Journal of Constructional Steel Research 149 (2018) 165–179

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Thermal behavior of gypsum-sheathed cold-formed steel composite assemblies under fire conditions

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ARTICLE INFO

Article history:
Received 3 May 2018
Received in revised form 6 July 2018
Accepted 19 July 2018
Available online xxxx

Keywords:
Thermal conductivity tests
Post-heated gypsum plasterboard
Fire experiments
Gypsum-sheathed composite assembly
Heat transfer model

ABSTRACT

Gypsum-sheathed cold-formed steel (CFS) composite assemblies consisting of CFS framing and gypsum plasterboard are widely used in modern buildings. This paper presents a detailed investigation of the thermal response of such assemblies under fire conditions. Limited to the accuracy of test devices for high-temperature low-thermal-conductivity material, previous results obtained from direct thermal conductivity tests of heated gypsum plasterboard may be unsatisfactory. Therefore, some transient-state thermal conductivity tests of post-heated gypsum plasterboard have been conducted, and the results truly reflect the tendency of thermal conductivity of gypsum plasterboard at elevated temperatures. Subsequently, six fire experiments on gypsum-sheathed composite assemblies were conducted under the ISO834 time-temperature curve. Significant local buckling is observed along the longitudinal direction of stud web, and the assembly cannot recover from the local deformation after the fire exposure. The fall off of fire side gypsum plasterboard occurs from approximately 690 °C to 750 °C. The aluminum silicate wool insulated gypsum composite panel is recommended for use as the sheathing of CFS composite assemblies for severe fire-resistance demand. Besides, a two-dimensional heat transfer model was built using the finite element method. The present thermal conductivity of post-heated gypsum plasterboard is verified by the heat transfer model and is recommended for use in the thermal response simulation of such assemblies under fire conditions, instead of the thermal conductivity tests of heated gypsum plasterboard. In addition, the fall off of fire side gypsum plasterboard is successfully simulated by using the birth-death element technique and the definition of critical temperature of gypsum plasterboard.

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1. Introduction

Gypsum-sheathed cold-formed steel (CFS) composite assemblies consisting of CFS framing and gypsum plasterboard (GP board) are widely used in modern buildings, for instance, as CFS partition walls, load-bearing walls and composite floors [1]. The fire performance of such assemblies raises increasing concerns in structural fire safety engineering. The present investigation focuses on the thermal response of non-load-bearing CFS composite assemblies under fire conditions.

Some fire experiments involving CFS composite assemblies have been conducted to determine the effect of different configurations on the fire performance of such assemblies [2–11], especially for CFS load-bearing walls. Among these investigations, only limited experiments have been conducted regarding the fire performance of CFS horizontal assemblies [7–9]. Due to the negative effect of the action of gravity, the thermal response of CFS horizontal assemblies might become more severe than that of CFS vertical assemblies. In addition, a type of gypsum composite panel was developed in previous investigations [3, 10, 11] and used as the sheathing of CFS composite assemblies. However, the thermal insulation performance of horizontal gypsum composite panels and CFS horizontal assemblies lined with gypsum composite panels has not been tested by fire experiments.

In addition to fire experimental investigations, numerical simulation is also an important approach to studying the fire performance of CFS composite assemblies [12–16]. During the modeling of such assemblies, the thermal physical properties (specific heat, density and thermal conductivity) of component materials become the most important parameters determining the accuracy of the thermal response simulation. In general, the thermal physical properties of cold-formed steel can be obtained from different structure design specifications, for instance, EC 3 Part 1.2. For GP board, the corresponding thermal physical properties can be obtained from different experiments. The specific heat and density of GP board at elevated temperatures can be obtained by DSC (differential scanning calorimetry) and TGA (thermal gravity analysis) of heated GP board [13]. DSC and TGA are mature technologies with good accuracy. Both steady and transient state test methods are currently used to test the thermal conductivity of GP board. However,

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https://doi.org/10.1016/j.jcsr.2018.07.023
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there are significant differences in the thermal conductivity tests of GP board at elevated temperatures. Theoretically, the corresponding test specimen should be the heated GP board. Chen, Mehaffey and Park carried out steady-state tests of the thermal conductivity of heated GP board [13, 17, 18], but the test results may be unsatisfactory due to the accuracy of the test devices for the high-temperature low-thermal-conductivity material. Therefore, both Chen and Mehaffey [13, 17] gave modified thermal conductivity curves of GP board at elevated temperatures, considering the effects of water vapor and radiative heat transfer of the cracked GP board. In addition, the high-temperature thermal conductivity meters for low-thermal-conductivity solid materials are much more expensive than the test devices for low-thermal-conductivity solid materials at ambient temperature. Therefore, some investigations carried out thermal conductivity experiments for post-heated GP board [19, 20], instead of the heated GP board.

This paper presents transient-state thermal conductivity tests of post-heated GP board, and the tests results are compared with the other results for the thermal conductivity of heated and post-heated GP board. Six fire experiments involving gypsum-sheathed composite assemblies are conducted under ISO834 standard time-temperature curves. The thermal insulation performance of the gypsum composite panel and the effect of the insulation configuration are discussed. In addition, a two-dimensional heat transfer model is built for these assemblies. The feasibility of using the present thermal conductivity of post-heated GP board, instead of the thermal conductivity of heated GP board, for the thermal response simulation of gypsum-sheathed composite assemblies under fire conditions is discussed.

2. Thermal conductivity experiments on GP board

The test specimens are circular plates with a diameter of 80 mm and are cut from the same batch of fire-resistant GP board (12 mm × 1200 mm × 3000 mm, thickness × width × length). According to the previous DSC tests of GP board [13], dehydration of calcium sulfate occurred from approximately 80 °C to 200 °C, and decomposition of calcium carbonate occurred from approximately 580 °C to 720 °C. To consider the influence of the dehydration and decomposition action, a total of 12 temperature levels were considered for the present thermal conductivity experiments, including 15 °C (ambient temperature), 80 °C, 160 °C, 220 °C, 300 °C, 400 °C, 500 °C, 580 °C, 670 °C, 720 °C, 800 °C and 900 °C. In this section, transient-state thermal conductivity experiments on post-heated gypsum specimens are conducted and planned to replace the direct thermal conductivity tests of heated GP board. The detailed test procedure is shown below.

(1) The first step is the heat treatment of gypsum specimens. The specimens are placed into the chamber of an electric furnace (Fig. 1). The furnace is heated to a temperature of approximately 30 °C less than the pre-set target temperature at a heating rate of 15 °C/min (Fig. 2). Then, the furnace temperature is kept constant for approximately 10 min to ensure a uniform temperature environment. Subsequently, the furnace is set to the target temperature using a slow heating rate of 5 °C/min and left for approximately 120 min to ensure a uniform target temperature distribution for the specimen. Then, the furnace is stopped. The specimens are taken out of the furnace after the furnace naturally cools to room temperature.

(2) The second step is the transient-state thermal conductivity test of post-heated gypsum specimens. The test device is a TPS 2500S by Hot Disk, as shown in Fig. 3a. The specimen is placed on the holder of a thermal conductivity meter (Fig. 3b), with a cylindrical shielding cover (Fig. 3c). Then, the thermal conductivity of post-heated specimens is tested by the transient plane source (TPS) method.

Fig. 1. Electric muffle furnace.

The present test results for the thermal conductivity of post-heated GP board are listed in Table 1 and compared with those obtained from other investigations, as shown in Fig. 4. The thermal conductivity in the present study is obtained from the transient-state test for the post-heated specimens, the thermal conductivities given by Ghazi are obtained from the steady-state test for post-heated specimens [19, 20], and the thermal conductivities given by Park, Chen and Mehaffey are obtained from the steady-state test for heated specimens [13, 17, 18]. In addition, both Chen and Mehaffey give modified curves of the thermal conductivity of GP board at elevated temperatures [13, 17]. Fig. 4 shows the following:

(1) Except for the temperatures between 110 °C and 140 °C, the results by Park are much lower than those by other researchers below 320 °C, probably due to the delayed heat transfer in the initial heating of their homemade test device; beyond 360 °C, the results obtained by Park are close to those by Ghazi and the present study.

(2) The thermal conductivity of GP board obtained in these investigations is different at ambient temperature, probably due to the different proportions of free water in the GP board; such a difference in the thermal conductivity is insignificant for the thermal performance of GP board under fire conditions due to the dehydration of GP board in the initial stage of fire exposure.

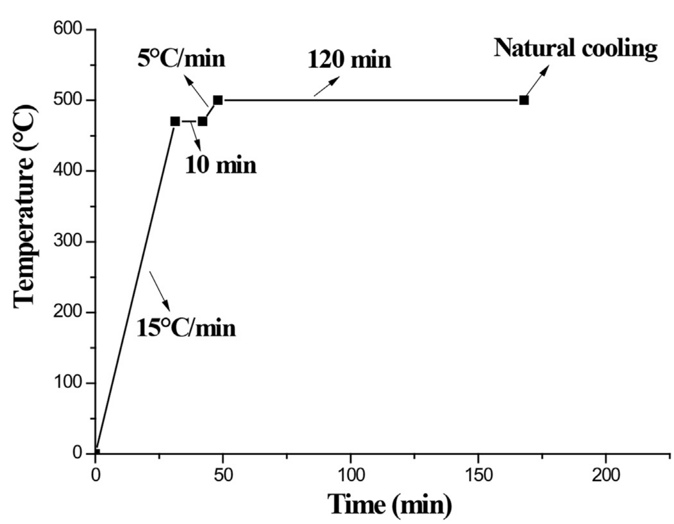

Fig. 2. Heat treatment at the temperature level of 500 °C

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