THERMAL BOWING TESTING OF PRECAST CONCRETE SANDWICH WALL PANELS

A report by

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16. Abstract

Thermal bowing is out-of-plane wall deflection, which is a common issue on sandwich panel walls caused by a temperature differential between a building interior temperature and the environmental conditions.

This report aims to better understand thermal load response of concrete sandwich wall panels. Full-scale testing was performed to verify the assumptions regarding thermal gradient, temperature variation at the cross-section level and thermal conductivity of the connectors.

It was found out that carbon fiber reinforced polymer nor glass fiber reinforced polymer connectors transfer a significant amount of heat from one wythe to the other, hence, the temperature in one wythe remained constant while the other was heated. Thermal bowing was measured, and it was found that following a rapid increase in temperature the out-of-plane deflection resulted in a relatively linear relationship between the temperature gradient and bowing.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

There are many advantages of using precast concrete insulated panels as loadbearing or non-loadbearing members over conventional solid panels. They are more thermally efficient, lighter, and provide fire protection to the insulation layer. The construction of sandwich wall panels normally comprises a layer of foam sandwiched in between two layers of concrete. Such layers are tied together by shear connectors which go through the insulation and provide certain level composite action. As building codes evolve, they have become more stringent regarding energy efficiency, especially thermal efficiency which is where a large portion of buildings energy is spent. This situation has motivated the increase in use of sandwich wall panels with fiber composite connectors due to their low thermal conductivity and relatively low cost.

The research presented in this report was aimed at thermally testing concrete sandwich wall panels by inducing a temperature gradient on one wythe relative to the other. Using this approach, the goal was to verify the assumptions made by different researchers regarding the shape of temperature gradients on the panel cross-section, to prove that FRP connectors transfer a negligible amount of heat between the wythes, and to quantify bowing on the panel caused by the temperature gradient on the cross-section.

1.1 Background

Concrete sandwich all panels (CSWPs), are the ideal solution to thermal efficiency because they are structural and thermally efficient and are capable of proving an unbroken thermal envelope when detailed properly (Sorensen et al. 2019). However, the stresses caused by temperature changes in concrete sandwich panels are known to cause out-of-plane bowing and stresses. In certain situations, these are as important as live and dead load stresses and may cause concrete cracking. In CSWPs design and construction, it is common to have non-composite panels when the designer expects a high temperature gradient, what yields a less economical design, but reduces the bowing. If a designer opts for a different composite behavior, the calculation of the thermal bowing is often estimated using classical mechanics equations for solid panels, which do not consider composite action and yield incorrect results most of the time yet are conservative.

Few testing programs have been carried out to study thermal bowing on CSWPs. One of the few studies can be attributed to Leung (1984), who tested a series of panels with steel ties and measured the deflection due to thermal gradients. Although it was the first testing of its kind, the construction of the specimens and the steel ties do not correspond to the current state of practice. The other testing in which bowing was measured correspond to Post (2006). Bowing was measured at different locations in this study and the connectors used in the construction of the panel where made from glass fiber reinforced polymer, which is one of the commonly used materials for purpose. However, the panel had solid sections connecting the wythes at different locations and several intermediate supports restraining its behavior making it highly difficult to analyze. Solid sections also complicate the analysis of this work, because they cause thermal bridging and hence affects thermal efficiency negatively and causing uneven heating (Sorensen, Dorafshan, & Maguire, 2017; Sorensen, Dorafshan, Maguire, & Thomas, 2019).

1.2 Objectives

The goal of this research was to provide the first testing of CSWP using FRP connectors with clean support conditions for the purpose of future development of analysis techniques. This will help the assumptions made by different researchers regarding the shape of temperature gradients on the panel cross-section, to prove that FRP connectors transfer a negligible amount of heat between the wythes, and to quantify bowing on the panel caused by the temperature gradient on the cross-section.

CHAPTER 2 EXPERIMENTAL PROGRAM

2.1 Introduction

This research was focused on thermally testing two sandwich wall panels with flexible FRP connectors. The main goal of the full-scale testing was to verify the assumptions made by different researchers regarding the shape of temperature gradients on the panel cross-section (Einea, Salmon, Fogarasi, Culp, & Tadros, 1991), to prove that FRP connectors transfer a negligible amount of heat between the wythes, and to quantify bowing on the panel caused by the temperature gradient on the cross-section.

2.2 Materials

Both reinforced concrete sandwich panels, P1 and P2, were reinforced with ASTM A615-Gr60 #3 rebar in both wythes and each way. The concrete used in the construction of the specimens had a 28 -day target strength of 5 ksi for P1, and 8 ksi for panel P2. The composition of the mixes is displayed in Table 1 and Table 2.

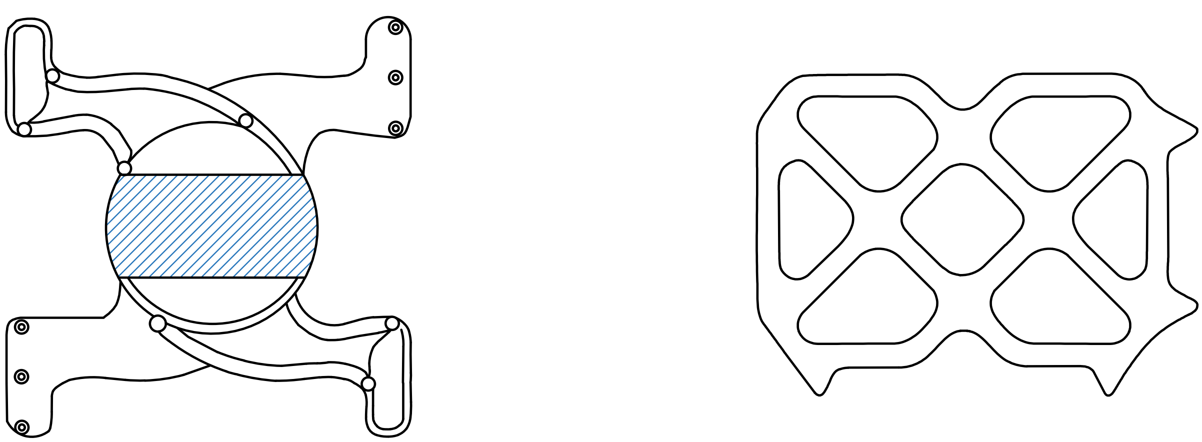
Table 1 Concrete Mix Design for concrete used in panel 1

Materials	Description/Type	Sp. Gr.		lb./cy (SSD)	Vol. ft³
Cement	ASTM C 150 TYPE II/V	3.15		658 lbs	3.35
Water			35.0 gal	292 lbs	4.67
Coarse Aggregate 1	ASTM C-33 #57 Coarse Agg	2.656		1550 lbs	9.35
Coarse Aggregate 2	ASTM C-33 #8 Coarse Agg	2.655		195 lbs	1.18
Fine Aggregate 1	ASTM C-33 Fine Agg	2.649		1340 lbs	8.11
Air			1%		0.35
Admixture	ASTM C494 Type A Low Range Water Reducer		23 Oz		
Total				4035 lbs	27.00

Table 2 Concrete Mix Design for concrete used in panel 2

Materials	Description/Type	Sp. Gr.		lb./cy (SSD)	Vol. ft³
Cement	ASTM C 150 TYPE II/V	3.15		640 lbs	3.26
Pozzolan	ASTM C618 Class F	2.3		112 lbs	0.78
Water			36	299.9 lbs	4.81
Coarse Aggregate 2	ASTM C-33 #8 Coarse Agg	2.655		1450 lbs	8.77
Fine Aggregate 1	ASTM C-33 Fine Agg	2.649		1450 lbs	8.8
Silica Fume	Silica Fume	2.2		25 lbs	0.18
Air			2%		0.54
Admixture	ASTM C494 Type A Low Range Water Reducer		15 Oz		
Admixture	ASTM C494 Type F High Range Water Reducer		45 Oz		
Admixture	ASTM C494 Type C Non-Chloride Accelerator Hydration Stabilizer		22 Oz		
Total				3977 lbs	27.00

The shear connectors used were made of fiber reinforced polymers, which are commercially available in the USA and other countries. The connector used in panel P1 was made of Carbon Fiber Reinforced Polymer (CF), and the connector used in panel P2 was made of Glass Fiber Reinforced Polymer (S).



(A) (B)

Figure 1 Connectors used in the construction of the full-scale specimens. Connector CF (A), Connector S (B)

The cross-section reinforcement and the required concrete strength was computed according to the design methodology developed in (Al-Rubaye, Sorensen, & Maguire, 2017; Al-Rubaye, Sorensen, Olsen, & Maguire, 2018; J. Olsen, Al-Rubaye, Sorensen, & Maguire, 2017) and minimum code requirements of ACI 318-14 (ACI Committee 318, 2014), see Figure 2. The length of panel P1 was 16 ft, whereas the length of panel P2 was 20 ft.

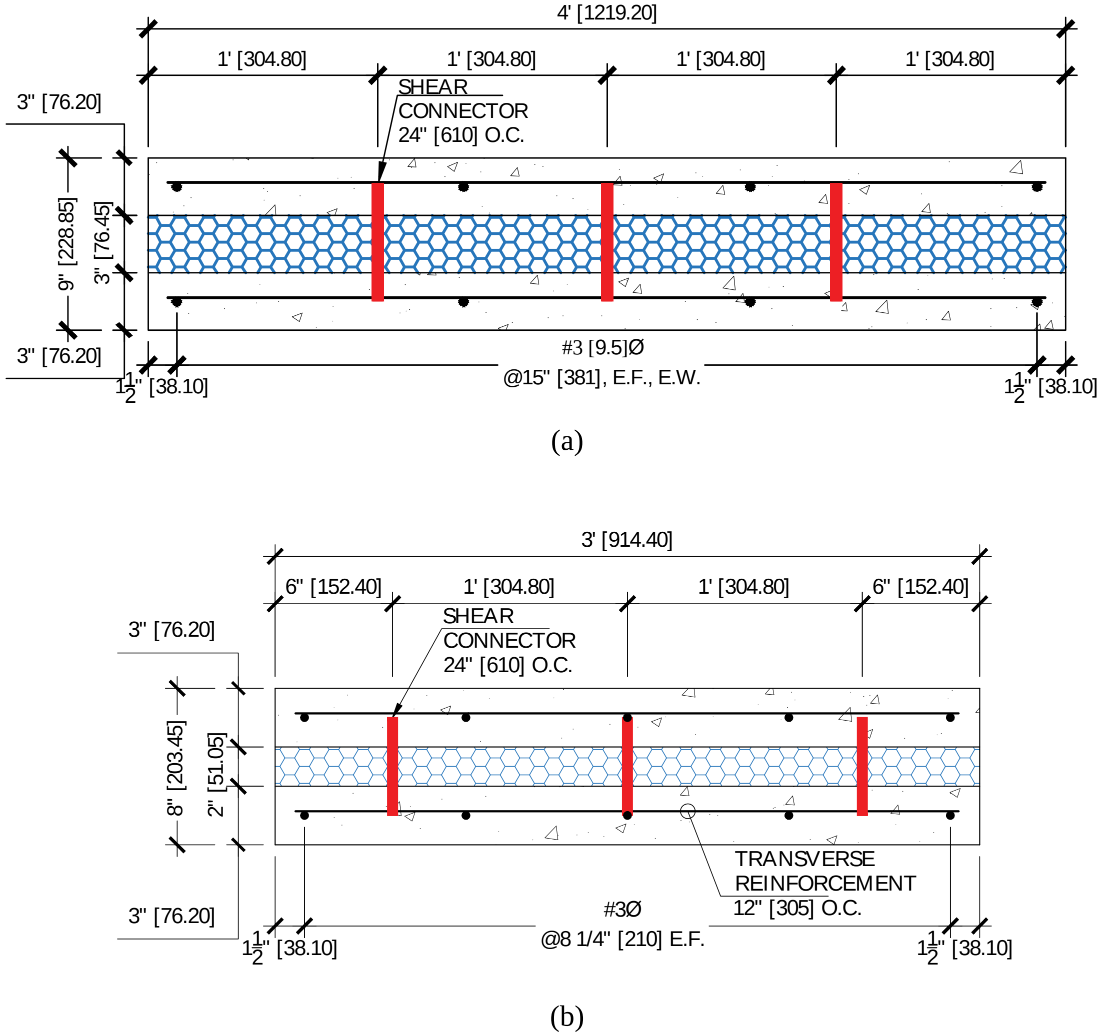
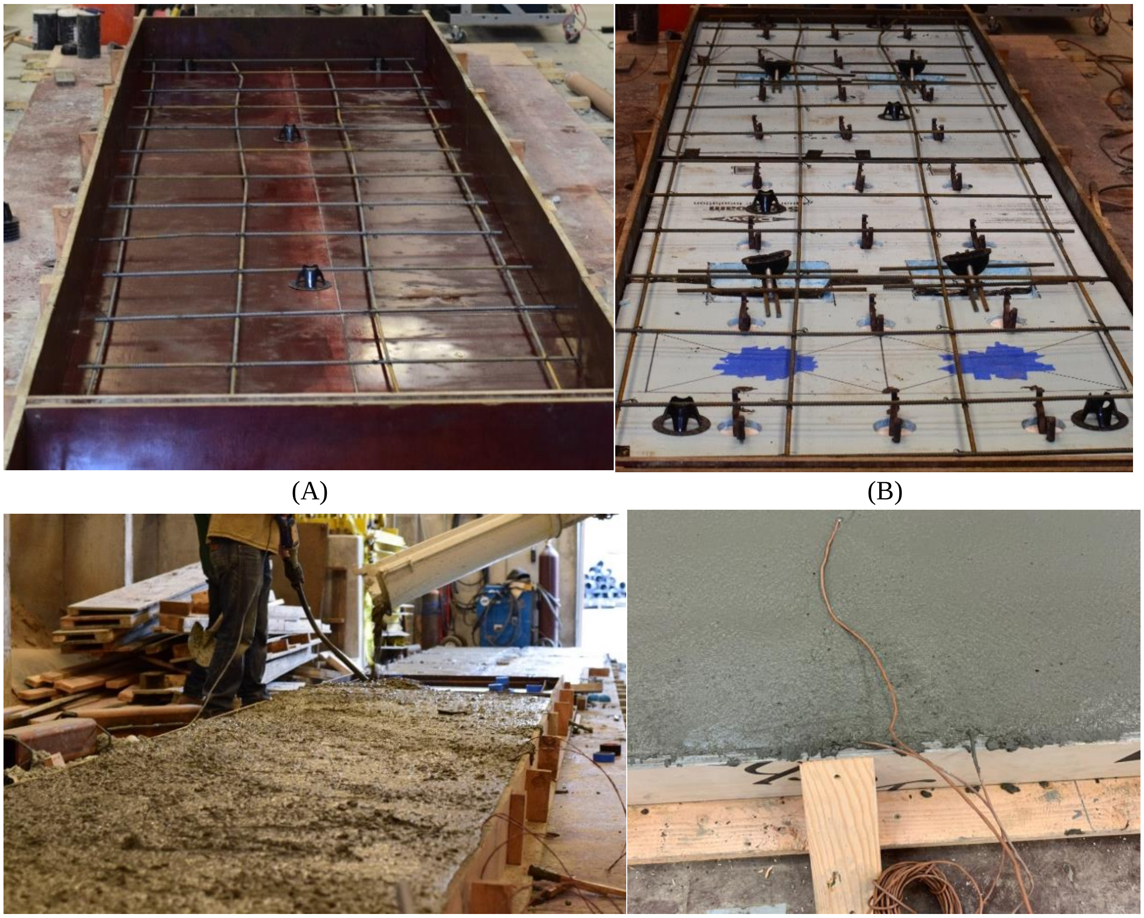


Figure 2 Panel P1 (a) and P2 (b) cross-section dimensions and reinforcement

2.3 Construction of full-scale specimens

The specimens were fabricated at the Utah State University SMASH Laboratory, Logan, Utah. The forms were built using HDO (high-density overlay) plywood and its height was adjusted according to the panel thickness. The basic fabrication procedure was the same for both specimens. Minimal differences were noted where appropriate. The fabrication process was as follow:

1. Fabricate the formwork and apply release agent to eliminate bond between the concrete and the plywood and allow easier form stripping.
2. Place the first layer rebar chairs and reinforcing steel mesh on the forms.
3. Pour first wythe concrete and vibrate accordingly.
4. Place the insulation layer with the thermocouples and shear connectors attached to it.
5. Vibrate the connectors to enhance bond between them and concrete.
6. Place the second layer rebar chairs and reinforcing steel mesh on top of the insulation layer.
7. Pour second concrete layer and vibrate accordingly.
8. Place lifting anchors. Lifting anchors can be placed before or after pouring the concrete depending on the anchor type and minimum embedment length.
9. Finish concrete and put the surface thermocouples sensors in place. These can be placed either before the concrete hardens (embedded in the concrete for P2), or after in hardens (externally attached for P1).
10. Remove the sandwich panels form the forms after concrete has reached strength.

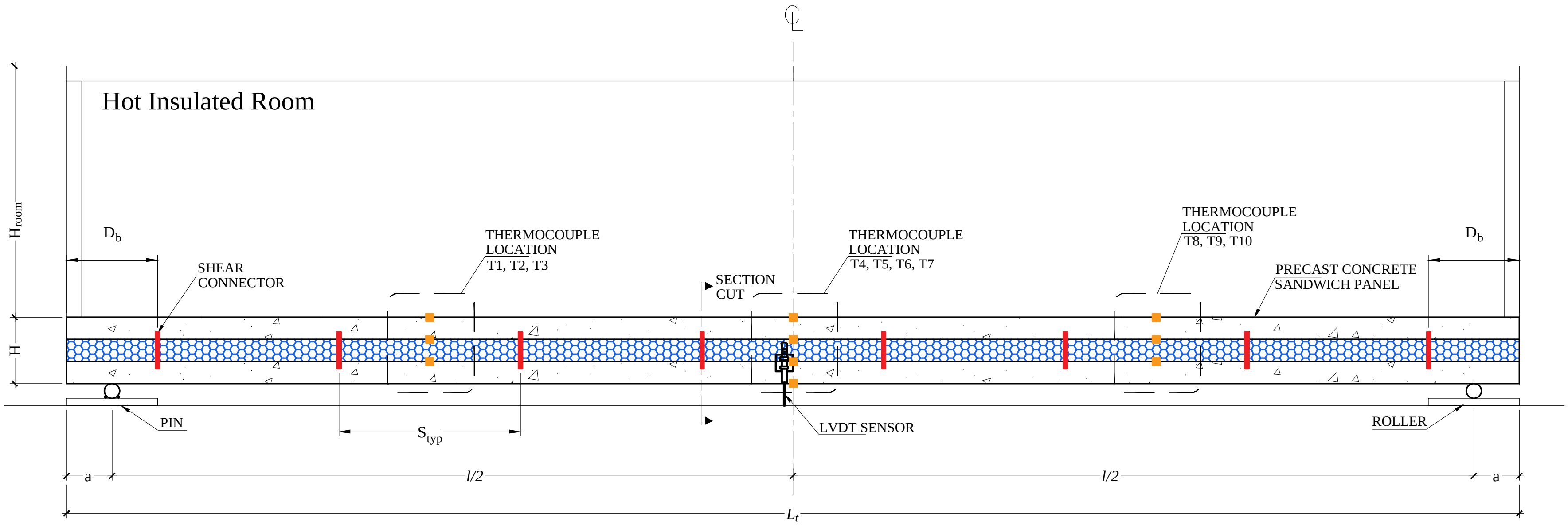


(A) (B) (C) (D)

Figure 3 Sandwich Panel Construction process

2.4 Test Setup

The panels were thermally tested using a hot-box approach. This procedure consists in building an insulated room on top of the panel and heat the interior of the insulated room at constant rate. The objective of this method is to isolate one of the wythes and heat it until the temperature differential of the wythe with respect of the other can induce significative deformations to the panel along the length. The temperature was tracked using a CR1000 datalogger and Type T thermocouple wire (TT-T-20-TWSH-SLE) at quarter points (Lt/4). The thermocouple, combined with the CR1000 data acquisition system has an accuracy of +/- 3^{o}F. The resulting out-of-plane CSWP deformations were measure using LVDT sensors and a BDI STS wireless data acquisition system, see Figure 4.



(A)

Panel	Variable						
	a	Db	H	Hroom	l	Lt	Styp
P1	6 in [152]	12 in [305]	9 in [229]	48 in [1219]	180 in [4572]	192 in [4877]	24 in [610]
P2	12 in [305]	12 in [305]	8 in [203]	48 in [1219]	216 in [5486]	240 in [6096]	24 in [610]

(B)

Figure 4 Test set-up. General view (A),and variables associated with the experimental setup (B)

2.5 Connector testing setup and configuration

The shear connectors used in both specimens were tested following the methodology in Jaiden Olsen, Al-Rubaye, Sorensen, & Maguire (2017). Each specimen had eight connectors in total and the concrete and foam thicknesses varied to follow the full-scale specimens, see Figure 5 and Figure 6. After the concrete reaches the target strength, usually 5 ksi, the specimens are demolded and tested using an experimental layout as the shown in Figure 7.

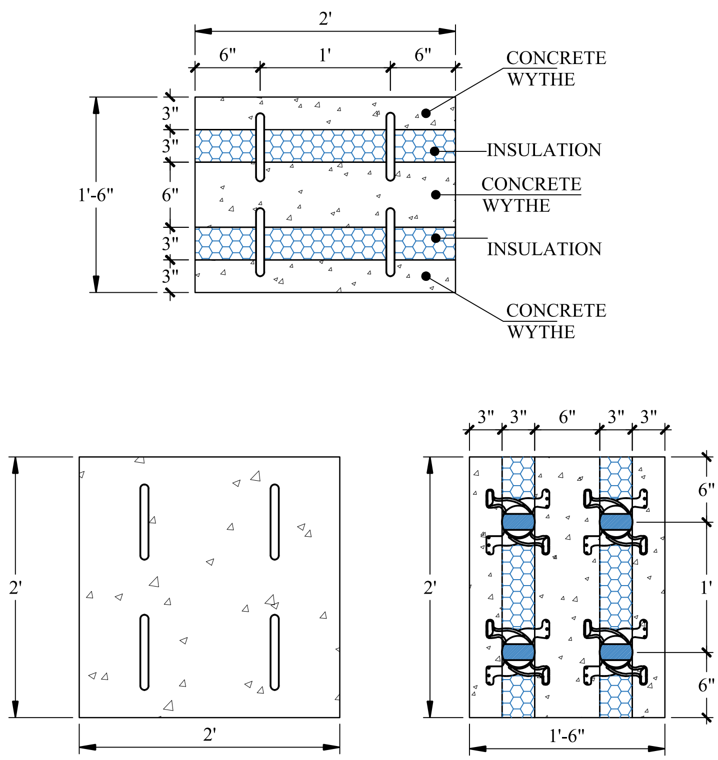


Figure 5 Double shear test specimens for connector CF

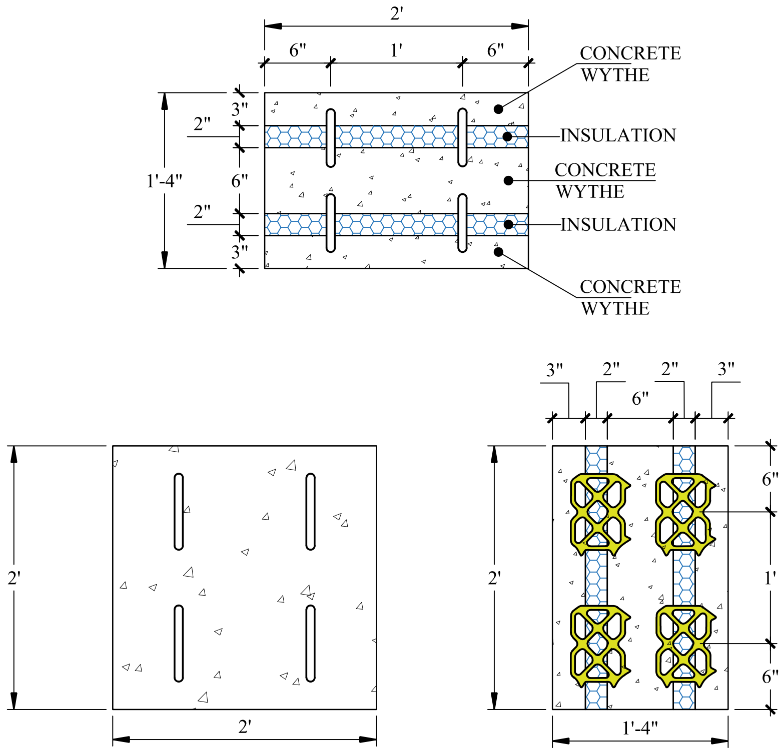


Figure 6 Double shear test specimens for connector S

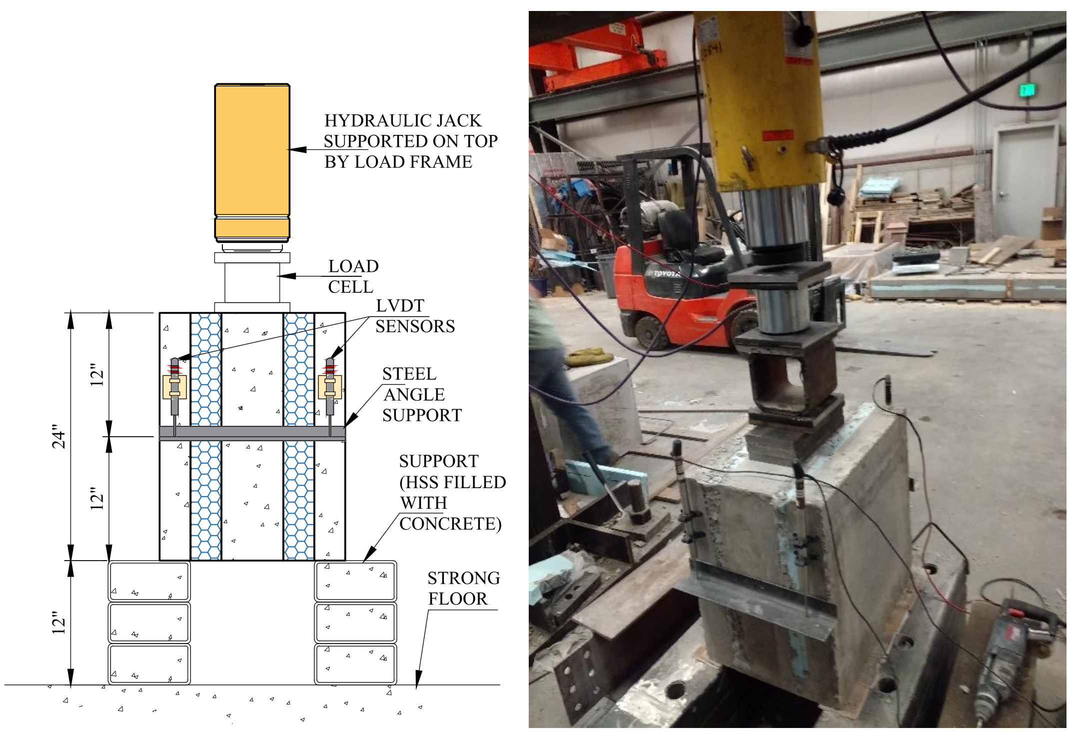


Figure 7 Double shear test specimen. Test layout (A), Installation of the LVDT displacement sensors (B)

2.6 Summary

The preceding chapter described the materials used in the fabrication of the test specimens and its process and instrumentation. Both panels were fabricated at the Utah State University SMASH laboratory.

CHAPTER 3 EXPERIMENTAL RESULTS

3.1 Material Testing

The following sections outline the results of the material testing from the CSWP thermal testing outlined in the previous chapter.

3.1.1 Concrete Testing

Concrete cylinders were sampled from fresh concrete for both tested panels and field cured next to the panel at all times prior to testing. The compression test was performed on the cylinders according to the ASTM C39 (ASTM, 2018) standard and the modulus of elasticity of concrete was performed following the ASTM C469 (ASTM, 2014). Coefficient of thermal expansion was measured according to AASHTO TP60, by Utah Department of Transportation personnel. The results for both concretes are presented in Table 3.

Table 3 Concrete testing results for the full-scale testing

Panel	Compressive Strength, f'c (ksi)	Modulus of Elasticity, Ec (ksi)	Coefficient of Thermal Expansion (strain/°F)
P1	8.74	6,216	6.58×10^{-6}
P2	10.53	6,201	6.38×10^{-6}

3.1.2 Connector Testing

The connectors employed in the fabrication of the specimens were tested in accordance to the procedure on (Jaiden Olsen et al., 2017). Stiffness of the connectors was estimated as the secant stiffness to 50% of the ultimate shear strength from the Load vs Deflection curve of two specimens tested for the connector used in panel P1 and five samples tested for connectors used in P2, see Figure 8a.and Figure 8b. The average ultimate load for the shear connectors used in P1 was 9.25 kips with a COV of 0.015, while the ultimate load for the connectors used in P2 was 3.83 kips with a COV of 0.09. These testing results correspond to the shear capacity of the connector on 3-inch foam for connector CF and 2-inch foam for connector S, tested on 5 ksi concrete.

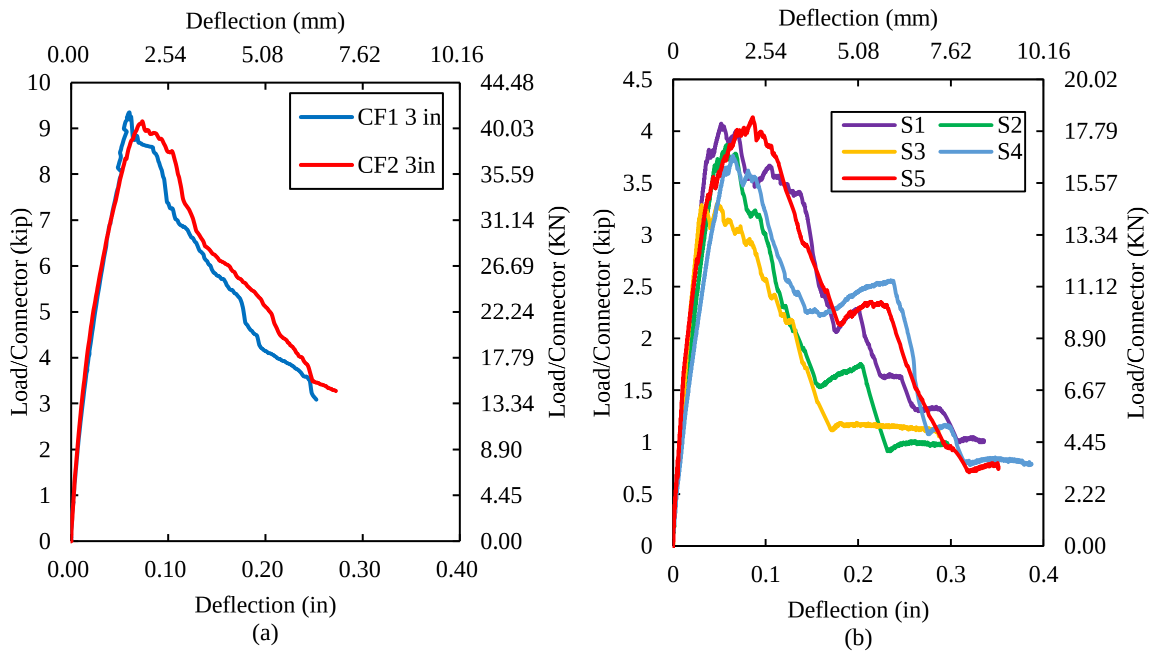
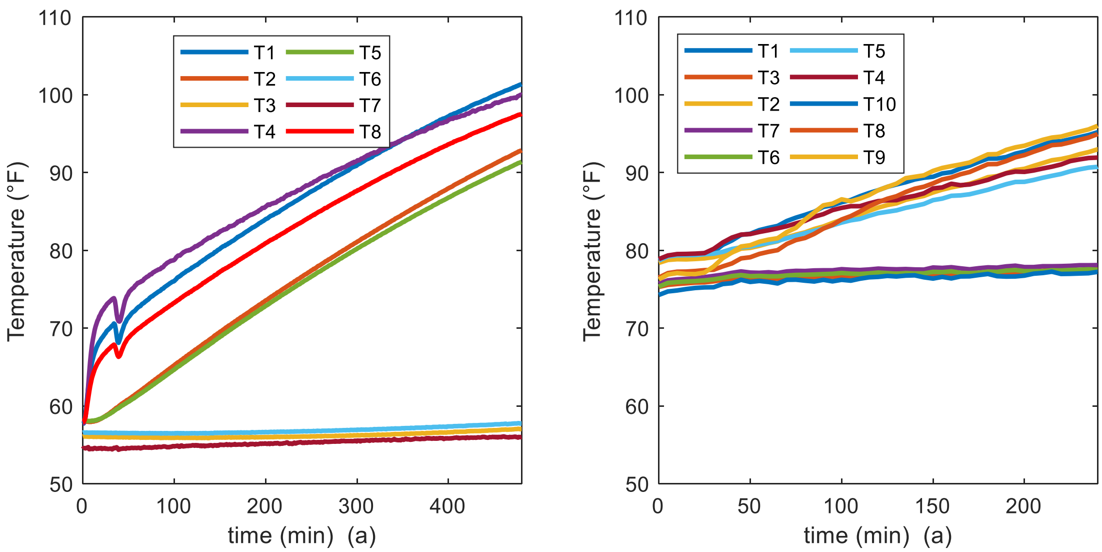


Figure 8 Load/Connector vs deflection for connectors used in P1 (a) and P2 (b)

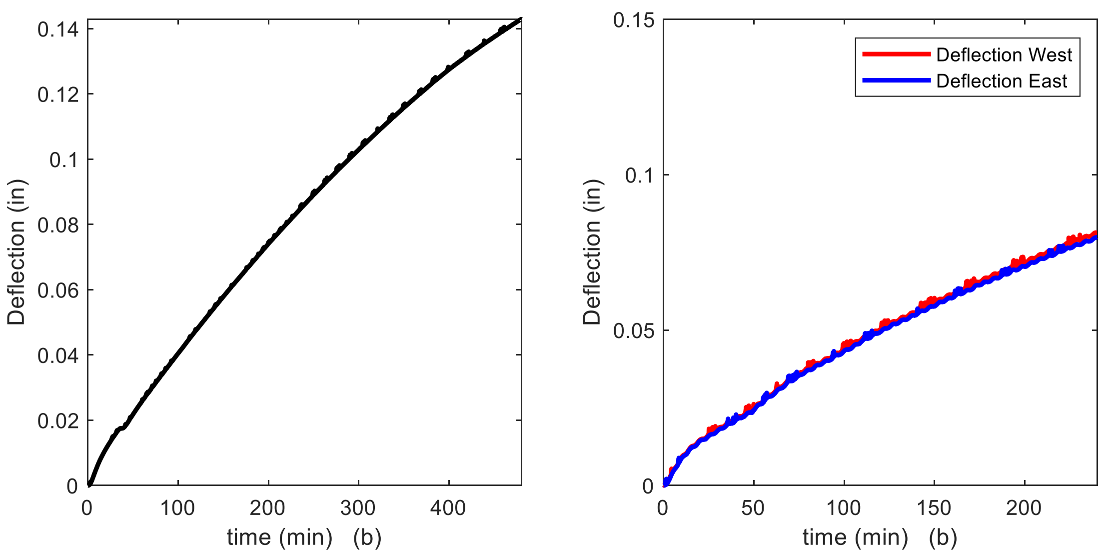
3.2 Full Scale Testing Results

Two full-scale panels were tested according to the procedure defined in the previous chapter. Figure 9 shows the temperature variation on different depths of the panels as a function of time for P1 and P2, and Figure 10 shows the deflection as a function of time caused by to the temperature differential in the panels. In Figure 9a the temperature rises at a near constant rate in the heated wythe after a few seconds, thought to be related to the time it took to heat up the insulated room. Similar effect was noticed in Figure 9b though less pronounced. The ambient temperature of the lab and the unheated wythe were 20 degrees F different between the two tests, affecting the achievable gradients. There does seem to be a temperature differential on the heated wythe and was approximately 10 degrees F for P1 and 5 degrees F for P2.



(A) (B)

Figure 9 Temperature variation over time on the sandwich panel P1 (A), P2 (B)



(A) (B)

Figure 10 Deflection variation over time on the sandwich panel P1 (A), P2 (B)

The temperature and deflection are plotted against each other in Figure 11 to show the effect of the temperature gradient (i.e., average temperature in the heated wythe minus the average temperature on the unheated wythe) on the out-of-plane deflection. The trend of the line shows a direct relationship between the temperature differential and the deflection measured after temperature increasing rate stabilizes, which confirms that the section was still uncracked at the end of the testing. The relationships do not appear completely linear, this is thought to be caused by the minor thermal gradient experienced in the heated wythe but seems to be very minor. Other contributing factors for potential non-linearity is the non-linearity of the connector stiffness and the bonding between the foam and the concrete slightly affected the curve, therefore the line is not completely straight. Panel P1 was tested for 8 hours, whereas panel P2 was tested for 4 hours.

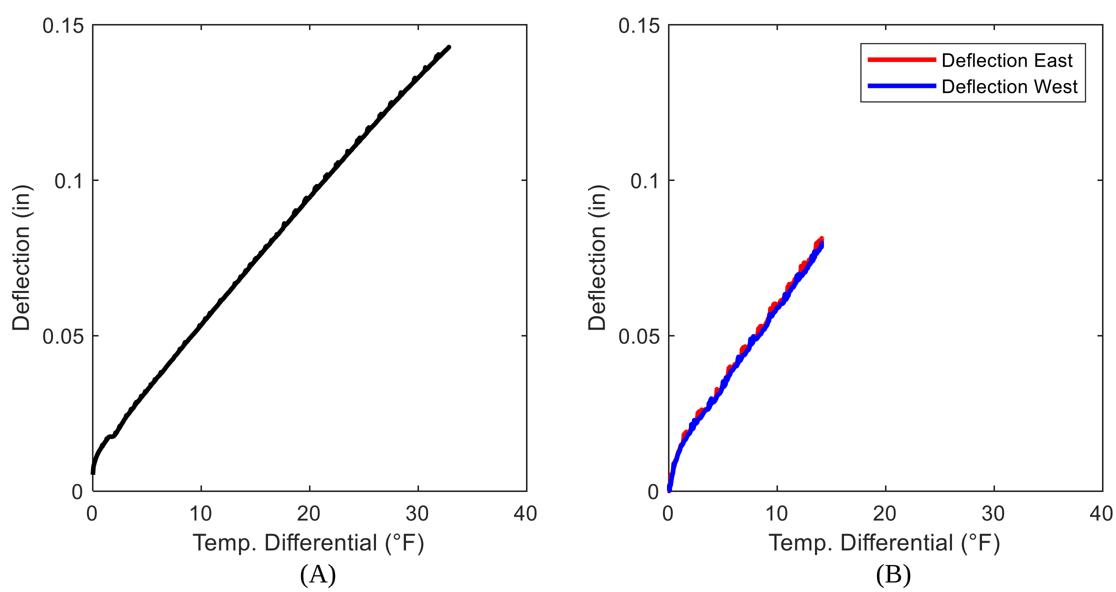


Figure 11 Deflection measurements versus temperature differential for panel P1 (A), and Panel P2 (B)

3.3 Conclusions

Two sandwich panels were thermally tested at the Utah State University SMASH Lab. Based on the results the following conclusions can be drawn:

1. The variation in temperature of the unheated wythe was practically zero, which confirms that CFRP and GFRP connectors used did not create a thermal bridge.
2. The variation in temperature between two points within the cross section, i.e., surface and interface insulation-concrete ranged 5-9 °F. Because the differences between measurements is small and very near the accuracy of the thermocouples used, these numbers were average. Native thermal gradients should be investigated in the future, however for design purposes it is likely the average thermal gradient can be used.
3. The average temperature gradient on the panel at the end of the testing was approximately 40°F for panel P1 and 17°F for panel P2.

CHAPTER 4 CONCLUSIONS

Two concrete sandwich wall panels were tested at the Utah State University Systems, Materials, and Structural Health (SMASH) Laboratory. The goal of this testing was to verify assumptions made by different researchers about the behavior of sandwich panels under thermal gradients. The following conclusions can be drawn based on the experimental results:

- The variation in temperature measurements in the heated wythe between two points is smaller when the thermocouple is embedded versus externally attached.
- There is a linear relationship between bowing and the thermal gradient in the elastic range after the stabilization of temperature.
- The variation in temperature of the unheated wythe was practically zero, which confirms that CFRP and GFRP connectors used did not create a thermal bridge.
- The variation in temperature between two points within the cross section, i.e., surface and interface insulation-concrete ranged 5-9°F. Such difference can be averaged for design purposes, or the average of the gradient can be computed for the whole panel.
- The average temperature gradient on the panel at the end of the testing was approximately 40°F for panel P1 and 17°F for panel P2.

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