THE MODELED AND MEASURED PERFORMANCE OF THICK CONTINUOUS INSULATION (CI) UNDER HEAVY CLADDING SYSTEMS

BY GARY PARSONS, JEFF HANSBRO, MIKE LAPHAM, MICHAEL MAZOR, PRASHANT SHEMBEKAR, AND MYRON MAURER

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INTRODUCTION

Several initiatives have been set in motion to help the building community improve energy use and environmental performance. Energy consumption and greenhouse gas (GHG) emissions from buildings account for 50% of U.S. totals for both categories.[1] The well-publicized Architecture 2030 Challenge of reducing building sector energy consumption to "carbon neutral" by the year 2030 has been adopted by the American Institute of Architects (AIA), U.S. Conference of Mayors, and many other professional and industry organizations across the nation.[2] Legislation now before Congress pertaining to 2010 building codes will likely mandate a 30% reduction in energy consumption standards, using the baseline of ASHRAE 90.1-2004 (American Society of Heating, Refrigeration and Air-Conditioning Engineers) and 2006 IECC (International Energy Conservation Code.)

THE CODES

Continuous foam insulation, referred to as "ci," is currently prescriptively required on above-grade steel frame walls in climate zones 2 through 8 in both the ASHRAE 90.1-2007 and 2009 IECC standards. The Prescriptive Building Envelope Option is outlined in Section 5.5 of ASHRAE 90.1-2007 and is commonly referred to as the "cookbook" method in which the required R-value or U-factor is listed in tables based on the climate zone in which the structure will be built.

When installed on the exterior of steel frame walls, ci significantly reduces the energy loss that would occur through wall assemblies with insulation only in the cavity, a design that exposes steel studs to thermal bridging. The magnitude of this effect for a wide variety of walls can be calculated using such tools as the ORNL Modified Zone Method Calculator[3] of the Oak Ridge National Laboratory. Installing the correct amount of ci outboard of the steel studs, in combination with eliminating batt insulation from the stud cavity, keeps the stud cavity at the same temperature and humidity as the interior space, thus reducing the potential for condensation to occur within the wall assembly. Thermodynamics, physics, and energy reduction targets all point to thicker ci as the right solution, but how does one use it and meet relevant installation and code requirements as well?

THE CHALLENGE

The IBC (International Building Code), Chapter 14 (Exterior Walls), requires that the cladding of the wall assembly be connected directly to the framing on a regular grid. Traditionally, this is accomplished by removing small sections of continuous exterior insulation to attach the fastening system directly to the steel framing. This method disrupts the ci's continuity, reducing the expected energy efficiency of the wall assembly. The preferred mechanism would attach the veneer over the ci with minimal through-foam fastener penetration. This method, however, relies on the physical properties of the ci to ensure the long-term durability and attachment of the cladding system.

The challenge in the industry is how structurally to attach various claddings over continuous insulations of any thickness and still manage to minimize the thermal shorts through the wall assembly to maintain a continuous insulation. This challenge becomes greater as the building industry increases the thickness of the continuous insulation in order to comply with the prescriptive R-Value requirements of the energy codes. The consensus committees charged with making energy codes more stringent have recently agreed to set the increased ci values in the prescriptive table to correspond to a maximum ci thickness of 3 in; however, uncertainty remains on which attachment mechanisms should be used over continuous insulation.

This paper focuses on research and modeling conducted to evaluate the performance of various thicknesses of a proprietary polyisocyanurate foam insulation when installed directly outboard of steel frame walls and clad with a three-coat stucco veneer. Finite element analysis was used to model the gravity-loading effect of a three-coat stucco veneer attached through a layer of ci into steel stud framing. In parallel, model validation was completed by conducting laboratory load testing of small-scale wall assembly mock-up samples. Property characterization of the polyisocyanurate continuous insulation layer is also discussed.

EXPERIMENTAL

FINITE ELEMENT ANALYSIS MODEL OF A PROPRIETARY CI COMPOSITE WALL ASSEMBLY

A finite element analysis (FEA) model of a proprietary ci composite wall assembly was constructed to perform nonlinear, transient, dynamic simulations using an LS-DYNA® software package. During a building's lifetime, walls are subject to various types of loading such as gravity, wind, seismic, etc. The steel stud frame serves as the primary load-bearing member in the wall, whereas exterior-applied loads are transferred to the steel stud frame through mechanical screw connections.

This report describes a computational model of a small but critical representative section of a steel stud/ci/washer/screw system. The critical representative section consists of a rigidly held steel stud with a continuous layer held by two adjacent screws on the same stud (spacing of which was chosen by common practice). The gravity load of three-coat stucco cladding was modeled by applying the appropriate proportional load to one screw computational for the model and through a load frame for the test fixture. The details of the section were chosen to enable close comparison between the model and laboratory scale tests.

Thus, proper modeling of a screw connection is one of the most important aspects of a robust FEA model. The sections that follow will detail the methodology that was developed and implemented to analyze the effect of a thick (1-in to 4.25-in) proprietary polyisocyanurate foam insulation on the structural performance of a composite wall system subjected to gravitational loading.

FEA MODELING OF MECHANICAL FASTENERS

Several types of screws can be used in the installation of a composite wall system. The load-bearing capacity of any screw depends on several parameters, including diameter, length, thread type, material yield strength, gauge of metal, etc. A complete three-dimensional (3-D) FEA model of a mechanical fastener was constructed using solid elements to represent the screw, washer, and steel stud plates, in which the screw was subject to shear (lateral bending) and tensile pull forces.[4,5]

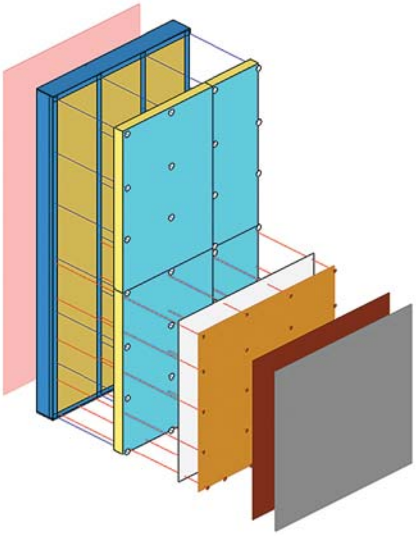

Figure 1 – Test setup and FEA model of screw-bending test.

Surface-to-surface contact of the screw

to sheet metal was modeled within LS-DYNA. *Figure 2* illustrates an experimental test setup and representative FEA model of a screw bend test to determine the force-deformation (F-d) response for different screws. Force-deformation refers to the movement of the fastener resulting from the application of load.

Experimental test results were then used to validate the 3-D FEA simulation results of each self-tapping steel fastener, ranging from #6 x 1-5/8 in to #10 x 5 in, as required for each wall system assembly. The experimental F-d response was then used as the input for the screw material model in LS-DYNA. *Figure 3* illustrates the one-dimensional beam model and the resulting experimental test results used as the input for the material model.

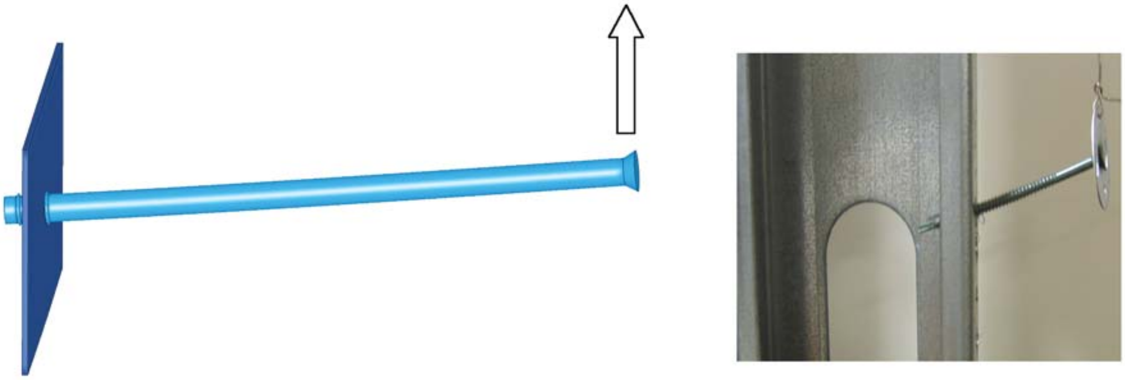

Figure 2 – Test setup and FEA model of screw-bending test.

LABORATORY EVALUATION OF WALL SYSTEM ASSEMBLIES

Laboratory validation of the predictive model was conducted by using a tensile test load frame. The load frame applies a known force to the wall section sample while also measuring the resulting sample deflection or deformation.

Experimental testing of wall system components was conducted using an Instron 5585H load frame with a reversible 5kN load cell. The load cell was pulled at a constant rate of 0.2 in/min to a pull distance of 0.75 in. An adjustable fixture was fabricated to enable various wall components and assemblies to be tested. It permitted precise control of the direction of the applied force. Data were collected using Instron Bluehill version 2.6.44 software at an acquisition rate of 50 microseconds.

TESTING PROCEDURE FOR FORCE-DEFORMATION RESPONSE OF FASTENER WITHOUT FOAM OR CLADDING

A series of tensile tests was completed using only fasteners and steel studs to provide validation data for the screw connection model. Self-tapping steel fasteners, ranging from #6 x 1-5/8 in to #10 x 5 in, were selected for fastener performance testing. Each fastener was drilled into an 18-gauge steel stud anchored to the stationary

Photo 1 – Fasteners in deflection.

Photo 2 – Test setup of fastener with foam.

test fixture. The fastener was screwed into the stud until the head of the fastener was at a distance from the stud equal to the thickness of the foam that would normally be attached with the specific fastener model (*Photo 1*). A companion washer was also placed on the screw prior to stud attachment and provided a convenient anchor point for tensile load cell attachment.

A wire cable was then attached from the tensile test frame load cell to the end of the fastener, and tension was applied while collecting force-deformation information. Five replicate tests were performed for each fastener length.

TESTING PROCEDURE FOR FORCE-DEFORMATION RESPONSE OF FASTENER WITH FOAM INCLUDED

A complete component assembly tensile test was performed in the same manner as the fastener test except that the foam layer was placed against the steel stud prior to fastener attachment (*Photo 2*). The wall section samples consisted of a 20-in-long steel stud, various thicknesses of insulating foam sheathing (1.0 in to 4.25 in), and the appropriate-length fastener for each foam thickness tested. Foam samples were 23-in-long by 6-in-wide strips. All samples were allowed to condition to 73°F

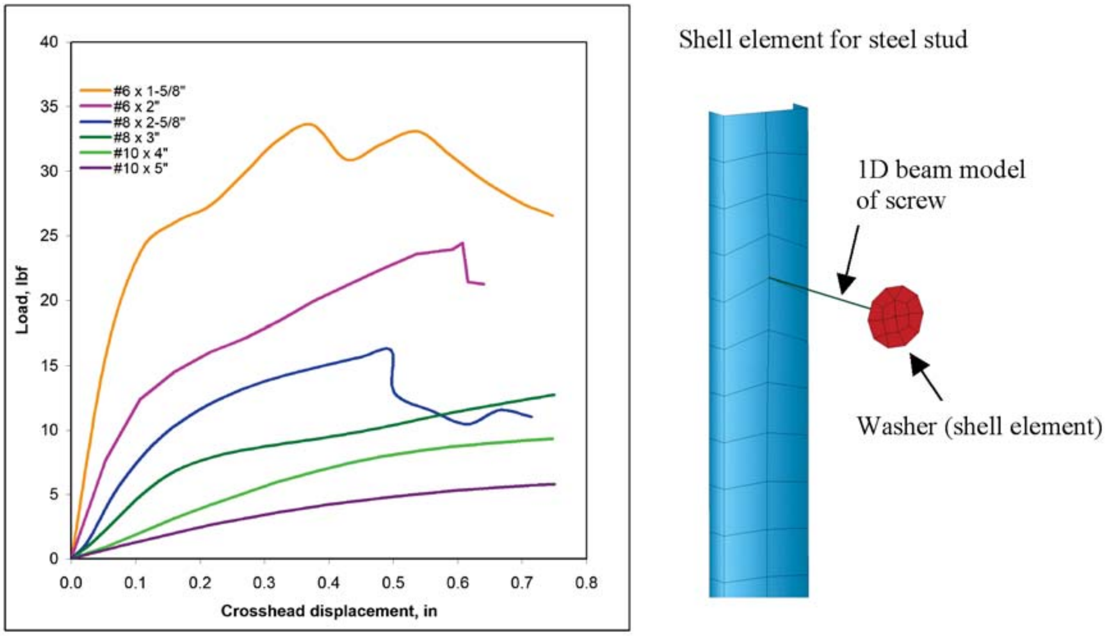

Figure 3 – One-dimensional beam model and test data used for input.

and 50% humidity for 48 hours prior to testing.

The stud length allowed use of two screws 16 in on center. If a single fastener were used, then there would be a tendency for the foam to pull away from the steel stud due to the moment force caused by applying force only to the fastener head. The "two-fastener" approach directs the load along the exterior plane of the foam, which more closely represents the load situation of an actual wall assembly.

It was assumed that the worst-case scenario would occur if the load were applied directly to the washer, which is next to the fastener head. The basis for this assumption is that the stucco layer is essentially a monolithic adhered coating, which will act to spread the weight of the stucco façade across the entire foam face. Application of the test load directly to the fastener ignores any load-spreading contribution of the stucco layer. Once attached, the wire cable was pretensioned with 0.5 lbs of force to improve reproducibility.

MATERIAL CHARACTERIZATION OF POLYISOCYANURATE (PIR) FOAM

The ci samples selected for this test were comprised of proprietary PIR foam covered with very thin metal facings. Because the facings do not contribute significantly to structural performance, they were not included in the testing model. The stress/strain data obtained from compression testing was used in the foam material model. All quasistatic compression testing was performed in accordance with ASTM D1621.[6]

Tests were performed using a materials test system (MTS) equipped with a 4,000-lbf (pound-force) load card and a 5.0-in displacement card. Test specimens were prepared by removing the metal facing from the foam by hand and by cutting 4.5-in-sq samples with a band saw. Specimen dimensions were measured using an Ono Sokki GS-503 linear gauge sensor. As PIR foam is anisotropic (physical properties are directionally dependent), three replicate tests were performed, each with the thickness aligned in the axial [i.e., length (X)], transverse [i.e., horizontal or width (Z)], and thickness [i.e., vertical or rise (Y)] directions respectively. Tests were performed with a programmed crosshead velocity of 0.45 in/min, and transient force and displacement data were recorded at a sampling rate of 10 Hz. *Figure 4* shows the compressive stress/strain input data used for transient

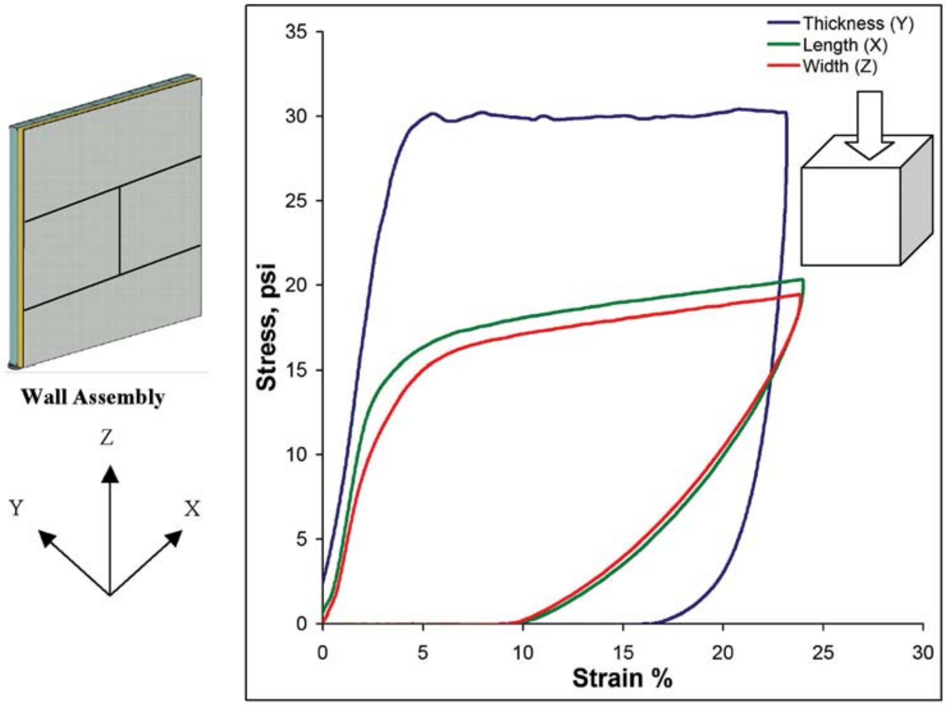

Figure 4 – Compression testing of PIR foam.

analysis. PIR foam exhibited the highest compressive strength in thickness direction of the board. LS-DYNA material model type 57 was used to model the highly compressible, low density PIR foam. Moreover, material model type 57 was based upon isotropic material behavior, and any effect of directional dependency required analysis by changing the input stress/strain data.

FEA CORRELATION VS. QUASISTATIC EXPERIMENTAL PULL TEST ON FASTENER EMBEDDED IN PIR FOAM

To understand the load-bearing contribution from the PIR foam and an adjacent fastener, an experimental bend test was devised. The test setup and corresponding FEA model setup are shown in *Figure 5*. One fastener is loaded in this testing. FEA modeling of the test setup is shown along with the correlation of force-deformation response. The 3-D FEA model provides detailed information about the sequence of failure of the individual components during the test. This could provide practical information, such as expected deformation of wall systems that include thick foam.

PIR foam compression at the upper screw location led to foam rotation. This subjects the lower screw to tension, thereby enhancing the bending resistance of the system. As seen in *Figure 6*, compared to the "only screw" (#10 x 5-in) case, the PIR foam connection (#10 x 5-in connection) provided higher strength due to this phenomenon. It was also observed that the connection strength was higher for greater-thickness PIR foam. This is due to the leverage effect of the longer screw.

The following section shows the test and FEA model correlation for three different thicknesses of PIR foam: 1.0 in, 3.0 in and 4.25 in. The material input parameters to these connection models consisted of the force-deformation response of #6 x 2-in, #10 x 4-in, and #10 x 5-in screws, respectively, for 1-D beam models and PIR foam property in the thickness direction of the board. The advantage of using a 1-D beam model for the screw was that the number of parameters causing variability was reduced substantially. For example, the effect of steel stud yield strength was no longer required since the force-deformation response of the screw had this effect incorporated therein. The validation of the 1-D beam model was obtained by comparing the output (FE result) with the input (experimental) force-deformation response. *Figure 7* shows the validation for #6 x 2-in, #10 x 4-in, and #10 x 5-in screws. The exact correlation is not surprising, as the beam model simply responds the same way as the input data under identical loading conditions.

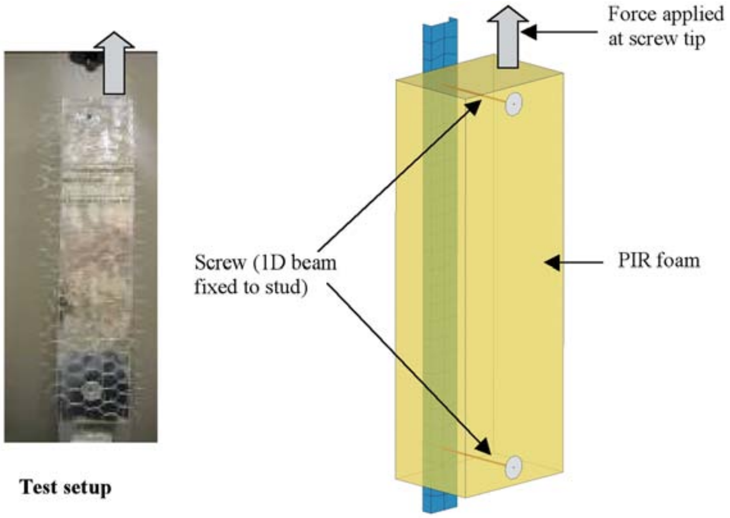

Figure 5 – Fastener test with PIR foam.

The connection model had several sources of variability, both in experimental test setup and FEA modeling. Some

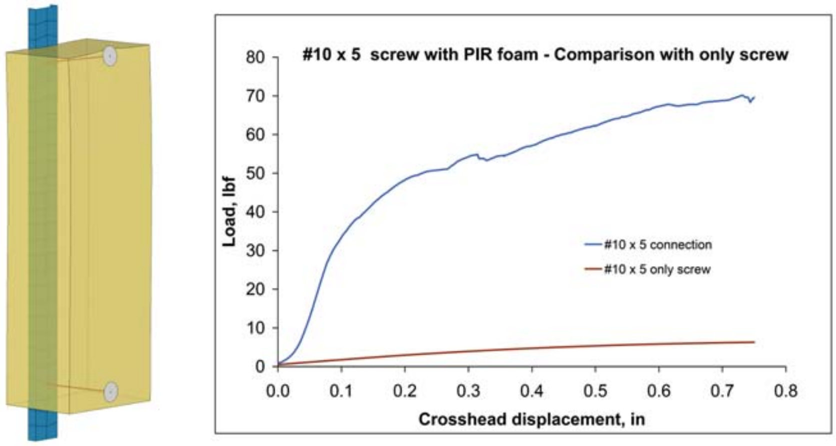

Figure 6 – Fastener test comparison.

of the major parameters and corresponding FEA model assumptions that could affect these results are

- PIR foam property. (Property in thickness direction is considered in analysis.)
- Screw spacing (16 in).
- PIR foam width (6 in).
- Metal lath tension. (Test was done without stucco; hence, no contribution of metal lath was considered in the analysis.)

Screw tightening resulting in contact of washer with foam is represented by tied surface-to-surface contact in LS-DYNA for upper and lower screw washers. The tied surface contact definition depicts the washer contact with foam due to initial tightening pressure as well as screw bending. The static friction coefficient of 0.5 and dynamic friction coefficient of 0.1 are considered in the analysis.

Figure 8 shows that the FEA model exhibited satisfactory correlation versus experimental test results for screw connections with PIR foam. The washer played an important role in load transfer and distribution. The foam compression in the thickness direction of the board was the governing property for this increase in connection strength.

Figure 8 indicates that the greater the thickness of foam, the higher the connection strength. *Figure 8* shows foam deformation in the connection test. The material's internal energy, or potential energy associated with deformation of material, indicates the load-bearing contribution of the members. It can be seen that the internal energy of PIR foam was much higher than even the upper screw that was loaded directly. Thus, the major load-bearing contribution in a connection test comes from PIR foam. This is an important experimental observation validated by FEA results that can form the basis of screw-pitch decisions for load bearing of exterior cladding such as stucco.

CONCLUSIONS AND FUTURE WORK

The industry has a great deal of experience using 1.5 in of ci under three-coat stucco and is comfortable doing so. In response to the need for superior energy performance, the thickness of ci is increasing beyond 1.5 in. This study analyzes the effect thicker foams have on fastener performance when using heavy cladding.

In the models tested, the lath was screwed through ci foam (1.0 in to 4.25 in) and into the metal studs. Thermal bridging

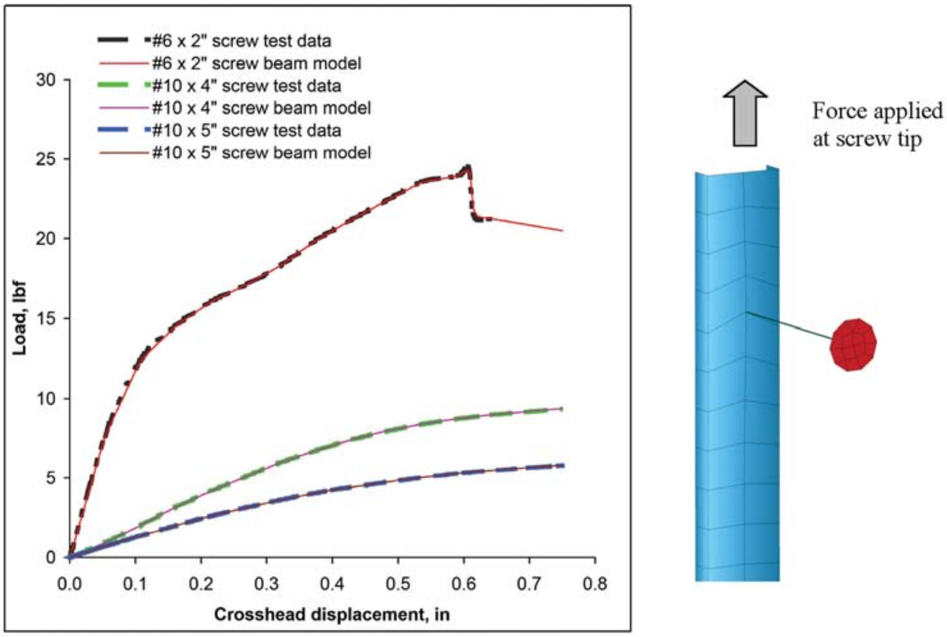

Figure 7 – Screw beam model validation.

of the foam was present only through the thin metal screws. This report describes a computational model of a small but critical representative section of a steel stud/ci/washer/screw system. The details of the section were chosen to enable close comparison between the model and laboratory scale tests. In both cases, the load deflection performances of various thicknesses of ci foam and fasteners were tested. The model results are bounded by the range of experimental results for all foam thicknesses. Good agreement between model and physical test results give confidence in using finite element modeling tools and parameterization methods. The work described above in larger 3-D wall sections (including stucco cladding) is under way (*Figure 10*).

The small section results described in this paper yield critical information on the mechanisms active in steel stud/ci/washer/cladding fastener composite systems. A stucco layer is estimated to contribute about 10 lbs per sq ft of force to the surface of the ci and fasteners due to gravity. If we assume that there are between 1 and 2 sq ft of stucco per fastener, the results of the testing and modeling indicate that the head of the fastener deflects approximately 0.1 in down for the 1.0-in, 3.0-in, and 4.25-in ci composite systems.

The energy analysis of the model indicates that the internal energy of the foam is the major contributor in the composite sys-

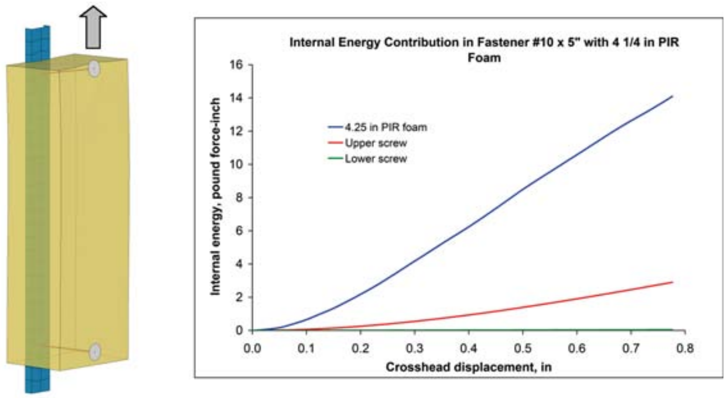

Figure 9 – Foam contribution in connection strength.

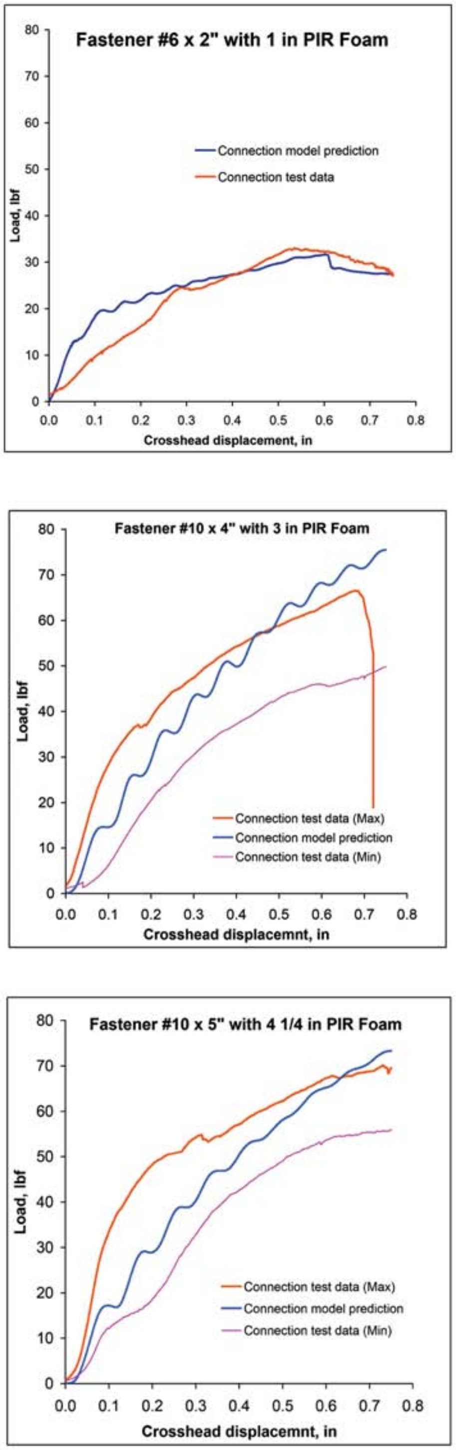

Figure 8 – Comparison of connection strength prediction with test data.

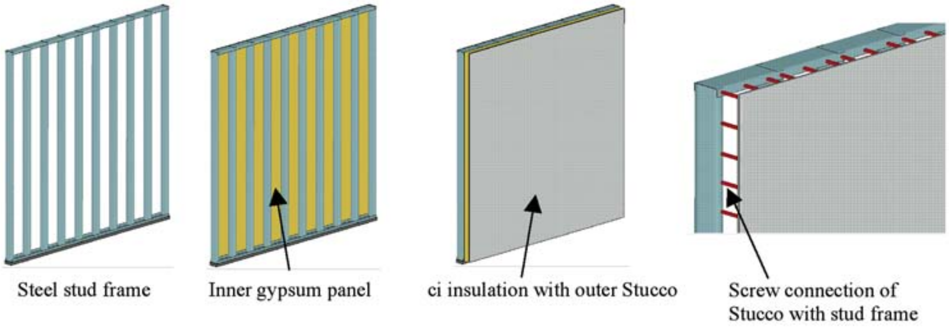

Figure 10 – A large 3-D ci wall assembly model with stucco.

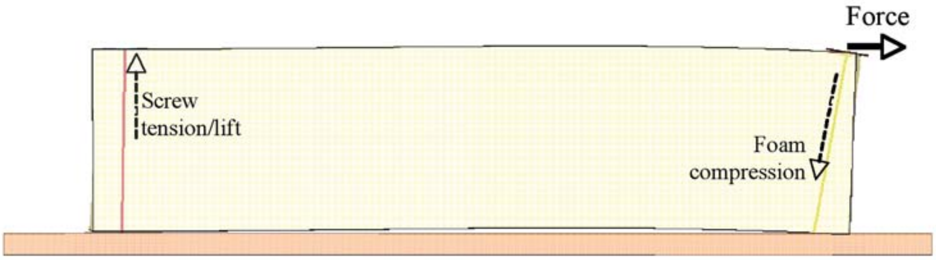

Figure 11 – Complex reaction of ci wall system to load.

tem (*Figure 9*). Graphic representation of the model indicates the influence of the load, the stud, and adjacent screw results in the foam simultaneously undergoing compression, tension, and bending in two dimensions (2-D). See *Figure 11*. The 2-D load transfer compensates for the increased moment arm of the longer screw.

In addition to expanding the model to a more complete wall section, further work is planned with other cladding types, environmental loads, and materials of construction.

Gary Parsons

Gary Parsons joined the Dow Chemical Company in 1982, after receiving a BS degree in chemical engineering from the University of Cincinnati. Gary has spent 27 years in various Dow divisions, including manufacturing and research and development, primarily in thermoplastics. Since 2006, Parsons has been the building science and application development leader in Dow Building Solutions, specializing in building enclosure energy management and weather protection products for residential and commercial construction.

Jeff Hansbro

Jeff Hansbro is the commercial construction applications development leader in North America for Dow Building Solutions. His previous positions at Dow include senior technical service development specialist and senior product development engineer. Prior to his employment at Dow, Hansbro worked at Celotex Corporation and BASF in their urethanes research divisions. Hansbro received his BS in chemical engineering from Wayne State University and is presently pursuing an MS in engineering and marketing at Northwestern University.

Mike Lapham

Mike Lapham is a senior research technologist with Dow Building Solutions, having received an associate's degree in plastic engineering technology and a BA in business management. He has spent 20 years with Dow, mostly in the area of material science, with an emphasis in fracture mechanics and rheology. He is currently working in new-business development, concentrating on prototype design and product performance characterization.

Author profiles continued on page 26.

BUILDING ENVELOPE KNOWLEDGE ASSESSMENT

Test your knowledge of building envelope consulting with the following questions developed by Donald E. Bush, Sr., RRC, FRCI, PE, past chairman of RCI's RRC Examination Development Subcommittee.

1. **What is the minimum offset between courses of wood shake shingles?**
2. **What should be the spacing between adjacent wood shakes?**
3. **When installing a slate roofing system, how does the installer determine the proper exposure of each slate?**
4. **What is the most common depth of steel deck roof panels?**
5. **A wood panel roof deck shows a span rating of 32/16. What center-to-center spacing of support studs is required?**
6. **What is the minimum nominal thickness of oriented strand board roof deck panels?**

Answers on page 26

BUILDING ENVELOPE KNOWLEDGE ASSESSMENT

Answers to questions from page 25:

1. **1½ inches**
2. **One-half inch**
3. **Length of slate minus three inches divided by two**
4. **1½ inches**
5. **32 inches, with the long dimension running across the supports**
6. **15/32 inch**

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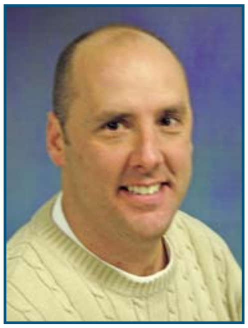
Michael Mazor

Michael Mazor is an R & D Fellow and the Dow Building Scientist for Energy Efficiency and Sustainability within Dow Building Solutions Business Group of The Dow Chemical Company. He joined Dow in 1989 and holds a PhD in physical chemistry from The University of Houston. His specialties include hygrothermal modeling and simulation, life-cycle analysis of energy-efficient building materials, and new-product development. Recent collaboration with the School of Natural Resources and Environment at the University of Michigan has resulted in the publication of a report by the *Journal of Industrial Ecology* describing the total global life cycle carbon balance of Dow foam insulation manufactured and installed for use in buildings.

Prashant Shembekar

Prashant Shembekar, a senior development specialist at Dow R & D, has been practicing use of finite element analysis for materials modeling and structural analysis for applications in various domains, including building and construction, for the last eight years.



Myron Maurer

Myron Maurer is an R & D Fellow within the Materials Engineering Center at The Dow Chemical Company. He joined Dow in 1993 and holds an MS in mechanical engineering from Michigan State University. Myron has published in 24 external publications/presentations, has 34 patents or patent applications, and has been the recipient of nine external awards for new product development.