Engineering Structures 138 (2017) 367–380

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Simplified model for partially-composite precast concrete insulated wall panels subjected to lateral loading

Matthew J. Gombeda [a,*], Patrick Trasborg [b], Clay J. Naito [a], Spencer E. Quiel [a]

[a] Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA 18015, United States
[b] JPMorgan Chase Bank, New York, NY 10179, United States

ARTICLE INFO

Article history:
Received 18 November 2016
Revised 11 January 2017
Accepted 26 January 2017

Keywords:
Insulated wall panel
Partially-composite behavior
Precast concrete
Shear tie

ABSTRACT

A simplified model to predict the partially composite response of precast concrete insulated wall panels to lateral loading is proposed. A conventional insulated wall panel design consists of two concrete wythes which sandwich a foam insulation layer. Shear ties are used to connect the two concrete wythes through the insulation layer – these ties can be designed to resist flexural demands via composite, partially composite or non-composite action of the section. Numerous types and configurations of shear ties (many of them proprietary) are available with a large range of constitutive properties, and thus the response of a wall panel can vary based on the type of tie used in its construction. Standard design practices do not consider the constitutive properties of the tie, compatibility of the wythes, or locations of the ties within the panel. A simplified model is proposed which incorporates the relative shear tie deformation as well as the tie's constitutive properties. The approach superimposes the sum of the force couple developed in each shear tie and the capacity of each concrete wythe via an iterative process by which the strength, deformation and level of composite action is calculated at each load increment. This model provides an accurate estimate of the load-deformation responses of these panels when subjected to lateral loads (perpendicular to the panel). The method is used to illustrate the sensitivity of flexural response in a precast insulated wall panel to tie properties and placement. The proposed model is demonstrated to be an effective tool for efficient flexural performance-based design and selective detailing of precast concrete insulated wall panels.

1. Introduction

Energy efficiency in buildings has become a major concern due to the threat of climate change and the increasing cost of utilities. Collins [1] demonstrated that energy saving benefits could be achieved by using a composite cladding system comprised of two concrete wythes (interior and exterior) with insulating foam sandwiched between them. The insulated wall panel concept further developed with research on the effect of insulation properties on the flexural stiffness of panels by Pfiefer and Hanson [2]. With the recent emphasis on sustainable construction, researchers and developers have refined the design of insulated panels to increase thermal resistance without compromising the structural integrity of the wall panel [3]. Shear ties are used to connect the two concrete wythes through the insulation layer – these ties can be designed to resist flexural demands via composite, partially composite, or non-composite action of the section. Thermally resistive shear ties comprised of carbon fiber-reinforced polymers (CFRP) or glass fiber-reinforced polymers (GFRP) have been shown to provide the flexural resistance required to resist the relevant design loads [4,5]. Though the thermal resistance of these panels is of great importance, it is also necessary to understand the structural behavior and failure limit states of these structures.

Accurate methods for calculating the composite response of insulated panels under service and ultimate loading are necessary for proper design of the panel system. Multiple approaches to assess the response of composite structures have been developed for a variety of structural applications. Research on composite action has been conducted on steel-concrete composite beams [6,7], concrete-timber structures [8–12], wood-based sandwich panels [13], and insulated concrete panels [14,15]. Most of these approaches assume linear elastic behavior in the structural components (including the shear ties) and do not account for a gap between interior surfaces of the structural materials where shear transfer occurs. Shear transfer relies on a combination of friction between the insulation and concrete layers with the combined shear loading mechanism in the ties. Although experimental

* Corresponding author.
E-mail address: mjg314@lehigh.edu (M.J. Gombeda).

http://dx.doi.org/10.1016/j.engstruct.2017.01.065

research has shown that a partial degree of composite action can be achieved through friction between the layers [16], the ties are needed to ensure shear capacity under service and ultimate loading. The gap created by the presence of the insulation layer between the wythes results in the development of shear, flexure and potentially axial force in the ties as the panel undergoes flexural deformation due to lateral loading (perpendicular to the panel's exterior surface). The moment developed in the ties results from a force couple created when opposing shear forces, separated by an eccentricity, are transferred to both concrete wythes at the locations of tie embedment. Traditional approaches are not easily extended to capture the localized flexural behavior of the ties.

Recently, approaches have been developed specifically for insulated wall panel systems. Benayoune et al. [17] showed that the ultimate strength and degree of composite action of a precast wall system is highly dependent upon the stiffness of the shear tie. Salmon and Einea [14] developed a method that, although effective for calculating thermal bowing deflections, is not applicable for determination of flexural strength. Bai et al. [18] developed a discrete model incorporating shear deformations and independent flexural behaviors of concrete wythes to create models of symmetric partially composite concrete sandwich panels. The model was limited to small elastic deformations and does not consider variation in deformation behavior of discretely placed tie types and their corresponding failure modes. Hodicky et al. [19] performed experimental testing on insulated concrete sandwich panels to examine the effect of varying geometric and material properties of different FRP ties on shear flow strength. By manipulating the spacing of distributed shear ties and thus the interaction surface area between the concrete and insulation, a change in the overall magnitude of shear stresses between the concrete wythes was observed. Chen et al. [20] conducted bending tests on eight large scale concrete sandwich panels and accounted for a variation in the distribution of FRP shear ties. The results showed that different types of shear ties produce varying levels of composite action, further motivating the need to include the properties and spatial distribution of ties into analysis methods of sandwich panels. Tomlinson and Fam [21] developed an approach to model the flexural response of partially-composite insulated wall panels with varying arrangements of shear ties and wall panel geometries. This methodology consists of an iterative approach that assumes a linear slip profile and integrates strain discontinuities caused by the ties to obtain an updated slip profile, however, shear tie constitutive properties are restricted to the elastic range. This may be suitable for elastic-brittle materials; however, ductile materials, which include metals and numerous plastics will realistically yield due to inter-wythe shear forces at large panel deformations.

This paper proposes a simplified model to assess the performance of both prestressed and non-prestressed concrete insulated non-loadbearing panels under out-of-plane loading. As stated in the title, the elements examined in this manuscript are insulated wall panels intended for use as part of the building envelope. Use of these panels for use as roof or slab elements was not considered in this paper. There are some cases such as refrigeration buildings that could also utilize the design concept for the roof diaphragm, however the main application is for wall panels. These elements are designed to resist of out-of-plane forces such as those generated from wind loads or pressure demands from blast events.

As an alternative to the aforementioned methods by others, the proposed model provides a simplified method for calculating panel performance from service loads through ultimate strength for a wide range of cross-section geometries and shear tie configurations. The intended application of the model is for use as a design and analysis tool and facilitates ease of implementation by the user without the prerequisite of commercial finite element software. It allows the user to easily input all relevant geometric and material parameters and determine the behavior of the panels without the need for building complicated finite element models. The proposed model incorporates the elastic and inelastic constitutive properties of the wythe-to-wythe shear ties, thus capturing the effect of tie ductility on the overall panel. Proper use of the model enables a simplified yet effective way to design and selectively detail tie arrangements for a desired level of performance and/or an intended failure mode or limit state in response to lateral loads. The proposed model is particularly applicable for the design of precast insulated wall panels to resist impulsive lateral loads such as blast and impact.

2. Background

Insulated precast concrete wall panels consist of a layer of foam insulation sandwiched between two layers, or wythes, of concrete. The insulating layer allows the panel to provide high thermal resistance without sacrificing the advantages offered by precast concrete construction, including design aesthetics, economic fabrication with higher quality control, or rapid erection. Shear ties which connect the two wythes through the insulation layer are commonly used to resist the shear and tension forces generated during fabrication, shipping, erection, and service life. The combinations of shear and tension on the ties vary over the loading history of the panel. In most cases compression between the wythes is assumed to be transmitted through the insulation.

While a physical connection between the concrete wythes is necessary to create composite action, this connection can allow heat to transfer directly between the wythes due to "thermal bridging," thereby decreasing the thermal efficiency of the panel [22]. However, the effects of thermal bridging can be diminished or effectively eliminated by utilizing shear ties made with material having low thermal conductivity with small cross-sectional area. Numerous shear tie systems (many of them proprietary) are currently available and offer varying levels of strength, stiffness, thermal resistance and cost. Shear ties may be placed at discrete locations or distributed along the length of the panel. They can be used to allow the interior and exterior wythe to work in tandem to resist external lateral loads, thereby inducing flexural response in the panel. For insulated panels constructed with shear ties, the flexural behavior can be classified as non-composite, composite or partially composite. These scenarios are examined for a typical section and span as illustrated in Fig. 1A.

Composite behavior is defined in this paper as the flexural resistance achieved by assuming a linear strain profile over the panel section (see Fig. 1B), similar to that in a solid concrete cross-section. Non-composite behavior exists when the interior and exterior wythes act in flexure independently to resist applied loads, and the flexural contribution of the insulation layer is assumed to be negligible. This is equivalent to the flexural response of two stacked slabs with a frictionless interface between them. Due to compatibility, the stacked slabs must have the same curvature, rotation and flexural displacement along the length. This results in measurable relative slip between the two wythes (Fig. 1C). Between these two extrema is the case of partially composite behavior, which is characterized by a level of shear force transfer between the interior and exterior wythes through the connection between them (Fig. 1D). These connectors allow relative slip between the panels (though less than that of non-composite panels) as a function of their shear resistance. The degree of composite action dictates the moment-curvature resistance of the section and hence the load-deflection behavior of the panel (Fig. 1E). As the degree of shear transfer increases, the response will trend toward that of a composite section – conversely, decreasing levels of shear transfer will trend toward the non-composite response.