BEST PRACTICES IN PRECAST INSULATED WALL PANEL DESIGN AND DETAILING

Venkatesh Seshappa, **P.E., S.E.,** Thermomass, Boone, IA
Darryl E. Dixon, Thermomass, Boone, IA

ABSTRACT

Precast Insulated Wall Panels (PIWPs), commonly known as sandwich wall panels, have been in the market for well over five decades. During this period, there have been a number of studies conducted on different wythe connector systems, thermal properties of the wall system and behavior of the wall system in different environmental conditions. However, we continue to see issues like cracking, thermal bowing and condensation on many walls. Most of these issues arise from poor design, incorrect detailing, and construction practices which should be avoided. This paper discusses some of these common issues and provides alternate details which can mitigate most of the problems noted above.

Keywords: Precast Insulated Wall Panel, Fiber Reinforced Polymer, Non-composite, Partially-composite, Thermal bridge, Thermographic imaging.

INTRODUCTION

Precast Insulated Wall Panels (PIWPs) have been used in building construction for over five decades[1]. A PIWP consists of a layer of insulating material "sandwiched" between two wythes of concrete. Typically, the two wythes of concrete and insulating layer are held together with discrete or continuous connectors that penetrate the insulation material. These connectors are designed to transfer loads during stripping, shipping, erection, and service life of the panel.

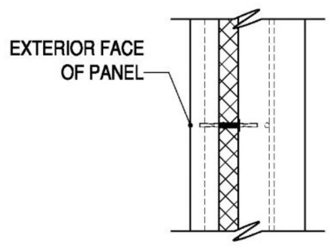


Figure 1 Generic Cross Section of Precast/Prestressed Insulated Wall Panel

Typically, PIWPs clad the exterior of a building and must resist gravity loads (self-weight and external loads when present), lateral forces (wind and seismic forces acting normal to the plane of the panel), and temperature gradients. In some cases, they may also function as shear walls to carry in-plane horizontal loads. PIWPs also provide a weather barrier to the outside environment and add to a building's aesthetics of the building exterior[2]. This paper concentrates on the best design and detailing practices for the successful construction of PIWPs.

GENERAL CLASSIFICATION OF PIWPs

PIWPs are generally classified as composite, partially-composite, or non-composite based on design methodology and connection devices used between the two concrete wythes. These classifications are well described in two references noted in above paragraphs and are reproduced here from *Design of Energy Efficient Partially-Composite Sandwich Wall Panels Using Fiber Composite Polymer (FRP) Wythe Connectors*[2].

> Composite Panels: Composite panels of a given total thickness will have nearly the same stiffness and strength as solid panels of the same thickness.
>
> Non-composite Panels: Non-composite panels will have roughly the same stiffness and strength as the sum of the stiffness and strength values for the individual concrete wythes.
>
> Partially Composite Panels: For similar panel geometries, partially-composite walls have stiffness values greater than non-composite panels and less than composite

panels and strength magnitudes greater than non-composite panels and less than or equal to composite panels.

TYPICAL ISSUES WITH PIWPs

A properly designed, detailed and fabricated PIWP will perform as intended for its particular use. However, when the panel is not designed, detailed and executed properly, several issues may occur such as cracking, thermal bowing, thermal bridging, and condensation.

Cracking: Cracking typically occurs when the exterior wythe of concrete tries to expand due to temperature increase and it is prevented from expanding by intermittent or continuous hard spots. Hard spots could be local full thickness concrete sections or rigid connectors between the two concrete wythes.

Thermal Bowing and Thermal Growth: Thermal bowing is defined as out of plane deflection of the wall panel due to strain gradient between the inside and outside of the panel due to temperature difference between the inside and outside[3]. Thermal growth is expansion of the exterior wythe relative to the interior wythe due to daily temperature swings.

Thermal Bridging: Thermal bridging is a thermal short circuit that is caused by highly conductive material penetrating or displacing the insulation between the two concrete wythes. As a result of thermal bridging, heat, air and moisture transfer occurs between the exterior and the interior wythes.

Condensation on interior concrete surfaces: If a building's use is such that it has higher humidity levels, (in gymnasiums and some manufacturing facilities, for example), condensation occurs on the interior surface at the locations of thermal bridges. This is mainly because highly conductive connectors are transmitting the heat from a local area inside to the outside leaving the water vapor in the interior air to condense at that now cold location created by the thermal bridge. This condensation could lead to mold and mildew growth on the wall.

Each of these issues is discussed in detail along with suggested possible remedies.

CRACKING

Cracking in concrete structures is common and may occur due to many reasons. Some cracking in concrete occurs due to creep and shrinkage. This type of cracking can be minimized by selecting proper materials, proper fabricating techniques and proper curing. This type of cracking can occur on any concrete structure and is not specific to PIWPs. However, since the exterior wythe of a PIWP is relatively thin, the surface would dry faster causing shrinkage cracks which are more likely to occur during summer months. There are also cases when concrete is placed on hot steel forms and reinforcing steel in precast plants where the casting beds are outside. When the concrete is placed on such hot forms and reinforcing steel, it sets faster and thus possible shrinkage occurs. This can be avoided by misting the hot steel forms and reinforcing prior to placing concrete. It appears that with the advent of ever newer admixtures and supplemental cementitious materials, the possibility of shrinkage cracks is more prevalent and therefore it becomes even more important to pay attention to the mix design. It is also important to provide adequate reinforcing near the surface to resist the tension strains due to temperature and shrinkage. Most of the building codes recommend a minimum reinforcing for temperature and shrinkage. Creep and shrinkage cracks can also be minimized by prestressing the exterior wythe of the wall.

Another cause of cracking on the exterior wythe is due to connecting the exterior wythe to interior wythe with full thickness concrete sections as explained previously. This type of cracking is seen predominantly in non-composite panels. To prevent these cracks, non-composite panels should allow for the exterior wythe to expand and contract due to temperature loads independent from the interior wythe. This is first achieved by providing a fully insulated section by extending the insulation from edge of panel to edge of panel. Secondly, the connectors provided between the two wythes of concrete should have enough strength and stiffness to support the weight of the exterior wythe, but not enough to transfer the shear forces induced due to flexure and temperature load.

On occasion, full thickness concrete sections are introduced in panels for varied reasons such as parapet extension, lifting hardware placement, and coping (Figure 2). In such instances, the contract documents and shop tickets detail full thickness concrete sections as monolithically cast (Figure 2). The drawings often do not show a cold joint or even a parting line between the two concrete castings. This practice often leads to panel cracking (Figure 3) because the expansion and contraction of the exterior wythe is limited by the full thickness concrete sections.

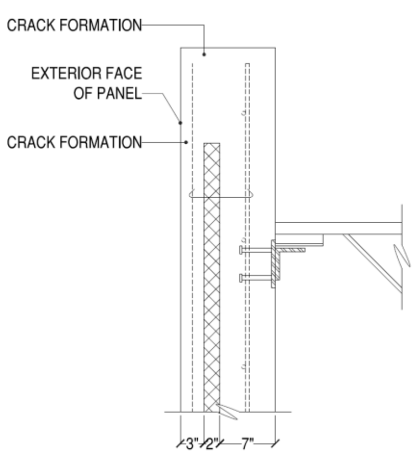


Figure 2 Top of panel detail (prone to crack)

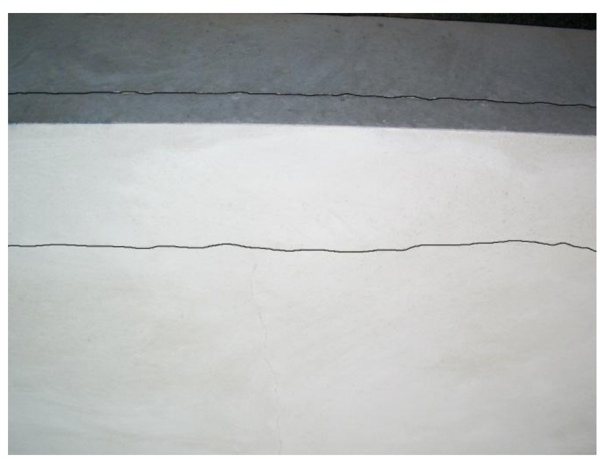


Figure 3 Crack developing at end of insulation and at top of panel (cracks highlighted for clarity)

The absence of that line on the drawings implies the full thickness concrete section is uniform in its make-up when in fact this is not the case with PIWPs. However, when the panel is cast, the exterior wythe is normally cast form edge to form edge. After the insulation is placed on top of the exterior wythe, the interior wythe concrete is placed on top and around the insulation on the same day but a few hours later. It is very difficult to cast the edge monolithically as shown in the detail. It should be noted that there is no reinforcing between the two wythes. Cracks can appear a few days after the panel is cast and stored in the yard or when the panel is erected in place.

There are many reasons why these full thickness concrete sections will not be uniform in its make-up which leads to cold joint. They are:

- Colored concrete used for exterior wythe, and gray concrete for interior wythe.
- Different strength concretes for interior and exterior wythe, which has different Modulus of Elasticity, E_c.
- Use of different type of aggregates in the two wythes.
- Use of certain admixtures in only one wythe.
- Different water – cement ratios for the two wythes.
- Use of alternate cementitious material in only one wythe.
- Casting the interior layer on exterior layer concrete which has reached initial set.

To mitigate cracks that may arise due to above reasons, the exterior wythe of concrete should be completely isolated. Detail as shown in Figure 4 is preferred to Figure 2 since the exterior wythe is free to expand and contract. Similarly, the insulation should be extended to edge of the opening as shown in Figure 5.

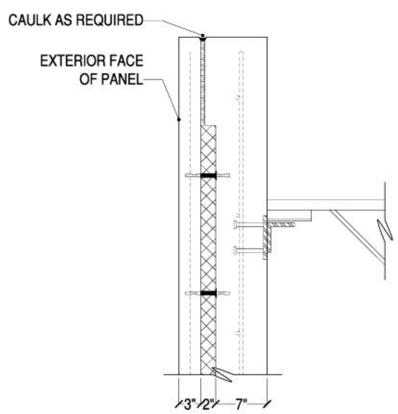


Figure 4 Preferred top of panel detail (mitigate cracking)

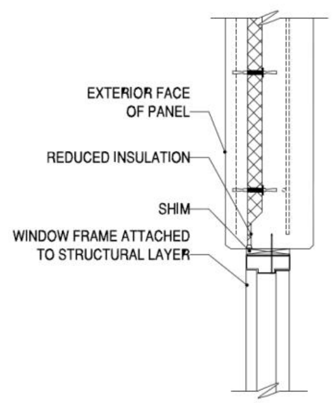


Figure 5 Detail at openings

Another common location for cracks is around the doors and windows. Cracks normally start at a corner of an opening and extend at an angle of 45° as shown in Figure 6. This is due to the stress concentration at the corners and can be mitigated by providing additional diagonal reinforcing bars that will be perpendicular to possible crack locations in the concrete wythes as shown in Figure 7.

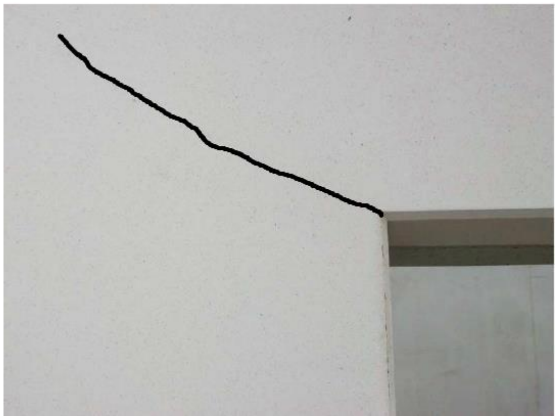


Figure 6 Crack originating from a corner of an opening (crack highlighted for clarity)

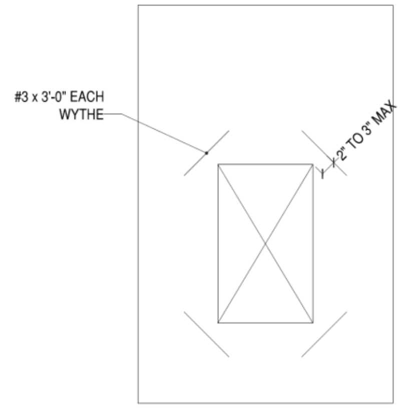


Figure 7 Reinforcing perpendicular to crack location

Composite and partially composite panels are also susceptible to cracking due to poor consideration of design and details. Figure 8 shows a photograph of PIWP with several vertical cracks highlighted. The wall's configuration is 3.5" exterior / 3" insulation / 3.5" interior and is designed as a composite panel. The wall panels of this building also have full thickness concrete sections at top and bottom, at all lifting hardware locations and around all openings. Cracks similar to those shown in Figure 8 were observed in almost all panels of the project.

Figure 8 Vertical cracks in the wall panel
(Cracks highlighted for clarity)

Locations of these cracks were very close to the location of galvanized C-anchors shown in the wall panel (Figure 9). The cross section shows the prestressing strands are not uniformly distributed over the entire width of the panel, thus causing stress concentration at the ends.

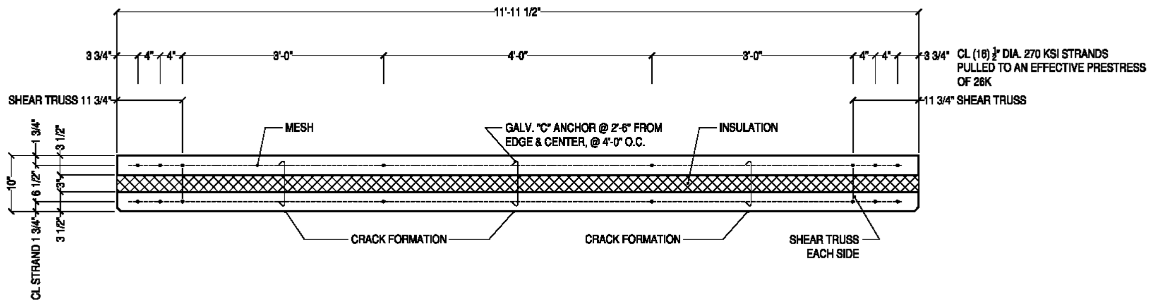


Figure 9 Typical cross section of the wall panel with crack formation locations

This building was erected in the middle of winter, and all panels were welded together at mid-height without any expansion joints. During summer months, the panels were trying to expand. However, since they were designed as composite panels the exterior wythe was not free to move and cracks formed where the compressive stress was minimum, i.e. between the strands near C-anchors. It is the authors' opinion that the prestressing strands should have been distributed evenly across the width in the panels without openings to avoid any stress concentration. In similarly prestressed wall designs, care should be taken to allow for thermal expansion of wall panels especially if all panels are connected with welded connections. Additionally, spalling of concrete on the interior wythe near welded connections was observed, which is also due to restricting the thermal expansion.

Another area of concern with composite and partially composite panels is the propagation of cracks toward the end of the panel (Figures 10 and 11). It is common to see the edges of panels detailed as monolithically cast concrete in both contract documents and on shop tickets. However as discussed earlier, the final edge condition results in a cold joint between the concrete wythes similar to non-composite PIWPs.

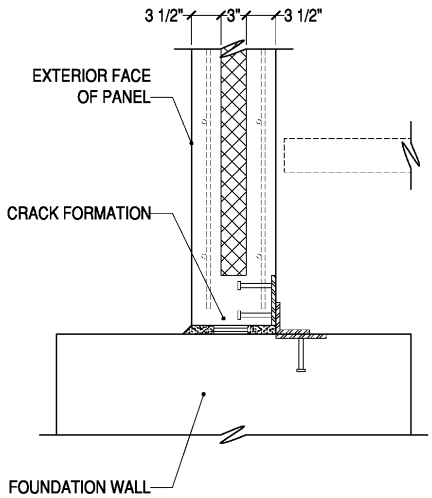


Figure 10 Base of the panel (prone to crack)

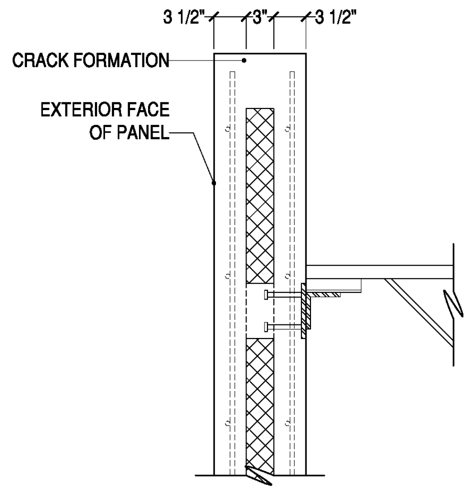


Figure 11 Top of panel detail (prone to crack)

Figure 12 shows a photograph of crack formation of a composite PIWP at the top of the parapet when two separate concretes were used. However, the design intent was to have a monolithically cast parapet as shown in Figure 11.

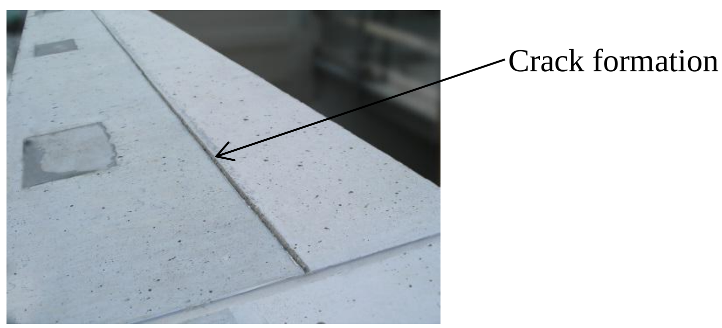


Figure 12 Crack formation at the top of parapet in composite panel

Preventing cracks in composite and partially composite panels due to cold joints may be achieved in several ways; the preferred way being to fully insulate the panel from edge to edge. Alternate details for the above two conditions are shown in Figures 13 and 14. The two wythes are tied together with "U" bars. If the top of the parapet is exposed and acts as coping or the bottom is subjected to termite, moisture, and freeze/thaw conditions, crack formation is undesirable and may cause maintenance issues.

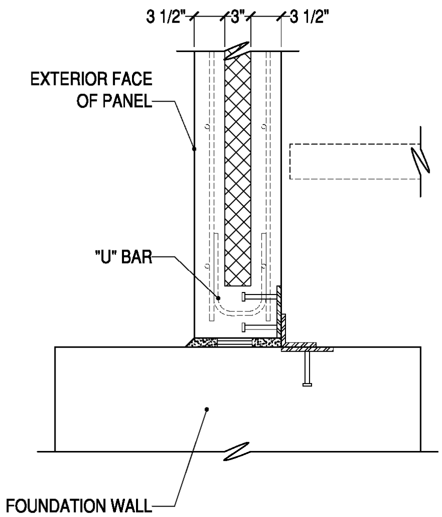


Figure 13 Alternate base of panel detail

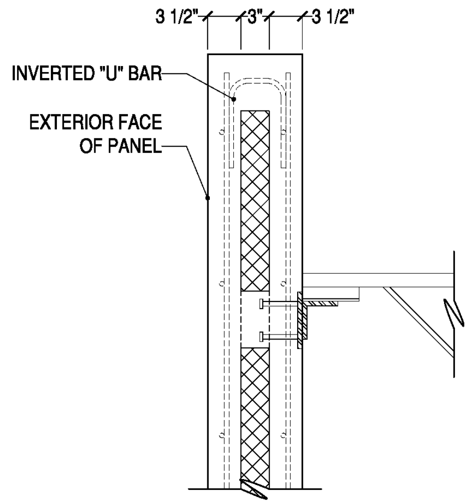


Figure 14 Alternate top of panel detail

It is quite common to use thin bricks on the exterior face of the PIWPs. Care should be taken not to bridge the thin brick across a possible cold joint in non-composite panels or an unreinforced, cold joint in a composite or partially composite wall panels. When the exterior wythe of concrete expands and contracts, the thin brick across the cold joint cracks as shown in Figure 15. Figure 16 shows improper detailing of the end of the panel.

Figure 15 Thin brick across a cold joint

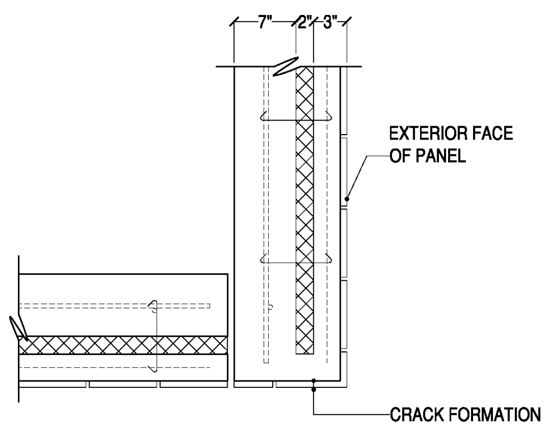
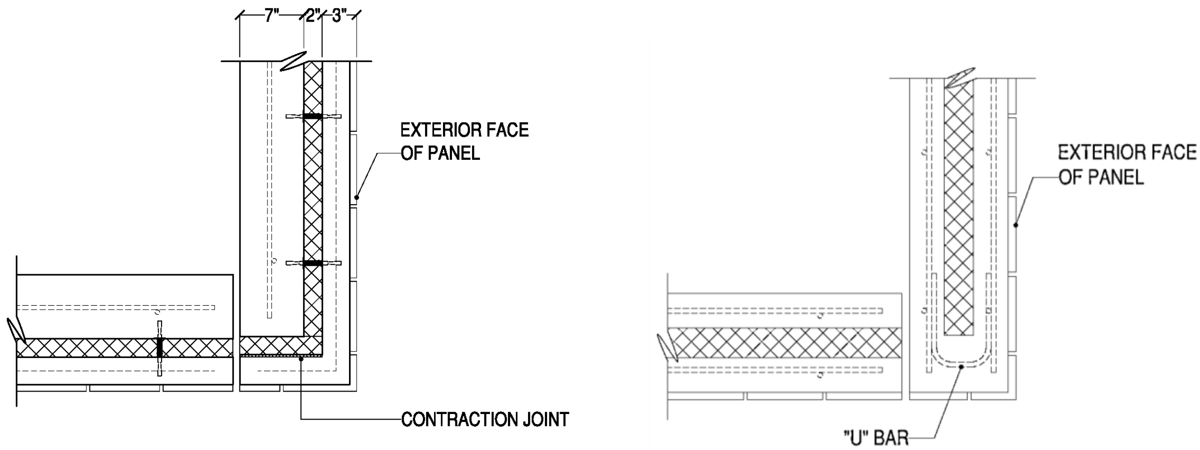


Figure 16 Improper detail of brick at end of panel

Figure 17(a) and 17(b) shows the preferred details at the end of both non-composite and composite and partially composite wall panel. With this preferred detail 17(a), a connector should not be used to in the return leg of the exterior wythe, i.e. the interior and exterior wythes are not connected in the return leg such that the return leg is free to expand and contract.



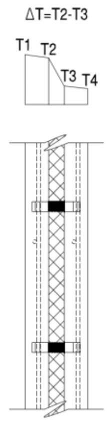
(a) Non-composite panel (b) Composite or Partially composite panel

Figure 17 Preferred detail at the end of the panel

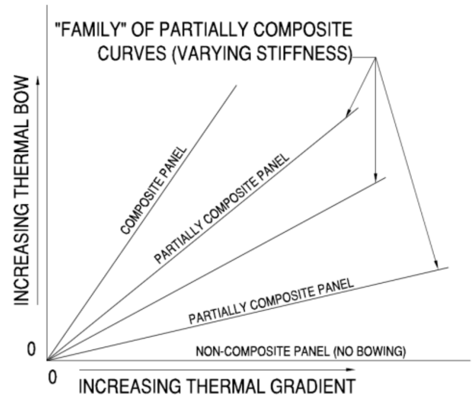
THERMAL BOWING AND THERMAL GROWTH

Due to the composite or partial-composite action, both concrete wythes are forced to act together when subjected to external loads including thermal gradients. When thermally efficient fiber composite wythe connectors are used in the PIWP's, one can assume that the thermal gradient will occur entirely in the insulation, see Figure 18(a). The generic tendencies of the three panel types when subjected to a thermal gradient are shown in *Design of Energy Efficient Partially-Composite Sandwich Wall Panels Using Fiber Composite Polymer (FRP) Wythe Connectors*[2] and are reproduced in Figure 18(b). As explained in that paper, "theoretically a non-composite panel exhibits no bowing because the lengthening or shortening of each wythe does not affect the other wythe. The stiffer the panel, the greater the thermal bowing is for a given span and thermal gradient."

As shown in Figure 18b, composite and partially composite panels are more susceptible to thermal bowing than non-composite panels. Typically, panels in the south-west corner of the building show more bowing than any other side due to higher thermal gradient and longer exposure to the sun. Thermal bowing can be minimized by connecting a number of panels together in each direction from the corner; however to negate the thermal bowing it is best to use non-composite panels.



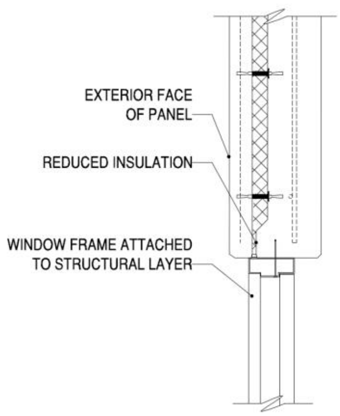
(a)



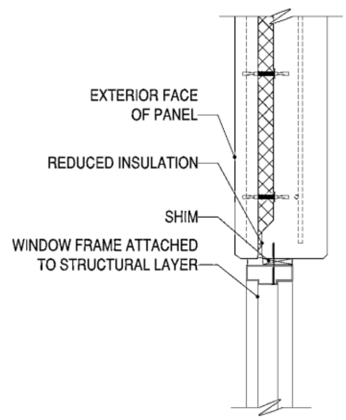
(b)

Figure 18 Typical thermal gradient and generic tendencies of insulated wall panels

Non-composite panels experience thermal growth of the exterior wythe when subjected to daily temperature swings. It is important to provide minimum reinforcement for temperature and shrinkage as recommended by the local codes. The authors recommend a minimum reinforcement of 0.058 in^2/ft. in each direction for exterior wythe up to 3 inch thick. The theoretical thermal growth for a 35 feet tall wall panel for 60°F temperature swing is about 0.13 inches. Due to this thermal growth of the exterior wythe, the door and window frames should not be attached to the exterior wythe. If the door and window frames are to be set beyond the insulation towards the exterior, then the rough opening in the precast panel should be about ¼ inches more than the frame. This enables the exterior wythe to expand without crushing the door or window frame as shown in Figure 19.



(a) Preferred detail when door and window frame is set behind exterior wythe



(b) Preferred detail when door and window is set towards exterior

Figure 19 Preferred Door and Window Details

It is not advisable to attach structural members like beams and canopies to the exterior wythe of the non-composite panels. However, in some cases, it is necessary to attach a structural member to the exterior wythe. In such cases, the member should not be attached just to the exterior wythe but to a full thickness concrete section as shown in figure 20 and 21 even though this creates some thermal bridge. Notice how the full thickness section is isolated from the exterior concrete by means of expansion joint on all sides of full thickness section.

Figure 20 Attaching Structural Member to exterior face

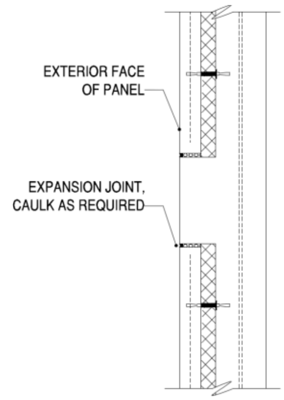


Figure 21 Proper detail for attachment to exterior face

THERMAL BRIDGING

As defined previously, thermal bridging is a thermal short circuit between the two wythes due to highly conductive connectors. These highly conductive connectors could be full thickness concrete sections, metallic connectors, welded steel trusses or other highly conductive embedded items in the wall panel. Thermal bridging is detrimental to the efficiency of the PIWPs since the energy is lost through the bridge. Thermographic imaging can be used to confirm the absence or presence of thermal bridging in a completed building. The Figures 22 and 23 show thermal image of each type.

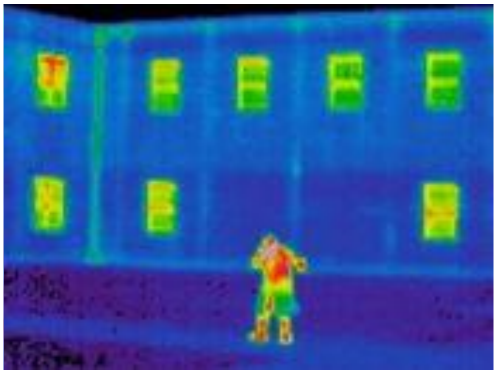


Figure 22 Thermogrpahic image showing no thermal bridges in the wall panels

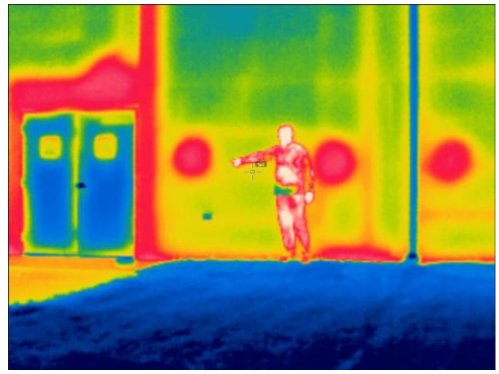


Figure 23 Thermographic image showing thermal bridges in the wall panels

In Figure 22, the person in the foreground is warmer than the wall surface. This figure shows some energy is lost through the windows and those spots are seen as red. Other than that, there are no other thermal bridges. However, in Figure 23, in addition to the person in foreground, the wall panels have numerous hot spots as shown by red color. The red color in the image represents the full thickness concrete sections as seen around the door opening and at the location of lifting inserts. Steel trusses in the wall panel can also be seen near the panel edge.

Figure 24 shows the elevation of a school gymnasium after a rain shower. Notice the dry spots in the wall panels, which are due to heat escaping through full thickness concrete sections in the wall panel and metallic connectors. Figure 25 shows the thermographic image of the same wall showing hot spots confirming the energy dissipation. The metallic connectors can be seen as dots in the field of the panel.

Figure 24 Photo of school gymnasium on a rainy day

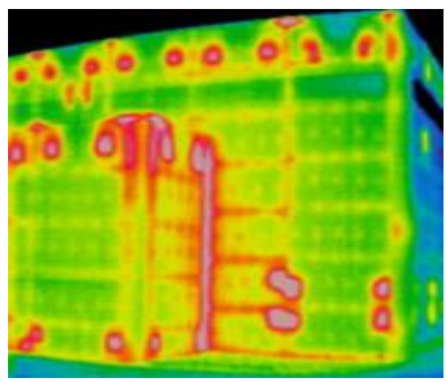


Figure 25 Thermogrpahic image of the same school showing thermal bridges

In a study conducted by Department of Energy[4] in 1999-2001, four panels with different wythe connectors were tested in a guarded hot box to determine the R-value of the wall panels. Table 1 below shows the summarized test results from the study.

Table 1: Energy loss due to thermal bridge

Measurement of thermal Loss in sandwich panels			
Panel Description	Material R-value [a]	Test R-value	Percent Loss
Panels with only steel ties	10.5	7.6	27.6%
Panels with only solid concrete	10.5	5.8	44.8%
Panels with solid concrete and steel ties	10.5	4.6	56.2%
Panels with FRP Connectors	10.5	10.5	0%

a. Value obtained summing R-values for concrete & insulation layers, no air films included.
Note: All are 3-2-3 panels made with extruded polystyrene.

HEAT TRANSFER

Many calculation methods are available to calculate the R-value of a wall panel. Fundamentals Handbook[5], 2005 edition, published by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), Inc. provides two steady-state, methods to calculate the R-values of walls. They are known as the isothermal planes (series-parallel) method and the zonal method. The PCI Design Handbook[3], Section 11.1.6 discusses the characteristic section method, which is a modified zonal method. However, the two methods from ASHRAE are the methods accepted by the building codes. The isothermal planes method is the most widely used and accepted method.

It is well known that concrete has inherent energy storing properties. This ability to store energy is extremely important in a sandwich wall panel. This type of wall is known as “high mass” wall. When the insulation extends from edge-to-edge of a wall panel, any stored energy within the high mass wall is released back in to the conditioned space when there is a demand. This ability of concrete to store energy and dampen the effect of temperature change on heating and cooling systems is known as the “Thermal Mass Effect”. “Low mass” walls are those which do not have the ability to store energy. An example of a low mass wall is a stud wall with insulation. The International Building Code[6] (IBC) allows the use of mass effect in the R-value calculation for sandwich walls.

As discussed earlier, thermal bridges affect the R-value of the PIWP. Some studies[4] have shown that the R-value lost due to thermal bridges could be as much as 56% compared to a properly constructed PIWP with edge-to-edge insulation. Typically, thermal bridges in PIWP create cold spots inside the building which increases the probability of condensation and damaging wet streaks.

AIR TRANSFER

In addition to thermal bridging, thermal loss is also credited to air infiltration and exfiltration which depends on the inside to outside temperature difference, the wind conditions, the location of the openings through which air enters the building and of course the air tightness of the building envelope. The addition of these forces equals the amount of energy loss due to air infiltration and exfiltration.

To control air infiltration and exfiltration due to wind pressures and stack effects, the code and standards bodies have begun requiring an air barrier system be incorporated within the building envelope. With regard to wall systems, PIWPs are uniquely positioned as concrete is recognized as an air barrier within the code which only leaves the joints between panels to be addressed for air tightness.

Thermographic imaging can be used to detect the air leakage between the joints and around the door and window frames.

MOISTURE TRANSFER

Moisture can move in PIWPs as vapor or as a liquid when the panel is cracked as shown earlier in this paper. Cracks in concrete create pathways for liquid moisture to travel by capillary flow. In PIWPs without cracked sections, only vapor is able to move by diffusing through the panels various materials. In the same way a temperature gradient through a PIWP relates to the heat transfer rate (R-value), the vapor pressure gradient relates to the vapor diffusion.

Condensation commonly occurs on the inside of PIWP walls at the instance of thermal bridges because the R-value of that wall at that location is diminished and thus the surface temperature is below the dewpoint temperature of the indoor air. All air contains water vapor and warm air carries more vapor than cold air. Therefore when warm, moisture laden air contacts a cool surface associated with a thermal bridge the air may cool below its dew point, allowing condensation to occur.

In the dew-point method of analysis, vapor diffusion equations (ASHRAE Fudamentals[5]) are used to predict the flow of water vapor through building materials. This steady-state tool can calculate the dew-point temperature based on water vapor flux, water vapor permeability, vapor pressure differences and thickness of materials using a vapor diffusion equation. Peak summer and winter conditions must be analyzed separately.

In a PIWP, it is preferred to have the dew-point occur within the insulation layer or the exterior wythe. If the dew-point occurs in the interior wythe, it is recommended to either increase the insulation thickness or to add a vapor retarding material (low permeance) towards the warm side of the insulation; meaning the inside of the insulation in cold climates and the outside of the insulation in hot and humid climates.

Steady-state analysis tools such as the isothermal planes and dewpoint method can be very helpful in providing answers to those essential and fundamental design questions needed early in the design phrase of a project and although ASHRAE no longer recommends the dewpoint as the sole basis of hygrothermal (hygrothermal analysis is combined analysis of both heat and moisture) design, they still believe the tool illustrates the basic principles of heat and moisture transport.

CONCLUSIONS

The owners and design community are demanding that PIWPs function as designed. They are requesting commissioning of these projects to prove that the wall panels were fabricated and installed per specifications and contract documents and meet the code requirements of continuous insulation etc. The authors have tried to provide some recommendations for common issues that arise out of poor consideration for material selection, design and detailing of PIWPs.

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