Structural and Hygrothermal Field Monitoring of Thick Continuously Insulated Wall Assemblies Utilized in a Multi-Story Residential Building

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ABSTRACT

There are numerous high-performance wall designs in which most of the insulation is located exterior to the wall framing. These walls are typically constructed with light-gauge metal framing to retain the insulation and support the cladding.

Continuous insulation is prescriptively required to be used with steel-stud construction in climate zones two through eight in order to comply with ASHRAE 90.1-2007 and 2009 IECC standards requirements. Use of continuous insulation significantly minimizes thermal shorts and improves the energy performance of wall assemblies. Using rigid foam insulation to support the cladding is an efficient method for achieving this requirement; however, monitoring of displacements is required for the industry to gain a better understanding of the structural performance of these systems.

This paper will present the initial detailed case study results from a building envelope rehabilitation project where a seven story structure was externally insulated with three inches of continuous extruded polystyrene insulation and clad with stucco. This building is in Vancouver, British Columbia which is located in Climate Zone five. The system's design used minimal insulation penetrations that included only screw fasteners. In order to better understand the performance characteristics of such a wall, detailed monitoring equipment was installed throughout the building to record dimensional and hygrothermal information for the continuously insulated wall assembly and its components. A description of the building instrumentation plan and performance data will be presented. Finite element predictions on other continuous insulation systems using polyisocyanurate (PIR) rigid foam board and NYSERDA studies will be compared to this actual work.

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INTRODUCTION

The subject building is a 64-unit social housing complex in a seven story reinforced concrete structure, with steel stud infill walls and commercial space on the first floor. The original envelope assemblies included cement stucco on steel-stud-infill walls, exposed mass concrete, brick at the first floor front elevation, and built-up roof systems on main and terrace-level roofs. Ongoing moisture-related problems (mainly at windows and wall assemblies), ageing roofs, and problematic integrations led to the need for comprehensive rehabilitation. The rehabilitation project commenced in the spring of 2010 and was completed in the spring of 2011 (FIGURE 1 and FIGURE 2).

FIGURE 1 - North Elevation Before Repairs

FIGURE 2 - North Elevation After Repairs

The original wall assembly consisted of 3½ inch steel studs at 16 inches on center spanning the concrete floor slabs, interior gypsum with a polyethylene vapor barrier, and batt insulation in the steel stud cavities. The original drawings called for rigid insulation on the exterior of the steel studs, covered by conventional stucco cladding. As originally built, semi-rigid fiberglass insulation was used (see FIGURE 3), and during the remediation project was observed to have been compressed against the studs and floor slab. Water entering the stucco would drain down through the insulation, often appearing at suite floors, especially at the ground floor. Removal of the stucco cladding revealed extensively deteriorated steel studs and moisture-affected drywall (see FIGURE 4). Stud shadowing due to temperature variations from more conductive steel studs was apparent from both the interior and the exterior. Though a remediation strategy involving selective steel stud replacement and repairs was contemplated, due to the extent of damage, the project team determined that it would be more cost effective to completely demolish large portions of the walls and install new tracks, studs and drywall.

FIGURE 4 – Semi rigid insulation with slab edge

FIGURE 3 - Extensive steel stud damage

CONTINUOUS INSULATION REQUIREMENT

In the United States it was reported that energy consumption and greenhouse gas emissions (GHG) from buildings account for 50% of U.S. totals for both categories.[1] Nationalized energy code bodies (ASHRAE 90.1, IECC), as well as regional energy code bodies (such as the California Building Energy Efficiency Standard), and green building standards (ASHRAE 189.1, IgCC) have made increased energy-use stringency of buildings their top priority. All of the groups mentioned have set aggressive target percentage energy efficiency increases over previous versions.

An outcome of the ASHRAE 90.1 and IECC code committees was to increase the use of Continuous Insulation (CI) on both vertical and horizontal areas of the building envelope. Good design not only considers the thermal performance of the wall, but also other performance requirements, such as structural attachment and air, vapor and moisture control.

ASHRAE 90.1 2007(2010), under the prescriptive path, requires continuous insulation on steel-framed buildings, defining continuous insulation as follows:

> ***"continuous insulation (c.i.):*** *insulation that is continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior, exterior, or is integral to any opaque surface of the building envelope."*

[1] Annual Energy Outlook 2009 W Early Release, Tables 2, 4, 5, and 18. U.S. Energy information Administration. Available at www.eia.doe.gov/oiaf/aeo/aeoref_tab.html (Dec. 2008).

The City of Seattle, Washington published a revised energy code in October 2010. In it, the following commentary was added to the definition of ci in order to provide more clarity to designers and builders:

> ***"Continuous insulation (c.i.):*** *Insulation that is continuous across all structural members without thermal bridges other than fasteners (i.e. screws and nails) and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building envelope. For the purposes of this definition of continuous insulation, only screws and nails are considered fasteners. Insulation installed between metal studs, z-girts, z-channels, shelf angles, or insulation with penetrations by brick ties and offset brackets, or any other similar framing is not considered continuous insulation, regardless of whether the metal is continuous or occasionally discontinuous or has thermal break material. (See Section 1332 for determination of U-factors for assemblies that include metal other than screws and nails.)"*
>
> *"Even isolated discontinuous metal elements such as brick ties have a thermal impact that is too large to be ignored."*

The Seattle definition was modified to provide commentary on what defines a fastener and the impact that continuous and non-continuous framing penetrations through insulation can have on the thermal performance of the assembly. This commentary was added in order to address the common construction practice of supporting cladding through insulation using metal framing, but not discounting the R-value of that insulation or other negative impacts.

HYPOTHESIS

A continuously insulated rain screen wall system constructed from three inches of extruded polystyrene insulation, with ⅞-inch Z-girts installed every 16 inches on center on top of the insulation boards using 4½ inch number ten corrosion-resistant self-tapping screw fasteners at six inches on center, provides a structurally robust wall that is dimensionally stable and complies with the prescriptive requirements of ASHRAE 90.1.

BACKGROUND

As originally constructed, the wall assembly at the subject building had two inch by four inch steel studs, with R12 batt insulation infill and a semi-rigid fiberglass-insulated sheathing estimated at one inch thick. Therefore, the total nominal R-value of the insulation was approximately R15. However, actual effective R-value was calculated at less than R9, once thermal bridging of the steel studs and compression of the semi-rigid insulation against the steels studs and concrete floor slabs was considered.

Original Wall System

- Cement stucco with wire lath
- Semi-rigid fiberglass insulation (approximately one inch thick)
- 3½ inch steel studs with fiberglass batt insulation infill
- Polyethylene air/vapor barrier
- ½ inch interior drywall

The new wall assembly includes three inches of Type IV rigid insulation with a nominal R-value of R15. As a whole, the assembly has an effective R-value of around R17.8—approximately twice that of the original assembly. Installing the insulation on the exterior also allows for the construction of a more durable and higher-performing wall assembly and facilitates the use of continuous self-adhered membrane to make the assembly air tight and water tight. The rain screen cavity is achieved by fastening the paperback lath on the outside face of the metal Z girt over which the sand cement three coat stucco is traditionally applied.

New (Rehabilitated Wall System)

- ⅞ inch acrylic stucco on paper backed lath
- ⅞ inch Z-girts at 16 inches on center, fastened with self-tapping screw fasteners at six inches on center
- three inches Type 4 rigid insulation (R15), joints taped
- SA Membrane
- ½ inch fiberglass faced exterior gypsum sheathing
- Existing 3½ inch steel studs
- Existing ½ inch interior drywall

Though common practice, cutting and fitting of rigid insulation around installed Z-girts can reduce the wall's effective insulation R-value by more than half. Table A3.3 from ASHRAE 90.1- 2007 demonstrates the impact of steel framing on the effective insulation values. In the assembly described above, the Z-girts are installed over the insulation instead and attached with screws back to the steel studs through the insulation and sheathing. Because the screw fasteners are the only metal components that penetrate through the insulation, the assembly conforms to the definition of continuous insulation mandated by many North American energy codes. The Z-girts are installed tight to the insulation and designed to be rigid enough to transfer gravity and wind loads to the insulation (see FIGURE 5).

FIGURE 5 - Galvalume Z-girts on 3" rigid XPS

In addition, eliminating the penetration of metal framing through the insulation reduces the thermal bridging that can lead to stud shadowing and increased risk of condensation (see FIGURE 6).

FIGURE 6 - Interior Moisture Damage Related to Condensation and Leakage

INDUSTRY CONCERNS

This project focused on properly redesigning the wall sections of the building envelope. The assembly used was chosen in consideration of its ability to control energy (heat), air, moisture and bulk water through the finished assembly and the adjoining assemblies (fenestrations, roof, floor, etc.), its vapor and condensation control properties, and its ability to meet energy and other code requirements. The assembly contains a thick layer of Dow STYROFOAM™ Brand SM Insulation, which is a CAN/ULC S701 Type IV classified extruded polystyrene rigid foam board. The STYROFOAM was chosen mainly for its low water absorption potential (lowest of all rigid foam plastic insulations), durability (used successfully in wall applications for more than 40 years to date), warranted R-5 per inch, and minimum 25 psi compressive strength. When installed properly, this method for providing continuous insulation (ci) reduces thermal bridging effects from the steel framing members and maintains the temperature and humidity of the inside stud cavity at levels similar to the building's interior conditions, thus reducing condensation potential in the cavity.

The choice of using foam plastic on a building typically requires specific product and/or system standards to be met, which can vary by code and jurisdiction. This building was constructed under the Vancouver Building By-Law, which allows this assembly in a non-combustible building as long as certain conditions are met with respect to the fire performance of the assembly.

The rapid increase in the thickness of ci on buildings due to more stringent energy codes, combined with increasing levels of enforcement and awareness, has raised many questions from the building community on the structural design when thicker layers of ci are included in a wall assembly. Recently, there have been a number of research projects relating to this subject.

- New York State Energy Research Development Authority (NYSERDA) Fastening Systems for Continuous Insulation, Final Report 10-11, April 2010. The Foam Sheathing Coalition published the following Tech Matters: Guide to Attaching Exterior Wall Coverings through Foam Sheathing to Wood or Steel Wall Framing, released 9/20/10 and updated 12/07/11 as a design guide confirmed through the testing conducted as part of the aforementioned NYSERDA report.[2].
- The Dow Chemical Company, Dow Building Solutions, Technical Evaluation Report No. 1105-01: Requirements for Attaching THERMAX™ ci Exterior Insulation & Three-Coat Stucco Cladding to Steel Stud Walls, Released 9/29/11 and updated 10/12/11.

The NYSERDA report "Fastening Systems for Continuous Insulation", is a research report investigating building codes, alternate fastener products (plastics), and construction issues, with prescriptive fastening tables developed for the installation of continuous rigid foam plastic insulation on the exterior of framed wall assemblies. The main findings and conclusions were as follows:

- Codes often referred to manufacturer's requirements for attachment of claddings. Manufacturers often limit attachment to rigid foam up to only one inch in thickness.
- Engineering analysis can be used to design cladding attachment.
- The only additional load the fastener needs to withstand is the increased gravity load due to the cantilever from the wall.
- The project focused on residential sidings (vinyl, fiber cement, wood lap and three-coat stucco).
- The study included siding applied directly over rigid foam and siding applied to furring strips applied over foam. The study also included the installation of

[2] http://www.foamsheathing.org/common/kb/techmatters.php

horizontal Z-furring strips installed through the insulation; however, we note that this assembly does not conform to the definition of continuous insulation.

- Constructability issues included the use of longer fasteners (air nailing generally limited to 3½ inches), screws cost more to install, and details are more difficult, including windows, corners, base of wall, decks, etc. Availability of longer screws was also noted as a concern.
- The report tested connections with structural wood panel sheathing and without, with the use of furring over the rigid foam, and with the siding directly connected back to the studs or sheathing. Both steel studs and wood studs were considered.
- Testing considered performance of siding or furring connections in downward shear. Tables were developed for attachment with and without furring to the variations of the wall assemblies described above.
- While this report considers both wind and gravity, it does not consider the wind load on the foam insulation. Foam insulation provides a good air barrier, which can reduce energy losses, but also attracts wind loads, as these loads will tend to act on the most airtight element in the assembly.
- The Dow Building Solutions TER No. 1105-01 was published as a design guide, based on a testing protocol of third-party systems wall testing, internal lab testing and internal FEA modeling. The TER is in agreement with the NYSERDA report on fastening systems for continuous insulation. The connection test data forms the basis of fastener recommendations in both the approaches. The FE model incorporates all the details of the wall constituents; therefore, it is able to provide maximum downward (gravity) load capacity of a wall system with good accuracy when compared to empirical formula-based strength calculations. Designers would need to choose an appropriate factor of safety.

STRUCTURAL DESIGN

The structural characteristics of the rigid XPS insulation are relied upon to support the dead and live loads of the cladding. The main structural loads include positive and negative wind pressure and long-term gravity load.

Wind loads are the largest loads to which the wall assembly will be subjected. For this project, the designers used a simple procedure and established the statistical 1 in 50-year return wind load for that location. Exposure factors, pressure coefficients and importance factors were applied to obtain a positive and negative design wind load for the building's cladding. For this building, a positive load of 1.23 kPa (25.7 psf) and a negative suction load of 1.31 kPa (27.4 psf) were established. The wind load will generally be attracted to the most airtight element of the wall assembly, with each component taking part of that load. Due to the complexity of predicting how this load will impact each component, we took the conservative approach of designing each component to withstand 100 percent of the wind loads. Furthermore, standard practice for fastening claddings often results in more frequent fastening than is required to withstand wind loads. These patterns are often established based on trades' past experiences and often relate to serviceability. As the cladding on this project is three-coat stucco, the fastening patterns required by the Association of Wall and Ceiling Contractors of British Columbia (AWCCBC) were followed, which are more stringent than those necessitated by wind loading. Prescriptive requirements of the WCABC include using minimum number eight self-tapping screws at no greater than six inches on center vertically to hold the lath to the metal Z-girts.

Positive wind loads can push the cladding and Z-girts onto the rigid insulation, and negative wind loads can pull the stucco lath and girt fasteners away from the insulation in tension. Negative wind loads can also push the XPS against the Z-girts. The insulation has a 25 psi (3600 psf) rating. Using a factor of safety of six for the insulation, the allowable compressive load is 600 psf. The vertical girts, with a three inch face every 16 inches, cover approximately 19% of the insulation. Therefore, positive (cladding load against insulation) or negative (insulation loading against girt) is resisted by the area of the girt covering the insulation. This results in an allowable load of 113 psf—well above the expected load of 27.4 psf. Suction loads are also resisted by the girt and lath fasteners. Girt fasteners were installed at eight inches on center vertically, with horizontal girts matching studs at 16 inches on center, resulting in a girt fastener every 0.89 ft^2, subjected to a 24 lbf load. The ultimate strength of the girt fastener is published by the manufacturer at 613 lbf, which provides a factor of safety of 25.5. Stucco lath fasteners, smaller and installed at the same spacing, result in a factor of safety of 20.8 (see TABLE 1).

TABLE 1 – Wind Load & Factor of Safety

Wind Load	Girt Fastener	Lath Fastener	Insulation
- 27.4 psf	FS=25.5	FS=20.8	n/a
+ 25.7 psf	n/a	n/a	FS=5.3

Builders, code officials and designers are often concerned with the gravity load of the cladding on the insulation. There is a common misperception that the fastener used to hold cladding in a continuously exterior-insulated wall assembly is subjected to shear and bending forces and will, therefore, bend the fasteners over time and cause the cladding to sag. This is not true, because when the face of the cladding is rigid or a rigid furring strip is used, downward gravity loads are transferred into the rigid insulation (see FIGURE 7).

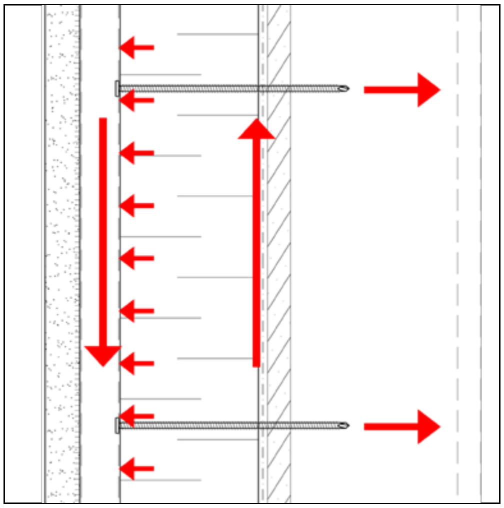

FIGURE 7 - Insulation Cladding Force Diagram

The gravity loads are designed to be resisted by the foam insulation. If the cladding moves downward, the fastener has to lengthen or insulation has to compress. If the insulation does not compress and the fastener does not stretch, then it braces the cladding. With a 3600 psf rating, a significant load is required to compress the insulation. This size of load is not produced with common claddings, as demonstrated in the picture below (FIGURE 8), where a 3500 pound concrete block is being held up by proprietary metal furring strips that are installed over rigid foam insulation. However, another common misconception exists that the fastener will bend and the cladding will deflect with increasing thicknesses of exterior continuous rigid insulation and cladding weights. While this may be true with some attachment methods, using a rigid exterior frame results in downward loads being transferred as compressive loads onto the insulation. One of the goals of this monitoring program was to confirm the structural stability of this type of system, as will be demonstrated by the deflection readings.

FIGURE 8 - Load Testing Mock-up Panel

Construction Schedule

Work commenced in April 2010, with the commencement of the demolition phase and removal of the cladding assembly. Extensive damage to the steel stud framing was uncovered, which eventually led to complete reconstruction of the exterior walls in most locations.

Sheathing installation started in July 2010, and the installation of the self-adhered membrane air, vapor and moisture barrier, rigid insulation and vertical Z-girts started in late July 2010.

During August 2010, monitoring was installed in three locations on the southeast elevation. Lath installation started near the end of August on the southeast elevation and was complete in early September. Lath installation started on the north elevation in early September and was complete in mid September.

Application of stucco scratch and brown coats started in early September, with the finish coat started in some locations at the end of September 2010. The main areas of stucco (north and south sides), where monitoring was installed, were complete with stucco scratch, brown and finish coats by early October.

It is useful to know when the cladding loads were applied so that deflection readings can be correlated with those dates in order to determine if there were measurable deflections of the wall cladding system.

The scaffolding and netting was removed in late December 2010 and early January 2011. The cladding replacement project was substantially complete on March 4, 2011 (see FIGURE 9).

FIGURE 9 - Completed Continuously Insulated Rain Screen Stucco System

BUILDING MEASUREMENTS

Building position measurements were taken on the south and north façades of the building, with sensors located on the second, fourth and sixth floors. Multiple floor locations were chosen to provide building dimensional change data as a function of building height, whereas locations on opposite façade orientations provided displacement data as a function of building exposure. Locations of measurement panels are indicated by the red squares in FIGURE 10 and FIGURE 11 below. Six insulation boards were instrumented for this case study. Information from three panels is reported, the north wall second floor and the south wall second and fourth floors. Information from the remaining three panels is not reported, as data was not consistently collected throughout the entire test period due to periodic data acquisition system outages.

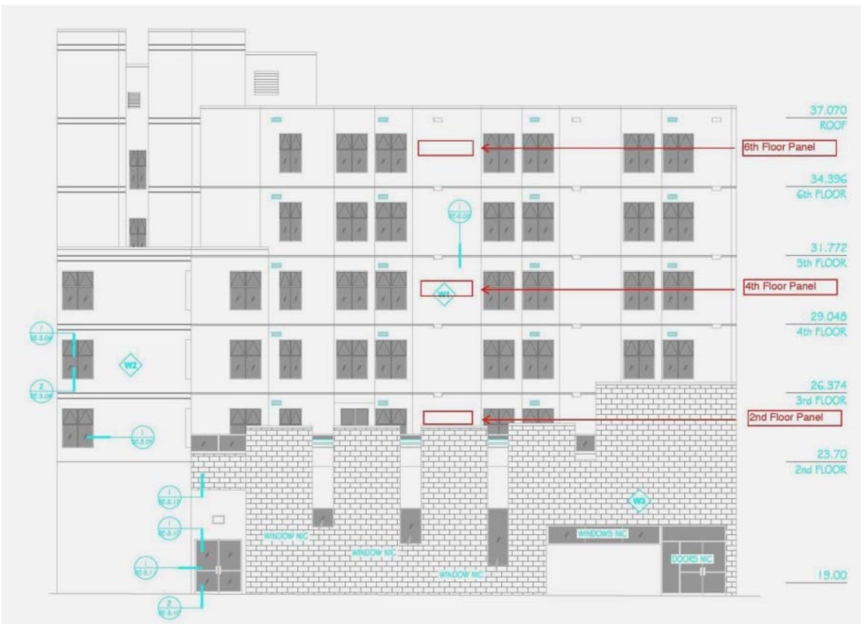

FIGURE 10 - Measurement Panel Locations (North Elevation)

FIGURE 11 - Measurement Panel Locations (South Elevation)

BI Technologies Model BI-404 linear displacement sensors (FIGURE 12) were installed to measure movement of the foam insulation panels. The position sensor accuracy is 0.085 mm ± 5%.

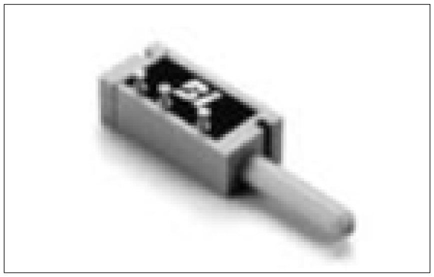

FIGURE 12 - Position Sensor

The sensors were installed along foam board joints to monitor foam displacement relative to the structural steel of the building via an external bracket directly attached to the interior steel studs. Sensor locations on an insulation board are shown in FIGURE 13. The sensors were installed within the foam using epoxy so that the sensor actuator would contact the “reference” bracket. The sensors were located approximately at the midpoint of the foam thickness to ensure the exterior cladding would be unaffected. Reference brackets were attached through the exterior gypsum and fastened to the steel studs within the wall cavity as shown in FIGURE 15. FIGURE 14 shows the reference brackets for a single measurement panel prior to installation of foam insulation. This attachment enabled foam movement relative to the steel structure to be measured. Each panel had three sensors on the bottom, one on each side, and one in the center. The three bottom sensors were labeled as Y axis, the two side sensors as X axis, and the center sensor as Z axis, which measured movement towards and away from the building. The sensor installation locations are shown in Figure 14 and Figure 15. Position data was collected every two hours and transmitted via wireless data acquisition units to the network analysis software. Figure 16 shows a completely wired insulation panel prior to installation of the exterior cladding.

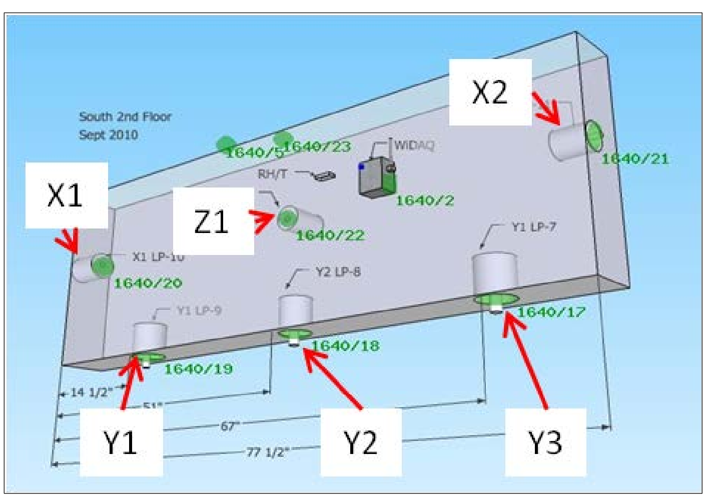

FIGURE 13 - Sensor Location in XPS Board

FIGURE 14 - Measurement Panel Location Prepared for Board Installation

FIGURE 15 - Close Up of Sensor Reference Bracket

FIGURE 16 - Measurement Panel after Installation of Displacement Sensors

Analysis of X Direction Displacement

FIGURE 17 depicts the movements of the X1 and X2 displacement sensors installed on the south wall second floor test panel between June 28 and July 5, 2011. The time period selected includes multiple day/night cycles in order to capture related cyclic displacement changes. Displacement is measured in millimeters. An increasing value for displacement indicates an increase in distance between the sensor and the reference bracket. Since the X-direction sensors are oriented on opposite ends of the insulation board, both sensor values simultaneously increasing would be indicative of the opposite board ends becoming closer together or the foam insulation board shrinking. Conversely, simultaneous decrease in X1 and X2 on the same foam panel would be indicative of foam board expansion. Changes in condition, particularly temperature, are known to affect the dimensions of many building materials, including foam. The foam dimensions reported in FIGURE 17 do not indicate any regular predictable changes resulting from a change in climatic condition such as temperature.

A statistical correlation between X1 and X2 would be expected if foam dimension changes were caused by temperature change. Statistical analysis of X1 and X2 indicates no correlation between these measurements.

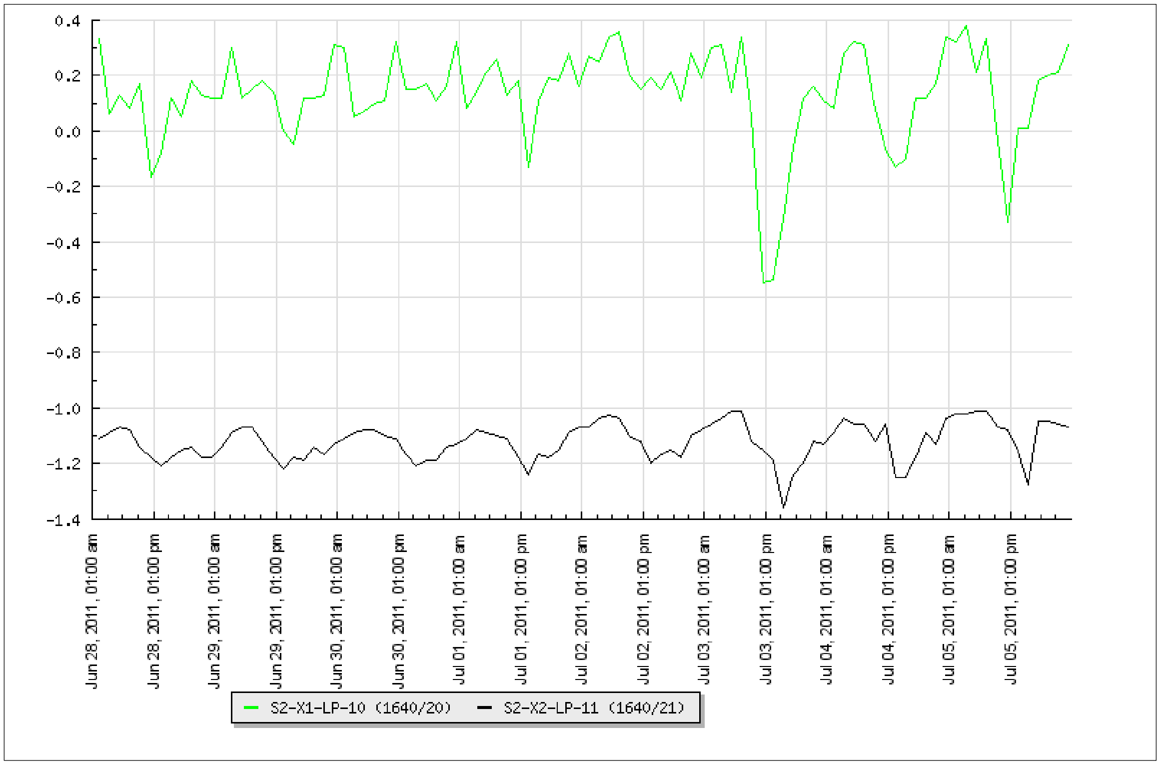

FIGURE 17 - X Displacement (2nd floor, South)

Analysis of Y Direction Displacement

A primary emphasis of this project was to characterize insulation or cladding movement related to gravity load. Three replicate measurements were taken in the direction expected to be most influenced by gravity load: the Y direction. FIGURE 18 describes the displacement in the vertical, or Y direction, for the second-floor measurement panel on the building's south side for the period between June 28 and July 10, 2011. Range of movement of all Y sensors on this panel is similar, and no apparent trend beyond small random movement was observed.

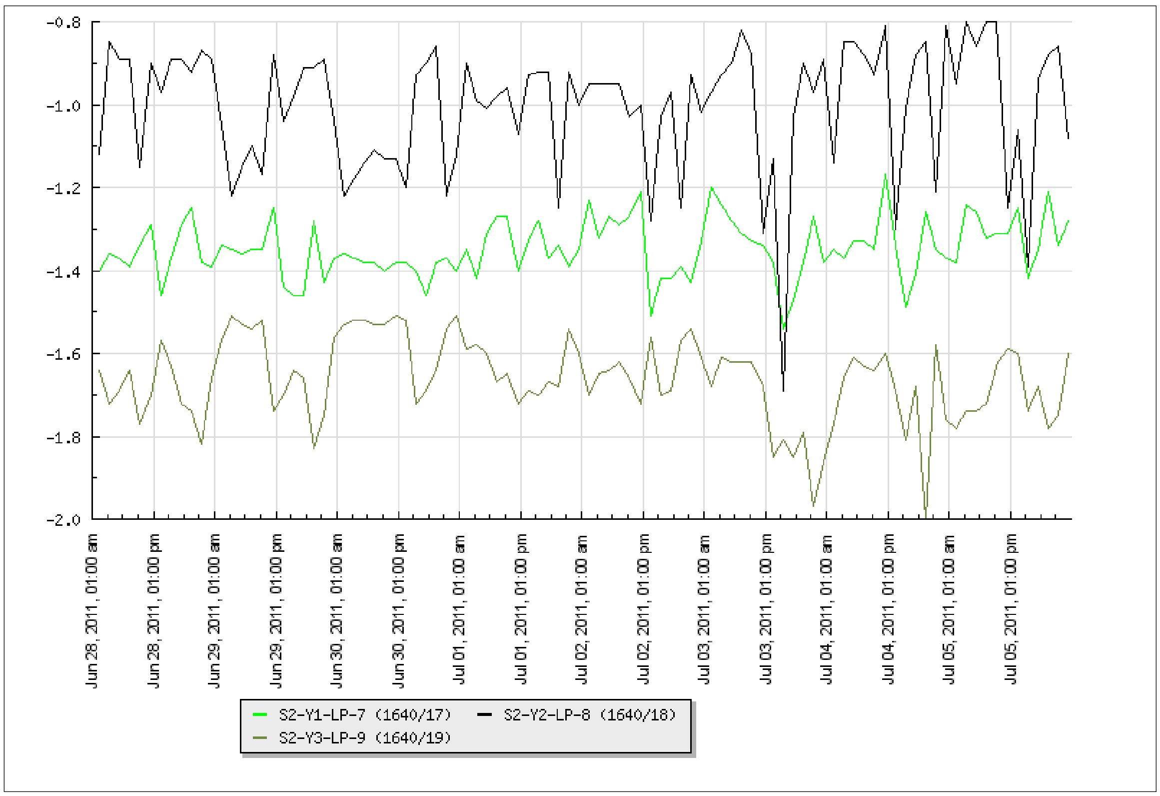

FIGURE 18 - Y Displacement (2nd floor, South)

FIGURE 19 represents movement in the gravity load, or Y direction, for the south wall second floor insulation panel for a longer time period, from April through September. No long-term negative trend was observed for this period, suggesting that the cladding system's gravity load was not causing the foam to creep. A gravity effect would be expected to cause a negative increase in the Y displacement. The straight line sections of the chart resulted from instances of data logger outage. As the loggers are solar powered, this was mostly likely due to insufficient sunlight available during those periods.

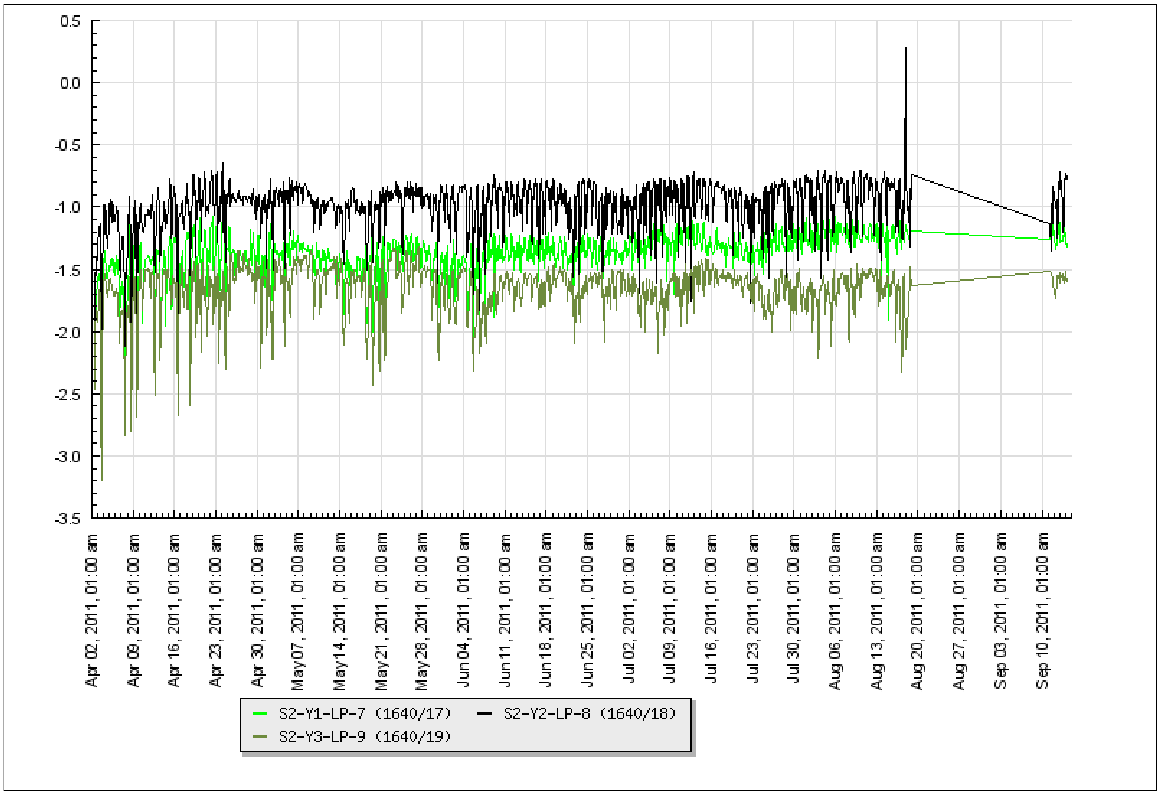

Figure 19 - Vertical Displacement (2nd floor, South)

Analysis of Z Direction Displacement

The Z displacement is shown in FIGURE 20 for the all three measurement panels: two on the south wall and one on the north wall. Over the measurement period, there was a slight upward trend in the Z displacement for the south-wall, second-floor panel; however, this trend was not evident on the other panels. This lack of Z-direction displacement confirms the wind resistance of this wall system, as movement of the foam away from the underlying sheathing would have been detected by this measurement.

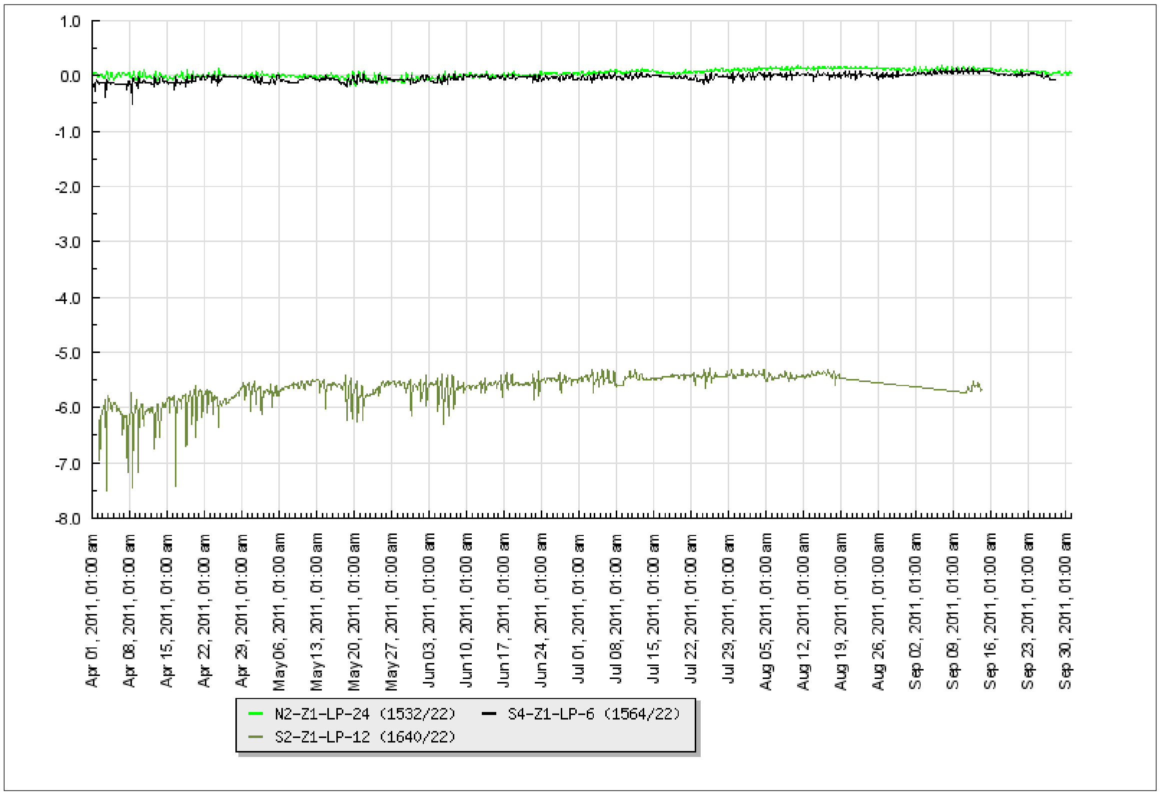

FIGURE 20 - Z Displacement (2nd floor, South)

Comparison of Y Displacement of North and South Walls

In FIGURE 21, Y deflection of south wall second and fourth floors and north wall second floor is reported The Y direction displacement lines show similar behavior, indicating that displacement behavior is unaffected by wall orientation or elevation.

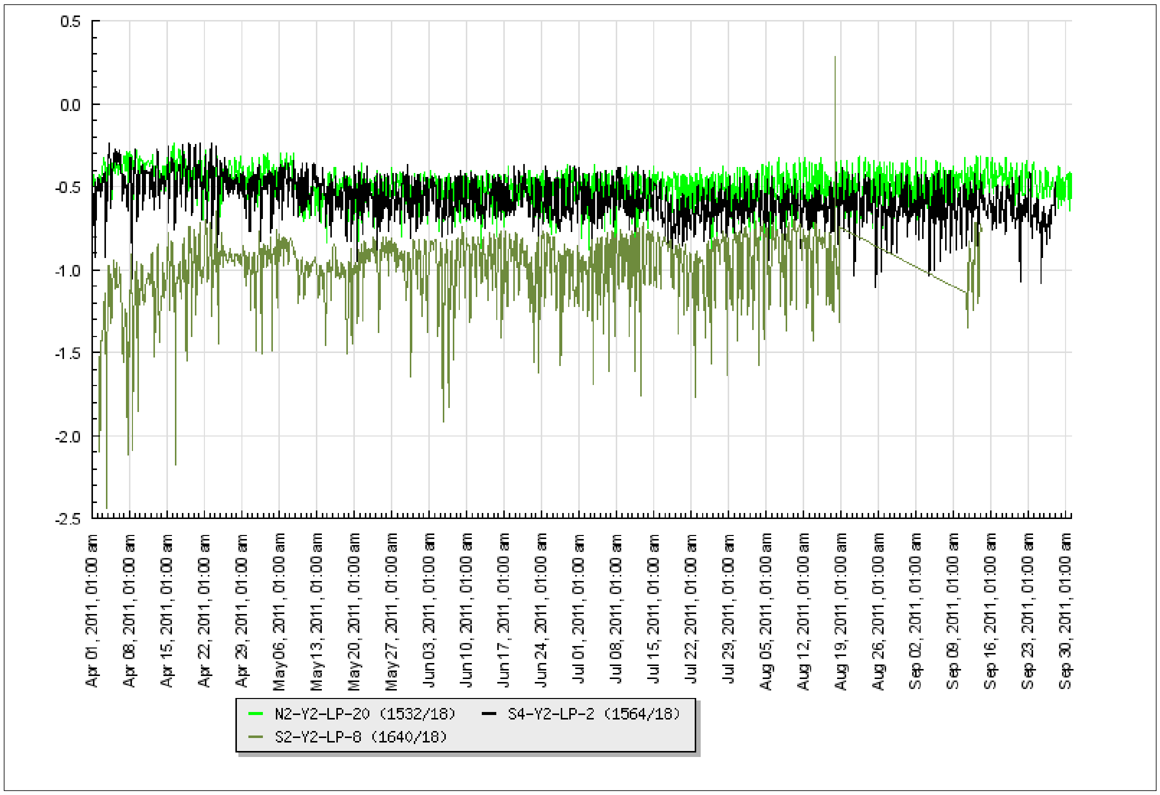

FIGURE 21 - Vertical Displacement Measurements of North and South Panels

Analysis of Movement Range in X, Y, Z Directions

Range of displacement of all XYZ sensors was generally between 0.10 and 0.90 mm for the time period from May through September, see FIGURE 22. If gravity load caused creep movement of the exterior cladding and associated movement of the foam insulation, it would be expected that Y direction movement would be greater than Z or X direction. The similar range of movement in all deflection directions suggests that gravity is not causing larger deflection.

	Temperature - C	X1 - mm	X2 -mm	Y1 -mm	Y2 -mm	Y3 -mm	Z1 -mm
Panel S2 (n=1317)							
Min	6.4	-1.0	-1.8	-2.2	-1.9	-2.4	-6.3
Max	20.5	-0.3	-1.4	-1.6	-1.0	-2.0	-5.8
Delta	14.1	0.8	0.4	0.5	0.9	0.5	0.5
Panel S4 (n=1595)							
Min	6.4	-0.9	-1.1	-1.5	-1.1	-0.9	-0.2
Max	19.7	-0.3	-0.5	-0.7	-0.6	-0.5	0.0
Delta	13.2	0.7	0.6	0.8	0.5	0.4	0.2
Panel N2 (n=1594)							
Min	6.3	-1.1	-0.4	-0.5	-0.9	-1.6	-0.2
Max	25.4	-0.4	0.2	-0.4	-0.5	-0.7	0.1
Delta	19.0	0.7	0.5	0.1	0.4	0.9	0.2

FIGURE 22 - Range of Displacement Change (May - Sep 2011)

Comparison of Building Measurements to Finite Element Modeling

The building dimensional change measurements were compared to the results of finite element analysis modeling of gravity creep performance of a similar heavy-cladding, thick-foam composite system[3] (Parsons and Hansbro 2011). Numerical models were created for a composite wall system comprised of three-coat traditional stucco cladding, nominal 11 psf weight with building paper and lath, attached over a layer of three inch polyisocyanurate (PIR) continuous insulation, with the objective of predicting the creep performance of thick continuous insulation systems. The modeled four foot by eight foot wall assembly was created using four inch number ten fasteners on 12-inch centers to attach the stucco system to the steel studs through the PIR layer. It is reasonable to compare the FEA model results of the PIR system to the XPS-insulated building measurements, based on the similar compressive modulus of the two different foam insulations. Compressive modulus is the key material input to FEA modeling. Though not identical, these materials can be considered reasonably similar in stiffness, with a modulus of 798 psi for a typical ASTM C 578 Type IV XPS (similar to CAN/ULC S701 Type four product) and a modulus of 841 psi for a typical ASTM C1289, Type One Class Two PIR.

For the three inch thick PIR case, a downward deflection due to gravity force of 2.25 mm is predicted to occur at the outermost surface of the foam insulation layer. Since the deflection measurements of the experimental building were taken at the midpoint in foam thickness, the predicted downward deflection would be 1.1 mm at that location. The actual deflection results are less than 1 mm in the gravity (or Y) direction, which suggests that modeling results overestimate the expected deformation due to gravity and should be considered very conservative.

[3] *Three-Coat Stucco Veneer Cladding Attachment Schemes for Thick Continuous Insulation (ci) foam Based on Experimentally Validated Finite Element (fe) Modeling. RCI 26th International Convention Proceedings, Reno NV April 2011(Gary Parsons, Dow Chemical Company; Jeff Hansbro, Dow Chemical Company)*

Influence of Temperature on Displacement

FIGURES 23, 24 and 25 all represent displacement in the Y direction for the north second-floor wall and south second- and fourth-floor wall as a function of temperature. Correlation coefficient (r2), summarized for all measurements in Figure 26, indicates little, if any, correlation between temperature and position. Typically, a coefficient of greater than 0.7 indicates a correlation, with an r2 value of 1 indicating perfect correlation between the variables.

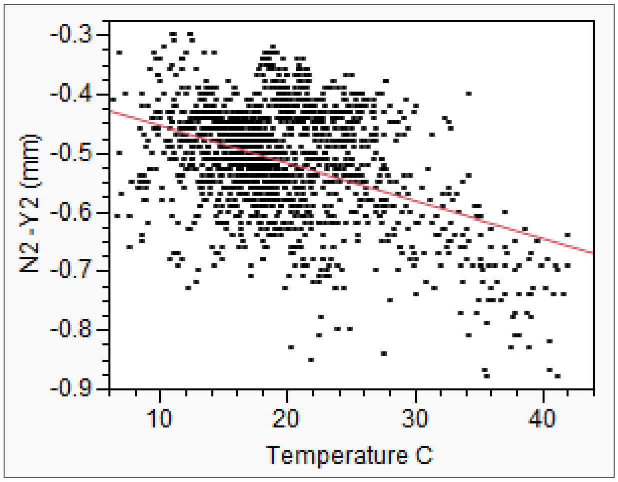

FIGURE 23 - Y2 Displacement as Function of Temperature (2nd floor, North)

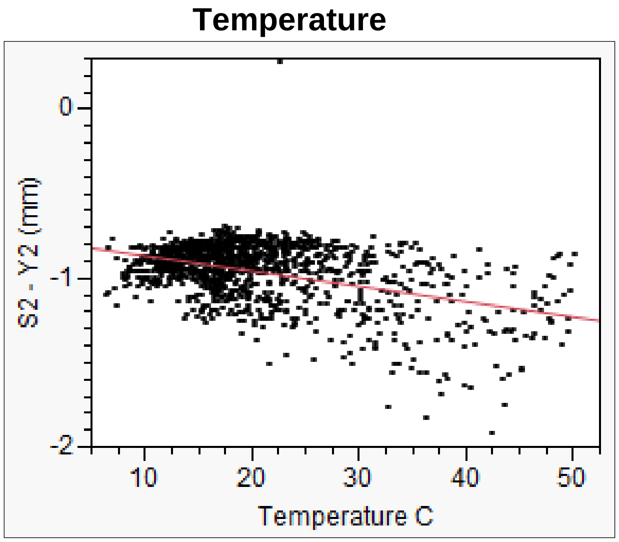

FIGURE 24 - Y2 Displacement as Function of Temperature (2nd floor, South)

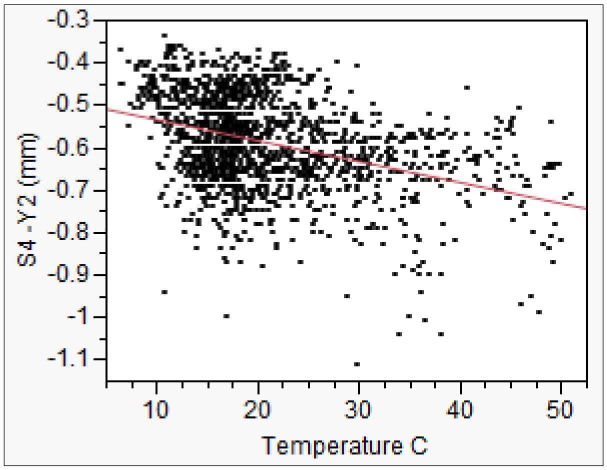

FIGURE 25 - Y2 Displacement as Function of Temperature (4th floor, South)

	Test Panel		
Sensor	N2 (n=1594)	S2 (n=1316)	S4 (n=1595)
X1	.02	0.25	0.19
X2	.24	0.08	0.16
Y1	.22	0	0.17
Y2	0.18	0.19	0.14
Y3	0.06	0.10	0.10
Z1	.24	0.02	0.23

FIGURE 26 - Correlation of Displacement and Temperature (r2)

Material	Coefficient of Thermal Expansion (m/m K)	Coefficient of Thermal Expansion (in/in F)	ΔT=35°C ΔL over 1.2m (48”)	ΔT=22°C ΔL over 1.2m (48”)
Mortar (Stucco)	(7.3-13.5) x 10^{-6}	(4.1-7.5) x 10^{-6}	0.3mm-0.57mm	0.19mm-0.36mm
Steel	13.0 x 10^{-6}	7.2 x 10^{-6}	0.54mm	0.34mm
XPS, Polyiso, EPS	62.7 x 10^{-6}	35 x 10^{-6}	2.63mm	1.65mm
Aluminum	22.2 x 10^{-6}	12.3 x 10^{-6}	N/A	N/A

FIGURE 27 - Coefficients of Thermal Expansion

The exterior of the wall assembly will see the biggest temperature fluctuations daily and seasonally. Over the year (from summer to winter), we see temperatures of up to 35°C and as low as - 4°C in the cavity. Daily, the temperature fluctuates 22°C. Deflections are measured partway through the insulation, while temperature measurements are made on the exterior side of the insulation; therefore, temperature fluctuations in the insulation will be a portion of the total temperature change on the exterior and interior. The data show smaller fluctuations, which may be due to location of measurement and restraint of insulation by adjoining boards and steel girts. A simple analysis of the range of displacement change as a function of the range in the temperature change, FIGURE 27, could lead to the conclusion that the displacement change is due to thermally driven expansion or contraction. In-depth statistical analysis of data, as described earlier, indicates this conclusion is not correct.

Hygrothermal Performance of the North Wall

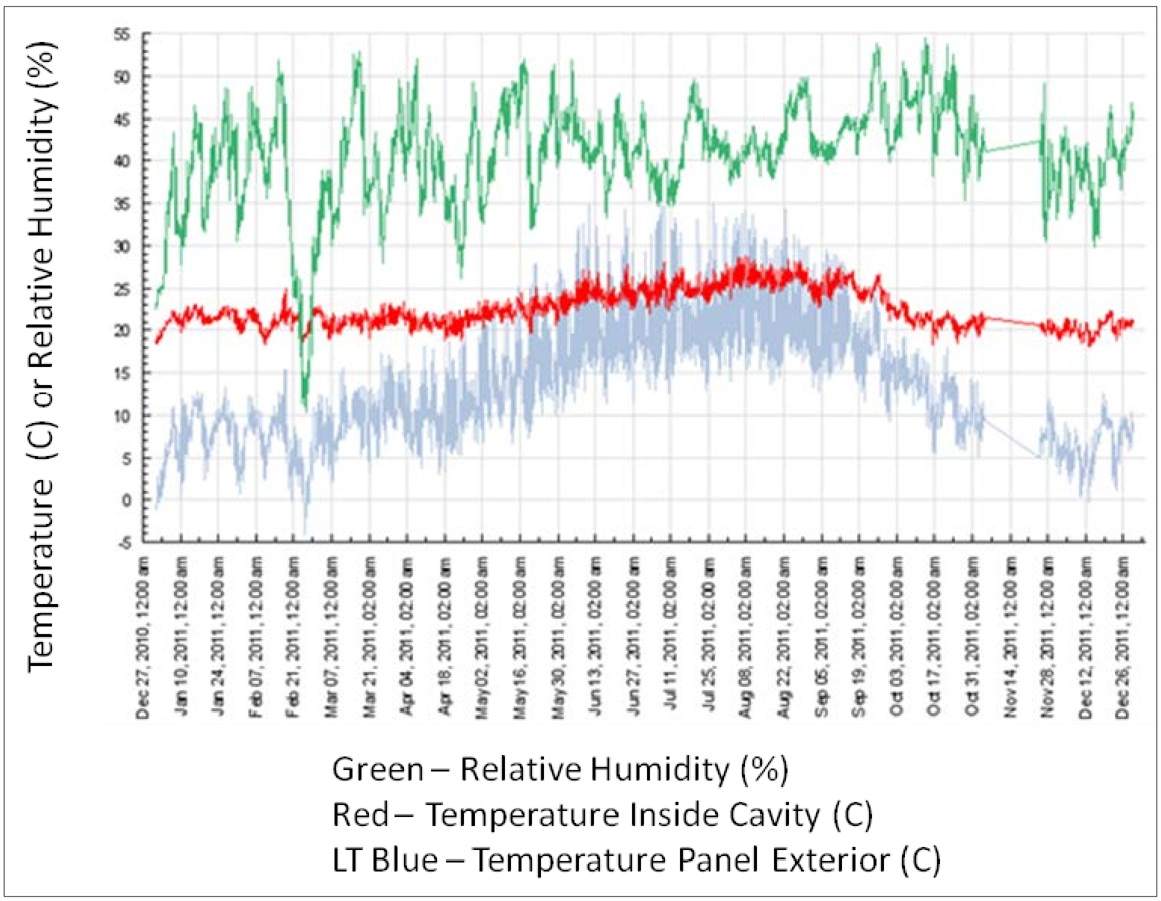

FIGURE 28 - Temperature and Relative Humidity (2nd floor, North)

Hygrothermal performance of the north-wall, second-floor panel is shown in FIGURE 28 for the period from January through December 2011. Both cavity interior and panel exterior temperatures, logged every four hours, are plotted in red and light blue, respectively. The beneficial effect of continuous exterior insulation can clearly be seen by comparing the cavity interior and panel exterior temperatures. The panel exterior temperature can vary by 25 to 30°C through a daily cycle, whereas the internal cavity temperature varies by only 2 to 3 °C and typically remains within a range of 20 to 28°C though the entire year-long measurement period.

The relative humidity within the cavity varies from 25 to 55 %. It is possible to estimate dew point based on temperature and relative humidity using the August-Roche-Magnus approximation. For example, if the conditions of 20°C and 55% relative humidity are chosen (i.e. the coolest temperature and highest relative humidity measured within the cavity), the dew point is approximately nine degrees Celsius. An estimated dew point that is much lower than the lowest measured cavity internal temperature confirms the expected low condensation potential within the cavity.

CONCLUSIONS

1. A continuously insulated rain screen wall system constructed from three inches of extruded polystyrene insulation, with ⅞-inch Z-girts installed every 16 inches on center on top of the insulation boards using 4.5" #10 self tapping fasteners at six inches on center, provides a structurally robust wall that complies with the prescriptive requirements of ASHRAE 90.1 and is dimensionally stable.
2. Range of displacement changes are similar in X, Y and Z directions, suggesting that gravity loads do not amplify movement in the Y, or gravity-loaded, direction.
3. The movement range in all directions does not appear to be related to the dimensions of the boards being measured. That is, movement in the Z direction, where the insulation board is three inches thick, is similar to measured movement in the X direction, where the board is eight feet long.
4. The correlation between temperature and displacement change is poor. While the total displacement being measured in the X and Y directions is what would be expected from thermal expansion of the foam, the statistical analysis of the data indicates that the displacement is not driven by thermal expansion or contraction. Movement in the Z direction is greater than expected from thermal expansion.
5. The measured hygrothermal performance of this wall confirms the expected performance of this wall construction. Temperature measurements indicate that the interior face of the exterior sheathing is at or near room temperature. Humidity measurements show little or no potential for condensation.
6. No stucco performance problems have been reported to the date of submission of this paper. The goal was to attach stucco to girts and girts to wall very well in order to reduce the risk of movement and potential for cracking. Proper mixing and curing of stucco is also important to stucco performance. Due to the controlled construction conditions (protected from rain and direct sunlight), mixing and curing was done properly, with a higher level of quality control, minimizing the risk of cracking or other problems, such as efflorescence.
7. Results indicate that this is a high-performance, thermally-efficient wall assembly with a low risk of condensation.

8. Possible areas for additional research include:
    a. Research expected movement of foamed plastic insulation due to differential temperature conditions and under restraint.
    b. Establish structural design parameters for designing rigid foam to support cladding and to withstand compression and bending loads that will vary depending on the design approach taken.