Structural Stability vs. Thermal Performance: Old Dilemma, New Solutions

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Both structural stability and good thermal performance are important requirements for building envelope components. Structural stability is generally being fulfilled by designers but good thermal performance is given only a secondary role in the design process. In many building envelopes, actual thermal performance falls quite a bit short of nominal design parameters given in standards. Very often only windows, doors, and a small part of the wall area meet standards requirements. In the other parts of the building envelope, unaccounted thermal bridges reduce the effective thermal resistance of the insulation material. Such unaccounted heat losses compromise the thermal performance of the whole building envelope.

For the proper analysis of the thermal performance of most wall and roof details, measurements and three-dimensional thermal modeling are necessary. For wall thermal analysis the whole-wall R-value calculation method can be very useful. In this method thermal properties of all wall details are incorporated as an area weighted average. For most wall systems, the part of the wall that is traditionally analyzed, that is, the flat part of the wall that is uninterrupted by details, comprises only 50 to 80% of the total area of the opaque wall. The remaining 20 to 50% of the wall area is not analyzed nor are its effects incorporated in the thermal performance calculations. For most of the wall technologies, traditionally estimated R-values are 20 to 30% higher than whole-wall R-values. Such considerable overestimation of wall thermal resistance leads to significant errors in building heating and cooling load estimations.

In this paper several examples of the use of whole-wall R-value procedure for building envelope components are presented. The advantages of the use of the whole wall R-value calculation procedure are also discussed. For several building envelope components, traditional clear-wall R-values are compared with the results of whole-wall thermal analysis to highlight significant limits on the use of the traditional methods and the advantages of advanced computer modeling.

INTRODUCTION

Background

This paper proposes the scientifically supported performance data on enhanced, energy-efficient wall systems and disseminate this information in an easy-to-use form to enable home builders and buyers to make informed wall selections. A logical progression from the development of the database and evaluation procedure described in this paper is for the building industry to develop a national consensus whole-wall thermal performance rating label. This will establish in the marketplace a more realistic energy savings indicator for consumers (builders, home owners. . .) faced with the decision of what wall system to select for their building.

A nationally accepted wall evaluation procedure may provide consumers with experimentally based information with which to determine the thermal performance differences between common dimensional lumber systems, which historically represent about 90% of the market (HUD 1993), and alternatives. At least one of the alternative systems (metal frame) anticipates attaining 25% of the residential wall market by the year 1997 (Nisson 1994, Dennis 1995).

In last years, a very fast development of innovative wall technologies offers advantages that will continue to gain acceptance for the systems as the cost of dimensional lumber rises, framing lumber quality continues to decline, availability fluctuates, and consumers' confusion about the environmental correctness of harvesting ‘‘old growth’’ wood as a building material remains. One constraint to greater acceptance of advanced walls is that there is no nationally accepted method of comparing the whole-wall thermal performance of different systems to each other and to wood-frame construction. Many wall technologies (steel frame, insulating concrete forms, low-density concrete blocks, concrete blocks with insulated cores, structural insulated core panels, engineered wood wall framing, and hybrid systems) are waiting for establishing a uniform rating procedure which will give them a chance for proper evaluation.

The following new thermal performance terms are used throughout this paper:

- **Center-of-Cavity R-value:** R-value estimation at a point in the wall's cross-sectional R-value containing the most insulation.
- **Clear wall R-value:** R-value estimated for a flat part of the wall which is uninterrupted by any wall details. This part of the wall is typically tested in hot-box.
- **Interface details:** A set of common structural connections between the exterior wall and other envelope components, such as wall/wall (corners), wall /roof, wall/ floor, window header, window sill, door jamb, door header, and window jamb, that make up a representative residential whole-wall elevation.
- **Whole-wall R-value:** R-value estimation for the whole opaque wall including the thermal performance of the ''clear wall'' area and typical envelope interface details.

In most cases, current thermal calculation procedures tend to overestimate the actual field thermal performance of today's popular housing designs, which feature large fenestration areas and floor plans with many exterior wall corners. This leads to the need for a thermal performance indicator to represent the whole wood-frame wall including thermal shorts created at wall interfaces with other envelope components. Such procedure, to gain popular acceptance, must be accurate yet simple enough to be understood by home buyers and builders, and permit thermal performance comparisons of alternative wall systems.

The effect of extensive thermal shorts on performance is not accurately reflected in commonly used simplified energy calculations that are the current bases for consumer wall thermal comparisons. The benefit of advanced systems with only a few thermal shorts will be clearly discernible by comparing whole-wall thermal performance ratings.

Presently, the framing effect (percentage reduction of clear wall area R-value from that estimated at the center of cavity) in the typical thermal evaluation of wood-frame wall systems, is handled by conducting a simple parallel-path calculation for the cavity and stud area. The area ratio between framing and cavity is almost always suggested by an authoritative source, such as the latest American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook—*Fundamentals* (ASHRAE 1993a). Then, the resulting wall thermal transmittance is compared to the desired value prescribed by either an enforced building energy code, volunteer home energy rating program, or standard. Sometimes only the center-of-cavity insulation material R-value is used for comparison to alternatives. With today's residential buildings increasingly constructed with materials such as metal, stress skin-insulated core panels, and novel composites, a more accurate rating is necessary. Opaque envelopes can no longer be compared by frequently misleading ''center-of-cavity'' insulation material or clear wall R-values. The development of more accurate, consumer-understandable wall labels will spur greater market acceptance of energy-efficient envelope systems.

SCOPE

In last decades, a very fast development of new construction technologies was observed. Several new framing technologies, where concrete or metal profiles provide structural stability, are available now to the builders. At the same time very effective insulation materials are used to construct a building envelope. Commonly used highly conducting structural materials (metal or concrete) make building envelopes a very complicated network of three-dimmensional thermal bridges. The effects of thermal bridges are intensified by a very high ratio between thermal conductivities of the structural and insulating materials. For the metal stud walls, such ratio is close to 1000. In addition, for massive walls, dynamic heat transfer processes have to be incorporated in energy analysis. In such environment, traditional steady-state, one, or two-dimmensional methods of thermal analysis are not very much useful.

That is why, structural stability is generally being fulfilled by designers but good thermal performance is given only a secondary role in the design process. Simply designers have not proper tools. In many building envelopes, actual thermal performance falls quite a bit short of nominal design parameters given in standards. Very often only windows, doors, and a small part of the wall area meet standards requirements. In the other parts of the building envelope, unaccounted thermal bridges reduce the effective thermal resistance of the insulation material. Such unaccounted heat losses compromise the thermal performance of the whole building envelope.

Today, major energy-consuming appliances and windows now have labels that tell consumers the energy cost implications of their purchase. However, when it comes to the walls, a dominant architectural feature of buildings, the consumer, along with designers, builders, and manufacturers, is uncertain at the least and misled at the worst about the energy implications of opaque wall systems. The market place is not fully accounting for the thermal shorts that exist in building walls. This results in the consumer not realizing the full energy cost savings anticipated by complying with energy codes and standards or meeting requirements of home energy rating systems. With the improvement in window efficiency, the potential exists for residential structures to have more windows. When more windows are installed in a building, more framing is needed. The greater the framing factor, the higher the overall thermal transmittance of the opaque wall. With metal-frame construction gaining popularity in residential construction, the thermal shorts potentially resulting from the relatively higher thermal conductivity of metal compared to wood can mean much more severe heat loss than can be accounted for by traditional simplified calculations.

Interface details make a difference. The consequences of poorly selected connections between envelope components are severe. Taking into account the interface details can have an impact on as much as 50% of the overall wall area, for some conventional wall systems, the whole-wall R-value can be as much as 40% less than what is measured for the clear wall section. The whole wall procedure highlights the importance of using interface details that minimize thermal shorts. Local heat loss through some wall interface details may be twice that estimated by simplified design calculation procedures that focus only on the clear wall. Poor interface details also may cause excessive moisture condensation and lead to stains and dust markings on the interior finish, which reveal envelope thermal shorts in an unsightly manner. This moist surface area can encourage the propagation of molds and mildews, which can lead to poor indoor air quality.

Today, the steady-state whole-wall R-value is the first element of four that are needed to compare whole- wall performance. The authors are working also on the thermal mass benefits, airtightness and moisture tolerance. For some wall technologies all four of the factors are important; for others only the first is relevant. A fifth factor growing in importance, is sustainability.

The usage of the proposed method, should contribute toward a larger effort to build an easily accessible database of advanced wall systems. The individual wall system results from this procedure will help gain system-specific acceptance by code officials, building energy-rating programs such as HERS Home Energy Rating System and EPA Energy Star Buildings, building designers, and builders. A user-friendly computer-accessed database is under development that could be used by the public to make whole-wall thermal performance comparisons. This database eventually encompass all the critical wall performance elements. The package is being developed for access on the Internet (http://www.cad.ORNL.gov/kch/demo. html). Features of the package will include:

- An easily accessible archive of experimental results for all tested wall systems, including downloadable drawings.
- A database of material thermal properties.
- An easy-to-use interface to a computer-generated database that allows the determination of the whole-wall thermal performance rating for a wide variety of building envelope systems and user specified wall elevations.

More than 40 types of building wall systems already have been analyzed by this method (Kosny and Desjarlais 1994; Kosny and Christian 1995a; Kosny 1994) using finite difference computer code (Childs 1993). Computer code was calibrated using test results for about 30 different walls (Kosny and Christian 1995b). This approach requires expertise in three-dimensional, finite-difference heat transfer modeling that is beyond the level normally available in residential building design and construction offices. Therefore, the preferred approach for making this procedure available is a user-friendly interface to a three-dimensional computer model database that incorporates this methodology for determining a whole-wall R-value for residential buildings. The interface allows users to define the building envelope in terms familiar to the industry rather than in the more complex three-dimensional analytical models. This evaluation procedure is based on not only a computer model, but a synthesis of experimental measurements and validated computer simulation, significantly strengthening its accuracy and building market acceptance potential.

PROPOSED METHODOLOGY FOR THE WALL THERMAL PERFORMANCE EVALUATIONS

Whole-Wall R-Value

A proposed procedure starts with American Society for Testing and Materials (ASTM) C236 or ASTM C 976 (ASTM 1989) test. A clear wall section, 8 ft by 8 ft (2.4m × 2.4m), is tested in a guarded hot box. Experimental results are compared with two or three-dimensional finite-difference computer modeling predictions. The comparisons helps in calibrating of the computer model. Although not necessary for every wall system, calibration of the computer model by the experimental results enhances credibility. After the model is calibrated, simulations are made for eight wall interface details: corner, wall/roof, wall/foundation, window header, window sill, door jamb, door header, and window jamb which make up a representative residential whole-wall elevation. Results from these detailed computer simulations are combined into the steady-state whole-wall R-value. A reference wall elevation is defined by the user to weigh the impacts of each interface detail. The whole wall procedure was detailly decribed by the authors in several papers (Kosny & Desjarlais 1994, Kosny & Christian 1995a, Kosny & Christian 1995b, Christian & Kosny 1995).

The proposed procedure requires 1.) testing the wall at steady state conditions;. 2.) calibrating the computer model with ‘‘clear wall’’ hot-box results. 3.) modeling the eight details making up a typical residential wall elevation and determine the area of influence of each detail; 4.) calculating whole-wall R-value; 4.) conducting parametric thermal analysis to improve details and whole-wall R-value.

Thermal Mall Benefits

Depending on the climate conditions, some of the wall systems with significant thermal mass, have the potential to reduce building annual heating and cooling energy requirements below that required by standard wood-frame construction with similar steady-state R-value. A procedure has been developed to measure and generate metrics that reflect this thermal mass benefit by providing an MEC-formatted table (Christian 1991). The procedure is as follows:

(1) Conduct a dynamic hot-box test to determine dynamic response factors.

(2) Run the three-dimensional model and compare it to dynamic hot-box test results from Step 1 and generate response factors.

(3) Run an ‘‘Equivalent Wall ‘‘ program, which generates a simplified one-dimensional wall that has the same dynamic thermal behavior as the actual complex wall tested in step 1. This task will generate a list of thermophysical properties for each uniform layer (R-value, thermal capacitance and thickness).

(4) Compare response factors for the three-dimensional wall generated in step 2 to the response factors of the simplified, one-dimensional wall generated in step 3. If there is an acceptable match, a set of envelope system thermophysical properties that can be used directly in whole-building simulation models is now available to define the energy-savings benefits of the thermal mass in different climates and building types compared to standard wood-frame walls.

(5) A whole-building simulation program such as DOE2 is run for the generated ‘‘equivalent wall’’ and standard code-compliant wood-frame wall on a standard building in six U.S. Climates. The mass effect will be determined by comparing the annual energy consumption from a standard house (using the ‘‘equivalent wall’’) to that resulting from the identical house with wood-frame walls.

(6) A report is prepared containing (a) a set of uniform-layer thermophysical properties for use in whole building simulation and (b) code-compliance tables and figures: Council of American Building Officials (CABO) MEC thermal transmittance tables for this specific wall system will be derived using the hot-box-validated analysis described above. The same procedure will be used to develop the generic tables found in the MEC for all walls with more than 6.0 Btu/ ft (19/W/m^2) of wall thermal capacitance (CABO 1995). This customized table can be used to show code officials’ compliance with the prescriptive U_w requirements in the MEC that are based on wood-frame constructions. Finally, a figure compliant with ASHRAE Standard 90.2 (ASHRAE 1993) will be developed.

The key to the above method is the ‘‘Equivalent Wall’’ program based on the equivalent wall theory for complex thermal structures (Kossecka & Kosny 1996). This theory expresses the role of storage effects in heat flow through an element. It leads to the definition of the structure factors, the dimensionless quantities, representing the fractions of heat stored in wall volume, in transition between two different states of steady heat flow, which are transferred across each of wall surfaces. These quantities, together with total transmittance and capacity, are the basic thermal characteristics of a structure. The conditions which represent the relationships between structure factors and response factors for a plane wall are derived in (Kossecka, Kosny 1996). It was proved by Kossecka and Kosny (1996) that walls of the same structure factors, have also similar dynamic characteristics, response factors, even if they are quite different in details. This led to the concept of the ‘‘equivalent wall’’—simple structure which has the same type of dynamic thermal behavior as a more complex one—and may be used as its substitute in whole building energy modeling.

Airtightness

A combination of ASTM Standards (C236 or C976 [ASTM 1989]) or E1424 and E283 (ASTM 1995) will be used to measure the air leakage and heat loss through wall assemblies under simulated wind conditions ranging from 0 to 15 mph (24 kph). Varying the differential pressures from 0 to 25–50 Pa should simulate the extremes to which a wall is exposed in a real building. However, because many of the leakage paths through an exterior wall of a residential building occur at the wall connections and not through the typical clear wall, which comprises the 8-ft by 8-ft (2.4-m × 2.4-m) test section, the test specimen will be modified to contain one light switch and one duplex outlet connected with 14-gauge wiring and possibly other details. With heat loss in a building reaching as high as 40 % due to infiltration (NAIMA 1994), including this performance parameter would be important, but the workmanship quality on the construction site compared to a laboratory specimen must be considered. A second complicating factor is that, over time, materials may shrink, crack, etc., and this will change the leakage over time. We will never completely predict the impact of all variables on the energy loss of buildings (e.g., workmanship). What is important is to establish a uniform baseline for all wall systems.

Moisture Tolerance

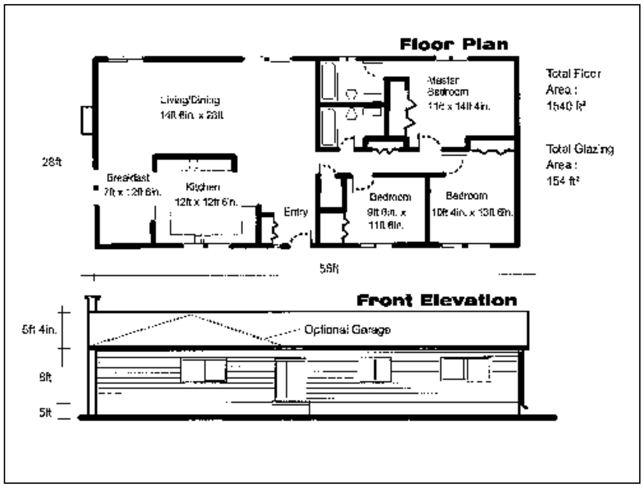
The wall moisture behavior, like the benefit of thermal mass, is a function of climate and building operation. The likelihood of annual moisture accumulation due to vapor diffusion of a particular wall system can be estimated by computer simulation. Moisture accumulation due to airflow into the wall is more difficult. One important feature to have in a long-lasting wall assembly is the ability for the wall to dry itself out if it should be built wet or pick up moisture due to a leak in the course of its in-service life. The drying rate can be modeled and measured in the laboratory. The potential for moisture accumulation (an undesirable characteristic) over specific full annual climatic cycles also can be modeled by heat and mass transfer codes such as MOIST and MATCH (Desjarlais et al. 1994).

EXAMPLES OF WHOLE-WALL R-VALUE CALCULATIONS

The whole-wall R-values have been estimated by the authors for eighteen wall systems. The finite-difference computer code was used (Childs 1993). For all eighteen of the systems, the procedure described above for calculating whole-wall R-value has been followed.

The whole-wall R-value was estimated for 18 wall systems listed in Table 1 along with the clear whole wall R-value. A reference building shown in Figure 1 was used to establish the location and area weighing of all the interface details. The comparison of these two values gives one a good overall perspective of the importance of wall interface details for both conventional wood, metal, masonry, and several high-performance wall systems. Frequently, the opaque wall thermal performance is simply described at the point of sale as the ''clear wall'' value. This means that the whole-wall R-value could be overstated from -3.3% to 26.5%, as shown by the last column in Table 1 ''$(R_{ww}/R_{cw}) \times 100\%$.'' Recognize that these differences can change by selecting different interface details with varying degrees of thermal shorts.

Figure 1. *Plan and Elevation of One-Story Ranch House*



Interesting comparisons can be made using the data in Table 1 to illustrate the importance of using a whole-wall R-value (R_{ww}) to select the most energy-efficient wall system. The difference between the clear wall and whole-wall R-value could be argued to be representative of the energy-savings potential of adopting the rating procedure proposed in this paper. With most building owners assuming they have the higher clear wall value rather than the more representative of reality, whole wall R-value.

Systems 5 and 6 show two different high-performance masonry units. If one uses the clear-wall R-value to choose the one with highest R-value one would pick system 5, the low- density concrete multicore insulation unit, because its R-value is 19.2h • ft^2 • °F/Btu (3.38 m^2 • K/W) compared to 15.22 h • ft^2 • °F/Btu (2.68 m^{2}K/W) for system 6, EPS block-forms. However, if one uses the whole-wall R-value as the criterion for choosing the most efficient system, one would choose just the opposite because system 6 has the higher value [15.72 h • ft^2°F/Btu .77 m^2 • K/W)] compared to 14.69 h • ft^2 • °F/Btu (2.59 m^2 • K/W). Another observation is that the whole-wall R-value of the foam-form system actually is higher than the clear wall values by more than 3%. This illustrates the effect of the high thermal performance of the interface details.

Systems 7, 8 and 9 are all conventional wood-frame systems. Note that the details impact the whole-wall R-value more for 2×6 walls than for 2×4 walls. The ratio of R_{ww}/R_{cw} is about 90% for the 2×4 walls and 84% for the 2×6 wall.

Comparing System 11, the 6-in (15 cm) stress-skin-panel wall, to system 9, the conventional 2×6 wood-frame wall, shows that the stress-skin-panel clear-wall R-value [25 h • ft^2 • °F/Btu, (4.35 m^2 • K/W)] is 51% higher than that of the 2×6 wall [16 h • ft^2 • °F/Btu, (2.88m^2 • K/W)]. When details are included in the whole-wall R-value, the percentage improvement is even greater (-58%), 21.59 h • ft^2 • °F/Btu (3.8m^2 • K/W) to 13.69 h • ft^2 • °F/Btu (2.41m^2 • K/W). This is an example of how advanced systems will generally benefit from a performance criteria that reflects whole-wall rather than the commonly used simplified clear-wall values.

Systems 12 through 18 listed in Table 1 are all metal. On average, the whole-wall R-value for these seven systems is

Table 1. *Whole Wall R-Value Data Base*

No	System description:	Clear wall R-value		Whole wall R-value		(R_{ww}/R_{cw}) × 100%
		hft^{2}F/Btu	m^{2}K/W	hft^{2}F/Btu	m^{2}K/W	
1.	12-in. (30-cm.) Two-core insul. units - concrete 120lb/ft^3 (1920 kg/m^3), EPS inserts - 1-7/8-in. (4.8-cm.) thick, grout fillings 24-in.(60-cm.) o.c.	3.7	0.64	3.6	0.63	97.3
2.	12-in. (30-cm.) Two-core insul units -wood concrete 40lb/ft^3 (640 kg/m^3), EPS inserts - 1-7/8-in. (4.8-cm.) thick, grout fillings 24-in.(60-cm.) o.c.	9.4	1.65	8.6	1.52	91.7
3.	12-in. (30-cm.) Cut-web insul. units - concrete 120lb/ft^3 (1920 kg/m^3), EPS inserts - 2-1/2-in. (6.4-cm.) thick, grout fillings 16-in.(40-cm.) o.c.	4.7	0.82	4.1	0.73	88.2
4.	12-in. (30-cm.) Cut-web insul. units -wood concrete 40lb/ft^3 (640 kg/m^3), EPS inserts - 2-1/2-in. (6.4-cm.) thick, grout fillings 16-in.(40-cm.) o.c.	10.7	1.88	9.2	1.61	85.6
5.	12-in. (30-cm.) Multicore insul. units -polystyrene beads concrete 30lb/ft^3 (480 kg/m^3), EPS inserts in all cores.	19.2	3.38	14.7	2.59	76.6
6.	EPS block-forms poured in place with concrete, block walls 1-7/8-in. (4.8-cm.) thick.	15.2	2.68	15.7	2.77	103.3
7.	2×4 wood stud wall 16-in.(40-cm.) o.c., R-11 batts, 1/2-in.(1.3-cm.) plywood -exterior., 1/2-in.(1.3-cm.) gypsum board -interior.	10.6	1.86	9.6	1.69	90.9
8.	2x4 wood stud wall 24-in.(60-cm.) o.c., R-11 batts, 1/2-in.(1.3-cm.) plywood -exterior., 1/2-in.(1.3-cm.) gypsum board -interior.	10.8	1.91	9.9	1.74	91.2
9.	2×6 wood stud wall 24-in.(60-cm.) o.c., R-19 batts, 1/2-in.(1.3-cm.) plywood -exterior., 1/2-in.(1.3-cm.) gypsum board -interior.	16.4	2.88	13.7	2.41	83.7
10.	Larsen Truss walls - 2×4 wood stud wall 16-in.(40-cm.) o.c., R-11 batts, - 8-in.(20-c) thick Larsen trusses insulated by 8-in. (20-cm.) thick batts, 1/2-in.(1.3-cm.) plywood -exterior., 1/2-in.(1.3-cm.) gypsum board -interior.	40.4	7.12	38.5	6.78	95.3
11.	Stress Skin Panel Wall, 6-in. (15-cm.) thick foam core - 1/2-in. (1.3-cm.) OSB boards, 1/2-in.(1.3-cm.) plywood -exterior., 1/2-in. (1.3-cm.) gypsum board -interior.	24.7	4.35	21.6	3.80	87.5
12.	4-in. (10-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior., - 1-in.(2.5-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in.(1.3-cm.) gypsum board -interior. NAHB Energy Consv. House Details.	14.8	2.60	10.9	1.91	73.5
13.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior., - 1/2-in. (1.3-cm.) wood siding, 1/2-in.(1.3-cm.) gypsum board -interior	7.4	1.31	6.1	1.08	82.6
14.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, - 1/2-in.(1.3-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	9.9	1.74	8.0	1.42	81.3
15.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior.,- 1-in.(2.5-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in. (1.3-cm.) gypsum board -interior. AISI Manual Details.	11.8	2.07	9.5	1.67	80.5
16.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, 1/2-in.(1.3-cm.) plywood -exterior, - 1/2-in. (1.3-cm.) wood siding, 1/2-in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	9.4	1.66	7.1	1.24	74.8
17.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, - 1/2-in. (1.3-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in.(1.3-cm.) gypsum board -interior. AISI Manual Details.	11.8	2.08	8.9	1.57	75.6
18.	3-1/2-in. (8.9-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior., - 1-in.(2.5-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in. (1.3-cm.) gypsum board -interior. AISI Manual Details.	13.3	2.35	10.2	1.80	76.5

Table 2. *Whole Wall R-Value Compared to In-Cavity R-Value*

No	System description:	In-cavity R-value		Whole wall R-value		(R_{ww}/R_{cw}) × 100%
		hft^{2}F/Btu	m^{2}K/W	hft^{2}F/Btu	m^{2}K/W	
7.	2×4 wood stud wall 16-in. (40-cm.) o.c., R-11 batts, 1/2-in.(1.3-cm.) plywood -exterior, 1/2-in. (1.3-cm.) gypsum board -interior.	13.6	2.40	9.6	1.69	70.2
8.	2×4 wood stud wall 24-in. (60-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, 1/2-in. (1.3-cm.) gypsum board -interior.	13.6	2.40	9.9	1.74	73.4
12.	4-in. (10-cm.) Metal stud wall, 24-in. (60-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, - 1-in. (2.5-cm) EPS sheathing - -in. (1.3-cm.) wood siding, 1/2-in. (1.3-cm.) gypsum board -interior. NAHB Energy Consv. House Details.	19.6	3.46	10.9	1.91	55.3
13.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, - 1/2-in. (1.3-cm.) wood siding, 1/2-in. (1.3-cm.) gypsum board -interior. AISI Manual Details.	14.6	2.58	6.1	1.08	41.9
15.	3-1/2-in. (8.9-cm.) Metal stud wall, 16-in. (40-cm.) o.c., R-11 batts, 1/2-in. (1.3-cm.) plywood -exterior, - 1-in. (2.5-cm) EPS sheathing - 1/2-in. (1.3-cm.) wood siding, 1/2-in. (1.3-cm.) gypsum board -interior. AISI Manual Details.	18.6	3.28	9.5	1.67	50.8

22 % less than the clear-wall values. Metal can be used to build energy-efficient envelopes, but not by using techniques common to wood-frame construction. The conventional metal residential systems reflected in Table 1 do not fare as well when the whole-wall R-value is used as the reference compared to all other systems displayed in Table 1. For example, if one is considering either system 6 (EPS block forms) or System 12 (a 4 in. metal stud wall), the clear-wall R-value is about the same, 15 h • ft^2 • °F/Btu (2.64 m^2 • K/W); however, if the comparison is made using the whole-wall R-value, the EPS foam-block system has a 45% higher value, 15.72 hft^{2}F/Btu (2.77 m^{2}K/W) to 10.86 hft^{2}F/Btu (1.91 m^{2}K/W). A detailed example showing all the details for the metal frame system 15 can be found in the proceedings of the December 1995 ASHRAE Envelopes VI conference (Christian, Kosny 1995).

Data presented in Table 2 shows the comparison between the center-of-cavity and whole-wall R-values. This suggests that when the realtor responds to a potential home buyer by stating the R-value of insulation across the cavity, the whole-wall R-value actually may be overstated by 26.6 to 58.1%. If one is comparing the thermal performance differences between metal (system 13) and wood (system 7) frames using center-of-cavity R-values, one would conclude there is no difference because both have center-of-cavity R-values of about 14 h • ft^2 • °F/Btu, (2.5 m^2 • K/W) . However, when the whole-wall R-value is used as the criterion for comparison, the 2×4 wood wall system is 56% better [9.58 h • ft^2 • °F/Btu (1.69 m^2 • K/W)], compared to 6.14 h • ft^2 • °F/Btu (1.08 m^2 • K/W) for the metal system.

These comparisons are not meant to imply one type of construction is always better than another. They are all based on representative details. Whole-wall R-values could change if certain key interface details were changed. The intent of making these sample comparisons is simply to point out the importance of having the whole-wall R-value available in the marketplace for guiding wall designers, manufactures, and home buyers to more energy-efficient systems.

CONCLUSIONS

In this paper a new procedure is proposed for comparing the thermal performance differences between diverse types of wall systems. This procedure ultimately will include four elements: whole-wall R-value, thermal mass benefits, air-tightness, and moisture tolerance. The whole-wall R-value procedure described in this paper should be considered for an adoption in the ASHRAE Standard 90.2 (ASHRAE 1993b), MEC (CABO (1995), and HERS (Home Energy Rating System) (DOE 1995). In addition, many of the code compliance documents that are available to show builders how to comply with applicable codes, standards and energy-efficiency incentive programs would benefit by using this whole-wall R-value procedure.

The whole-wall R-value is a better criterion than the clear-wall and much better than the center-of-cavity R-value methods used to compare most types of wall systems. The value includes the effect of the wall interface details used to connect the wall to other walls, windows, doors, ceilings and foundations.

The market focus on clear-wall or even worse center-of-cavity R-value, is misleading and inhibiting the market penetration of high-performance wall systems into the residential construction industry. It is necessary to use a whole-wall R-value, for builders and building owners to appreciate the added thermal benefits of many of the alternatives to conventional wood-frame wall construction. The use of a whole-wall R-value could guide decisionmakers to select wall systems that have whole-wall R-values 25%–50% higher than for wall systems that have significant thermal shorting (high misleading center-of-cavity and clear-wall R-values compared to whole-wall R-value).

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