Efficient Structural Sandwich Wall Panels Devoid of Thermal Bridges

Sani Mohammed Bida, F. N. A. A. Aziz, Mohd Saleh Jaafar, Farzad Hejazi and Abu Bakar Nabilah

Abstract Reinforced concrete sandwich wall panels are developed to reduce the effect of thermal transmission across the wall systems. The reduction of the thermal transmission is achieved through incorporation of an insulating layer. However, this insulating layer led to a reduction of structural performance. The provision of shear connection in the sandwich system improved its structural integrity and increased with increase in a number of shear connectors. However, if the shear connectors are placed directly across the layers of the concrete wythes, it will decrease its thermal efficiency. The thermal and structural performance works in contrary effect to an increasing number of shear connectors. Hence, optimizing both structural and thermal efficiencies simultaneously in reinforced concrete sandwich system has been a challenge for a very long time. Therefore, this paper presents an alternative approach focusing on the thermal path method to produce an optimum shear connector used. This approach eliminates the direct transmission path between the two wythes and, at the same time, avoids the use of alternative materials such as fibre-reinforced polymers which could be uneconomical. With this method, both thermal and structural efficiencies are optimized using only conventional concrete and steel materials.

Keywords Precast concrete sandwich panel · Shear connection
Thermal performance

S. M. Bida (✉) · F. N. A. A. Aziz · M. S. Jaafar · F. Hejazi · A. B. Nabilah
Department of Civil Engineering, Faculty of Engineering, Housing Research Centre,
Universiti Putra Malaysia, Serdang, Selangor, Malaysia
e-mail: informsani@yahoo.com

F. N. A. A. Aziz
e-mail: farah@upm.edu.my

M. S. Jaafar
e-mail: msj@upm.my

F. Hejazi
e-mail: farzad@fhejazi.com

A. B. Nabilah
e-mail: nabilah@upm.edu.my

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1 Introduction

Interest in high-rise structural buildings in urban centres is on the increase due to the competition for the scarce available spaces. These structural buildings are made up of either beam–column frameworks or wall–slab systems. The wall–slab systems are structurally very efficient, but exhibit high thermal transmission. The thermal radiation through the surface of the wall of the buildings transfers heat into the building as a result of difference in temperature between the internal and external areas of the building environment. The heat absorbed into the building is determined by the thermal conductivity of the materials used [1]. Usually, the temperature rise due to heat transmission across buildings is overcome through provision of air-conditioning system for thermal indoor comfort or provision of heaters in the case of buildings in cold regions. Unfortunately, the mechanical air-conditioning system is one of the highest energy consuming equipment in buildings, thus, the need to renew the wall design systems towards sustainable development becomes highly imperative.

Substantial percentage of world's total energy consumptions and greenhouse emissions result from building sector due to high HVAC equipment usage [2, 3]. In America, a significant share of energy consumption comes from housing with about 50–70% coming from heating and cooling and air-conditioning [4]. In Europe, buildings account for about 30% of energy use which could be more in hotter parts of the word. This has led to global warming which has become a challenging phenomenon with far-reaching consequences. Attempts to curb this challenge in other areas of research include recycling and reducing fossils fuel consumption [5].

In the construction industry and modern architecture, emphasis on sustainable green infrastructural development through minimization of thermal transfer between outside and inner parts of buildings has been the principal focus of research. This is achieved through the provision of insulation layer between the building components, thus, leading to the paradigm shift to precast concrete sandwich systems (PCSS). This approach has helped significantly in producing thermally efficient non-structural components. Al-Ajlan [6] reported that the use of insulation layer in building elements is considered the most effective way of conserving energy. Hacker [7], also emphasized that utilizing insulation in household components would minimize annual energy requirement both for heating and cooling.

Therefore, this global renewed interest in energy conservation has called for demand in energy efficiency in building components such as precast concrete sandwich panels (PCSP) system. This technology is a product of industrialized building system (IBS) that have gained popularity in civil engineering applications due to its thermal performance [8, 9]. PCSP offers better thermal efficiency than other traditional masonry or solid wall building construction methods due to the insulation layer created between the concrete wythes. The two sides of the separated wythes are required to be connected through the insulation layer. The connection points cause thermal transfer from one side of the panel to the other and is referred to as thermal bridges [10–13]. Since the choice of insulation, shear connection and wythes materials significantly affects the PCSP behaviour in terms of strength and thermal performances, a paradigm shift in the material used for PCSP system from conventional concrete and steel to foamed concrete and fibre-reinforced polymers (FRP) for wythes and shear connection design, respectively, has been observed. These approaches are quite expensive, and the availability in commercial quantity for turnkey projects is still in doubt.

Precast concrete sandwich panel is a sustainable and environmentally friendly building composite system due to their thermal performance, though with reduced structural performance. This paper presents thermal path approach to insulated precast concrete sandwich panel using the conventional reinforced concrete system. The shear connectors are staggered between the two faces of the panels to avoid direct thermal transfer.

2 Experimental Programme

2.1 Materials

The precast concrete sandwich panels (PCSP) were produced from combinations of concrete for wythes and shear studs, reinforcement bars for shear connections and BRC steel wire mesh for wythes reinforcement. Specimen size 500 × 500 × 150 mm was designed and produced as shown in Fig. 1, and the thickness of each wythe is 40 mm. The shear stud 150 × 50 mm was used as connection point. Figure 2 shows the shear connector locations which are staggered to prevent direct thermal bridges and the spacing of the connectors were varied between 200, 300,

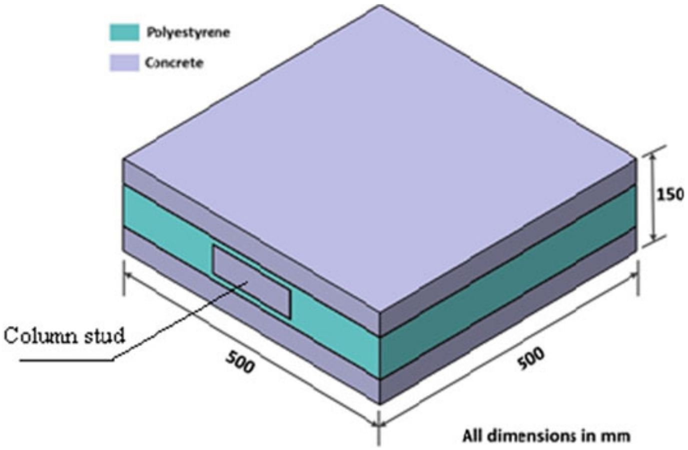

Fig. 1 Specimen used for the thermal transmission experiment

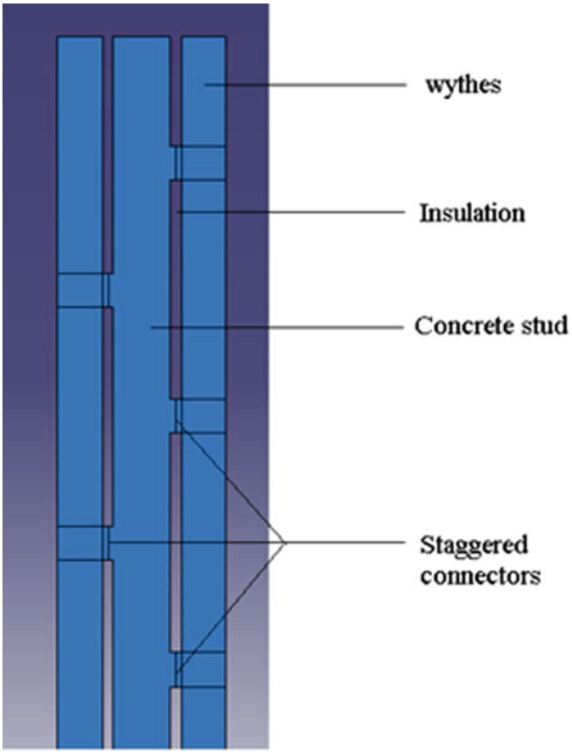

Fig. 2 Section through the column stud shear connection

400 mm and the control specimen and designated as P200, P300, P400 and P0, respectively. A ready mix concrete of 28 days target strength 40 MPa was used using 10 mm maximum aggregate size. BRC steel wire mesh 6 mm diameter and 100 × 100 mm opening was used as vertical and horizontal reinforcement in each wythe. Polystyrene insulation material was used between the wythes in other to minimize the thermal transmission. The choice of insulation material was based on the combined properties such as thermal resistance, water absorption, economy and availability in local markets. In this regard, 70 mm thick polypropylene was used as insulation material between the column studs. The column stud positions comprise 10–50–10 mm section for insulation–concrete–insulation, respectively. All the polystyrene materials are glued to the dry surfaces of the precast concrete panels after curing using polystyrene friendly adhesives.

2.2 Methodology

A steady-state thermal conductivity test using calibrated hot box method (CHB) in conformity with ASTM C 1363 [14] was used to measure the hot and cold temperatures of both air and surfaces of the PCSP assembly system. The specimen

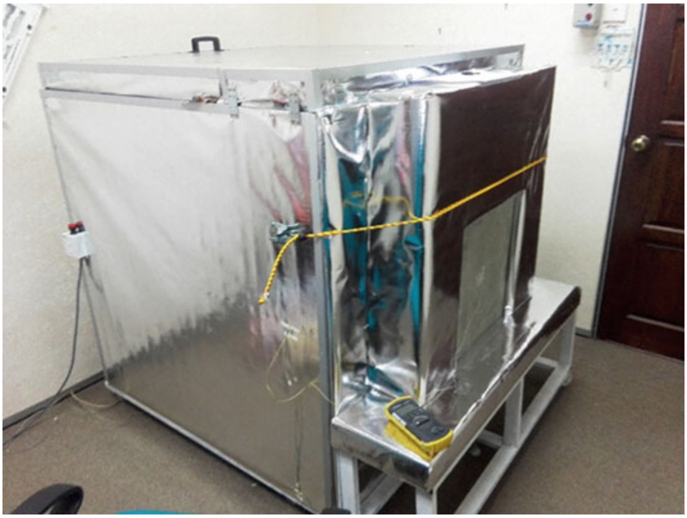

Fig. 3 Hot box apparatus

comprises two sides which are set up as hot and the cold side. The hot side is made up of hot chamber or box while the room where the box is located represents the cold side. Each face of the specimen contains surface thermocouple attached to the concrete surface of the specimen. Additional one thermocouple in each chamber was used to measure the air temperature until steady state is reached. All the devices were attached to the data logger and configured before the commencement of the experiment. The experiment was carried out for a period of 600 min with a maximum steady temperature of 60–65 °C, and the hot box apparatus is shown in Fig. 3. The wall specimens were designed with shear connectors spaced at 200, 300, 400 mm and the control designated P200, P300, P400 and P0, respectively.

3 Results and Discussion

The temperature profile for the cold surfaces was recorded until the change in temperature becomes negligible or attained steady-state conditions. The experiment was carried out for a period of 600 min when the steady state was attained as shown in Fig. 4. The cold surface temperature of the in the cold chamber was observed to decrease gradually before it begins to rise for all the specimens except the control which shows linear increment in surface temperature. The reduction in the surface temperatures on the respective samples is due to the thermal path which is design parallel to the ambient surface receiving the heat energy. The thermal transmission parallel to the sample surface is slower than the transmission perpendicular to the ambient surface. This is consistent with the 'thermal conductivity' as provided in

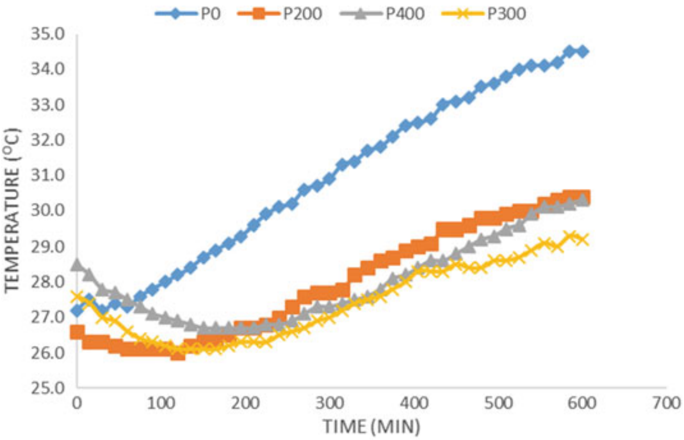

Fig. 4 Cold surface temperature of the samples

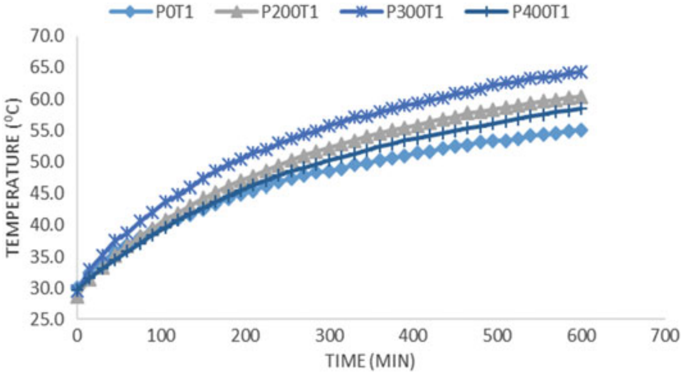

Fig. 5 Hot surface temperature of the samples

American Society of Heating, Refrigeration and Air-conditioning Engineer's handbook ASHRAE [15]. Also, as shown in Fig. 4, the result reveals that the delay in the heat transmission increases with increase in the length of the thermal path. Despite the difference in the initial cold surface temperature, delays in heat transmission of 120, 165 and 210 min were recorded for shear connection spacing designs of 200, 300 and 400 mm, respectively. On the other hand, the control shows higher cold surface temperature and increases linearly although other specimens had reached the steady state.

Figure 5 shows temperature profile of hot surface of all the specimens under consideration. It could be observed that the control specimen recorded the lowest hot surface temperature because, most of the heat is transmitted to the cold side much more than the other specimens design using the thermal path approach (P200, P300 and P400). The result shows that the hot surface temperature increases with increase in thermal path length for control, 200 and 300 mm spacing. However, the 400 mm design is inconsistent with the expected result which falls between 200 and 300 mm shear spacing designs. This behaviour is due to the higher initial temperature of the cold surface at the start of the experiment. It was deduced that the more the difficulty of the heat to transfer to the other side of the wall, the higher the hot surface temperature.

Figure 6 shows the difference in temperature between the hot and the cold surfaces of the specimens. The temperature difference is one of the major determinants of thermal conductivity. The higher the temperature difference the lower the thermal conductivity. In this experiment, the temperature difference increases with increase in shear connection thermal path length. The differences of up to 75% were recorded between the control and the 300 mm shear connection design. This approach helps in optimizing the thermal efficiency and will be further research to determine the structural capacity of the panel system before it can be utilized as structural component.

In line with the provision of ASTM C1363 [14], the air temperature profile in both hot and cold chambers is recorded as shown in Fig. 7. It was observed that the

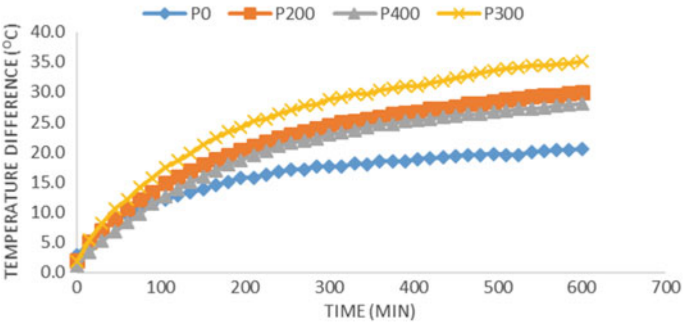

Fig. 6 Temperature difference between hot and cold sample surfaces

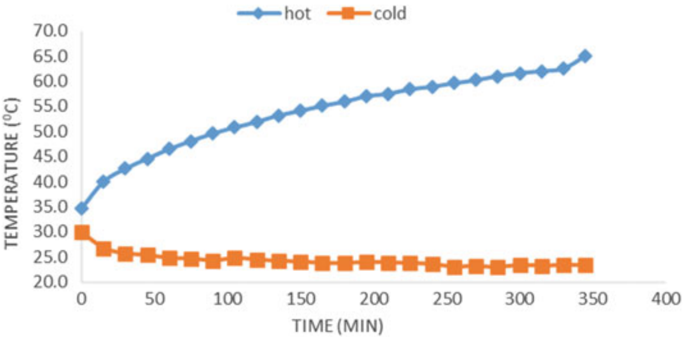

Fig. 7 Air temperatures in the hot and cold chambers

temperature falls between 23 and 65 °C which is within the limits provided in the aforementioned code of between −40 and 85 °C.

4 Conclusions

This experiment was carried out to determine the thermal performance of insulated precast concrete sandwich panels using hot box method under constant temperature refers to as steady-state conditions. Based on the results obtained and subsequent analysis, the following conclusions were drawn:

1. The thermal transmission across the specimen is directly proportional to the length of the thermal path.
2. The time lag for heat transfer depends on the direction of the thermal path, either parallel or perpendicular to the ambient surface of the panel system. The heat transmittance is slower for thermal path parallel to the ambient surface of the wall system making it more efficient.
3. Delay in the heat transfer of about 60 min is achieved for every 100 mm thermal path design parallel to the surface of the heat source (hot side).

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