Analytical Investigation of Thermal Performance of Precast Concrete Three-Wythe Sandwich Wall Panels

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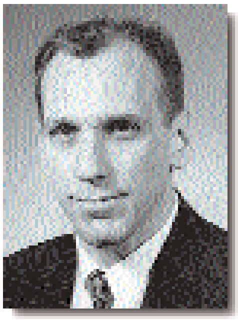

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Precast concrete sandwich wall panels are commonly constructed of two wythes of concrete separated by a layer of thermal insulation. In these two-wythe panels, solid concrete regions which extend directly through the entire thickness of the panel are often provided with embedded hardware for lifting, handling, and connections, or to provide composite action. These solid concrete regions have a significant adverse impact on the thermal performance of the panels. This research was directed towards the development of precast concrete three-wythe sandwich wall panels with improved thermal and structural performance. A three-wythe panel has three concrete wythes and two insulation layers, and all three concrete wythes are connected by solid concrete regions that are staggered in location so that no concrete path extends directly through the entire thickness of the panel. Practical panel configurations of three-wythe panels were developed, and their thermal performance was evaluated by estimating thermal resistance (R-value) using finite element method.

Precast concrete sandwich wall panels are often used for building exterior cladding and may also serve as bearing or shear walls. Often, both concrete wythes are of the same thickness, and the surface of the exterior wythe may include architectural details such as reveal strips to provide the desired panel aesthetics. In this paper, panels with two concrete wythes and one insulation layer are referred to as two-wythe panels.

In a typical sandwich wall panel, wythe connectors are used to tie the two concrete wythes together and to keep the panel intact during handling and service conditions. The wythe connectors pass from one concrete wythe to the other concrete wythe through the insulation layer. Thus, the placement of the connectors interrupts the continuous insulation layer. These interruptions are known as "thermal bridges." Depending upon the material used to make the connectors in a panel, these thermal bridges can conduct energy at a much higher rate than the insulation, thus reducing the effectiveness of the insulation.[1] According to McCall,[2] in some cases, the thermal performance of a panel may be decreased by as much as 40 percent by the large quantities of heat conducted through the shear connectors and the concrete regions that penetrate the insulation.

The thermal performance of a panel can be evaluated by estimating its thermal resistance (R-value, the reciprocal of material conductance). The R-value of a material or assembly of materials is a quantity that is often used to describe the thermal performance of building construction.[3, 4] The R-value calculation for a sandwich panel includes analyzing the panel for the effects of thermal bridges.

Fig. 1 shows three typical two-wythe panels. The panels are commonly described by a three-digit sequence of numbers, where each digit in the sequence denotes the thickness of one of the layers in the panel. For example, a 3-2-3 panel is comprised of two 3 in. (76 mm) thick concrete wythes separated by a 2 in. (51 mm) thick insulation layer.

As shown in Fig. 1, solid concrete regions (i.e., regions where the insulation layer is omitted) are provided for a variety of reasons including the placement of inserts for lifting and handling, connections to the foundation and roof, and connections to adjacent panels. These locations of solid concrete also act as thermal bridges and can have a significant adverse impact on the thermal performance of the panels. Kosny et al.[5] tested panel configurations similar to those presented in Fig. 1(a) using the Guarded Hot Box Method.[6] They reported that a 45 percent reduction in R-value was observed when solid concrete regions were added.

The research described in this paper is directed towards the development of precast concrete three-wythe sandwich wall panels (referred to as the three-wythe panels) with improved thermal performance as compared to the insulating properties of currently produced two-wythe panels. Fig. 2(a) shows a typical three-wythe panel. A three-wythe panel has three concrete wythes and two insulation layers. Solid concrete regions between successive concrete wythes are staggered in location, thereby eliminating all direct through-thickness thermal paths through solid concrete. Further explanation of the three-wythe panel is given in the next section.

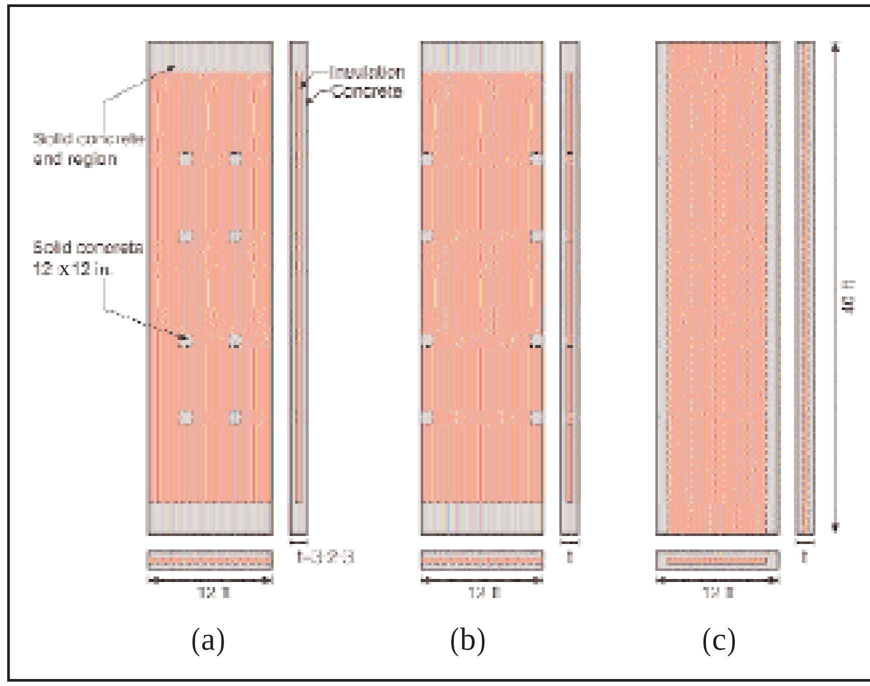


Fig. 1. Typical two-wythe panel configurations.

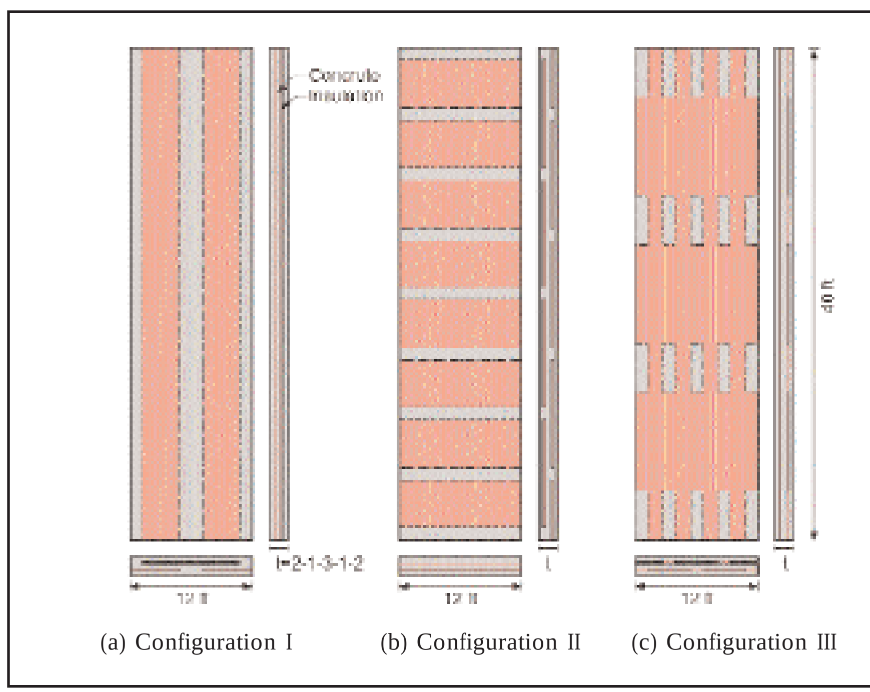


Fig. 2. Three-wythe panel configurations.

The authors describe the thermal performance of precast concrete three-wythe sandwich wall panels. Possible panel configurations of the three-wythe panels are proposed, and their thermal performance is studied by estimating R-values using the finite element method (FEM) analysis. Also, R-values computed using FEM were compared with experimental results and with R-values computed using ASHRAE Handbook methods. Com-

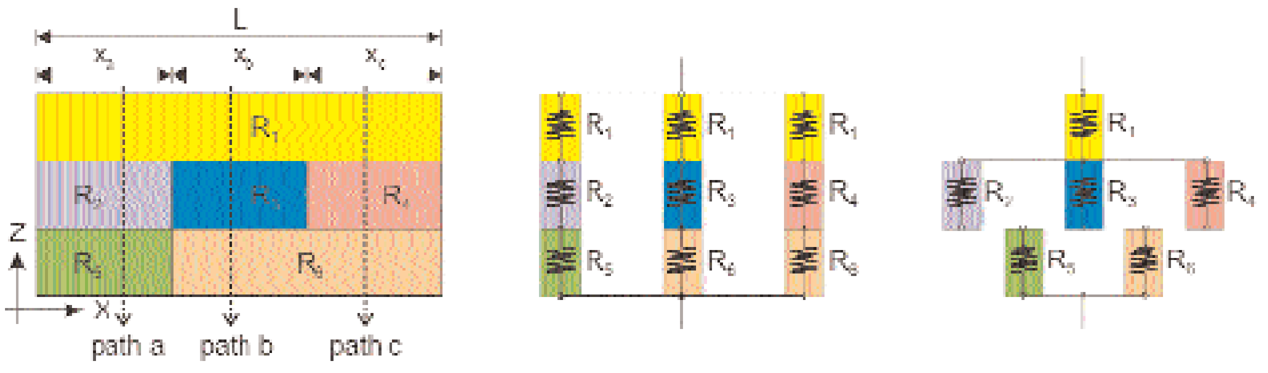


Fig. 3. Illustration of the parallel flow and isothermal plane methods.

plete details of the work presented in this paper are provided by Lee and Pessiki.[7, 8]

PROPOSED THREE-WYTHE PANELS

Fig. 2 shows three possible general configurations of the three-wythe panel. Similar to the two-wythe panels, the three-wythe panels are described by a five-digit sequence of numbers. For example, a 2-1-3-1-2 panel is comprised of two outer 2 in. (51 mm) thick concrete wythes, one inner 3 in. (76 mm) thick concrete wythe, and two 1 in. (25 mm) thick insulation layers between concrete wythes as shown in Fig. 2.

In contrast to the two-wythe panels shown in Fig. 1, the three-wythe panels do not include any regions of solid concrete that extend directly through the full thickness of the panel. Thus, the thermal path length through which heat is conducted through the concrete is increased in the three-wythe panel as compared to the two-wythe panel.

In Configuration I (Fig. 2a), the solid concrete regions between wythes are staggered in the width direction of the panel. For this configuration, the panel cross section is uniform along the panel span. In Configuration II (Fig. 2b), the solid concrete regions between wythes are staggered in the span direction of the panel so that the panel cross section is uniform across the width of the panel. Finally, for Configuration III (Fig. 2c), the locations of solid concrete regions between wythes are staggered in both the width and span directions.

Several potential advantages of the three-wythe panel include the following:

1. Improved thermal performance over that of the current two-wythe panel due to the staggered placement of the concrete connections between wythes. Increased R-values may lead to a reduction in the life-cycle costs of buildings made with the three-wythe panel. Results of an investigation of the steady-state thermal performance of the three-wythe panel are presented in this paper.

2. Composite action between wythes may be provided by concrete.

3. Increased spanning capabilities due to thicker overall wall panels may lead to extension of the range of applicability of precast concrete sandwich wall panels.

4. Locations of thickened concrete regions where wythes are connected may be used for the placement of the embedded hardware that is required to handle and erect the panels.

5. All of the prestressing steel may potentially be placed in the center of the three-wythe panel, which should afford better corrosion protection; further, this may also reduce at least one production requirement (prestressing is only done once), which may partially offset the increased production requirements of the three-wythe panel as compared to the two-wythe panel.

The three-wythe sandwich wall panel includes several potential disadvantages as compared to the two-wythe panel, the most obvious of which may be increased production time and cost. Thus, the three-wythe panel may not be economically feasible for all applications.

ASHRAE R-VALUE ESTIMATES

The American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook – Fundamentals (ASHRAE Handbook[9]) describes three methods to compute R-values through a material or assembly of materials using electric-circuit analogies. These methods are the parallel flow, isothermal plane, and zone methods. In these methods, the thermal resistances of the materials are treated as electrical resistances that are arranged in parallel or in series flow methods, or a combination of the two analogies, to estimate the thermal resistance of the assembly. A brief description of each method is given below.

Parallel Flow Method

The parallel flow method computes the R-value by assuming that heat flows in parallel paths with no lateral heat flow between paths. The R-value calculation of an assembly of materials using the parallel flow method is illustrated in Fig. 3. The assemblage (Fig. 3a) is comprised of six different materials with resistances, R_1 through

R_6, and heat flows in the negative Z-direction. The R-value is computed considering each independent heat flow path (a, b, and c) in parallel as shown in Fig. 3a. The resistance of each path is the sum of the individual resistances in series along the path as shown in Fig. 3b. The parallel flow method can be written in equation form as:

$$\frac{1}{R} = \left(\frac{x_a}{L}\right)\frac{1}{R_a} + \left(\frac{x_b}{L}\right)\frac{1}{R_b} + \left(\frac{x_c}{L}\right)\frac{1}{R_c} + \ldots + \left(\frac{x_n}{L}\right)\frac{1}{R_n} \tag{1}$$

where R_a, R_b … R_n are the net resistances of each parallel path, and x_a, x_b … x_n are the respective fractions of the total length, L, of the assemblage ($L = x_a + x_b + \ldots + x_n$).

Isothermal Plane Method

The isothermal plane method computes the R-value by assuming that lateral heat flows in each layer so that isothermal planes result. For a layer that includes two or more materials with different conductivities, the parallel flow method is used to obtain the resistance of that layer. The resistances of succeeding layers are added in series to obtain the resistance of the entire assembly. The R-value calculation of the isothermal plane method is illustrated in Fig. 3c for the same assembly of materials used to illustrate the parallel flow method. The isothermal plane method can be written in equation form as:

$$R = R_{L1} + R_{L2} + R_{L3} + \ldots + R_{Lm} \tag{2}$$

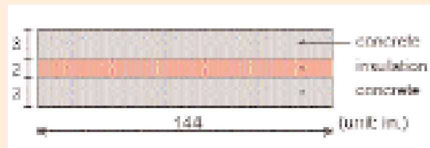
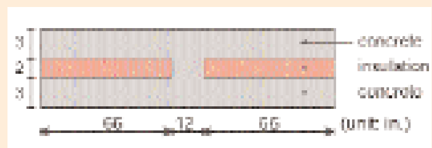
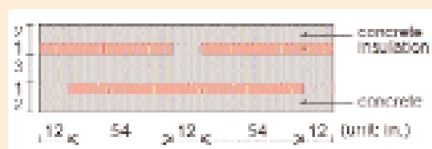
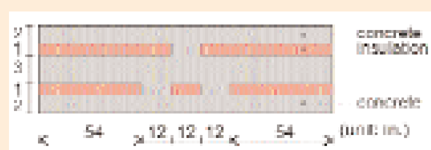
where R_{L1}, R_{L2} … R_{Lm} are individual resistances of each layer that are calculated by the parallel flow method described in Eq. (1).

Zone Method

When an assembly contains widely spaced, high thermal conductivity elements of substantial cross-sectional area, the zone method to compute the R-value can be used. The zone method involves two separate computations; one for a chosen limited portion containing the highly conductive element, and the other zone for the remaining portion of simpler construction. The isothermal plane method is applied by adding area resistances, R/A, of elements in series for each separate zone. The two computations are then combined using the parallel flow method.

The key to successful application of the zone method is the correct determination of the size of each zone. The ASHRAE Handbook explains empirical width calculations for each separate zone. The PCI Design Handbook uses the zone method to calculate the influence of thermal bridges created by metal wythe connectors.[10] Recent work at Lehigh University provides an alternative method to calculate the influence of thermal bridges created by regions of solid concrete in two-wythe panels.[11, 12]

Table 1. R-value calculation of two- and three-wythe panels.

Panels	R-value (hr·sq ft·°F/Btu) Parallel flow method	Isothermal plane method	FEM
Case (a) 	9.13	9.13	9.13
Case (b) 	6.55	3.04	5.86
Case (c) 	7.85	2.77	7.21
Case (d) 	7.85	2.77	6.06

Note: 1 hr·sq ft·°F/Btu = 0.1761 m²·°C/W; 1 in. = 25.4 mm.

ASHRAE Handbook Methods Versus Finite Element Analyses

In current practice in the precast concrete industry, R-values of wall panels are sometimes estimated using the parallel flow and isothermal plane methods. However, these ASHRAE Handbook methods do not adequately consider the lateral heat flow that occurs in sandwich wall panels. Table 1 demonstrates the weaknesses of the ASHRAE Handbook methods, and supports the rationale for using FEM calculations in the current work presented in this paper.

Table 1 shows R-value calculations for different panel configurations including both two- and three-wythe panels. Shown in the table are cross sections of prismatic panels and corresponding R-values computed using the parallel flow method, the isothermal

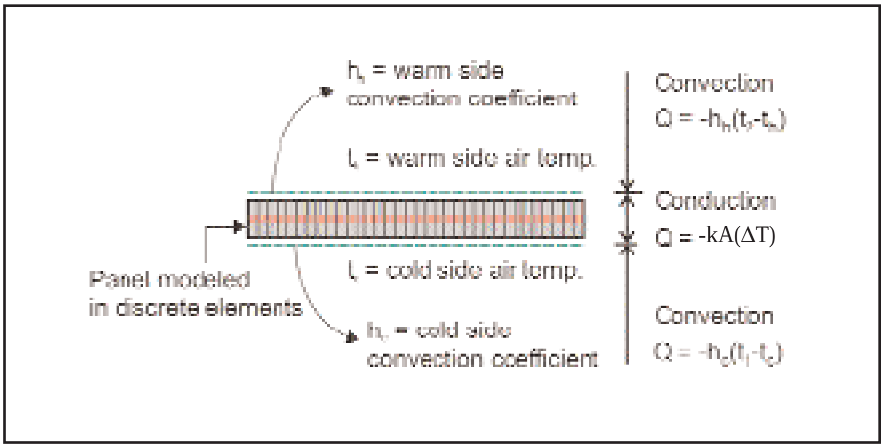


Fig. 4. Finite element method model.

plane method, and FEM analysis.

In all cases, constant material conductivity values of k_{con} = 12.05 Btu·in./hr·sq ft·°F (1.74 W/m·°C) for concrete and k_{in} = 0.26 Btu·in./hr·sq ft·°F (0.037 W/m·°C) for insulation were used. Air film resistances of 1.46 and 4 Btu/hr·sq ft·°F (8.29 and 22.7 W/m^2·°C) were used. For the FEM analyses, two-dimensional steady-state heat transfer analyses were executed. Details of the FEM analyses are explained in the next section. The purpose of Table 1 data is for comparison of the results obtained from the ASHRAE Handbook methods to that of FEM analyses.

For Case (a) of a 3-2-3 panel (Table 1), which does not have any thermal bridges, the same R-value is obtained from the parallel flow and isothermal plane methods. The FEM analysis also predicts the same R-value as shown. For Case (b) of a 3-2-3 panel (Table 1), which includes a thermal bridge, different R-values are obtained from the parallel flow and isothermal plane methods. The FEM analysis also predicts a different R-value from the two ASHRAE Handbook methods.

For Cases (c) and (d) presented in Table 1 for the 2-1-3-1-2 panels containing the same amounts of concrete and insulation in each wythe, one can intuitively expect that these two different panel configurations would lead to different R-value results because the placement of the concrete and insulation is different in the fourth wythe between the two cases. However, when the electric-circuit analogy is used, the parallel flow method gives the same R-value of 7.85 hr·sq ft·°F/Btu (1.38 m^2·°C/W) for both panels, and the isothermal plane method gives the same R-value of 2.77 hr·sq ft·°F/Btu (0.49 m^2·°C/W) for both panels. Therefore, the parallel flow and isothermal plane methods are not capable of accounting for the difference in thermal performance between the two panels. On the other hand, for the FEM results, Case (c) produces a higher R-value as compared to Case (d) because Case (c) has a longer heat flow path through the thickness of the panel along the concrete thermal bridge between wythes.

From the discussion above, it is concluded that the ASHRAE Handbook R-value calculation methods cannot be applied to estimate the R-value of the three-wythe panels – this is because the ASHRAE Handbook methods do not properly include the effect of lateral heat flow occurring in the three-wythe panels.

FEM APPROACH

Several ASTM Standard Test Methods are available to estimate the steady-state thermal resistance of building components such as walls, floors, and roofs. ASTM's Guarded Hot Box Method is a general test method which can be used to estimate the thermal performance of sandwich wall panel assemblies.[6] In this work, the FEM approach was used to estimate the R-value of the three-wythe panel by modeling the Guarded Hot Box Method. The Guarded Hot Box Method is briefly described below, followed by an explanation of how this method is modeled using finite elements.

Guarded Hot Box Method

The Guarded Hot Box Test Method is performed using an apparatus of the same name; the guarded hot box consists of a metering box, a guard box, and a cold box. The test panel is placed between the metering box and the cold box, and exposed to warm air at the metering and guard boxes, and cold air at the cold box. In the Guarded Hot Box Method, testing is performed by establishing and maintaining the desired steady temperature differential across a test panel for a period of time to ensure constant heat flow and steady temperatures. At this time, the heat flow, Q (Btu/hr), is measured.

Q is a measure of heat in the metering box through a known area of the panel, A (sq ft). Surface temperatures of the warm and cold sides of the test panel are also measured under steady-state conditions. Then, the thermal resistance, R, can be obtained as:

$$R = \frac{A(t_2 - t_1)}{Q} \tag{3}$$

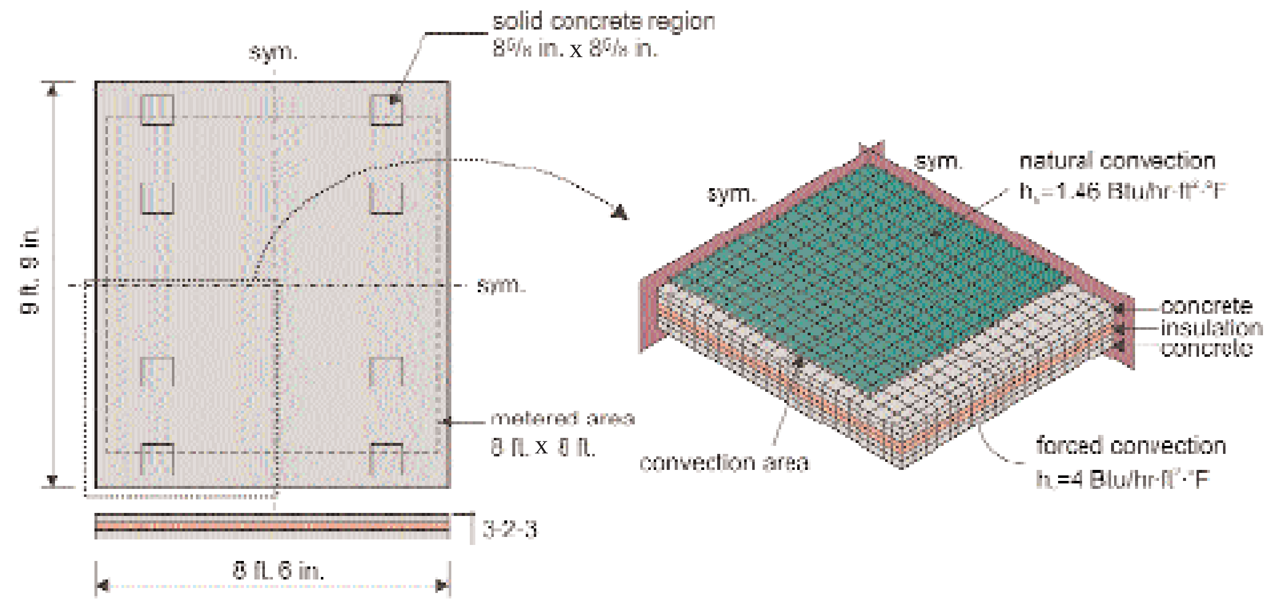
where t_1, t_2 (°F) are area-weighted mean temperatures of the two surfaces.

An alternative approach is to include air film resistances in the determination of thermal resistance. In that case, the overall thermal resistance, R_T, is:

$$R_T = \frac{A(t_h - t_c)}{Q} \tag{4}$$

where t_c and t_h are ambient air temperatures (°F) of cold and warm sides, respectively.

In building applications, the overall thermal resistance, R_T, is often used as the R-value for a panel; in this paper, all R-values are presented in terms of overall thermal resistance values. Often, the thermal resistance, R, given in Eq. (3) is called surface-to-surface R-value, and the overall thermal resistance, R_T , given in Eq. (4) is called



(a) Panel geometry (b) FEM model

Fig. 5. Sandwich wall panel tested by Kosny et al.[5]

air-to-air R-value.

FEM Approach to Determine R-values

A panel under study was modeled using finite elements for conditions present in the Guarded Hot Box test[6] and results of the analysis (temperature and heat flow) were used to compute an R-value. All FEM heat transfer analyses were executed using the SAP 90 Heat Transfer Analysis Program.[13]

FEM model – Fig. 4 shows the FEM model of a test panel in the metered area of the Guarded Hot Box Method. Only convection and conduction heat transfer are considered. From the warm air to the surface of the panel, convection heat transfer occurs according to a relationship of $Q = -h_h(t_2 - t_h)$; where h_h is a convection coefficient on the warm side of the panel. Inside the test panel, heat is transferred in conduction, and heat is transferred with a relationship of $Q = -k(A\Delta T)$; where k is the material conductivity and ΔT is a temperature difference.

Finally, from the panel to the cold air, convection heat transfer occurs again with a relationship of $Q = -h_c(t_1 - t_c)$; where h_c is a convection coefficient on the cold side of the panel. All radiation effects were ignored because these are minimized with selected materials in guarded hot box facilities.

Depending upon the panel geometry, either two- or three-dimensional heat transfer analyses were performed to estimate R-values of the panels. When the panel is prismatic (see Fig. 2a and b), such two-dimensional heat transfer analysis is conducted with the two-dimensional FEM model. When the panel is non-prismatic such as the case of Fig. 2(c), three-dimensional heat transfer analysis is conducted using the three-dimensional FEM model.

The concrete and insulation were modeled with plane elements in the two-dimensional analyses, and with solid elements in the three-dimensional analyses. Mesh refinement studies were performed to determine an appropriate element size and aspect ratio of the element (a ratio of the longest dimension to the shortest dimension of an element). The impact on R-values as a function of element size and aspect ratio, along with program execution time, were examined to arrive at final element size and shape. Complete details of the modeling are given in Lee and Pessiki.[7, 8]

Material conductivities – All materials were treated as isotropic with constant conductivity. A concrete conductivity of k_{con} = 12.05 Btu·in./hr·sq ft·°F (1.74 W/m·°C) and insulation conductivity of k_{in} = 0.26 Btu·in./hr·sq ft·°F (0.037 W/m·°C) were consistently used for all FEM analyses unless k_{con} and k_{in} were parameter variables to study the influence of material conductivity. According to McCall,[2] k_{con} = 12.05 corresponds to the concrete material having a density of 150 pcf (23.6 kN/m^3), and k_{in} = 0.26 corresponds to the expanded polystyrene insulation material.

Boundary conditions – Convection boundaries were specified as shown in Fig. 4 on both surfaces of the panel. Convection boundaries also function as loading. Plane elements were used to specify convection boundaries in three-dimensional analyses, and frame elements were used in two-dimensional analyses. In the Guarded Hot Box Method, the test panel is in contact with moving cold and warm air. Considering air velocity, temperature, and surface material of the panel, convection coefficients were determined according to the ASHRAE Handbook.

In the FEM model, a forced convection boundary was specified for the

Table 2. Comparison of R-values for a sandwich wall panel tested by Kosny et al.[5]

Method	R-value* (hr·sq ft·°F/Btu)	Analysis result / Experimental result
Parallel flow method	6.47	1.12
Isothermal plane method	3.36	0.58
FEM	5.48	0.94
ASTM C-236	5.80	—

Note: 1 hr·sq ft·°F/Btu = 0.1761 m^2·°C/W.
* All R-values in this table are surface-to-surface R-values.

cold surface of the panel, and a natural convection boundary was specified for the warm surface of the panel. For both convection boundaries, constant convection coefficients were used. An adiabatic surface was assumed where a symmetry boundary condition existed. In order to simplify the numerical model and analysis, and to reduce program execution time, a symmetry condition of the panel was used.

Verification of the FEM Model

The results of physical experiments to measure R-values of three different wall systems were compared with FEM analyses of the same three wall systems to verify the FEM approach to determine R-values. The three wall systems are: (1) sandwich wall panel containing regions of solid concrete;[5] (2) sandwich wall panel without any concrete thermal bridge;[14] and (3) concrete block walls with core insulation.[15] The first verification example is presented here, and complete details are presented in Lee and Pessiki.[7, 8]

Kosny et al. studied the thermal performance of sandwich wall panels that included solid concrete regions. The solid concrete regions were used as panel wythe connectors, and their effect on the thermal performance of the panel was investigated experimentally.[5]

Fig. 5a shows the configuration of the sandwich wall panel. The wall panel is a 3-2-3 sandwich wall panel, and the concrete wythes are connected by eight $8^5/_8$ x $8^5/_8$ in. (219 x 219 mm) solid concrete regions. The panel was tested using the Guarded Hot Box Method.[11] Because the panel had to be supported to the testing frame, the guarded box covered only four concrete penetrations as shown in the dotted line in Fig. 5a. The remaining four penetrations straddled the boundary between the metering box and the guard box.

FEM model and analysis – The FEM model is shown in Fig. 5b. This is a three-dimensional heat transfer problem where one-quarter fraction of the panel was modeled considering panel symmetry conditions as shown in Fig. 5a.

Eight-node solid elements were used for both concrete and insulation. The maximum aspect ratio of the elements was 1:3. Constant conductivity was used for each material as k_{con} = 12.5 Btu·in./hr·sq ft·°F (1.80 W/m·°C) for concrete, and k_{in} = 0.2 Btu·in./hr·sq ft·°F (0.029 W/m·°C) for extruded polystyrene insulation. These conductivity values were obtained from Reference 5. For the boundary condition of the FEM model, an adiabatic wall boundary was specified for both symmetry sides and free edges of the panel. For warm and cold surfaces of the panel, shell elements were used to specify convection heat transfer, and coefficients are shown in Fig. 5b.

Comparison – Table 2 shows the R-values obtained from the experiment and from the different analysis methods. All R-values in this table are surface-to-surface R-values without including air resistances of the panel. Also shown in the table is the ratio of each analytical result, divided by the experimental result. Table 2 shows that the parallel flow method overestimated the experimentally determined R-value, and the isothermal plane method underestimated the R-value. The FEM result was very close to the experimental result, and it was approximately 6 percent lower.

TEMPERATURE DISTRIBUTIONS

The FEM heat transfer analysis provides the temperature at each node for all of the elements. The temperature distributions in the two- and three-wythe panels help to understand the manner in which heat is transferred through the panels. Panel cross sections and typical temperature distributions in two- and three-wythe panels are shown in Fig. 6. For both two- and three-wythe panels, the concrete thermal bridge width is 24 in. (610 mm), and the top and bottom ambient air temperatures are 125°F (51.7°C) and 25°F (–3.9°C), respectively.

As shown in Fig. 6a, the panel surface temperatures in the two-wythe panel deviate dramatically from the ambient air temperatures at the solid concrete region. This solid concrete region clearly functions as a thermal bridge. Also, lateral heat transfer occurs in the panel near the solid concrete region, as can be seen from the temperature contours (the direction of heat flow is perpendicular to the temperature contours).

In contrast, for the three-wythe panel of Fig. 6b, the panel surface temperatures at both the hot and cold sides are relatively uniform as compared to the two-wythe panel. Lateral heat flow also occurs in the three-wythe panel, primarily in the center concrete wythe of the panel as shown by the temperature contours. It is also noted that the temperature on the surface of the three-wythe panel is similar to ambient air temperature, and, therefore, may prevent condensation on the surface of the panel.

PARAMETRIC STUDIES

The thermal performance of the three-wythe panels were analyzed and compared with that of two-wythe panels. Parametric studies were performed for various panel configurations of two- and three-wythe panels, and material conductivity variations were also considered in the study.

Panel configurations and corresponding FEM models treated in the parametric studies are shown in Figs. 7 through 10. Depending on the panel configurations, either panel cross section or plan views are shown with a light gray color representing concrete and pink indicating insulation. All panels are 12 ft (3.66 m) wide and 40 ft (12.19 m) long.

Variables

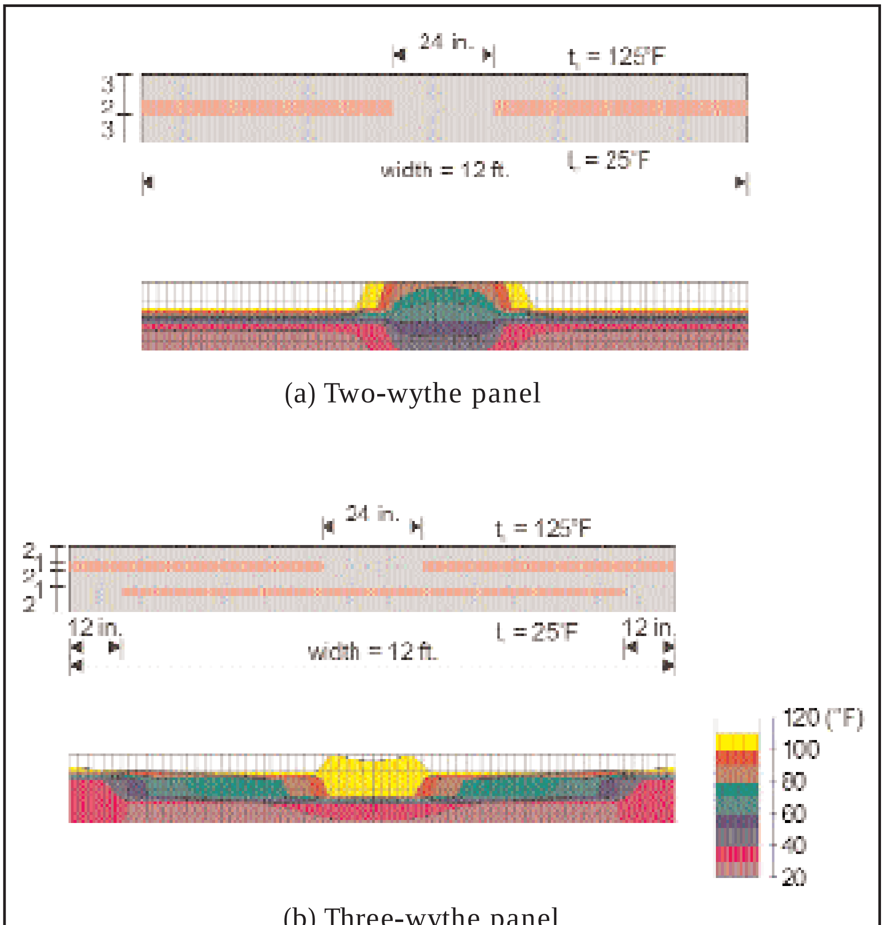
Panel configuration – The A- and B-series panels are all two-wythe panels with Fig. 7a showing a cross section view of an A-series panel. In the analyses of the A-series panels, the concrete thermal bridge width (x1) is varied (see Fig. 7a). The A-series panels are idealized cases of two-wythe panels. In typical two-wythe panels, solid concrete regions are located at either the ends, sides, or inside of the panel as shown in Fig. 1. Two different panel thickness combinations (3-2-3 and 3-4-3) and eight concrete thermal bridge widths [x1 = 0, 4, 8, 12, 24, 36, 48, and 60 in. (x1 = 0,102, 203, 305, 610, 914, 1220 and 1525 mm)] were considered in the A-series panels.

Fig. 7b shows a B-series panel in plan view at the insulation layer. The B-series panels are the same as shown in Fig. 1a. The length of the concrete thermal bridge (x2) varies as shown in Fig. 7b, and the width of the thermal bridge is kept constant at 1 ft (305 mm). Only one panel thickness of 3-2-3 is considered for the B-series panels.

Fig. 8 shows a cross section view of an E-series panel. The E-series panels are three-wythe panels and correspond to Configuration I shown in Fig. 2a. Variables treated in the E-series panels are the panel thickness and the concrete thermal bridge width (x1) (see Fig. 8).

Three different panel thickness combinations (3-1-3-1-3, 2-1-3-1-2 and 2-1-2-1-2) and eight concrete thermal bridge widths [x1 = 0, 4, 8, 12, 24, 36, 48, and 60 in. (x1 = 0, 102, 203, 305, 610, 914, 1220 and 1525 mm)] were considered in the analyses of the E-series panels. As an example, the 2-1-3-1-2 panel, with x1 = 24 in., is shown in Fig. 8. D-series panels are similar to the E-series panels. The D-series panels have a total 4 in. (102 mm) insulation thickness while the E-series panels have a total 2 in. (51 mm) insulation thickness.

Fig. 9 shows a cross section view of an O-series panel. The O-series panels are three-wythe panels similar to the E-series panels, but with more concrete ribs in the cross section. It is



(a) Two-wythe panel

(b) Three-wythe panel

Fig. 6. Temperature distribution of two- and three-wythe panels.

noted here that the O-series panels may actually be a more practical panel configuration for panel handling and the installation of embedded lifting hardware.[7, 8] Variables treated in the O-series panels are the panel thickness combinations (3-1-3-1-3, 2-1-3-1-2, and 2-1-2-1-2) and the concrete thermal bridge widths [x1 = 0, 4, 8, 16, 24, 32, 48, and 64 in. (x1 = 0, 102, 203, 406, 610, 813, 1220 and 1626 mm)]. As an example, the 2-1-3-1-2 panel, with x1 = 24 in., is shown in Fig. 9. Similarly, the N-series panels have a total 4 in. (102 mm) insulation thickness while the O-series panels have a total 2 in. (51 mm) insulation thickness.

Fig. 10 shows a longitudinal cross section view of a G-series panel. The G-series panels are three-wythe panels and correspond to Configuration II shown in Fig. 2b. Variables treated in the G-series panels are the panel thickness and the insulation overlap length (x3) as shown in Fig. 10. A fixed concrete thermal bridge width of 12 in. (305 mm) is used for all panels as shown in the figure; this width is simply assumed for the purpose of estimating the R-value of the panel with respect to the insulation overlap length (x3).

Three different panel thickness combinations (3-1-3-1-3, 2-1-3-1-2, and 2-1-2-1-2), and six insulation overlap lengths [x3 = 0, 6, 12, 24, 36, and 48 in. (x3 = 0, 152, 305, 610, 914, and 1220 mm)] are considered in the analyses of the G-series panels. As an example, the 2-1-3-1-2 panel, with x3 = 12 in. (305 mm), is shown in Fig. 10. The F-series panels are similar to the G-series panels. The F-series panels have a total 4 in. (102 mm) insulation thickness while the G-series panels have a total 2 in. (51 mm) insulation thickness. Several other panel configurations corresponding to Configuration III shown in Fig. 2c

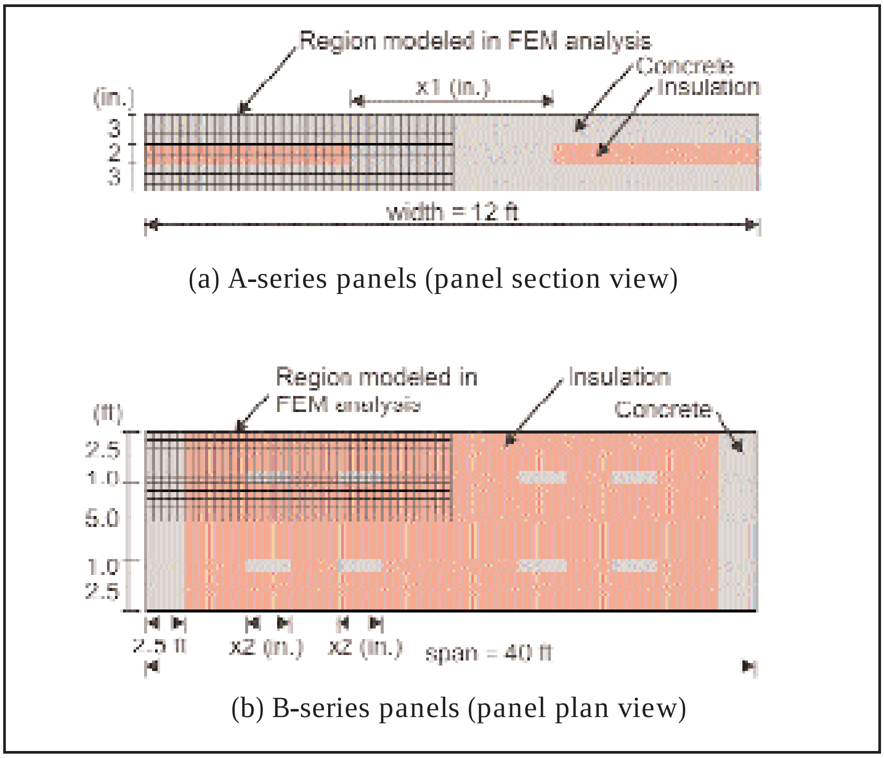


Fig. 7. A- and B-series panel configurations.

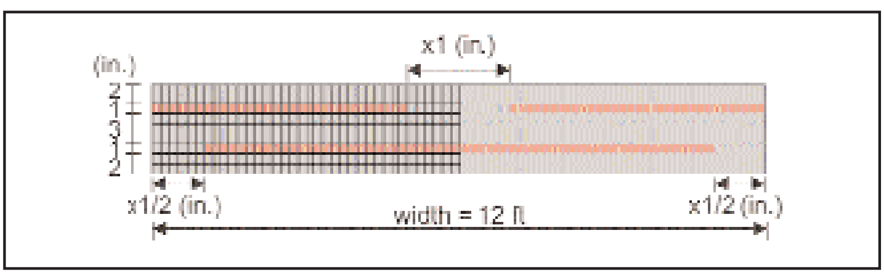


Fig. 8. E-series panel configurations (panel section view).

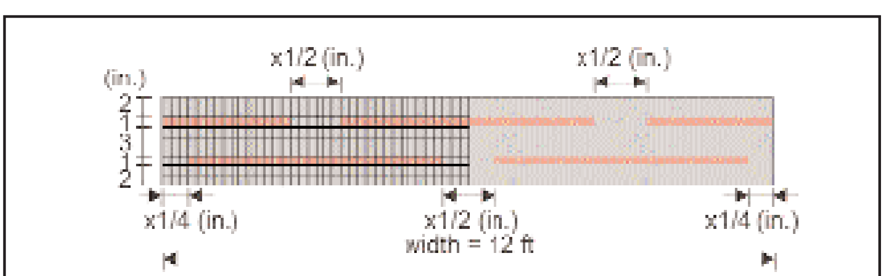


Fig. 9. O-series panel configurations (panel section view).

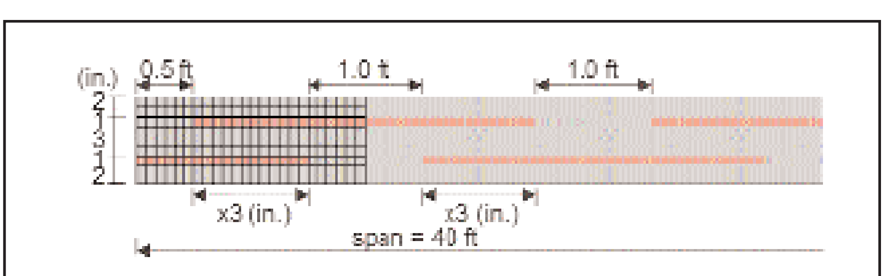


Fig. 10. G-series panel configurations (panel section view).

were also considered in the parametric studies. Complete details are presented in Lee and Pessiki.[7,8]

Material conductivities – The conductivities of the insulation and concrete were varied to examine how the R-values of the panels were affected. The R-values are compared for A-series (3-2-3), E-series (2-1-2-1-2), and O-series (2-1-2-1-2) panels with same total thickness of insulation and concrete. Only panels having total thermal bridge widths of 24 in. (610 mm) were investigated for the material conductivity variation; these are considered to be more practical than other panel configurations.

Table 3 shows insulation conductivities for various insulation materials which are typically used for the sandwich wall panels in practice.[4] As shown in the table, insulation conductivity ranges from 0.1 to 0.35 Btu·in./hr·sq ft·°F (0.014 to 0.05 W/m·°C). Based on these values, four insulation conductivities, k_{in} = 0.1, 0.2, 0.26, and 0.35, were selected as variables, and in these analyses the concrete conductivity is kept constant at k_{con} = 12.05 Btu·in./hr·sq ft·°F (1.74 W/m·°C).

Table 4 shows a relationship between concrete conductivity and concrete density adapted from ASHRAE Handbook,[9] McCall,[2] and PCI Design Handbook.[10] As shown in Table 4, concrete conductivity ranges from 4.2 to 20 Btu·in./hr·sq ft·°F (0.6 to 2.9 W/m·°C). Based on these values, four concrete conductivities, k_{con} = 4.17, 7.14, 12.05, and 13.33, were selected as variables, and in these analyses, the insulation conductivity is kept constant at k_{in} = 0.26 Btu·in./hr·sq ft·°F (0.037 W/m·°C).

Parametric Study Results – Panel Configuration

A-, E- and O-series panels – Fig. 11 shows a plot of R-values versus concrete thermal bridge width, x1 (in.), for A-, E-, and O-series panels which have a total of 2 in. (51 mm) insulation thickness. As shown in Fig. 11, all R-values decrease with increased thermal bridge width, i.e., the thermal performance of the panel decreases with an increased area of solid concrete that penetrates the insulation layer.

The R-value decreases rapidly at small values of x1, and slowly converges to the R-value of solid concrete panel case (R-value is 1.6 hr·ft²·°F/Btu (0.28 m²·°C/W) for the solid concrete panel). Thus, the thermal bridge effect is more significant at a smaller thermal bridge width, and then gradually decreases. However, the degree of R-value decrease of the three-wythe panel is less than that of the two-wythe panel.

As shown in Fig. 11, the three-wythe panels (E- and O-series) exhibit higher R-values than the two-wythe panels (A-series). Therefore, better thermal performance of the panel can be achieved using the three-wythe panel. If it is assumed that a practical concrete region width is in the range of 12 to 24 in. (305 to 610 mm), then 30 to 50 percent higher R-values were obtained for the E-series panels as compared to the A-series panels, and 20 to 35 percent higher R-values were obtained for the O-series panels as shown in the Fig. 11.

Comparing E- and O-series panels, R-values of the E-series panels were higher than those of the O-series panels. This is because the thermal path of O-series panels is shorter than that of the E-series panels. The R-values of the O-series panels were about 10 percent lower than the E-series panels.

A-, D- and N-series panels – Fig. 12 shows a plot of R-values versus concrete thermal bridge width, x1 (in.), for A-, D-, and N-series panels that have a total of 4 in. (102 mm) insulation thickness. The plot of Fig. 12 is very similar to Fig. 11. R-values decrease with increased x1, and the three-wythe panels (D- and N-series) exhibit higher R-values than the two-wythe panels (A-series). If it is assumed that a practical concrete region width is in the range of 12 to 24 in. (305 to 610 mm), then 50 to 90 percent higher R-values were obtained for the D-series panels as compared to the A-series panels, and 40 to 70 percent higher R-values were obtained for the N-series panels as shown in Fig. 12. Thus, a three-wythe panel can be more efficient when using thicker insulation panels.

Comparing D- and N-series panels, R-values of the D-series panels were higher than those of the N-series panels. Again, this is because the thermal path of N-series panels is shorter than that of the O-series panels. The R-values of the N-series panels were about 15 percent lower than the D-series panels.

In Fig. 12, the top three results show the 3-2-3-2-3, 2-2-3-2-2, and 2-2-2-2-2 D-series panels with a total of 4 in. (102 mm) insulation thickness. The middle three results are from the 3-2-3-2-3, 2-2-3-2-2, and 2-2-2-2-2 N-series panels with a total of 4 in. (102 mm) insulation thickness. The plots

Table 3. Insulation conductivity for various insulation types.[4]

Insulation material	Insulation conductivity, k_{in} (Btu·in./hr·sq ft·°F)
Polyisocyanurate	0.18 0.15~0.10
Expanded polystyrene – extruded (smooth skin surface)	0.2
Expanded polystyrene – molded bead	0.26~0.23
Phenolic	0.16~0.23
Cellular glass	0.35

Note: 1 Btu·in./hr·sq ft·°F = 0.1442 W/m·°C.

Table 4. Concrete conductivity for various concrete densities.

	Concrete conductivity, k_{con} (Btu·in./hr·sq ft·°F)		
Concrete density (pcf)	ASHRAE Handbook[9]	McCall[2]	PCI Design Handbook[15]
150	10 ~ 20	12.05	—
145	—	10.9	13.33
140	9 ~ 18	9.87	12.05
120	7.9	6.61	7.14
100	5.5	4.43	4.17

Note: 1 Btu·in./hr·sq ft·°F = 0.1442 W/m·°C; 1 pcf = 0.1571 kN/m³.

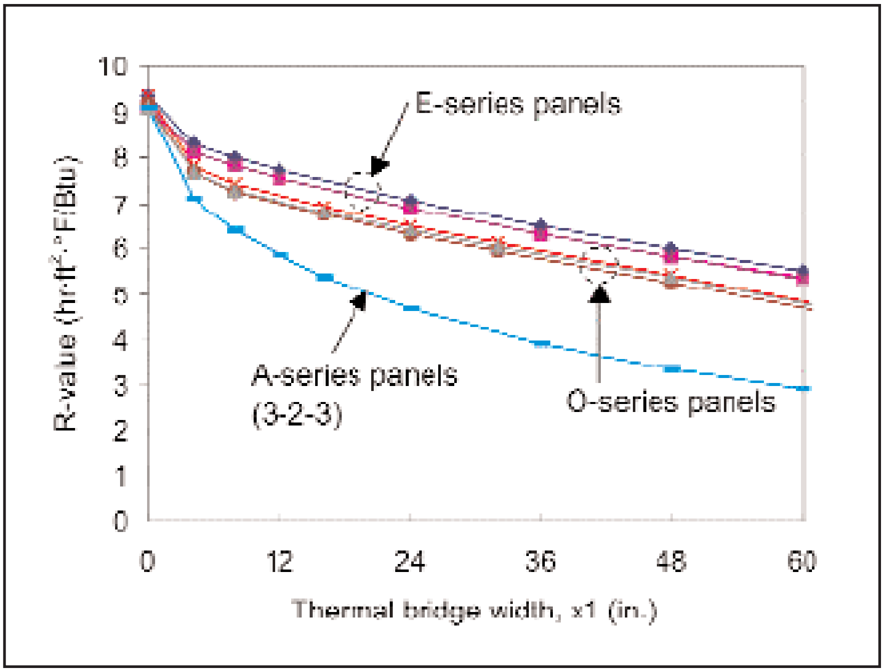


Fig. 11. R-value versus thermal bridge width for A-, E-, and O-series panels.

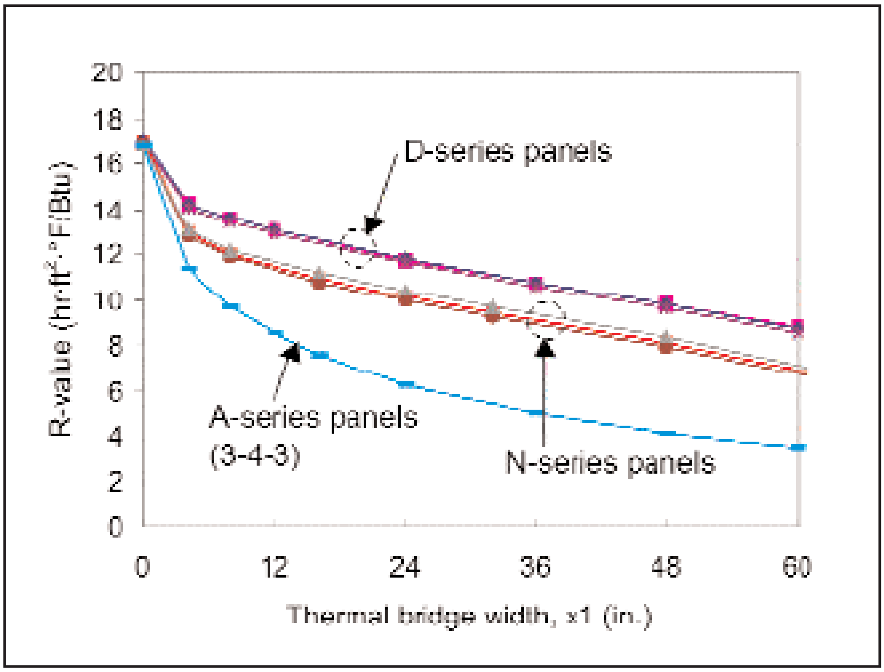


Fig. 12. R-value versus thermal bridge width for A-, D-, and N-series panels.

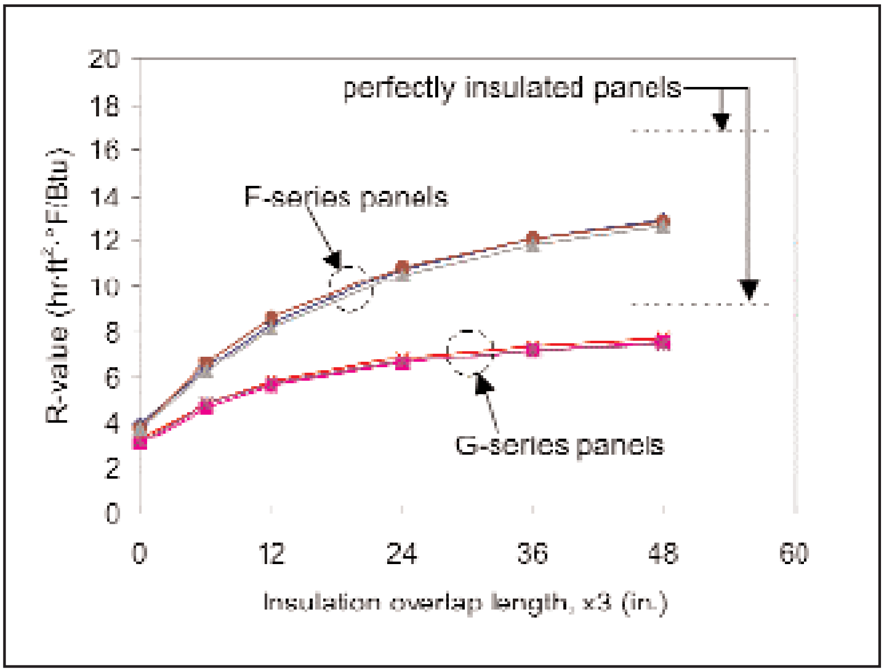


Fig. 13. R-value versus insulation overlap length for F- and G-series panels.

for individual panels within each series are almost identical, indicating that the concrete wythe thickness does not have much of an effect on the R-value of the panel. This result also can be seen in Fig. 11 of the E- and O-series panels.

F- and G-series panels – Fig. 13 shows a plot of R-values with respect to the insulation overlap length, x3 (in.). The plot shows that the R-value increases when the insulation overlap length, x3, increases, and converges to the perfectly insulated panel. This is because the thermal path along which the heat flows increases when x3 increases, so that better thermal performance is obtained for a large insulation overlap length panel. On the other hand, the slope (or rate of change) of R-value decreases with increasing x3. This decreasing R-value gradient indicates that the insulation overlap effect is more significant at smaller overlap lengths, and then gradually decreases.

In Fig. 13, the top three results are from the F-series panels that have a total of 4 in. (102 mm) insulation thickness. The bottom three results are from the G-series panels which have a total of 2 in. (51 mm) insulation thickness. These results indicate that a concrete layer thickness does not greatly affect the R-value of the panel, but insulation thickness does significantly affect the R-value.

When x3 is equal to 48 in. (1220 mm), R-values of the F- and G-series are 12.8 and 7.6 hr·sq ft·°F/Btu (2.25 and 1.34 m²·°C/W), respectively. These values correspond to 76 and 83 percent of the R-values for perfect panels which do not contain any thermal bridges [16.9 and 9.2 hr·sq ft·°F/Btu (2.98 and 1.62 m²·°C/W), respectively].

Parametric Study Results – Material Conductivity

As noted earlier, insulation conductivities were varied from 0.1 to 0.35 Btu·in./hr·sq ft·°F (0.014 to 0.05 W/m·°C), with the constant concrete conductivity of k_{con} = 12.05 Btu·in./hr·sq ft·°F (1.74 W/m·°C). Concrete conductivities varied from 4.2 to 20 Btu·in./hr·sq ft·°F (0.6 to 2.9 W/m·°C), with the constant insulation conductivity of k_{in} = 0.26 Btu·in./hr·sq ft·°F (0.037 W/m·°C).

Insulation conductivity variation – Fig. 14 shows the relationship between R-value and insulation conductivity, k_{in}. For both the two-wythe (A-series, 3-2-3) and three-wythe (E- and O-series, 2-1-2-1-2) panels, the R-values decrease when the insulation conductivity increases, and the R-values of the three-wythe panels are higher than those of the two-wythe panels for the given panel configurations.

As shown in Fig. 14, the R-values of the three-wythe panels are relatively higher than those of the two-wythe panels for low insulation conductivities. This demonstrates that a three-wythe panel can be more efficient when using low conductivity insulation material. Using an insulation material of k_{in} = 0.2, which is often used in practice, 64 and 50 percent higher R-values were obtained for E- and O-series panels, respectively, as compared with the A-series panels.

Concrete conductivity variation – Fig. 15 shows the relationship between R-value and concrete conductivity, k_{con}. For both the two- and three-wythe panels, the R-values decrease when the concrete conductivity increases, and the R-values of the three-wythe panels are higher than those of two-wythe panels.

Fig. 15 also shows that the impact of concrete conductivity on thermal resistance is small and is about the same for the two- and three-wythe panels in a practical concrete conductivity range. When a concrete with a density of about 140 to 150 pcf (22 to 24 kN/m^3) is used to make a panel, the concrete conductivity is in a range of k_{con} = 9 to 15 Btu·in./hr·sq ft·°F (1.3 to 2.2 W/m·°C).

As shown in Fig. 15, R-value plots are relatively flat in the practical range. Comparing E- and O-series panels, which are considered to be practical panels, the R-values of the E-series panels were approximately 7 percent higher than the O-series panels.

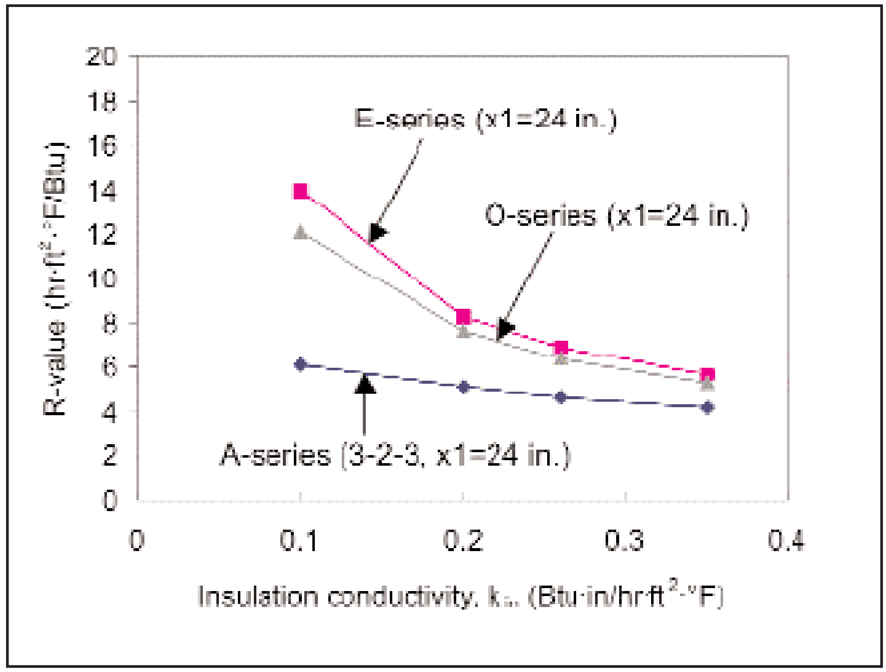


Fig. 14. R-values for insulation conductivity variation.

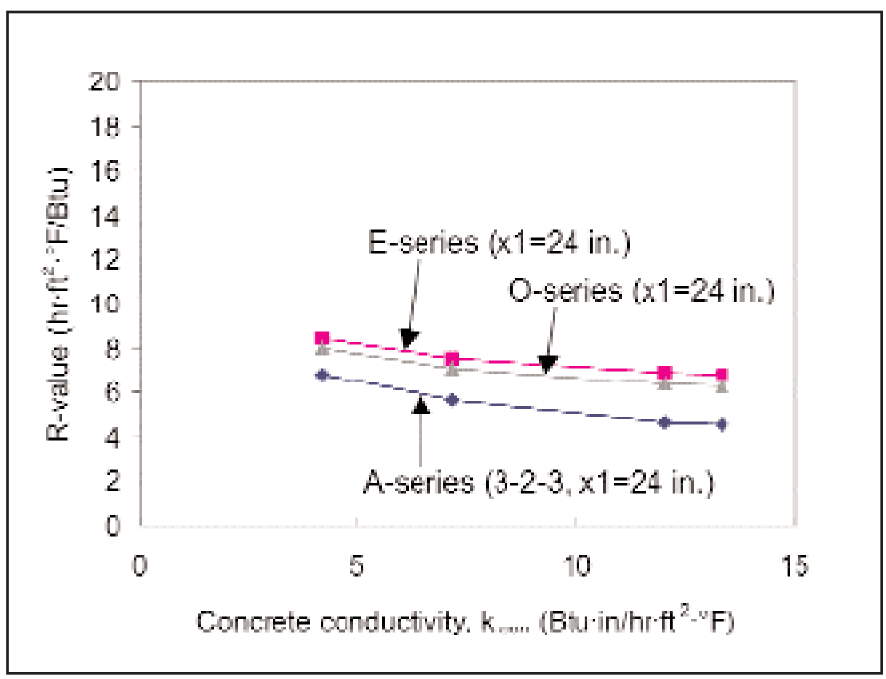


Fig. 15. R-values for concrete conductivity variation.

Further Discussion

Fig. 16 shows the relationship between R-value and the solid concrete area ratio, and illustrates the thermal performance of the two- and three-wythe panels having a total of 2 in. (51 mm) insulation thickness. The solid concrete area ratio (sq ft/sq ft) is computed by dividing the solid concrete area by the total panel area. For the two-wythe panels of the A- and B-series panels, the solid concrete area is the concrete area that penetrates the insulation layer. For the three-wythe panels, the solid concrete area is the average area of solid concrete that penetrates the top and bottom insulation layers. The total panel area is uniform for all panels, and is equal to 480 sq ft (44.6 m^2).

The trend lines in Fig. 16 show that the R-value decreases as the solid concrete area ratio increases. The bottom dotted trend line represents the two-wythe A- and B-series panels, and the upper trend lines represent the three-wythe panels. The R-values of the three-wythe panels are higher than those of the two-wythe panels with respect to same solid concrete area ratio.

This indicates that the solid concrete area does not affect the R-value of the three-wythe panel as much as it impacts the R-values of the two-wythe panel. It is, therefore, concluded that the thermal performance of concrete sandwich wall panels can be improved by using three-wythe panels instead of the traditional two-wythe panels.

Finally, it is noted that traditional two-wythe panels have significantly reduced R-values, even with a small solid concrete area ratio (see Fig 16). When the solid concrete area ratio is

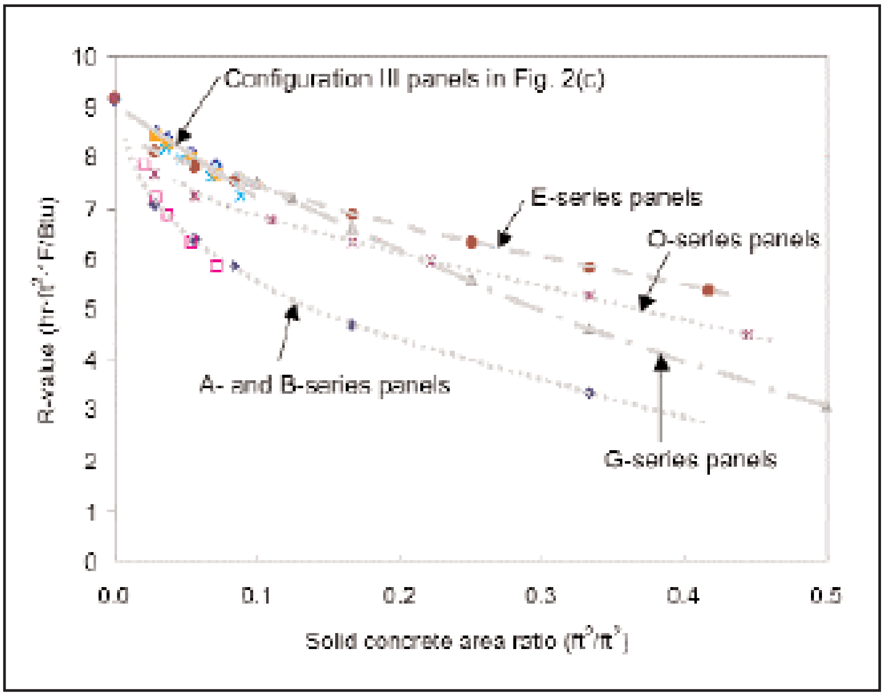


Fig. 16. R-value versus solid concrete area ratio for two- and three-wythe panels.

0.1, the R-value of the two-wythe panel is 5.5 hr·sq ft·°F/Btu (0.97 m^2·°C/W), almost a 40 percent reduction in R-value from that observed for the perfect panel with an R-value of 9.2 hr·sq ft·°F/Btu (1.62 m^2·°C/W).

CONCLUSIONS

The major conclusions based on the analyses presented are as follows:

1. ASHRAE Handbook R-value calculation methods do not provide accurate estimates of the R-values of three-wythe panels. Other methods should be used to estimate the R-values of three-wythe panels, such as FEM analyses or experimental methods. From the work presented in this paper, the FEM approach is shown to be an acceptable means to compute R-values of three-wythe panels.

2. The thermal performance of a three-wythe panel is superior than that of a two-wythe panel due to the increased length of the thermal path through the solid concrete in the three-wythe panel as compared to the two-wythe panel.

3. The R-value of a three-wythe panel increases as the insulation overlap length increases because the thermal path length through the solid concrete increases. The insulation overlap effect is more significant at smaller overlap lengths, gradually decreasing as overlap length increases.

4. Concrete wythe thickness does not have a significant effect on the R-value of either two- or three-wythe panels. Insulation layer thickness does have a significant effect on the R-value.

5. Three-wythe panels demonstrate superior thermal performance (i.e., have a higher R-value) from the use of a thicker insulation panel, or a lower conductivity insulation material, as compared with two-wythe panels.

6. Panel surface temperatures for the three-wythe panel are more similar to ambient air temperature as compared to the two-wythe panel; this may prevent condensation on the surface of the panel.

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1. Gabor, L., "Thermal Steady State Analysis," *Build International*, V. 4, No. 1, January-February 1971, pp. 58-63.
2. McCall, W. C., "Thermal Properties of Sandwich Panels," *Concrete International*, V. 7, No. 1, January 1985, pp. 35-41.
3. Holman, J. P., *Heat Transfer* (Fifth Edition), McGraw-Hill Book Company, New York, NY, 1981, 570 pp.
4. PCI Committee on Precast Sandwich Wall Panels, "State-of-the-Art of Precast/Prestressed Sandwich Wall Panels," PCI JOURNAL, V. 42, No. 2, March-April 1997, pp. 92-134.
5. Kosny, J., Childs, P., and Desjarlais, A., "Thermal Performance of Prefabricated Concrete Sandwich Wall Panels," Oak Ridge National Laboratory Building Technology Center, Oak Ridge, TN, 1999, 44 pp.
6. ASTM, "ASTM C236-89: Standard Test Method for Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box," *Annual Book of ASTM Standards*, V. 04.06, American Society for Testing and Materials, West Conshohocken, PA, 2001.
7. Lee, B., "Development of a Precast Prestressed Concrete Three-Wythe Sandwich Wall Panel," Ph.D. Dissertation, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, May 2003, 373 pp.
8. Lee, B., and Pessiki, S., "Development of a Precast Prestressed Concrete Three-Wythe Sandwich Wall Panel," ATLSS Report No. 03-05, Lehigh University, Bethlehem, PA, April 2003, 294 pp.
9. ASHRAE, *ASHRAE Handbook – Fundamentals* (I-P Edition), American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1997.
10. *PCI Design Handbook: Precast and Prestressed Concrete*, Fifth Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1999.
11. Lee, Y., "Development of the Characteristic Section Method to Estimate R-Values of Precast Concrete Sandwich Wall Panels," M.S. Thesis, Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, May 2003, 102 pp.
12. Lee, Y., and Pessiki, S., "Development of the Characteristic Section Method to Estimate R-Values of Precast Concrete Sandwich Wall Panels," ATLSS Report No. 03-06, Lehigh University, Bethlehem, PA, April 2003, 73 pp.
13. *SAP 90 - Heat Transfer User Manual*, Computer and Structures Inc., Berkeley, CA, 1990.
14. Snyder, M. K., "Heat Transfer Measurements of Corewall Insulated Sandwich: Prestressed Concrete Wall Panel System with 2-in. Thick Factory Installed 1-pcf Polystyrene Bead Board Insulation," Butler Manufacturing Company Research Center, Grandview, MO, 1980, 13 pp.
15. Shu, L. S., Fiorato, A. E., and Howanski, J. W., "Heat Transmission Coefficients of Concrete Block Wall with Core Insulation," Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings, ASHRAE SP28, 1979, pp. 421-435.

APPENDIX — NOTATION

- A = metered area in Guarded Hot Box Method (sq ft)
- h_c = convection film coefficient for cold side of panel (Btu/hr·sq ft·°F)
- h_h = convection film coefficient for warm side of panel (Btu/hr·sq ft·°F)
- k_{con} = concrete conductivity (Btu·in./hr·sq ft·°F)
- k_{in} = insulation conductivity (Btu·in./hr·sq ft·°F)
- Q = heat flow (Btu/hr)
- R = R-value, thermal resistance, surface-to-surface R-value (hr·sq ft·°F/Btu)
- R_T = R-value, overall thermal resistance, air-to-air R-value (hr·sq ft·°F/Btu)
- t_1 = area-weighted surface temperature of cold side (°F)
- t_2 = area-weighted surface temperature of warm side (°F)
- t_c = ambient air temperature for cold side of panel (°F)