Structural Testing of Screws through Exterior Insulation for Steel-Frame Walls

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ABSTRACT

As the construction industry moves toward more energy-efficient buildings, exterior insulation has been recognized as an effective solution for increasing the thermal performance of wall assemblies. Previous research and in-situ performance have shown that using only screws directly through exterior insulation to provide cladding attachment is a thermally and structurally efficient solution for wood-frame walls (Baker and Lepage 2014). For steel-frame walls, however, there is still scepticism regarding this method of cladding support, and cladding attachment clips are currently the more common solution.

This study focused on the impact of density and thickness of insulation materials on the structural performance of a cladding attachment system where the exterior insulation is installed and held in place using only screws and steel furring fastened in to a steel stud back-up wall. In particular, this study investigated the use of exterior stone wool insulation, which may be perceived as insufficiently rigid in comparison to competing foam plastic insulations such as extruded polystyrene insulation (XPS) for this type of insulation and cladding installation approach. In addition to the structural performance, airtightness, water penetration, and constructability considerations of this system are also discussed.

Overall the study aims to provide important information for the industry as to the viability of the screws through exterior insulation cladding attachment approach in steel stud wall applications to facilitate the expanded use of exterior insulation as part of non-combustible wall assembly design. This study found that insulation thickness to be the most impactful on the measured load-deflection response of the system; however, the load-deflection response was typically similar and sufficiently strong and stiff within the range of typical cladding weights such that this system would likely be able to provide sufficient cladding support for the insulation thicknesses tested.

INTRODUCTION

The use of long-fasteners through exterior insulation to support exterior claddings is becoming an increasingly popular construction method due primarily to the reduced thermal bridging by the elimination of clip or continuous rail style (i.e., Z-girt) cladding supports which penetrate the insulation. While significant testing has been completed for this type of assembly for the use of wood studs and furring, less work has been done to characterize the response when used with steel studs. This study addresses this knowledge gap by providing load testing of long screws through exterior insulation when installed in to steel stud walls.

This study consists of a series of tests similar to those performed in Structural Testing of Screws through Thick Exterior Insulation (Tatara and Ricketts 2017) for wood frame construction but instead of plywood strapping and a

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wood-frame backup wall, non-combustible materials such as steel stud and tracks, and gypsum sheathing were used. The difference in performance in these assemblies is of particular interest because the lack of embedment of the fastener when used in steel studs will likely cause the connection to act primarily as a pin-type connection, whereas when installed in to wood, testing shows that embedment creates moment resistance at the connection point, allowing for load to be carried by the moment resistance of the screw. This potential difference in the load resistance of the screw attachment to the structure can potentially cause more reliance on the compressive strength of the insulation to create a truss and resist the cladding dead load. Measurement of the load resistance and assessment of the load-deflection characteristics of this system are the primary objectives of this work.

Test wall specimens were constructed to assess the performance of different arrangements of this cladding support system. These specimens were designed to allow for evaluation of the load-deflection response of the system considering different parameters. These parameters include:

- Compressive strength of the insulation
  8 lb/ft³ (8 pcf, 128 kg/m³) stone wool, 11 lb/ft³ (11 pcf, 176 kg/m³) stone wool, and XPS (Type 3)
- Insulation thickness
  3 in., 6 in., and 9 in. (76 mm, 152 mm, and 229 mm)

Various studies have been conducted in this area, including recent work performed by the University of Waterloo and others as part of the Building America program and by the New York State Energy Research and Development Authority (Smegal and Straube 2011, Baker and Lepage 2014, Lstiburek and Baker 2014, P. Baker 2014). The majority of these studies focused on application, implementation, and long-term creep (movement) and field exposure of this type of cladding attachment system in wood frame construction. These research and in-situ performance tests have shown that this cladding attachment system can adequately support typical cladding loads. Exterior continuous insulation is particularly important in steel frame construction due to the relatively high thermal conductivity of the framing; however, less work has been done to characterize the performance of this cladding attachment approach for steel stud back-up walls. The previous work by Lepage for testing of a similar support structure with steel stud back-up walls (2013), as well as the previous work by the authors (Tatara and Ricketts 2017), has been used for relative comparison against the results of the current work.

This paper provides a summary of select findings presented in Structural Testing of Screws through Exterior Insulation for Steel-Frame Walls (Tatara and Ricketts 2019). This document can be referenced for additional information regarding the methodology and test results.

METHODOLOGY

Test Wall Specimens

To test the performance of the wall assemblies, a 4 ft by 6 ft (1220 mm by 1830 mm) backup wall was constructed with 18-gauge 3-5/8 in. by 1-1/4 in. steel framing at 16 in. (406 mm) on centre (o.c.) complete with an 18-gauge top track and 20-gauge bottom track. The centre stud was installed in the centre of the backup wall. The backup wall framing was securely fixed to a platform constructed with 1-1/2 in. by 1-1/2 in. by 1/4 in. (38 mm by 38 mm by 6 mm) hollow structural steel sections (HSS), 2x2 lumber, and plywood sheathing. The steel backup wall framing was sheathed with 1/2 in. (13 mm) exterior gypsum board sheathing and bituminous self-adhered membrane applied with primer per the manufacturer's instructions and typical steel frame construction.

Insulation, typically 2 ft by 4 ft (610 mm by 1220 mm), was placed in staggered layers per typical installation and secured with 20-gauge 7/8 in. by 1-1/4 in. (22 mm by 32 mm) steel furring (hat track) and 3 screws per furring. Furring was installed with flanges away from the insulation at 16 in. (406 mm) o.c. to match the stud spacing so that the screws can penetrate into the backup wall framing as shown in Figure 1.

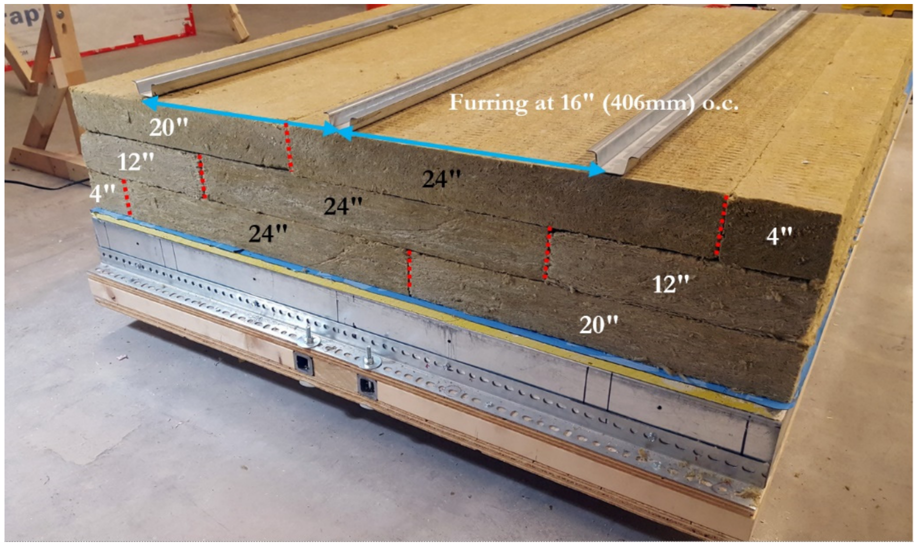

Figure 1 An example of staggered insulation installation (9" of 11 pcf stone wool shown).

Similar to wood frame construction, 3 in. (76 mm) insulation thickness makes it fairly easy to hit the studs, but it becomes more difficult as the insulation thickness increases up to 6 in. and 9 in. (152 mm and 229 mm), even with self-drilling fasteners. In a laboratory condition with the test wall situated in a horizontal position, it was possible to ensure that the screws penetrated the backup wall framing at 90°; however, ensuring screw penetration into backup wall framing members is more difficult in real-world applications. Note that the portion of the test wall that was loaded (centre furring, center screws, and center layers of insulation) was replaced after each set of tests.

Insulation Selection

One of the concerns regarding installation of thick stone wool insulation without the use of clips or girts is that this type of insulation may not have high enough compressive strength, as compared foam plastic insulation. Table 1 summarizes compressive strength and density of the insulations tested, obtained from manufacturer's product data sheet where available.

Table 1. Compressive Strength and Density of Insulation

Insulation Type	Compressive Strength ASTM C-165, psf (kPa)		Density ASTM C-303, lb/ft³ (kg/m³)
	at 10%	at 25%	
Stone Wool (8 pcf)[i]	439 (21)	1065 (50)	8 (128)
Stone Wool (11 pcf)[ii]	584 (28)	1566 (75)	11 (176)
	ASTM D-1621, psf (kPa)		**-**
XPS (Type 3)[iii]	2880 (140)		-

[i] (ROCKWOOL 2018), [ii] (ROCKWOOL 2018), [iii] (Owens Corning® 2013)

Screw Selection

Three different lengths of roofing pan head fasteners were selected for this testing. The screws used in this testing were selected based on which manufacturer offered all of the required lengths for testing in the same thread and shank diameter, and with the same mechanical properties (e.g., tensile strength, pullout resistance). Having the same mechanical and physical properties (with exception of length) was the determining factor because having the screws as one of the constants in the test wall assemblies was necessary to be able to isolate and evaluate the other factors affecting the performance of the wall assemblies. Physical and mechanical properties of the fasteners, obtained from the manufacturer's technical datasheet (Altenloh, Brinck & Co. U.S., Inc. n.d.), are summarized in Table 2.

Table 2. Physical and Mechanical Properties of Roofing Fastener Used in This Study

Properties	Reported Value
Nominal Length, in. (mm)	5, 8, and 11 (127.0, 203.2, and 279.4)
Head Diameter, in. (mm)	0.438 (~11.1)
Thread Diameter, in. (mm)	0.237 (~6.0)
Shank Diameter, in. (mm)	0.180 (~4.6)
Thread Density, Threads per Inch (TPI)	13
Fastener Tip Characteristic	#2 Drill Point, 0.130 in. (3.3 mm) Diameter
Tensile Strength, lbf (kN)	3200 (~14.2)
Shear Strength, lbf (kN)	2200 (~9.8)
Pullout Capacity[i], lbf (kN)	675 (~3.0)

[i] Based on 18-gauge steel substrate with yield strength of 33.0ksi (227.5MPa)

In steel frame construction, the structural capacity of the screw is impacted by the screw's thread density and the gauge and yield strength of the intended fastening substrate (steel framing). In this test, given the screw lengths available, the screws were selected to penetrate at least 3/4 in. (~19 mm) into the steel framing to ensure that the major diameter would be in contact with the steel framing. The screws were installed at 12 in. (300 mm) vertical spacing with an effective tributary area of 1.33 ft^2 (0.124 m^2) per screw. The pan head screws were installed so that the screw head flange (underside) was flush to the furring. A torque wrench was used to measure how tightly the screws were installed. Torque of approximately 20 in.-lb (~ 2.3 Nm) was applied to install the screws with qualitatively very little pre-compression of the insulation layers.

Testing Apparatus

The cladding gravity load was simulated by mechanically applying a load on the center furring of a test wall assembly using a custom-built testing apparatus capable of logging displacement and load at 0.5-second intervals. This testing apparatus is equipped with a servomotor, a worm drive with 30:1 ratio, and a S-type load cell[1] rated to 1000lb (~454 kg). The servomotor allowed for precise control of linear position and speed of the mechanical stage with a motor linked to sensors for position and load feedback[2]. The mechanical stage is connected to a 12-turn-per-inch (TPI) threaded rod (via S-type load cell), which is turned by 30-tooth worm wheel connected to a worm that is driven by a motor with 2000 steps per turn. This setup provided 720,000 steps-per-inch (~28,346.5 steps/mm) and the displacement was logged in millimeters to 2 decimal places. The interface that controlled the servomotor with feedback from the sensors (position and load) was written in a load-based programming. This means that the load instead of position (displacement) determined movement of the mechanical stage, allowing the tests to be performed in such a way that the apparatus would displace until a specified load is reached and hold that load for a specified duration. If the furring were to deflect, the programming would cause the mechanical stage to move to compensate to ensure that the specified load is applied consistently, thus simulating a dead load.

In order to apply load to the center furring, the load was transferred from the testing apparatus (mechanical stage) to the steel furring using a steel strap tie. The height of the mechanical stage was adjusted to match the height of the steel furring in order to load it as parallel to the sheathing as possible; however, as the furring was loaded, the insulation experienced some compression, and consequently, load was applied at a slight angle. This is discussed in more detail in: Testing Variables and Limitations.

[1] The load cell was configured to read at 10 Hz but the load was logged at 0.5 s intervals and the accuracy of the reading depended on the accuracy of the load cell and the 24-Bit analog-to-digital converter (ADC).
[2] Displacement accuracy of ±0.03 mm under load and load accuracy of ±1 kg.

Test Procedure

The test was performed with test wall situated horizontally to isolate the cladding load applied by the test apparatus while negating the self-weight of the insulation. Each test wall specimen was loaded twice as follows:

- First Loading - Loaded to 46 kg (101 lb) or 15.3 kg (33.8 lb) per fastener and held for 2 hours, then released
- Second Loading - After the first loading, loaded to 408 kg (899 lb) or 136 kg (299.8 lb) per fastener and the load was held for 120 seconds then released

Two loading cycles were applied so that the initial load displacement response could be evaluated using a load representative of a relatively heavy cladding, and then the load displacement response under second loading could be measured to assess the impact of "seating" of the strapping in to the insulation. Additionally, the second loading significantly exceeds the weight of the typical claddings, with the intent of stressing the system well beyond typical in-service loads to evaluate the response. For reference, the weight range of typical cladding types is indicated in load-displacement plots provided in this paper.

In both tests, the furring was displaced at 0.118 in./min (3 mm/min) until the specified load was reached, at which point the testing apparatus maintained the load by either holding the position or pulling/pushing the furring for 2 hours for the first loading, and 120 seconds for the second loading. Note that in most cases the furring did not return to the original location after the first loading, and the second loading was initiated after the completion of the first without resetting the furring to the original location.

RESULTS AND DISCUSSION

Evaluation of Insulation Types

Figure 2 plots the test result for wall assemblies with 6 in. (152 mm) of insulation and compares the load-displacement response of the test wall specimens with 8 pcf stone wool, 11 pcf stone wool, and XPS (Type 3) insulation. The plots provided are from the first and second loadings for each assembly. As illustrated in Figure 2, the load-displacement response is relatively linear, showing little difference in stiffness between the wall assembly types; however, as expected, the most rigid insulation (XPS) provides the stiffest response and the insulation with the least compressive strength, 8 pcf stone wool, deflects the most. The curves for the second loadings show smaller differences in stiffness between the wall assembly types than during the first loading. When a screw is loaded at 25 lb (11.3 kg), the difference in displacement between the XPS assembly (0.021 in. (0.53 mm)) and 8 pcf stone wool (0.022 in. (0.56 mm)) was negligible.

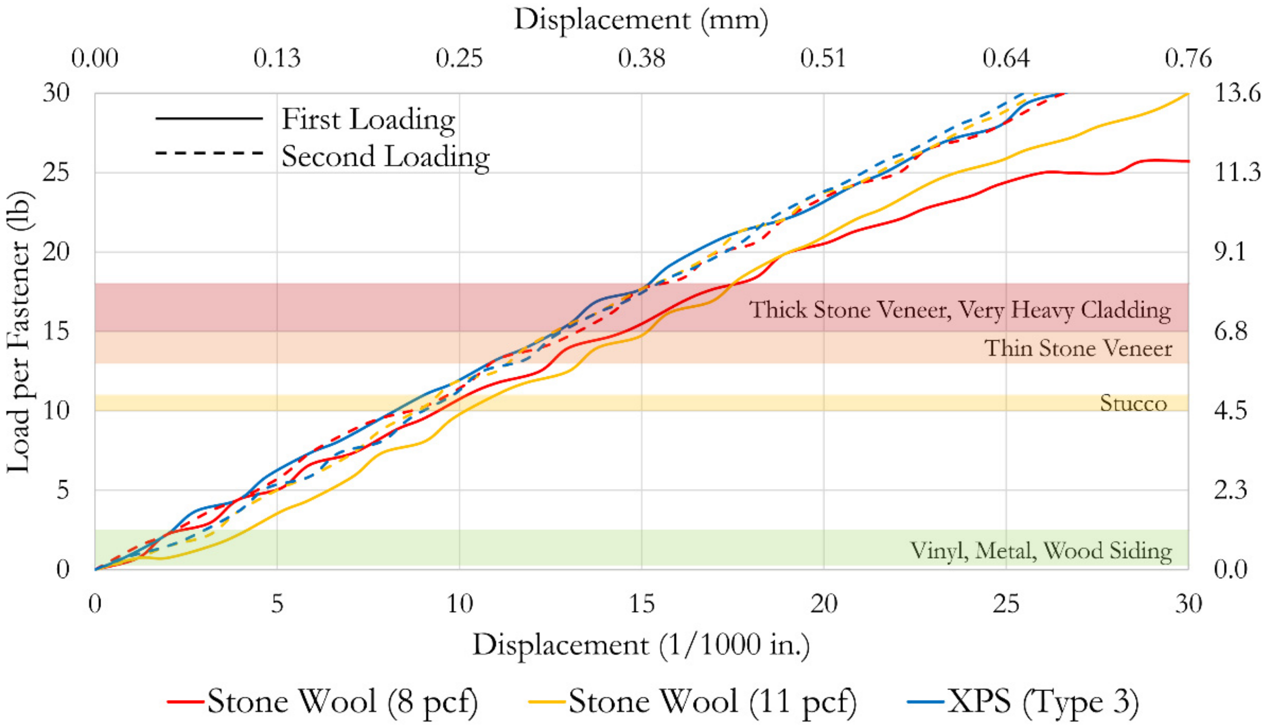

Figure 2 Load-displacement plot comparing different insulation arrangements at 6 in. (152 mm) thickness. The plot provided is for first and second loading of each setup.

Figure 3 provides the load-displacement data for the higher test load range during the second loading. Additionally, the load-displacement data from tests performed in Structural Testing of Screws through Thick Exterior Insulation (Tatara and Ricketts 2017) for wood frame construction for the same insulation thickness and type is provided in the figure for a comparison. Note that the plot range shown in Figure 2 is highlighted with a red box. As illustrated in Figure 3, at between 30 lb (14 kg) and 60 lb (27 kg) of load on a screw there is an inflection point in the load-displacement curves. At higher loads, the impact of the difference in insulation compressive strength is more apparent, though these loads are well beyond typical cladding dead loads anticipated in service. The yielding point is lower and less pronounced for test walls with steel back-up walls compared to the load-displacement response of test walls with wood back-up walls. This observation is likely due to difference in bending resistance of fasteners in wood frame system and rotational resistance of fasteners in steel frame system. The initial response for steel back-up wall is less stiff; however, at approximately 0.040 in. (1.0 mm) of displacement, the load-displacement response starts to become more similar to findings from tests performed for wood frame construction.

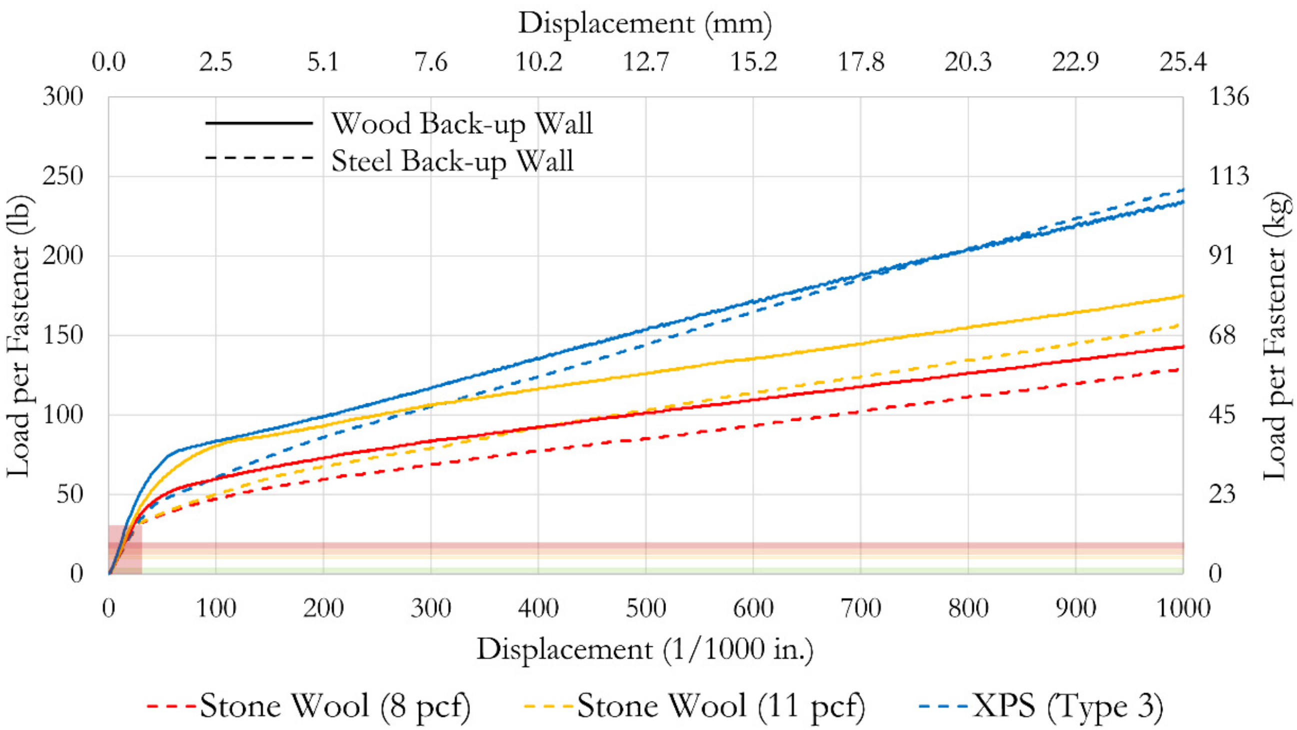

Figure 3 Load-displacement plot comparing different insulation arrangements at 6 in. (152 mm) thickness. The plot provided in dashed line is for the second loading of each setup (steel back-up wall) and the load-displacement data from tests performed for wood frame construction (Tatara and Ricketts 2017) is provided in solid line. Note that the plot range shown in Figure 2 is highlighted by a red box.

Evaluation of Insulation Thickness

Figure 4 plots the load-displacement relationship for the test walls with 3 in., 6 in., and 9 in. (76 mm, 152 mm, and 229 mm) of 11 pcf stone wool insulation. As illustrated, assemblies with 3 in. (76 mm) of insulation experienced the least deflection (0.012 in., 0.30 mm) when the screw is loaded at 25 lb (11.3 kg) while 6 in. and 9 in. (152 mm and 229 mm) thickness of insulation had a similar load-displacement response up to this load (~0.023 in., 0.58 mm). Based on these results, the insulation thickness has a larger impact on the load-deflection response than does the insulation compression strength. The load-displacement response observed in this study was comparable to Lepage's (2013) testing on commercial wall assemblies with steel stud back-up walls which found that the furring strips attached through exterior insulation (4 in., 102 mm) can sufficiently support light weight claddings.

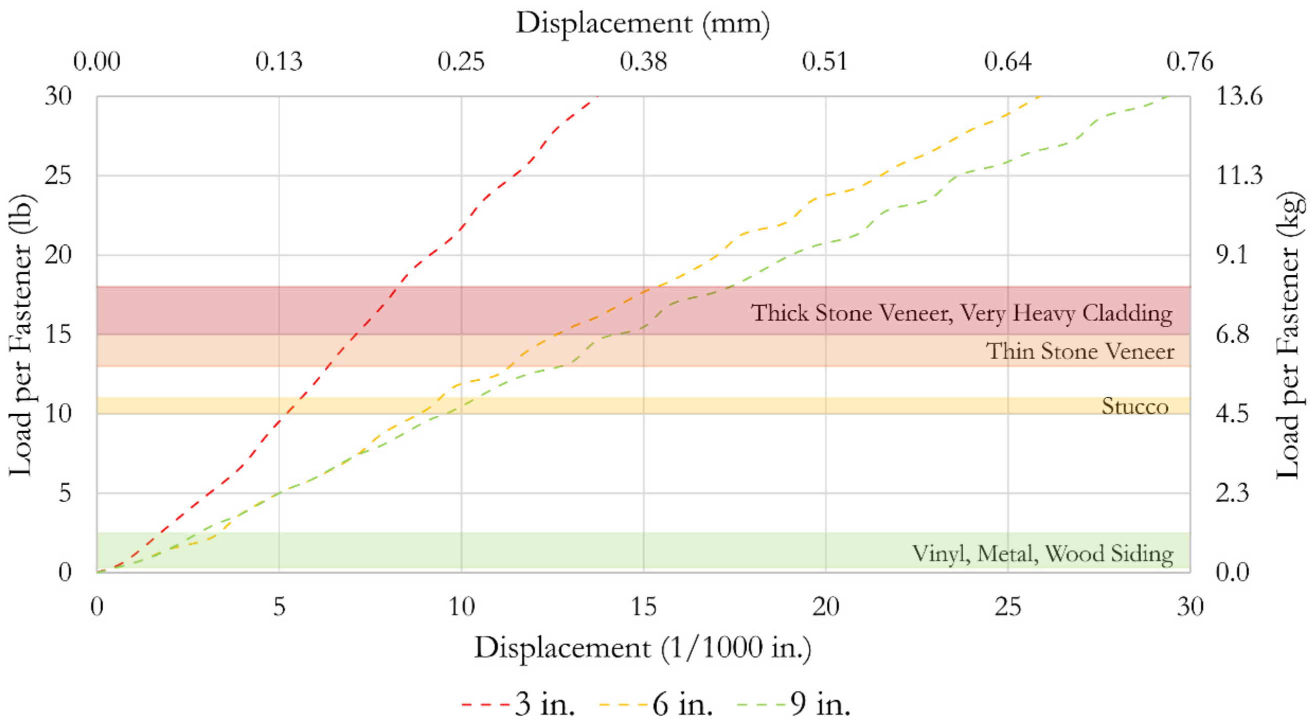

Figure 4 Load-displacement plot comparing 11 pcf stone wool insulation at 3 in., 6 in., and 9 in. (76 mm, 152 mm, and 229 mm) thicknesses. The plot provided is for the second loading of each setup

Other Considerations

In addition to the structural considerations, it is also important to consider the air and water control implications of fastening through the sheathing membrane, and this importance is increased for fasteners which miss the structural steel framing. In wood construction, embedment of the fastener in to the surrounding wood framing or sheathing has been shown to assist in the sealing of the penetration and the sheathing can provide some level of securement for the fastener; however, fasteners through sheathing membranes applied over gypsum wall board substrates have been shown to have difficulty self-sealing, and often can substantially damage the gypsum wall board and sheathing membrane as they attempt to self-tap in to the steel stud during installation. To mitigate this when using clip-type cladding attachment systems, sealant is sometimes installed behind the clip to assist in sealing the fastener penetrations. This approach is not possible when using only long screws through the insulation. Furthermore, if a fastener were to miss the stud, the exterior gypsum wall board will not provide a secure connection for the fastener, and thus it is likely that significant damage could be done to the sheathing membrane. If an installer, having realized that the fastener had missed the stud, were to remove the fastener, a hole would be left in the sheathing, and would likely be difficult or impossible to detect from the exterior due to the overlying insulation material. Further work is planned to characterize the risk associated with this likely difference in performance.

Testing Variables and Limitations

An important limitation of this study is that it evaluated only the cladding dead load on the cladding attachment system; however, wall systems are subject to other loadings (i.e., wind) that should also be accounted for in a complete structural design.

Because the testing apparatus and mechanical stage were fixed flush with the furring, as the screws were loaded, the furring compressed the insulation as the screws started to rotate and, consequently, this allowed a slightly out of plane load to be applied to the furring. A plunger type deflection gauge was used to measure the compression of the insulation approximately at the center of the furring (near the middle fastener) when furring was loaded to 101 lb (46 kg) and 899 lb (408 kg). Based on this measurement, the estimated angle at which the load was applied was calculated and is provided in Table 3. The calculated values are all obtained from tests performed on the test wall specimens with 11 pcf stone wool as this insulation was the only insulation type tested at all three thicknesses. The measured decrease in the 8 pcf stone wool insulation thickness and the loading angle are also provided in the table for comparison (row shaded in grey).

Table 3. Measured Decrease in 11 pcf Stone Wool Insulation Thickness and Estimated Loading Angle

Applied Load on Furring	Nominal Insulation Thickness	Decrease in Insulation Thickness 1/1000 in. (mm)	Decrease in Insulation Thickness %	Loading Angle[i] (Degrees)
101 lb (46 kg)	3 in. (76 mm)	2 (0.051)	<0.1	<0.1
101 lb (46 kg)	6 in. (152 mm)	2.5 (0.064)	<0.1	<0.1
101 lb (46 kg)	6 in. (152 mm)[ii]	7.5 (0.191)	<0.1	<0.1
101 lb (46 kg)	9 in. (229 mm)	4 (0.102)	<0.1	<0.1
899 lb (408 kg)	3 in. (76 mm)[iii]	N/A	N/A	N/A
899 lb (408 kg)	6 in. (152 mm)	227 (5.766)	3.8	0.5~1.1
899 lb (408 kg)	6 in. (152 mm)[ii]	640.5 (16.269)	10.1	1.5~3.1
899 lb (408 kg)	9 in. (229 mm)	287 (7.290)	3.2	0.7~1.4

[i] Assuming the distance between the mechanical stage and furring is 1 ft ~ 2 ft (305 mm ~ 610 mm)

[ii] This row provides measured decrease in 8 pcf stone wool insulation thickness and estimated loading angle

[iii] The decrease in 11 pcf stone wool insulation thickness at 3 in. was not measured during the second loading at 899 lb (48 kg) due to deflection gauge malfunction

CONCLUSION

This work evaluated the impact of insulation thickness and type on the load-deflection response of long screws through exterior insulation cladding support systems when a simulated dead load was applied. This study found that:

1. The impact of the compressive strength of the insulation materials on the overall stiffness of the test wall assembly was negligible when screws were loaded up to 25 lb (11.3 kg), which is indicative of common cladding loads. The difference in deflection between 6 in. (152 mm) of rigid foam insulation (XPS) and semi-rigid insulation (8 pcf stone wool) was 0.005 in. (0.13 mm) at 25 lb (11.3 kg) during the first loading.
2. The tests performed on wall assemblies with insulation thicknesses of 3 in., 6 in., and 9 in. (76 mm, 152 mm, and 229 mm) showed that the wall with 3 in. of insulation is noticeably stiffer compared to the walls with 6 in. (152 mm) or 9 in. (229 mm) of insulation.
3. Each test wall was loaded twice, and more deflection was consistently experienced on the initial loading, though the difference in deflection between loadings was relatively small. For the test wall specimen with 6 in. of 8 pcf stone wool, the difference in deflection between the first and second loading when loaded to 25 lb (11.3 kg) was 0.005 in (0.13 mm).
4. In a laboratory condition with test wall situated in a horizontal position, it was possible to ensure that the screws penetrated the backup wall framing; however, ensuring 90° screw penetration into backup wall framing members would likely be difficult in real-world applications, and there is potential for missing the framing members. This can have potentially impact air and water control performance for the system.
5. The initial load-displacement response for this cladding support system installed on steel back-up walls is less stiff than when it is used with wood back-up walls; however, the system is likely to provide sufficient strength and stiffness to support the dead load of most common claddings in either arrangement.

ACKNOWLEDGMENTS

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