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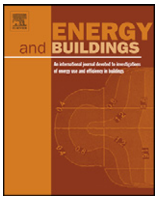

Modeling the hygrothermal performance of selected North American and comparable European wood-frame house walls

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ABSTRACT

In North America, the exterior finish of wood-frame house walls usually consists of a siding, a water resistive barrier, and an oriented strandboard (OSB) sheathing. In Europe, the exterior finish uses the External Thermal Insulation Composite System attached to a gypsum board sheathing. This study was performed to compare the hygrothermal performance of American and European walls by using a finite-element model. Analysis showed that the European wall has better thermal performance mainly because of the heat-insulating ability of the expanded polysterene (EPS) layer. But when the EPS was reduced to the same thickness as the siding used in American construction, the thermal performance of the European wall did not fare any better than the American structure. The resistance of the European wall to moisture damage was also better than the American walls. One reason for this is the high diffusion resistance of the EPS. But this same high diffusion resistance works to the detriment of an Exterior Insulation Finish System (EIFS) wall if water is able to infiltrate the structure. When water leakage is present, the water content of the OSB in the EIFS wall reaches levels that make it vulnerable to mold growth and fungal decay.

1. Introduction

Wood is one of the most preferred building materials because it is renewable and has excellent properties such as good aesthetic appearance, high strength relative to its weight, easy workability, and good heat insulation capacity. In addition, wooden residential buildings result in less carbon dioxide emission during manufacture, operation, and disposal [1,2]. Several studies prove that wood frame buildings cause less carbon dioxide emission than other types of buildings [3–5]. Life cycle analysis also shows that unlike other building materials, wood mitigates climate change [6–8]. As environment protection plays a more important role, it is expected that utilization of wood as a building material will increase [9,10].

Although almost all elements of a building can be made of wood, different geographical areas have different traditions for using wood for buildings. In North America, a very high percentage of residential buildings is made of wood [11]. In Europe, the main building materials are stone and brick. Wood is a highly preferred building material in geographical locations where it is present in quantitative and qualitative abundance. Today as it was during the time of the European settlements, wood is readily available in the U.S. and therefore is used widely for construction.

The European society looks back to a very long architectural history. The desire to preserve their own social and cultural traditions has made the Europeans hold on to using the traditional stone and brick construction. However, there are areas in Europe where wood is used widely in building construction such as Scandinavia and the mountain areas in the Alps and Carpathian mountains [12]. Even though wood is used in residential building construction in those European regions, the construction detail of those houses are different from those found in the U.S. Instead of vinyl, fiberboard, or fiber-cement siding, the houses in Europe use the External Thermal Insulation Composite System (ETICS) as exterior wall finishing [13–15]. The system is very similar to the Exterior Insulation Finish System (EIFS) used in North America and consists of a finish coat, a base coat with reinforcing mesh, and an expanded polystyrene. ETICS is attached to the wood frame structure using fiber-reinforced gypsum board as sheathing.

The difference in the construction details point to differences in the performances of the North American and European wood-frame housing constructions. The home building industries of the two continents can benefit from a systematic comparison of the advantages and disadvantages of the two construction methods. The aim

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Table 1
Sizes and physical properties of the elements of the American I and American II wall structures.

Layer	Material	Thickness [mm]	Thermal conductivity [W/mK]	Heat Capacity [J/kgK]	Diffusion Resistance Factor [-]	Monitor location
Siding	Fiber Cement Board	9.5	0.245	840	1	1
Water barrier	Tyvek	0.1	3	1,500	14	
Sheathing	OSB	15.5	0.13	1,500	650	2
Wall core	Wood frame	89 (140)	0.13	1,600	50	3
	Fiber glass	89 (140)	0.04	840	1.3	
Vapor barrier	Polyethylene membrane	0.1	2.3	2,300	1,500,000	4
Interior board	Gypsum board	12.7	0.16	870	7.03	
Total thickness		**126.9 (177.9)**				5

Note: The wood frame, fiber glass, and total thicknesses for the American II wall structure are in parenthesis.

of this study is to compare the energy efficiency and moisture resistance of typical North American and European wood-frame houses using a hygrothermal simulation model.

2. Materials and methods

Typical residential structures from North America and Europe were selected, virtual models were constructed, and specific material properties were assigned to each wall element in order to run simulations that compare the heat and moisture performances of different wall constructions using a finite element mathematical modeling technique.

2.1. Wall structures

For this investigation, the core wood frames of the wall structures were made of spruce. Using 38 mm × 140 mm studs is gaining popularity in North America but the majority of the present construction still utilizes 38 mm × 89 mm studs. Therefore, in addition to the European wall structure, two types of American wall construction were included in the analyses:

American I: had 38 mm × 89 mm actual-dimension studs (1½″ × 3½″ actual dimensions, 2″ × 4″ nominal dimensions) with 0.41-m (16-in.) on-center spacing.
American II: had 38 mm × 140 mm actual-dimension studs (1½″ × 5½″ actual dimensions, 2″ × 6″ nominal dimensions) with 0.61-m (24-in.) on-center spacing.
European: had 60 mm × 140 mm actual-dimension studs with 0.625-m on-center spacing.

The wall height in both American wall structures was 2.74 m (9 feet). The framing-to-insulation ratio of the wall was 0.13 in American I and 0.10 in American II. In comparison, the European structure had a wall height of 2.8 m and a framing-to-insulation ratio of 0.16. To calculate the framing-to-insulation ratio, the total

Table 2
Sizes and physical properties of the elements of the European and EIFS wall structures.

Layer	Material	Thickness [mm]	Thermal conductivity [W/mK]	Heat Capacity [J/kgK]	Diffusion Resistance Factor [-]	Monitor location
ETICS[a]	Lime mortar fine	5	0.7	850	15	1
	EPS[b]	60	0.04	1,500	50	
Sheathing	Fiber-reinforced gypsum board[c]	12.5	0.47	850	10	2
	OSB[d]	12.5	0.13	1,500	650	
Wall core	Wood frame	140	0.13	1,600	50	3
	Fiber glass	140	0.04	840	1.3	
Vapor barrier	Polyethylene membrane	0.1	2.3	2,300	1,500,000	4
Interior board	Gypsum board	12.5	0.2	850	8.3	
Total thickness		**230.1**				5

[a] External thermal insulation composite system.
[b] Expanded polystyrene.
[c] This is the sheathing material for the European wall.
[d] This is the sheathing materials for the EIFS wall and the EIFS with leakage wall.

wall area occupied by the bottom sole plate, double top plates, and studs were divided by the total wall area occupied by the insulation. The space between the studs was filled with fiber glass insulation in all three wall structures.

The core wood frames were covered with different types of boards. In North America, the frame is sheathed with oriented strandboard (OSB) to the outside and with gypsum board to the inside. In Europe, the side facing the exterior is covered with fiber-reinforced gypsum board while the one facing the interior of the house is covered with gypsum board. Polyethylene membrane was used as vapor barrier between the interior gypsum board and the wood frame in all three wall structures. Both American wall structures were finished with wood–fiber cement composite siding, which is one of the most frequently used sidings besides vinyl and brick. Just behind the fiber cement siding was a laminated membrane (Tyvek) that served as a water barrier. This laminated membrane has high vapor permeability and, therefore, allows the flow of moisture. In the European structure, an External Thermal Insulation Composite System (ETICS) was used for the siding. Tables 1 and 2 show the sizes and physical properties of the elements of the wall structures.

2.2. Modeling technique

In this study, the WUFI Pro 5.0 finite element program was used to model and compare the different wall structures in order to predict heat and moisture performances. WUFI has been proven to be useful in predicting hygrothermal conditions with sufficient accuracy [16–18]. The software makes it possible to place monitors at different locations in the wall structure to hourly record the temperature and relative humidity. The temperature and relative humidity play important roles in determining the equilibrium moisture content of materials and indicate the possibility of condensation hazard. The locations of five monitors in each wall construction are indicated by arrows in the last column of Tables 1 and 2.

2.3. Weather condition

For a meaningful comparison of their hygrothermal performance, it was assumed that the different structures were all located in Indianapolis, Indiana. Although it is possible to use arbitrary weather data after appropriate file transformation in modeling with WUFI, the program contains several weather data for numerous cities around the world. The cold-year weather for Indianapolis was selected from the program's built-in database. Selecting the coldest year provides information on the wall structure's heat and moisture performance at a relatively extreme condition, making it possible to detect the weakest points in the wall structure in terms of condensation problems. Another reason for choosing Indianapolis as reference location is because its climate is similar to the climate of cities in Western and Central Europe. The average cold-year temperature in Indianapolis is 10.6 °C, which is similar to the yearly average temperature of 10.4 °C in Vienna and 10.3 °C in Brussels. Zürich and Munich are 2 °C colder. The cold-year average relative humidity is 75% in Indianapolis while the relative humidity values are 73% in Vienna, 81% in Brussels, and 78% in Zürich and Munich.

2.4. Description of modeling parameters

Analysis of the driving rain rose for Indianapolis showed that rain load on a façade comes mainly from the Southeast and so the wall structures were oriented facing the Southeast direction. The indoor climatic conditions were based on ASHRAE 160 Standard [19]. The temperatures were set to 22 °C (71.6 °F) for heating and 25 °C (77 °F) for cooling. The floating indoor temperature shift was 2.8 °C (5 °F). The exterior surface heat resistance was set to 0.0588 m^2 K/W and the interior surface heat resistance was 0.125 m^2 K/W. The surface radiation properties were set according to the material specification listed in the WUFI database. In the case of the European wall, the exterior short-wave radiation absorptivity was set at 0.4 while the long-wave radiation absorptivity was 0.9. Both American wall structures were finished with wood–fiber cement composite siding. The short wave radiation absorptivity of this siding is 0.7 while the long wave radiation absorptivity is 0.9. Based on the radiation parameters, the finite element model calculates infrared heat loss in case of clear sky and heat gain in case of sunshine.

The simulations were run for three years using the cold-year weather data during each year of simulation. In the first year, the initial water contents of the different components were set to the equilibrium moisture content conditions that corresponded with a temperature of 20 °C and relative humidity of 60%. The moisture and temperature profiles at the end of year 1 were used as initialization files for the year 2 simulation. The same approach was implemented for the year 3 simulation.

3. Results and discussion

3.1. Heat resistance

The results of the calculations showed that the European wall construction had the lowest overall heat transfer coefficient or *U*-factor of 0.205 W/m^2 K. This is equivalent to an *R*-value of 28. The American I wall construction had a *U*-factor of 0.408 W/m^2 K or an *R*-value of 14, while the American II wall construction had a *U*-factor of 0.272 W/m^2 K or an *R*-value of 21.

The difference in heat resistance between the American I and II wall structures was considerable. American II had 50.2% higher heat resistance than the American I wall structure. The higher heat resistance for American II can be explained by the thicker frame and fiber glass insulation. At present, almost 90% of the residential buildings in the United States and Canada have wood frames using mainly the American I wall structure [11]. Most likely, the difference in construction cost between the two American wall structures is not as significant as the difference between their heat resistance values. Due to rising energy prices and because the energy used to construct and operate buildings constitutes 48% of the total energy used in the United States [20], building more American II rather than American I structure should be seriously considered.

In this study, the European wall structure had the highest heat resistance and thus the highest energy efficiency. This wall structure had 32.6% higher heat resistance than American II and 99.3% higher resistance than American I. For decades now, the European Union has enforced energy efficiency directives for European buildings [21,22]. Although no such directives exist in the United States, it was reported that there has been a slight improvement in the energy efficiency of residential building in this country between 1997 and 2001 [23]. If one compares the construction details of the European and the American II walls, the materials and thicknesses of the components are almost the same starting from the sheathing inward. The superior thermal performance of the European construction is due mainly to the expanded polystyrene (EPS) in the ETICS layer. If the thickness of the EPS were reduced to 5 mm so that the total thickness of the ETICS layer is roughly the same as that of the siding in the American II construction, the *U*-factor of the European wall will increase to 0.285 W/m^2 K, resulting in an *R*-value of 20. In this case, the insulation value of the European and American II walls would be roughly the same.

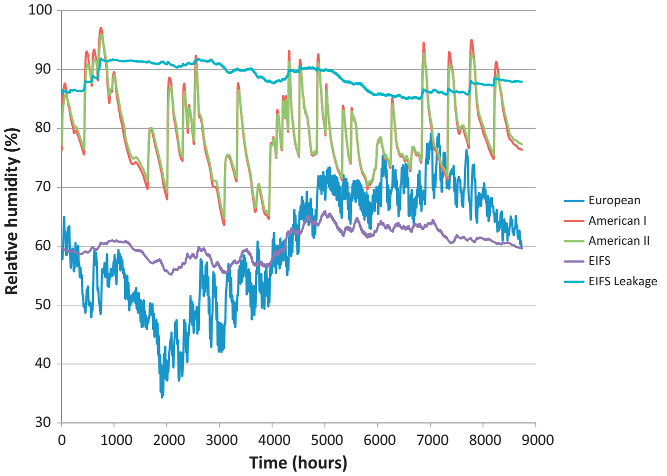

Fig. 1. Hourly variation in relative humidity at monitor location 2 during year 3 of the simulation for the different types of wall construction. Hour 0 corresponds to 1:00 am of January 1 and hour 8736 corresponds to 12:00 midnight of December 31.

3.2. Relative humidity on the sheathing

The relative humidity at all monitor locations within the wall was considerably lower in the European than in the American construction. None of the wall structures indicated condensation problem. As an example, Fig. 1 shows the relative humidity changes in monitor location 2 (front side of the sheathing) during the third year of the simulation. One reason for the low relative humidity at this location in the case of the European construction is that the fiber-reinforced gypsum board is being shielded by the ETICS layer. That layer has a relatively high diffusion resistance that retards vapor movement in both directions. Therefore it separates the sheathing from the ambient humidity better than the fiber cement board siding and the water barrier for the American wall structures. There is also a large difference in diffusion resistance and porosity between the OSB and fiber-reinforced gypsum board sheathings. The OSB used in this study had a diffusion resistance of 650 while the diffusion resistance of fiber reinforced gypsum was only 10. The porosity of OSB was 0.6 m^3/m^3 while the porosity of gypsum board was 0.3 m^3/m^3. Therefore, the reaction time of the reinforced gypsum board to outside relative humidity was faster than the OSB.

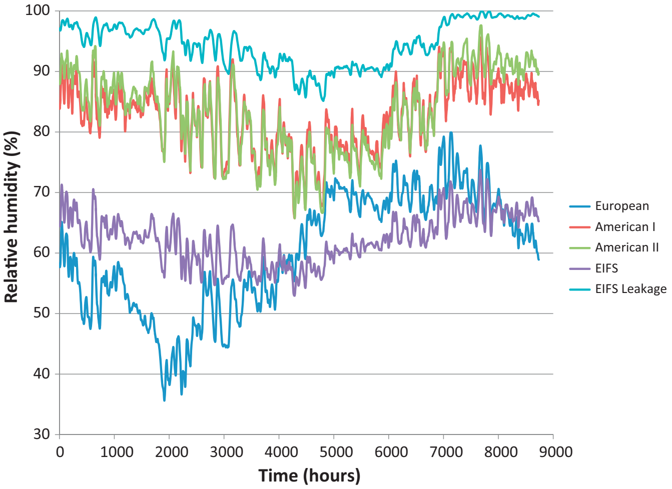

Fig. 2. Hourly variation in relative humidity at monitor location 3 during year 3 of the simulation for the different types of wall construction. Hour 0 corresponds to 1:00 am of January 1 and hour 8736 corresponds to 12:00 midnight of December 31.

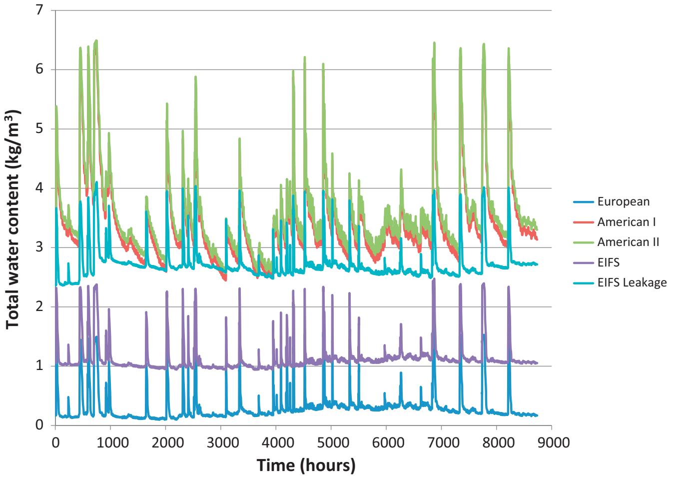

Fig. 3. Hourly total water content values for the different wall constructions for year 3 of the simulation. Hour 0 corresponds to 1:00 am of January 1 and hour 8736 corresponds to 12:00 midnight of December 31.

3.3. Relative humidity in the insulation space

High relative humidities were found on the face of the fiber glass insulation closer to the exterior (monitor location 3) during the heating period and the face closer to the house interior (monitor location 4) during the air-conditioning period. Due to the higher insulation capacity and high diffusion resistance of the EPS in the European structure, the condensation hazard in all layers of this wall structure was lower than in the American walls.

In the American I and American II wall structures, the relative humidity values rose above 90% several times, with the peak value reaching as high as 98% at monitor location 3 (Fig. 2). During the heating period, the inside surface of the sheathing is colder in the American II than in the American I wall due to the thicker insulation layer in the American II structure. In the European wall structure on the other hand, the relative humidity at monitor location 3 did not rise above 90%, the highest relative humidity being 83%.

In all cases, during the air conditioning period, the relative humidity at monitor location 4 was high but no condensation was found. In the American I and American II wall structures the relative humidity values rose above 90% several times, reaching maximum values of 99%. In the European wall structure, the relative humidity at monitor location 4 did not exceeded 90%, reaching a maximum value of only 81%.

3.4. Water content

Fig. 3 shows the hourly total water content values for the different wall constructions for year 3 of the simulation. The peaks in the graphs occur during rainy days. The large magnitude of the peaks masked the general pattern of the baseline, which is not constant but rather followed the same time trend as the relative humidity graphs of Fig. 1. The total water content values of the wall structures were significantly higher in the American walls than in the European wall. The average total water content was about 3.5 kg/m^3 with a peak of 6.4 kg/m^3 in both American structures; in the European structure, the average total water content was 0.3 kg/m^3 with a peak of 1.6 kg/m^3.

The total water content difference between the American and European wall structures is due to the differences in the hygroscopicities of the materials that made up the different wall layers.

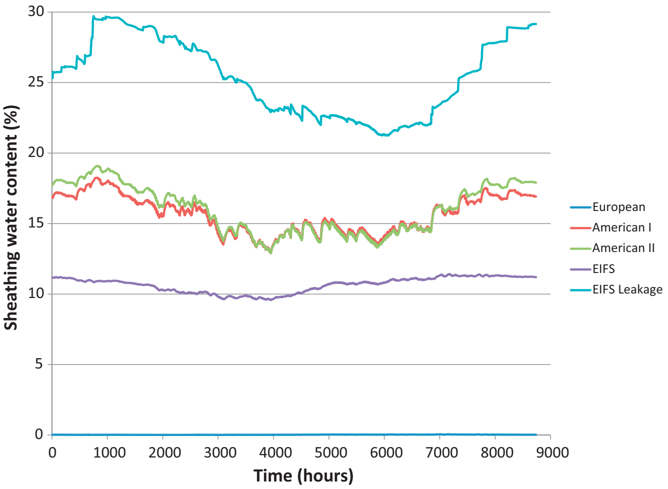

Fig. 4. Hourly variation in sheathing water content for the different wall constructions for year 3 of the simulation. Hour 0 corresponds to 1:00 am of January 1 and hour 8736 corresponds to 12:00 midnight of December 31.

The American wall structures contain more wood elements in the OSB and fiber cement board than the European wall structure. At a temperature of 20 °C and relative humidity of 60%, the moisture storage function in WUFI generated equilibrium water contents of 97.9 kg/m^3 and 65.0 kg/m^3 for fiber cement board and oriented strand board, respectively. In the European structure, limestone mortar, EPS, and (glass) fiber-reinforced gypsum board were used in the layers where the wood–fiber-based materials in the American wall were located. The equilibrium moisture contents of lime mortar (4.2 kg/m^3), EPS (0.7 kg/m^3), and fiber-reinforced gypsum (0.2 kg/m^3) are significantly lower than those of OSB and fiber cement board.

The equivalent of ETICS in North American construction is the Exterior Insulation Finish System (EIFS). But instead of a fiber-reinforced gypsum board sheathing, EIFS typically has an OSB sheathing. The use of a more hygroscopic component resulted in a total water content for the EIFS wall structure that was higher than that of the European wall but still lower than those of the American I and American II walls (Fig. 3). The use of OSB in the EIFS wall also had an effect on the hourly variation in the relative humidity at the different monitor locations. As shown in Figs. 1 and 2, there was a reduction in the relative humidity range for the EIFS wall compared to the European wall. This is mainly because of the high water storage capacity of OSB which tends to modulate wild swings in the wall cavity relative humidity.

The component of the American walls that is most sensitive to moisture-related problems is the OSB sheathing. In order to minimize mold growth and fungal decay, the water content of the OSB on a dry mass basis must be kept below 20%. Fig. 4 displays the variation in the water content of the OSB sheathing in the American I and II walls during year 3 of the simulation. It is apparent from the figure that moisture-related problems in these structures were largely avoided. The same could be said for the European wall, where the water content of the fiber-reinforced gypsum board sheathing stayed very close to 0% moisture content during the simulation period. When the fiber-reinforced gypsum board of the European wall was replaced with OSB (see profile for EIFS in Fig. 4), the water content of the sheathing went up but remained way below the level that could cause major problems.

The main reason for the low water content of the OSB sheathing in the EIFS wall is the high diffusion resistance factor of the EPS, which minimizes the effect of fluctuation in exterior weather condition on the sheathing water content. This same high diffusion resistance of the EPS also works to the detriment of the EIFS wall if water is able to infiltrate the structure. In the 1990s, several cases in North Carolina and other regions of the U.S. with high amount of precipitation brought to light the susceptibility of houses with EIFS wall to moisture-related problems [24,25]. If water intrudes into the wall structure, it cannot dry out fast enough that water accumulates in the OSB, resulting in dangerously high water content that makes the wall predisposed to mold growth and eventually causes OSB fungal decay. To check this case of water infiltration, a simulation was run on the different wall constructions assuming that 1% of the wind-driven rain hitting the façade accumulates in the wall. It was assumed that this water was deposited in the water barrier behind the siding in the case of the American I and American II structures. Since the EIFS wall (European wall with fiber-reinforce gypsum board replaced with OSB) did not have a water barrier, it was assumed that water was deposited in the OSB sheathing. These assumptions are in accordance with ASHRAE Standard 160 [19].

The relative humidity variation at monitor location 2, relative humidity variation at monitor location 3, total water content, and sheathing water content for the EIFS wall with water leakage are included in Figs. 1–4, respectively. The corresponding graphs for American I and American II walls with water leakage essentially showed similar profiles as those without water leakage. The results of the simulation illustrated the dramatic rise in the relative humidity, total water content and sheathing water content in the EIFS wall. The relative humidity was constantly high, going beyond the 90% level on several occasions. The total water content is now almost at the same level as the American walls. The more serious problem is highlighted in Fig. 4, where the sheathing water content is now above 20% the whole year and is greater than 25% for more than half the year. These results validate the moisture-related problems that plagued the EIFS industry in the 1990s. Therefore, if EIFS is to be used in regions with high outside humidity and driving rain, the system requires extra high quality sealing and must have provision for water drainage.

4. Summary and conclusions

This study using a finite-element method to compare typical American and European wall structures under the same climatic conditions resulted in the following findings:

- The American II wall structure has a higher heat resistance than the American I wall structure because of the thicker fiber glass insulation. With rising energy prices, building more homes with an American II wall structure should be seriously considered.
- The European wall has a higher heat resistance compared to the American walls. The expanded polystyrene in the ETICS layer contributes considerably to the energy efficiency of the European wall structure. The thermal advantage of the European wall disappears when the thickness of the expanded polystyrene is reduced to the same thickness as the siding of the American II wall.
- The relative humidity and the water content are lower for the European wall compared to the American walls and so the European wall structure has lower condensation risk. The lower water content of the European wall is due to the use of components with low hygroscopicities.
- The ETICS layer in the European wall isolates the inner part of wall from exterior humidity. But if water gets into the wall, the ETICS layer traps the water in the wall. This is especially serious in the case of the EIFS wall where the water content of the OSB sheathing is kept high, resulting in higher risk for mold growth and fungal decay. In contrast, the fiber cement board in the American walls has much lower diffusion resistance and so the wall behind the siding can dry out easily.

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