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USE OF SIMULATION TOOL TO ASSESS HYGROTHERMAL RESPONSE OF WOOD FRAME BUILDING ENVELOPES IN TAIWAN / L'APPLICATION D'OUTILS DE SIMULATION POUR ESTIMER LA RÉPONSE HYGROTHERMIQUE D'ENVELOPPES À OSSATURE DE BOIS À TAÏWAN

Phalguni Mukhopadhyaya[1], Ramez El Khanagry[2], David van Reenen[1], Curt Copeland[3], Kumar Kumaran[1], Paul J. Newman[3], and Ehab Zalok[2]

[1] Institute for Research in Construction, National Research Council, Canada. (http://irc.nrc-cnrc.gc.ca)
[2] Carleton University, Canada. (http://www.carleton.ca)
[3] Canada Wood Group and Council of Forest Industries, Canada. (http://www.cofi.org)

ABSTRACT

In Canada wood frame exterior building envelope construction is widely used. However, this type of building envelope construction is not traditionally used in Taiwan. This paper presents result from a research project that investigated the hygrothermal (i.e. moisture and thermal) performance of the wood frame exterior building envelope construction practices in Taichung (Taiwan). This has been done using a two-dimensional hygrothermal simulation tool. The first series of simulations was conducted for exterior building envelope constructions that had no air leakage. Thereafter, selected simulations were also conducted with air leakage through the exterior building envelope. The outputs from the simulations have been analyzed with the help of a moisture response indicator called RHT index. Simulation results indicate the relative performances and suitability of different types wood frame building envelope constructions in Taichung (Taiwan).

RÉSUMÉ

Au Canada la construction d'enveloppe à ossature de bois est très répandue, alors qu'à Taïwan, ce type de construction n'est pas traditionellement utilisé. Cet article présente les résultats d'un projet de recherche consistant à examiner la performance hygrothermique (relative au transfert de chaleur et d'humidité) de plusieurs types de construction d'enveloppe extérieure à ossature de bois dans un contexte applicable à Taichung à Taïwan. L'étude fut réalisée à l'aide d'un outil de simulation hygrothermique bidimensionnel. La première série de simulations s'appliquait à des types de construction d'enveloppe de bâtiments sans écoulement d'air. Par la suite d'autres scénarios de simulations incluant de l'écoulement d'air furent étudiés. Les résultats des simulations ont été interprétés par rapport à un indicateur de réponse hygrique appellé indice RHT. De cette façon on a établit le niveau de performance relative et l'applicabilité de plusieurs types d'enveloppes de bâtiment à ossature de bois aux conditions particulières qu'on retrouve à Taichung à Taïwan.

INTRODUCTION

Traditional wood frame exterior building envelope construction is widely used in Canada and its ability to manage the exterior and interior moisture and thermal (i.e. hygrothermal) loads is well known from the field performance records over the years. However, this type of building envelope construction is not traditionally used in Taiwan. At present, the Council of Forest Industries (COFI), an association of British Columbia forest industry partners, is promoting wood frame building envelope constructions and developing the market for the use of Canadian wood products in Taiwan. However, this is not possible without knowing the consequences and the ability of the wood frame building envelope assemblies to manage the hygrothermal loads in the climatic conditions of Taiwan. This is a long-term performance issue that becomes even harder to resolve when there is no comprehensive field performance data, as in this case.

In order to address this issue (i.e. non-existence of field performance data), a collaborative research project has been initiated by the National Research Council (NRC) of Canada and the Council of Forest Industries (COFI) to investigate the long-term performance of wood frame building envelope constructions (walls and roofs) in Taiwan using a computer-aided hygrothermal simulation tool. In recent years hygrothermal simulation tool has been widely used for the evaluation of the thermal and moisture response of the building envelopes (Mukhopadhyaya et. al.2003; Mukhopadhyaya et. al.2008). The two-dimensional hygrothermal simulation tool, *hygIRC-2D*, developed at the Institute for Research in Construction of the National Research Council Canada, has been used in this project. This project has evaluated the performance of several wall and roof assembly constructions using this simulation tool. The results of these simulations are presented in the following sections.

RESEARCH SIGNIFICANCE

The primary objective of this study is to evaluate the hygrothermal performance of various wood-frame building envelope designs in Taichung (Taiwan) using the hygrothermal simulation tool *hygIRC-2D*. The numerical simulations have been done on four types of exterior walls and two types of unvented roofs. Initially, the roof and wall constructions were simulated assuming no air leakage through the assemblies. Subsequently, simulations with air leakage were conducted on two of the wall constructions. As a result, the effects of vapour diffusion could be assessed independently of air leakage.

HYGROTHERMAL SIMULATION TOOL

Hygrothermal models are mathematical tools that can be used for moisture design of building envelopes (Hens 1996). The hygrothermal simulation tool used in this study is a computer aided numerical model, *hygIRC-2D*, that can predict the moisture response of building envelopes. *hygIRC-2D* is continuously evolving as a research tool, developed by a group of researchers at the Institute for Research in Construction (IRC) of the National Research Council (NRC), Canada. Interested readers can refer to the publications by Karagiozis (1997) and Djebbar et al. (2002a,b) for further details. These documents outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC-2D* and the techniques used to solve them numerically. The reliability of *hygIRC-2D* outputs has been established through laboratory measurements and benchmarking exercises (Maref et al. 2002; Hagentoft et al. 2004). The effective use of *hygIRC-2D* to analyze and obtain meaningful results, however, demands a proper physical understanding of the problem, an appropriate definition of input parameters and the ability to judiciously interpret the outputs from the simulation tool (Mukhopadhyaya and Kumaran, 2001; Mukhopadhyaya et al. 2001; Kumaran et al. 2003; Mukhopadhyaya et al. 2008).

INPUTS AND ASSUMPTIONS FOR *hygIRC-2D*

A number of major input parameters are required for *hygIRC-2D* simulation, such as: (1) Wall construction details; (2) Material properties; (3) Boundary conditions; (4) Exposure duration; (5) Initial moisture content and temperature; and (6) Air leakage.

The following sections outline these input parameters as applicable for this study

WALL CONSTRUCTION DETAILS

Several different wall and roof designs (Figure 1) were evaluated to compare their hygrothermal performance. Canada Wood submitted these designs, with construction details, to the IRC researchers for hygrothermal performance evaluation under Taichung weather conditions. As mentioned earlier, simulations were first conducted with no air leakage. These include the following exterior wall and roof designs: (1) Wall 1 – Classic cold weather wall with rain screen, (2) Wall 2 – Hot humid wall with air barrier inside and outside, and rain screen, (3) Wall 3 – Super E® wall, (4) Wall 4 – Low cost wall without rigid foam insulation, (5) Roof 1 – Unvented truss roof with XPS and glass fibre insulation, and (6) Roof 2 – Unvented truss roof with spray-on foam insulation.

MATERIAL PROPERTIES

hygIRC-2D simulation requires eight sets of material properties. These properties are air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity and water vapour permeability. These materials properties were obtained from the NRC-IRC's hygrothermal materials properties database (Kumaran et al (2002); Kumaran et al (2004); Mukhopadhyaya et al (2004)) and were determined in the NRC-IRC's Insulation and Building Materials Laboratory.

BOUNDARY CONDITIONS

Hourly recorded Taichung weather data for the year 2001 were used as outdoor/external boundary conditions. These weather data were obtained from the weather bureau of Taiwan. Of the available weather data, 2001 was the year with the most rainfall. *hygIRC-2D* requires the following hourly recorded weather components: temperature, relative humidity, wind velocity, wind direction, rainfall, solar radiation and cloud index. Table 1 provides general climatic conditions (based on recorded data from 1971 to 2000) for Taichung, and Figures 2a, 2b and 2c show the temperature, relative humidity and rainfall data for the year 2001.

The indoor conditions (temperature and relative humidity) used in these simulations were for a controlled indoor environment based on summer and winter seasons, identified according to the criteria specified in the 'Specifications to National (Canada) Energy Code for Houses, (Swinton and Sander, 1994)'. If the monthly average outdoor temperature was below 11 °C it was considered winter. If the monthly average temperature was above 11 °C it was considered summer. Since the average monthly temperature in Taichung did not drop below 11 °C, summer conditions were always used. Indoor conditions in Taichung were developed based on conversations with building science professionals who had knowledge of building practices in Taiwan. The indoor conditions were 25 °C temperature and 65% relative humidity throughout the year.

EXPOSURE DURATION

All simulations were conducted for a period of 3 years (one year weather data repeated). The exposure duration for each year started on 01 January and ended on 31 December.

INITIAL MOISTURE CONTENT AND TEMPERATURE

In any hygrothermal simulation, the user defines the initial moisture content of each wall component at the beginning of the first year. It was assumed in this study that the initial moisture content of each wall component is equivalent to the corresponding relative humidity of 30%, derived from the sorption isotherm of the respective materials. Similarly, the initial temperature across the entire cross section of the wall was assumed to be 20°C. In this study, the first two years of the simulation are considered to be an initial conditioning period, and all the observations are made on the basis of the hygrothermal response of the wall assembly during the third year.

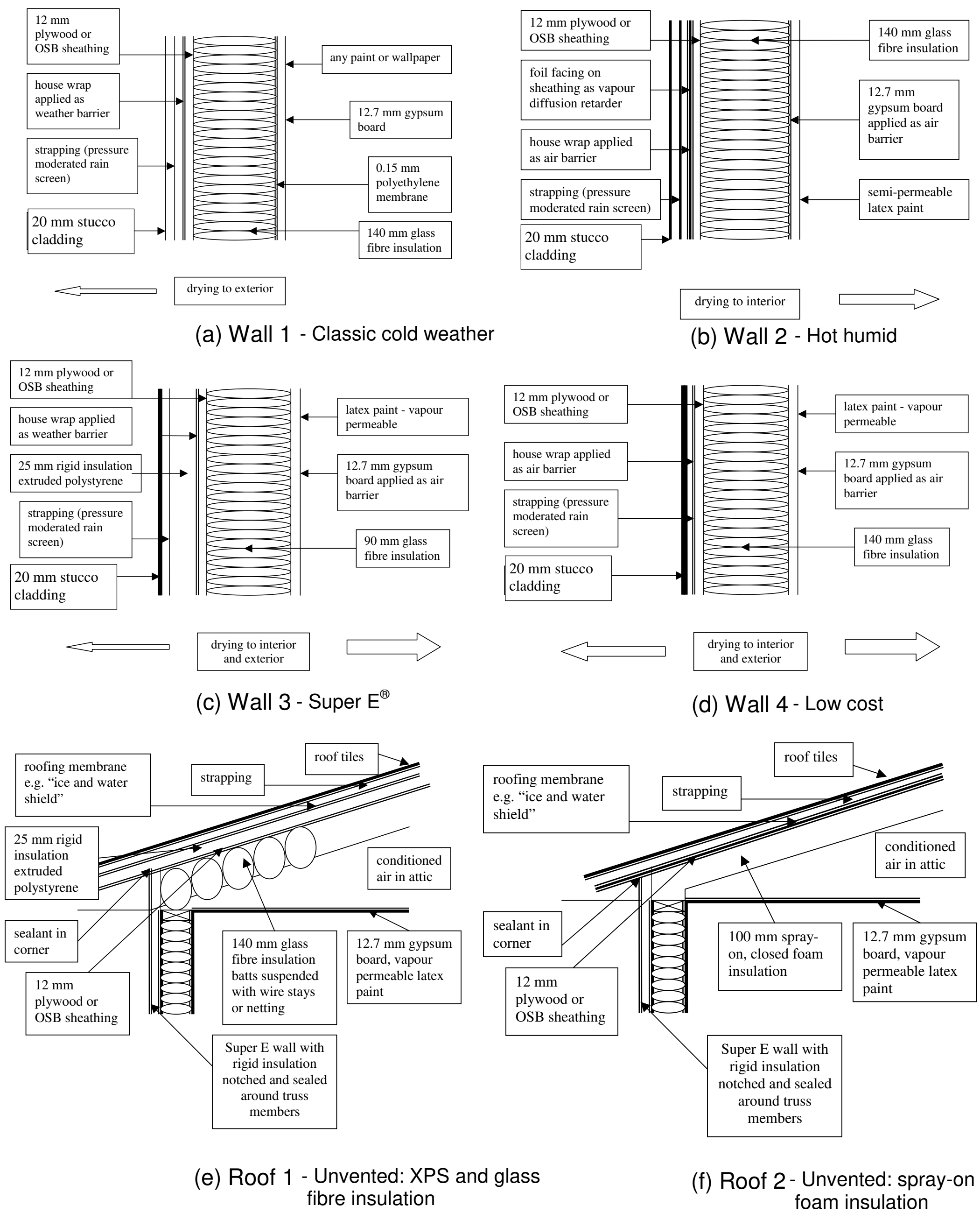


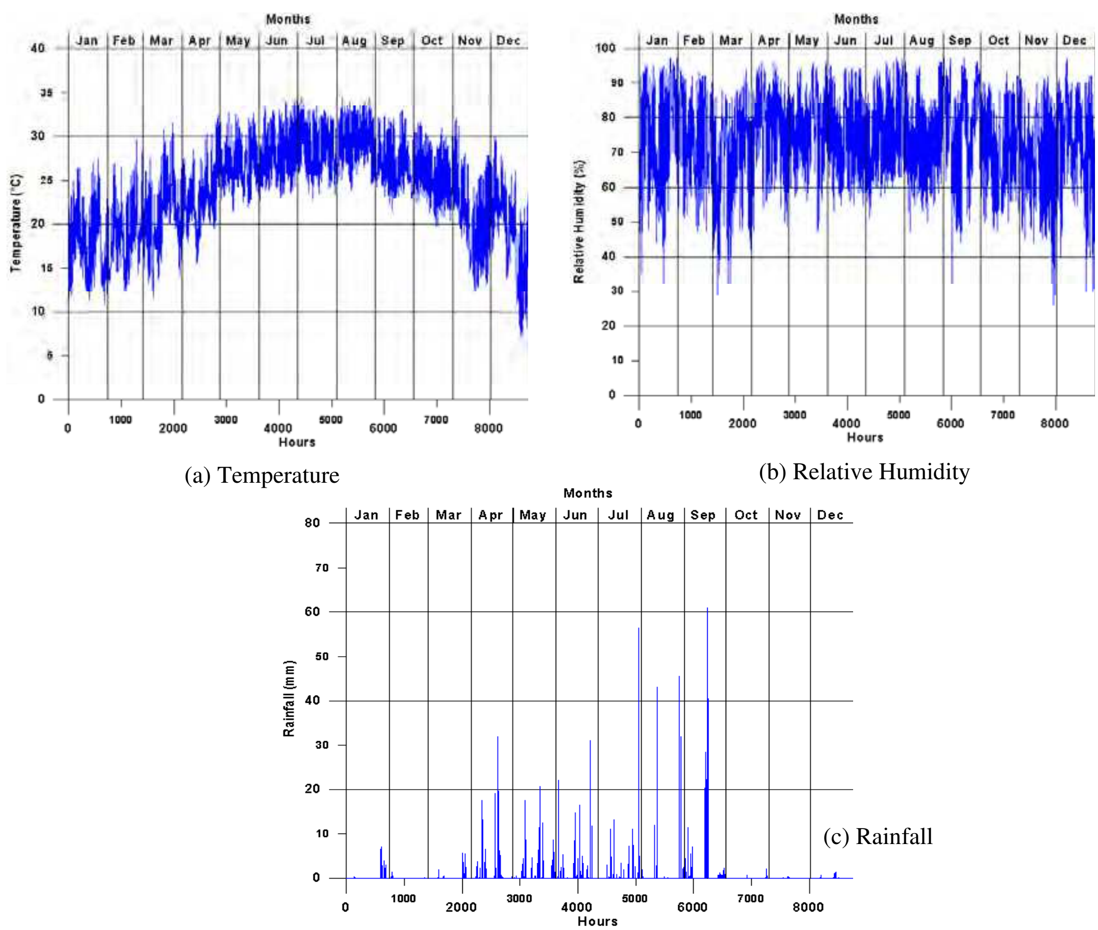
FIGURE 1: WALLS AND ROOFS CONSTRUCTION DETAILS

AIR LEAKAGE

To understand the effects of imperfect air barriers in the wall constructions, air leakage was introduced in: (1) Wall 3 – Super E® wall, and (2) Wall 4 – Low cost wall. An air leakage path was created through each of the wall assemblies. The air would enter/exit, depending on the characteristics of indoor and outdoor pressure, along a crack at the exterior top of the wall and then travel through the insulation cavity and exit/enter at the interior bottom of the wall (Figure 3). This size of the crack was based on the normalized leakage area (NLA), which is the area of the crack in cm^2 divided by the area of the wall in m^2. In this study specifically an air leakage level of 1.5 NLA was considered.

TABLE 1: CLIMATE+ SUMMARY OF TAICHUNG

Mean Annual Temperature	23° C
Highest Monthly Mean Maximum Temperature (July)	33° C
Lowest Monthly Mean Maximum Temperature (January)	22° C
Highest Monthly Mean Minimum Temperature (July)	25° C
Lowest Monthly Mean Minimum Temperature (January)	13° C
RH Mean, Coldest Month	76%
RH Mean, Hottest Month	77%
Annual Precipitation	164 cm
Mean for Dominant Wind*	1.6 m/s @330 degrees (Az.)
+ Based on data from 1971 to 2000; * Year 2003	



(a) Temperature

(b) Relative Humidity

(c) Rainfall

FIGURE 2: TEMPERATURE, RELATIVE HUMIDITY AND RAINFALL DATA FOR TAICHUNG

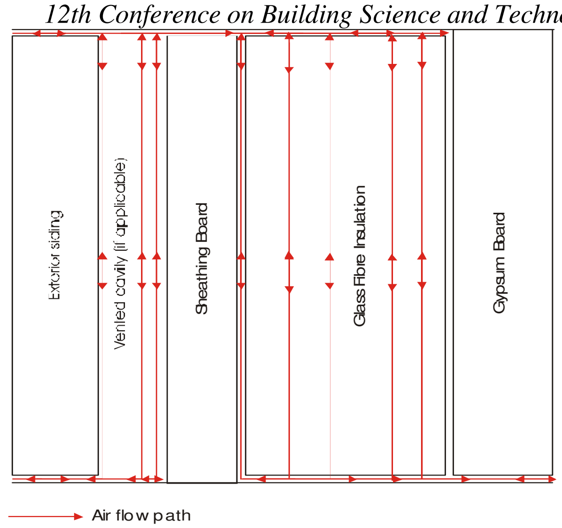


FIGURE 3: SCHEMATIC AIRFLOW PATH.

SIMULATION RESULTS

A significant amount of data was generated by *hygIRC-2D* simulations and subsequently post-processed for the detailed evaluation of the hygrothermal response of the building envelopes (Mukhopadhyaya and van Reenen 2007). For relative comparison of hygrothermal performance of the building envelope assembly, a hygrothermal performance indicator (RHT Index) was used in this study as described in the following paragraphs.

RHT INDEX – THE PERFORMANCE INDICATOR

It is widely accepted that building materials are subject to deterioration under the combined effects of temperature and moisture. The most deleterious conditions are those in which moderate or high temperature is coupled with high humidity for extended periods (Nofal and Morris 2003). This study uses a long-term hygrothermal response indicator, called the RHT index, derived from the relative humidity (RH) and temperature (T) conditions inside the building envelope cross section over a period of time for any specific area of the cross-section. The RHT index is an indicator used to quantify and compare the hygrothermal response of the wall assembly. This index captures the duration of moisture and thermal conditions coexisting above threshold RH and T levels. RH and T are given linear weight in the RHT index. It is to be noted that for many materials this may not always be the case when assessing their long-term performance while subjected to varying and elevated moisture conditions. A different weighting for RH and T can be determined only through controlled long-term experiments. The RHT index as defined in this study is:

$$Cumulative\ RHT = \sum (RH - RH_X) \times (T - T_X) \qquad [1]$$

for $RH > RH_X\%$ and $T > T_X°C$ at every hour of the simulation.

Where, RH_X and T_X are the threshold values for relative humidity and temperature respectively.

In this study two sets of threshold levels were used. The first set was with an RH of 80% at 0 °C temperature, hereafter referred as RHT80. The second set was with an RH of 95% at 0 °C temperature, hereafter referred as RHT95. The cumulative RHT was a summation done on an hourly basis for the final two years of the simulation.

During any time step when either or both $RH \leq RH_X\%$ and $T \leq T_X$ °C, the RHT value for that time step is zero. A schematic diagram for the generation of RHT index value is shown in Figure 4. The results presented in the following section use the cumulative two-year RHT index as a single-value hygrothermal response indicator. A higher value of RHT index indicates a greater potential for moisture-related deterioration. It is to be noted here that two different walls with similar cumulative RHT values can still have very different hygrothermal responses. At the same time, climates or conditions that seem intuitively to be quite different can produce similar cumulative RHT values. It is also to be mentioned here that the threshold RHT index value that borders a safe and unsafe hygrothermal design of a wall system is yet to be defined.

DISCUSSION

Computer simulations for each assembly design were subsequently processed to produce the following graphical displays: (i) RHT Analysis for 80% RH and 0°C; (ii) RHT Analysis for 95% RH and 0°C; (iii) Moisture accumulation in each material component over the review period; (iv) Total moisture and moisture content (%) in the wood components over the review period; (v) Temperature and relative humidity in the wood components over the review period. However, it is not practical to present all results in this paper, hence, only brief discussion on significant observations is presented in the following paragraphs. Readers may wish to refer to the publication (Mukhopadhyaya and van Reenen 2007) for the entire information.

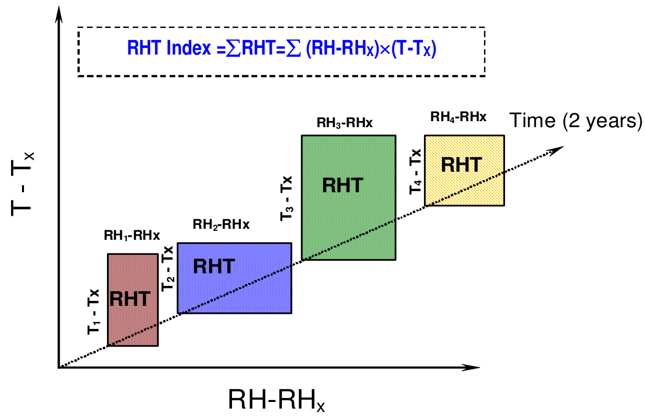


FIGURE 4: SCHEMATIC DIAGRAM TO EXPLAIN RHT INDEX CALCULATION

WALLS WITH NO AIR LEAKAGE

The hygrothermal simulations of the wall assemblies indicate that Wall 1 (classic cold weather) has an area of high hygrothermal loading (i.e. high RHT index values) along the interior side of the poly sheet (Figure 5). Wall 2 shows an area of moderately high RHT index values in the plywood layer (Figure 6). The RHT95 indices for all four walls, including Wall 3 and Wall 4 (Figures 7 and 8), specifically show higher levels of hygrothermal loading in the exterior cladding.

The moisture content in the plywood layer for all of the walls, during the 3rd year of simulation, generally stays in the range from 8 % to 12% (Figure 9). However, Wall 2 has an extended period of higher moisture content, near 17%, during the months of February and March. There was also a short peak in moisture content in the month of September for Wall 1 (19%) and Wall 4 (15%).

The moisture content in the bottom and top plate stays in the range of 15% to 20% for all of the walls with the exception of Wall 1 (Figure 10). Wall 1 has an extended period above 20% moisture content from July to November.

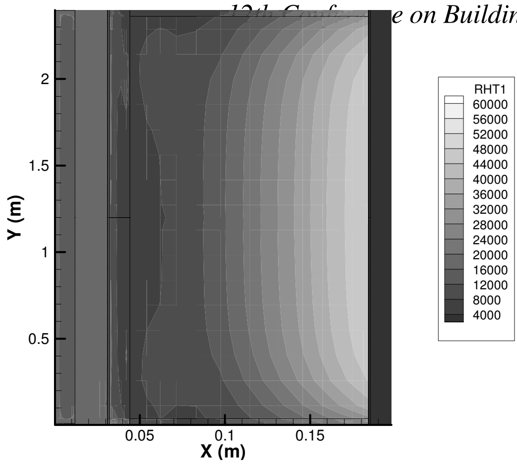


FIGURE 5: WALL 1 – RHT80 ANALYSIS

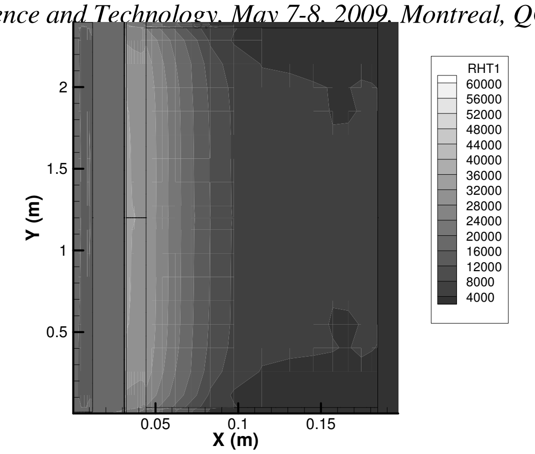


FIGURE 6: WALL 2 – RHT80 ANALYSIS

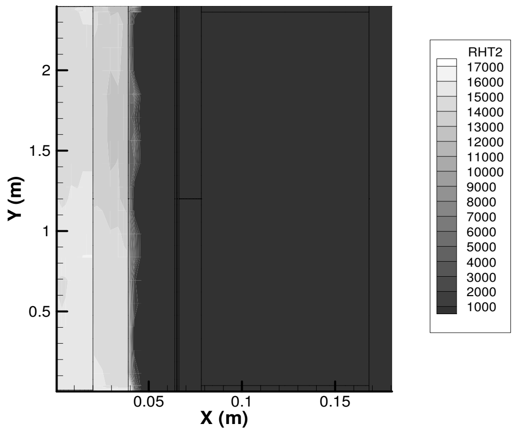


FIGURE 7: WALL 3 – RHT95 ANALYSIS

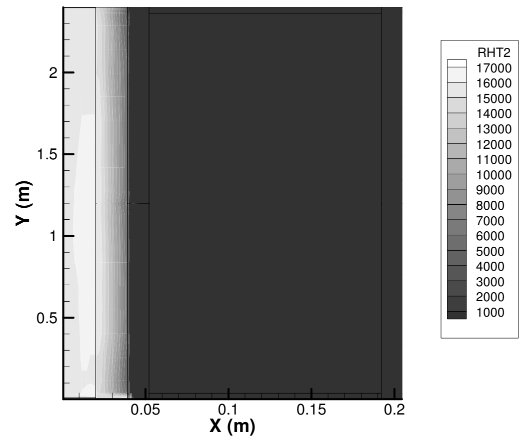


FIGURE 8: WALL 4 – RHT95 ANALYSIS

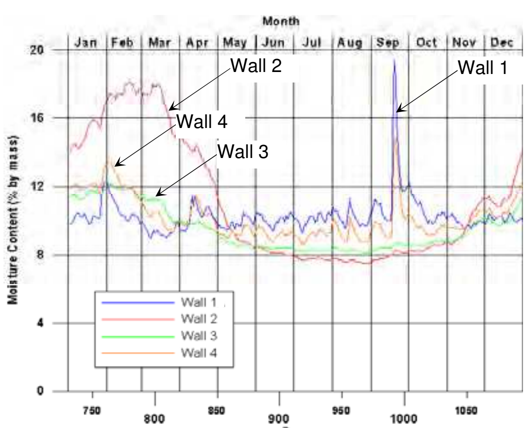


FIGURE 9: AVERAGE MOISTURE CONTENT IN PLYWOOD.

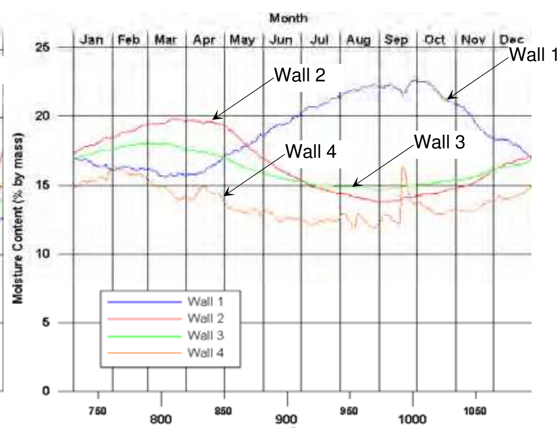


FIGURE 10: AVERAGE MOISTURE CONTENT IN BOTTOM PLATE

ROOFS

The two unvented roofs (Figures 1e and 1f) that have been examined are Roof 1 (traditional truss with rigid, XPS foam over and glass fibre insulation under sheathing) and Roof 2 (traditional truss with spray-on foam insulation under sheathing).

The RHT80 index values show similar results for both the roofs, with the highest values of RHT indices present in the roof tiles (Figures 11 and 12).

While looking at the total moisture content in these two roofs, Roof 2 has higher total moisture content for the year being examined (Figures 13 and 14). In the plywood, the moisture content in Roof 2 varies around 25% while Roof 1 varies from 10% to 20% (Figure 15). An estimate of the moisture content in the rafters was calculated from the relative humidity in the insulated space. In this case the moisture content also remained higher in Roof 2 (Figure 16).

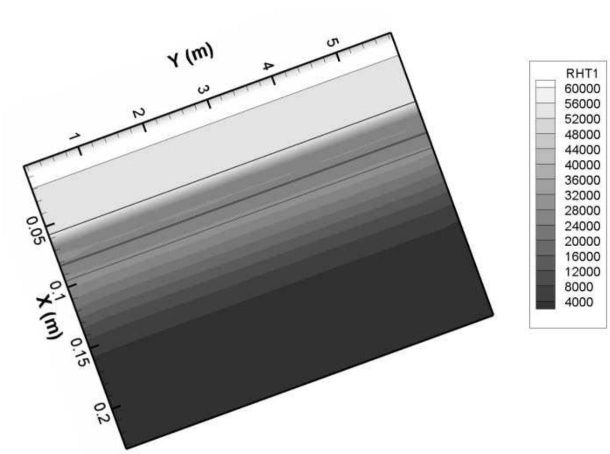


FIGURE 11: ROOF 1 – RHT80 ANALYSIS

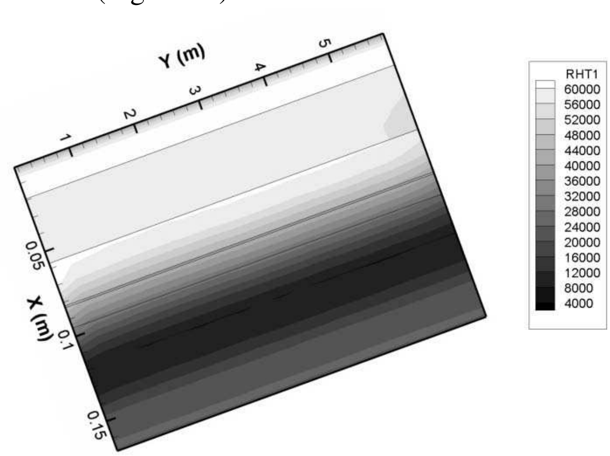


FIGURE 12: ROOF 2 – RHT80 ANALYSIS

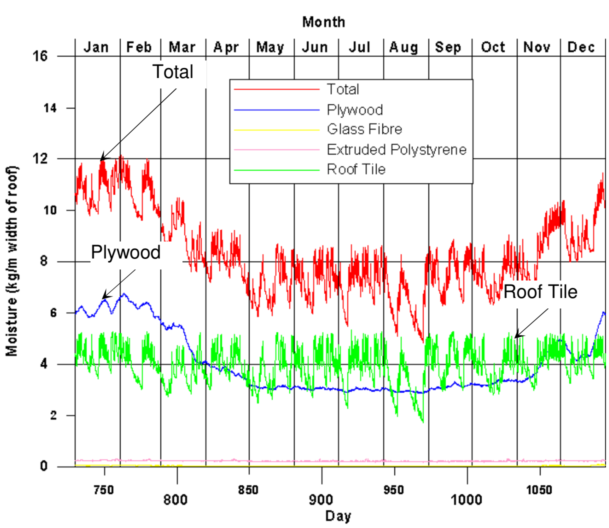


FIGURE 13: MOISTURE ACCUMULATION IN COMPONENTS OF ROOF 1

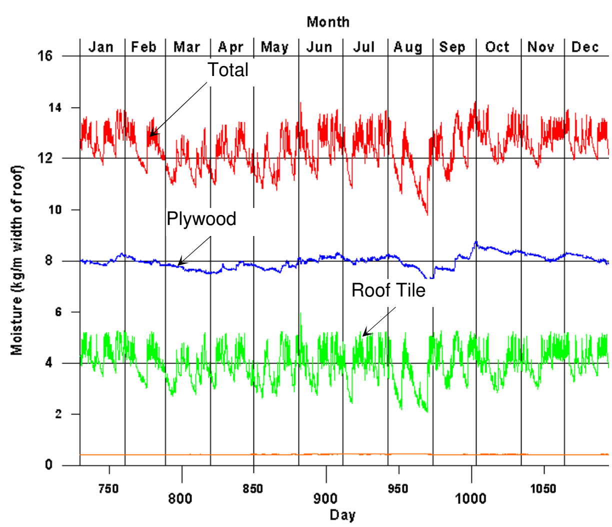


FIGURE 14: MOISTURE ACCUMULATION IN COMPONENTS OF ROOF 2

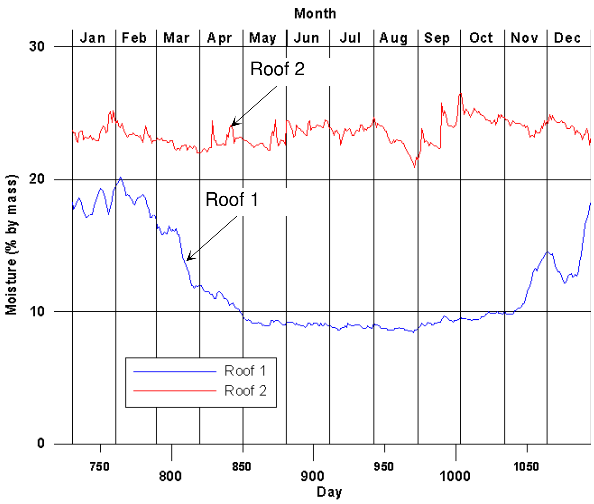


FIGURE 15: MOISTURE CONTENT IN PLYWOOD

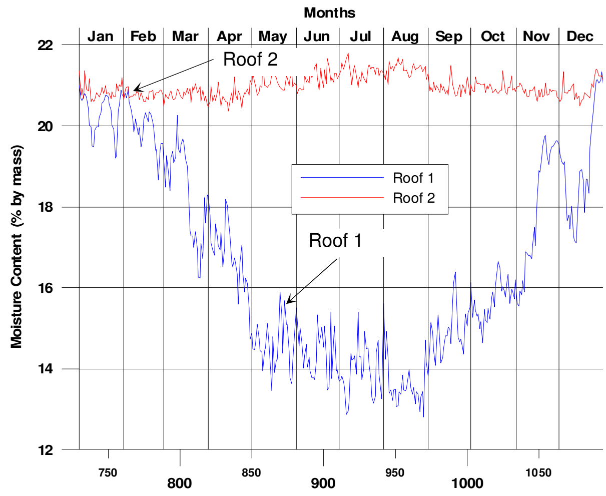


FIGURE 16: MOISTURE CONTENT IN RAFTERS

WALLS WITH AIR LEAKAGE

Hygrothermal simulations with one level of air leakage (1.5 NLA) were conducted on *Wall 3* (Super E®) and *Wall 4* (low cost). The RHT80 index values are shown in *Figures 17 and 18*. There are visible areas of higher hygrothermal loading (i.e. higher RHT index) inside the stud space and on the bottom plate in both walls with air leakage.

The moisture content in the plywood remained in the range of 8% to 14% for all simulations (Figure 19) and in general air leakage did not influence the moisture content of the plywood significantly. In the top plate the moisture content remained in the range of 12% to 18% (Figure 20). With air leakage there were lower moisture contents in the top plate than in the simulations with no air leakage. In the bottom plate the moisture contents were higher in the simulations with air leakage (Figure 21). In *Wall 3* the moisture content reached a level of around 21% for the period from January to March, and in *Wall 4* the moisture content reached a level of over 25% for the same period.

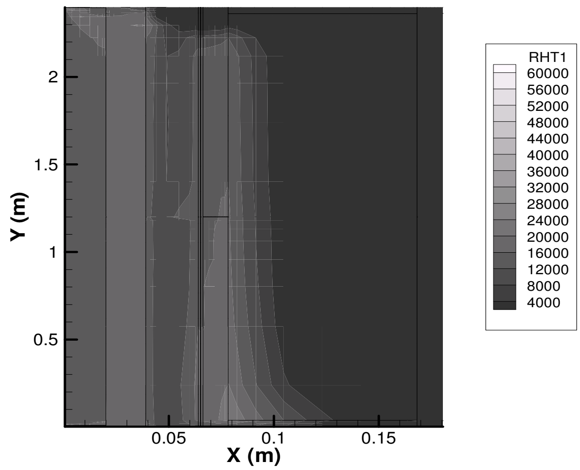


FIGURE 17: WALL 3 WITH AIR LEAKAGE – RHT80 ANALYSIS

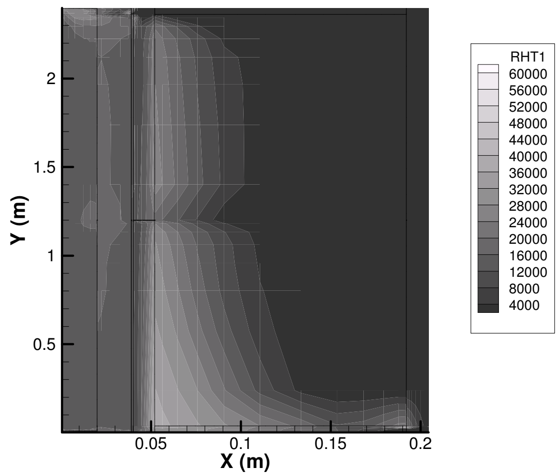


FIGURE 18: WALL 4 WITH AIR LEAKAGE – RHT80 ANALYSIS

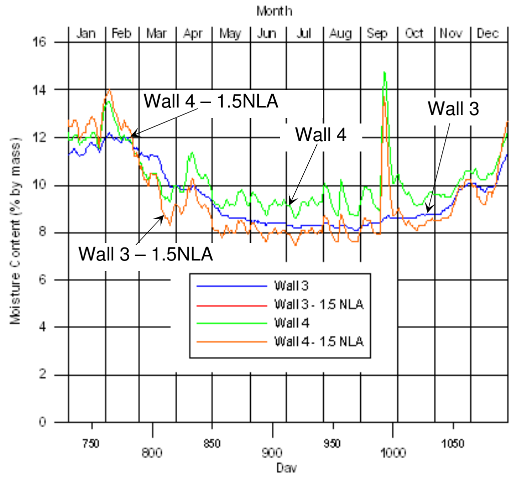


FIGURE 19: MOISTURE CONTENT IN PLYWOOD

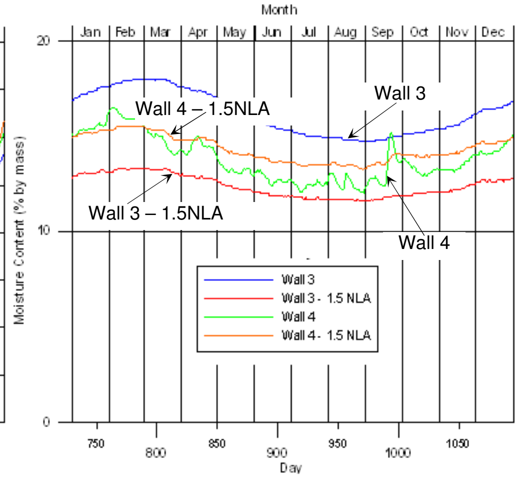


FIGURE 20: MOISTURE CONTENT IN TOP PLATE

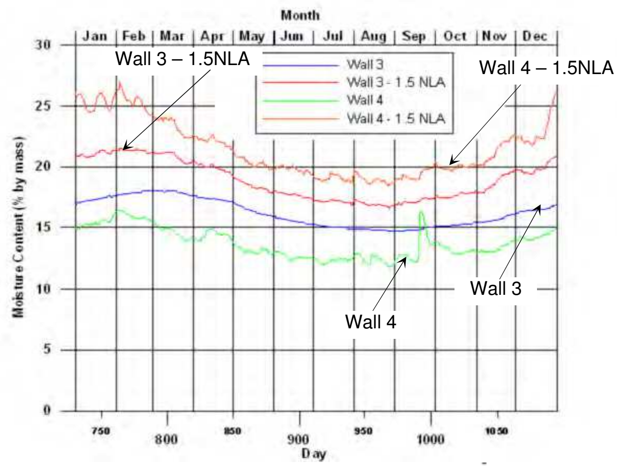


FIGURE 21: MOISTURE CONTENT IN BOTTOM PLATE

CONCLUSIONS

Following three major observations can be made from the results presented in this paper:

1. Under conditions with no air leakage the classic cold weather wood frame wall indicated the increased concern for long-term hygrothermal performance related issues. There were areas of wall cross sections where higher moisture content and RHT indices occurred.
2. The unvented roof simulations show that roof tile is the most vulnerable to higher hygrothermal loading. The roof with foam over and insulation under the sheathing had lower moisture contents in the wood components of the construction.
3. Air leakage was simulated in both the Super E® wall and the low cost wall. The simulation results showed increased hygrothermal loading in the stud cavity and on the bottom plate.

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