, affected by the placement of steel connectors because of a heat conduction mechanism called *thermal bridging*. McCall [1] reported that the presence of steel connectors could reduce the thermal resistance of sandwich walls as low as 43%. Thermal resistance is frequently called *R value* and is defined as Eq. (1):

$$R = \frac{\Delta T}{Q} \tag{1}$$

where ΔT is the temperature difference and Q is the heat flux across the constituent layers. Given the effective management of energy is a primary concern in the architectural community, considerable research effort has been made. Bush and Stine [2] tested composite concrete sandwich panels embedded with truss-type connectors. The connector consisted of top and bottom rods (8 mm in diameter) welded with diagonal members (6 mm in diameter) and had a depth of 125 mm with a bay size of 200 mm. The insulation thickness used was 51 mm. Monotonic and fatigue tests were conducted in three-point bending to examine the potential degradation of system performance. The proposed truss tie connectors improved composite action between the constituent layers, including shear stress redistribution. Deterioration of bond due to cyclic load was observed. Benayonne et al. [3] examined the effect of shear connectors on the composite behavior of precast concrete sandwich walls. Medium-size walls (750–1500 mm wide × 120 mm thick × 1500 mm to 2000 mm long) with shear ties were loaded in flexure. Finite element models were developed using simplified

* Corresponding author. Tel.: +1 303 352 3653.
E-mail address: jimmy.kim@ucdenver.edu (Y.J. Kim).

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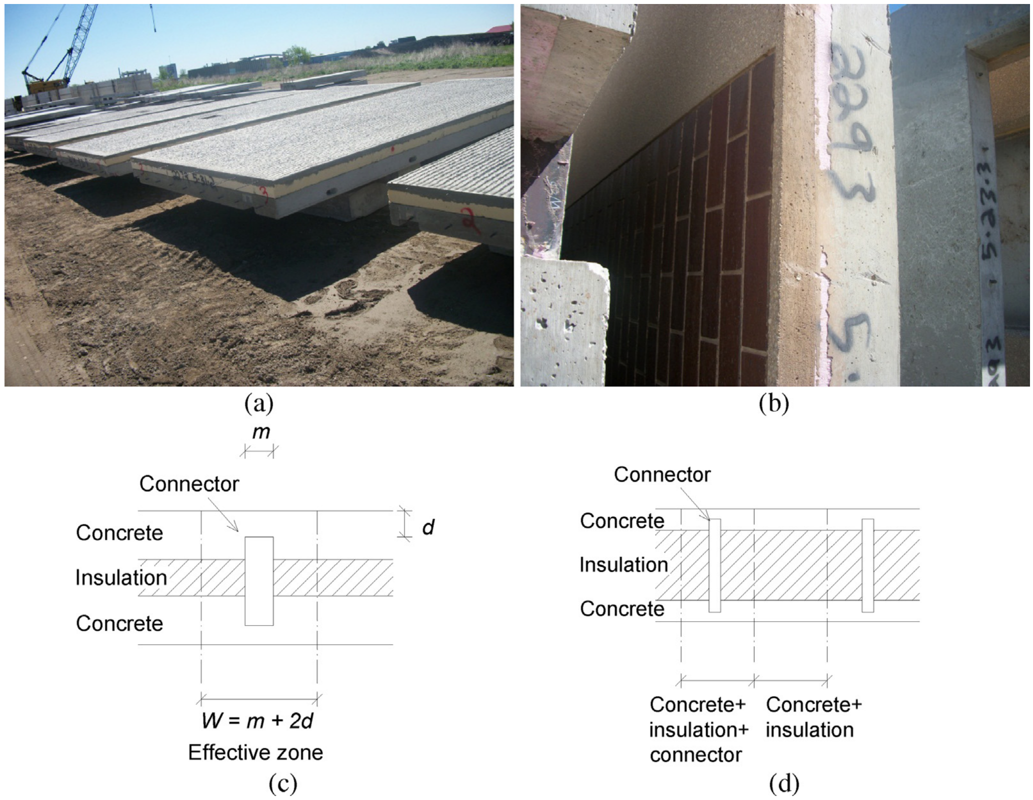

Fig. 1. Typical precast sandwich panels and design approaches: (a) insulated architectural wall; (b) decorative wall; (c) zone method; (d) parallel flow method.

two-dimensional shell elements to predict test data. The degree of composite action was studied with an increasing external load. The stiffness of the connectors noticeably influenced the composite behavior of the system. Lee and Pessiki [4,5] examined the thermal response of two-wythe sandwich wall panels based on finite element analysis. The simulated panel size was 610 mm × 610 mm. Parameters studied were the spacing and diameter of steel connectors, the thickness of concrete and insulation layers, and material conductivity. Predicted R values were compared with an existing design equation. A revised design method was then proposed for practicing engineers. Sibilio et al. [6] evaluated the behavior of precast sandwich panels, based on a simple finite difference method. Numerical results indicated that light weight panels could be developed, while mechanical connectors caused thermal discontinuity. Naito et al. [7] conducted an experimental study to evaluate the mechanical behavior of insulated concrete sandwich panels. Concrete blocks (76 mm to 127 mm thick) and insulation layers (50 mm thick) connected with various shear ties were monotonically loaded in a push-out condition to obtain the shear strength of the specimens. Large-scale sandwich wall specimens (813 mm wide × 3657 mm long × 203 mm thick) were also tested to examine flexural behavior such as moment-curvature response, stiffness, shear slip, and failure load. Test results showed the strength of sandwich wall systems was influenced by the type of shear tie and the surface roughness of insulation materials. Joudi et al. [8] examined the effect of insulation layers on the energy performance of sandwich panels. A dynamic simulation model was developed to predict thermal emissivity on the panels. Selection of adequate building materials was discussed to preserve usable energy. Oliver [9] reported thermal characteristics of gypsum boards, in particular for thermal energy storage in buildings. Performance of several building materials was comparatively studied and the effectiveness of gypsum was elaborated in terms of heat storage.

As discussed above, most existing research was concerned about mechanical responses and predicted thermal behavior of sandwich panels. Although some numerical studies examined the thermal performance of precast concrete sandwich panels, there still is a dearth of understanding of the contribution of connectors to the thermal behavior of such structural members, particularly from an experimental perspective. This paper presents a test program to study the thermal characteristics of precast concrete sandwich walls having various steel connectors subjected to a typical temperature range in cold regions. A finite element model was constructed and validated with test data. A parametric study was conducted to elucidate the effect of geometric properties on thermal resistance. Existing design approaches were evaluated.

2. Research significance

Precast concrete sandwich walls are commonly constructed using steel ties to connect multiple wythe layers. Such wall systems function as load bearing or non-load bearing elements with favorable thermal performance. Use of steel connectors, however, increases the degree of heat loss because of their large thermal conductivity. The majority of existing research as to the thermal behavior of precast sandwich walls has focused on numerical investigations without rigorous experimental validation and has been conducted using simplified connector configurations (i.e., equivalent cross-sectional area rather than modeling actual shape). Design methods currently employed also simplify the contribution of steel connectors for the sake of calculation convenience. Specific information about the performance of various connectors is, therefore, not available and refined thermal analysis is required. This research program experimentally investigates the thermal response of precast concrete sandwich wall elements having three types of connectors and evaluates the