Composites Part B 89 (2016) 340–351

Contents lists available at ScienceDirect

Composites Part B

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

Reliability-based flexural design models for concrete sandwich wall panels with continuous GFRP shear connectors

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ARTICLE INFO

Article history:
Received 30 June 2015
Received in revised form
6 October 2015
Accepted 20 November 2015
Available online 6 January 2016

Keywords:
A. Glass fibres
B. Strength
C. Statistical properties/methods
D. Mechanical testing
Design model

ABSTRACT

This paper proposes design models for insulated concrete sandwich wall panels (SWPs) with GFRP grids against a flexural failure. The design models are developed by considering both ultimate and serviceability limit states. First, mean-prediction models for evaluating ultimate moments and cracking moments of SWPs are proposed, and second, they are further developed into design models by adding capacity factors (or safety factors). The capacity factors are statistically determined using the method provided in Eurocode 1990: 2002 [1]; this method considers the random distribution of resistance defined by evaluating both modeling and parametric uncertainties. Two capacity factors are calibrated for an ultimate limit state function and a serviceability limit state function. For a more convenient design process, a unified capacity factor is determined by combining both factors into a function of a nominal ultimate moment. The unified factor can be applied to achieve the ultimate limit state requirement, and at the same time it automatically achieves the serviceability requirement.

1. Introduction

Insulated concrete sandwich wall panels (SWPs) are widely used for the exterior walls of office, commercial and industrial buildings, warehouses, and cold storages. They consist of layers of concrete wythes separated by insulation. Various kinds of SWPs have been or are now being developed because of growing demand driven by their excellent thermal efficiency and structural performance [2]. When they are used as structural members, their structural performance can be weakened by the insulation between the wythes. Therefore, their strength should be ensured through a proper design of shear connectors to provide near-full composite action [3]. The importance of shear connectors can easily inferred even from other types of composite members [4,5]. In addition, shear connectors need to be devised to prevent the thermal bridge effect between the two concrete wythes [6]. One of the most attractive materials for shear connectors is fiber-reinforced polymer (FRP), which has a higher tensile strength than traditional structural materials along with lower thermal conductivity, lighter weight, and better corrosion resistance. For example, one kind of FRP, glass fiber reinforced polymer (GFRP) has 2–4 times the strength of carbon steel with 0.5% of the thermal conductivity of carbon steel, which prevents a thermal bridge or condensation well. Table 1 shows the comparison of various structural materials in terms of tensile strength, density and thermal conductivity.

The structural performance of a shear connector depends on its material and shape, which determine the load-transferring mechanism. Shear-connector shapes can be classified into two groups: non-continuous and continuous. Non-continuous connectors include C-tie, M-tie, and Z-tie, and continuous connectors include bent wire, truss-shaped, and grid-type connectors [10].

Experimental and theoretical studies have examined the structural performance of non-continuous shear connectors in SWPs. Pessiki and Mlynarczyk [11] compared the effects of carbon steel M-tie connectors and solid concrete ribs to the degree of composite action of a sandwich panel and found that the former has a lower contribution. Woltman et al. [12] carried out an experimental study comparing bar-type GFRP shear connectors and polypropylene shear connectors and found that the bar-type GFRP connector showed better structural effects in terms of strength and stiffness. Tomlinson and Fam [13] carried out four-point bending tests of SWPs with the bar-type GFRP shear connectors and found that the connectors can make almost 80% of the full composite action compared to the theoretical flexural strength of fully composite SWPs.

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http://dx.doi.org/10.1016/j.compositesb.2015.11.040
1359-8368/

Table 1
Material property of shear connectors [7–9].

Material	Strength, MPa	Density, kg/m^3	Thermal conductivity, W/m·K
GFRP	482–2410	1800	0.3
Steel	240–689	7850	60
Aluminum	210	2700	191
Concrete	28–56	2300	2.1

Experimental and theoretical studies have also investigated the performance of continuous shear connectors. Truss-shape steel shear connectors were found to improve the composite action of SWPs [3,14,15], and an SWP with three wythes together with a solid concrete rib was found to achieve almost full composite action [16]. In addition to steel and concrete shear connector types, Salmon et al. [17] proposed an FRP shear connector to prevent the thermal bridging effect often observed in steel or concrete connectors. Pantelides et al. [18] used shell connectors made of carbon fiber reinforced polymer (CFRP) and achieved shear capacity, but the production process of the SWPs suffered. SWPs with GFRP NU-tie [19] were proposed by a research team from the University of Nebraska. They examined their effects on the flexural capacity and stiffness of SWPs. Naito et al. [20] carried out push-off tests to examine the shear strength of SWPs under uniform loading. They compared 14 types of shear ties, including both non-continuous and continuous types of shear connectors made of carbon steel, CFRP, and GFRP. Experimental and theoretical studies on CFRP-based grid-type (continuous) connectors [21,22] and GFRP-based grid-type connectors [2,23] demonstrated good structural performance, achieving near-full composite action. Fig. 1 illustrates various types of shear connectors, including non-continuous and continuous types.

Of the various types of shear connectors used for SWPs, this study focuses on GFRP grid-type shear connectors. These connectors have already demonstrated a satisfactory structural and thermal performance [2,23]. In spite of the existing experimental and theoretical studies on the use of GFRP in shear connectors, challenges remain in crafting a practical structural design for SWPs with GFRP shear grids under bending, and clear design guidelines have not yet been developed for SWPs. The use of FRP in structural design is mainly for structural members other than sandwich panels [7,24]. The only currently existing guideline is the acceptance criteria developed by ICC Evaluation Service [25], but it relies mainly on experimental shear strength data for the design of shear connectors. The PCI document [26] contains design guidelines for SWPs but they rely purely on material properties information from manufacturers. In addition, those documents focus mainly on the resistance of shear connectors; no legal or standardized guidance for SWP design against bending failure exists yet. To apply the above-mentioned documents to SWP design against bending, the degree of SWP composite action should be simplified to full-composite or non-composite action. However, the actual behavior of an SWP is realistically a semi-composite action, and the degree of composite behavior is determined by parameters such as panel size and the types and sizes of shear connectors. Semi-composite action occurs when using continuous and non-continuous shear connectors because SWPs gradually lose full-compositeness due to serviceability failures such as early cracking [2].

Thus, this study aims to develop design models to predict the design resistance of SWPs under bending by considering their semi-composite action based on reliability analysis. We herein limit our application to SWPs reinforced by grid-type GFRP shear grids. The design models will be developed using the following steps and methods, none of which are found in the literature to the best of our

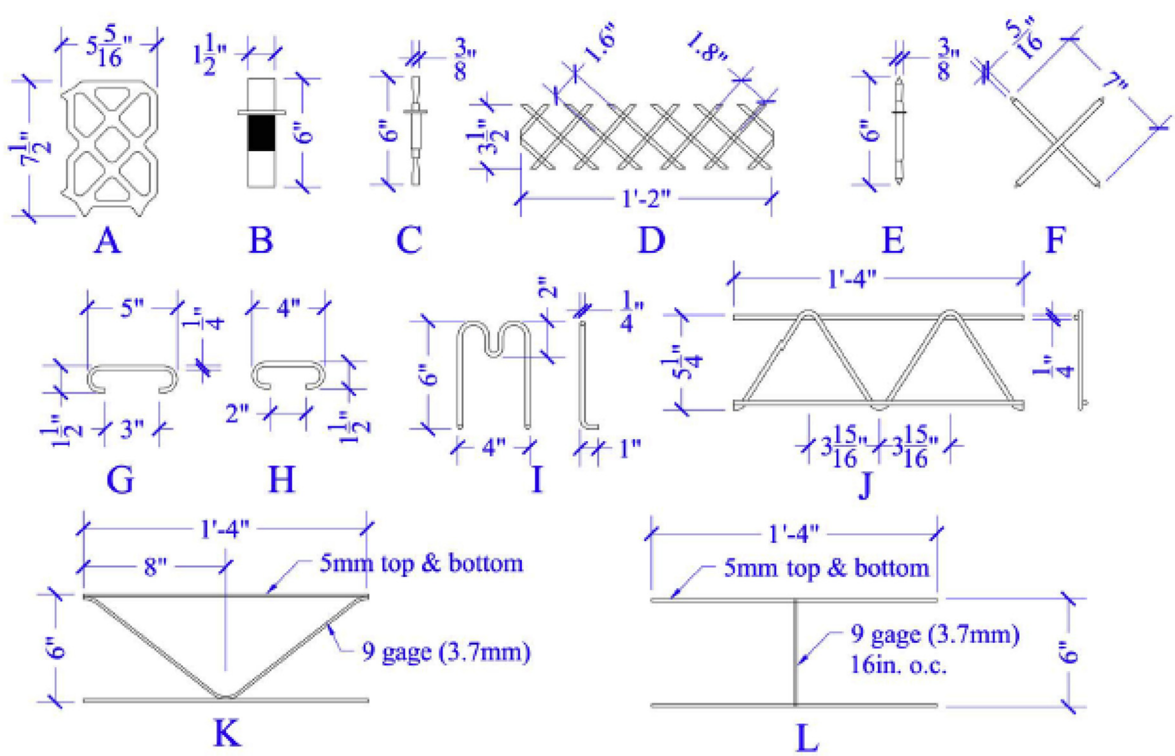

Fig. 1. Continuous and non-continuous types of shear connectors for SWPs [20]: (A) Delta GFRP grid, (B) Composite GFRP pin, (C) noncomposite GFRP pin, (D) CFRP C-grid, (E) GFRP TeploTie, (F) Basalt FRP RockBar, (G) Carbon steel C-clip, (H) Stainless steel C-clip, (I) Galvanized steel M-clip, (J) Steel welded wire girder, (K) Hot-dipped galvanized steel truss, (L) Hot-dipped galvanized steel ladder.