A Precision Weighing System for Helping Assess the Hygrothermal Response of Full-scale Wall Assemblies

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ABSTRACT

The overall hygrothermal behavior of wall assemblies and their related performance is dependent on a number of factors, including properties of the materials used in the assembly as well as the boundary conditions to which the assembly is subjected. Performance assessment, in terms of the rate of energy transfer through the assembly, requires determining heat loss as a function of time in steady-state conditions. Assessing hygrothermal performance, on the other hand, requires, in addition to determining heat transfer constants, knowledge of the mass transfer of air and moisture through the assembly. In small-scale tests, these transient effects can be monitored in real time to offer a ready means of calculating the physical constants of given materials or components. In tests of full-scale wall assemblies, for example, monitoring the change in mass over time can present certain technical challenges if measurable and reproducible data are to be obtained. To assist the benchmarking of computer models that simulate such types of hygrothermal effects, a balance is required that can assess minute changes in mass. Ideally, the balance should measure the effects on a continuous basis such that changes in weight in relation to time can be readily determined. This paper describes the design of, and experimental results derived from, a weighing system for full-scale wall assemblies. The system is capable of continuously monitoring weight changes of 2.5-by-2.5-m walls having nominal weights of up to 225 kg (to the nearest 1g). The weight data have been used to determine weight loss over time in wood sheathing affixed to a wood frame when exposed to steady-state laboratory conditions. The data were used as a basis for helping benchmark an advanced hygrothermal computer model—hygIRC.

INTRODUCTION

The overall hygrothermal behavior of wall assemblies and their related performance is dependent on a number of factors, including properties of the materials used in the assembly as well as the boundary conditions to which the assembly is subjected. Performance assessment, in terms of the rate of energy transfer through the assembly, requires determining heat loss as a function of time in steady-state conditions. Assessing hygrothermal performance, on the other hand, requires, in addition to determining heat transfer constants, knowledge of the mass transfer of air and moisture through the assembly. In small-scale tests, these transient effects can be monitored in real time to offer a ready means of calculating the physical constants of specific materials or components. In larger scale tests—for example, full-scale wall assemblies—monitoring the change in mass over time can present certain challenges if measurable and reproducible data are to be obtained. These requirements must also be met when benchmarking simulation models, as is being undertaken by Maref et al. (2001). In this work, a hygrothermal simulation model (hygIRC) is being used to determine the hygrothermal response of exterior wall systems when subjected to climatic loads of North American climates. Simulation model hygIRC is an advanced hygrothermal model that has been developed at the Institute for Research in Construction (IRC). It is an enhanced version of the "LATENITE" model developed jointly by IRC and the VTT (Finland) (Salonvaara and Kara-

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giozis 1994, 1996; Karagiozis et al. 1995; Karagiozis and Kumaran 1997).

A precision weighing system was developed that assists in benchmarking the advanced hygrothermal model. The intent was to develop a balance capable of assessing changes in mass due to loss of moisture in a wall system with sufficient accuracy as to help verify the assumptions inherent to the model. Such a balance should measure the effects on a continuous basis such that changes in weight in relation to time can readily be determined as well.

Previous Work on Benchmarking Simulation Models

There are some known attempts at providing validation of simulation models, notably from the combined efforts of the IEA Annex 24 (Hens 1996) and more recently from work carried out in Norway at the Norwegian University of Science and Technology (Geving and Uvsløkk 2000).

The work carried out by those working within the IEA Annex 24 focused on using intermodel comparison as one of three possible means identified to provide validation of simulation models—the other two being analytical and empirical verification. Analytical verification, recognized as being useful for testing algorithms, was not attempted and empirical verification was only tried in certain instances. Verifications were restricted to summing up mass quantities, such as total moisture content and amounts of condensed moisture, and thermal values such as temperature, fluxes, and total energy flow. Although these comparisons provided some insight into the applicability of the different models, no straightforward validation through experimentation was completed. It was, however, suggested that more rigorous validation through well-controlled experimentation should form the basis for future work in this area.

Geving and Thue (1996) undertook measurements and computer simulations of the hygrothermal performance of lightweight roofs from which a comparison was made between experimental results and simulations undertaken on a number of different models. Comparison was made between the moisture content at a specific location in a given wood component derived from the experiment and that obtained from the simulation. In none of the cases was there complete agreement between results for moisture content of the components obtained from either method, and no explanations were provided as to why the discrepancies occurred.

Geving and Karagiosis (1996) reported on field measurements and computer simulations of the hygrothermal performance of wood-frame walls in which temperature and moisture content were measured at various locations in the wall assembly. It was conjectured that the "overall trend" was in good agreement between measurements and model predictions of moisture contents in wooden components, although the most significant lack of agreement was the higher values obtained from simulation in the early winter period. No specific reasons were afforded for the discrepancies, although it was noted that there existed many difficulties related to simulating field experiments—in particular, modeling an adequate representation of the imperfections inherent in the real structure as well as uncertainties in the input data.

Following the many attempts to use field measurements to help validate hygrothermal simulation models and having gained some understanding of the limitations of such experiments, Geving and Uvsløkk (2000) have since published useful data intended as a basis from which validation of models can be made; no reports have yet been published that provide a comparison between model predictions and the set of data offered in this report.

The task of validating simulation models is apparently both a difficult and time-consuming task without appropriate tools from which, at least, an overall assessment of the degree to which the model reproduces the experimental results can rapidly be ascertained. It was to this end that a weighing system was conceived that would help assist in determining the total weight change in a specimen over a test period. It was reasoned that this would provide quantitative data from which average moisture contents in key components could readily and rapidly be obtained and reconciled with simulation results and that the measurable hygrothermal effects, evident over the course of the test period, could likewise be continuously monitored.

This paper describes the design of, and experimental results derived from, a precision weighing system for full-scale wall assemblies. The system is capable of weighing, to the nearest gram, 2.5-by-2.5-m walls having nominal weights of 225 kg (500 lb) continuously over the test period. The weight data have been used to determine weight loss over time in wood sheathing affixed to a wood-frame wall assembly when exposed to steady-state laboratory conditions. The data were used as a basis for helping benchmark hygIRC, a hygrothermal computer simulation model. Details regarding the design and operation of the device are provided, as well as results derived from a specific drying experiment. The usefulness of the experimental results is highlighted from a comparison to computer simulations using hygIRC.

DESCRIPTION OF WEIGHING SYSTEM

The weighing system is capable of determining the rate of evaporation of water from a wall assembly specimen in which key wall components have been conditioned prior to test trials to adsorb significant quantities of water (i.e., 20% to 60% weight for which 60% is oversaturation of the component). Specimen weights may vary up to approximately 225 kg (500 lb), whereas the initial weight of water in specific components of the test panel might be in the order of approximately 20 kg. The current setup provides a resolution of ca. 1/90000 or 2.5 grams of moisture in 225 kg total specimen weight. A rough calculation suggests that for a 2.44-by-2.44-m (8-by-8-ft) specimen composed of two oriented strand board (OSB) sheathing at, for example,

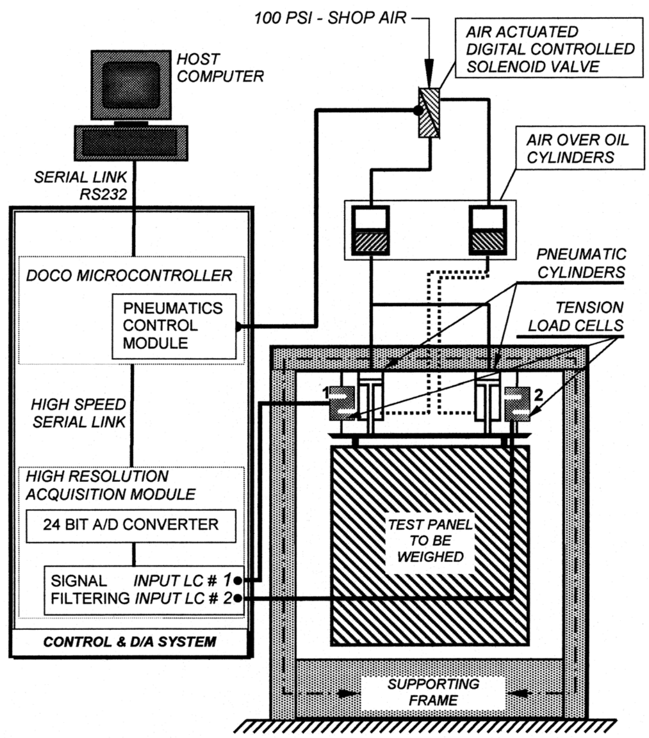

Figure 1 *Schematic of precision wall weighing system showing principal system components.*

5% moisture content (MC) (i.e., 2 kg moisture in 40 kg dry weight), a resolution of 1/90000 will discern a change of 0.125% MC (i.e., 2.5 g in 2 kg). Hence, the ability of the system to detect changes in MC is greater than an order of magnitude at 5% MC.

Over the course of the test, the specimen must be weighed repeatedly over the test period that may extend up to four weeks. From a technological point of view, there are two main difficulties—compensating for the zero drift, which undoubtedly occurs in load cells when subjected to long-term loading conditions, and providing for the precision needed to resolve minute changes in moisture content of assembly components.

The "precision wall weighing system" (Figure 1) is, itself, composed of the following three subsystems:

1. Mechanical weighing system
2. Data acquisition system
3. Software system

A brief description of each item is provided below and the principle of operation is likewise described.

Mechanical Weighing System

The mechanical weighing system consists of two load cells attached to a structural steel frame and a pneumatic lift system composed of two pistons to which the wall is attached by means of a transverse connection bar. The load cells used in this system are type "S," each capable of sustaining loads of up to 114 kg (250 lb), such that two load cells can sustain a total load of 227 kg (500 lb). The capacity of the weighing system can be increased without loss of resolution by replacing the load cells with models capable of sustaining heavier loads.

The lift system is composed of two pneumatic pistons, both having a 200 mm (8 in.) stroke, and these are affixed to the transverse connection bar that transmits the weight of the wall specimen to these pistons. This arrangement permits moving the specimen over a distance of about 25 mm (1 in.) and, in turn, permits the load cells to take up the specimen load and, hence, provide data on the weight of the specimen each time a measurement is taken. This operation is very important since load cells inherently drift from their "zero" position if operated for periods of time exceeding two to three days. Given that a test sequence might be taken over several weeks, and in some cases months, the possibility of eliminating the effects of load cell zero drift become paramount. The manner in which the load cells are configured also permits determining the center of gravity of the specimen along its transverse axis and, hence, determining as well possible moisture transport from one side of the assembly to the other.

Data Acquisition System

The data acquisition system is composed of an acquisition card to which a high-resolution acquisition system specifically devised for capturing data from the load cells is connected. This high-resolution system permits filtering and then converting the analog input signal obtained from each load cell to a digital format via a 24-bit analog to digital converter. The output signals, once digitized, are sent to the host computer via a serial port.

The analog to digital converter (signal to data bit) used in the data acquisition system is a bridge transducer, typical of those used in precision weighing applications. This converter is a SIGMA-DELTA type device that permits conversions having a 24-bit resolution (i.e., 2^{24} = 1/16777216). A programmable gain amplifier is integrated to the converter that permits analyzing a vast number of input signals from ±10 mV to 80 mV. It also contains a programmable numerical filter that allows elimination of high-frequency noise, typically evident on the input signal. Whereas the resolution is high (i.e., ca. 1/100,000), the response time is poor. Thus, only two acquisitions per second can be made using this technique.

The data acquisition and control card is utilized as the interface to the host computer and the acquisition system and is connected to the host through the serial port. Likewise, this device permits activation of an air-actuated solenoid valve that controls the action of the pneumatic pistons that cause the wall specimens to be raised or lowered upon instructions from the host computer.

Software System

The software permits configuration of different operational parameters, such as the frequency of acquisition cycles, the delay before acquisitions are started, the number of conversions to be taken at each reading, as well as the type of filtering required for the input signal. This software application also permits visualizing the acquired data on a continuous basis, as well as information related to the load cell calibration.

Principle of Operation

Once in operation, the software system automatically causes the wall to be weighed at specific predetermined intervals and captures the necessary data for each cell over a preassigned number of readings from which average values are calculated. Also, upon each intervening cycle, the load cells are reset. The acquisition sequence is completed over the following four stages:

1. The pneumatic pistons, fully retracted, place the wall specimen in an "up" position and thereby relieve the load cells of the weight of the wall. A reading of each load cell is then taken, representing the "zero," or setpoint, for each cell.
2. The pistons are then slowly extended, thereby lowering the wall specimen and, thus, engaging the load cells. After a programmable delay, a second reading is taken from each load cell. The delay permits the wall to stabilize itself in the lowered position and ensures that the load cells are properly engaged prior to a reading being taken.
3. From this reading, the initial reading obtained for the setpoint is subtracted, and the weight of the wall can now be determined.
4. The wall is brought to the "up" position once again, thus liberating the load cells from their load and the subsequent cycle starts from Stage 1.

It should be noted that each reading is composed of 100 consecutive conversions and an average is calculated on these 100 data items. This permits increasing the system resolution by a factor of roughly 10. Each conversion takes about a second. This is principally due to the process of numerical filtration as well as the converter. Thus, each reading having 100 conversions requires about two minutes to complete.

APPROACH

The overall intent of the validation program was to determine the hygrothermal behavior of full-scale (2.44-by-2.44-m) wood-frame assemblies when subjected to steady and transient state hygrothermal conditions in a controlled laboratory environment. The experimental work consisted of determining measurable hygrothermal effects that could be recorded and compared to that derived from using the computer model hygIRC. The evaluation program consists of a series of experimental steps for which a notional overview from the initial step to that of the final stage is provided in Figure 2.

The overall program included real-time point measurements of temperature, relative humidity, and bulk moisture content of materials. At each step, moisture, temperature, and humidity sensors are placed in a predetermined pattern on the face of either side of the specimens such that the change in physical properties over the course of the experiment can be monitored on a continual basis. At each succeeding step, additional wall components are added to the test specimen and the experiment is repeated for set conditions such that the effects of individual components can be confirmed from previous results obtained on both small (Kumaran and Wang 1999) and mid-scale tests (Maref et al. 2001). Experimental results are compared to hygIRC to verify the extent to which the model can adequately reproduce the expected hygrothermal effects given the boundary conditions to which the specimen has been subjected.

The envelope environmental exposure facility (EEEF) was used to subject specimens to simulated climatic effects (Figure 3). The EEEF is capable of subjecting full-scale specimens, having nominal dimensions of 2.44-by-2.44-m, to simulated interior and exterior climatic conditions over extended periods of time. The exterior climatic conditions can be varied over a range of –47ºC to + 48±0.5°C with the capability of either maintaining a steady-state setpoint or executing a temperature ramping regime. Humidity control is achieved through a pneumatically actuated fogger coupled to a setpoint controller and can maintain humidities ranging from 10 to 100±3% RH in steady-state conditions. Simulated interior climatic conditions can be varied from 23ºC (ambient laboratory) to 30±1°C at steady-state ambient humidities (ca. 30% to

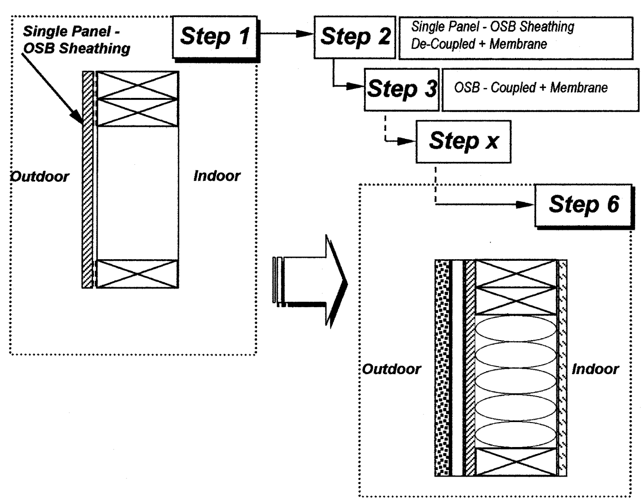

Figure 2 *Stepwise approach to achieving benchmarking objectives.*

Figure 3 *EEEF: Envelope Environment Exposure Facility.*

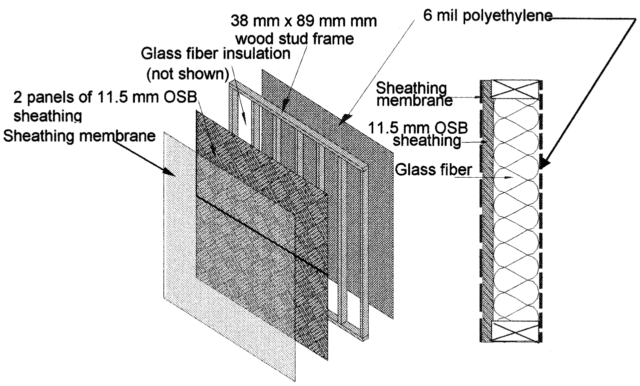

Figure 4 *General configuration of wall assembly specimens.*

60% RH). Air pressure differential across the assembly is not currently possible and neither was this a test parameter.

Benchmarking Trials on Full-Scale Specimens

General Description of Test Specimen. A full-scale test was carried out in controlled laboratory conditions (EEEF) over a period of time sufficiently long as to permit quantifying gravimetrically the change and rate of change in moisture content of a critical wall assembly component—in this case, the wood sheathing (OSB).

The full-scale tests proceeded in a series of steps, each step evaluating the hygrothermal response of a full-scale specimen to specified laboratory conditions. The experimental step described in this paper consisted of evaluating the hygrothermal properties of the wall assembly shown in Figure 4.

The nominal size of the specimen is 2.44 by 2.44 m with the structural components composed of two panels of 7/16 in. (11.5 mm) OSB sheathing placed on a 38-by-89-mm (2-by-4-in.) wood stud frame having vertical studs centered every 406 mm (16

Figure 5 *Positioning the precision weighing system support frame.*

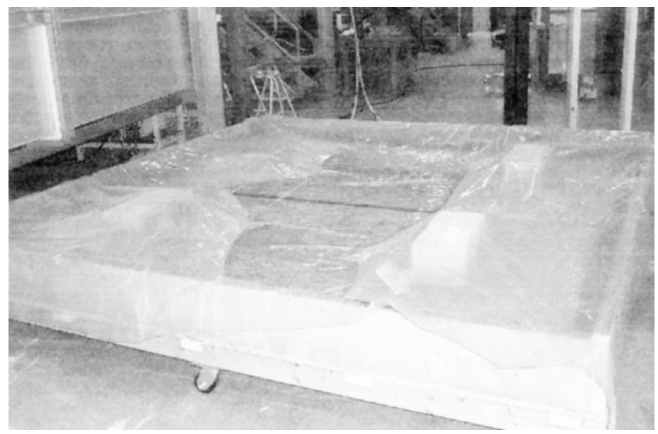

Figure 6 *Wood sheathing (OSB) component in soaking bath.*

in.). The single layer of OSB sheathing was attached to, but decoupled from, the structural wood frame, the decoupling being achieved by coating the wood frame with a water impervious lacquer. A spun-bonded polyolefin sheathing membrane, used as a water resistant barrier, was applied to the sheathing board. Glass-fiber insulation was placed within the wood frame in the cavities between the studs, and, on the opposite side of the frame, a single sheet of polyethylene (6 mm) was installed as a vapor barrier. A double top plate was used in the assembly of the test frame to which a steel cleat was bolted to accommodate connection to the transverse beam on the weighing system. The assembly used screw fasteners to permit easy disassembly and reuse of noncritical components.

Preparation of Test Specimen. The full-scale wood frame, on which the OSB sheathing mounted, was placed within the opening of the precision weighing system frame, as shown in Figure 5. The two panels of OSB sheathing were weighed to determine their initial weight. They were then placed in a sealed bath (Figure 6) to soak for two days so that a moisture content of at least 40% (weight) would be attained.

This nominal level of moisture content was deemed sufficient for the purposes of this benchmarking exercise. Thereafter, water was drained from the bath; however, the OSB remained in the bath for another 48 hours, sealed with tape to prevent moisture egress from the bath. This period was used to help ensure that uniform moisture content in the OSB was achieved prior to mounting it on the wood frame. Over this period, the moisture content of the OSB was monitored every six hours. Relative values of moisture content were obtained at 20 uniformly distributed points on both primary surfaces of the board using a moisture meter. These measurements provided an indication of the uniformity in wetting of the specimens. Upon removal from the sealed baths, the OSB sheathing was weighed once again to determine the initial moisture content prior to being mounted in the test frame. The result for both boards is given in the next section. Subsequently, the sheathing boards were sealed at their edges, except the interface between the OSB panels, thus ensuring that the drying occurred only on the primary surfaces. The panels were then mounted on the wood frame and secured by means of screw fasteners.

Test Conditions. Actual boundary conditions on either side of the wall components were chosen such that rapid moisture loss in the saturated components was achieved in a four-week time frame. The simulation was performed using the temperature and relative humidity values recorded over the course of the full-scale experiments carried out within the EEEF. Figures 7 and 8 show the temperature and relative humidity for interior and exterior conditions, respectively, conducted over a period of 35 days. As shown, the initial conditions include the temperature and relative humidity.

RESULTS

Figure 9 shows a comparison between simulated and total measured MC of OSB derived from experimental results. The initial total MC for both boards in the assembly, as described in the previous section, is ca. 51%. After 33 days, a value of 16% MC is attained. These results indicate a very good agreement between the results obtained from simulation and those derived from experiment. In fact, the greatest difference between the simulated and the experimental results after 33 days is not more than 1.4% MC.

No adjustments to the model were made to minimize the differences between results from simulation and those of the experiment. However, differences between results may be due to a number of factors—the most significant are thought to be related to the manner in which the simulation at the surface of the OSB sheathing was implemented in the program. Specifically, the simulation assumes that there is perfect contact between the membrane and the sheathing board. In fact, in the real system, there always exists some interstitial space between these components. The net affect of this assumption is that the drying rate of the sheathing board in the simulation is decreased and this, in turn, underestimates the loss in moisture content over time, as is shown in Figure 9.

In general, the simulations were able to adequately predict the time required for the OSB sheathing to reach equilibrium moisture content; essentially, hygIRC is clearly able to mimic the drying process in this wall assembly. In each of the experimental steps so far reported, simulation results have

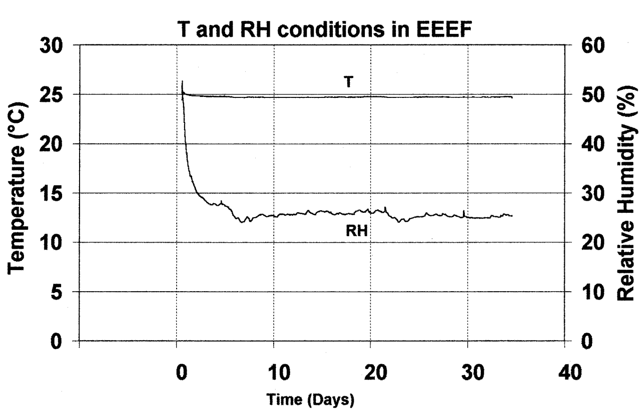

Figure 7 *Environmental conditions within EEEF.*

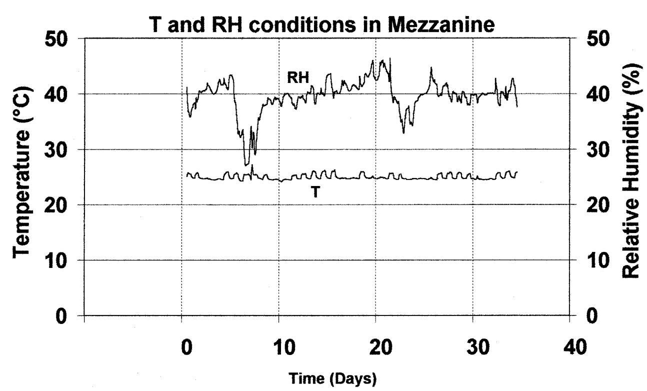

Figure 8 *Environmental conditions outside EEEF.*

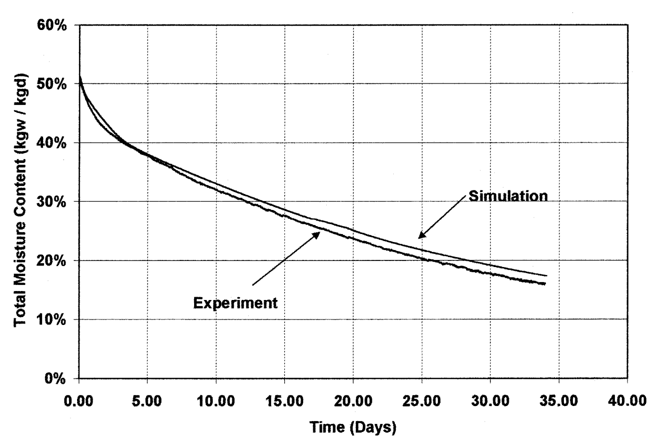

Figure 9 *Comparison of experimental and simulated drying results in terms of total moisture content (%) of OSB sheathing wall components.*

shown very good agreement with those derived from the experiment. Indeed, the greatest difference that is evident when comparing the results derived from simulation and those obtained from experiment is ca. 5%.

A number of such types of experiments have been made in the stepwise approach to help validate hygIRC. Although these results are not provided here, they will be made available in subsequent publications. Nonetheless, the results demonstrate the usefulness of the precision weighing system for helping evaluate key hygrothermal effects in selected wall assembly components.

CONCLUDING REMARKS

A precision weighing system has been devised that permits readily assessing the overall change in moisture content of specific wall components within a wood-frame wall assembly. Wall specimens subjected to known climatic conditions over a period of 35 days were monitored continuously and the moisture content of key components compared to that simulated in a hygrothermal computer model. The experimental results derived from the precision weighing system indicate a close agreement with that provided in the simulation, and this, in turn, underscores the importance of such a tool to assist in validating simulation models. Additional work in this area continues and will be reported in more detail at a later date.

ACKNOWLEDGMENTS

The authors would like to thank Mr. M. Swinton for having made many useful suggestions regarding the development of the weighing system. As well, we would like to thank Mr. D. Richard of DOCO Microsystems for having persevered with completing the installation, troubleshooting, and commissioning of the precision weighing system. Thanks are likewise extended to Mr. D. Booth for having assisted Mr. Richard and having completed the installation of all electrical and data acquisition components for the EEEF and for having set up and carried out the experiments. Our gratitude is likewise extended to Mr. M. Nicholls and Mr. D. Perrier for having fabricated and assembled the apparatus and helped set up the experiments, and to Mr. T. O'Connor for support in further development of the EEEF facility.

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