Manufactured Panelized Roof System for Residential Buildings

S.C. Mantell, J.H. Davidso, G. Mittelman, and G.L. Di Muoio,
Department of Mechanical Engineering, University of Minnesota
G.E. Mosiman and J.C. Carmody,
Center for Sustainable Building Research, University of Minnesota
T. Okazaki, C.K. Shield, and B.J. Siljenberg,
Department of Civil Engineering, University of Minnesota
D.H. MacDonald, Mattson MacDonald Young

ABSTRACT

This paper describes the design and application of a self-supporting and insulated panelized residential roof/attic system. An overview of the design methodology is presented for a panel concept that has been prototyped and tested for structural performance. The truss core concept has separate structural and insulating components integrated into a single panel at an offsite manufacturing facility. The structural component is comprised of two thin metal face sheets and an internal metal web. The web extends the entire length of the panel from soffit to ridge. The insulation is foamed-in-place during manufacture either on the interior or exterior of the structural member as appropriate for the climate. A finish sheet is applied to form the exterior roof or interior finish. Connections between panels and at the soffit and ridge are designed to address water vapor management, structural requirements, and desired architectural features. Application of the panelized roof to an energy efficient home in a warm humid climate is provided in a case study.

Introduction

The University of Minnesota and its industry partners are collaborating to develop the panelized residential roof system. Conventional residential roof construction in the United States utilizes closely spaced roof trusses supporting a layer of sheathing and roofing materials. Gypsum board is typically attached to the lower chord of the trusses forming the finished ceiling for the occupied spaces. With insulation placed above the ceiling plane, this creates an unconditioned attic. While this roof system has benefited from efficiency improvements and costs have become optimized over time, it still has disadvantages the industry would like to overcome. From the standpoint of energy use, mechanical systems and ducts that are placed in the unconditioned attic increase energy consumption for heating and cooling.

Recently techniques have been employed to move the insulation to the space between the trusses at the roof plane thus creating a conditioned attic with the ducts placed inside the insulated envelope. The energy benefits of this approach have been documented (e.g., Desjarlais et al. 2004; Hendron et al. 2004; Rudd 2005). Desjarlais et al. (2004) modeled the energy savings of cathedral attics in diverse climates (Atlanta, Boulder, Dallas, Miami, Minneapolis, and Phoenix) and found that for ducts of typical length and leakage rates, energy savings of 5 to 40% could be realized, depending on climate, insulation level and duct leak rate. The building industry partners see the approach using trusses as an interim solution. With closely-spaced trusses and insulation applied from below, this is still a complicated process taking time and involving several trades. The availability of skilled workers is another concern. Another approach to accomplish placing insulation in the roof plane utilizes structurally insulated panels (SIP) placed on supporting beams and/or trusses. Custom-designed rafter systems typically utilized in cathedral ceilings are another option.

Concerns were expressed by the industry partners and research team about conventional SIP or cathedral roof construction as the ultimate solution. SIP panels still require an underlying support structure and long-term durability questions arise in terms of moisture control and the structural properties of the foam. One of the potential advantages of a SIP panel is the foam layer. This feature has the potential to reduce thermal bridges and air leakage compared to placing insulation between trusses or rafters. However wood spline and metal locking joints utilized in traditional SIPs construction can result in thermal bridges and gaps in the foam. The cathedral ceiling approach does not necessarily require underlying support or rely on foam for structure but it is still a custom designed option requiring high-level workmanship.

The goal of the project that emerged from these concerns was to create the next generation roof system with the following characteristics:

- Manufactured panels that incorporate structure, insulation, and possibly the interior and exterior finish materials
- Panels that only require support at the ends with no intermediate supporting structure
- Optimal energy performance by minimizing the use of thermal bridges and creating airtight seals of all joints
- Minimal risk of moisture problems
- Durable with at least a 50-year life.
- Applicable to a range of design styles, climates and conditions
- Fast, easy erection in the field with minimal reliance on skilled labor
- Potential for incorporation of factory-installed solar systems into the panel
- Lowest possible costs

The proposed panel design is based on meeting these criteria. In the evolution of the panel design, it became clear that a panel meeting these criteria would have a number of performance advantages but at a higher cost than conventional roof truss construction. The cost gap is less when compared to SIP or cathedral ceiling systems but it still exists. Cost analysis and design refinements are ongoing. Potential opportunities to further reduce costs take advantage of systems integration. For example, cost and material savings result if the structural panel itself also serves as the finish roof. Similarly, the significant cost of field-installed solar systems may be dramatically reduced with factory installation. In addition to these potential advantages, the use of the roof panel system results in different costs and benefits depending on the house design and the application. Two examples with the best cost-benefit picture are (1) a more steeply-sloping roof with occupied space in the attic, and (2) a low-sloping roof with no attic or separate ceiling panel. The panelized roof system, illustrated in Figures 1 and 2 for a simple gabled attic, uses structural panels with rigid insulation. The panels are supported by a ridge beam and are designed to cantilever over the exterior wall forming an overhang. Figure 1 shows a steeply sloping roof with usable attic space while Figure 2 shows a lower sloped roof with a cathedral ceiling on the inside.

In this paper, we describe one concept for such a panelized roof system—the truss core panel. The truss core panel has a steel structural component and a foam insulating layer incorporated into a single panel. A steel structure was selected to facilitate a continuous manufacturing process. Panel designs are presented for a horizontal span of 20 ft for 6/12 and 10/12 pitch roofs in both northern and southern climates. Architectural details at panel-to-panel connections, the soffit, the ridge and gable end are provided. A case study is presented to demonstrate application of the panelized roof system to an energy efficient home in a hot moist climate.

Figure 1. Panelized Roof System with Steep Sloping Roof (10/12 pitch)

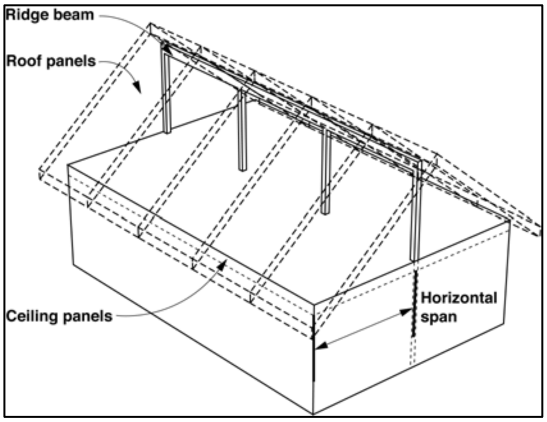
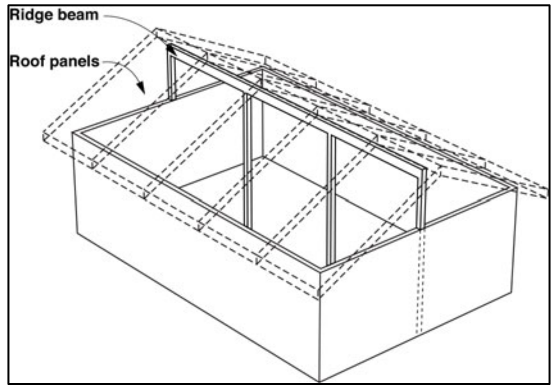


Figure 2. Panelized Roof System with Low Sloping Roof (6/12 pitch)



Panel Design

Two versions of the truss core panel are shown in Figures 3 and 4. In both cases, the steel structural component is comprised of two face sheets and an internal metal web (core). The internal web consists of V-channels continuously laser welded to the face sheets. The edges of the structural component parallel to the V-channels are finished with a laser welded C-channel. Panels are installed such that the webs are oriented longitudinally, with webs spanning the longest unsupported length. In our consideration of hygrothermal performance and manufacturability, a variety of foams were considered (Davidson et al., 2007). Foam-in-place PUR is recommended for a number of reasons: It is suitable for a continuous manufacturing process, has a service temperature of 194 to 248°F, is not susceptible to mold, and has been recommended over thermoplastic foams (such as polystyrene) in the event of fire (Davies, 1994). In the future, bio-based foam resins, such as PUR derived from vegetable oil (Narine et al., 2007), may be attractive if their long term structural properties are suitable.

When the insulation is located on the exterior of the panel (Figure 3), the vapor barrier (the steel structure) is located on the conditioned side of the panel. As shown, a sheet of OSB is placed on top of the foam during manufacture. The PUR/OSB bond is formed during the foaming process. The OSB sheet facilitates attachment of conventional exterior roofing materials. When the insulation is located on the interior of the panel (Figure 4), the vapor barrier is on the exterior panel surface. This panel utilizes an integral ribbed steel face sheet as the finish roof surface. The interior finish sheet can be installed as part of the foaming process. In both designs, deflection of the structure due to any temperature difference across the panel is eliminated, and the required depth of insulation (compared to placing insulation within the web structure) is minimized. As shown in the architectural details that follow, for both panel configurations, the panel-to-panel connections do not span the insulation and thus do not compromise the insulating value of the foam. Without insulation, the truss core design is well suited for relatively thin ceiling panels.

Design Methodology

In designing the panel, structural and thermal loads are considered for three U.S. climate zones (I, II, and III) corresponding to the southern, middle and northern regions of the U.S. (Figure 5). The sum of the dead, live and wind loads for the three climate zones are listed in Table 1 for 6/12 and 10/12 slopes. Loads are combined following the AISI Allowable Strength Design procedure (AISI, 2001a). In conventional structural insulated panels (SIPs) used for wall construction, the panel also experiences a thermal load, which corresponds to the temperature gradient across the panel. One of the advantages to the truss core panel is that the foam carries the thermal load. Because the metal structural component is much stiffer than the foam and has no thermal gradient, there is no thermal bowing of the panel. For each climate zone, the panel is designed to support the combined loads without exceeding (i) the deflection limit (horizontal span length/240) set by the International Code Council (ICC, 2003a) and (ii) the material strength or buckling limits. Panel hygrothermal performance for roof assemblies has been evaluated to select the depth of insulation required to achieve the R-value specified by the International Energy Conservation Code (ICC, 2003b) for each climate (Table 1) and to avoid moisture related problems including condensation, mold/mild growth, decay, and metal corrosion.

Structural Performance

An analytic design tool has been developed. The analytic model is comprised of several submodels corresponding to performance criteria for deflection, stress, face sheet and web buckling, postbuckling and web crippling. The structural component is analyzed as a beam that is simply supported at the ridge and soffit and subjected to a uniformly distributed load. The distributed load corresponds to the combined dead, live and wind loads. Given the loading and

Figure 3. Truss Core Roof Panel with Exterior Foam

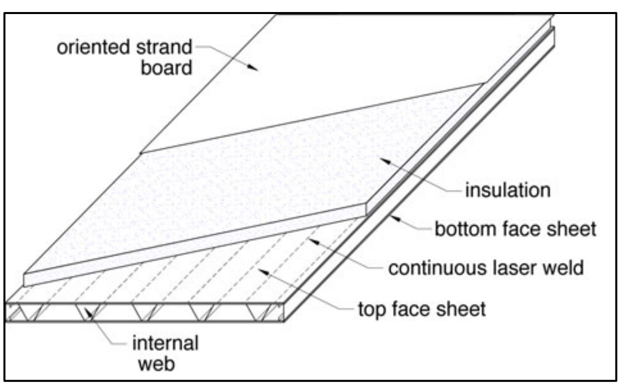


Figure 4. Truss Core Roof Panel with Interior Foam

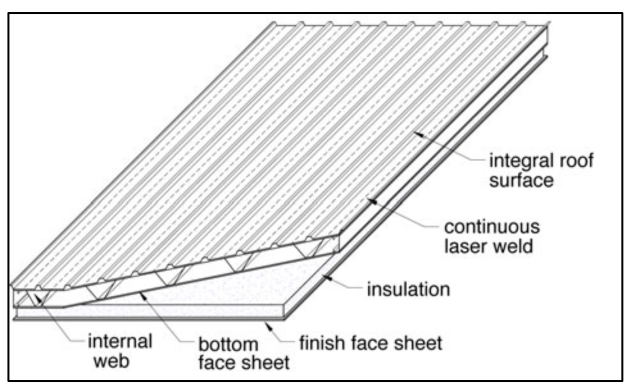


Figure 5. Load Regions Based on Snow and Wind Loads Specified by the Residential Building Code (ICC, 2003a)

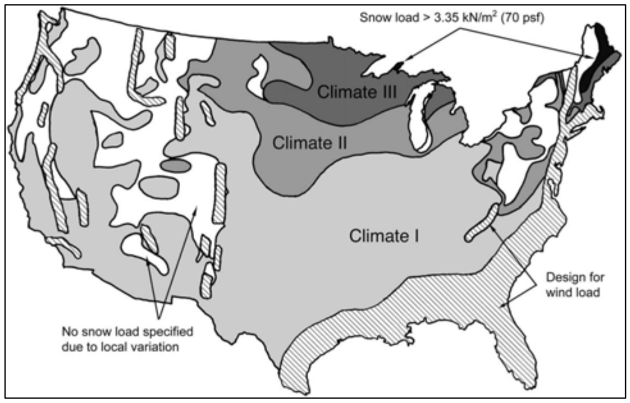


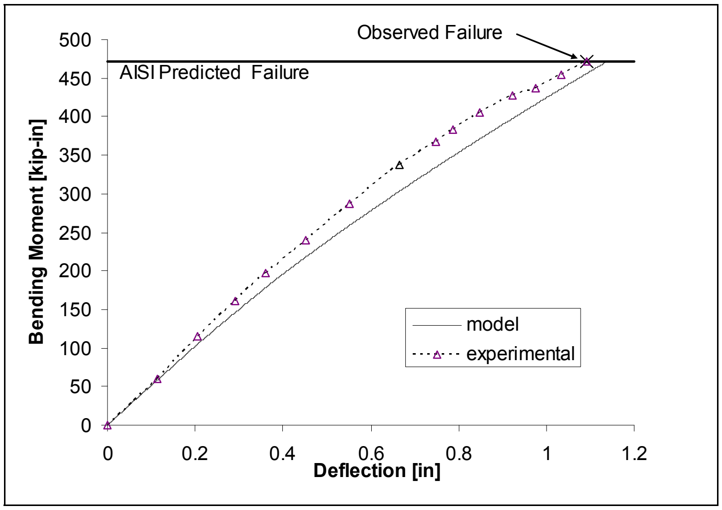
Table 1. Loads for the U.S. Climate Zones shown in Figure 5 (ICC, 2003a, 2003b)

Roof Pitch	Climate I	Climate II	Climate III
Combined load normal to the panel (lb/ft^2)			
6/12	32.9	45.4	73.9
10/12	32.5	41.3	58.4
R-value (hr·ft^2·^{o}F/Btu)	30	40	40

support conditions, panel deflection and stresses within the panel components are evaluated. Stresses within the structural component can cause buckling of the top face sheet and web elements. The stress limits corresponding to the onset of buckling are determined following a classical mechanics approach (Timoshenko, 1961). As is typical of deck and sandwich steel structural components, the panel will support loads beyond those associated with the onset of buckling. The load at which the panel collapses, referred to as the moment capacity, is determined by a nonlinear postbuckling analysis described in the AISI code for cold formed steel structures (AISI, 2001a). Local buckling failure of the webs at the supports is modeled following the web crippling criteria identified in the AISI code (2001a, 2001b).

The model has been verified experimentally for a full scale prototype. Figure 6 shows model predictions of deflection as a function of flexural moment and flexural moment capacity compared to experimental data. A simply supported 7.2 ft wide truss core panel with a span of 16 ft. was tested under a uniform load to determine its flexural capacity. The panel was set on load cells at its ends and loaded with sand uniformly until failure. Midspan deflection was measured using dial gages. Strain gages were applied to the top and bottom face sheet at midspan to detect yielding. The measured load-displacement response compared well to the load-displacement response determined using the effective width method adopted from the AISI cold formed specifications (AISI, 2001a, 2002). Ultimate failure occurred when the tension face sheet (bottom) yielded at a moment of 471 kip-in, causing a large inelastic local buckling across the entire width of the top face sheet. This local buckling of the face sheet also caused the web at midspan to buckle. Our model predicts an inelastic buckling moment at failure of 473 kip-in, a difference of approximately 0.4%. In summary, there is excellent agreement between the experimental data and the analytic models of panel structural performance (i.e. deflection, failure loads, and failure modes).

Figure 6. Comparison of Predicted and Measured Panel Deflection and Moment Capacity



Hygrothermal Performance

The hygrothermal performance of each panel is modeled for both arrangements in a variety of climates. As shown in Figures 3 and 4 placement is considered on both the exterior and interior side of the steel structure. The depth of PUR in the panel is based on ICC (2003b) guidelines for R-value (R-value equals approximately 5.75 hr·ft^2·^{o}F/Btu/in.).

Moisture transport in the two panel assemblies is predicted for a number of U.S. cities. Initially we modeled the exterior foam panel for roof applications in International Falls. This location was selected to represent an extreme cold, humid climate. Additional analyses were carried out in several locations with significant heating and cooling loads (Detroit, Omaha, and Salt Lake City) as well as for primarily cooling dominated climates (Las Vegas, El Paso). The interior foam panel, which has an integral standing seam metal roof, was modeled in Houston, Los Angeles, San Diego, Phoenix, New Orleans, Tampa and Miami.

The moisture transport was modeled using WUFI 2D-3.0 (Künzel, 2005). The simulations were carried out for a period of 3 years to ensure independency of the results on the initial conditions and to observe the seasonal as variations in moisture transport. Data from year 3 are used to assess the potential for failure due to (i) condensation, (ii) mold or mildew, (iii) wood decay, and (iv) metal corrosion. Because the model assumes local thermal equilibrium between the foam matrix and the air, it cannot be used to assess condensation within the foam. We assess the risk of condensation at the PUR/steel interface based on the temperature difference between the metal surface of the truss core structural component and the adjacent PUR. In all simulated cases, this temperature difference was too low to drive condensation.

Gypsum and OSB are susceptible to mold at RH > 80%. Brief periods of high RH are acceptable as long as the monthly average is less than 80%. OSB is also susceptible to decay. The maximum allowable moisture content in the OSB layer is 20% (ASHRAE, 2005). A variety of criteria have been suggested to assess the risk and rate of corrosion of carbon steel and other metals. Corrosion of carbon steel can begin at RH = 60%, but the rate of corrosion is very low for RH < 80%. ISO standards (9223 and 9224) specify that corrosion is likely if relative humidity at the metal surface is greater than 80% and the temperature is above freezing. The number of hours for which a metal surface is exposed to these conditions is termed the Time of Wetness (TOW). The ISO 9223 standard provides corrosion rates based on the material and

TOW. In this paper we report the TOW at the interface of the truss core metal face sheet and the PUR. Although there are situations for which the TOW is low or zero, many climates pose some risk of corrosion and thus we recommend a protective coating be applied during manufacture.

The computational domain is shown in Figure 7. The metal structure was treated as an impermeable boundary for both panels. The model of the exterior foam panel is shown in Figure 7a. R-40 hr·ft^2·^{o}F/Btu is achieved with a 7 in. thick PUR foam layer (the insulating value of the roof finish is not included in this value) on the exterior of the metal structural component. The exterior finish of the panel is 0.5 in. OSB that adheres to the PUR and is put in place at the factory as part of the foaming process. A variety of roof finishes are possible. In the present study, we assume that asphalt roof paper and shingles are attached to the OSB finish sheet. The present model assumes the steel structure is the interior finish. Future work will consider additional interior finish materials.

The assembly modeled for the interior foam panel is shown in Figure 7b. A 5.2 in. PUR layer attached to the interior of the metal structure provides R-30 hr·ft^2 ^{o}F/Btu. The interior face sheet is 0.5 in. gypsum board with primer and an acrylic paint finish. The exterior integral metal roof is not modeled because the interior face sheet of the steel structure provides an impermeable boundary condition for moisture transport.

The interior surface boundary conditions are set within WUFI to represent typical conditions. The interior temperature is 68°F to 71.6°F and the relative humidity has a mean value of 50 ±10%. Exterior temperature and relative humidity are specified within WUFI for each climate. Convective thermal boundary conditions were specified at both exterior and interior surfaces. The specified heat transfer coefficients are 3.2 and 1.6 Btu/hr·ft^2·^{o}F, respectively. (These values represent forced convection on the exterior and natural convection on the interior. Results are insensitive to changes in these values over the range that might be expected in the field.) Solar radiation and long wave radiation from the exterior surface to the sky are neglected. Symmetry boundary conditions are set at the edges of the panel. The initial temperature and relative humidity within the panel were set to 68°F and 80%. The material properties required by the model are listed in Table 2.

Figure 7. Hygrothermal Model of Truss Core Panel Assemblies (not to scale) (a) exterior foam panel and (b) interior foam panel.

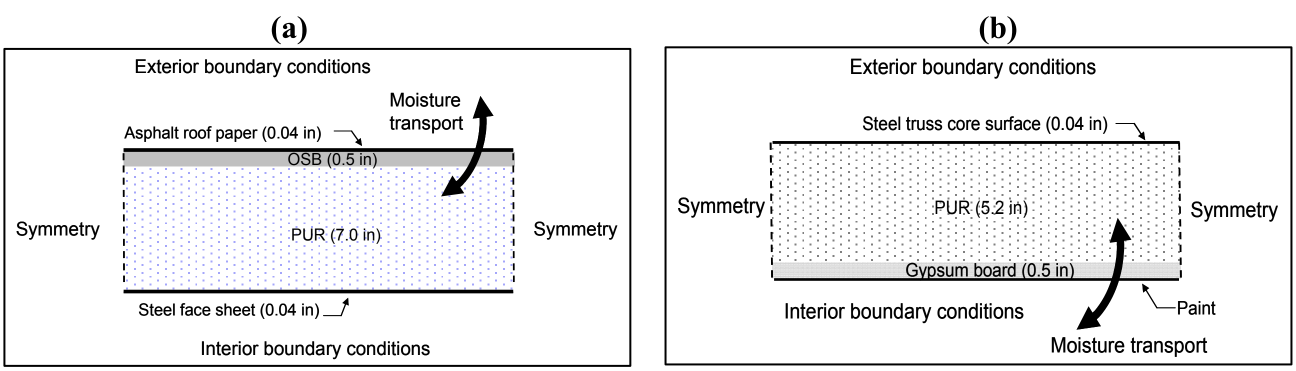


Table 2. Material Properties for Moisture Analysis

	Density [lb_m /ft^3]	Porosity	Specific heat [Btu/lb_m·°F]	Thermal conductivity [Btu/hr·ft·°F]	Water vapor diffusion resistance dry
Asphalt paper	56.75	0.001	358.35	5.78	2014
OSB	40.58	0.95	449.13	0.053	813
Gypsum	39	0.7	207.84	0.092	7
PUR	2.43	0.99	351.18	0.143	88.9
Steel	431.92	0.00001[1]	116.1	23.1	10^6

[1] The steel face sheet is treated as a material with very low porosity to simulate an impermeable boundary.

In International Falls, the exterior foam panel (Figure 7a) has excellent hygrothermal performance. The panel performs well also in the mixed heating and cooling climates of Omaha, Detroit and Salt Lake City and cooling dominated cities of Las Vegas and El-Paso. On the other hand, in Houston, transport of the higher outdoor humidity air in the foam results in unacceptable relative humidity at the PUR/metal interface unless the metal is coated to prevent corrosion. An unprotected metal face sheet will be at risk of corrosion from May to January. The TOW is 6167 hr/year. In addition, relative humidity of the OSB finish exceeds 80% from January to May and in December. If an exterior OSB layer is utilized as shown in Figure 7a, the exterior foam panel is appropriate for geographic locations with monthly average RH less than 80%. It might be possible to use a borate or copper treated OSB or replace the OSB with a vented option for more humid climates. These options are not addressed in the present study.

The interior foam panel provides excellent hygrothermal performance in Los Angeles, San Diego, Phoenix, New Orleans, Tampa and Miami. The only potential problem revealed by the model is the risk of corrosion at the PUR/metal interface in Houston and Las Vegas and by inference in cooler locations. The steel structural component serves as an impenetrable boundary to the exterior. This interface is expected to be near the outdoor temperature. Thus water vapor is cooled as it moves through the gypsum and foam insulation. The RH at the PUR/metal interface exceeds that in the conditioned space during cool periods in both Houston and Las Vegas. For example, in Las Vegas, the TOW at the interface is 1560 hr/yr. In Houston, TOW =850 hr/yr. In Los Angeles, San Diego, Phoenix, New Orleans, Tampa and Miami metal corrosion at the metal/PUR interface is not a concern because winter temperatures are warmer. In climates where corrosion is a concern, the steel must be protected. Condensation at the PUR/metal interface is not an issue in any of the cities mentioned above. However, there are climates (such as International Falls) in which condensation at the interface can occur and an interior foam panel is not appropriate.

Typical Designs for Residential Construction

To illustrate the use of panelized roof construction, panels were designed for a house with a gable style roof with a horizontal span of 20 ft and a 6/12 or 10/12 roof pitch. Two structural component depths were considered, 5.5 in. and 7.25 in. A custom matlab program was created that includes the analytic expressions for the structural performance criteria. The program considers many combinations of panel geometry (i.e., face sheet and web thicknesses, web angle, web spacing, number of webs and panel structural component depth) to determine an optimum panel design. Panel designs reported in Table 3 are optimized for minimum structural component weight. For climate I-6/12 pitch, the lowest weight panel is achieved with a 5.5 in deep structural truss core component; for the other climate and roof pitch combinations, the lowest weight panel is achieved with a 7.25 in deep structural component.

Table 3. Minimum Weight Truss Core Panel Specifications Designed for a 20 ft Horizontal Span (panel width is 8 ft)

Climate and Roof Pitch	Total Panel Depth[1] [in]	Truss Core Structural Component						
		Structure Depth [in]	Structure Weight [psf]	Top sheet thickness [in]	Bottom sheet thickness [in]	Number of V Channels	Web thickness [in]	Web angle θ [°]
I-6/12	10.7	5.5	4.72	0.043	0.034	5	0.043	75
I-10/12	12.4	7.25	5.26	0.038	0.034	5	0.050	80
II-6/12	12.4	7.25	5.45	0.044	0.034	4	0.059	85
II-10/12	12.4	7.25	6.18	0.054	0.036	5	0.054	80
III-6/12	14.2	7.25	6.50	0.045	0.035	6	0.060	85
III-10/12	14.2	7.25	7.75	0.075	0.034	6	0.060	75

[1] Total panel depth includes PUR insulation required to achieve R-30 (climate I) or R-40 (climates II and III)

Architectural Details

The joint details for two different applications of the panel system were developed. These applications are:

1. a steep slope attic with storage/living space (10/12 pitch) that utilizes an exterior foam panel with a nailbase panel finish layer for field application of traditional roof finish layers (Figure 8, with details in Figures 9-12); and
2. a shallow slope roof with cathedralized ceiling (6/12 pitch) that utilizes an interior foam panel with an integral metal roof surface (Figure 13, with details in Figures 14-17).

For each application, the panel-to-panel joints, ridge joints and soffit joints are shown. The basic principles used in all details are as follows: (i) create overlapping layers to ensure drainage of rainwater, (ii) design panels and joints to be easy to assemble in the field with a minimum number of parts, (iii) provide a continuous moisture barrier on the interior of the assembly in the exterior foam panel and on the exterior of the assembly in the interior foam panel, and (iv) minimize thermal bridging

Specific joint designs depend on panel loads, span length and panel face sheet thicknesses. The joint designs shown here are applicable to either a 11.8 ft (short) or 20 ft (long) horizontal span for either climate II or climate III. There is a beam that extends the full length of the ridge and is supported at the ends and at intermediate locations as necessary. Beam size will depend on the frequency of supports. The span length and load reflect the maximum loads at the particular joint under consideration. This conservative structural analysis approach ensures that the joint details are adequate for all climates and spans.

Figure 8. House Section for Steeply Sloping Roof with Conditioned Attic

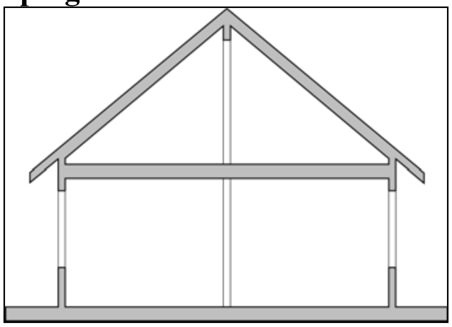


Figure 9. Panel to Panel Joint Detail – Exterior Foam Panel

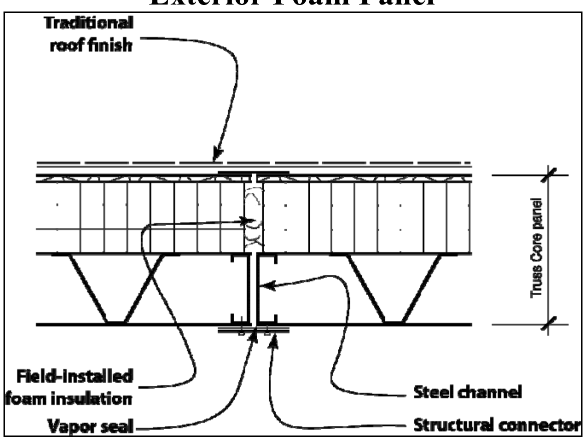


Figure 10. Gable End Wall Detail – Exterior Foam Panel

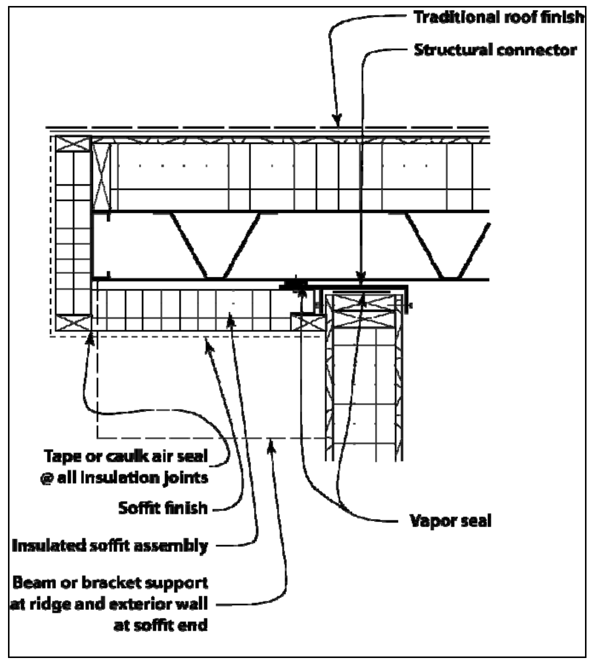


Figure 11. Ridge Detail – Exterior Foam Panel

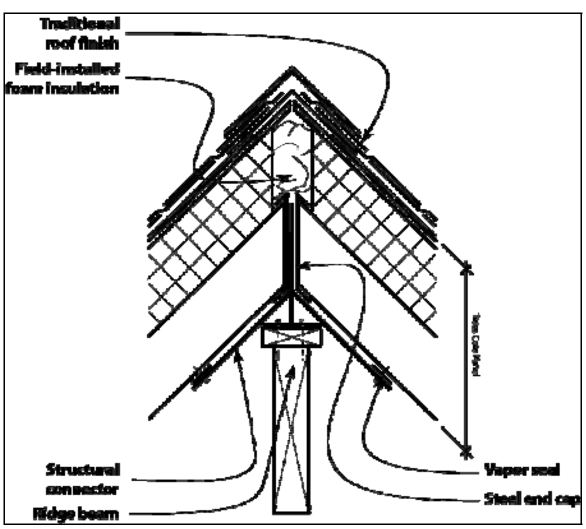


Figure 12. Soffit Detail – Exterior Foam Panel

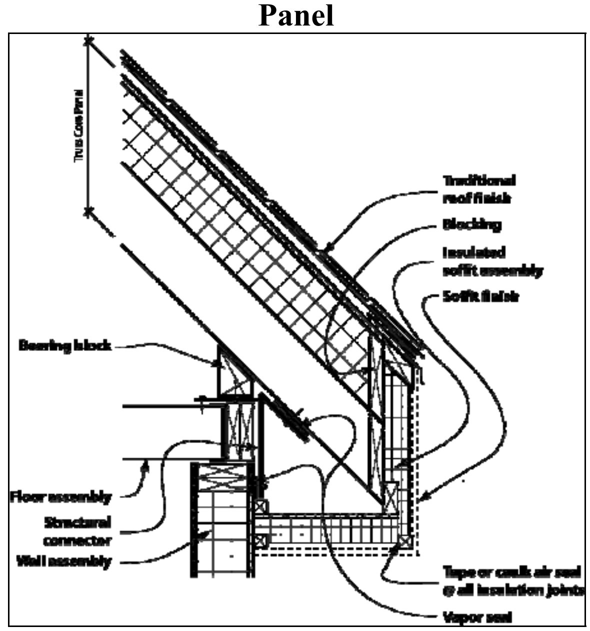


Figure 13. House Section for Low Sloping Roof with Cathedral Ceiling

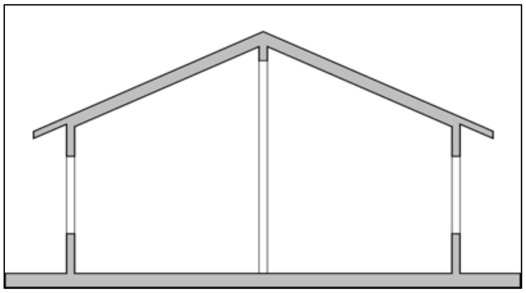


Figure 14. Panel to Panel Joint Detail – Interior Foam Panel

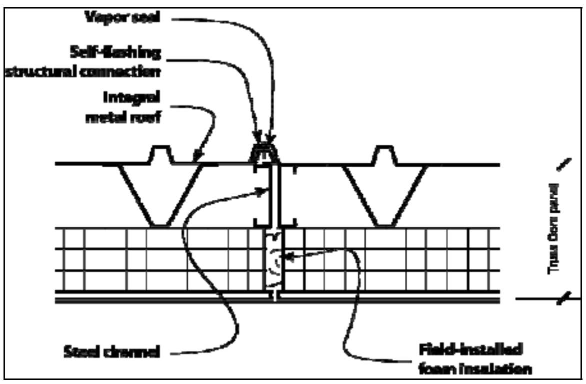


Figure 15. Gable End Wall Detail - Interior Foam Panel

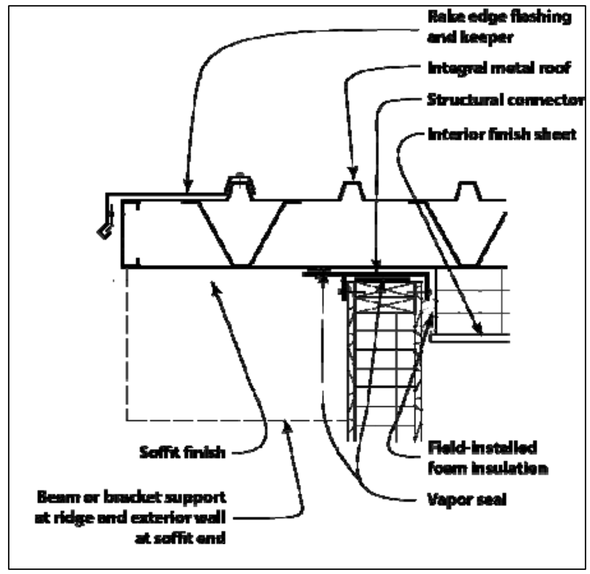


Figure 16. Ridge Detail - Interior Foam Panel

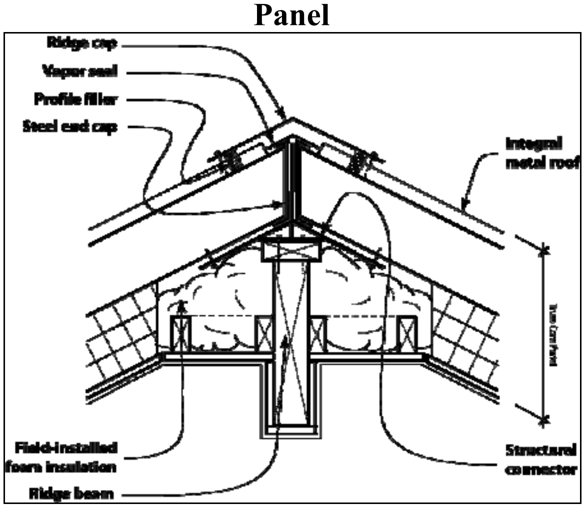
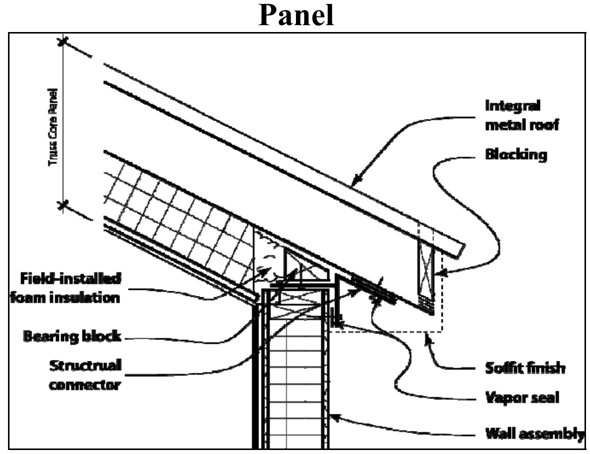


Figure 17. Soffit Detail – Interior Foam Panel



Panel-to-Panel Joints

The panel-to-panel joint running parallel to the V-shaped web within the truss core panel must transfer all loads between adjacent panels. In the structural analysis, wind and live loads, concentrated loads and in plane wind shearing loads are considered. In the panel to panel joint for exterior foam panels (Figure 9), the structural connection between panels is made with a continuous 3 in. wide 20 ga. steel plate. This plate is fastened to the panel edges with #10 sheet metal screws spaced 24 in on center. This connection takes place on the bottom side of the panel, where it also serves to support a self-adhesive membrane vapor seal tape. For the interior foam panel (Figure 14), the structural connection is made on the top surface of the panel by use of a lapped, self-flashing joint. This joint is fastened with #10 sheet metal screws with integral neoprene or rubber washers, spaced 24 in. on center. A layer of double-faced butyl sealing tape is placed between the lapped metal layers of the joint as a vapor seal and as a second layer of protection against water intrusion at the fastener penetration. The field installed insulation foam can be either a one or two part PUR.

Gable End Wall Joints

The gable end wall is structurally fastened to the roof panel by the use of a continuous, 14 ga. welded sheet steel connector. Continuous support of the panel is provided by beam or bracket supports at the ridge, and in plane with the exterior wall on the soffit end of the panel. Vapor sealing is accomplished with double-faced butyl tape applied to the top plate of the wall assembly, and to the top of the structural connector.

Gable end wall joint design for the exterior foam panel (Figure 10) requires the use of rigid foam insulation and blocking to wrap the fascia and soffit faces of the panel to avoid thermal bridging. This insulation layer must be made airtight with air-sealing tape or other means to avoid air infiltration into the assembly. Blocking may be provided as needed for attachment of finish materials. The beam or bracket supports are potential locations thermal bridges or air infiltration, and must be constructed of low thermal conductivity materials and detailed carefully to avoid these issues. Gable end wall joint design for the interior foam panel (Figure 15) uses field-applied PUR to ensure insulation continuity at the joint. This insulation may be applied after panel insulation by means of holes drilled into the joint cavity from below. If continuous beams are used to support the panel, they must be made of low thermal conductivity materials to avoid thermal bridging. Finish materials may be applied directly to the panel, or to blocking, as required.

Ridge Joints

The ridge joint is made structurally sound by the use of a continuous, 14 ga. welded sheet steel connector. This connector is fastened to a continuous ridge beam with #8 x 1.5 in. wood screws spaced 24 in. on center, staggered. The panels are fastened to the connector with #12 self-tapping sheet metal screws spaced 12 in. on center. Steel C-channel end caps are welded to the ends of the structural component of the truss core panel to provide reinforcement and to allow flexibility in locating air and vapor seals.

Ridge joint design for the exterior foam panel (Figure 11) employs field-applied foam insulation to ensure insulation continuity between panels on opposite sides of the ridge. Vapor sealing is accommodated on the structural connector. Ridge joint design for the interior foam panel (Figure 16) requires field-applied PUR insulation on the interior of the assembly, in plane with the panel insulation. Blocking must be included at the ridge to allow attachment of fireproofing and finish materials, as required. The ridge beam is a potential thermal bridge in this design, so should be constructed of wood or other low-thermal conductivity material. Vapor sealing is accomplished on the exterior side of the assembly. Figure 16 shows a vented option, where air is allowed out of the assembly at the ridge through openings created by cutting back the peaks of the metal corrugations. These openings are covered by a sheet metal ridge cap, and venting is ensured by use of an air-permeable profile filler under the edges of this cap.

Soffit Joints

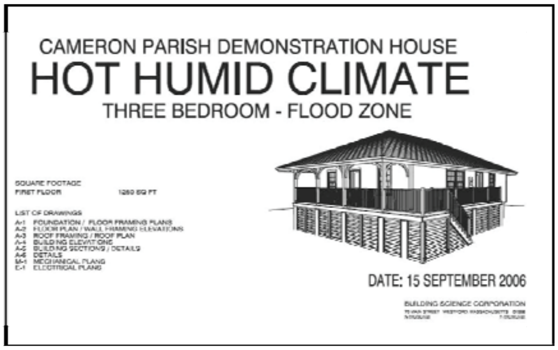
The soffit connection allows the panel to cantilever beyond the face of the exterior wall of the building. This configuration allows maximum architectural flexibility, and facilitates quick field assembly. A welded 14 ga. sheet metal connector was designed. In conjunction with a continuous beveled bearing block, this connector serves to support the loads imposed by gravity, uplift forces imposed by wind, and any residual thrust forces encountered at the soffit location. The panel is fastened to the connector with #10 self-tapping sheet metal screws spaced 24 in. on center along the length of the connector.

For the exterior foam panel (Figure 12), the crucial concern at the soffit is ensuring the continuity of the insulation layer to avoid thermal bridging through the structural component of the truss core panel. To accommodate fastening of this layer, blocking is installed in the ends of the panels. Additional blocking for finish materials and rigid insulation may then be applied as needed. Air and vapor seals are located on the structural connector. Insulation placed to the outside of these seals should be sized appropriately for the climate. This insulation layer must be made airtight with air-sealing tape or other means to avoid air infiltration into the assembly. The soffit design for interior foam panel (Figure 17) is substantially simpler, due to the interior location of the roof insulation layer. As with the exterior foam panel design, air and vapor seals are located on the structural connector. Blocking is again employed to provide fastening surfaces for finish materials. Figure 17 shows a vented option, with perforated blocking used at this location. This accommodation for venting must be designed to drain condensation that may form under some climatic conditions. Continuity of the insulation layer is ensured by use of field-applied foam at the wall / roof joint, as shown. This insulation may be installed through holes drilled into the cavity from below.

Application

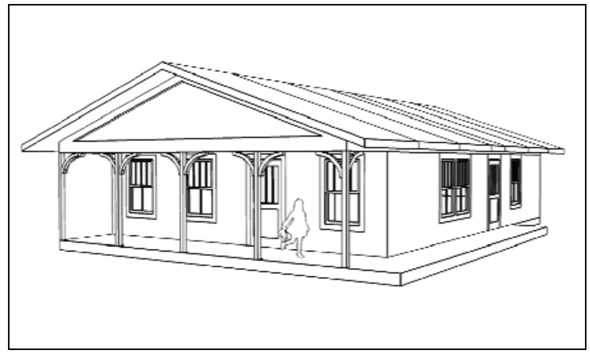
An ongoing effort is aimed at testing the applicability of the truss core panel to actual house designs. A series of affordable, high efficiency case study house designs form the baseline for these tests (Lstiburek and Straube, 2008). Examples of houses designed for cold climates (Pontiac, Michigan) and hot humid climates (Cameron Parish, Louisiana) are currently under study. The Cameron Parish example is shown in Figure 18. The footprint of the enclosed space of this house is 1260 ft^2, and the front porch is 180 ft^2. The roof will require 12 panels, 8 ft wide by approximately 18 ft long, and two panels 4 ft wide by approximately 18 ft long.

Figure 18. Habitat Congress House Design



BSC©Building Science Consulting. Reprinted with Permission. (Lstiburek and Straube, 2008)

Figure 19. Modified Habitat Congress House Design



Some basic modifications to the baseline designs are necessary to accommodate the panels. The hip roof indicated for the original design is not compatible with the panel system. The original plan was developed for roof trusses that span from exterior wall to exterior wall. The truss core panel system requires the use of a ridge beam that needs intermediate support along its length. For a hip roof, a support would have been needed directly below, or adjacent to, the joint between hip ridge segments and the main ridge of the house. Addition of this support would have required extensive redesign of the house. A gable roof is substituted to eliminate these conflicts (Figure 19).

To accommodate support of the ridge beam at the front of the house, the number of structural bays expressed by the porch columns is increased from three to four. This change allows the location of a column directly beneath the ridge beam. The front door of the house is likewise shifted away from the centerline of the façade, and an additional window is included to maintain the visual consistency of the four-bay structure. This simple house design utilizes the panel-to-panel, gable end, ridge and soffit details shown in Figures 13-17.

Conclusions

The insulated truss core panelized roof system described in this paper was conceived to provide several benefits compared to conventional residential construction. Panels are designed to be manufactured off site. Each panel is composed of a steel structural member and an insulating layer of foam polyurethane, which self adheres to the steel during manufacture. In some cases, the steel panel can serve as the finished roof. The panels are self-supporting over relatively long spans without intermediate support except for a ridge beam. As demonstrated in prior studies, energy is saved by placing the insulation at the roof plane when HVAC ducts are located in the conditioned attic. In addition, the insulated panel reduces thermal bridges and air leakage compared to placing insulation in between trusses or rafters in cathedral ceilings. The steel component of the panel is a vapor barrier. Results of a model of moisture transport in the panel for a number of U.S. cities show that hydrothermal performance is sensitive to the location of the foam layer relative to the vapor barrier. The only prevalent problem is the potential for corrosion of unprotected steel at the PUR/steel interface. This problem occurs in panels with exterior foam when outdoor humidity levels are high. It occurs in panels with interior foam when outdoor temperatures are low. The concern can be addressed in both cases by coating the metal surface. The other moisture concern is the potential for decay of OSB if it is used as an exterior finish for roofs with shingles. In the future we will investigate venting of the OSB or alternate materials.

The panelized roof system makes the most economic sense when applied in two situations: (1) a house with an open cathedral ceiling and no attic, or (2) a house with livable space in a finished attic. An unfinished attic is less economical because of the need for both roof panels and attic floor system without the benefit of additional livable space. The panel system can be applied to a wide range of house designs but it will be easiest to install on houses with relatively simple forms. Roof forms without valleys take advantage of the material savings from an integral roof finish. The roof system can be applied to an otherwise conventionally-built house. However, the greatest construction and economic efficiency as well as the best architectural design may be realized with a complete system of panelized roofs and walls with a modular supporting structure.

Acknowledgements

This paper was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-04NT42114. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the views of the DOE.

References

[AISI] American Iron and Steel Institute. 2001a. North American Specification for Design of Cold-Formed Steel Structural Members, 2001 Edition.

[AISI] American Iron and Steel Institute. 2001b. Commentary on North American Specification for Design of Cold-Formed Steel Structural Members, 2001 Edition.

[AISI] American Iron and Steel Institute, AISI Manual Cold Formed Steel Design, 2002 Edition.

[ASHRAE] American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2005. Thermal and Moisture Control in Insulated Assemblies-Fundamentals, Chapter 23. Atlanta, GA: ASHRAE

Davidson, J. H., Mantell, S. C., Briscoe, C., Schoenbauer, B., Huang, D., and J. Carmody. 2007. "Options for an Energy Efficient Panelized Residential Roof" In *Solar 2007, Proceedings of the 36th ASES Annual Conference*. Boulder, CO: American Solar Energy Society.

Davies, J.M. 1994. "Core Materials for Sandwich Cladding Panels" In *International Conference on Building Envelope Systems and Technology*, pp. 299–306, Singapore.

Desjarlais, A. O., T. W. Petrie, and T. Stovall. 2004. "Comparison of Cathedralized Attics to Conventional Attics: Where and When do Cathedralized Attics Save Energy and Operating Costs?" In *Performance of Exterior Envelopes of Whole Buildings IX International Conference*. Atlanta, GA: ASHRAE.

Hendron, R., S. Farrar-Nagy, R. Anderson, P. Reeves, and E. Hancock. 2004. "Thermal Performance of Unvented Attics in Hot-Dry Climates: Results from Building America" *ASME Journal of Solar Energy Engineering*, **126**, pp. 732-737.

[ICC] International Code Council. 2003a. *2003 International Residential Code for One- and Two-Family Dwellings*. International Code Council, Country Club Hills, IL.

[ICC] International Code Council, 2003b, *2003 International Energy Conservation Code, International Code Council*. International Code Council, Country Club Hills, IL.

[ISO] International Organization for Standardization. 1992a. *ISO 9223 Corrosion of Metals and Alloys -- Corrosivity of Atmospheres Classification.* Geneva, Switzerland: ISO.

[ISO] International Organization for Standardization. 1992b. *ISO 9224 Corrosion of metals and alloys -- Corrosivity of Atmospheres Guiding values for the Corrosivity Categories.* Geneva, Switzerland: ISO.

[ISO] International Organization for Standardization. 2002. *ISO 11303 Corrosion of Metals and Alloys -- Guidelines for Selection of Protection Methods Against Atmospheric Corrosion.* Geneva, Switzerland: ISO.

Künzel, H., M. Holm, A. Zirkelbach, D. and Karagiozis A.N. 2005. "Simulation of Indoor Temperature and Humidity Conditions Including Hygrothermal Interactions with the Building Envelope" *Solar Energy*, **78**, pp. 554-561.

Lstiburek, J. and J. Straube. 2008. "BSP-032: Designs that Work: Hot-Humid Climate (New Orleans, LA)," *www. buildingscience.com*.

Narine, S. S., Kong, X., Bouzidi, L., and P. Sporns. 2007. "Physical Properties of Polyurethanes Produced from Polyols from Seed Oils: II. Foams" *Journal of the American Oil Chemists' Society*, 84, pp. 65–72.

Rudd, A. 2005. "Field Performance of Unvented Cathedralized (UC) attics in the USA" *Journal of Building Physics*, 29(2):145–169.

Timoshenko, S. P. and J. M. Gere. 1961. *Theory of Elastic Stability*. New York, McGraw-Hill.

WUFI 2D-3.0, Institute of Building Physics. 2005. Oberlaindern Germany.