STRUCTURAL AND HYGROTHERMAL ANALYSIS OF HYBRID WALL SYSTEMS

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ABSTRACT

In building and specifying high-performance walls systems, we have found that systems created from combinations of materials and approaches usually provide optimum performance. Integration of many different materials is necessary. This study investigated a set of hybrid walls that used a combination of exterior insulation diagonal metal strapping, closed cell spray polyurethane foam, and cavity fill insulation. The hybrid wall systems were financially analysed for cost effectiveness, thermally modeled for whole wall R-values, hygrothermally modeled for moisture durability, and structurally tested to ASTM E72.

Results showed that the hybrid insulated wall systems can cost-effectively provide robust thermal, air, moisture, and water barrier systems in one assembly while also providing structure. The cost analysis using RSMeans CostWorks showed that the optimal hybrid wall has an incremental cost at \$2.20/ft^2 of enclosure wall when compared to a standard 2×6 wall with OSB. Thermal modeling using Therm5 showed the importance of insulation placement to effectively reduce energy loss. Hygrothermal modeling using WUFI showed that the proposed hybrid walls reduced condensation risk from air leakage in cold climates by between 95% and 100% compared to a standard 2×6 wall with OSB sheathing. The ASTM E72 structural testing shows that the ultimate racking strength of a diagonally strapped XPS sheathed wall is tripled with the addition of 1.5 in. (38mm) of closed cell spray polyurethane foam to each stud bay. When compared to a standard 2 × 6 advanced framed wall with OSB, the hybrid walls showed 50% higher ultimate strength with significantly less displacement.

The results of the analysis and testing show that hybrid walls are one of the most promising technologies for high performance residential wall assemblies.

INTRODUCTION AND BACKGROUND

Experience and demonstration projects from the US Department of Energyís Building America program have shown that systems made up of a combination of materials and approaches will usually provide optimum performance. Although other researchers have examined the composite effect of high density spray polyurethane foam in light wood frame wall assemblies in conjunction with structural sheathing (Parasin and Nagy 1991), there is a lack of research into wall systems that do not use typical wood structural sheathing. To address this gap, research was conducted by Building Science Corporation into a series of hybrid wall assemblies through a public-private partnership funded by the U.S. Department of Energyís Building America program. This research project evaluated the cost and the thermal, hygrothermal, and structural properties of the proposed assemblies. Dow Building Solutions as an industry partner provided the equipment, laboratory space, laboratory technicians, and materials to complete the structural testing of the hybrid assemblies.

METHODOLOGY

A number of hybrid insulated wall systems were compared to a common standard advanced framed wall. The hybrid walls utilized a combination of exterior insulation, diagonal metal strapping, and spray polyurethane foam, and left room for cavity-fill insulation. This design strategy can provide structure as well as effective thermal, air, moisture, and water barriers systems. Housewrap as a drainage plane is not required because the taped exterior insulation is used as the drainage plane. Structural sheathing (such as OSB) is also unnecessary because the composite action of the high-density spray polyurethane foam transfers the shear capacity of the insulating sheathing and a diagonal metal strap to the advanced framed wood wall.

The exterior insulating sheathing products used were 1.5 in. (38mm) extruded polystyrene (XPS) and 1.5 in. (38mm) and 3 in. (76mm) foil-faced polyisocyanurate (PIC). Cellulose and fiberglass fibrous insulations were used to fill the stud space gap remaining after the installation of 1.5 in. (38mm) of closed-cell spray polyurethane foam (ccSPF). The thickness of the ccSPF was chosen as 1.5 in. (38mm) because it was determined that this is likely the thinnest that can be reliably installed in a single pass to create both an air barrier and to transfer the structural loads from the wood frame to the insulating sheathing. A complete list of wall components is available in TABLE 1.

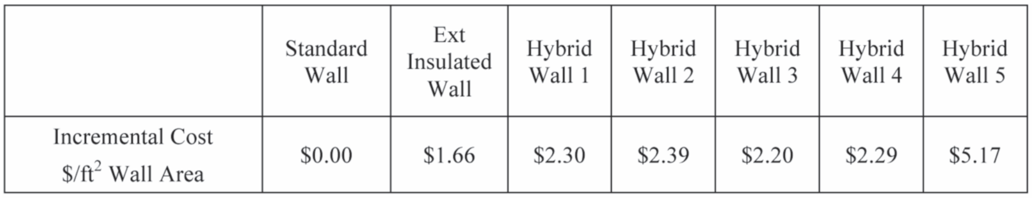
Analysis included costs, thermal performance, hygrothermal performance and structural integrity. Each proposed hybrid wall assembly was assigned a cost relative to standard construction. The incremental costs were determined by consulting with builders and verified with the Reed Construction Data costs. Therm5 was used to determine the thermal properties of each assembly. Wärme und Feuchte instationär (WUFI) was used to measure the hygrothermal properties. Details about the structural testing are provided within the structural testing section.

		Standard Wall	Ext Insulated	Hybrid Wall 1	Hybrid Wall 2	Hybrid Wall 3	Hybrid Wall 4	Hybrid Wall 5
Exterior Finish	Any	•	•	•	•	•	•	•
Drainage	Housewrap	•	•					
	Exterior Insulation w/ Sealed Joints			•	•	•	•	•
Exterior Insulation	1.5 in. (38mm) XPS		•	•	•			
	1.5 in. (38mm) PIC					•	•	
	3 in. (76mm) PIC							•
Structural	7/16" OSB Sheathing	•	•					
	ccSPF / Metal Strap			•	•	•	•	•
Framing	Advanced Framed	•	•	•	•	•	•	•
Cavity Insulation 1	1.5 in. (38mm) ccSPF			•	•	•	•	•
Cavity Insulation 2	Cellulose			•		•		•
	Spray fiberglass				•		•	
	R21 Fiberglass Batt	•	•					
Interior Finish	Painted Gypsum	•	•	•	•	•	•	•

TABLE 1: WALL ASSEMBLY DETAIL SUMMARY

ANALYSIS OF COSTS

TABLE 2 summarizes the associated incremental labour and material costs of the hybrid walls over the standard wall. The initial step to 1 in. (25mm) XPS exterior insulating sheathing is $\$1.66/\text{ft}^2$. The incremental cost of $\$2.30/\text{ft}^2$ for Hybrid Wall 1 includes 1.5 in. (38mm) ccSPF insulation, cellulose insulation, and 1.5 in. (38mm) XPS exterior insulating sheathing. Hybrid Wall 2 at $\$2.39/\text{ft}^2$ includes 1.5 in. (38mm) ccSPF insulation, blown fiberglass insulation, and 1.5 in. (38mm)XPS exterior insulating sheathing. Hybrid Walls 3 and 4 are the same as 1 and 2 but use 1.5 in. (38mm) PIC in place of the 1.5 in. (38mm) XPS insulating sheathing. The significant increase in cost for Hybrid Wall 5 at $\$5.17/\text{ft}^2$ is related to the additional insulating sheathing, but also includes longer fasteners, window box-outs, and vertical wood strapping for cladding attachment. The hybrid wall with the least incremental cost is Hybrid Wall 3 at $\$2.20/\text{ft}^2$.



	Standard Wall	Ext Insulated Wall	Hybrid Wall 1	Hybrid Wall 2	Hybrid Wall 3	Hybrid Wall 4	Hybrid Wall 5
Incremental Cost $\$/\text{ft}^2$ Wall Area	\$0.00	\$1.66	\$2.30	\$2.39	\$2.20	\$2.29	\$5.17

TABLE 2: INCREMENTAL COSTS

It is important to note that although a system may cost more initially, the more expensive wall (as specified in this project) will be more energy efficient, and this energy-cost savings must be taken into account over time. It cannot be ignored that a system that is slightly more expensive initially may have to be implemented to save a significant amount of energy and cost over the entire life of the structure, which is often much longer than a standard mortgage. Research has shown that walls exceeding an R-value of 35 in an Ontario climate can financially pay back through during the life of the initial mortgage through energy savings while reducing greenhouse gas emissions (Grin 2008). Because the building enclosure is designed to use less energy, the energy and greenhouse gas emissions savings extend for the life of the building and not just for the duration of the initial mortgage.

ANALYSIS OF THERMAL PERFORMANCE

Therm5 was used to calculate the clear system R-values of each hybrid assembly. Comparing installed R-values can be misleading as it does not account for thermal bridging or where the insulation is installed. The clear system R-value provides a more accurate value for comparison. Clear wall refers to the R-value of an assembly containing only insulation and minimum necessary framing materials at a clear section with no windows, corners, columns, or architectural details, and no intersections with roofs, foundations, or other walls. Advanced framing with 2 × 6 (38mm x 140mm) studs at 24 in. (600mm) on center studs, a single top plate and bottom plate, two stud corners, and simplified framing around openings has been shown to result in assemblies with a 16% framing factor. An 8 ft. (2.4m) section of wall with a 16% framing factor was used to simulate advanced framing. The Therm5 modeling of a clear wall R-value simply represents a point of comparison using each assembly's relative R-value. The thermal analysis results are summarized in TABLE 3.

	Standard Wall	Ext Insulated Wall	Hybrid Wall 1	Hybrid Wall 2	Hybrid Wall 3	Hybrid Wall 4	Hybrid Wall 5
Installed R-Value (RSI)	21 (3.7)	26 (4.6)	30 (5.3)	31 (5.5)	34 (6.0)	35 (6.2)	43 (7.6)
Clear System Modeled R-Value (RSI)	17.7 (3.1)	24.8 (4.4)	26.9 (4.7)	27.6 (4.9)	29.4 (5.2)	30.1 (5.3)	39.3 (6.9)

TABLE 3: INSTALLED AND CLEAR SYSTEM R-VALUES

Hybrid Wall 1 has an apparent installed R-value that exceeds the Standard Wall by R-8.6, but performs R-9.2 better as a clear system primarily because of the reduction in thermal bridging. The hybrid walls perform incrementally better and Hybrid Wall 5 performs the best with a clear system R-value of 39.3.

ANALYSIS OF HYGROTHERMAL PERFORMANCE

Hygrothermal modeling predicts the moisture-related risk associated with each hybrid wall. During modeling, the key value monitored was the dew point potential of particular surfaces of the assembly. This is based on assumed indoor temperature and relative humidity and measured average outdoor temperature and relative humidity for two locations. These measurements will determine the susceptibility of the assembly to moisture damage in a representative warm and cold climate. The material properties from WUFI's Generic North American Materials database were utilized for the simulation of the proposed hybrid walls. The testing will not include extreme values usually associated with major disasters, such as earthquakes or flooding.

The outdoor climatic data files provided with WUFI for New Orleans as well as Minneapolis were left unaltered. The indoor conditions varied on a sinusoidal curve with a period of one year. The temperature ranged from 68°F (20°C) in the winter to 75°F (24°C) in the summer. The relative humidity (RH) ranged from 30% in the winter to 60% in the summer.

In above grade walls in cold climates, winter time outward air leakage and vapor condensation are concerns. Condensation happens on surfaces with temperatures below the dew point of the air that is in contact with them. To determine whether the assembly has the possibility for air leakage condensation, the dew point of the interior air, as well as the surface temperatures within the wall assembly, must be calculated. Since WUFI outputs data in an hourly format, it is possible to calculate the number of hours there is condensation potential on surfaces within the wall. The number of hours the wall is at risk for condensation then becomes the metric to compare the expected durability of the assembly in regard to air leakage condensation. If the interior RH is high, the air leakage condensation risk is higher as the dew point of the interior air is higher and it contains more moisture. Based on this information, it can be shown which walls would be less durable if the air leakage condensation is able to cause moisture-related deterioration.

For the Standard Wall, the possible condensation plane is the inside face of the OSB. The total hours of possible condensation is calculated by adding up all of the hours that the temperature of the inside face of the OSB is below the dew point of the interior air. The annual total indicates the total annual risk of condensation. For the exterior insulated wall, the condensation surface considered was the inside face of the exterior insulation. In the case of the hybrid walls the inside face of the ccSPF was monitored for condensation risk. As the amount of insulation present outside of the possible condensation plane increases, the associated risk decreases. This is most significant when comparing any one of the hybrid walls to the standard case. A summary of the calculated hours of condensation and the reduction in condensation potential for each modeled wall for Minneapolis can be found in TABLE 4. In this climate, Hybrid Wall 1 showed a 95% decrease in risk compared to the Standard Wall. Hybrid Wall 3 showed a 98% reduction and Hybrid Wall 5 showed a 100% decrease and no condensation potential risk. The hygrothermal analysis for New Orleans did not show any significant air leakage condensation risks.

	Hours of Possible Condensation	Reduction in Condensation Potential
Standard Wall	3878	N/A
Exterior Insulated Wall	2049	47%
Hybrid Wall 1	176	95%
Hybrid Wall 2	514	87%
Hybrid Wall 3	85	98%
Hybrid Wall 4	370	90%
Hybrid Wall 5	0	100%

TABLE 4: AIR LEAKAGE CONDENSATION RISK SUMMARY FOR MINNEAPOLIS

It should be noted that in the hybrid cases, the condensation plane is a material that is not affected by moisture whereas the OSB wall will deteriorate eventually if the wetting is significant and is not balanced with drying. Although the condensation plane is not affected by moisture it is important to note that if sufficient condensation could occur it is possible to drain down and contact other materials that may be affected. Since drying is minimal during periods of condensation, the severity of condensation increases the further the sheathing temperature falls, and the longer it spends, below the dew point of the interior air.

STRUCTURAL ANALYSIS

It is hypothesized that the hybrid walls do not need structural sheathing (such as OSB) because the composite action of the high-density spray polyurethane foam is used to transfer the shear capacity of the insulating sheathing and a diagonal metal strap to the advanced frame wood wall. American Society for Testing and Materials (ASTM) E72 (Standard Test Methods of Conducting Strength Tests of Panels for Building Construction) structural testing was completed to compare the proposed hybrid walls to a known, building-code-compliant, and frequently built wall assembly.

To help determine the level of interaction provided by the ccSPF and insulating sheathing, three variations of the hybrid wall were tested. The fibrous insulation and drywall were not included in the structural testing. The thickness of the ccSPF was not significantly varied between tests and was installed to 1.5 in. (38mm).

SPECIMEN CONSTRUCTION

Three samples of each test wall were built in order to increase the certainty of the findings. TABLE 5 contains brief descriptions of each test wall.

Standard Wall	Standard 2 × 6 (38mm x 140mm) advanced framing 7/16 in. (11mm) OSB sheathing nailed in place
Structural Test Wall A	Standard 2 × 6 (38mm x 140mm) advanced framing Diagonal metal strapping 1.5-in. (38mm) XPS insulating sheathing Stud bays remain empty for this test
Structural Test Wall B	Same as Test Wall A with 1.5 in.(38mm) ccSPF installed in all bays
Structural Test Wall C	Same as Test Wall A but replace XPS with 1.5 in. (38mm) foil-faced polyisocyanurate as exterior insulation and 1.5 in. (38mm) ccSPF installed in all bays.

TABLE 5: STRUCTURAL TEST WALL SUMMARY

Wall assemblies were constructed by laboratory technicians according to a step-by-step construction method, following verbal instructions and detailed specifications. In order to ensure the testing closely related to real world construction, a wood spacer was attached to the base of the steel testing apparatus. The bottom plate of the wall was then affixed to the wood spacer. This ensured the bottom plate would be attached to wood as it would be in the field, rather than being bolted directly to steel.

Upon completion of the testing, cores were taken through the test specimens to verify that the average ccSPF thickness was 1.5 in. (38mm). The ccSPF thicknesses varied from 1.5 in. (38mm) to nearly 2 in. (51mm), but the areas that were thick were small and localized.

TESTING PROCEDURE

Each wall was physically tested by a hydraulic ram pushing on the top corner of the wall parallel with the top plate. The load was transferred to the full length of the top plate through an aluminum beam attached to the top plate. The horizontal displacement of the bottom plate and the top plate were measured. Bottom plate lift was also measured but was not a factor in this testing. Subtracting the bottom plate displacement from the top plate displacement calculates the horizontal displacement of the top plate in relation to the bottom plate. These values, as well as the corresponding hydraulic ram loads, were digitally recorded.

The ASTM E72 test measures deflection as a result of a set of loadings. The loading was applied at a rate of 395 lbs. per minute. Data (force and deflection) were recorded at 10 readings per second. The loading process completed during this testing was as follows:

1. Ram locates wall and zeros its displacement measurement
2. Loading to 790 lb (360 kg), and full release of loading
3. Loading to 1,570 lb (714 kg), and full release of loading
4. Loading to 2,360 lb (1073 kg), and full release of loading
5. Load to failure. 4-inches (102mm) of deflection or 30,000 lb (13636 kg).

STRUCTURAL RESULTS

A summary graph of all of the structural testing results is shown in FIGURE 1 following the discussion.

Standard Wall

The Standard Wall was framed identically to all of the other test walls, but was sheathed with OSB. The 1,570 lb (714 kg) and 2,360 lb (1073 kg) loadings produced displacement that did not return to zero upon releasing the loading. The primary failure mode for this wall was the loosening of the fasteners through the OSB sheathing followed by the fasteners tearing out of the OSB. The sheets of OSB were intact except for the fastener locations. This failure mode was typical of all three walls tested.

Structural Test Wall A

The purpose of testing Structural Test Wall A was to obtain a basic understanding of the strength of a diagonally strapped, 1.5-in. (38mm) XPS sheathed wall. This shows the baseline for the hybrid wall testing and allows calculations of the added strength provided by the ccSPF insulation and its interaction effect with the exterior insulating sheathing. The wall was unable to obtain the 2,360 lb. (1073kg) and failed by exceeding a 4 in. (102mm) displacement. The diagonal metal strap took much of the loading and pulled out its nails while the XPS insulating sheathing took minimal load with the nails easily pulling through the XPS. The XPS sheets twisted in plane and the fasteners tore out the edges of the sheets. This failure mode was typical of all three walls tested.

Structural Test Wall B

Structural Test Wall B contained approximately 1.5 in. (38mm) of ccSPF in all stud bays directly against the XPS sheathing and depicts Hybrid Wall 1 and Hybrid Wall 2. The installation of ccSPF tripled the ultimate load capacity of the assembly up to nearly 6000 lbs (2700kg) and greatly reduced the associated displacement at each load. The load was transferred from the wood framing to the ccSPF and into the XPS sheathing as well. The sheets did not twist in plane as they did in the case of Wall A. During final failure, approximately the top 2 feet (600mm) of each stud bent while the load was transferred from the top plate to the stud and to the ccSPF and sheathing. Failure occurred when the left stud began tearing free from the ccSPF. The tear then propagated along the underside of the top plate. Finally, the top plate shifted along the top of the studs shearing the nails out of the studs. This was followed by shear tearing along the full length of the underside of the top plate as it released from the ccSPF. This failure mode was typical of all three walls tested.

Structural Test Wall C

Structural Test Wall C contained approximately 1.5 in. (38mm) of ccSPF in all stud bays directly against the PIC exterior insulation and depicts Hybrid Wall 3 and Hybrid Wall 4. Structural test wall C performed the best of all walls tested. Test Wall C maintained very little residual displacements through loadings up to 2,360 lbs. (1073 kg) and displaced the least of any of the walls tested. Each loading began at nearly zero displacement. The ultimate strength of the PIC sheathed walls was very similar to that of the XPS sheathed walls and exceeded 6,000 lbs. (2700kg) of force. The failure mode of the PIC insulated walls is very similar to that of the XPS walls. The left-most stud tore free from the ccSPF and was followed by the shearing of the top plate along the top of the studs. This failure mode was typical of all three walls tested.

Structural Testing Comparison Summary

The testing showed that the ultimate strength of a diagonally strapped XPS sheathed wall is tripled with the addition of 1.5 in. (38mm) of ccSPF to each stud bay. When compared to a standard 2 × 6 (38mm x 140mm) advanced framed wall with OSB a hybrid exterior insulated wall with diagonal metal strapping and 1.5 in. (38mm) of ccSPF within the stud bays the hybrid wall has a 50% higher ultimate strength while displacing less.

Each of the proposed hybrid walls exceeds the structural capacity of a standard advanced framed wall with OSB sheathing. Specifically hybrid walls 3 and 4, which used PIC exterior insulation, provide the highest ultimate strength while displacing the least and, more importantly, can be loaded and unloaded up to 2,360 lb (1073kg) without residual displacement.

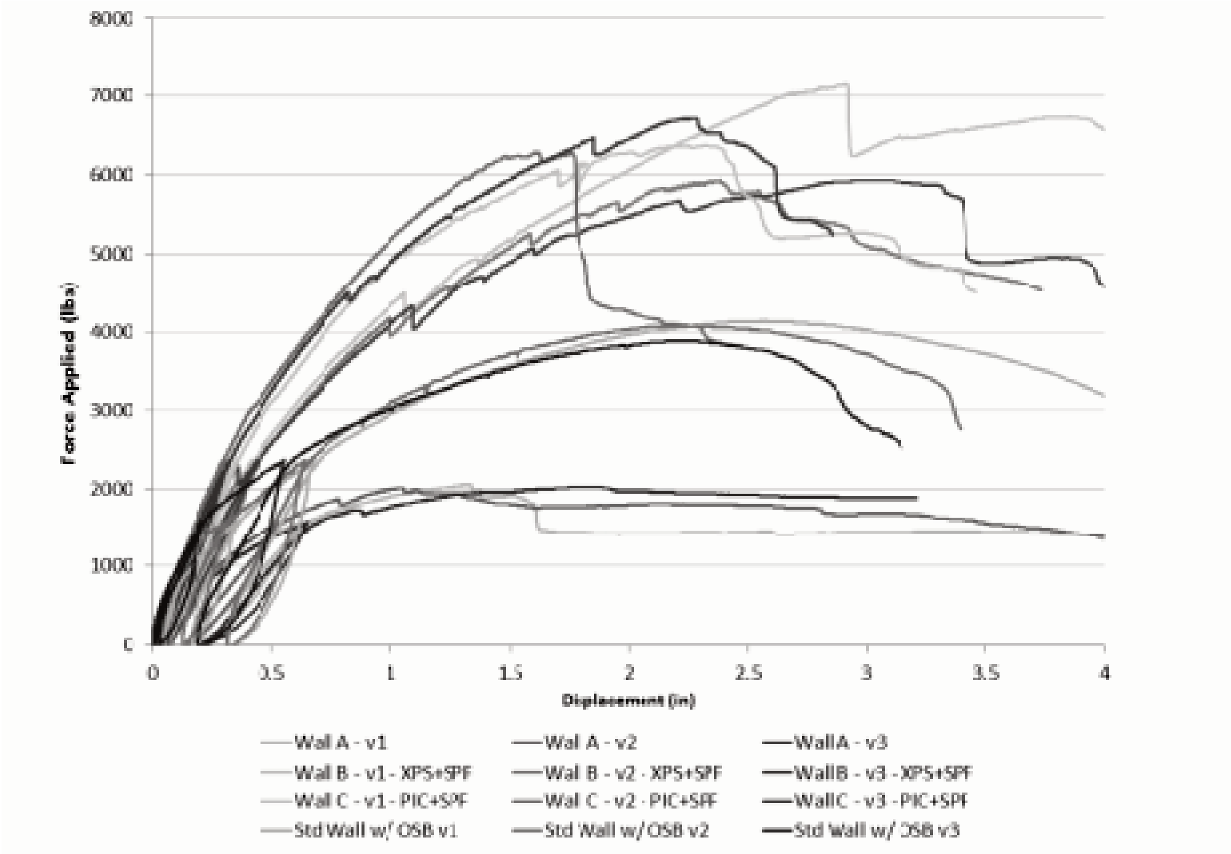


FIGURE 1: STRUCTURAL TESTING COMPARISON SUMMARY GRAPH

CONCLUSIONS

Wall systems, composed of combinations of materials and approaches, usually provide optimum performance. The hybrid walls analyzed utilize a combination of exterior insulation, diagonal metal strapping, and closed-cell spray polyurethane foam, while leaving room for cavity-fill insulation. This research has demonstrated that this design strategy is cost effective and structurally sound and can provide effective thermal, air, moisture, and water barrier systems in one assembly.

Thermal modeling using Therm5 showed the importance of insulation placement to reduce thermal bridging and that Hybrid Wall 3 and 4 had higher clear wall R-values than the standard walls or Hybrid Walls 1 and 2. Hybrid Wall 5 with 3 in. (76mm) of exterior insulation had the highest clear wall R-value but also had a high associated incremental cost.

Hygrothermal modeling using WUFI showed that the proposed hybrid walls reduced air leakage condensation risk in cold climates by between 95% and 100% compared to a standard 2◊6 (38mm x 140mm) wall with OSB sheathing.

The ASTM E72 structural testing shows that the ultimate racking strength of a diagonally strapped XPS sheathed wall is tripled with the addition of 1.5 in. (38mm) of closed cell spray polyurethane foam to each stud bay. When compared to a standard advanced framed wall with OSB, the hybrid walls showed 50% higher ultimate strength while displacing less. Specifically Hybrid walls 3 and 4, using PIC exterior insulation, provide the highest ultimate strength while displacing the least. Also important, the hybrid walls could be loaded and unloaded with up to 2,360 lbs. (1073 kg) without residual displacement.

The optimal wall in terms of cost, thermal, hygrothermal, and structural analysis is Hybrid Wall 3. Hybrid Wall 3 has the lowest associated incremental cost at $2.20/ft2, the lowest air leakage condensation risk (less than 1% of the year in Minneapolis) and is one of the best structural performers. The results of the rigorous analysis and testing show that hybrid walls are one of the most promising technologies for high performance residential wall assemblies.

Hybrid Wall 3 consists of the following:

- Exterior vertical wood strapping for cladding attachment
- 1.5-in. (38mm) foil-faced polyisocyanurate board insulation
- Diagonal metal strapping
- 2 × 6 (38mm x 140mm) advanced framed wall
- 1.5-in. (38mm) closed-cell spray polyurethane foam in each stud bay
- 3-in.(76mm) cellulose insulation
- 0.5-in.(12mm) gypsum with latex paint finish.

ACKNOWLEDGEMENTS

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