HYGROTHERMAL PERFORMANCE CLASSIFICATION METHODOLOGY FOR WOOD-FRAME WALL ASSEMBLIES

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ABSTRACT

Multi-attribute assessments of wall performance consider physical, economic and aesthetic parameters, including difficult to predict factors such as relative ease of construction. This paper builds on research conducted into multi-attribute wall system performance assessment and focuses particularly on the hygrothermal performance modelling of opaque wood-frame wall assemblies commonly employed in Canadian low-rise housing construction.

This paper is based on a differentiation between *compatibility* and *detailing* as determinants of performance. Compatibility involves the selection and arrangement of opaque wall system materials to achieve satisfactory hygrothermal performance in response to particular indoor and outdoor environmental conditions. Detailing is largely interested in arranging materials and components so that each assembly provides acceptable performance, and then connecting assemblies such as foundations, walls, windows and roofs so that the overall integrity of the building-as-a-system is achieved. This paper argues that hygrothermal compatibility may be adequately predicted using current simulation tools, however, detailing considerations fall beyond the capabilities of today's software and depend strongly on expert heuristics.

The main body of the paper presents the application of a wall classification system methodology to assess the suitability of wood-frame wall assemblies in various Canadian climatic zones. A probabilistic approach to determining boundary conditions, combined with performance thresholds for degradation phenomena, such as mould and corrosion, is investigated using hygrothermal simulation software. The results are used to form a hygrothermal wall performance classification methodology that would assist designers in selecting suitable assemblies for a given set of environmental conditions.

The paper concludes by placing into perspective the relationship between hygrothermal performance and other design variables such as first cost, durability, energy efficiency and aesthetics. Innovative design requires a structured, first principles approach, but for the vast majority of cases, the complexities and risks associated with wall designs become much more manageable when a reliable classification methodology is made available to designers and builders.

INTRODUCTION

Wood-frame wall construction is the predominant building envelope system for low-rise residential buildings in Canada. For the most part, this type of construction provides satisfactory performance, but there remain instances when these systems fail to provide acceptable moisture management leading to mould growth and deterioration of wooden structural members.

With the introduction of objective-based codes in Canada, wood-frame wall assembles may be designed according to two compliance paths (CCBF 2004). The first is essentially based on the previous prescriptive requirements of the National Building Code of Canada (acceptable solutions) and the second path (acceptable alternatives) is based on demonstrating equivalent performance to acceptable solutions. One of the main reasons for adopting objective-based codes remains the inherent limitations of the first compliance path, which does not fully consider all of the emerging arrangements of approved materials for building envelopes.

As new building materials are introduced into the residential construction industry, the first compliance path may not reliably deliver satisfactory envelope performance because the substitution of traditional materials within wall assemblies by innovative materials may lead to hygrothermal behaviour incompatibilities. Hence the need for a methodology to classify the hygrothermal performance of wood-frame wall assemblies.

Thus, for the vast majority of residential building envelopes designed in the absence of moisture engineering expertise, incompatible arrangements may be reasonably avoided. Conversely, in support of the first compliance path, development of a table of permissible wood-frame wall assemblies for various climatic zones in Canada would simplify design and improve the assurance of acceptable performance.

HYGROTHERMAL WALL PERFORMANCE CLASSIFICATION

The hygrothermal performance of building envelopes has been investigated by numerous researchers and methods (Straube and Burnett 2001). The innovative concept being advocated in this paper is to apply a classification methodology to the practical design and construction of wood-frame wall assemblies.

It is widely recognized by hygrothermal performance modelers and building science practitioners that hygrothermal simulation software is limited in its ability to absolutely predict actual performance. Defects, air leakage and other random phenomena are difficult to simulate and there remain many sources of uncertainty in hygrothermal modelling (Holm and Künzel 2002). This paper is based on a differentiation between *compatibility* and *detailing* as determinants of performance. Compatibility involves the selection and arrangement of opaque wall system materials to achieve satisfactory hygrothermal performance in response to particular indoor and outdoor environmental conditions. Detailing is largely interested in arranging materials and components so that each assembly provides acceptable performance, and then connecting assemblies such as foundations, walls, windows and roofs so that the overall integrity of the building-as-a-system is achieved. This paper argues that hygrothermal compatibility may be adequately predicted using current simulation tools, however, detailing considerations fall beyond the capabilities of today's software and depend on expert heuristics.

In practical terms, workmanship and materials are imperfect. Within the context of a cold climate and Canadian construction practices, these assumptions guide prudent designers to assume flawed construction that must be compensated with redundant control measures focused on moisture management. However, Canadian building codes permit residential construction without the necessary involvement of design professionals.

Rather than attempting to develop hygrothermal modelling tools that accurately predict the performance of flawed workmanship and/or detailing, the approach taken in the research supporting this paper is to identify the risk of moisture management problems for various wall assemblies based on local climatic and indoor occupancy conditions. The level of risk may be used as an indicator of whether or not a particular wall assembly may be considered as an acceptable solution or alternative within the context of Canada's objective-based codes. The proposed classification system is summarized in Table 1.

Table 1 *– Proposed classification system for wood-frame wall assemblies and related considerations.*

CLASSIFICATION	CONSIDERATIONS
Fit (Acceptable Solution)	The wall assembly is capable of providing satisfactory hygrothermal performance assuming imperfect (flawed) design (detailing) and workmanship. Walls having this classification would be considered ***acceptable solution***s under the objective-based codes.
Feasible (Alternative Solution)	The wall assembly is capable of providing satisfactory hygrothermal performance assuming competent design and workmanship. Walls having this classification would be considered ***alternative solutions*** under the objective-based codes.
Unfit (Not Permitted)	The arrangement of materials within the wall assembly cannot deliver acceptable hygrothermal perfomance regardless of the quality of design and workmanship. Walls having this classification would be classified as ***not permitted*** under the objective-based codes.
Note: The terms fit or unfit are used with respect to intended purpose (e.g., fit for intended purpose) within the context of satisfactory hyrothermal performance for a given set of climatic and indoor occupancy conditions.	

It should be noted that many of the acceptable solutions for wood-frame wall construction are in fact alternative solutions. They are considered acceptable within the context of normative construction practices based on acceptable past performance, but do not necessarily reflect a limit-states design approach to moisture management. This paper argues that for new materials and methods, a more rigorous methodology should be made available to designers and builders.

DEVELOPMENT OF METHODOLOGY

The approach to the development of the hygrothermal performance classification methodology proposed herein consists of the following procedures:

1. Establishment of base case parameters for moisture management by simulating variations of material arrangements and boundary conditions for a wood-frame wall assembly with proven performance;
2. Deriving performance indices that can be heuristically translated into probabilities of moisture problems (failures).

3. Applying these performance indices to a series of simulations for various wall assemblies in order to classify their hygrothermal performance.

A number of assumptions have been used to guide the modelling approach employed in this research. These attempt to reflect a limit-state design approach to moisture management recognizing that full development of a statistically significant methodology is still evolving through numerous research activities (Lstiburek 2002).

1. Imperfect workmanship is assumed and this is modelled by removing all critical moisture control elements from the wall assembly. Isolated air barrier discontinuities and resulting air leakage due to flawed workmanship is simulated by removing the vapour barrier material from the assembly in a cold climate zone, unless redundant layers are designed/constructed to provide air leakage control (Straube and Schumacher 2003).
2. Improper construction practices are assumed such that materials are considered fully saturated at the beginning of the simulation cycle (i.e., materials have been exposed to inclement weather without proper protection during storage on site). This could also represent wall material saturation from water penetration.
3. High interior moisture loads are assumed as this represents a worst case scenario for occupancy conditions.
4. The non-northerly wall orientation that receives the most rainfall is selected to simulate the worst case for wetting and solar-driven moisture.
5. Time of year for the commencement of simulations is selected to provide the least amount of initial drying following the onset of occupancy.
6. Additional considerations include modifying the vapour permeance of exterior screen materials to simulate vented air spaces.

This approach provides a conservative assessment of acceptable hygrothermal performance because it represents a quasi-worst case scenario that is possible both according to how wood-frame housing is constructed and subsequently occupied and maintained. Inexperienced may construct the building envelope with flaws using materials that have not been protected against excessive wetting on site. It is also conceivable that over the expected useful service life of housing, the integrity of the air/vapour barrier may be compromised by degradation and unwitting occupant behaviour (e.g., puncturing of the air/vapour barrier, improper operation of mechanical ventilation, etc.). Since housing can be designed in the absence of moisture engineering expertise, constructed by untrained personnel and occupied by people with no formal building-as-a-system knowledge, the proposed methodology significantly reduces the risk of envelope failures when all of these factors are coincident.

EXAMPLE APPLICATION

The example which follows is based on hygrothermal simulations using the hygIRC 1-D software developed by IRC/NRC (Maref et al. 2004). 1-D hygIRC is a user-friendly one-dimensional version of IRC's hygIRC, a state-of-the-art hygrothermal computer model.

The example wood-frame wall assembly modelled within hygIRC 1-D is depicted in Figure 1. It is a wall construction that was commonly employed in R-2000 houses and has exhibited acceptable performance.

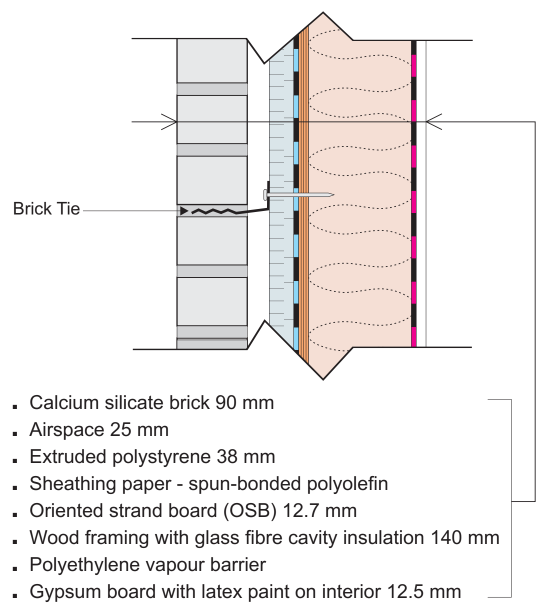

Figure 1 *– Wall assembly employed in example application of classification methodology. Note that polyethylene is detailed as the primary air barrier.*

A cold climate zone was selected for this example, specifically Ottawa, Ontario, Canada. The process consisted of performing a series of simulations according to the assumptions noted previously, beginning with the wall as depicted in Figure 1, to gauge the following key performance parameters:

Total Moisture – the moisture content in a specific material layer(s) that is susceptible to moisture damage/degradation.

RHT(80) - Conditions detrimental to moisture sensitive materials at the 80%RH level and T greater than 5 degrees Celsius, generally indicative of corrosion potential

RHT(95) - Conditions detrimental to moisture sensitive materials at the 95%RH level and T greater than 5 degrees Celsius, generally indicative of wood decay. It is assumed this index predicts mould thresholds, but thresholds proposed by other research will also be investigated (Sedlbauer 2002).

Note: The RHT Index characterizes the simultaneous occurrence of moisture and temperature conditions that are prerequisites for typical deterioration mechanisms, such as corrosion and wood decay – it is an indicator of increasing risk of those deterioration mechanisms occurring.

The first simulation of the reference wall was conducted according to the previously noted assumptions, except that materials are dry. A high vapour permeability cladding was selected (calcium silicate brick) to simulate a vented airspace. The results for total moisture content of the OSB sheathing (the critical element in the cavity wall assembly) are shown in Figure 2 for a 6-year period and indicates that the moisture content approaches 10.3%, far below the generally accepted threshold of 28% needed to support wood decay. It should be noted that in order to account for uncertainty in hygrothermal calculations and to minimize the risk of risk of mould growth, wood moisture contents above 20% are considered unacceptable by the proposed methodology. The RHT(80) and RHT(95) values have not been shown because they are zero in both cases, indicating no risk of moisture problems in this wall assembly.

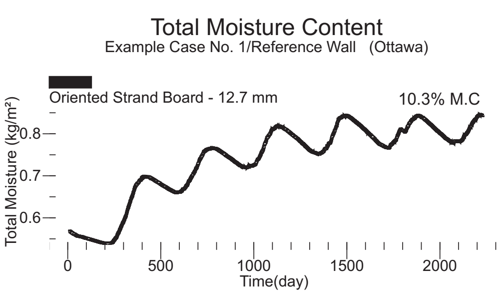

***Figure 2** – Total moisture of OSB sheathing in reference wall assembly over a 6-year period.*

The next simulation assesses a variation on this wall assembly that has also been widely constructed with very few instances of unacceptable hygrothermal perfomance. Essentially, the extruded polystyrene insulation (XPS) is removed from the wall assembly with all of the other layers remaining. The results of hygrothermal simulation for the same 6-year period are depicted in Figure 3.

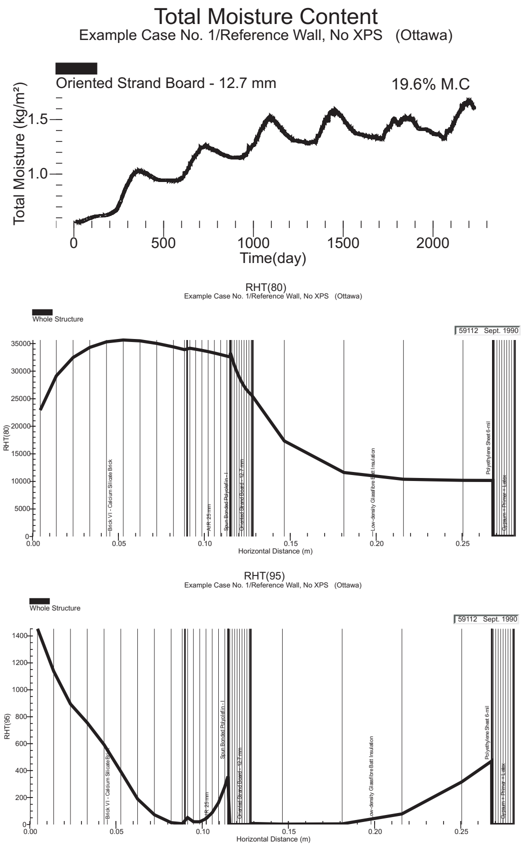

***Figure 3** – Total moisture of OSB sheathing and RHT indices of whole structure for reference wall without XPS exterior insulation.*

The moisture content of the OSB sheathing can be seen to approach the conservative 20% threshold, confirming the acceptable performance of this wall assembly as witnessed in actual wall construction. The RHT(80) index ranges from approximately 25,000 to 33,000 indicating a much higher risk of corrosion for elements such as brick ties compared to the reference wall assembly. The RHT(95) index is approximately 350 at the outer surface of the spun-bonded polyolefin membrane indicating negligible risk of wood decay for the OSB.

It is important to note that the RHT indices are cumulative over the 6 year period, hence to approximately determine the annual RHT indices, these values should be divided by the number of years when analyzing single year simulations.

Up to this point in the series of simulations, a high level of airtightness has been assumed for both assemblies. The next set of simulations attempts to examine the situation where air leakage occurs. The hygIRC 1-D program does not model air leakage through flaws/defects, hence its effects were approximated by removing the polyethylene vapour barrier for each of the two previous cases. The results are depicted in Figures 4 and 5, respectively.

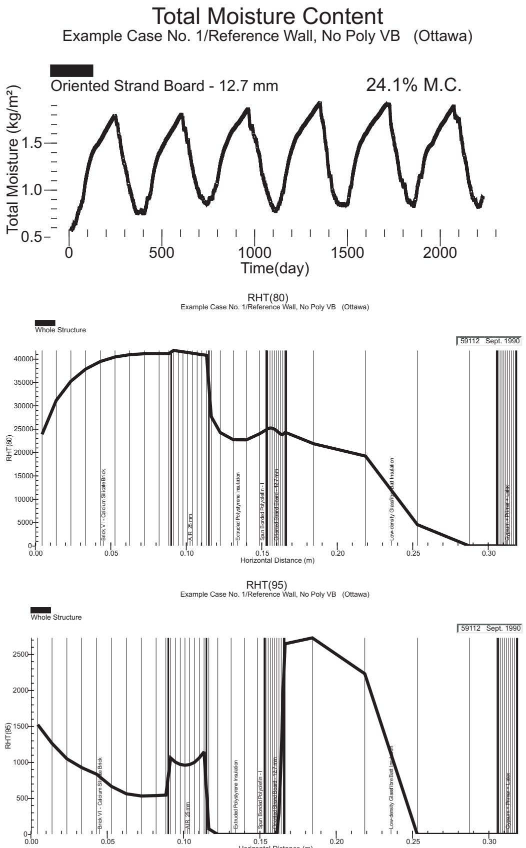

Figure 4 – Total moisture of OSB sheathing and RHT indices of whole structure for reference wall without polyethylene vapour barrier.

The moisture content of the OSB sheathing can be seen to approach 24.1%, well above the 20% threshold. The RHT(80) index averages approximately 25,000 in the OSB sheathing, similar to the previous case. The RHT(95) index is approximately 2,700 at the inner surface of the OSB sheathing and over the outer 20 mm of the glass fibre insulation. This is significantly higher that the value of 250 for the second case where the exterior insulation was removed, indicating an unacceptably high risk of wood decay in the OSB and the outer region of the wood studs, as often evidenced in actual moisture problems observed in the field.

In reality, wood-frame wall assemblies are not constructed without vapour barriers in cold climate zones, and field evidence suggests that vapour diffusion and air leakage are well controlled in contemporary Canadian housing. This simulation is intended to examine the resistance to moisture damage afforded by the wall assembly when workmanship and/or materials are flawed/defective. It attempts to take an approach similar to the limit states design of building structures where the statistically weakest material must withstand the statistically largest imposed load.

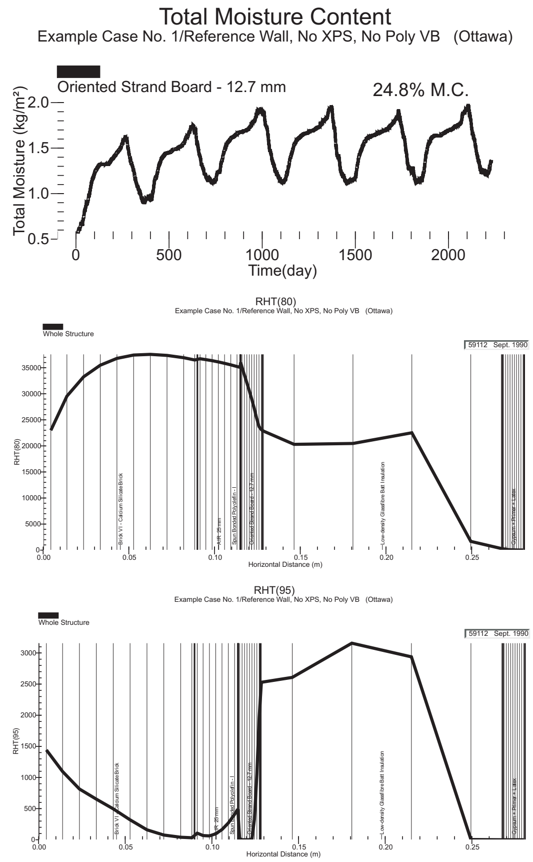

Figure 5 – Total moisture of OSB sheathing and RHT indices of whole structure for reference wall without XPS exterior insulation and polyethylene vapour barrier.

Results for the reference wall without the XPS and polyethylene vapour barrier are illustrated in Figure 5. The moisture content of the OSB sheathing can be seen to approach 24.8%, marginally higher than the previous case where the XPS was provided (likely due to drying to the interior because the vapour barrier is absent). The RHT(80) index within the OSB ranges from approximately 23,000 to 35,000 and extends well within the stud cavity. The RHT(95) index is approximately 2,500 at the inner surface of the OSB sheathing, slightly lower than the previous case, but indicates a migration to over half the thickness of the glass fibre insulation. This signifies the highest risk of wood decay over all cases examined and in limit states terms predicts failure of the wall assembly with respect to moisture management.

The interesting question at this point in the research is to formulate a fit wall assembly that mitigates against the risk of corrosion, wood decay and mould growth when the primary moisture control elements are flawed (i.e., the vapour barrier is removed). Several iterations were conducted for increasing thicknesses of XPS up to 100 mm and the results for this thickness applied to the reference wall are depicted in Figure 6. The moisture content of the OSB sheathing approaches 21.6%, slightly above the conservative threshold but still below the 28% commonly accepted threshold for wood decay. The RHT(80) index ranges about the 23,000 level and falls away within the cavity. The RHT(95) index peaks at approximately 1,400 at the inner face of the OSB sheathing and falls away sharply within the cavity.

Under this admittedly crude limit states design approach, this wall assembly may be considered “fit” for its intended purpose with respect to moisture management.

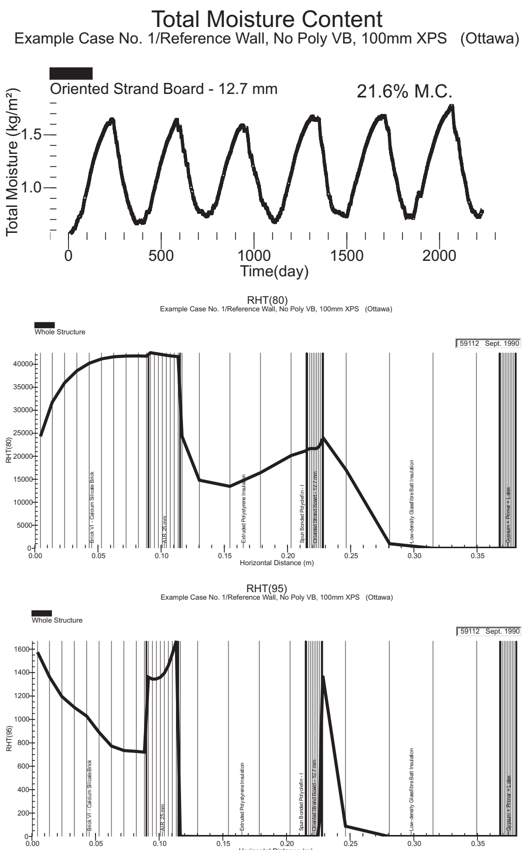

Figure 6 – Total moisture of OSB sheathing and RHT indices of whole structure for reference wall having 100 mm XPS insulation, no polyethylene vapour barrier.

To this point in the simulations, initial boundary conditions for the materials comprising the various wall assemblies have been “dry” to reflect ideal material handling practices on site. The effects of construction moisture will now be examined to determine their influence on this “fit” candidate wall assembly. The initial moisture content of the OSB and the cavity insulation was set at 25% to simulate wet sheathing and studs. The results are depicted in Figure 7.

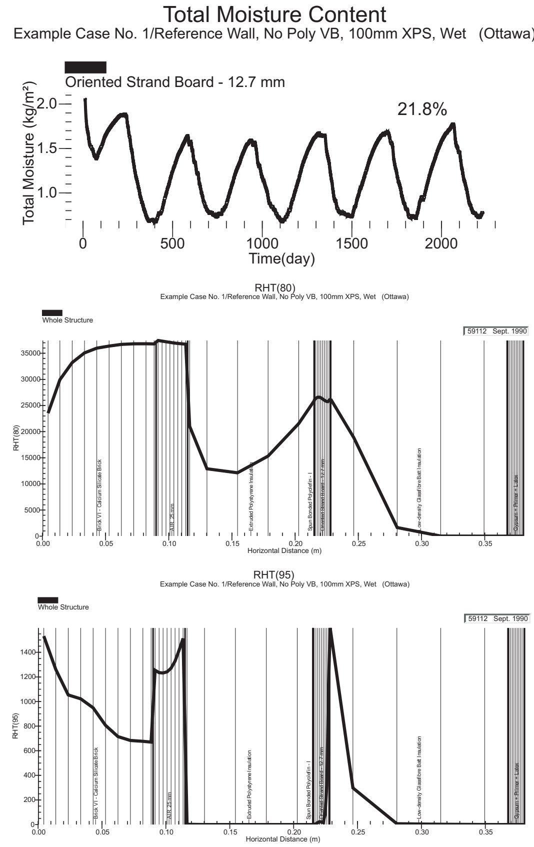

Figure 7 – Total moisture of OSB sheathing and RHT indices of whole structure for previous wall assembly constructed with wet sheathing and studs.

The results of this simulation indicate that the wall assembly is very forgiving of wet materials. The moisture content of the sheathing rebounds to practically the same long-term level as when dry materials are used. RHT indices are virtually identical reflecting the minimal initial influence of the wet materials followed by drying to ambient levels.

A simulation of this wet construction with the polyethylene returned in place would be needed to confirm acceptable moisture management.

As a result of this analysis, and according to the proposed classification system, the wood-frame wall having 100 mm of extruded polystyrene insulation would be deemed “fit” in term of moisture management in Ottawa. The reference wood-frame wall assembly with 38 mm XPS exterior insulation and without would be considered “feasible” assuming a prescribed level of vapour diffusion resistance and airtightness was achieved. Either of these two wall assemblies that did not achieve acceptable levels of air leakage and vapour diffusion control would be “unfit” and therefore deemed not to comply with code requirements.

DISCUSSION

The methodology presented in this paper is intended to provide a reasonable means of deploying readily available and relatively simple-to-use hygrothermal performance simulation software to assist designers and builders in achieving compliance with objective-based codes. This does not conflict with continuing efforts to improve and validate the accuracy of hygrothermal modelling tools. Indeed, research undertaken by groups such as SPC 160P: Design Criteria for Moisture Control under the auspices of ASHRAE Technical Committee 4.4 - Building Materials and Building Envelope Performance will further advance the limit states design of moisture control for buildings. But until such time as limit states design for moisture control has attained the same degree of reliability as its structural design counterparts, it is important to develop simplified methods that deploy available software so that innovation can advance with minimal risk of failure.

Returning to an earlier discussion in this paper, readers may ask, "What about resistance to exterior moisture?" To some extent, this is crudely handled by saturating materials and seeing if they dry out. Another answer is to remove cladding protection and expose the remaining wall assembly to unrestricted wind and precipitation to see if it continues to perform acceptably. Alternatively, it may be recognized that unlike arranging materials for hygrothermal compatibility, some aspects of wall design and construction demand attention to detailing and workmanship. The idea behind this paper is to advance the compatibility of constituent materials comprising exterior walls, not to predict moisture loads due to improper detailing and workmanship. The research attempts to respond to the current condition which may now be recognized as not having changed for several decades.

''*At the moment we are in a position where the traditional approach of learning from failures and copying what worked has broken down. The information is not communicated to those involved. This is not only due to a lack of resolve among those concerned; it is extremely difficult to accommodate all of the new information in view of the rapid changes in materials, details and performance expectations.*'' (Timusk 1992, as quoted in Bomberg and Onysko 2002)

FUTURE RESEARCH

Future research in the near term will require an application of the proposed methodology over a variety of wood-frame wall assemblies across a range of moisture indices (Cornick and Dalgliesh 2003). In addition to arrangements using currently available materials, theoretical materials with selective hygrothermal properties will be modelled to extend work by others on vapour permeable building envelopes (Simonson, Ojanen, and Salonvaara 2005). The relationship of RHT indices to the prediction of mould growth is another important area of research in the near term.

In the longer term, research efforts will include a multi-attribute assessment of wall system performance as presented in earlier work (Kesik and De Rose 2004). A key attribute is the life cycle cost efffectiveness. In view of escalating energy costs, many of the conventional wood-frame wall systems now commonly employed may no longer be cost effective in terms of their energy efficiency. It will be important to investigate the hygrothermal performance, durability, buildability and aesthetics of cost effective, energy efficient wood-frame wall systems.

Further in the future, there is a need to re-visit existing acceptable solutions and determine if they are providing the same factor of safety that will be demanded of novel wall systems seeking acceptance under limit states moisture management criteria.

CONCLUSIONS

In view of the methodology for the hygrothermal classification of wood-frame wall assemblies presented in this paper, the following conclusions are submitted for consideration:

1. The application of relatively simple and readily-accessible hygrothermal modelling software is needed to advance innovative wood-frame wall assemblies for use by the "average" designer and builder. Otherwise, wood-frame walls in Canadian housing will be largely confined to acceptable solutions under objective-based codes.
2. While it is acknowledged that research and development in support of more sophisticated applications is necessary to advance limit states design for moisture management, interim means of enabling building envelope design innovation are presently needed by the building industry.
3. In the absence of rigorous limit states methods and criteria for moisture management, it is still possible to make effective use of existing tools through approximate heuristic methods such as the one presented in this paper.

4. The current and expected escalations in energy prices will demand more energy efficient wood-frame wall assemblies that provide durability and acceptable moisture management. Practical means of classifying innovative wall assemblies according to their climatic locations must be provided to designers and builders, so that they may be deemed alternative solutions under objective-based codes. Consideration should be given to the reality that the vast majority of Canadian housing does not benefit from building envelope design expertise, in particular, moisture engineering expertise.

In summary, it is important to recognize that the practical application of simulation tools in building design is as important as the research supporting simulation tool development.

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