State-of-the-Art of Precast Concrete Sandwich Panels

Amin Einea, P.E.
Ph.D. Candidate
University of Nebraska
Omaha, Nebraska
and Professional Engineer
Leo A. Daly Company

David C. Salmon
Assistant Professor
University of Nebraska
Omaha, Nebraska

Gyula J. Fogarasi
Senior Consultant
Steinman Boynton Gronquist & Birdsall
New York, New York
(Visiting Professor at the University of Nebraska at the time this paper was prepared)

Todd D. Culp
Graduate Student
University of Nebraska
Omaha, Nebraska

Maher K. Tadros
Cheryl W. Prewett Professor of Civil Engineering and Director
Center for Infrastructure Research
University of Nebraska
Omaha, Nebraska

Precast Concrete Sandwich Panels (PCSP), used as exterior walls in multi-unit residential, commercial, and warehouse buildings, are structurally and thermally efficient building elements, and they are in use worldwide; yet, there is very limited available information on the various design, production and construction philosophies. This paper presents the PCSP systems most widely used in North America and Europe as exterior walls for low rise commercial and warehouse buildings. The constituents of these panels are described, and some of the limited available research results are discussed. The theory of analysis for volume change effects is explained and numerical examples are given. A discussion of issues in need of further research is provided. Some widely used PCSP systems in North America and Europe are described in Appendix A, and the names of producers are included for further reference.

Precast Concrete Sandwich Panel (PCSP) systems are composed of two concrete wythes separated by a layer of insulation. The concrete wythes are connected through the insulation layer by concrete webs, metal connectors, plastic connectors, or a combination of these elements (see Fig. 1).

PCSP systems are favored over other wall systems because of their superior thermal and structural efficiency. Under the same heat gradient conditions, PCSP walls have been shown to require lower peak loads, by about 13 percent for heating and 30 percent for cooling, than insulated metal or woodframed walls having the same U-value.[1] Like other precast concrete products, PCSP systems are manufactured under a controlled environment with a wide range of architectural finishes.

Sandwich panels are used for a variety of applications. This paper focuses on the types of sandwich panels most popular in North America and Europe for use in low rise commercial buildings and warehouses. These panels typically range from 12 to 55 ft (4 to 17 m) in height and from 4 to 12 ft (1 to 2.4 m) in width, and are produced in long fixed or rolling (moving) beds.

This paper provides a detailed description of the various components used in PCSP construction, especially the connectors and the insulation. Recent available research is briefly discussed. The theory used in calculating volume change effects with application to differential temperature is presented, and numerical examples are given in Appendix B to illustrate its application. The method is shown to be general and applicable to fully as well as partially composite members. The paper concludes with coverage of issues in need of further research. Some of the most popular PCSP systems are described in Appendix A with specific references for more details.

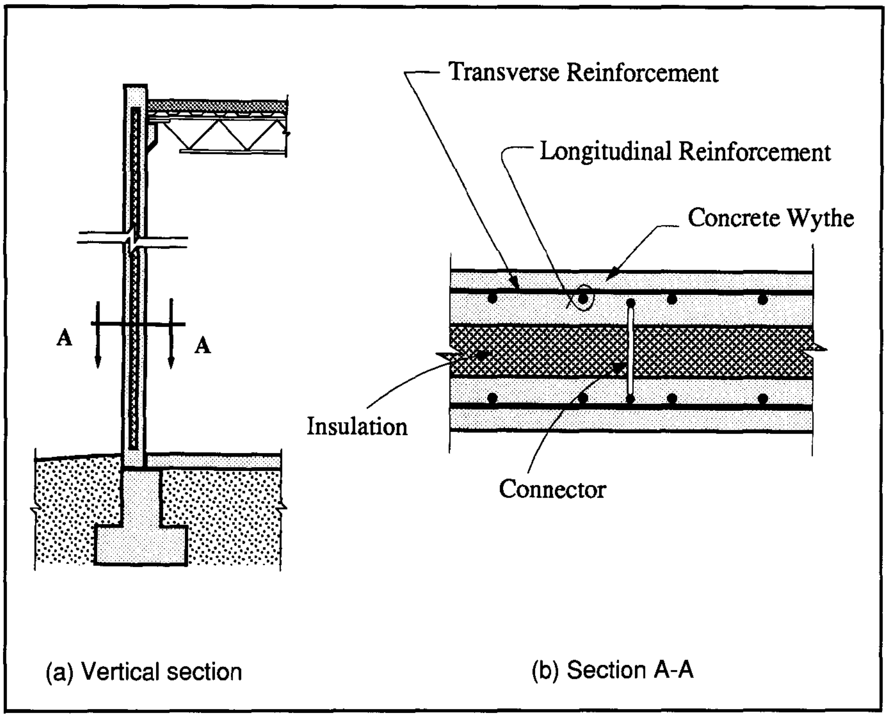


Fig. 1. Typical loadbearing PCSP wall.

TERMINOLOGY

Some of the terminology used in this paper is defined below and illustrated in Fig. 1.

Fully Composite Panels – Sandwich panels whose wythes are connected in such a way that both wythes resist applied flexural loads as if they were an integral section. In this case, connectors must transfer the required longitudinal shear so that the bending stress distribution on the cross section of the panel is as shown in Fig. 2a.

Partially Composite Panels – Sandwich panels in which the connectors can transfer between zero and 100 percent of the longitudinal shear required for a fully composite panel. The bending stress distribution in this type of panel is shown in Fig. 2b.

Non-Composite Panels – Sandwich panels in which the two concrete wythes are connected with elements (connectors) that have no capacity for longitudinal shear transfer. If the two concrete wythes are of equal stiffness and reinforcement, each wythe resists 50 percent of the load and the bending stress distribution is as shown in Fig. 2c. However, in most non-composite panel systems, the applied loads are resisted by only one of the two wythes, in which cases the bending stress distribution is as shown in Fig. 2d.

R-Value (°F•ft²•h/Btu) – Thermal resistance equal to the reciprocal of the thermal conductance which is defined as the number of British thermal units (Btu) that will pass through a square foot area of material in one hour if the temperature difference between the two surfaces of the material is 1°F.

Open/Closed-Cell Insulation – Cellular insulation in which gas can/cannot readily pass from one cell to another. Closed-cell insulation, comprising the majority of insulation used in construction, has a higher R-value than open-cell insulation. In closed-cell insulation, cells are primarily independent of one another, thus preventing the movement of gas between the cells and thereby reducing the temperature transmission between neighboring cells.

Connectors – Various concrete, steel or plastic elements that connect the concrete wythes in PCSP systems through a layer of insulation sandwiched between the concrete wythes.

CONSTITUENTS OF SANDWICH PANELS

Concrete Wythes

The thickness of each concrete wythe depends on its structural function, concrete cover, anchorage of connectors, stripping, and finish. Although some publications[1-4] provide guidelines for the thicknesses of

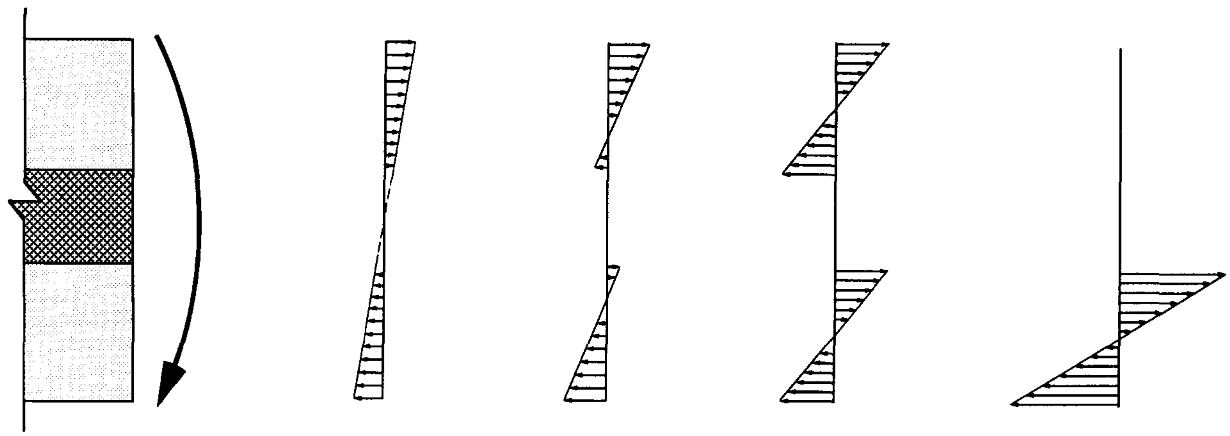


Fig. 2. Stress distribution diagrams in PCSP systems due to pure bending.

wythes, each PCSP producer has determined appropriate thicknesses for their own practice. The concrete wythes can be divided into structural wythes and non-structural wythes.

Structural Wythe – A wythe is considered structural if it provides a significant contribution to the load resistance of the panel. In fully or partially composite panels, both concrete wythes are structural. In non-composite panels, either one of the wythes is structural and the other is non-structural, or both wythes are structural and independently resist the applied loads in proportion to their relative stiffnesses. Although the minimum recommended thickness of structural wythes is 2 in. (50 mm) if prestressed and 3 in. (76 mm) if non-prestressed,[2] a thickness as small as ¾ in. (19 mm) has been used.[5] Reinforcement of structural wythes varies based on dimensions, structural requirements, and serviceability requirements of the panel.

The longitudinal reinforcement depends on the span of the panel, thicknesses of the wythes, degree of composite action, applied loads, and serviceability requirements. This reinforcement may consist of prestressing strands or wires, reinforcing bars or wire mesh, or a combination thereof. The transverse reinforcement depends on the spacing of connectors, thickness of the wythes, applied loads, and temperature changes. This reinforcement may be small reinforcing bars or wire mesh.

Non-Structural Wythe – A non-structural wythe, sometimes called cladding or a floating wythe, is one whose contribution to the structural strength of the panel is insignificant. It is used primarily for aesthetic purposes, weathering, and to encase the insulation. The thickness of the non-structural wythe should be kept to a minimum to reduce differential temperature across its thickness and to reduce panel weight. Its thickness should be sufficient to provide proper reinforcement protection, if required, and anchorage of the connectors.

The thickness of the non-structural wythe is generally 2 in. (50 mm) for a plain surfaced wythe, and 2½ in. (64 mm) for a ribbed wythe. Wythes as thin as 1½ in. (38 mm) have been used. Reinforcement in these wythes, if any, is used mainly to prevent excessive cracking due to temperature, creep and shrinkage effects. It may consist of wire mesh or small reinforcing bars, and occasionally light prestressing. This reinforcement should also be sufficient to support the weight of the wythe itself. In some systems, joints are created in the non-structural wythe to control shrinkage cracks.

Insulation

The thickness and type of insulation depends on the thermal properties of the insulation material used, the design temperature of the structure and the desired thermal resistance of the panel. Generally, a minimum thickness of 1 in. (25 mm) is used. The insulation should have low absorption to minimize the loss of water from the freshly placed concrete. Thermal and other material properties of various insulation materials are discussed in Refs. 1, 4, and 8.

Discontinuity of the insulation should be minimized by using the largest possible insulation panel sizes and by avoiding the butt joint shown in Fig. 3a. Openings around connectors may be packed with loose or formable insulation to reduce concrete penetrations which can result in thermal bridging as described later in the section on Thermal Efficiency.

Some types of insulation can transfer shear stresses, up to 10 psi (0.069 MPa), between the concrete wythes due to bonding of the insulation to the concrete.[6,7] Designers typically ignore this contribution to the shear transfer capacity (composite action) with the assumption that this bond breaks dur-

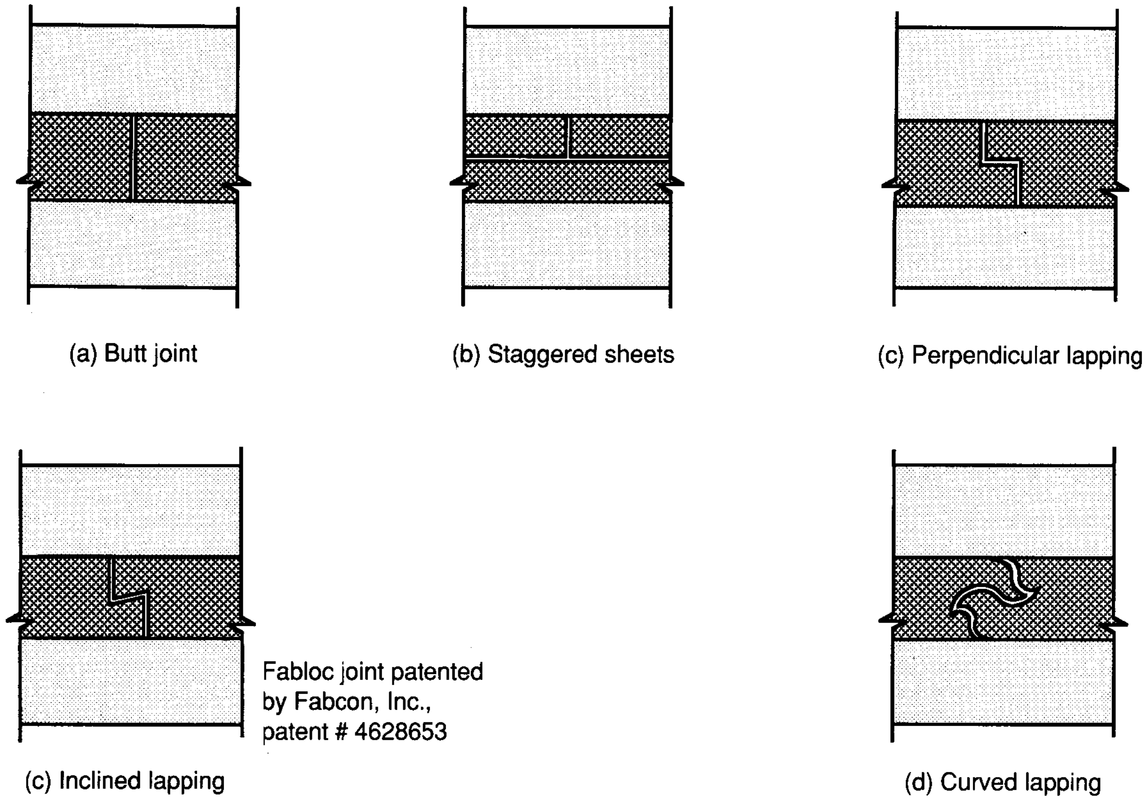


Fig. 3. Insulation joints in sandwich panels.

ing shipping and erection or due to cyclic differential volume changes during the service life of the panel. In certain non-composite panel systems, bond breaking sheets or release agents are used to effectively eliminate this shear transfer capacity which may cause undesirable behavior due to differential volume changes. To reduce the shear capacity of the insulation wythe itself, it may be made of two layers as shown in Fig. 3b.

Insulation used in sandwich panels is generally rigid cellular board which has superior thermal and physical properties over non-cellular insulation. Cellular insulation is comprised of a solid which makes up the cellular matrix containing minute gas bubbles. The gas can be air, chlorofluorocarbon (CFC), carbon dioxide or other blowing agents, and it occupies most of the insulation volume.

In general, a cellular insulation material is made by introducing a blowing agent into a raw substance in its liquid state, allowing the substance to expand under the influence of the blowing agent, and curing the expanded product to maintain its expanded form. Slight differences in the manufacturing process and the raw materials distinguish the characteristics of the insulation produced. Some of the commonly used types of insulations in PCSP systems are discussed next.

Expanded Polystyrene (EPS) – This material is formed by either a molding or an extrusion process. In the molding process, tiny polystyrene beads are impregnated with a blowing agent, typically pentane. The beads are then exposed to pressurized steam, causing the blowing agent to vaporize and thereby partially expanding the beads. They are then placed in large molds and exposed to pressurized steam, causing them to fully expand and fuse together to form a solid piece called a billet. The billet can then be cut into boards.

The extrusion process begins with a molten polymer impregnated with a pressurized liquid blowing agent. The impregnated polymer is then extruded at elevated pressure and temperature through a die onto a conveyor system at atmospheric temperature and pressure. The blowing agent vaporizes as it passes through the die, causing the polymer to expand. High density skins occur naturally on the extruded boards.

Polyurethane – This material is manufactured by mixing polyol and polyisocyanate (in the liquid state) where they react in the presence of a catalyst, a blowing agent, and other additives to become a foam. This insulation can be produced by various techniques, such as molding, spraying or other methods.

Polyisocyanurate – This material is made from the same basic ingredients as polyurethane, but with a different formulation. This product exhibits thermal stability and flammability characteristics superior to polyurethane. Regarding the factors influencing insulation selection, some of the insulation properties related to PCSP applications are listed in Tables 1 and 2 and shown in Fig. 4. The significant factors that may influence the selection of insulation for PCSP systems are described next.

Table 1. Typical physical properties of cellular thermal insulations (Ref. 8).

Properties	Expanded Polystyrene (Molded)		Expanded Polystyrene (Extruded)		Polyurethane (PUR) and Polyisocyanurate (PIR)	
Apparent Density, lb/ft^3(b)	0.8-2.0		1.4-4.0		1.7-3.0	
Open Cell Content, %	5-40		1-7		2-10	
Heat Capacity, Btu/lb °F(c)	0.27-0.31		0.27-0.31		0.20-0.5	
Coefficient of Linear Thermal Expansion, in./in. °F (x10^{-6})(d)	25-40		25-40		30-60	
Maximum Use Temperature, °F(e)	165		165		250 PUR 250-300 PIR	
Combustibility	Combustible		Combustible		Combustible	
Apparent Water Vapor Permeability, perm in.(f)	0.6-5.0		0.4-1.4		2.0-4.0	
Water Absorption, vol% ASTM C 272 (24-hr immersion)	<2.5		<0.3		2-5	
Price (\$/ft^2)(g)	0.08-0.30		0.24-0.57		0.35-0.73	
	ρ = 1.0 lb/ft^3	ρ = 2.0 lb/ft^3	ρ = 1.4 lb/ft^3	ρ = 4.0 lb/ft^3	ρ = 2.0 lb/ft^3	ρ = 6.0 lb/ft^3
Shear Strength, perpendicular to rise lb/in.^{2}	20	35	...	70	20	100
Compressive Strength, parallel to rise, lb/in.^{2}	10-14	25-33	15-25	115-125	25-35	100

(a) The date reported are for the purposes of general comparison, and the values may not be representative of every product available in the marketplace. The range in values may be considerable due to the variability between specific products within a given type and other factors relating to the testing of the products.
(b) To convert from lb/ft^3 to kg/m^3, multiply by 16.0.
(c) To convert from Btu/lb °F to kJ/kg K, multiply by 0.144.
(d) To convert from in./in. °F to m/m °C, multiply by 1.8.
(e) To convert from °F to °C, use the equation: $T_{(°C)} = (T_{(°F)}-32)/1.8$.
(f) See ASTM D 2126. To convert from perm in. to ng/Pa s m, multiply by 1.46.
(g) Obtained from various suppliers for 1 in. thick board insulation, prices vary with density, quantity ordered, and the supplier.

Table 2. Variation of thermal resistance for 1.0 in. 25.4 mm thickness insulation °F ft^2 h/Btu (Ref. 8).

Mean Temperature, °F	Expanded Polystyrene			Polyurethane and Polyisocyanurate	
	Molded		Extruded	Unfaced or High-Permeance Facings	Low-Permeance Facings
	1.0 lb/ft^3	2.0 lb/ft^3	4.0 lb/ft^3	ρ = 1.7 - 3.0 lb/ft^3	ρ = 1.7 - 3.0 lb/ft^3
25	4.3	5.0	5.6	5.6 - 6.2	6.7 - 7.7
40	4.2	4.8	5.4	5.9 - 6.7	7.1 - 8.3
75	3.8	4.3	5.0	5.6 - 6.2	6.7 - 7.7
110	3.6	4.0	4.7	5.3 - 5.9	6.3 - 7.1

(a) Mechanical Properties: The mechanical properties of cellular insulation vary with specific products, test procedures and specimen dimensions. The values given in Table 1 are for insulation without facing. Facing can greatly enhance the strength of insulation if it has proper thickness and has sufficient interface bond with the insulation. Some insulation materials are anisotropic, possessing different properties parallel rather than perpendicular to the direction of its thickness. The strength and modulus of elasticity of cellular insulation normally increase with decreasing temperature.

(b) Aging Effects: The R-value of cellular insulation materials decreases with time due to environmental factors such as physical deterioration and water absorption. In addition, closed-cell insulation materials blown by agents other than air experience another type of aging caused by a time-dependent change in the composition of the cell gas atmosphere. Insulation, such as molded bead polystyrene, does not experience this type of aging because it is expanded using air as a blowing agent as can be seen in Fig. 4.[8] In some insulation products, facings such as aluminum foil are bonded on both faces of the insulation product to retard the aging mechanism. This type of aging may occur over 100 years,[8] but most of it occurs shortly after the production of insulation. The aging effect is an important factor that needs to be considered in the selection and design of insulation.

(c) Mean Temperature Effects: The relationship between the R-value of cellular insulation and the mean ambient temperature, within the temperature ranges for PCSP systems, varies from one insulation material to another as listed in Table 2. However, for most insulation materials, the thermal resistance decreases with temperature due to the increase in thermal conductivities of the cell gases.

(d) Moisture Effects: The presence of moisture can have an adverse effect on both the R-value and the mechanical properties of cellular insulation. Because the thermal conductivity of water, especially when frozen, is significantly higher than that of the insulation, the total R-value can be sacrificed if water is allowed into the cell matrix. Facings used in some products may work as an impervious barrier to moisture which can highly reduce this effect. Also, higher density materials generally have lower permeability, but the integrity of the cellular matrix has a large influence on the absorption capability of the insulation.

(e) Thickness Effects: Generally, the R-value per unit thickness decreases with the increase in thickness of insulation. An insulation board twice as thick will not possess twice the thermal resistance. Up to 5 percent reduction can be attributed to thickness effect. This effect varies for different insulation materials.

(f) Other Considerations: Solvent resistance, dimensional stability, corrosivity, handleability, resistance to solar radiation, flame spread, combustibility and other properties may be important considerations during storage, service, and for specific applications.

CONNECTORS

Connectors are used to tie the concrete wythes together and to keep the insulation in place. They can be classified into two major categories: shear connectors and non-shear connectors.

Shear Connectors

Shear connectors are those which can transfer longitudinal shear, resulting from flexure in the panel, from one wythe to the other. These connectors may resist shear in one or two perpendicular directions.

1. One-Way Shear Connectors – These connectors can be further subdivided into concentrated and continuous connectors.

(a) Concentrated One-Way Connectors: Comprising small-size bent bars, as shown in Fig. 5a, they are made of ¼ in. (6 mm) diameter corrosion resistant mild or stainless steel bars. Expanded perforated plate connectors, shown in Fig. 5b, and flat sleeve anchors, shown in Fig. 5c, were developed for use in double-tee sandwich panels in conjunction with cylindrical sleeve anchors. These connectors will be described later.

(b) Continuous One-Way Connectors: Generally, these run the full length of the panel. This type of connector is popular in the United States. Two types of steel trusses are shown in Figs. 6a and 6b. The main difference between the two is that the top chord of the first type consists of two bars and its bottom chord consists of light gauge double bent plates, while both the top and bottom chords of the second type consist of a single bar. Continuous bent bars, Fig. 6c, are similar to their concentrated counterparts. Expanded perforated plate connectors, consisting of long pieces, as shown in Fig. 6d, are also commonly used in North America. Reinforced concrete webs are continuous, solid concrete links at least 1 to 2 in. (25 to 50 mm) wide, reinforced with steel trusses or continuous bent bars,

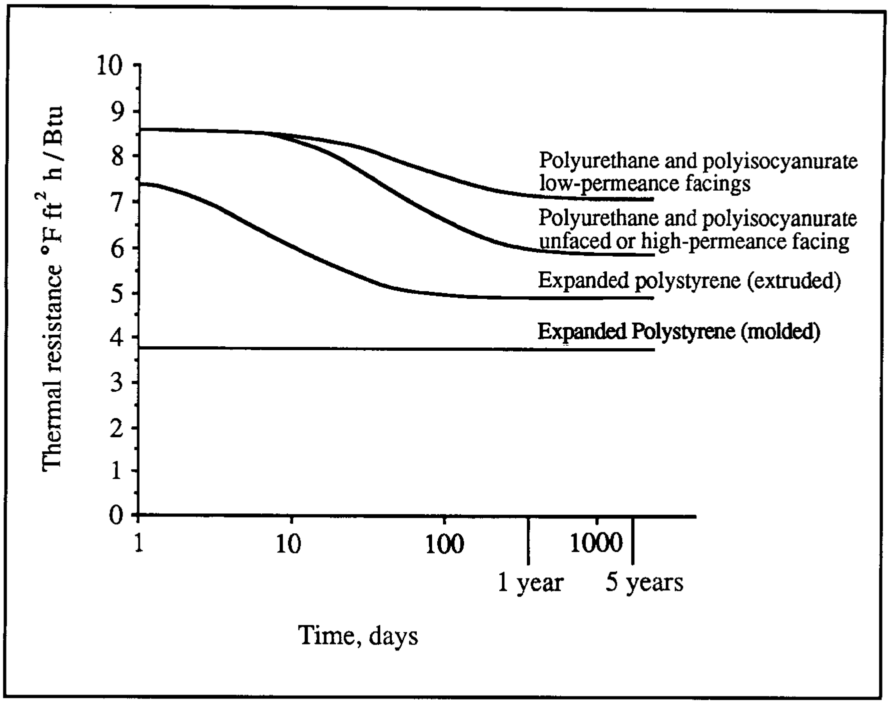


Fig. 4. Thermal resistance vs. time for 1.0 in. (25.4 mm) materials aged at ambient conditions and measured at a 75°F (25°C) mean temperature (Ref. 8).

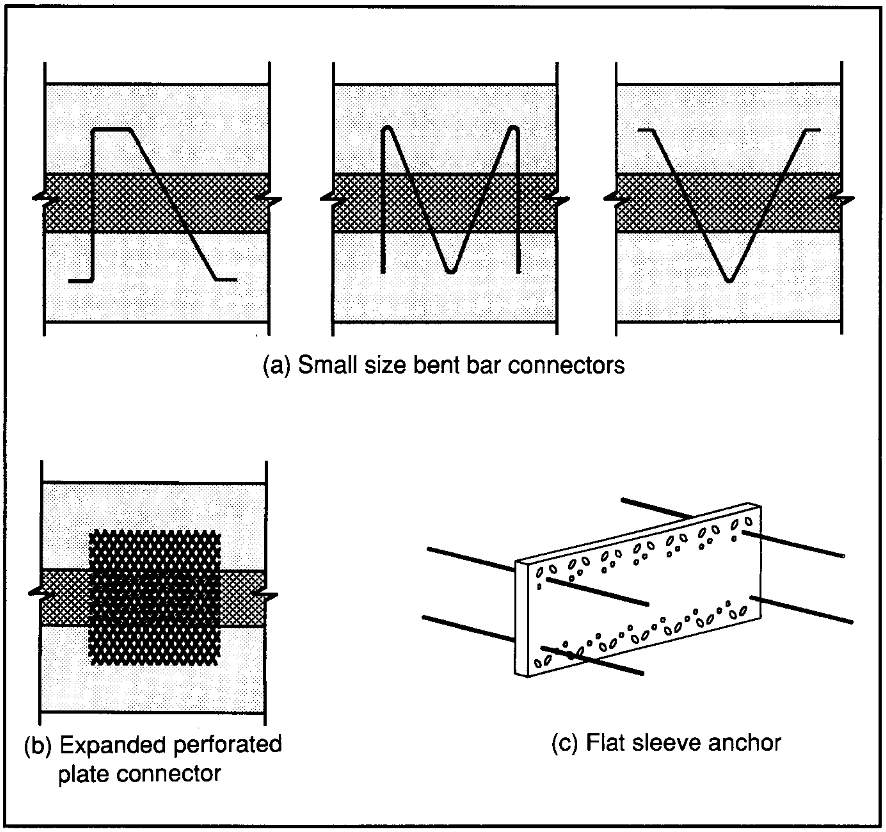


Fig. 5. Concentrated one-way shear connectors.

as shown in Fig. 7. The PCI Architectural Precast Concrete Manual[2] does not recommend the use of web connectors for two reasons: (1) they rigidly connect the two concrete wythes, each of which is subject to significantly different deformation, thus developing forces which may lead to cracking, and (2) the webs act as significant heat sinks and reduce the insulating effectiveness of the panel, as well as possibly

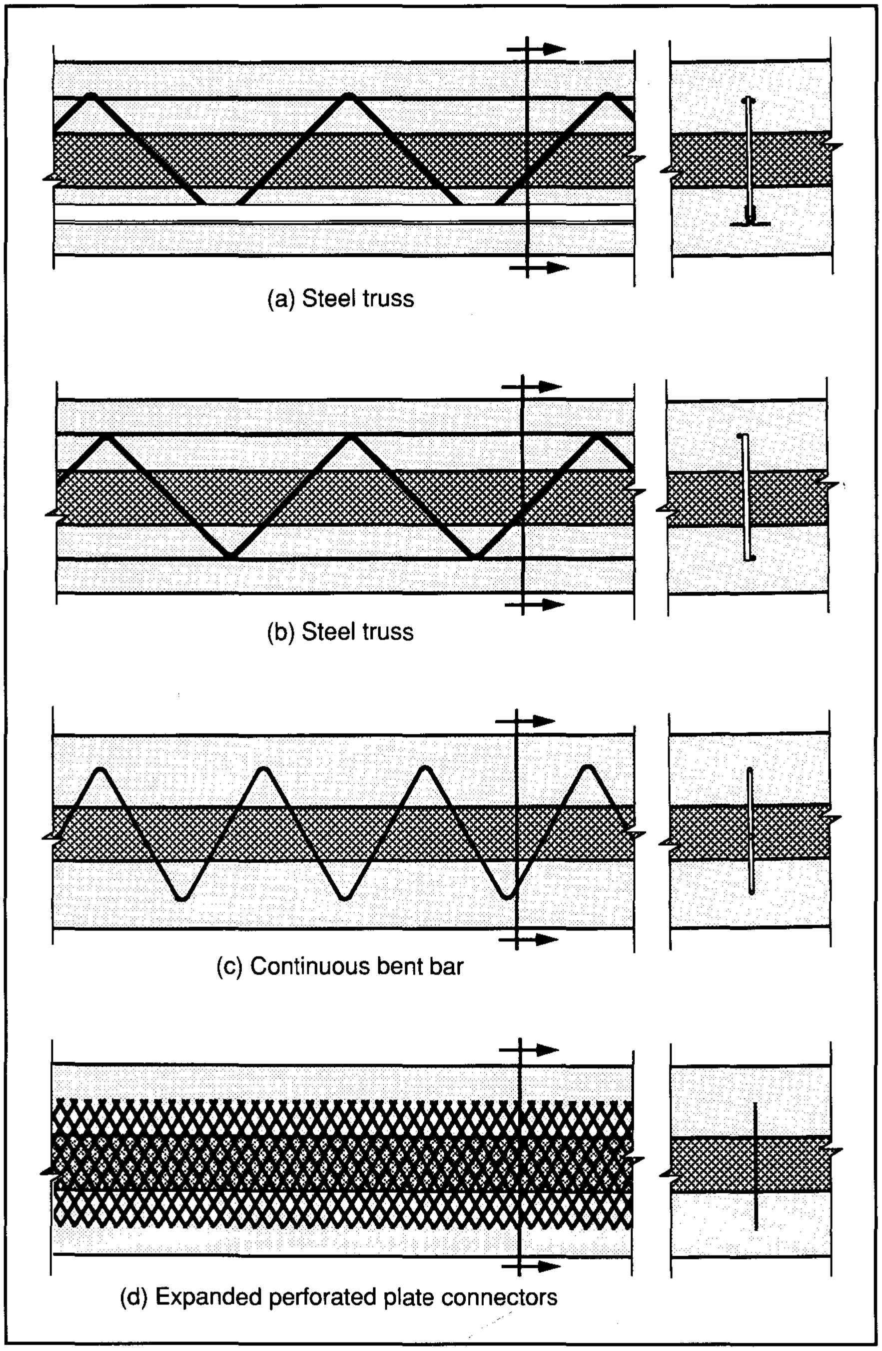


Fig. 6. Continuous one-way shear connectors.

causing local condensation and discoloration. Despite the above-mentioned reservations, this type of connector is widely used in North America because of its superior fire resistance achieved by encasing the insulation and the reinforcement completely in concrete.

2. Two-Way Shear Connectors – These connectors have comparable shear capacity in two directions in the plane of the panel. Commonly used connectors of this type are:

(a) Cylindrical Sleeve Anchors: These connectors shown in Fig. 8a, are strong in resisting torsion as well as shear. They are intended for use in non-composite panels to transfer the weight of the non-structural wythe to the structural wythe, as described later in the section on Arrangement of Connectors.

(b) Crown Anchors: These connectors, shown in Fig. 8b, are popular in Europe. They are made by bending small diameter bars into a three-dimensional configuration.

(c) Concrete Blocks: These connectors, shown in Fig. 9, are large concrete links between the concrete wythes. They can be either concentrated, almost square shaped blocks, as shown in Fig. 9a, or continuous links across the top and bottom of the panel, as shown in Fig. 9c. These blocks are also intended to encase the panel lifting inserts.

Non-Shear Connectors

These connectors can transfer only a negligible amount of longitudinal shear from one wythe to the other. They are commonly used in North America in non-composite panels to transfer tension or compression forces due to stripping, storage, transportation, erection, wind, and seismic loads from a non-structural to a structural wythe. In addition, they prevent separation, peeling or wrinkling of the non-structural wythe. They are used in composite panels in conjunction with shear connectors if the spacing of the shear connectors is too large. This type of connector can be divided into metallic and non-metallic connectors.

(a) Metallic Connectors: The most popular metallic connectors are pin connectors. They are mostly 12 to 14 gauge (2 to 2.7 mm) galvanized or stainless steel bars bent into various configurations as shown in Fig. 10a. Proper anchorage into both concrete wythes can be accomplished through deforming or hooking at the pin ends. The most commonly used methods to install these connectors are: (1) pushing the pins from top, through the insulation, into the freshly cast bottom wythe, (2) pressing the insulation board, with the pins prefixed in it, onto the freshly cast bottom wythe, or (3) fixing the pins onto the reinforcement of the bottom wythe and casting the bottom wythe with the pins in place.

Continuous welded ladder connectors, as shown in Fig. 10b, are also used as non-shear connectors. They are equivalent to equally spaced pins.

(b) Non-Metallic Connectors: These connectors are made of non-reinforced or fiber reinforced plastics. The use of plastic pins may be advantageous in avoiding condensation at connector locations inside

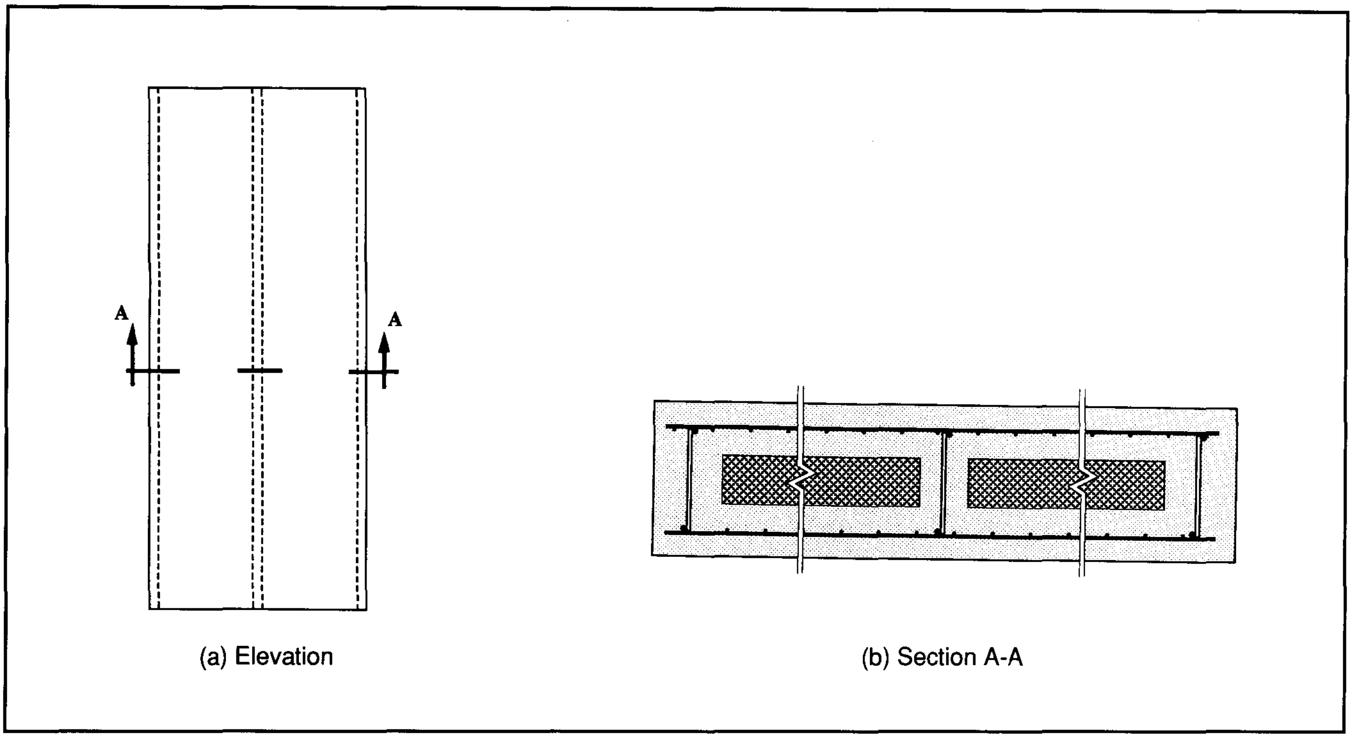


Fig. 7. Reinforced concrete webs.

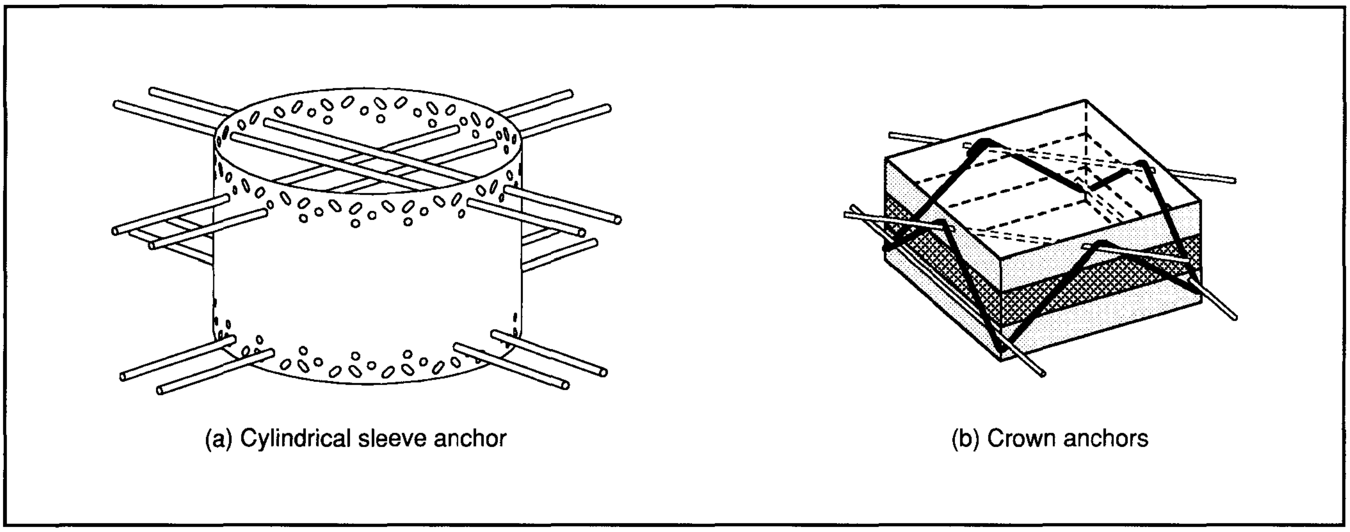


Fig. 8. Two-way concentrated shear connectors.

buildings where the humidity is high. Consideration must be given to the effect of plastic connectors on the fire resistance of the panel and to the long-term creep effect of connectors.

Two types of non-metallic pin connectors are in use in North America: a non-reinforced polypropylene pin as shown in Fig. 11a, and a glass fiber reinforced vinyl ester resin pin shown in Fig. 11b. These connectors are installed by pushing through the insulation layer into the freshly placed concrete of the bottom wythe.

Arrangement of Connectors

The arrangement and spacing of connectors in PCSP systems vary depending on several factors, such as desired composite action, applied loads, span of the panel and type of connectors. Although some guidelines are given in the literature, such as in Refs. 1, 2 and 7, there are no rules for arranging the connectors.

Some commonly used arrangements of connectors in non-composite panels are given in Fig. 12. Many design engineers recommend the use of a two-way concentrated shear connector at the centroid of the non-structural wythe, as shown in Fig. 12a, in order to transfer the weight of the non-structural wythe to the structural wythe and to allow the non-structural wythe to expand or contract freely due to volume changes.

One-way concentrated shear connectors can also be used in non-composite panels as shown in Fig. 12b. They are oriented along the two major axes of the panel. This arrangement allows for shear and some torsional, but no flexural, restraint between the two wythes.

In some non-composite double-tee

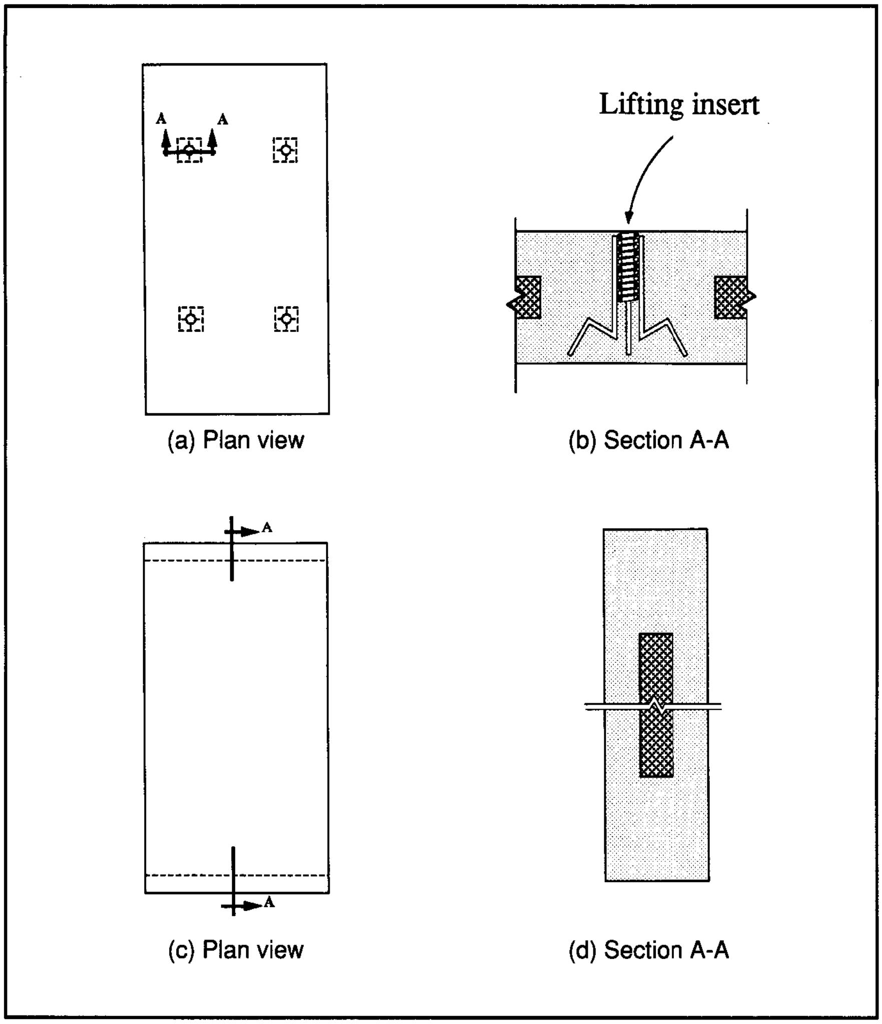


Fig. 9. Concrete block connector.

panels, a cylindrical sleeve anchor is used at one of the tee-webs. A flat sleeve anchor is placed in the other tee-web in the same horizontal level, as shown in Fig. 12c, for lack of anchorage depth available in the flat portions of the panel.

Non-shear connectors are spaced as shown in Fig. 12 to transfer tension or compression forces due to stripping, storage, transportation, wind and seismic forces to the structural wythe and to prevent separation and wrinkling of the wythes. A commonly used spacing is 2 ft (600 mm).

In composite panels, the main connectors are shear connectors. Steel trusses, concrete webs or other elements, as described previously, are used. Their number depends on such factors as panel width and degree of composite action desired. Non-shear connectors are also used where the distance between the shear connector exceeds an acceptable limit of approximately 2 ft (600 mm).

System Details

Details between the various elements of a building system are extremely important for a system to perform satisfactorily. The thermal

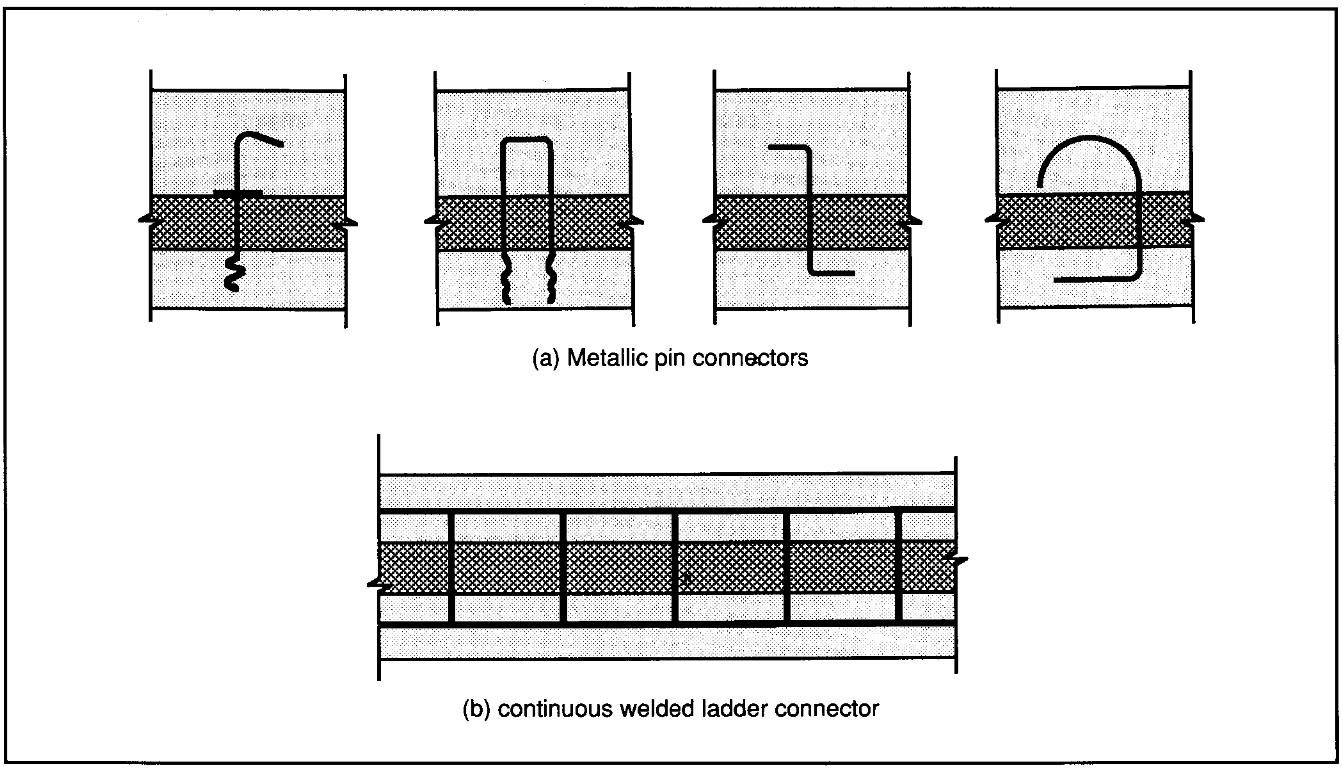


Fig. 10. Non-metallic shear connectors.

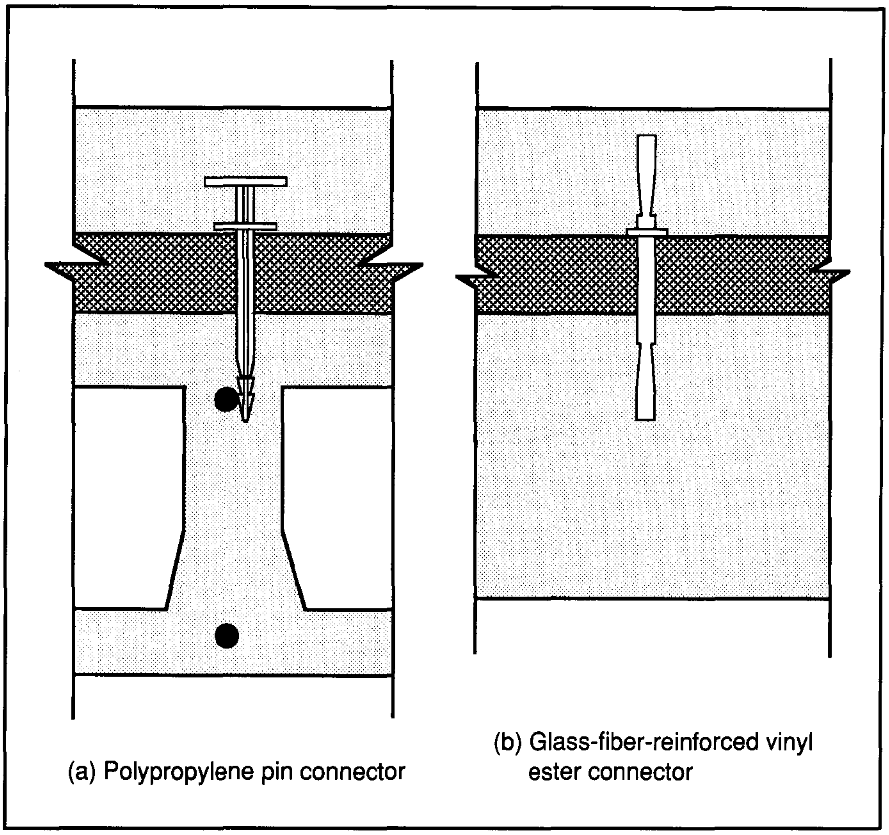


Fig. 11. Plastic pin connectors.

barrier should continue from one panel to the next and between the wall, roof and ground floor. In addition, allowance for panel deformation due to temperature and other volume changes must be made; otherwise, the system must be designed to resist the induced forces.

Experience has shown that both of these design methods for handling deformations due to volume changes have been used with success. Also, it has been observed that greater bowing due to temperature effects occurs in the parts of the building facing direct sunlight (south, southeast and southwest) than in other parts.

While this factor has not yet been quantified, it should be recognized in the detailing of composite panel walls.

Useful connection details are given in the PCI Architectural Precast Concrete Manual[2] representing American practice, and in Ref. 13, representing European practice.

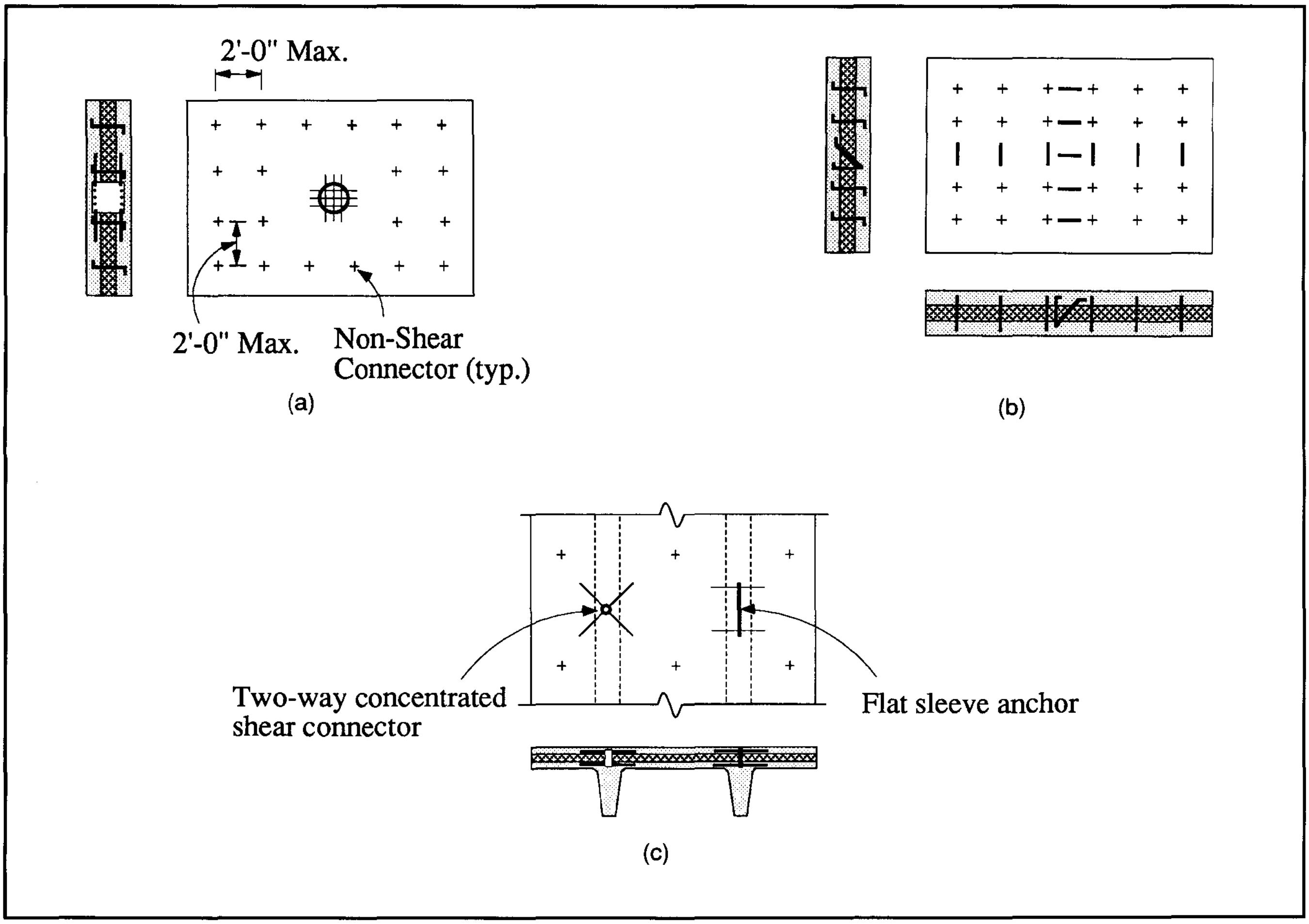


Fig. 12. Examples of non-composite panels, arrangement of connectors (see Ref. 1).

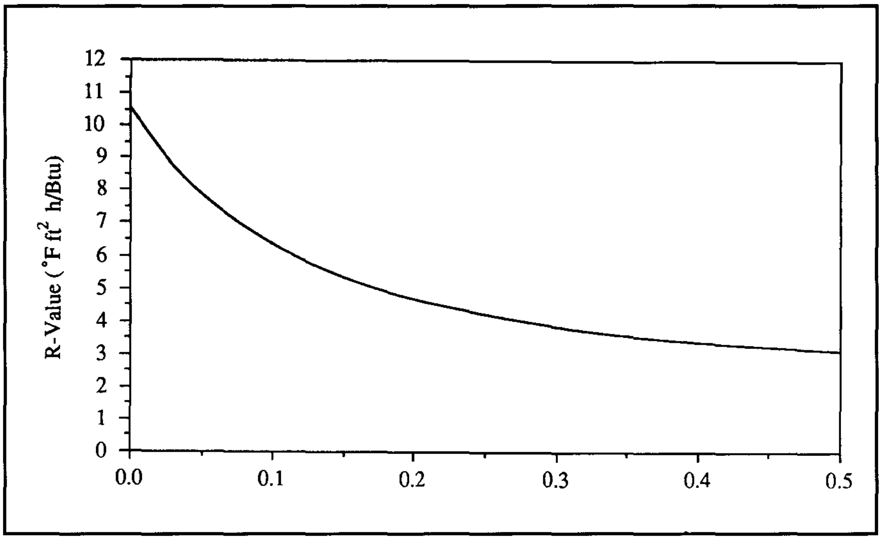


Fig. 13a. Effect of percentage area of stainless steel connectors on the R-value of PCSP systems due to thermal bridging (see Ref. 7).

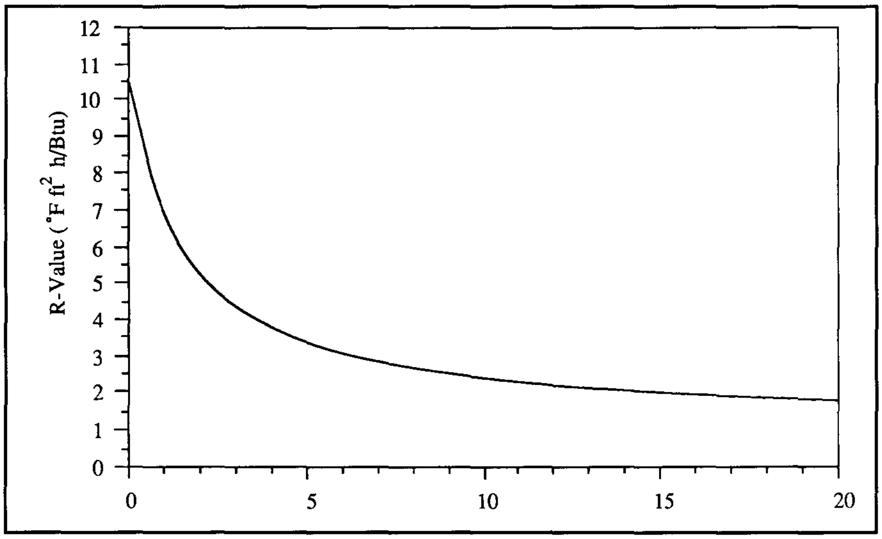


Fig. 13b. Effect of percentage area of concrete penetrations on the R-value of PCSP systems due to thermal bridging (see Ref. 7).

RECENT RESEARCH

The complexity of the interaction between the various components of PCSP systems has led researchers to rely on experimental observations supplemented with simplified analytical studies. Small scale models are extremely difficult to make and use, and full scale testing is expensive. This partially explains the lack of information on this important type of construction. Another reason is reluctance of some producers to share proprietary information with their competitors.

Most experimental work on load resistance has included shear and/or flexural tests. The shear test is performed by applying shearing forces in the mid-thickness planes of the concrete wythes to find the shear capacity of the connectors and the contribution of the insulation to shear interaction between the concrete wythes. The interface shear is important in determining the degree of composite action. In a flexural test, a panel is subjected to out-of-plane transverse loads to determine the overall flexural capacity of the panel.

At the University of Oklahoma, composite panels were subjected to shear and flexural tests.[14] The panels were 8 in. (200 mm) thick, 16 ft (5 m) long, and 8 ft (2.4 m) wide with steel truss connectors. The research team had difficulty preventing concrete from leaking into the insulation joints at the connectors. In some instances, the quantity was such that a concrete web formed, which influenced assessment of the connector stiffness and the system's energy efficiency.

Wade et al. conducted extensive testing on non-composite panels with glass fiber reinforced plastic pin connectors. In their final report,[7] they presented detailed information about the structural and energy performance of panels utilizing those connectors. They found a significant composite action achieved if porous insulation is used. Such action cannot be counted on in design for long-term performance. The researchers have recommended the use of extruded polystyrene board to reduce permeability and preserve the insulation value in the long term.

Another interesting result of this study is illustrated in Fig. 13. It demonstrates that a stainless steel connector's area of as little as 0.1 percent causes a 41 percent reduction in the thermal resistance of the panel. Similarly, concrete penetrations of as little as 1 percent of the total panel surface can cause a 37 percent reduction in the thermal resistance (R-value) of the panel.

At the Technical Research Center of Finland, shear tests were performed on 4 x 4 ft (1.2 x 1.2 m) panels. Several types of connectors with different arrangements as well as different types of insulation were used. The shear load vs. displacement curves for all the different samples were plotted for comparison.[15,16]

Research on optimization of composite panels for structural and thermal performance is underway at the University of Nebraska. The main sponsors of the study are the Nebraska Department of Energy and Wilson Concrete Co. The research is scheduled for completion in late 1992, and a report will be available shortly thereafter.

Based on their experimental work, Phillips and Sheppard[17] suggest a procedure to account for partial composite action. The procedure involves development of a semi-empirical reduction coefficient to be applied to the gross sectional moment of inertia of the panel to obtain the panel's

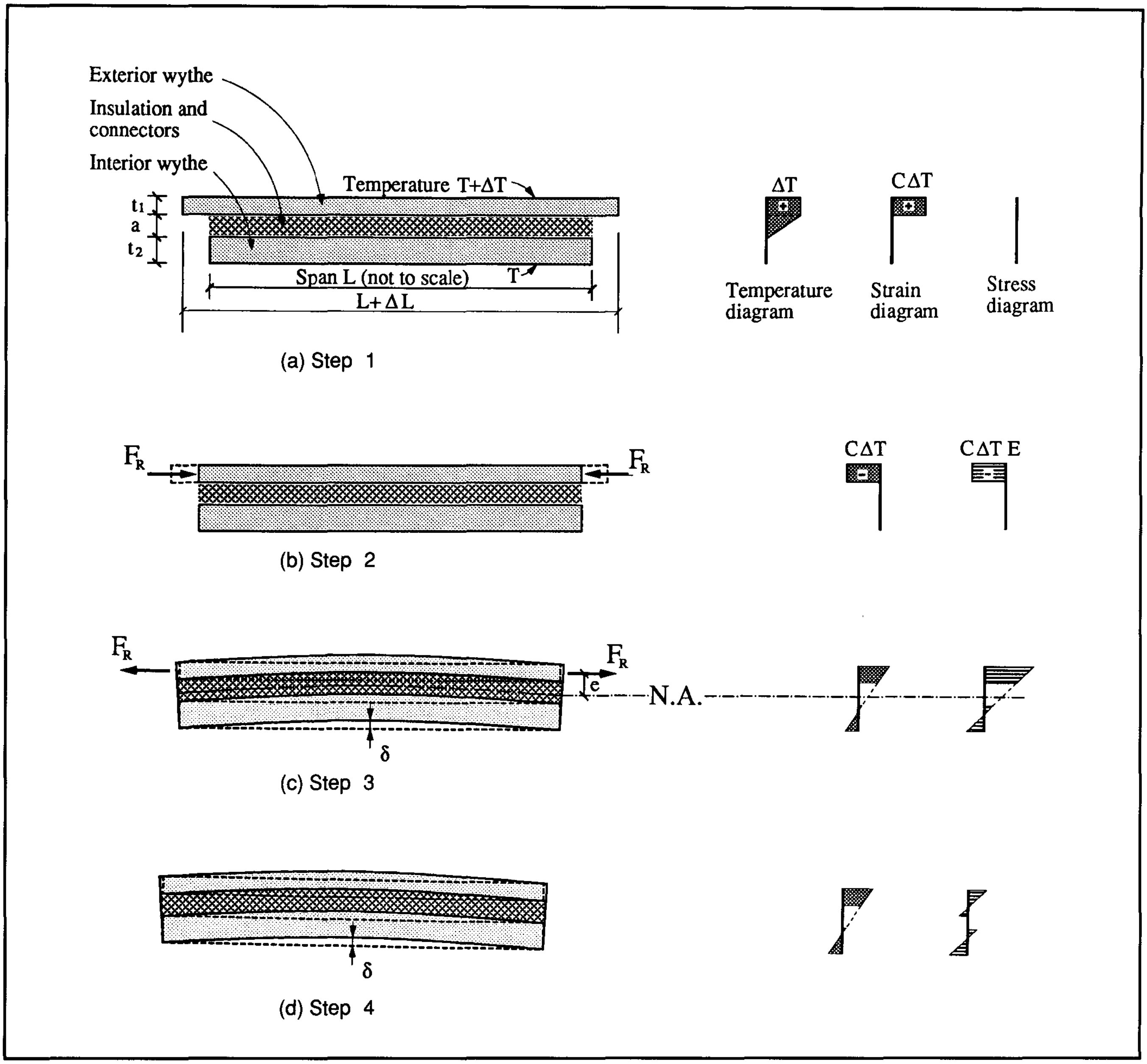


Fig. 14. Steps of analysis for steady-state thermal gradients. (Note: Vertical scale is exaggerated for clarity and symbols are defined in the Analysis for Volume Changes and Appendix B.)

effective moment of inertia. The reduction coefficient is based on the type of connector used.

Comprehensive analytical studies have been reported by Holmberg and Pelm,[18] and Hopp and Hermstad.[19]

ANALYSIS OF COMPOSITE PANELS FOR VOLUME CHANGES

A general method for calculating the stress and deformation of composite sandwich panels due to temperature change, creep and shrinkage is presented in the next section. It is based on the theory described in Ref. 20. This theory has been successfully implemented in computer programs for analysis of segmental and composite bridges, but can easily be adapted for PCSP systems. For the sake of clarity, a general description of the procedure is given without complicated equations. Illustrations are given only for analyzing temperature effects. Numerical examples illustrating the use of this procedure are provided in Appendix B.

Assumptions

1. Plane sections remain plane after bending. This is accurate for shallow flexural members such as PCSP systems.

2. Homogeneous material and linear stress-strain relationship are assumed. This assumption requires stress levels below the proportional limit of the material, which is generally true at service load level.

3. Steady-state temperature conditions are assumed. The effect of transient temperature would require modifications not included in this study.

Steps of Analysis

Step 1 – Allow the various layers (fibers) of each wythe to deform freely under the effect of the temperature change to which the panel is exposed.

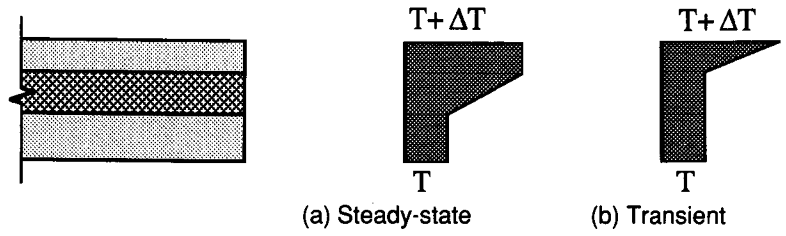


Fig. 15. Temperature variation through concrete sandwich panels.

For this to occur, longitudinal interface shear resistance is assumed to be nonexistent by debonding (slicing) the various layers, as shown in Fig. 14a. This step results in zero stress. Strain equals $C \cdot \Delta T$, where C is the coefficient of thermal expansion and ΔT is the temperature change at the corresponding layer (fiber). The strain distribution is identical to the ΔT diagram in the concrete, assumed here to be uniform for clarity of presentation. Other temperature variation diagrams across the panel thickness would be treated similarly. No support reactions are developed at this stage.

Step 2 – Offset the deformation created in Step 1 by introducing a set of restraining forces as shown in Fig. 14b. The introduced forces result in the stress and strain diagrams shown in the figure for the special case of uniform temperature rise in the exterior layer only. An additional restraining bending moment would be required if the temperature diagram centroid and the wythe centroid do not coincide.

Step 3 – The restraint created in Step 2 restores compatibility. However, now equilibrium is violated. To offset this external restraint, a set of equal and opposite forces must be applied, as shown in Fig. 14c. Here, the forces are applied to the "reconnected" panel. If the panel is fully composite and simply supported, the analysis would only require simple hand calculations. In some practical cases, neither condition is met. For example, if truss connectors are solely used to connect the two wythes, the stiffness of the trusses is not likely to produce full composite action. If this practical composite action is to be represented in a more exact form, a plane frame analysis using a computer program would be needed to obtain accurate stresses and deformations.

Step 4 – Combine the results of Steps 1 through 3 to obtain the required net effects, as shown in Fig. 14d.

ISSUES IN NEED OF FURTHER RESEARCH

Thermal Efficiency

The use of metal and/or concrete connectors in PCSP systems can significantly reduce thermal efficiency, as stated in the section on Recent Research. These penetrations act as heat sinks (or thermal bridges) through which heat is transferred from one wythe to the other. Research on quantification and minimization of thermal bridging while maintaining the superior qualities of PCSP systems is needed. The current project at the University of Nebraska is a contribution to this effort.

Fire Protection

The fire endurance time of sandwich panels with different thicknesses of concrete and insulation layers varies from 1 hour 23 minutes to 4 hours 25 minutes.[21] Research on fire endurance is especially important for panels with non-metallic connectors because of the low stiffness of the connectors under high temperature conditions.[7] Specific measures, such as appropriate concrete covers and design safety factors, can be used to increase the feasibility of non-metallic connectors in sandwich panels.

Volume Changes

It is well known that concrete experiences some volume changes during its service life. Creep and shrinkage of concrete, relaxation of the prestressing steel (if prestressing is used), as well as temperature variations can cause significant deformations and stresses, especially in composite panels.

The theory of volume change analysis is well established and experimentally verified especially for bridges.[20] However, specific application to sandwich panels, described earlier under Analysis of Composite Panels, needs to be experimentally verified. Also, design criteria need to be developed for these effects.

Transient Vs. Steady-State Temperature Effects

A distinction must be made between two types of changes: steady-state temperature changes and transient temperature changes. The difference lies in the time associated with each type since temperature conduction through the thickness of a material is a function of time. Concrete sandwich panels are made of relatively thin wythes. Steady-state temperature differences between the two faces of a panel causes uniform temperature within the thickness of each of the concrete wythes while the total temperature difference occurs through the insulation, as shown in Fig. 15a.

On the other hand, the daily transient temperature difference occurs in a shorter time than is required to equalize the temperature throughout the thickness of the concrete wythes, as shown in Fig. 15b. The effects due to both types of temperature differentials can be calculated if the contributory parameters are properly assessed.

The geometry of the panels and material properties can be estimated. Also, reasonably accurate temperature records are kept by weather bureaus. However, for effects of transient temperature changes, direct exposure to sunlight plays a major role. The temperature of the exposed surface is normally much higher than the surrounding ambient temperature.

This difference is affected by several variables such as weather conditions, surface roughness, color, reflectance and duration of exposure. Thus, it is difficult to estimate the temperature distribution through the thickness of the panel.

This phenomenon has been attributed to causing noticeable bowing in PCSP walls facing south. Research is needed to accurately determine the magnitude and significance of temperature changes due to direct solar exposure.

SUMMARY

Precast concrete sandwich panels are structurally and thermally efficient exterior wall systems with attractive architectural features. Various fully, partially, and non-composite sandwich panel systems are used throughout the world in commercial and residential buildings. The sandwich panel systems most commonly used in North America and Europe for low rise commercial and warehouse buildings typically range from 12 to 55 ft (3.7 to 17 m) in height and from 4 to 12 ft (1.2 to 3.7 m) in width and are produced in long fixed or rolling (moving) beds. The constituents of these panels are described in this paper with emphasis on the connectors and the insulation.

The main characteristics and components of a few widely used PCSP systems are presented in Appendix A. More detailed information on these systems may be obtained from the producer listed with each system. The characteristics of cross-section, insulation material and connectors vary among the systems. However, current partially and fully composite panel systems, and some non-composite panel systems, are made with steel connectors, reinforced concrete connectors or a combination of these.

Available information is limited. Some of the significant research results are presented in this paper. Results indicate that concrete and steel penetrations through the insulation may cause significant loss of thermal resistance. Concrete penetrations of as little as 1 percent of the total panel surface have been shown to cause up to 37 percent reduction in the thermal resistance (R-value). Also, stainless steel penetrations of as little as 0.1 percent have been shown to cause up to 41 percent reduction in thermal resistance.

Temperature and other volume change effects may cause significant stresses and deformations which must be accounted for in design. Published methods are available for evaluating these stresses and deformations. A general analysis procedure is outlined in the text of this paper and is illustrated with numerical examples in Appendix B.

Several issues, including thermal efficiency, fire endurance, and volume change effects, are currently being debated among panel designers and producers in North America. Dedicated research is required to address these issues and to better understand sandwich panel behavior over a range of wythe and connector designs. Research on optimization of structural and thermal performance of PCSP panels is being carried out at the University of Nebraska, with a report scheduled for completion in late 1992.

ACKNOWLEDGMENT

This paper was prepared as a part of a research project on "Energy Optimization of Precast Concrete Sandwich Panels," sponsored by the Nebraska Energy Office, Wilson Concrete Co., and the Center for Infrastructure Research at the University of Nebraska-Lincoln. Messrs. Jagdish Nijhawan, Morrie Workman and Ken Rech of Wilson Concrete Co. provided valuable input to the project.

REFERENCES

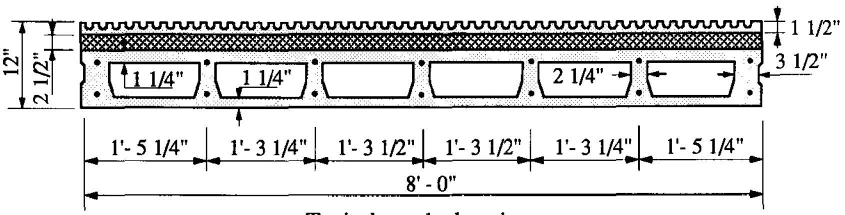
1. *PCI Design Handbook – Precast and Prestressed Concrete*, Third Edition, Precast/Prestressed Concrete Institute, Chicago, IL, 1985, Chapter 9, pp. 2-22, 55-61.
2. *Architectural Precast Concrete*, Precast/Prestressed Concrete Institute, Chicago, IL, 1989, pp. 280-286.
3. *Manual for Structural Design of Architectural Precast Concrete*, Precast/Prestressed Concrete Institute, Chicago, IL, 1977, Chapter 6, pp. 1-15.
4. *ASHRAE Handbook – Fundamentals*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, NY, 1985.
5. Insteel Construction Systems, Inc., Brunswick, GA, Product Information Literature.
6. "FABCON Guide Specifications for Precast, Prestressed Concrete Hollow Walls and Planks," FABCON Inc., Savage, MN.
7. Wade, T. G., Porter, M. L., and Jacobs, D. R., "Glass-Fiber Composite Connectors for Insulated Concrete Sandwich Walls," *Report*, Engineering Research Institute, Iowa State University, Ames, IA, 1988.
8. Strzepek, W. R., "Overview of Physical Properties of Cellular Thermal Insulations," Insulation Materials, Testing, and Applications, ASTM STP 1030, D. L. McElroy and J. F. Kimpflen (editors), American Society for Testing and Materials, Philadelphia, PA, 1990, pp. 121-140.
9. Dayton Superior Company, Miamisburg, OH, Product Information Literature.
10. Keystone Steel and Wire Corporation, Peoria, IL, Product Information Literature.
11. Meadow Steel Co., Tampa, FL, Product Information Literature.
12. "Thermomass Building Systems – Architectural/Engineering Manual," Composite Technologies Corporation, Ames, IA, 1987.
13. Cziesielski, E., "Physical Principles of Sealing Joints in External Walls," *Bauphysik*, Germany, 1987, pp. 188-195.
14. "Behavior of Composite Sandwich Panels," *Progress Report*, University of Oklahoma, Norman, OK, 1989.
15. Jokela, J., and Sarja, A., "Development of Reinforcement of Sandwich Facade Element," *Research Note No. 19*, VTT-Technical Research Center of Finland, Espoo, 1981.
16. Olin, J., Ratvio, J., and Jokela, J., "Development of Heat Economy and Construction of Facade Elements," *Research Report No. 28*, VTT- Technical Research Center of Finland, Espoo, 1984.
17. Phillips, W. R., and Sheppard, D. A., *Plant Cast Precast and Prestressed Concrete*, Prestressed Concrete Manufacturers Association of California, Sacramento, CA, 1980.
18. Holmberg, A., and Pelm, E., "Behavior of Load Bearing Sandwich-Type Structures," *Handout No. 49*, State Institute for Construction Research, Lund, Sweden, 1965.
19. Hopp, J., and Hermstad, A., *Sandwich Elements – Construction Handbook of Concrete Elements*, Norwegian Concrete Industries Association, Oslo, Norway, 1986.
20. Tadros, M. K., Ghali, A., and Dilger, W. H., "Time-Dependent Analysis of Composite Frames," *Journal of Structural Division*, American Society of Civil Engineers, V. 103, No. ST4, April 1977, pp. 871-884.
21. Gustaferro, A. H., and Martin, L. D., (for PCI Fire Committee), "Design for Fire Resistance of Precast Prestressed Concrete," Precast/Prestressed Concrete Institute, Chicago, IL, 1988.

APPENDIX A
PRECAST CONCRETE SANDWICH PANEL SYSTEMS

Some of the most common precast concrete sandwich panel systems in North America and Europe are briefly described in Tables A1 through A7.

Table A1. Typical Fabcon sandwich panel.

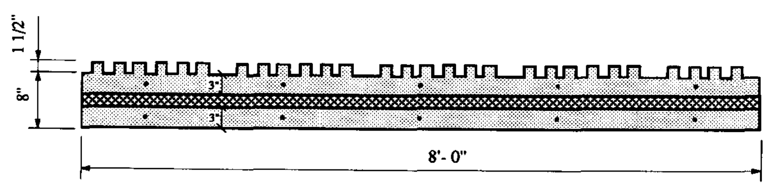
		Company	Contact
System/ Developer	**Fabcon**	Fabcon Incorporated 6111 West Highway 13 Savage, Minnesota 55378	David W. Hanson (800) 727-4444
Wythes	Structural wythe is 8 in. (20 cm) hollow-core. Non-structural wythe is 1.5 in. (38 mm) with different architectural finishes (ribbed, scored, etc.).		
Reinforcement	Structural wythe contains pretensioned strands in the long direction and lateral reinforcing bars throughout the panel. Non-structural wythe is not reinforced.		
Insulation	Polystyrene 2 1/2 in. (64 mm), occasionally urethane, insulation boards premarked for connector locations and lapped with patented inclined lapping joints.		
Connectors	Proprietary Fabcon polypropylene pins spaced at 2 ft (0.6 m) typically, and denser at the top and the bottom of panels.		
Composite	None.		
Casting method	Long line rolling beds with slip forms to create the voids.		
Uses	Industrial and commercial buildings up to 54 ft (16 m) high loadbearing walls.		
Additional comments	Typical panel width is 8 ft (2.4 m). The use of polypropylene connectors creates no thermal bridges nor condensation points. Connectors permit free movement of the non-structural wythe, causing no thermal bowing.		



Typical panel, plan view

Table A2. Typical Corewall sandwich panel.

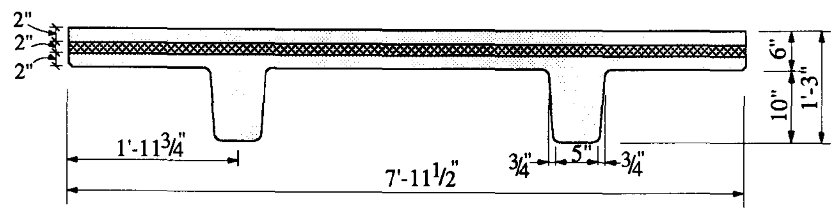
		Company	Contact
System/ Developer	**Corewall**	Corewall, Inc. 701 Evans Avenue, Suite 800 Toronto, Ontario M9C 1A3	Don Paton (416) 626-6050
Wythes	Both wythes are structural, 2 in. (25 mm) thick minimum for exterior wythe and 3 in. (76 mm) thick minimum for interior wythe.		
Reinforcement	Both wythes are prestressed in the long direction.		
Insulation	Polystyrene insulation from 2 to 6 in. thick (50 to 150 mm).		
Connectors	Proprietary M type shear connectors.		
Composite	Non-composite for cold temperature applications or semi-composite for normal applications.		
Casting method	In long fixed beds, and saw cut or bulkheaded into required lengths.		
Uses	Industrial and commercial buildings up to 40 ft (12 m)		
Additional comments	Typical panel width is 8 or 10 ft (2.4 or 3 m), different architectural finishes are applied by patented roller process (ribbed, exposed aggregate, colored, etc.).		



Typical panel, plan view

Table A3. Typical Dukane sandwich panel.

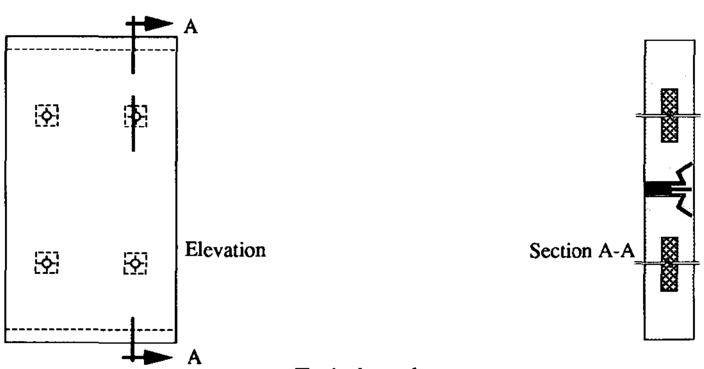
System/ Developer			
		Company	**Contact**
System/ Developer	**Dukane**	Dukane Precast, Inc. 600 West Fifth Avenue Naperville, IL 60563	John E. Dobbs (708) 355-8118
Wythes	Structural wythe is double T or flat solid. Non-structural wythe is 2 in. (50 mm) thick.		
Reinforcement	Structural wythe is prestressed in the long direction and wire mesh in flange section. Non-structural wythe contains mesh throughout the panel.		
Insulation	Expanded polystyrene 2 in. (50 mm) thick minimum.		
Connectors	C-shaped shear connectors and solid blocks of concrete at both ends and around lifting inserts.		
Composite	None assumed.		
Casting method	In long double tee or flat molds.		
Uses	Industrial and commercial buildings up to 45 ft (14 m).		
Additional comments	Typical panel width is 8 ft (2.4 m).		



Typical panel, plan view

Table A4. Typical Tindall sandwich panel.

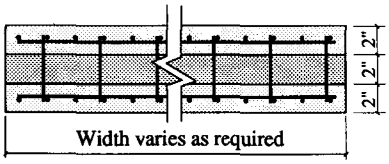
		Company	**Contact**
System/ Developer	**Tindall**	Tindall Concrete Products, Inc. P.O. Box 1778 Spartanburg, SC 29304	Kim Seeber (803) 576-3230
Wythes	Both wythes are structural 2 in. (50 mm) thick minimum.		
Reinforcement	Both wythes are prestressed in the long direction. Wire mesh is used in both wythes at both ends and in areas of the lifting inserts.		
Insulation	Insulation board 2 in. (50 mm) thick.		
Connectors	Solid blocks of concrete at both ends, solid blocks of concrete around lifting inserts, and steel trusses, or M or C connectors elsewhere.		
Composite	100 percent composite action can be achieved.		
Casting method	In long fixed beds.		
Uses	Industrial and commercial buildings up to 50 ft (15 m) mostly in regions with low temperature changes.		
Additional comments	Typical panel width is 12 ft (3.7 m).		



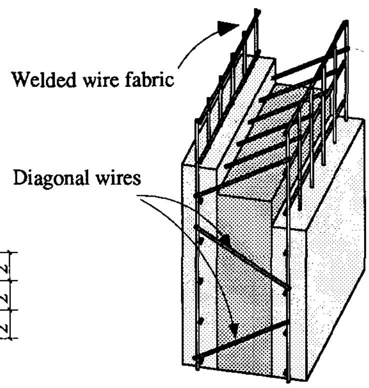
Typical panel

Table A5. Typical Insteel sandwich panel.

System/ Developer	**Insteel**	**Company**	**Contact**
		Insteel Construction Systems, Inc. 2610 Sidney Lanier Drive Brunswick, GA 31520	Edward D. Hummel (912) 264-3772
Wythes	Both wythes are structural, 3 in. (76 mm) thick minimum.		
Reinforcement	Welded wire fabric throughout both wythes.		
Insulation	Polystyrene board from 1 1/2 to 4 in. (38 to 100 mm) thick, polyisocyanurate or phenolic foam may be used for higher (R) values.		
Connectors	Nine to eighteen galvanized diagonal wires per square foot penetrating insulation layer and welded to the wire mesh reinforcement of both concrete wythes.		
Composite	100 percent composite action assumed.		
Casting method	In long beds.		
Uses	Industrial and commercial buildings.		
Additional comments	Manufactured steel/insulation panels come 4 ft wide and from 4 to 24 ft (1.2 to 7.3 m) long. These panels are manufactured by special machines which place a layer of wire mesh on each side of the insulation board, insert the galvanized wires through the insulation, and weld the wires to both wire mesh layers. Steel/insulation panels can be structurally joined to accommodate any size of PCSP.		



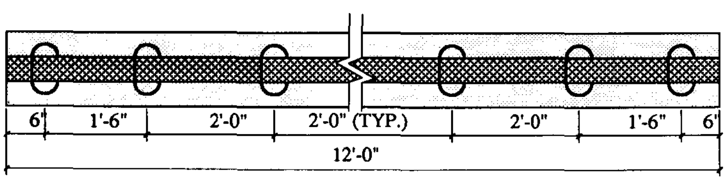
Typical panel, plan view



Partial cut

Table A6. Typical Metromont sandwich panel.

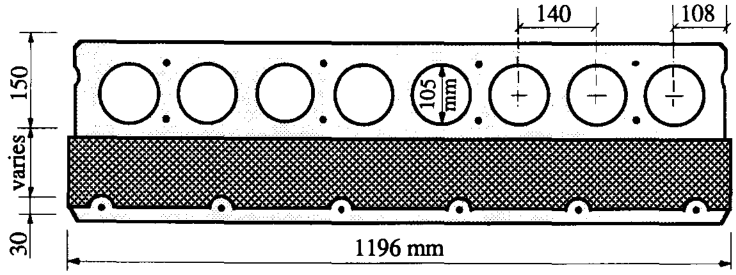
System/ Developer	**Metromont**	**Company**	**Contact**
		Metromont Material Corp. P.O. Box 2486 Greenville, SC 29602	Harry Gleich (803) 269-6767
Wythes	Both wythes are 2 in. (50 mm) thick.		
Reinforcement	Both wythes are reinforced with wire mesh and prestressed by 3/8 in. (9.3 mm) diameter strands at 24 in (0.6 m) on center.		
Insulation	Expanded or extruded polystyrene insulation board 2 in. (50 mm) thick.		
Connectors	Along with solid blocks of concrete at both ends and around lifting inserts, C ties are placed at 2 ft (0.6 m) each way or fiber reinforced plastic connectors at 16 in. (0.4 m) each way.		
Composite	100 percent composite is assumed in design.		
Casting method	In long fixed beds, and bulkheaded into required lengths.		
Uses	Industrial and commercial buildings.		
Additional comments	Typical panel width is 12 ft (3.7 m) and height from 15 to 40 ft (4.6 to 12m).		



Typical panel, plan view

Table A7. Typical Variax sandwich panel.

		Company	**Contact**
System/ Developer	**Variax**	Partek Concrete Oy Ab P.O. Box 61 Helsinki, SF-00500, Finland	Jutta Hamekoski 358-0-39441
Wythes	150 mm (6 in.) hollow-core structural wythe and 30 mm (1.2 in.) non-structural wythe.		
Reinforcement	Structural wythe is prestressed by 9.3 mm (3/8 in.) diameter strands. Non-structural wythe is lightly reinforced and cut by expansion joints at 6 to 12 m (20 to 40 ft) on center.		
Insulation	50 to 120 mm (2 to 5 in.) polystyrene insulation.		
Connectors	4 mm (3/16 in.) diameter stainless steel pins at 600 to 1000 mm (2 to 3.5 ft) on center.		
Composite	None.		
Casting method	In long fixed bed by Elematic type hollow-core extruder.		
Uses	Industrial, commercial and apartment buildings.		
Additional comments	Typical panel width is 1200 or 2400 mm (4 or 8 ft).		



Typical panel, plan view

APPENDIX B
NUMERICAL EXAMPLES OF ANALYSIS FOR VOLUME CHANGES

For each of the following examples, a panel of 9 in. (229 mm) overall thickness is considered. The panels are assumed simply supported with a span length L = 30 ft (9.15 m), modulus of elasticity E = 4000 ksi (27580 MPa), coefficient of thermal expansion of concrete $C = 6 \times 10^{-6}$ in./in./°F, and a temperature rise of the exterior face relative to the interior face, ΔT = 50°F (28°C).

The solution steps explained in the Analysis of Composite Panels for Volume Changes are followed in all the examples. They are repeated below in equation format for easy interpretation. The computations in the examples are for a 1 ft (0.305 m) wide panel strip.

Step 1 – The strain at any fiber = $C \cdot \Delta T$, where C and ΔT are as defined in the section on volume changes. No stresses are induced in this step.

Step 2 – The strain at any fiber = $-C \cdot \Delta T$.

The stress at any fiber = $-E \cdot C \cdot \Delta T$.

The stress resultant F_R is the the volume of the stress diagram.

Step 3 – The moment $M = F_R \cdot e$, where e is the eccentricity of the resultant, F_R.

The strain at any concrete fiber

$$= \frac{P}{EA} \pm \frac{My}{EI}$$

The stress at any concrete fiber

$$= \frac{P}{A} \pm \frac{My}{I}$$

The deflection at midspan (bowing)

$$\delta = \frac{ML^2}{8EI}$$

Notes:

1. In this step, the cross-sectional area A and the moment of inertia I are for the entire cross-section of the 1 ft (0.305 m) strip of panel.

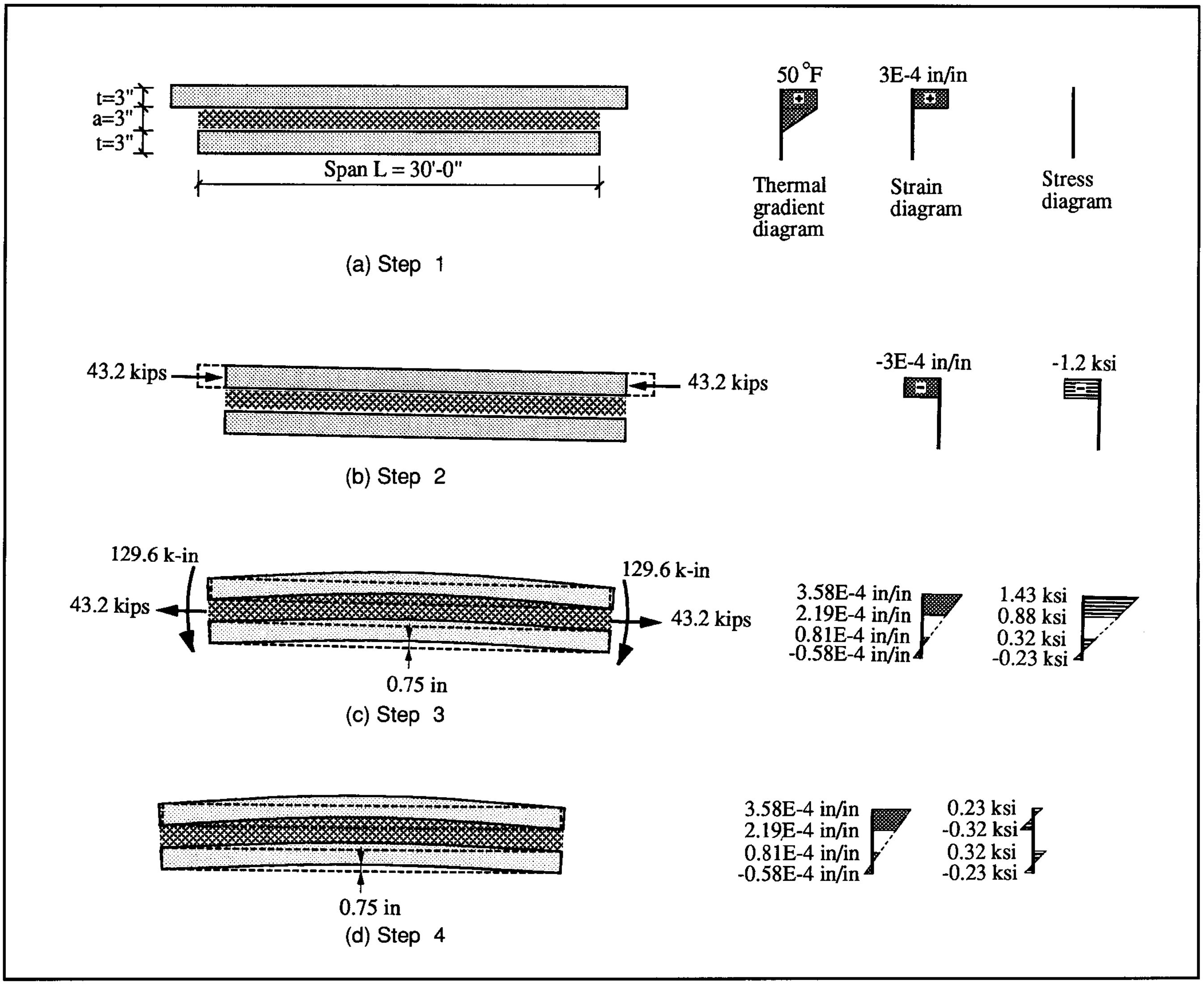


Fig. B1. Example 1, PCSP subject to a steady-state thermal gradient. [Note: Vertical scale is exaggerated for clarity, and numbers are for 1 ft (0.305 m) wide strip.]

Table B1. Resulting deformation and stresses due to thermal gradients in composite panels (Examples 1 to 4).

Example number	Cross Section of Panel	Thermal gradient diagram (°F)	Final strain diagram (in/in)	Final Stress diagram (Ksi)	Midspan deflection (in)
(1)	3" 3" 3" Sandwich Panel	+ 50	3.58E-4 2.19E-4 0.81E-4 -0.58E-4	0.23 -0.32 0.32 -0.23	0.75
(2)	9" Solid Panel	3" + 50 *	3E-4 -1E-4	-0.53 0.67 -0.4	0.72
(3)	9" Solid Panel	+ 50	3E-4 0.0	0.0 0.0	0.54
(4)	9" Solid Panel	50	2.5E-4 -0.5E-4	-0.2 0.1 -0.2	0.54

•This thermal gradient is unrealistic for solid panels and it is presented here for demonstration only. That of Examples (3) is more realistic for steady-state conditions, and that of Example (4) is more realistic for transient conditions.

2. The equations shown above for this step apply only if the panel is fully composite. If full composite action cannot be substantiated, the panel can be analyzed by other structural analysis methods.

Step 4 – Final strain, stress and deflection values are obtained by algebraically adding those from Steps 1 through 3.

Fig. B1 shows the thermal gradient, strain and stress diagrams for all steps of the analysis for Example 1. Table B1 summarizes the results of Examples 1 through 4 for comparison.

Remarks:

1. The midspan deflection in Examples 3 and 4 is identical although the final strain and stress diagrams are different.

2. An interesting result is that constant thermal gradients cause residual stresses in composite sandwich panels while quadratic thermal gradients cause residual stresses in solid panels.