Initial and Long-Term Movement of Cladding Installed Over Exterior Rigid Insulation

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Initial and Long-Term Movement of Cladding Installed Over Rigid Insulation

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Definitions

BSC	Building Science Corporation
EPS	Expanded polystyrene
IECC	International Energy Conservation Code
lbf	Pounds per Foot
LVDT	Linear Voltage Distance Transducer
MF	Mineral Fiber
OSB	Oriented Strand Board
PIC	Polyisocyanurate
psf	Pounds per Square Foot
RH	Relative Humidity
SPF	Spruce-Pine-Fir
XPS	Extruded Polystyrene

Executive Summary

Changes in the International Energy Conservation Code (IECC) from 2009 to 2012 have resulted in an increase in minimum insulation levels required for residential buildings. Not only are the levels increased, but the use of exterior rigid insulation has become part of the prescriptive code requirements. With more jurisdictions adopting the 2012 IECC, builders will be required to incorporate exterior insulation in the construction of their exterior wall assemblies.

For thick layers of exterior insulation (levels greater than 1 ½ in.), many contractors and designers use wood furring strips attached through the insulation back to the structure as a means to provide a convenient cladding attachment location (Straube and Smegal 2009; Pettit 2009; Joyce 2009; Ueno 2010). However, there has been a significant resistance to its widespread implementation due to a lack of research and understanding of the mechanisms involved in the development of the vertical displacement resistance capacity. In addition, the long-term in-service performance of the system has been questioned due to potential creep effects of the assembly under the sustained dead load of the cladding and effects of varying environmental conditions.

Previous research has provided significant insight into the mechanics as well as long-term performance of exposed assemblies that use wood furring strips attached through the insulation back to the structure to provide a cladding attachment location. However, several key research questions still remain:

- What are the impacts of different fastener types in the system capacity?
- What is the impact of screw shaft bearing on the insulation material?
- What are the impacts of material expansion and contraction on the pre- and post-compression forces in the assemblies?
- Can deflection movement for heavier weight claddings be mitigated by denser fastener spacing?

This research was an extension of previous research conducted by BSC in 2011, and 2012 (Baker 2013a; Baker and Lepage 2014). Each year the understanding of the system discrete load component interactions, as well as impacts of environmental loading, has increased.

From the research, it was determined that using larger fasteners can increase the system capacity; however, simple cantilever bending tests significantly underestimate the actual capacity of the screw in the system. With the inclusion of the wood furring strip as the screw shaft bearing on the furring strips results in a double bending action. The portion of vertical load resistance capacity provided by the screw fasteners in double bending was determined to be around 4 lbf per fastener based on a standard #10 wood screw and 7 lbf per fastener based on a Headlok screw at 1/16 in. deflection (based on a 4 in. spacing between the oriented strand board sheathing and the furring).

The impact of the screw shaft bearing on the insulation is not insignificant, though it is difficult to accurately quantify. Measurements indicated a doubling of capacity based on a simple

cantilever test, assuming only the base layer of insulation is rigidly attached to the structure and up to 8 times the capacity if both layers of insulation are rigidly attached.

Thermal expansion and contraction of materials can have a significant effect on the compression forces in the assembly. Measured results indicated a 100 lbf change over a temperature range of 130°F to –30°F. The changes in compression forces will impact the friction resistance component of the assemblies and may also play a role in the resistance provided by the compression strut. These fluctuations are also theorized to be the cause of the diurnal movements measured in the long-term exterior exposure testing (Baker and Lepage 2014).

There is a direct correlation between the number of fasteners used in the assembly and the system capacity. Dividing the total load resistance by the number of fasteners for each of the three tests yielded almost identical load versus deflection plots. This is important from a design perspective, as the results would indicate that the system capacity can be modified by increasing or decreasing the number of fasteners used in the assembly.

The long-term exterior exposure testing provided significant insight into the actual in service performance of the cladding attachment systems. Cladding weight resulting in 30 lbf per fastener load was too great for the assembly, and unacceptable creep of the system was clearly observed. By contrast limiting the cladding weight to 8lbf per fastener demonstrated very stable performance. The assemblies loaded to 15 lbf per fastener showed pretty stable performance as well, however, there may be a slight indication of system creep occurring with these assemblies. Based on current information to date, it is recommended to use a maximum load per fastener of no more than 10 lbf based on a standard #10 wood screw installed through up to 4 in. of insulation (Table 1). Higher capacities would be expected with larger screws or reduced insulation thickness.

Table 1. Recommended Vertical Fastener Spacing (Minimum #10 Wood Screw) Based on Cladding

Cladding Weight (psf)	16 in. o.c. Furring	24 in. o.c. Furring
5	18	12
10	9	6
15	6	4
20	4	3
25	3	2

1 Problem Statement

1.1 Introduction

Energy consumption reduction is increasing in importance in our society. The building industry is reacting by focusing on designing and building lower energy use buildings. The trend has been reinforced in building codes. Changes in the International Energy Conservation Code (IECC) from 2009 to 2012 have resulted in an increase in minimum insulation levels required for residential buildings. Not only are the levels increased, but the use of exterior rigid insulation has become part of the prescriptive code requirements. With more jurisdictions adopting the 2012 IECC, builders will be required to incorporate exterior insulation in the construction of their exterior wall assemblies. This is not surprising, as the addition of insulation to the exterior of buildings is an effective means of increasing the thermal resistance of both wood-framed walls as well as mass masonry wall assemblies. The location of the insulation to the exterior of the structure has many direct benefits, including: (1) higher effective R-value from reduced thermal bridging; (2) higher condensation resistance; (3) reduced thermal stress on the structure; as well as other (4) commonly associated improvements such as increased air tightness; and (5) improved water management (Hutcheon 1964; Lstiburek 2007).

The current prescriptive thermal resistance values for exterior rigid insulation required on the exterior walls as outlined in Table R402.1.1 of the 2012 IECC can be achieved for most climate zones without significant changes to current building practices, as the levels typically will require less than 1 ½ in. of insulation (IECC 2012). For insulation up to 1 ½ in. in thickness, direct attachment of cladding assemblies through the insulation back to the structure is a practical construction technique and one that is currently address in Table R703.4 of the International Residential Code (IRC 2012). Beyond 1 ½ in. of thickness, alternate means for cladding attachment are generally required due to current market availability of fastener lengths for cladding nail guns. This has created a problem for projects that are looking to exceed this 1 ½ in. practical limit. For thick layers of exterior insulation (levels greater than 1 ½ in.), many contractors and designers use wood furring strips attached through the insulation back to the structure as a means to provide a convenient cladding attachment location (Straube and Smegal 2009; Pettit 2009; Joyce 2009, Ueno 2010).

The technique is particularly well suited to retrofit projects that might otherwise be limited (in terms of space conditioning energy use reductions) due to existing construction dimensional constraints. This fits directly into the Building America goals of substantial reductions in energy consumption. While the energy benefits are apparent and easy to understand, the practical implementation has run into barriers that have slowed widespread adoption.

There is significant resistance to its widespread implementation due to a lack of research and understanding of the mechanisms involved in the development of the vertical displacement resistance capacity. In addition, the long-term in-service performance of the system has been questioned due to potential creep effects of the assembly under the sustained dead load of the cladding and effects of varying environmental conditions.

Previous research has provided significant insight into the mechanics as well as long-term performance of exposed assemblies that use wood furring strips attached through the insulation

as a cladding attachment location (Baker 2013a; Baker and Lepage 2014). However, several key research questions still remain:

- What are the impacts of different fastener types in the system capacity?

- What is the impact of screw shaft bearing on the insulation material?

- What are the impacts of material expansion and contraction on the pre and post compression forces in the assemblies?

- Can deflection movement for heavier weight claddings be mitigated by denser fastener spacing?

The research completed was aimed at addressing these questions with the ultimate goal to help further the understanding of the mechanics involved. It was understood by the research team that detailed development of a full matrix of recommendations or specific design methodology was not going to be possible given the number of possible factors and testing that would have been involved. The primary intent was to focus on examining the relative magnitude of the discrete load components in the system to help further the general understanding and provide some preliminary guidance. Further refinements to the implementation of this strategy will be possible with additional testing and research.

1.2 Cost Effectiveness

A preliminary evaluation was completed looking at the incremental cost of the varying thickness of insulation installed to the exterior of the wall assemblies. This preliminary cost analysis used foil-faced polyisocyanurate (PIC) as the baseline exterior insulation. Cost data for the exterior insulation were taken from RS Means Construction Data (2011 Reed Construction Data). Costs included in the analysis were the installed cost of the insulation material, 1×3 wood furring strips spaced at 16 in. o.c., and wood screws spaced at 24 in. o.c. vertically for the attachment of the furring back to the structure. A cost markup of $100 per window in the reference model was used as an estimate of the additional cost for trim extensions that would be needed to account for the additional thickness of foam added to the exterior of the home. This value is an estimate, as actual costs can be highly variable due to the many different design choices available for window placement, exterior window trim design, and attachment.

Other items such as house wrap or sheathing tape, self-adhered membrane flashings, metal flashings, siding, and siding fasteners were omitted from the analysis, as these items are associated with recladding and water management, and would be part of the retrofit project regardless of the addition of exterior insulation.

Simulations were run using BEopt simulation software developed by the National Renewable Energy Laboratory. An example home was used as the baseline to help demonstrate the benefits of using exterior insulation as part of a house energy retrofit. This benchmark home was assumed to be around 1950s era two-story slab-on-grade construction and had the basic characteristics listed in Table 2.

Table 2. Benchmark House Characteristics

House Characteristics	ft^2
Finished Floor Area	2312
Ceiling Area	1156
Slab Area	1156
Wall Area	2799
Window Area	410 (17.7% glazing ratio)

The wall conductance performance was isolated from all other aspects of the home, to examine the cost effectiveness of this single strategy. The analysis was designed to examine the cost of the measure in conjunction with cost reductions due to lower energy use. The analysis combined the present worth of the cost of the measure (financed over a 5-year period at a 7% interest rate) and the cost of energy used (based on a 30-year period and a fuel escalation rate of 2%). A cost-optimized result has the lowest combined present worth of the both the cost of the measure and fuel cost over the period of the analysis. A cost-neutral result is one where the combined present worth of the measure and the fuel cost is lower than the present worth of the fuel cost of the benchmark home.

In this analysis, given the assumed age of the home, the benchmark home had an uninsulated wall cavity (as per guidance from the 2011 BA Benchmark Protocol). The benchmark house characteristics are listed in Table 3.

Table 3. Benchmark House Specifications

House Characteristic	Specification
Ceiling	Uninsulated, vented (R-2)
Walls	Uninsulated 2 × 4 @ 16 in. o.c. (R-3.8)
Windows	Double clear, metal frames (U = 0.45. solar heat gain coefficient = 0.55)
Infiltration	0.88 nACH

Table 4 illustrates the parametric steps that were run in the analysis. The analysis was completed for various climate zones ranging from 3A through 7A (as defined by the 2012 IECC) with the associated reference cities listed in Table 5.

Table 4. Parametric Steps and Cost

Parametric Step	Description	Cost/ft^2
R	Benchmark (uninsulated 2 × 4 wall)	N/A
1	R-13 cavity fill insulation	$2.20
2	R-13 cavity fill + 1 in. exterior insulation (R-6.5)	$3.55
3	R-13 cavity fill + 1.5 in. exterior insulation (R- 9.75)	$3.76
4	R-13 cavity fill + 2 in. exterior insulation (R-13) + 1 × 4 wood furring	$5.73
5	R-13 cavity fill + 2 layers of 1.5 in. exterior insulation (R-19.5) + 1 × 4 wood furring	$7.19
6	R-13 cavity fill + 2 layers of 2 in. exterior insulation (R-26) + 1 × 4 wood furring	$7.58

Table 5. Reference Cities

City	Climate Zone
Dallas, TX	3A
Kansas City, MO	4A
Boston, MA	5A
Duluth, MN	7A

Results of the analysis are provided in Appendix A. Results indicated that for cold climate zones (4 and higher), insulation up to 1 ½ in. (parametric step 3) was shown to be a cost-optimized solution. This resulted mainly due to a jump in the cost of the measure with the addition of wood furring strips and screw fasteners when thicknesses of exterior insulation of 2 in. or more were used. Even with the jump in costs, insulation thickness ranging from 2 in. to 4 in. (parametric steps 4, 5, and 6) were still demonstrated to be cost neutral as part of this simplified analysis in all cities except for Dallas, Texas.

While the analysis run focused on conductance improvements only, there is some argument to be made that the addition of exterior insulation would likely also improve the overall airtightness of the assemblies (Ueno 2010). The benefits from increased airtightness are known to be very important in cold climate construction; however, it is also more difficult to isolate and apportion to individual measures.

1.3   Other Benefits

Using exterior insulation has many additional benefits other than simply increased thermal resistance. The single largest benefit is the increased condensation resistance that this strategy provides for cold climate buildings (Straube and Burnett 2005; Lstiburek 2007). The placement of the insulation to the exterior of the building acts to keep all of the structural elements at a much more even temperature throughout the year, reducing the risk of interstitial condensation. For wood structures, this can significantly reduce the potential for wood decay; an added benefit is that the seasonal thermal and moisture variations of the wood frame are greatly reduced. In masonry building, the potential for freeze thaw is practically eliminated, since this approach not only keeps the masonry warmer, but also address the exterior rainwater absorption into the masonry, which is the leading moisture source related to freeze thaw damage to buildings.

In addition to keeping the structure warm and preventing condensation, the use of the furring strips creates a significant upgrade in water management. The increase in drainage and drying that is provided by the ¾-in. gap created by the furring strips provides much additional protection against water infiltration problems. The use of a drainage gap is a base recommendation for most cladding installations regardless of whether or not exterior insulation is used (Lstiburek 2010). The fact that the furring strips are an intrinsic component of this system provides a significant added benefit to the long-term durability of these wall assemblies.

2 Previous Work

The earliest work that examined a wood-to-wood connection with rigid insulation installed in the joint was conducted by the U.S. Department of Agriculture Forest Products Laboratory (Aune and Patton-Mallory 1986a, 1986b). This researched looked to validate the European Yield Theory for wood-to-wood connections with gaps up to 1 in. The European Yield Theory (first conceived in the 1940s) is based on an equilibrium of forces caused by rotation of fasteners in wood members; this theory predicts performance of the connection at the point where yielding of materials (wood or fastener) has developed. The equations as set out in the American Forest and Paper Association Technical Report 12 *General Dowel Equations for Calculating Lateral Connection Values* predict performance of a multitude of failure modes, with the governing mode being the one with the lowest yield capacity (AFPA 1999).

The results from the Forest Products Laboratory, while similar in concept, did not provide much useful data when examining the attachment of furring strips over the insulation for cladding attachment purposes. A 1-in. gap may be considered large when looking at wood-to-wood structural connections, but it is small when looking at the application of furring strips installed over insulation where a minimum 2 in. would generally be expected, and thicknesses up to 8 in. or more being possible. Still, these tests being conducted with extruded polystyrene (EPS) insulation, gave way to the idea of possibly adopting the yield equations for the application of wood furring strips over exterior insulation.

Several groups such as the Foam Sheathing Coalition, the New York State Energy Research and Development Authority/Steel Framing Alliance funded research into the vertical load capacity of furring strips, installed over exterior insulation, that are fastened back to a wood or steel structure. The primary goal of the research by the Foam Sheathing Coalition and the New York State Energy Research and Development Authority/Steal Framing Alliance was to develop pre-scriptive code tables for attaching cladding to framing over continuous insulation (Bowles 2010). The research methodology adopted the European Yield Theory as the basis for the analysis.

For wood frame test specimens, the measured data were compared to the predicted performance of the yield equations as determined by the TR-12 (and calculated based on actual properties of the materials used in the testing). This research concluded that the 5% offset yield prediction as calculated using the TR-12 formulas, resulted in a reasonably accurate prediction of the shear load at a deflection of 0.01 in. While there was no mathematical connection between these values, the research team considered this to be an adequate basis for designing for a 0.01-in. deflection limit given the scope of the research. In addition, a divisor of 1.5 was applied to the calculated results to address potential concerns of assembly creep under sustained loads. The methodology was used to develop prescriptive code tables for attaching furring strips to framing over continuous insulation (Bowles 2010).

In 2011, Building Science Corporation (BSC) under the Building America Program began what turned out to be a multiyear research program that examined both short-term loading as well as long-term loading of wall assemblies using furring strips fastened back through the insulation as the primary cladding support structure (Baker 2013a, 2013b; Baker and Lepage 2014). The combined results of this research are discussed below.

During the course of reviewing previous research, BSC determined that acceptable deflection instead of ultimate capacity of the systems governed the design. For lap sidings and panel claddings with joints (metal, vinyl, wood, and fiber cement), movement is aesthetic in nature and not a health and safety issue. The acceptable amount of deflection will be a function of acceptable aesthetics for the cladding system chosen. For most lap siding or panel cladding systems, variations up to 1/16 in. or even 1/8 in. may be acceptable because the material and installation tolerances are easily greater than the potential gap development (Baker 2013a, 2013b). This analysis shaped the research plan, which intended to look at vertical movement of the furring strip with respect to the structural wall as the performance criteria for design.

The research conducted by BSC was developed around two principal topics: (1) system mechanics, and (2) long-term sustained loading. The test plan also expanded upon previous testing by the American Forest and Paper Association and the New York State Energy Research and Development Authority (which had typically been limited to EPS insulation only) to include the following insulation types:

- EPS

- Extruded polystyrene (XPS)

- Foil-faced PIC

- Rigid mineral fiber (MF).

Full-scale initial load response (or short-term) testing of assemblies using 4 in. of exterior insulation indicated a system capacity of approximately 45–50 lbf per fastener at 1/16 in. of vertical deflection. The results were consistent regardless of insulation type used except for one outlier test of rigid MF that demonstrated a capacity of 65 lbf at 1/16 in. of deflection (Baker 2013a).

Observations made during the initial load full-scale testing (such as slippage between material layers) raised questions regarding mechanisms that contributed to vertical displacement resistance. The small-scale load component tests were developed to evaluate specific mechanisms of load resistance with the hope to better understand the relative magnitude of each in the development of the full system capacity. The components of interest were: (1) rotational resistance of the fasteners; (2) strut and tie component of the compression of the insulation; and (3) friction between material layers. These three load components are illustrated in Figure 1.

The results of the research provided some useful insights into the magnitude of the various load components, even if many of the exact mechanisms could not be accurately predicted. From the results it appeared that friction forces in the assembly may be significant, particularly at initial and small vertical deflections. The amount of friction due to precompression could be quite variable, however, as measured precompression forces were noted to change dramatically over time and with changing environmental conditions. The strut and tie model was demonstrated to provide additional capacity; however, the results were not clear as other unanticipated factors appear to affect the total capacity such as additional resistance from screw shaft bearing on the insulation materials. The bending capacities of the screw fasteners were noted to contribute a much lower amount to the system total when compared to the other studied mechanisms; however again, the testing did not yield conclusive results (Baker and Lepage 2014).
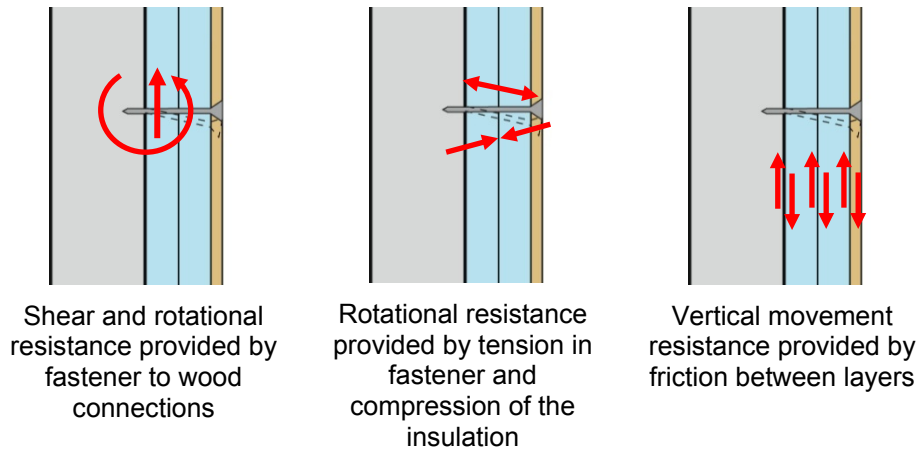
| Shear and rotational resistance provided by fastener to wood connections | Rotational resistance provided by tension in fastener and compression of the insulation | Vertical movement resistance provided by friction between layers |

Figure 1. Load component schematics

(Baker and Lepage 2014)

Long-term tests were also completed to evaluate the performance of the systems under sustained gravity loads. The first series of tests were completed on full-scale assemblies with 4 in. of rigid insulation in a controlled laboratory environment. Four assemblies were tested using different insulation types (as listed previously). Each assembly was loaded to 30 lbf per fastener. A fifth assembly was also constructed using 4 in. of XPS insulation. This fifth assembly was loaded to only 8.6 lbf per fastener.

The test assemblies loaded to 30 lbf per fastener demonstrated very stable performance in the laboratory environment. Most assemblies did not record a deflection greater than 1/32 in., with the exception of the PIC sample, which had a deflection of ~3/32 in. The fifth assembly loaded to 8.6 lbf per fastener had very little observed movement (~1/200 in.) (Baker 2013a).

During the course of the research it was noted that movement of the assemblies appeared to have a stronger correlation with environmental changes that from sustained loading as both upward as well as downward movement was noted. From the test data collected, it was not possible to differentiate movements of the samples that result from prolonged loading (creep) or from environmental changes. Because of the suspected climate sensitivity, additional testing of exterior samples exposed to a variety of temperature and humidity conditions was recommended.

A second round of long-term testing was developed to study the impacts of climate exposure on the vertical movement of furring strips attached over exterior insulation. A total of 12 assemblies were constructed (four different insulation types loaded to three different levels, 8 lbf/fastener, 15 lbf/fastener, 30 lbf/fastener) in an outdoor exposed environment. Vertical deflection movements of the furring strip with respect to the framing were measured at various intervals between July 2012 and September 2012. Assemblies loaded 8 lbf per fastener had recorded movement on the order of 1/32 in. Similarly, assemblies loaded to 15 lbf per fastener had recorded movement on the order of 1/32 in., with the exception of the EPS assembly, which measured around ⅛ in. It was noted, however, that the majority of the movement in the EPS assembly occurred during the initial loading period and that the long-term movement was in line with the other assemblies. Assemblies loaded to 30 lbf per fastener had recorded movement between ⅛ in. and ¼ in. (Baker and Lepage 2014).

As a subset to this research, one of the assemblies was monitored over the course of 3 days to examine the daily movement of the furring strip. Daily movements on the order of ±1/64 in. to ±1/32 in. were measured over the 3-day period. This movement magnitude was greater than the movement recorded during the laboratory long-term loading testing conducted the previous year, reinforcing the importance of climate exposure on the assemblies (Baker and Lepage 2014).

3 Analysis and Test Method

The research plan is divided into several distinct sections:

1. Fastener bending

2. Screw shaft bearing

3. Expansion and contraction of materials

4. Fastener spacing

5. Environmental exposure.

In order to limit the number of variables across the various elements of the research, all of the tests were designed to keep certain aspects consistent so that results from one test can be more directly compared to test results from another test. The basis of design for the test assemblies is highlighted in Table 6.

Table 6. Materials Used in the Laboratory and Field Testing

Component	Material
Framing	2 × 4 spruce-pine-fir (SPF) standard wood framing
Sheathing	7/16-in. oriented strand board (OSB)
Building Wrap	Dupont Tyvek building wrap
Insulation	4-in. thick rigid insulating sheathing (2 layers of 2 in.)
Furring Strips	Nominal 1 × 3 SPF utility-grade lumber
Screws	6-in. long screws

Results from past research did not indicate that insulation type greatly affected the measured performance. In order to reduce the test iterations for this research, the insulation types were limited to two types (Table 7). The choice on insulation type was based primarily on availability of materials.

Table 7. Insulation Materials

Insulation Type	Product	Brand
Type IV XPS	C-200 Styrofoam	Owens Corning DOW Chemical
Foil-Faced PIC	Thermax CI	DOW Chemical

3.1 Fastener Bending

Previous research conducted by BSC in 2011 and 2012 maintained a single fastener type across the testing in order to avoid introducing another variable into an already complex system. The basis of design was assumed to be a #10 standard zinc-plated wood screw. In reality many fastener types are available and used by contractors for this application. Testing of four different fasteners was completed to evaluate the importance of fastener type on the system. The four fasteners chosen are listed in Table 8 and depicted in Figure 2.

Table 8. Screw Fastener Types

Screw Type	Length
#10 Standard Zinc-Coated Wood Screw	6 in.
#10 Exterior-Grade Coated Wood Screw	6 in.
Fastenmaster Headlok	6 in.
¼-in. Hot Dipped Galvanized Lag	6 in.

Figure 2. Screw fastener types

A random sample of five of each type of screw was selected and the physical dimensions of each screw (Figure 3) were measured using digital calipers. The average dimensions for each screw type are listed in Table 9.
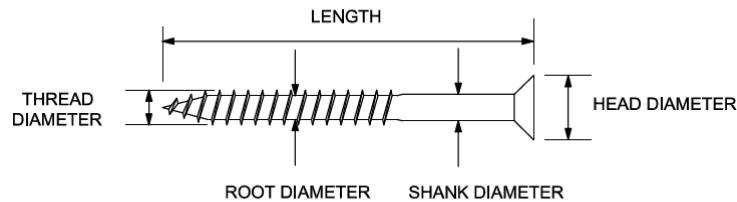
Figure 3. Measurement locations for fastener characterization

Table 9. Screw Measurements

Screw Type	Length (in.)	Shank Diameter (in.)	Shank Length (in.)	Root Diameter (in.)	Thread Diameter (in.)	Head Diameter (in.)
Standard #10 Wood Screw	6	0.149	1.9	0.136	0.198	0.368
Coated #10 Wood Screw	6	0.153	3.5	0.136	0.220	0.369
Headlok	6	0.196	4	0.179	0.259	0.635
¼-in. Lag	6	0.241	1.9	0.194	0.253	0.431

All of the testing was completed by incrementally increasing the load with calibrated dead weights and recording the associated deflection of the system. Each assembly was loaded until approximately ⅛ in. of deflection[1] was recorded. The ⅛-in. deflection was felt to be representative of twice the acceptable deflection (1/16 in.) of cladding systems in service (Baker 2013a, 2013b). Two different test configurations were used to evaluate the bending resistance of different fasteners.

3.1.1 Test 1: Cantilever Bending Test

Test 1 was designed to evaluate the screw performance under simple bending similar to a cantilever beam. The fasteners were loaded at a ⅜-in. inboard of the screw head to represent the center thickness of the wood furring strip. Deflection measurements were taken between the face of the OSB sheathing and the top of the screw head using a dial deflection gauge (Figure 6). All four fastener types were used in this phase of the testing with three tests for each type being completed. Schematics of the test setup are shown in Figure 4 and Figure 5. The test procedure is outlined in Appendix B.
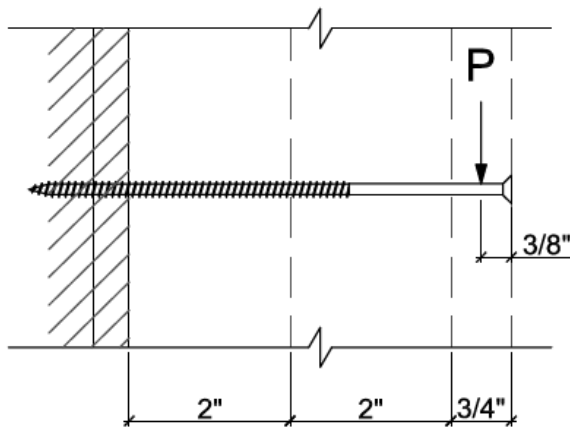
Figure 4. Bending test 1 simple cantilever schematic

Test sample designed to accommodate 3 individual tests for each sample built. This was done to allow identical test samples to be constructed for both cantilever tests as well as double bending tests. Each of the three test fasteners is loaded independently and at different times.
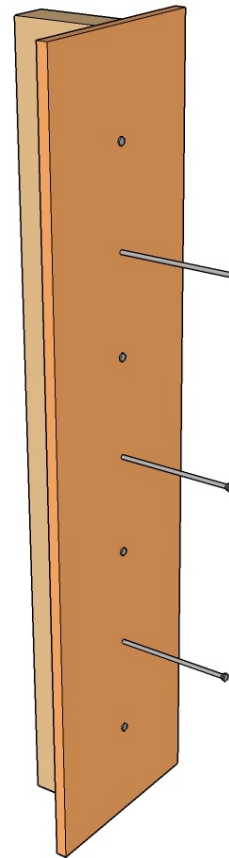
Figure 5. Bending test 1 test sample configuration

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[1] Some of the tests were loaded beyond the ⅛ in. in order to get enough data points in the analysis.
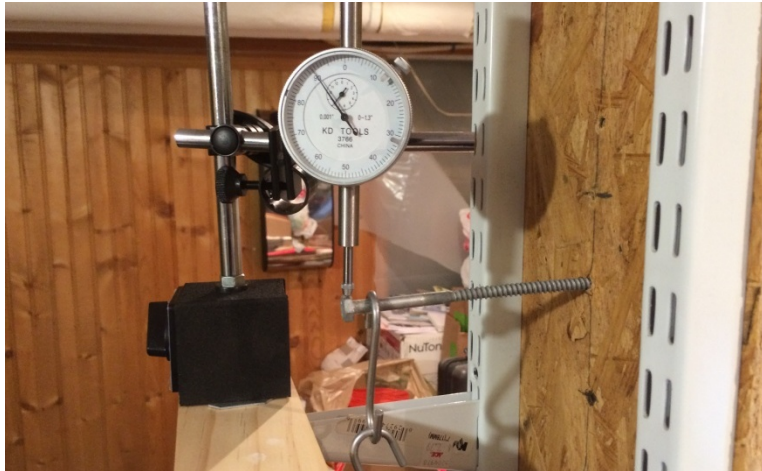
Figure 6. Simple cantilever screw bending test

3.1.2 Test 2: Double Bending Test

Test 2 evaluated the screw performance with double bending similar to a beam with a fixed end and a free and guided end. For this series of tests two fasteners were installed through a 1 × 3 wood furring strip. The fasteners were spaced 16 in. apart. Two fasteners were used to limit rotation of the furring strip when loaded. In addition, the load was attached to the midpoint of the ¾-in. dimension near or at the bottom of the furring strip to create a load path at ⅜ in. inboard of the screw head as used in Test 1. Deflection measurements were taken between the face of the OSB sheathing and a metal angle bracket attached to the face of the furring strip using a dial deflection gauge. For this phase of testing the fastener types were limited to the standard #10 wood screw and the Headlok screws based on the results of the simple cantilever tests. For each fastener type a minimum of three tests was completed. Schematics of the test set up is illustrated in Figure 7 and Figure 8. The full test procedure is outlined in Appendix C.

Two different test protocols were used during this phase of the testing. The development of the two protocols was due to a preliminary test where the last load increment was maintained for several days. During this time of sustained loading, additional system deflection was noted. Since much of the previous testing conducted by BSC and others followed a relatively quick timeframe for loading, it was felt to be important for comparison purposes to examine the screw bending load component following a similar "initial load response" test methodology. In addition, given that additional system deflection was noted under the sustained load, it was also felt to be important to conduct some tests that allowed the assembly to "settle-in," which led to the second "settled load response" test methodology. The intent was to see if there was a significant difference between the two results, as this may impact the long-term performance of the furring strip assembly.
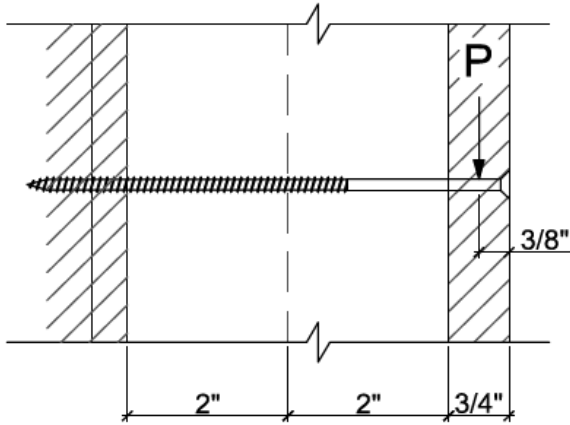
Figure 7. Bending test 2 double bending schematic

Test sample designed to accommodate 1 test for each sample built. Each test was completed by loading the furring strip at 2 screws attached into the middle of the narrow dimension of the furring strip 1 ½ in. from the bottom. The deflection measurement was taken at an angle bracket fastened to the face of the furring strip.
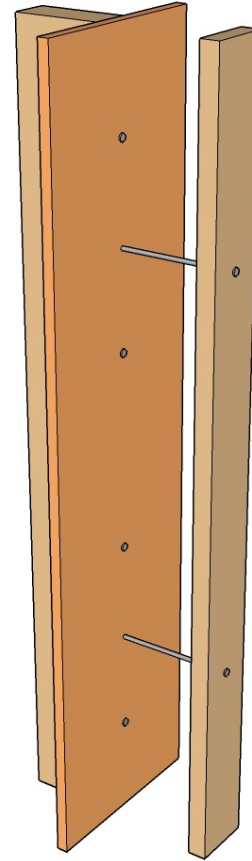
Figure 8. Bending test 2 test sample configuration

3.1.2.1 Protocol 1—Initial Load Response

The test assembly was loaded incrementally at approximately 3 lb per increment every minute until the desired deflection was achieved.

3.1.2.2 Protocol 2—Settled Load Response

The test assembly was loaded incrementally at approximately 3 lb per increment with each load increment maintained for an hour or more.[2] In this protocol the assembly was unloaded and then reloaded between each load increment.

3.2 Screw Shaft Bearing

The screw shaft bearing on the insulation was suspected to be an additional source of resistance to vertical displacement of the furring strips (Baker and Lepage 2014). Additional single-screw bending tests were completed to evaluate the impact of the insulation material on the deflection resistance of the assembly.

The impacts of screw shaft bearing were evaluated using a modification of Test 1 (See Appendix B) from the previous section. For these tests insulation was added to the test assembly. In order to isolate other impacts such as friction due to compression forces and rotation resistance from

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[2] Some increments were loaded for several days where the test was run over the course of a weekend.

the strut and tie effect, no furring strip was used in the tests. The test fastener was installed through the insulation with the fastener head held ¾ in. away from the face of the rigid insulation. The test fastener was then loaded ⅜ in. away from the fastener head to simulate the center load of a flush driven fastener in a ¾ in. furring strip (Figure 9).

The test configuration was designed to rigidly attach the base layer of insulation to the test frame while leaving the outer layer to move more freely. This was felt to be the best means to capture what might be occurring in the full scale test as the base layer of insulation is more coupled to the sheathing and the outer layer of insulation more coupled to the furring. To accomplish this, the base layer of the insulation was attached to OSB sheathing using four 8d nails spaced approximately 4 in. away from the location of the test fastener. The second layer of rigid insulation was taped at the top of the assembly using strips of 2-in. wide sheathing tape.

One additional test was conducted that rigidly attached both layers to see what the impact was. For this test set up both layers of rigid insulation were fastened using four #10 wood screws and 1-in. diameter metal plate washer. The fasteners were again spaced approximately 4 in. away from the location of the test fastener.
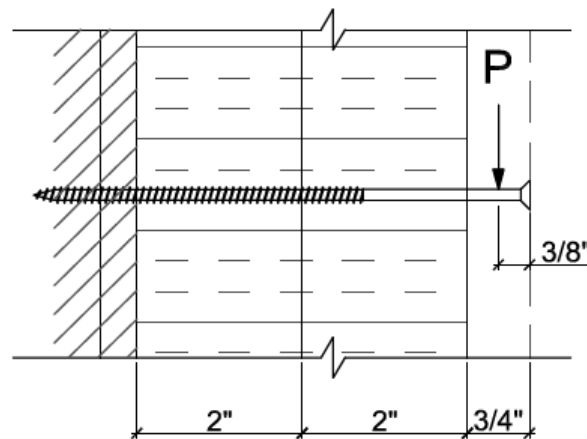
Figure 9. Screw shaft bearing test schematic

3.3   Expansion and Contraction of Materials

Compression forces have been identified to be potentially significant in limiting the vertical deflection of the furring strips (Baker 2013a; Baker and Lepage 2014). Compression forces are introduced into the assembly at (1) the time fastening of the furring strips to the structure, and (2) at loading of the furring strips due to fastener rotation (strut and tie effect). These compression forces were also demonstrated to be highly variable as they changed over time due to an initial relaxation and under changing environmental conditions. A test protocol was developed to examine the impacts of temperature on the compression forces present in the assembly.

A test protocol was developed to examine the impacts of environmental changes on the compression forces in the assembly (See Appendix D for the test protocol). Two test assemblies were constructed, the first using XPS insulation and the second using PIC (Figure 10 through Figure 13). The screw fastener was installed through the center of a low profile load cell placed

at the face of the wood furring strip (Figure 14). The screw clamped the entire assembly together and was tightened to an initial pre-compression force of approximately 150 lb.[3] Due to limited availability of fastener length, the overall insulation thickness was reduced for the testing from 4 in. to 3 in. to accommodate the added thickness of the load cell and metal washers. This was done so that the amount of fastener embedment into the structure could be maintained at 1 ¼ in. (typical embedment depth used in other aspects of BSC's research).
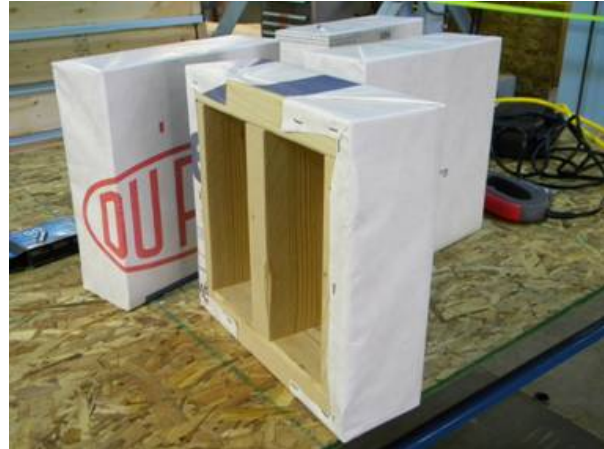

Figure 10. Assembly frame

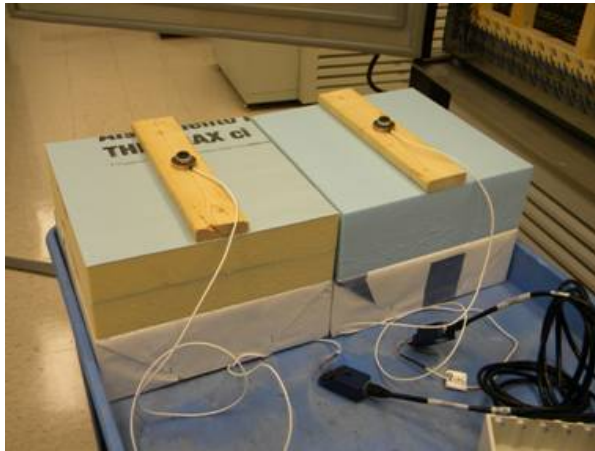**Figure 11. Test assemblies prior to installation of insulation**

Figure 12. Test assemblies during initial relaxation period

Figure 13. Framing for climate chamber opening

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[3] 150 lb is the average precompression force measured in research conducted by BSC in 2012 for a flush-driven flat head #10 wood screw.
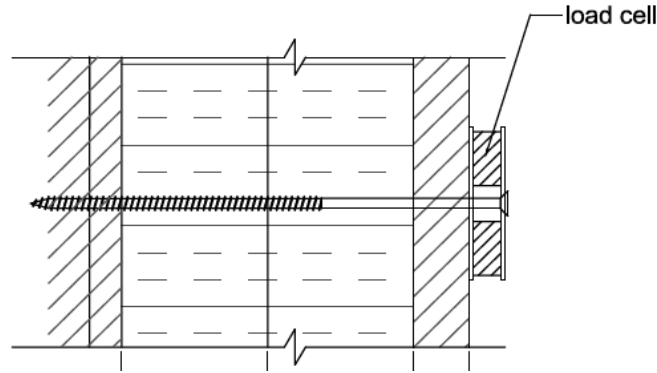
Figure 14. Expansion and contraction test schematic

After construction, the test assemblies were held at constant temperature and relative humidity (RH) until the initial relaxation occurred and the compression forces stabilized (Figure 15). The typical relaxation noted for the assemblies was between 30 lbf and 50 lbf (approximately 20%–30% of the initial measured compression force).

Once the compression force became stable, the assemblies was inserted into a climate chamber and cycled through a variety of temperatures over several days (Figure 16). The temperatures were varied between –30°F and 130°F over a 24-hour period. The cycle was repeated for 5 days. During the cycles the temperature, RH, and compression forces were measured and recorded.

Figure 15. Screen shot of data collection during initial relaxation phase

Figure 16. Assemblies installed in climate chamber opening

3.4 Fastener Spacing

Previous research has used an assumption that the capacity of the systems can be determined on a per fastener basis. The testing conducted by the New York State Energy Research and Development Authority used test samples with two fasteners (Bowles 2010). BSC tests were conducted using a consistent vertical fastener spacing of 16 in. o.c. on 96-in. tall test assemblies with a total of seven fasteners per furring strip (Baker 2013a; Baker and Lepage 2014).

The impact of fastener spacing was evaluated through large-scale full assembly tests (see Appendix E for the test protocol). The tests were completed by applying a load to the furring strip and measuring the deflection difference between the furring strip and the OSB sheathing. The assemblies were 96 in. tall and 16 in. wide, with a single furring strip attached back to the structure (Figure 17). The load was applied with an overhead hoist and measured with a load cell installed between the hoist and the furring strip (Figure 18 and Figure 19). The deflection was recorded with a linear voltage displacement transducer (LVDT). The magnetic base of the LVDT was attached to metal plates fastened to the base of the test assembly structure. The deflection was measured at a metal angle bracket attached to the front face of the wood furring strip (Figure 20).

Figure 17. Full height deflection test assembly

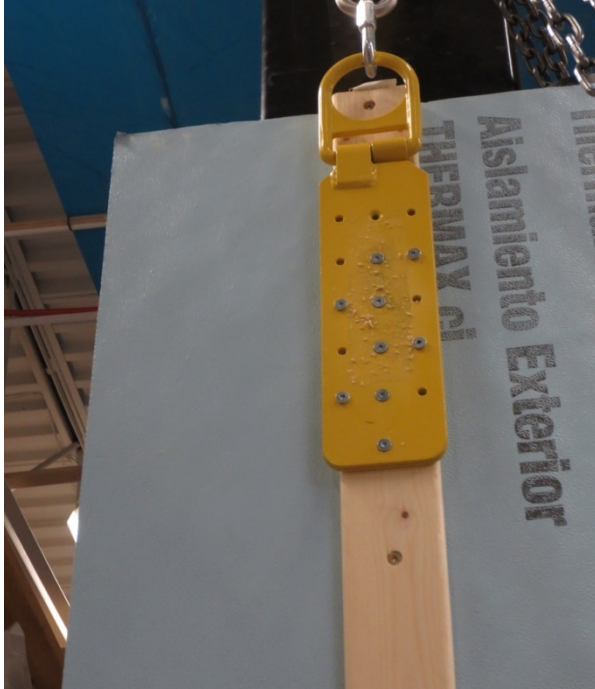**Figure 18. Load cell installed between furring strip and hoist**

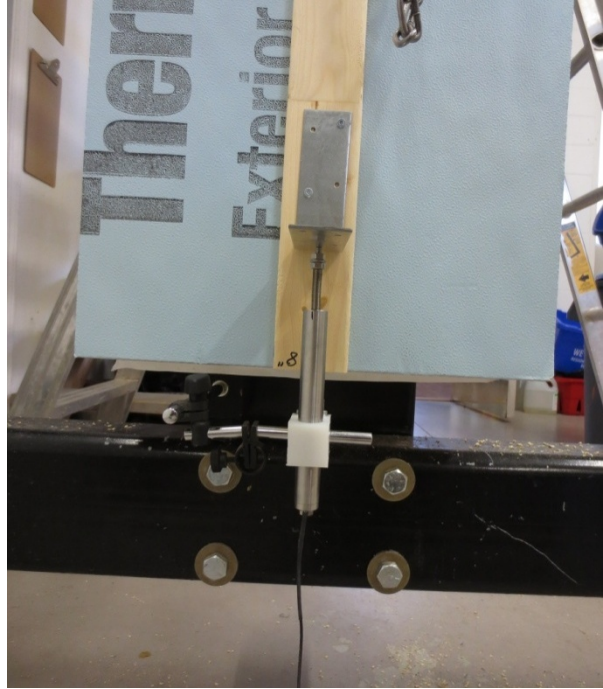**Figure 19. 5000-lb anchor at top of furring strip**

Figure 20. LVDT at base of assembly

Three different fastener spacings were evaluated. For each assembly a fastener was placed at the top and bottom of the furring strip as well as at the spacing indicated. This resulted in the following number of fasteners used per test setup:

- Number of fasteners = wall height/screw spacing + 1

- 8 in. o.c. = 96/8 + 1 = 13 fasteners total

- 16 in. o.c. = 96/16 + 1 = 7 fasteners total

- 24 in. o.c. = 96/24 + 1 = 5 fasteners total.

The load magnitude and deflection data were simultaneously recorded during each test.

3.5 Environmental Exposure

Previous research identified that changing environmental conditions may have a significant impact on the vertical movement of the system (Baker 2013a, 2013b; Baker and Lepage 2014). A field exposure test was developed to evaluate the long-term performance and movement of furring strips in an exposed outdoor environment over a 1-year period.

The exposure test site was located in Waterloo, Ontario, Canada. A total of 12 assemblies were constructed (four different insulation types loaded to three different levels, 8 lbf per fastener, 15 lbf per fastener, and 30 lbf per fastener). Each assembly was 96 in. (8 ft) tall by 16 in. wide constructed with 2 × 4 wood framing and 7/16 in. OSB sheathing covered with a spun bonded polyolefin building wrap. The insulation was installed in two layers of 2 in. thickness for a total thickness of 4 in. A 96-in. long furring strip was attached back through the insulation to the stud through the use of 6-in. long #10 pan head wood screws spaced 16 in. o.c. vertically (total of seven fasteners per panel).

Each test assembly was loaded with metal weights evenly distributing the required load over the wood furring to replicate the mass distribution of a cladding (Figure 21). Weights were used in lieu of real claddings to isolate other potential effects caused by the cladding system itself (shrinkage or expansion, weight changes due to rainwater absorption, differences in solar radiation exposure of the underlying insulation, etc.).

The walls were oriented south, as it was hypothesized that the temperature effects of solar radiation may play a noticeable role in the effective deflection of the walls. In order to protect the insulation from ultraviolet damage, the walls were covered with a lightweight corrugated plastic cladding panel (Figure 22).

Figure 21. Exposed wall assemblies loaded to representative cladding weights

Figure 22. Lightweight cladding panel installed over the test wall assemblies

Vertical deflection movements of the furring strip with respect to the framing were measured at various intervals between the beginning of July 2012 and end of August 2013 (415 days total). The measurements were made using digital calipers between a square metal post attached to the bottom of the frame and a metal angle attached to the face of the wood furring strip.

4 Discussion

4.1 Fastener Bending

The testing completed in this phase of the research was looking to examine the load resistance component provided by the screw fasteners compared to the total measured capacity of the system. The results of the testing for the simple cantilever and double bending can be seen in Figure 23 and Figure 24, respectively.
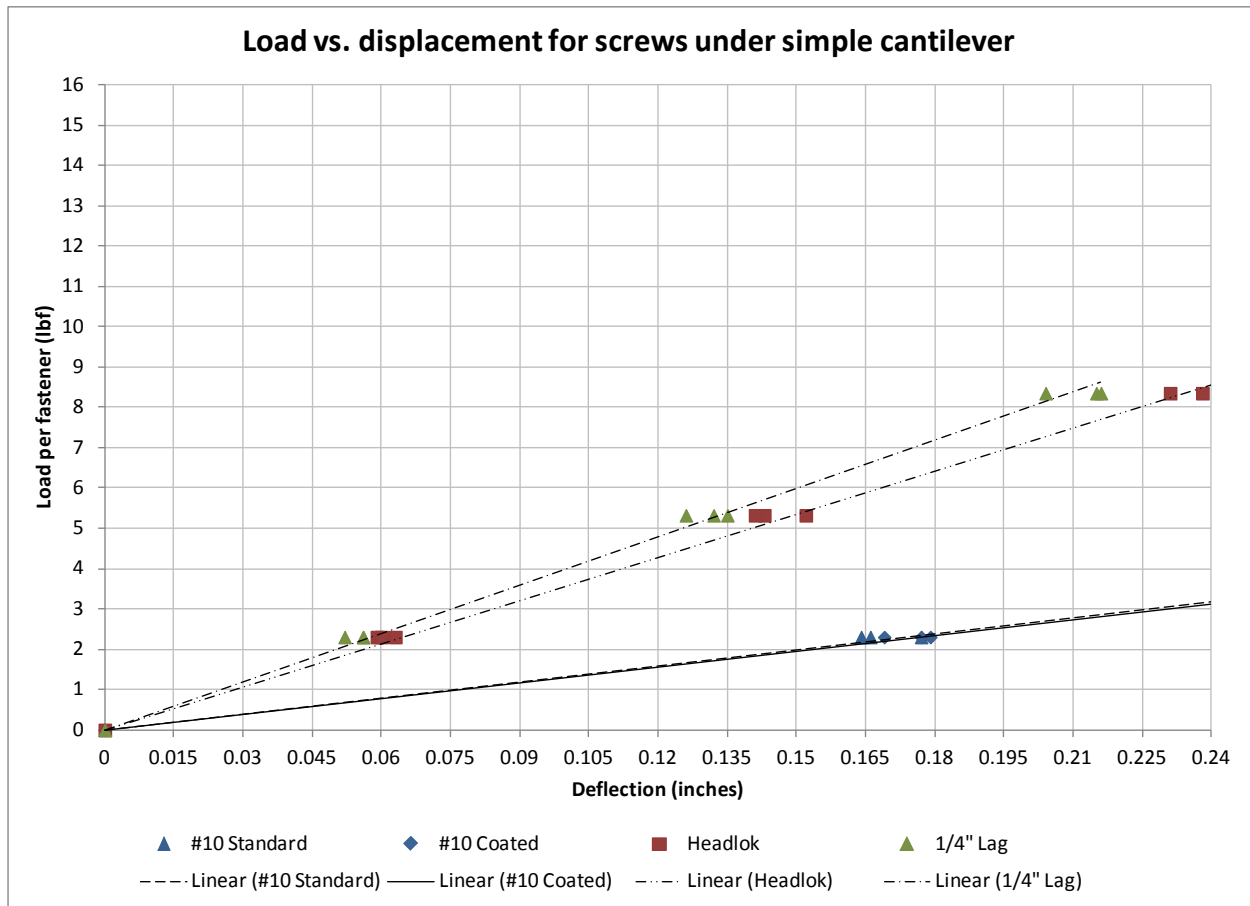
Figure 23. Load versus displacement for various screw types under cantilever loading
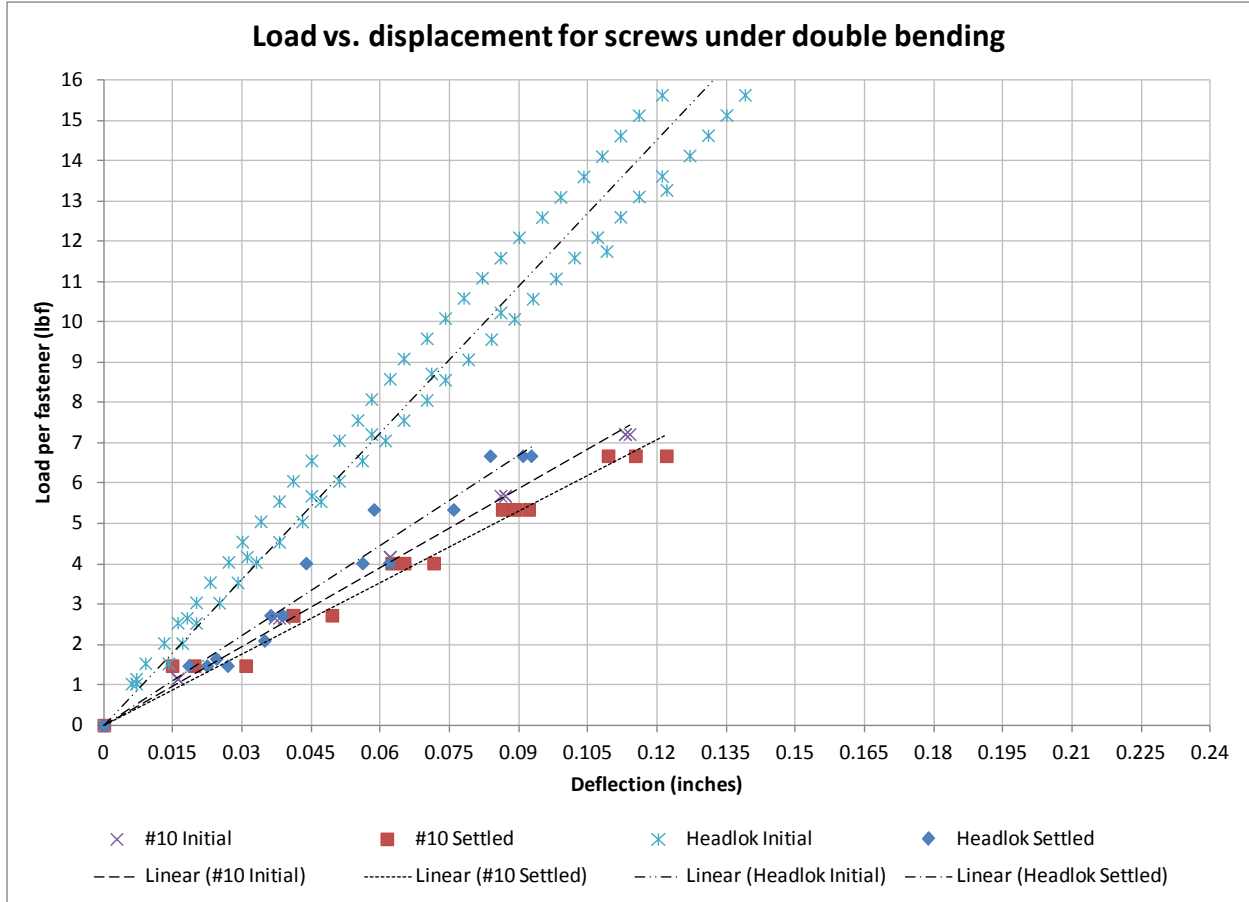
Figure 24. Load versus deflection of screws under double bending

The tests completed with #10 wood screws had very consistent and repeatable results for both simple cantilever and double bending tests. In addition, the results from double bending testing did not demonstrate any notable difference regardless of whether Protocol 1 (initial load response) or Protocol 2 (settled load response) was used. A total of six double bending tests were performed (three initial load response and three settled load response) with almost identical results.

The capacity of a cantilevered #10 wood screw at 1/16 in. deflection was noted to be around 1 lbf. By contrast the capacity of a #10 wood screw under double bending at 1/16 in. was noted to be around 4 lbf. The screws subjected to the double bending demonstrated 4 times the capacity of the simple cantilever tests (Figure 25).
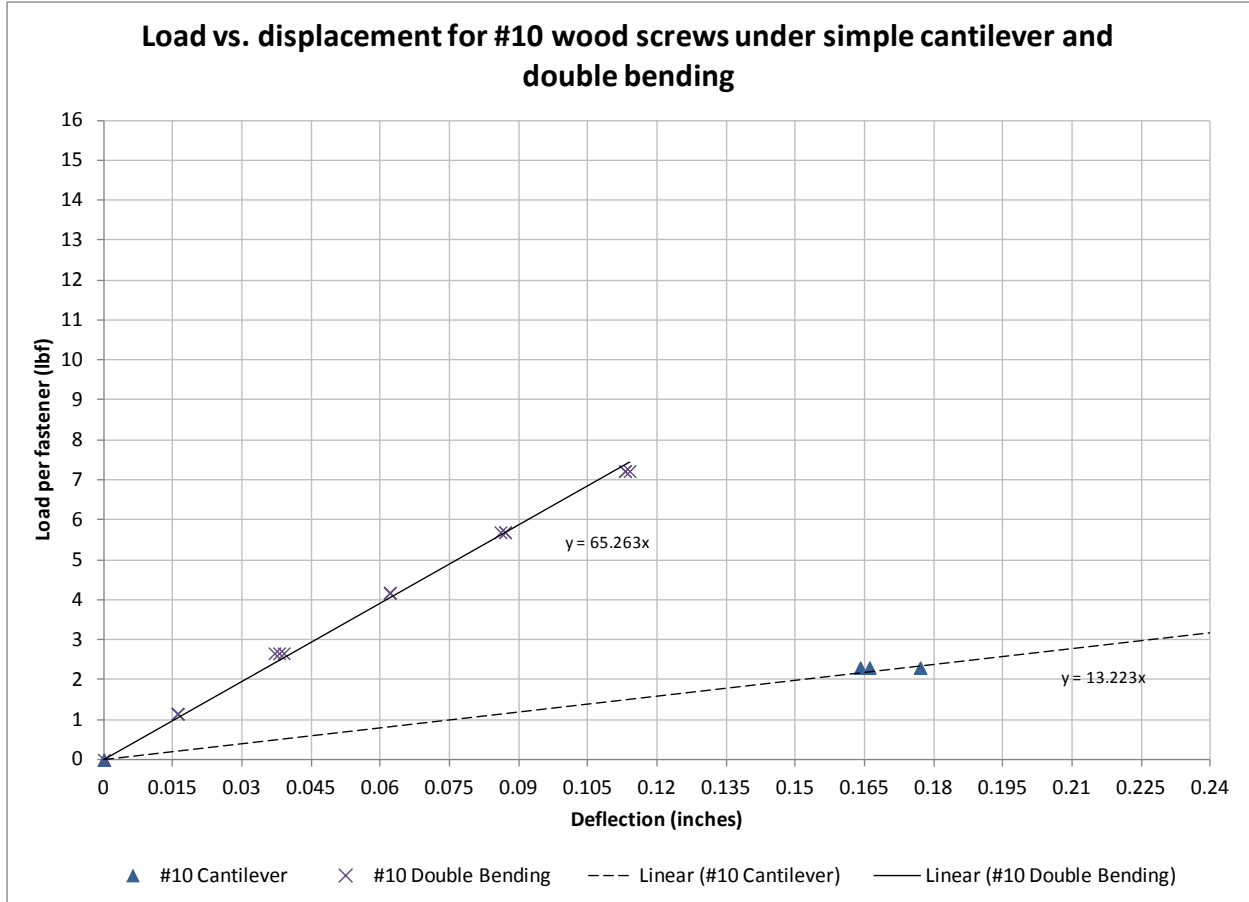
Figure 25. Load versus deflection for #10 wood screw under simple cantilever and double bending

The simple cantilever tests completed with the Headlok screws were very consistent; however, there was some fluctuation in the measured results from the double bending test depending on which loading protocol was used.

From the results the capacity of a cantilevered Headlok wood screw at 1/16 in. deflection is around 2 lbf. By contrast the capacity of a Headlok wood screw under double bending at 1/16 in. is around 7 lbf based on initial load response tests and 4 lbf based on settled load response tests. The results from the initial load response tests were about 3.5 times the magnitude of the simple cantilever tests. The results from the settled load response tests were around 2 times the magnitude of the simple cantilever tests (Figure 26).
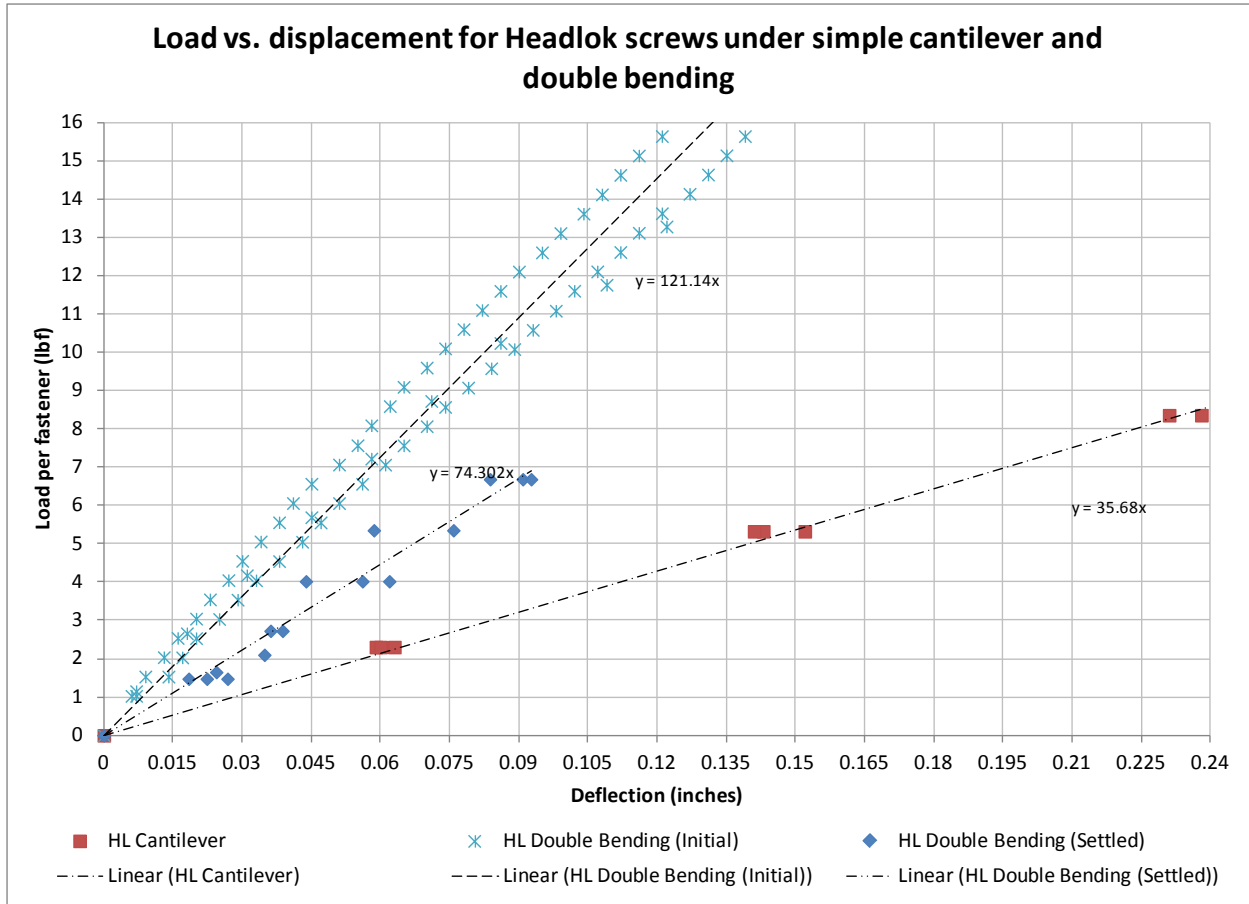
Figure 26. Load versus deflection for Headlok screw under simple cantilever and double bending

The difference in the initial load response and settle load response test with the Headlok fasteners may be due to several factors. One possibility is bearing failure of the wood furring at the fastener shaft due to the magnitude of the loading. Another possibility is due to slippage of the furring along the length of the fastener shaft under loading. Initially four tests were completed following Protocol 1, with results from one of the tests being questioned due to noted slippage of the screw head at the furring strip (Figure 27). The noted slippage correlated in a drop in the system load response capacity. Slippage was also a noted with the tests completed following Protocol 2.

The slippage was thought to be due in part to the geometry of the fastener head. The Headlok fastener has a cone profile that extends 3/16 in. inboard of the flat portion of the screw head that would push the furring strip inwards along the screw shaft during vertical loading of the system.

In order for the slippage to occur some bearing settlement of the wood furring on the fastener must occur as well. It is unclear at this point if the movement (1) was a result of bearing failure of the wood; (2) contributed to additional bearing failure of the wood; or (3) was some combination of the two.

Slippage of this nature would not be expected in a full system configuration, as the rigid insulation would prevent the inward movement of the furring strip along the shaft of the fastener.

Due to this it is felt that the results of the two test protocols provide a reasonable boundary of the expected performance of the system.
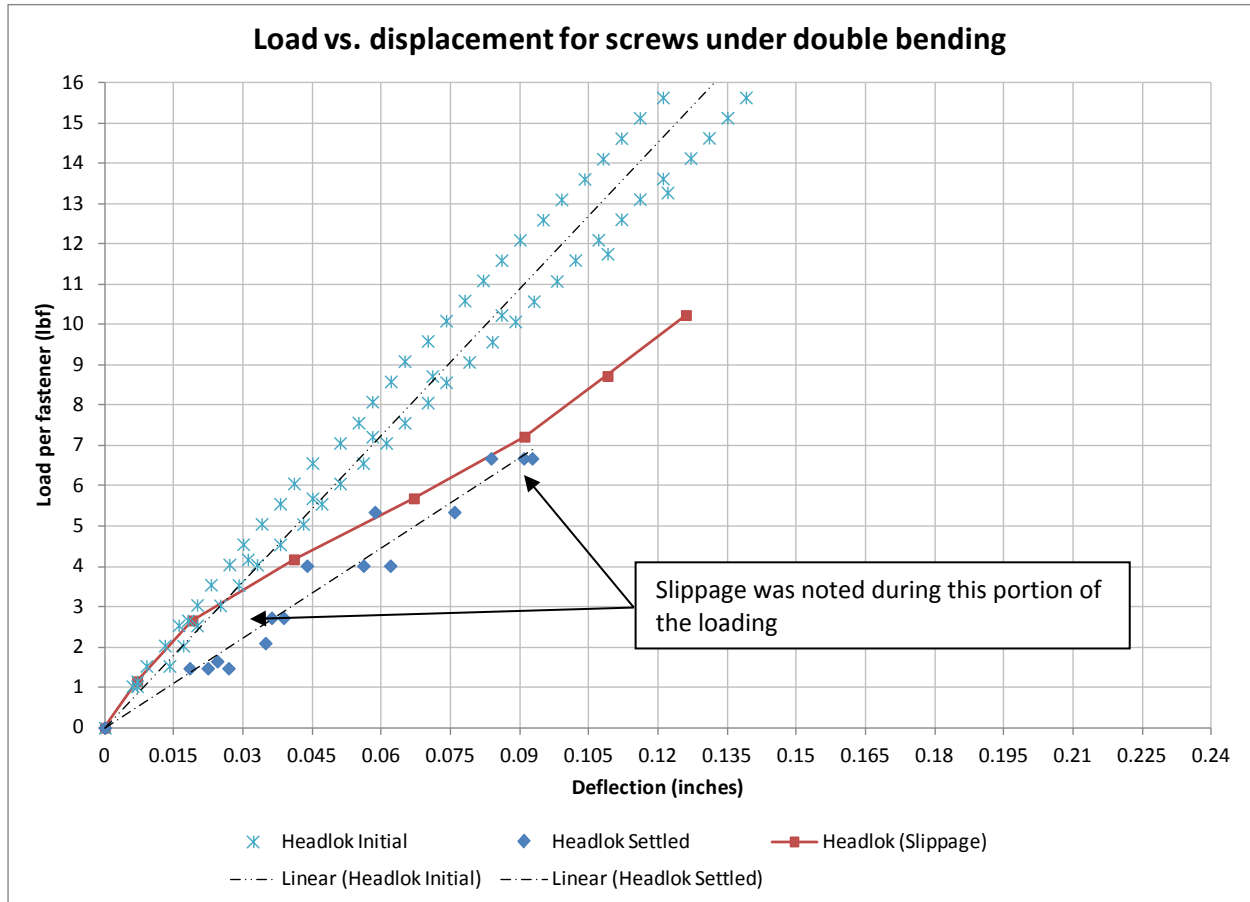
Figure 27. Load versus deflection of Headlok screws under double bending—effects of screw head slippage

4.2 Screw Shaft Bearing

The intent of the screw shaft bearing testing was to examine the effects of the insulation on the bending resistance capacity of a fastener. Devising a test protocol that could accurately capture these effects was not possible, since the insulation is coupled with the furring strip and will move as the furring strip deflects. Also, using furring strips in the test were not possible as other effects from system friction and compression would be captured in the test results. Due to this, the intent was only to get a sense of the potential magnitude of the screw shaft bearing, and not to draw any strong conclusions from the test results.

The results of the test are illustrated in Figure 28. Based on the original test setup with only the base layer rigidly attached, the insulation increased the capacity of the screw fastener from around 1 lbf to 1.5 lbf (PIC) to over 2 lbf (XPS).

In the second test where both layers of insulation were rigidly attached back to the structure, the initial load response capacity was approximately 7 lbf. In the second test, the assembly was also

allowed to stay loaded for 3 days until movement stabilized. Even after settling, the load was approximately 5 times that of a simple cantilever test with no insulation.
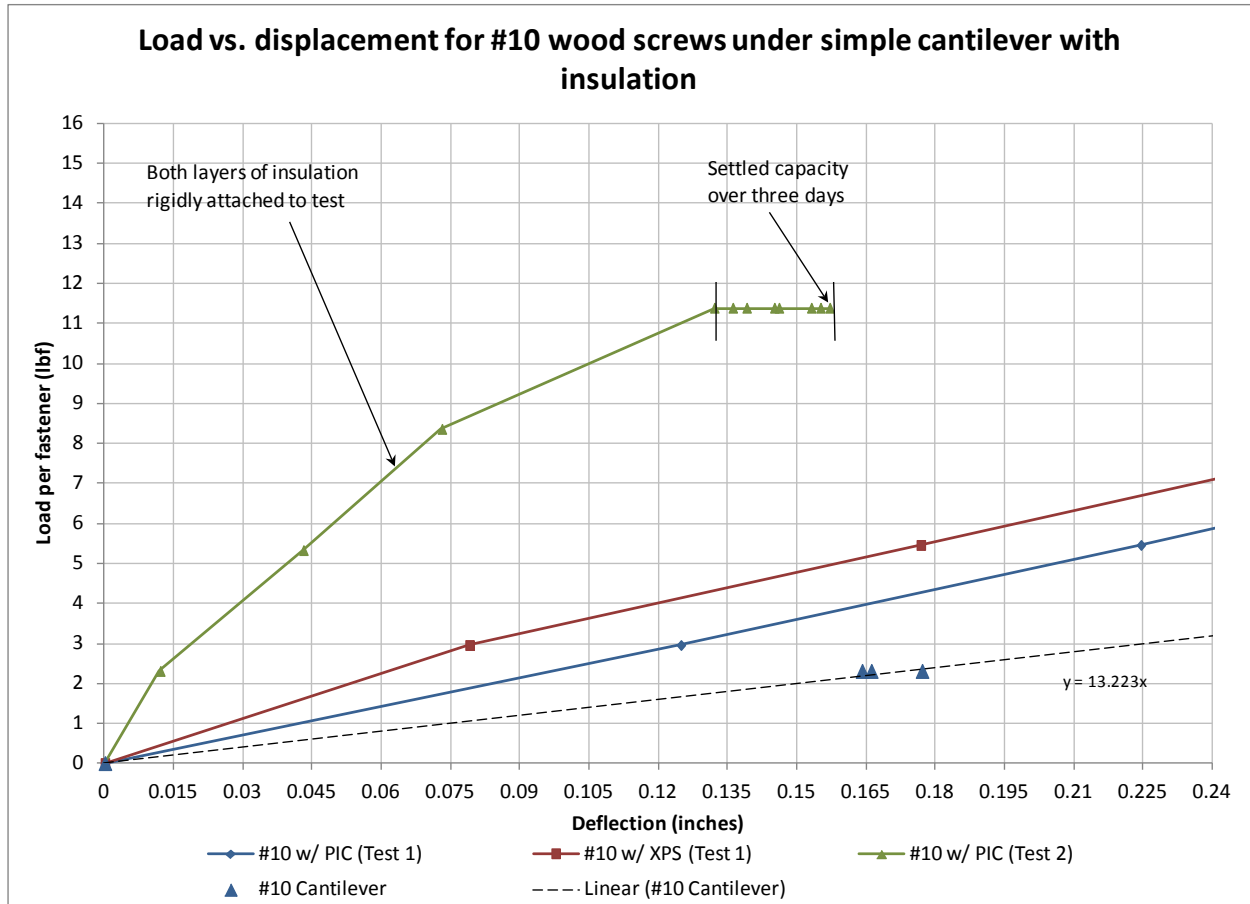
Figure 28. Load versus deflection for #10 wood screw under simple cantilever with insulation

While these results provide a wide possible range of performance, they are still felt to be useful. The screw shaft bearing may be contributing to the total load measured in a full assembly test. This is important since the capacity was noted to drop over several days, and this portion of the capacity would not be recommended to be used in design.

4.3 Expansion and Contraction of Materials

Based on previous research it was theorized that expansion and contraction of materials due to varying temperatures could be significant due to differences in the coefficients of thermal expansion of materials. Examples of linear coefficients of thermal expansion of the materials used in the test assemblies can be seen in Table 10. The values provided for the insulation materials were taken directly from the manufacturers' product data. The values for wood and steel are for generic materials.

The thermal expansion of wood is generally considered to be minimal (2×10^{-6} in./in./°F to 3×10^{-6} in./in./°F), while the thermal expansion of insulation materials can be much higher (35×10^{-6} in./in./°F for the XPS insulation used in the testing).

Table 10. Coefficients of Thermal Expansion

(Baker and Lepage 2014)

Material	Coefficient of Thermal Expansion (10^{-6} in./in./°F)
XPS	35
PIC	Not available from manufacturer
Steel	7.3
Wood	2 to 3

Looking at the data collected during the testing, there is a strong correlation between the compression forces in the assembly and changing temperature (Figure 29). At times when the RH changed, little to no effect can be seen. This is not surprising, as the timeframe for the changes in RH was short compared to time required to adsorb and desorb moisture from materials.
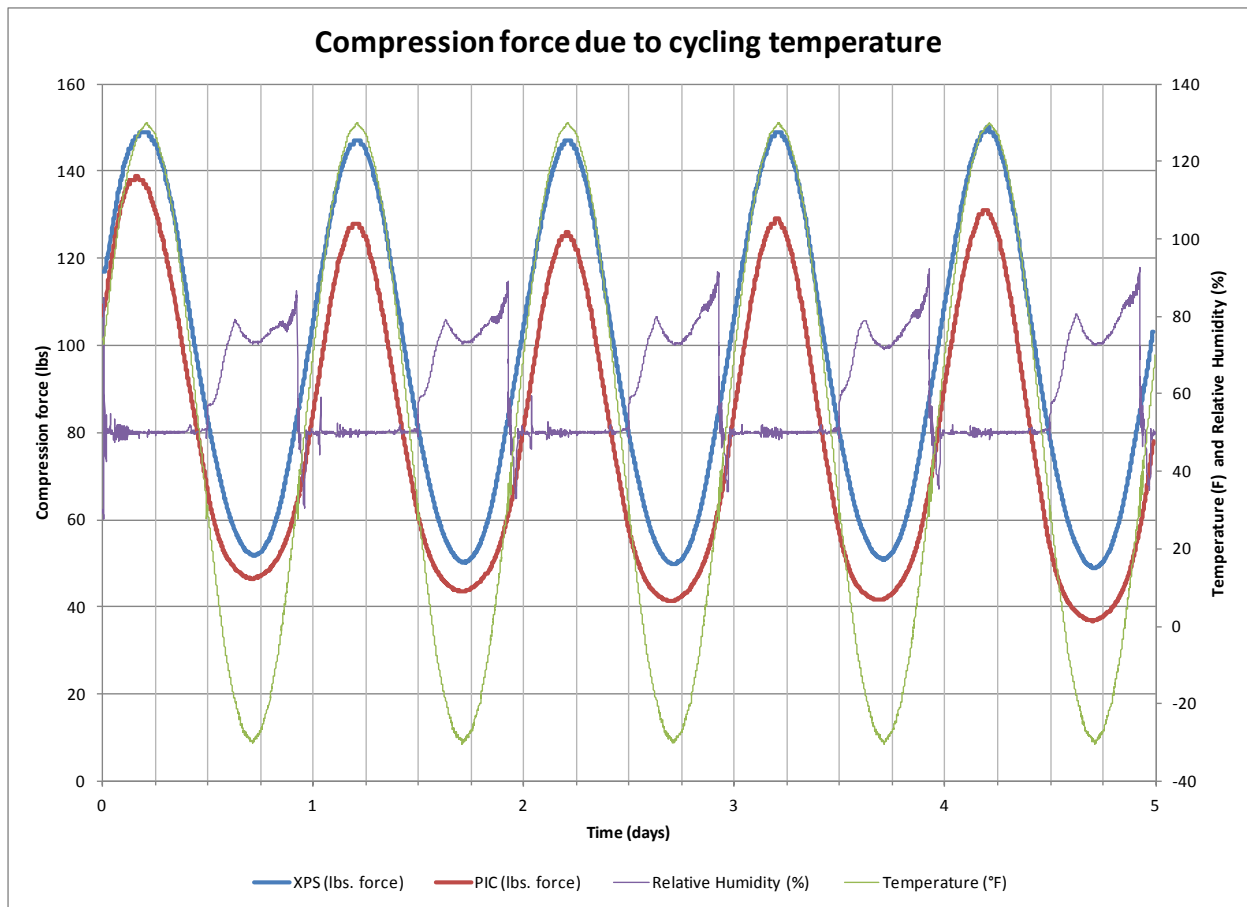
Figure 29. Change in compression forces based on changing environmental conditions

For the XPS insulation, the changes appeared stable (no indications of a reduction in compression forces after each subsequent cycle), varying over a 100-lbf range between −30°F and 130°F (Figure 30).

26
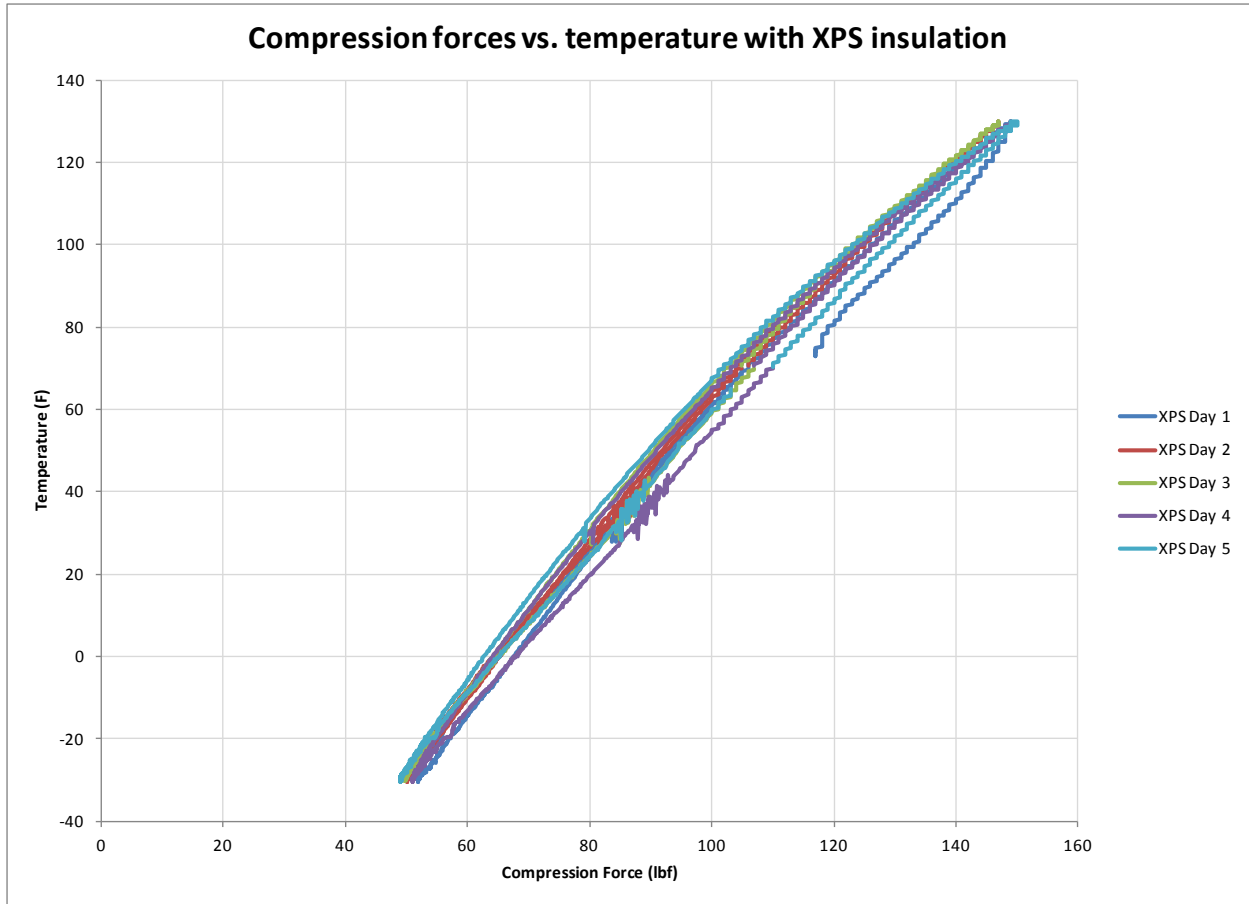
Figure 30. Compression force versus temperature with XPS insulation

For the PIC, the changes were close to the same magnitude (approximately 90-lbf range between –30°F and 130°F), though there may be an indication of some creep occurring in the assembly as each cycle appears to have a slight decrease in compression forces (Figure 31). Given the length of the test, no definite conclusions can be made.
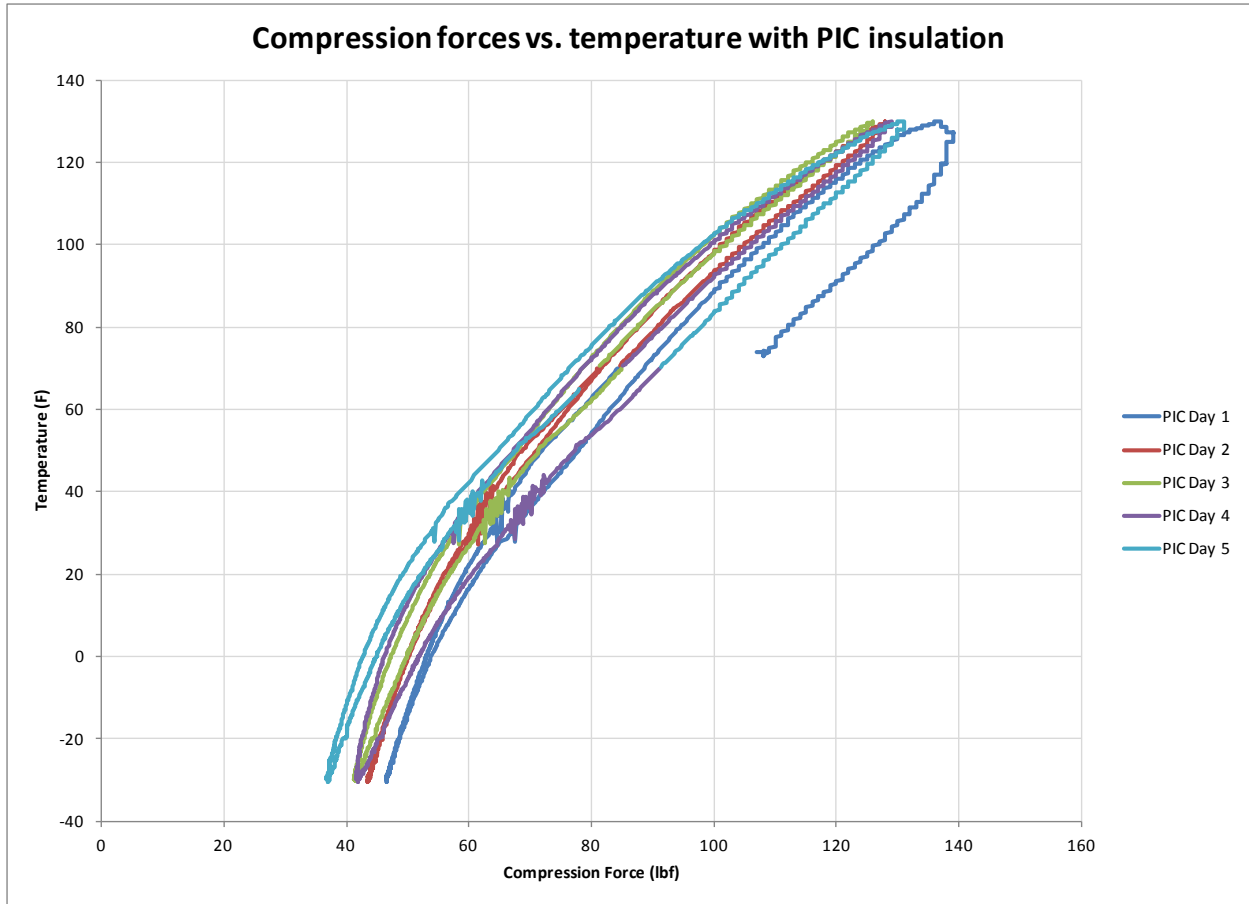
Figure 31. Compression force versus temperature with PIC insulation

The fluctuations in the compression forces will directly affect the magnitude of friction resistance component of the assemblies. It may also directly affect the compression strut. It is theorized that the loss of compression from thermal contraction may be compensated by additional rotation of the fastener to maintain a portion of the normal force magnitude attributed to the compression strut. During thermal expansion, the opposite may occur, as the increase in normal forces may result in the straightening of the fastener (in essence reverse rotation).

These fluctuations are thought to be the cause of the observed diurnal deflection changes noted in the 2012 exterior exposure research where daily movements on the order of ±1/64 in. to ±1/32 in. were measured for one of the assemblies over a 3-day period (Baker and Lepage 2014).

4.4 Fastener Spacing

Looking at the data from the fastener spacing tests, it is apparent that there is a direct correlation between the number of fasteners used in the assembly and the system capacity. The results of the full assembly tests can be seen in Figure 32. The total loads were then divided by the number of fasteners to determine the per-fastener load versus displacement plots (Figure 33). Dividing the total load resistance by the number of fasteners for each of the three tests yielded almost identical load versus deflection plots. The resultant load range at 1/16 in. deflection was between 40 lbf and 50 lbf per fastener. These results are intuitive, as all of the load resistance components are

directly related to the installation of the fastener (bending, screw shaft bearing on insulation, and compression/friction forces). This is important from a design perspective as the results would indicate that the system capacity can be modified by increasing or decreasing the number of fasteners used in the assembly.
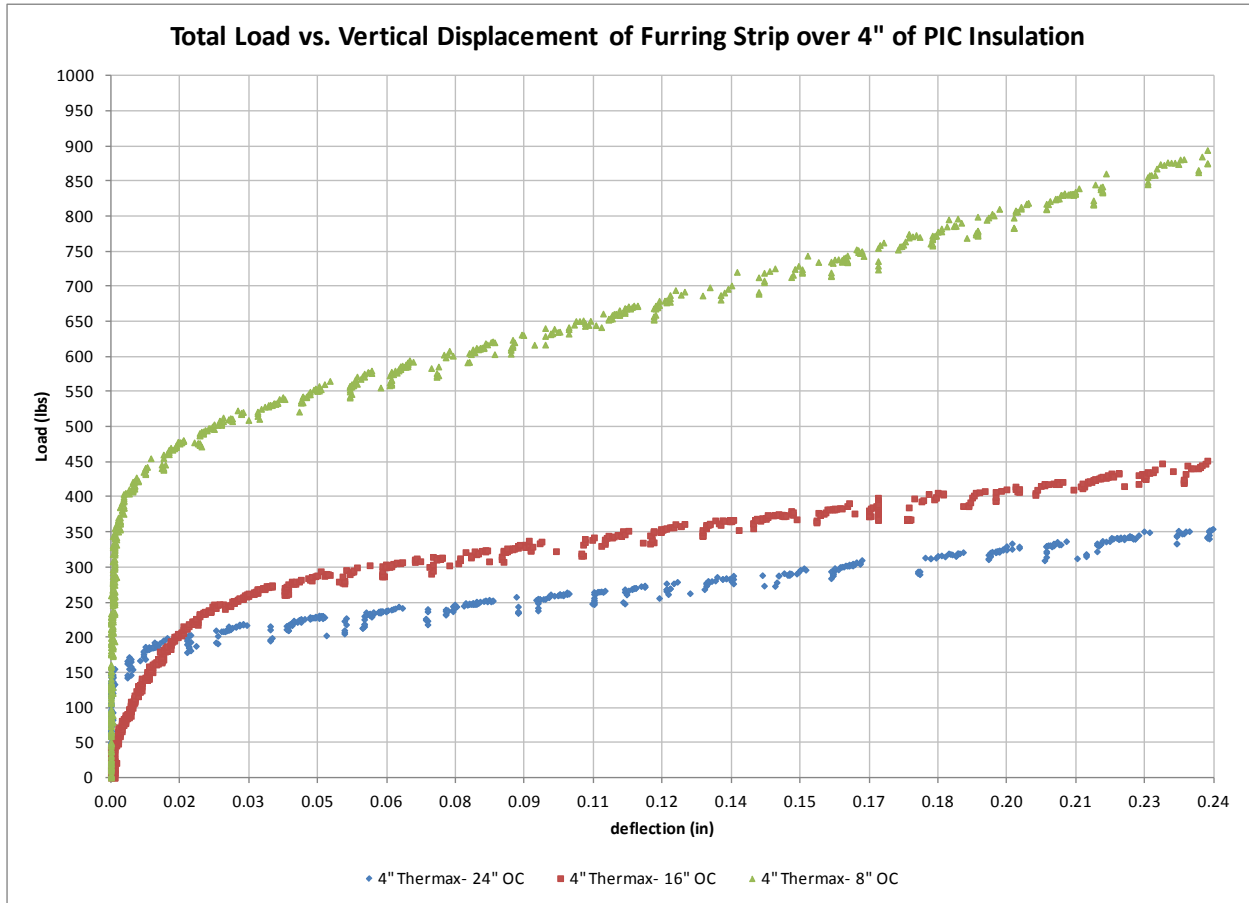

Figure 32. Total load versus vertical displacement of furring strip over 4 in. of PIC insulation
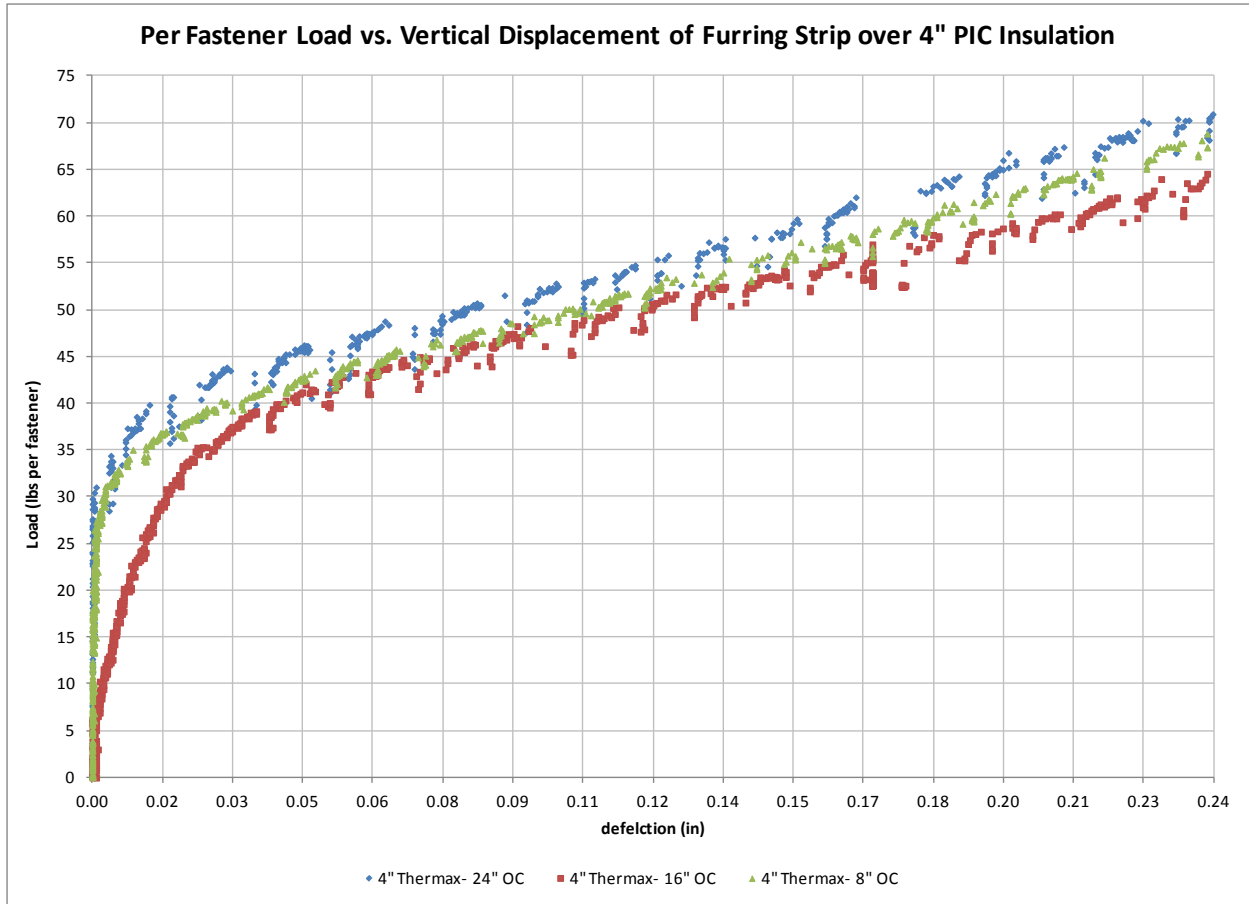
Figure 33. Per fastener load versus vertical displacement of furring strip over 4 in. of PIC insulation

4.5 Environmental Exposure

The deflection data gathered from the long-term exposure testing have probably yielded the most useful results. For the 8 lbf per fastener load assemblies the assemblies do not appear to be demonstrating any long-term creep (see Figure 34).

For 15 lbf per fastener assemblies, the performance also appears generally stable; however, at around the beginning of May 2013, there appears to be a slight increase in the deflection of the assemblies (see Figure 35). This increase may be an indication of a slight system creep, though the amount would still be currently within an acceptable range.

For the 30 lbf per fastener assemblies, the system creep is very noticeable (see Figure 36). Similar to the 15 lbf per fastener assemblies (yet much more apparent), there appears to be a change in the system performance around the beginning of May 2013.

It was around this time in April and May that some of the test panels were damaged in a storm event. This activity (storm damage and repairs) does correlate with the change in the deflection. It is possible that the repair activities affected the test panels; however, it cannot be stated with certainty one way or another.
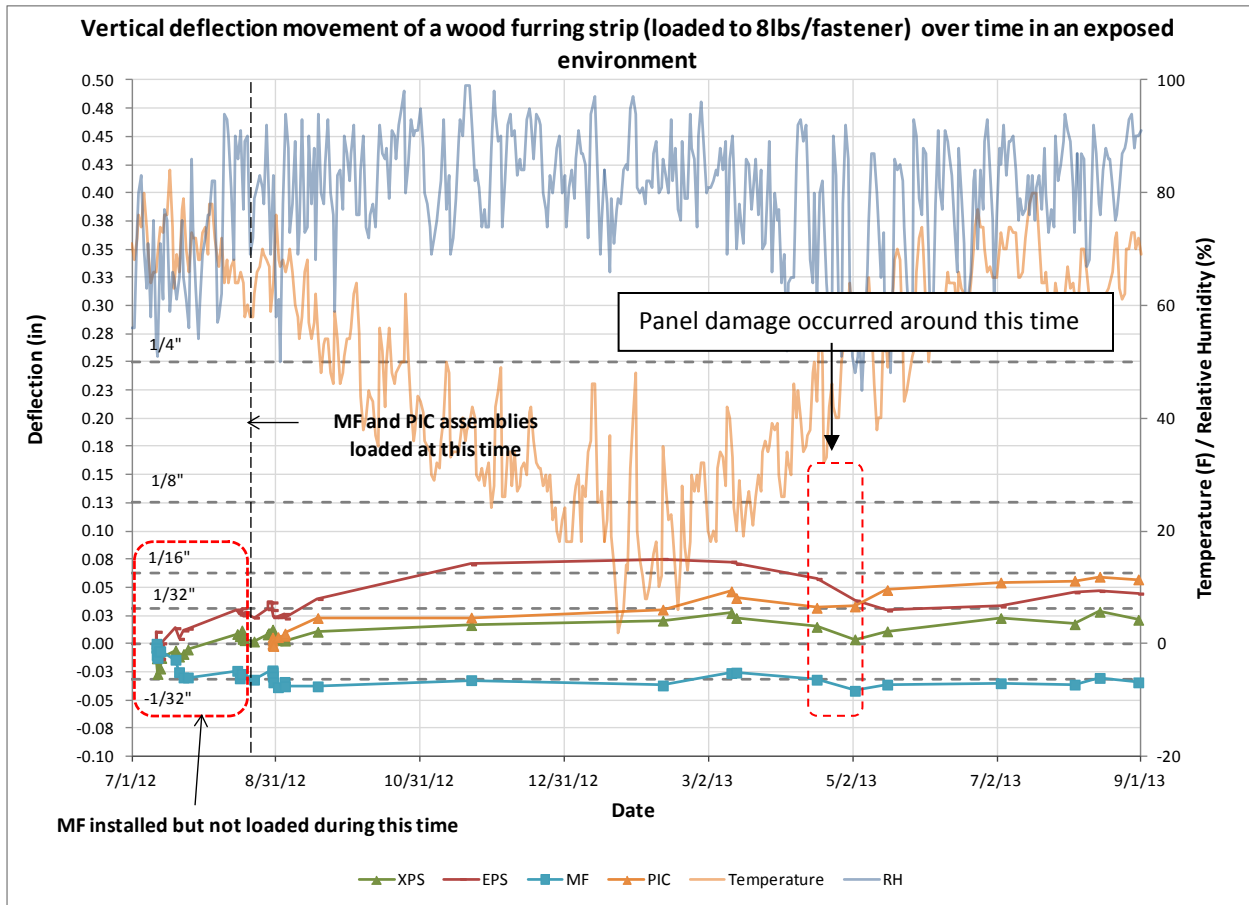
Figure 34. Long-term environmental exposure of simulated 8 lbf per fastener cladding load
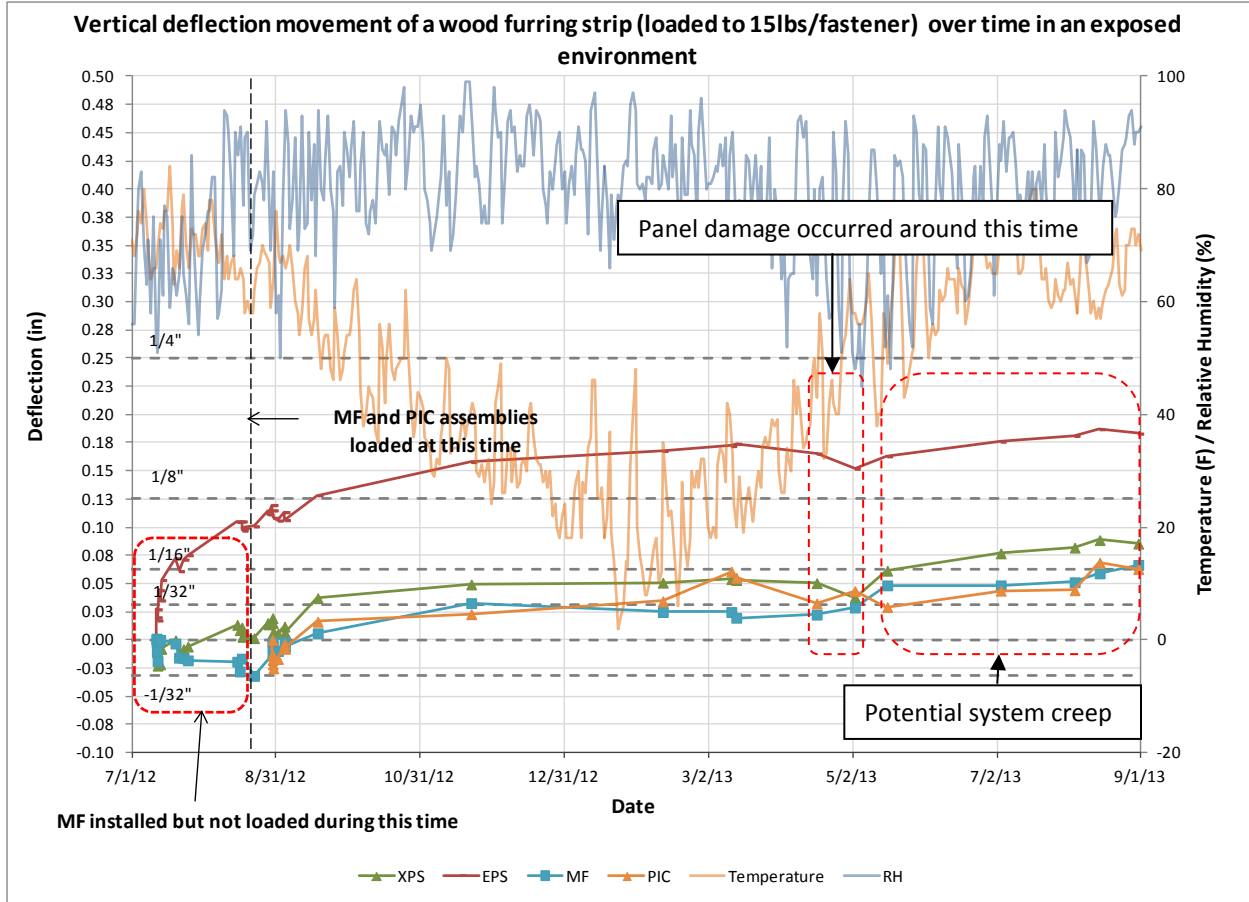
Figure 35. Long-term environmental exposure of simulated 15 lbf per fastener cladding load
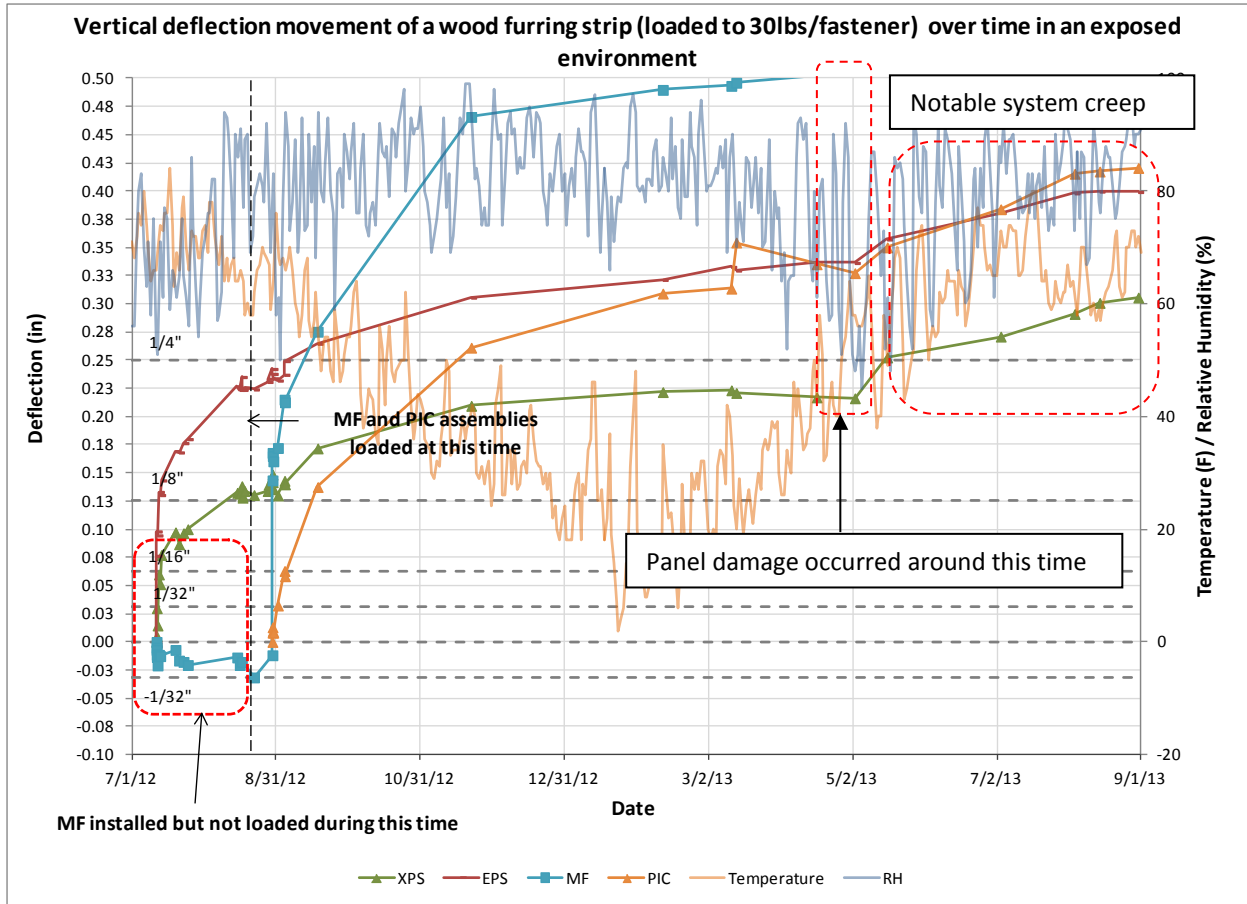
Figure 36. Long-term environmental exposure of simulated 30 lbf per fastener cladding load

4.6   Previous Research and Updated Understanding

This research was an extension of previous research conducted by BSC (Baker 2013a; Baker and Lepage 2014). Each year the understanding of the system discrete load component interactions, as well as impacts of environmental loading, has increased.

Each year, the baseline wall assembly has been maintained the same to facilitate direct comparisons of one aspect of the research to another.

Looking at the full-scale wall assembly short-term (initial load response) results for 4 in. of rigid insulation, the results have consistently been 40–55 lb per fastener, except for one outlier test of MF that was 65 lb at 1/16 in. of deflection.

Screw bending tests using #10 wood screws (initial load response in double bending) were measured at around 4 lbf per fastener. This represents approximately 8% of the total measured capacity. Using larger screws can increase this capacity.

Screw shaft bearing on the insulation under initial load response may contribute anywhere from 1 lbf per fastener to 10 lbf per fastener (2%–20%). The actual magnitude is really not known, but some portion should likely be assumed.

Precompression forces were generally measured at around 150 lbf per fastener using a standard cordless driver and a #14 ratchet setting. This initial precompression force has been measured to relax after initial loading. Controlled measurements this year demonstrated a loss of about 20%–30% within a day after initial loading.

The friction resistance component is directly related to the normal or compression forces engaged in the system. Table 11 is displaying measured results of the coefficient of static friction between the building wrap and the rigid insulation (Baker and Lepage 2014).

Table 11. Static Friction Test Results

(Baker and Lepage 2014)

	Static Coefficient of Friction
EPS	0.27
XPS	0.23
MF	0.45
PIC	0.26

As an example, if the initial compression force in the assembly measured 100 lbf per fastener, the corresponding friction resistance of the assembly would be around 25 lbf per fastener for the foam plastic insulation materials and upward of 45lb per fastener for rigid MF, for rigid foam plastics (in this example) the load resistance component would represent approximately 50% of the total measured capacity.

The rotational resistance provided by the strut and tie model is still the most poorly quantified. The amount of vertical displacement resistance is a function of the inward movement of the furring strip due to a potential rotation of the fastener. A simplified analysis based on the geometry conducted by BSC in 2012 showed minimal inward movement compared to the vertical displacement (1/500-in. inward movement at ⅛-in. vertical displacement). The same analysis showed that in a frictionless strut and tie model, a significant compressive force (26 lbf) would be generated for a small amount of vertical load (0.8 lbf). While these numbers are purely theoretical, this is an interesting result, as it would indicate that the importance of the strut and tie aspect of the system may have more to do with compression loads generating friction forces in the system than with the actual resistance to rotation being provided. The additional 26 lbf of compression force in the same example would create 6lbf of friction force, which is an order of magnitude greater than the 0.8 lbf of vertical load assumed in the frictionless example (Baker and Lepage 2014).

It seems likely that friction is a dominant load component in short-term (or initial response) tests. Unfortunately, the friction component has also been identified as being one of the most variable components and is difficult to accurately quantify in terms of long-term performance. The expansion and contraction of materials research showed large variations in the compression forces experience in the system (100 lbf change over 160°F temperature cycle). Given daily temperature and seasonal temperature variations, large swings in the compression forces, and by extension the friction forces, would be expected.

The fluctuations in the compression forces will directly affect the magnitude of friction resistance component of the assemblies. It may also directly affect the compression strut. It is theorized that the loss of compression from thermal contraction may be compensated by additional rotation of the fastener to maintain a portion of the normal force magnitude attributed to the compression strut. During thermal expansion, the opposite may occur, as the increase in normal forces may result in the straightening of the fastener (in essence reverse rotation).

It is encouraging, however, from the initial load response testing examining the impact of fastener spacing, that assemblies can be designed on a per fastener basis. Heavier claddings can be supported by increasing the number of fasteners used.

The long-term testing that has been completed provides better insight into the actual performance of the systems. It was seen in the 2011 BSC research that very little movement or creep was noted in assemblies under sustained loads when the environmental conditions were relatively stable (Baker 2013a). The 2012 through 2013 long-term testing conducted in an exposed environment yielded very different results. From this set of testing it was clear that a cladding weight resulting in 30 lbf per fastener load was too heavy for the assembly, and that unacceptable creep of the system was clearly observed. By contrast, limiting the cladding weight to 8 lbf per fastener demonstrated very stable performance. The assemblies loaded to 15 lbf per fastener showed pretty stable performance as well; however, there may be a slight indication of system creep occurring with these assemblies.

Based on current information to date, it is recommended to use a maximum load per fastener of no more than 10 lb. Table 12 is proposed to provide guidance for spacing of screw fasteners for wood furring strips attachment through up to 4 in. of rigid insulation based on cladding loads. Most siding type cladding assemblies such as metal, vinyl, wood, and fiber cement are 5 psf or less. In fact, wood siding is typically less than 2 psf. Stucco assemblies would typically be around 10 psf, and adhered stone veneers can be as much as 25 psf.

Table 12. Recommended Vertical Fastener Spacing (Minimum #10 Wood Screw) Based on Cladding Weight

Cladding Weight (psf)	16-in. o.c. Furring	24-in. o.c. Furring
5	18	12
10	9	6
15	6	4
20	4	3
25	3	2

5 Conclusions

The research conducted was designed to examine the following questions:

- What are the impacts of different fastener types in the system capacity?

- What is the impact of screw shaft bearing on the insulation material?

- What are the impacts of material expansion and contraction on the pre- and postcompression forces in the assemblies?

- Can deflection movement for heavier weight claddings be mitigated by denser fastener spacing?

The portion of vertical load resistance capacity provided by the screw fasteners was determined to be around 4 lbf per fastener based on a standard #10 wood screw and 7 lbf per fastener based on a Headlok screw at 1/16 in. deflection. Using a simple cantilever bending test to significantly underestimate the actual capacity of the screw bending in the system as the screw shaft bearing in the furring strips results in a double bending action. Initial load resistance capacities for screws under double bending were around 4 times that of a simple cantilever test for #10 wood screws and 3.5 times the value of a simple cantilever test for Headlok screws. It was clear from the testing that increasing the size of the screw fastener did result in increased capacity. However, it also appeared that the bearing strength of the wood members might be a limiting factor for the screw fastener capacity.

The screw shaft bearing on the insulation was difficult to capture effectively in a test method, since the insulation is coupled with the furring strip and will move as the furring strip deflects. Also, using furring strips in the test were not possible, as other effects from system friction and compression would be captured in the test results. Two test methods were done. The first rigidly attached only the first 2-in. layer of insulation back to the structure with the second layer installed, but allowed to move slightly. The second rigidly attached both layers back to the structure. The results indicated that the capacity of a cantilevered screw is approximately double given the first test protocol and approximately 8 times that of the simple cantilever given the second protocol. In the second test, the assembly was also allowed to stay loaded for 3 days until movement stabilized. Even after settling, the load was still approximately 5 times that of a simple cantilever test with no insulation.

The assemblies react to changes in temperature. The changes are likely due to thermal expansion and contraction of the insulation material. For the XPS insulation, the changes varied over a 100-lbf range between –30°F and 130°F. For the PIC, the changes were close to the same magnitude (approximately 90-lbf range between –30°F and 130°F), though there may be a slight indication of some creep occurring in the assembly. Given the length of the test, no definite conclusions can be made. It is theorized that the loss of compression from thermal contraction may be compensated by additional rotation of the fastener to maintain a portion of the normal force magnitude attributed to the compression strut. During thermal expansion, the opposite may occur, as the increase in normal forces may result in the straightening of the fastener (in essence reverse rotation). These fluctuations are thought to be the cause of the observed diurnal deflection changes noted in the 2012 exterior exposure research where daily movements on the

order of ±1/64 in. to ±1/32 in. were measured for one of the assemblies over a 3-day period (Baker and Lepage 2014).

There is a direct correlation between the number of fasteners used in the assembly and the system capacity. Three tests were performed using three different fastener spacings. Dividing the total load resistance by the number of fasteners for each of the three tests yielded almost identical load versus deflection plots. This is important from a design perspective, as the results would indicate that the system capacity can be modified by increasing or decreasing the number of fasteners used in the assembly.

The long-term exterior exposure testing provided significant insight into the actual in service performance of the cladding attachment systems. A 30 lbf per fastener load resulted in unacceptable creep of the system. By contrast limiting the cladding weight to 8 lbf per fastener demonstrated very stable performance. The assemblies loaded to 15 lbf per fastener showed pretty stable performance as well; however, there may be a slight indication of system creep occurring with these assemblies. This potential system creep also correlates with a storm event which damaged some of the test panels in May 2013. It is possible that the repair activities affected the test panels; however, it cannot be stated with certainty one way or another.

Based on current information to date, it is recommended to use a maximum load per fastener of no more than 10 lbf based on a standard #10 wood screw installed through up to 4 in. of insulation. Higher capacities would be expected with larger screws or reduced insulation thickness.

This recommendation is conservative, as it is based on a single maximum limit. Modifying aspects of the assembly such as using larger diameter fasteners or thinner amounts of exterior insulation would be expected to result in an increase in the allowable per fastener load resistance, and allow for larger fastener spacing. Additional research to examine these variables in a long-term exposure setting would be recommended to further refine the recommendations.

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Appendix A: BEopt Simulation Graphs

Dallas, Texas

Utility Rates: $0.13/kWh
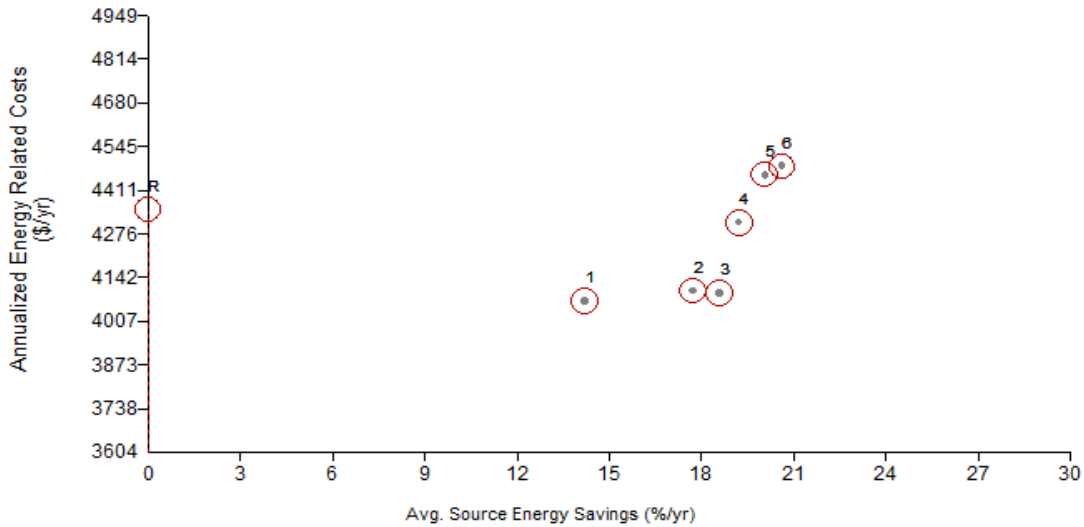$1.09/therm

Figure 37. Annualized energy-related costs versus average source energy savings for Dallas
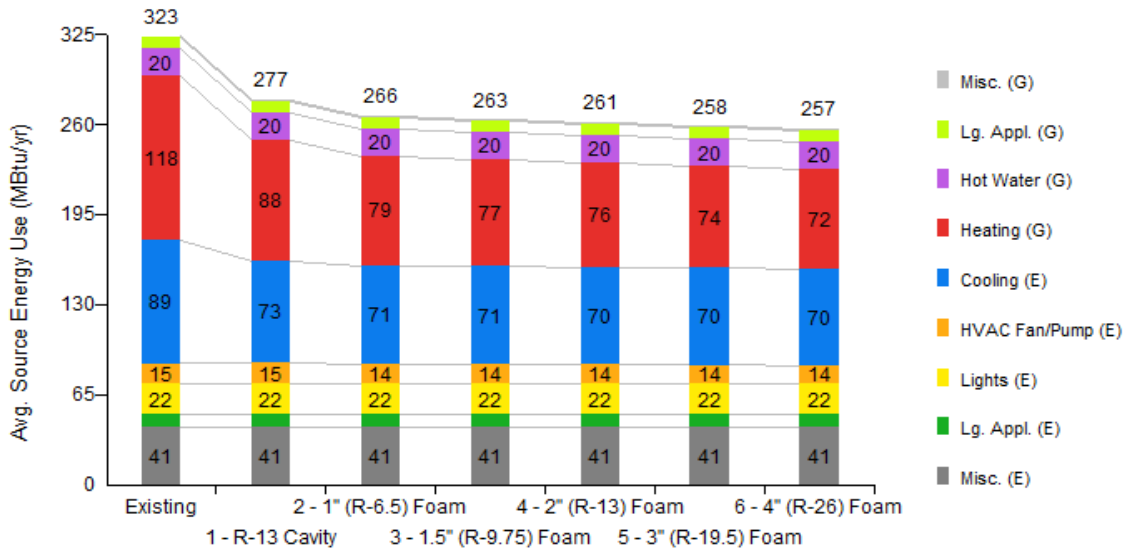

Figure 38. Average source energy savings reduction versus insulation level for Dallas

Kansas City, Missouri
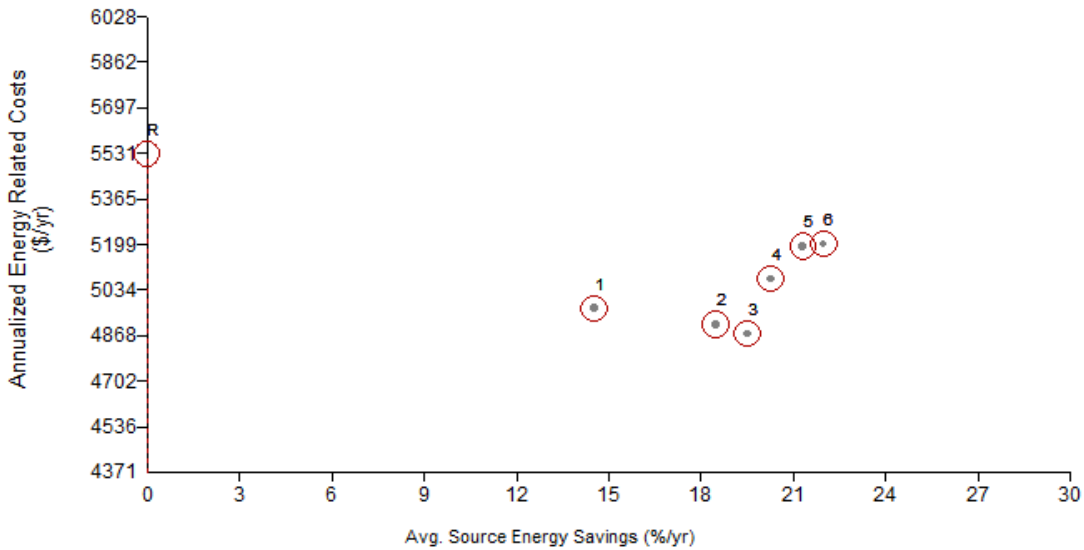
Utility Rates: $0.08/kWh
$1.23/therm

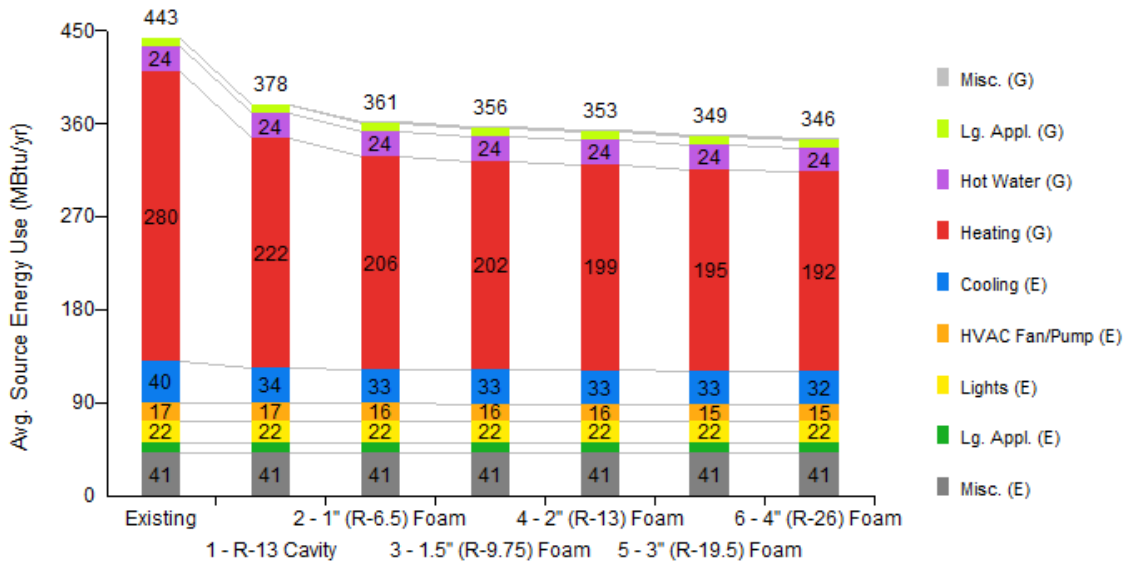**Figure 39. Annualized energy-related costs versus average source energy savings for Kansas City**

Figure 40. Average source energy savings reduction versus insulation level for Kansas City

Boston, Massachusetts

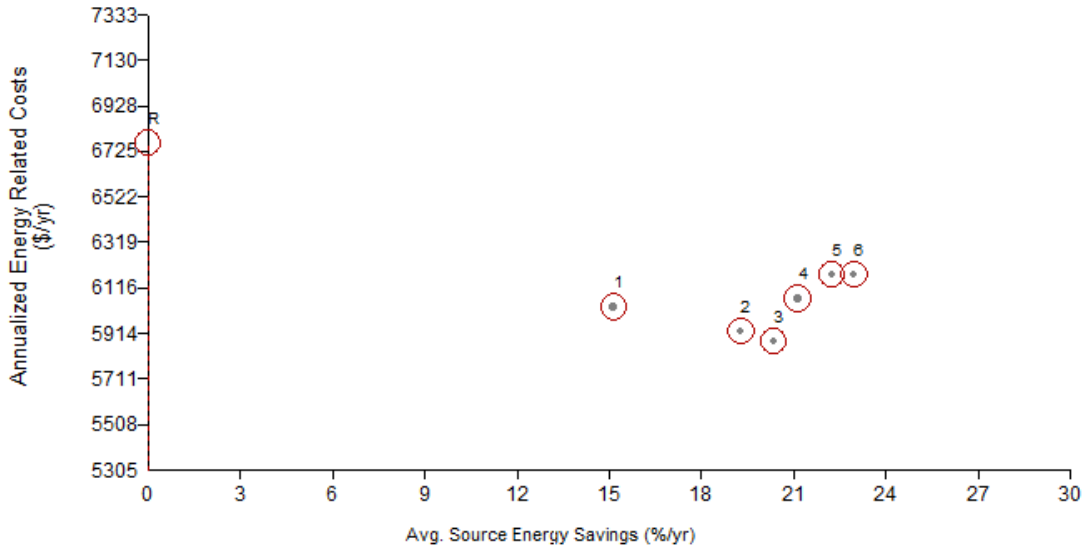Utility Rates: $0.18/kWh
$1.70/therm

Figure 41. Annualized energy-related costs versus average source energy savings for Boston

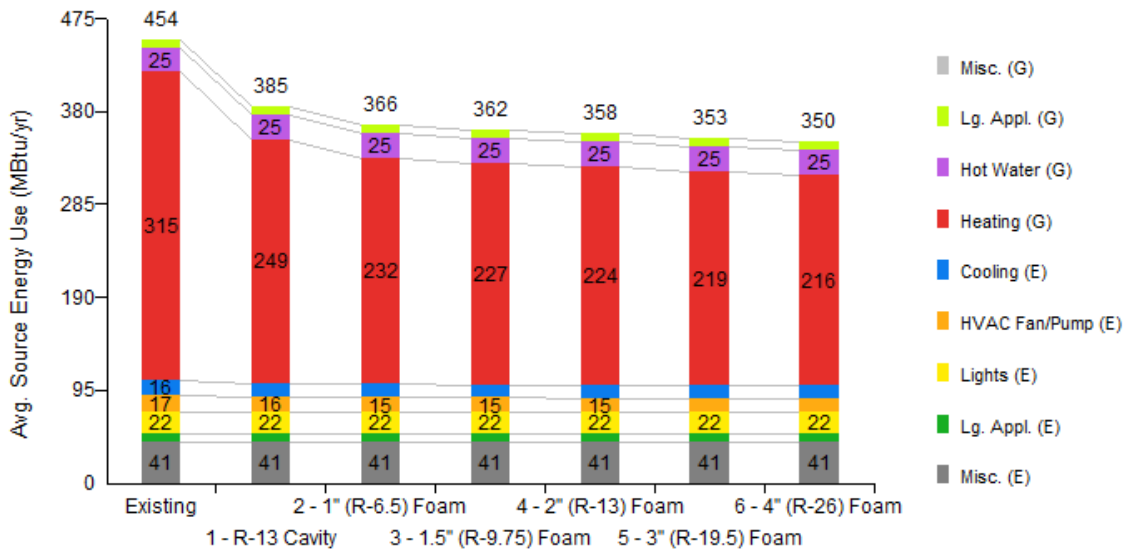**Figure 42. Average source energy savings reduction versus insulation level for Boston**

Duluth, Minnesota

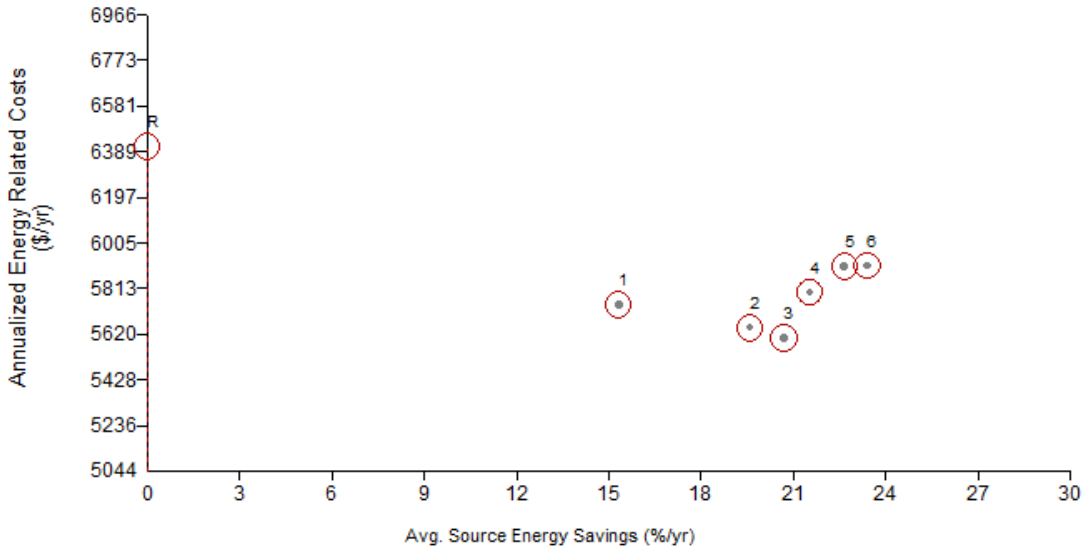Utility Rates: $0.10/kWh
$0.87/therm

Figure 43. Annualized energy related costs versus average source energy savings for Duluth
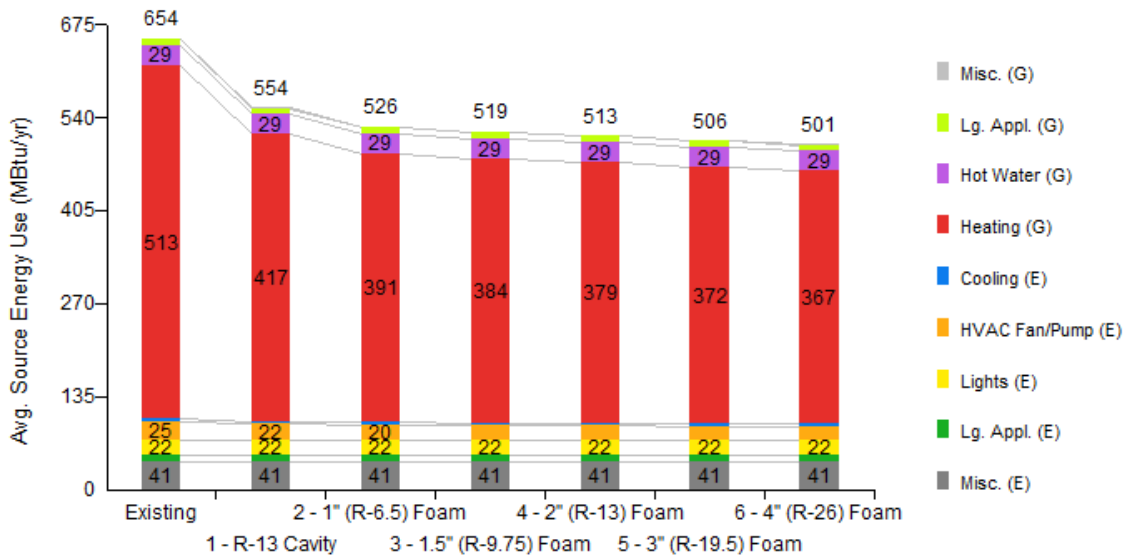

Figure 44. Average source energy savings reduction versus insulation level for Duluth

Appendix B: Cantilever Bending Test Protocol

Support Structure

A wood frame support structure was constructed and attached the top of a work bench. The support structure was designed to accommodate a minimum 32-in. tall test sample held vertically in place.

Test Sample

Each test sample was constructed of 2 × 4 SPF wood studs with 7/16-in. OSB sheathing screwed to the stud use #8 × 1.75-in. wood screws at 8 in. oc beginning 4 in. from the bottom of the test panel. The height of the sample was 32 in. to allow for three cantilever tests to be conducted on each sample.

Each test fastener was installed perpendicular into the test panel so that the fastener head was held away from the face of the OSB sheathing a distance of 4.75 in. Each test was spaced 8 in. o.c. and located at the midpoint between the sheathing screws.

Measuring Device

Measurements were taken with a dial deflection gauge accurate to 0.001 in. A support bracket was installed to the face of the OSB sheathing to support the base of the deflection gauge. The needle of the deflection gauge was placed at the top of the head of the test fastener.

Loading Mechanism

The tests fasteners were loaded at a distance of ⅜ in. inboard of the fastener head (4.375 in. from the face of the OSB) to represent the midpoint of the ¾-in. wood furring strip. The test fastener was loaded via weights calibrated to 0.001 lbf. The weights were placed inside a bucket that was hung by a metal hook at the load point on the fastener shaft. The weights of the metal hook and bucket were also measured and used as the initial load step in the test procedure. Double-sided tape was wrapped around the fastener shaft at the loading location to prevent slippage of the hook.

Test Procedure

A baseline deflection reading was taken once the deflection gauge needle was positioned on the fastener head.

The hook and bucket were carefully placed at the load point and the weight increment added to the system recorded. The first deflection reading was taken approximately 30 seconds to 1 minute after initial loading.

Each subsequent load step is achieved by placing a calibrated weight carefully into the bucket and recording the weight increment. Each subsequent deflection reading was taken approximately 30 seconds to 1 minute after loading.

The test procedure was repeated until the desired system deflection was achieved.

Appendix C: Double Bending Test Protocol

Support Structure

A wood frame support structure was constructed and attached the top of a work bench. The support structure was designed to accommodate a minimum 32-in. tall test sample held vertically in place.

Test Sample

Each test sample was constructed of 2 × 4 SPF wood studs with 7/16-in. OSB sheathing screwed to the stud use #8 × 1.75-in. wood screws at 8 in. o.c. beginning 4 in. from the bottom of the test panel. The height of the sample was 32 in. to allow for three cantilever tests to be conducted on each sample.

Each furring strip test sample was installed with two test fasteners spaced 16 in. o.c. with the first fastener positioned 8 in. from the bottom of the test sample and located at the midpoint between the sheathing screws. The furring strip was held away from the face of the OSB a distance of 4 in. Each test was spaced 8 in. o.c.

Measuring Device

Measurements were taken with a dial deflection gauge accurate to 0.001 in. A support bracket was installed to the face of the OSB sheathing to support the base of the deflection gauge. The needle of the deflection gauge was placed on top of a 2-in. × 2-in. metal bracket attached to the face of the wood furring strip.

Loading Mechanism

The wood furring strips were loaded at the ⅜ in. midpoint of the thickness of the furring strip (4.375 in. from the face of the OSB). One #6 × 0.75-in. wood screw was installed on either side of the furring 1 ½ in. above the bottom edge (two fasteners total). The test furring was loaded via weights calibrated to 0.001 lbf. The weights were placed inside a bucket that was hung by a metal hooks on the fasteners installed at near the bottom of the furring strip. The weights of the metal hooks and bucket were also measured and used as the initial load step in the test procedure.

Test Procedure

A baseline deflection reading was taken once the deflection gauge needle was positioned on the metal angle bracket.

The hook and bucket were carefully placed on the load points and the weight increment added to the system recorded. The first deflection reading was taken approximately 30 seconds to 1 minute after initial loading.

Each subsequent load step is achieved by placing a calibrated weight carefully into the bucket and recording the weight increment. Each subsequent deflection reading was taken approximately 30 seconds to 1 minute after loading.

The test procedure was repeated until the desired system deflection was achieved.

Appendix D: Expansion and Contraction Test Protocol

Climate Chamber

Thermatron climate chamber, opening size (40 in. × 40 in.), temperature range (–40° to 355°F), RH range (10%–98%). Door of chamber replaced with two layers of 2-in. XPS insulation installed over a wood stud frame with openings cut out to fit test samples.

Test Sample

Each test sample was constructed of 2 × 4 SPF wood studs with 7/16 in. OSB sheathing attached to the studs with 8d nails. The panels are 12 in. wide × 12 in. tall with a vertical center stud to provide the attachment location of the screw fastener. Each panel is covered with Tyvek Buildingwrap, Two layers of 1 ½-in. rigid insulation (12 in. wide × 12 in. tall), and a single 12-in. long 1 × 3 SPF furring strip installed vertically along the center with a one Headlok screw fastener.

Measuring Device

Measurements were taken with a doughnut style low profile compression load cell (500 lbf ± 0.4 lbf accuracy). The load cell is installed on the exterior face of the wood furring strip. Standard zinc-plated metal washers added as needed to create a 1-in. total thickness between the screw head and the face of the furring.

Loading Mechanism

The system was preloaded to an initial compression of 150 lbf. The loading was accomplished using a cordless drill/driver set to a #14 ratchet setting to drive the fastener close to the target load. Final precompression completed by hand using a screw driver.

Test procedure

The test panels are maintained at laboratory conditions (~70°F and 30% RH) for a 48-hour period.

The test panels are inserted into the openings in the climate chamber door. The climate cycle is started at 70°F and cycled between 130°F and –30°F in a 24-hour period following a sinusoidal curve. The RH is kept as close to 50% as possible during each cycle (this level was not practical to be maintained at very low temperature). The cycle is run for 5 days. Temperature, RH, and compression force magnitude is recorded every minute.

Appendix E: Fastener Spacing Test Protocol

Support Structure

The vertical stud of the test sample was anchored to the steel support structure of the overhead hoist loading mechanism.

Test sample

Each test sample is 16 in. by 96 in. tall, and constructed with a single 92-in. tall vertical 2 × 4 SPF wood stud installed between a single 16-in. long 2 × 4 SPF bottom plate, and 16-in. long 2 × 4 SPF double top plate. 7/16-in. OSB sheathing is attached to the stud use #8 × 1 ¾-in. wood screws spaced 12 in. o.c. The test samples are covered with Tyvek, fastened with staples. Two layers of 2-in. thick Thermax is applied, and attached in place using 1-in. × 3-in. SPF furring strip fastened with 6 in. long #10 flat-head screws. For each assembly a fastener was placed at the top and bottom of the furring strip as well as at the spacing indicated. This results in the following number of fasteners used per test setup:

- Number of fasteners = wall height/screw spacing + 1

- 8 in. o.c. = 96/8 + 1 = 13 fasteners total

- 16 in. o.c. = 96/16 + 1 = 7 fasteners total

- 24 in. o.c. = 96/24 + 1 = 5 fasteners total.

Measuring Device

Measurements are taken with an LVDT accurate to 0.001 in. A metal plate is installed to underside of the bottom plate to support the magnetic base of the LVDT. The needle of the LVDT is placed to the underside of a 4 in. x 4 in. metal bracket attached to the face of the wood furring strip.

Loading Mechanism

The assembly is loaded via an overhead hoist connected to a 5000-lbf anchor attached to the top of the 1 × 3 wood furring strip. The load is measured through a strain gauge load cell installed between the hoist and the anchor.

Test procedure

An initial baseline deflection reading was taken prior to commencing the test. Each assembly is loaded by slowly raising the overhead hoist at a rate of approximately 1/64 in. per minute. Simultaneous load and deflection readings are taken every 0.5 seconds until a maximum load of 1000 lbf is achieved.