A COMPARISON OF THERMAL BRIDGING CALCULATION METHODS

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ABSTRACT

Thermal bridges have a large effect on the thermal performance of building envelopes, significantly increasing winter heat loss and summer heat gain. Also, condensation on thermal bridging elements can result in mold and mildew growth (with accompanying reduction of air quality), staining of surfaces, and serious damage to building components. Significant energy savings and improved structural integrity would result if design practices successfully addressed thermal bridging problems.

A research project was sponsored by ASHRAE to address these problems. This paper compares several methods of calculating thermal bridging effects against the results from physical testing and computer simulation. Existing methods are evaluated for simplicity, accuracy, and ease of interpretation. Procedures assessed include ASHRAE parallel-path, isothermal planes, and zone methods; the European standard ISO/DIS-6946-1; the ORNL modified zone method; the methods suggested in ASHRAE Standard 90.1 and in the draft 1995 National Energy Code of Canada; and two-dimensional finite-volume computer simulation.

INTRODUCTION

There are four objectives for the research project associated with this paper:

- evaluate the performance of common wall assemblies and their thermal bridges,
- evaluate design and construction methods (e.g., sheathing) to ameliorate the impact of thermal bridges,
- evaluate current methods of predicting thermal resistance of construction types and thermal bridges, and
- develop new or revise existing calculational methods.

This paper deals mainly with the third objective: the major known calculational methods are evaluated for accuracy by comparison with physical test results and detailed computer modeling, with comments made about the ease of use and applicability of each method. Although the research project deals with several construction types, this paper focuses on steel-framed walls, as these constitute one of the most common thermal bridging problems.

METHODOLOGY

Six metal-frame wall systems were tested in a rotatable climate simulator (RCS) facility, including 8-ft by 8-ft (2,440-mm by 2,440-mm) sections of the following specimens:

A.1a 5/8-in. (16-mm) gypsum wallboard.
b Nominal 4-in. (100-mm) C-shaped 18-gauge steel studs (15/8-in. [41-mm] flange) at 24 in. (610 mm) o.c., with R-11 (RSI 1.94) full-width fiberglass insulation batts. The construction includes top and bottom tracks that are the same thickness as the studs.
c 5/8-in. (16-mm) gypsum wallboard.

A.2 The same as A.1, with nominal 1-in. (25-mm) expanded polystyrene (EPS) added to the exterior.

A.3 The same as A.1, with nominal 1½-in. (38-mm) EPS added to the exterior.

B.1a 5/8-in. (16-mm) gypsum wallboard.
b Nominal 6-in. (150-mm) C-shaped 18-gauge steel studs (15/8-in. [41-mm] flange) at 24 in. (610 mm) o.c., with R-19 (RSI 3.35) full-width fiberglass insulation batts. The construction includes top and bottom tracks of the same thickness as the studs.
c 5/8-in. (16-mm) gypsum wallboard.

B.2 The same as B.1, with nominal 1-in. (25-mm) EPS added to the exterior.

B.3 The same as B.1, with nominal 1½-in. (38-mm) EPS added to the exterior.

The specimens were tested at approximately 50°F (10°C) and 100°F (38°C), with natural convection on the warm side and moderate airflow on the cold side (to ensure a uniform cold-side temperature). All specimens were instrumented and tested in accordance with ASTM

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C 236 (ASTM 1987). Additional thermocouples were placed in locations determined through the use of preliminary finite-volume modeling (to identify regions where thermal gradients would be of interest). Thermal conductivity of all materials used in the construction were measured in accordance with ASTM C 518 (ASTM 1985) for use as data input in the finite-volume analysis and in the various calculational methods described in this paper (except the metal components, which were measured using the ASTM E 1461 (ASTM 1992) laser-flash diffusivity technique). The individual components of each wall assembly were measured to determine physical dimensions for use in the simulation and calculation methods.

The test specimens were also modeled using a two-dimensional finite-volume heat transfer program (EE 1993). Simulations are performed by drawing a cross section of the specimen or assembly to be analyzed (using a simple CAD interface), applying the as-tested boundary conditions to the structure, and refining the finite-volume grid as required to provide increased accuracy in areas of interest. The program determines temperature distribution and heat transfer within the structure and thermal transmittance/resistance through areas of interest.

The specimens were modeled by analyzing three representative sections: a stud at the edge of the specimen, a stud in the center of the specimen, and the track that runs along the top and bottom of the specimen. All models include a portion of the insulated cavity that is large enough to ensure that the heat transfer at the edge of the structure is not affected by the thermal bridge presented by the metal stud. The results of these simulations were then area-weighted to produce a total-product thermal resistance for the entire 8-ft by 8-ft (2,440-mm by 2,440-mm) specimen. Thus, the simulation produces temperatures, total heat flow, and thermal resistance results that can be compared against the physical test results for the same parameters to provide additional information.

Nine methods of calculating thermal resistance were also investigated.

- The parallel-path and isothermal-planes methods are often considered to be two separate calculational methods, although this is not really true. The *ASHRAE Handbook—Fundamentals* (ASHRAE 1993a) suggests that these methods provide upper and lower limits on the true thermal resistance, and "examination of the construction will usually reveal whether a value closer to the higher or lower calculated value should be used." In the absence of a highly conductive layer that would enhance lateral conduction (as is the case with steel-framed walls), the *Handbook* suggests a value closer to the parallel-path method.
- The *Handbook* is not specific as to where the "true" thermal resistance will occur between parallel-path and isothermal-planes calculations. A recent International Standards Organization standard (ISO 1995) attempts to provide guidance by recommending the arithmetic mean of the two methods, while the draft version of Canada's *National Energy Code* (NRC 1995) suggests a result two-thirds closer to the isothermal-planes result than the parallel-path result, using a thermal conductivity of 430 Btu-in./(h·ft^2·°F), or 62.1 W/(m·K), for the steel components.
- The *ASHRAE Handbook* also describes an approach for simplifying the steel-stud assembly favored by the Building Research Association of New Zealand (BRANZ). This approach involves simplifying the C-shaped cross section of the stud as a rectangular block of an effective conductivity, representing the stud and its internal cavity. The BRANZ method has been examined using parallel-path and isothermal-planes methods, combined as recommended by ISO and NEC (referred to herein as *BRANZ/ISO* and *BRANZ/NEC*).
- *ANSI/ASHRAE 90.1* (ASHRAE 1993b) includes a table of effective R-values for wall sections with metal studs.
- The zone method accounts for the fact that a thermal bridge acts over an area larger than the thermal bridge itself (as is implied by the parallel-path method) but not over the entire specimen (as is implied by the isothermal-planes method). Recent studies (Barbour et al. 1994; Kosny and Christian 1995) suggest a modified zone method to account for the fact that the effective area of the thermal bridge also depends on the amount of sheathing insulation and cavity insulation.

All of these methods were used to evaluate the total-product thermal resistance for the entire 8-ft by 8-ft (2,440-mm by 2,440-mm) specimen. These methods are normally used in a simple two-dimensional calculation, but the three-dimensional method used here allows the calculated results to be compared directly to test and simulation results.

COMPARISON OF RESULTS: TEST AND SIMULATION

The results from physical testing and numerical modeling are compared in Table 1. Following standard practice, these values are listed without film coefficients (i.e., the values given are surface-to-surface resistances).

Several observations can be made from the data in Table 1. First, although R3.75 was added, going from specimen A.1 to specimen A.2 (or from B.1 to B.2), the measured and simulated results show a much higher change: R4.7 from A.1 and A.2 and R4.55 from B.1 and B.2. Part of the difference can be attributed to contact

TABLE 1 Comparison of Test and Simulated Thermal Resistance

Specimen	Test R-Value, h·ft²·°F/Btu (m²·°C/W)	Simulated R-Value (RSI) h·ft²·°F/Btu (m²·°C/W) No Contact Resistance	Simulated R-Value (RSI) h·ft²·°F/Btu (m²·°C/W) Contact Resistance	% Difference from Test No Contact Resistance	% Difference from Test Contact Resistance
A.1	7.81 (1.38)	7.01 (1.23)	7.68 (1.35)	−10.2	−1.7
A.2	12.52 (2.21)	11.72 (2.06)	12.18 (2.15)	−6.3	−2.7
A.3	13.85 (2.44)	13.42 (2.36)	13.87 (2.44)	−3.0	+0.1
B.1	9.56 (1.68)	8.84 (1.56)	9.74 (1.72)	−7.4	+1.9
B.2	14.11 (2.49)	13.92 (2.45)	14.57 (2.57)	−1.3	+3.3
B.3	15.72 (2.77)	15.72 (2.77)	16.35 (2.88)	0	+4.0

resistance between the insulating sheathing and the gypsum wall board but certainly not the entire amount. Most of the variation is due to the reduction in the effect of the thermal bridging. The same effect is seen between A.1 and A.3 (or B.1 and B.3), where 1.5 in. of expanded polystyrene (or R5.4) is added, and the results show a difference of R6.0 – R6.2.

The comparison between test and simulated results shows a larger variation in the base-case specimens (A.1 and B.1) than in the insulated-sheathing specimens. In fact, the error becomes smaller as the overall thermal resistance increases, both as a percentage of the thermal resistance (which would be expected) and in absolute terms. The difference is probably due to contact resistance between the metal studs and the wall board. The simulation did not include any such resistance (as indicated in the columns labeled "No Contact Resistance"), which was probably present in the physical test specimen.

The *ASHRAE Handbook—Fundamentals* (ASHRAE 1993a) suggests that contact resistance can be important where highly conductive materials are used and it varies from 0.06 to 0.6 h·ft²·°F/Btu (0.01 to 0.1 m²·°C/W); a value of 0.2 h·ft²·°F/Btu (0.035 m²·°C/W) has been suggested (Shirtliffe 1995). The results of the simulation including this suggested value of contact resistance between the studs and the wall board are shown in Table 1 (in the columns labeled "Contact Resistance"). This changes the average difference between simulation and test from −4.7% to +0.8%. A similar study of steel framing systems (Barbour et al. 1994) showed simulation to be 3.7% lower than test (again, probably due to the presence of contact resistance in the test specimens).

These results show that computer simulation can achieve a good approximation of test results; the accuracy of the test facility is estimated at ±5%, and the simulation results are of that order of magnitude, especially when the effect of contact resistance is included. This is also seen with a comparison of surface temperatures from the simulation and physical test results. An array of five type-T thermocouples was placed at one-inch intervals, starting from the centerline of a stud. Figures 1 through 3 compare the measured temperatures with predicted warm-side surface temperatures from the computer simulation. The measured temperatures are, on average, 0.7°F (0.4°C) colder than the computer-predicted results, which is within the thermocouple accuracy of ±0.9°F (0.5°C).

Figures 1 through 3 also show the effects of added insulation on the warm-side surface temperature. Specimen B.1 (the 2-by-6 frame wall) is 2°F to 2.5°F (1°C to 1.4°C) warmer than specimen A.1 (the 2-by-4 frame wall); the specimens in Figures 2 and 3 (with insulated sheathing) are 1°F to 4.5°F (0.5°C to 2.5°C) warmer than the specimens in Figure 1, which have no insulated sheathing. The greatest effect of temperature increase (and therefore the greatest increase in thermal resistance) with the addition of insulated sheathing occurs directly over the stud, in the area of the thermal bridge. This reinforces the observation that adding insulated sheathing provides a greater increase in the effective thermal resistance than would be computed by adding the thermal resistance of the sheathing itself. Comparing Figures 1 and 2, we see that the surface temperature far from the stud increases by about 1°F (0.5°C) with the addition of one inch of expanded polystyrene, but the surface temperature at the stud is increased by 2.5°F to 3°F (1.4°C to 1.7°C). Therefore, it appears that the insulated sheathing reduces the effect of thermal bridging in addition to providing increased thermal resistance.

The series A assemblies were resimulated with ASHRAE winter design conditions (70°F [21°C], interior; 0°F and 15-mph wind [−18 °C and 6.7 m/s wind] on the exterior), as shown in Figure 4. Assembly A.1, with no insulated sheathing, shows a temperature depression of 12.3°F (6.8°C) due to the thermal bridge, which is reduced to 7.1°F (3.9°C) with the addition of 1 in. (25 mm) of EPS and 6.2°F (3.4°C) with 1.5 in. (38 mm) of EPS. Psychrometric evaluation implies that adding 1 in. (25 mm) of EPS raises the maximum room-side relative humidity from 52% to 71% (or to 76% for 1.5 in. [38 mm] of EPS) before moisture condenses on the wall surface at the thermal bridge.

COMPARISON OF RESULTS: TEST AND CALCULATION

The results of the various calculation methods are shown in Figure 5, relative to the test results for all six

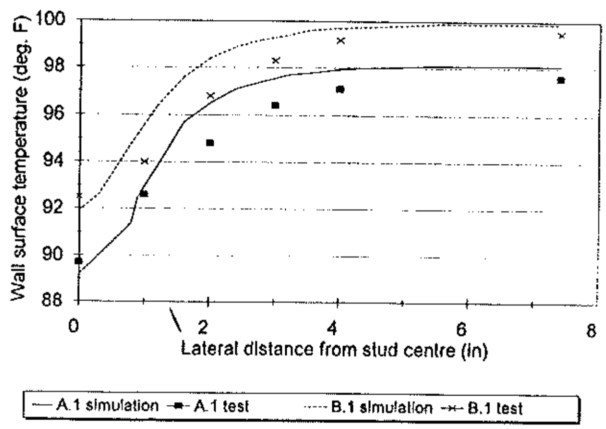

Figure 1 Warm-side surface temperatures (no insulated sheathing).

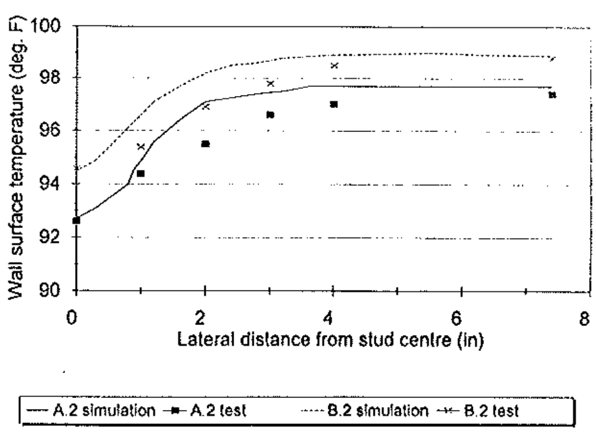

Figure 2 Warm-side surface temperatures (nom. 1 in. insulated sheathing).

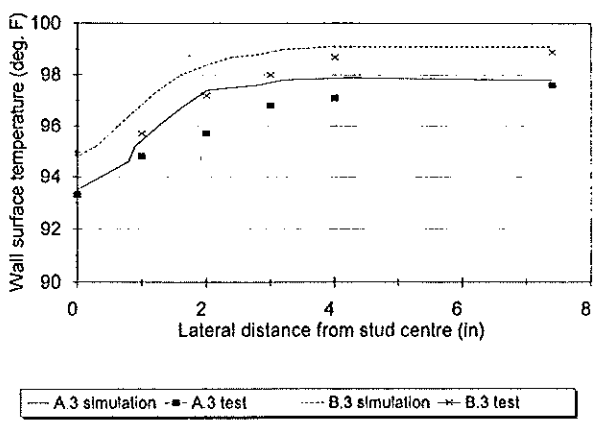

Figure 3 Warm-side surface temperatures (nom. 1.5 in. insulated sheathing).

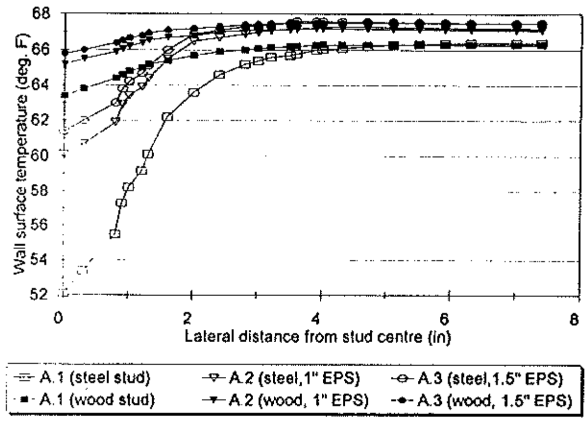

Figure 4a Warm-side surface temperatures (nom. 2×4 steel-stud walls).

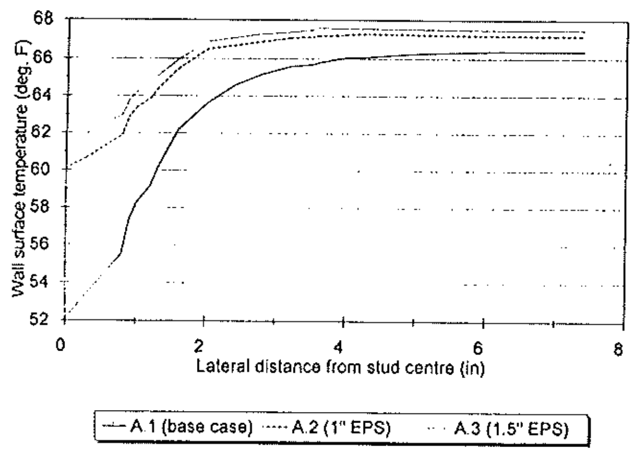

Figure 4b Warm-side surface temperatures (nom. 2×4 frame walls).

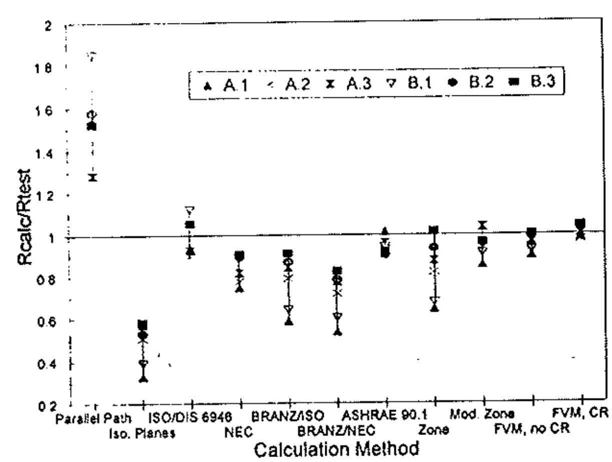

Figure 5 Comparison of calculation and test results.

assemblies. As expected, the parallel-path and isothermal-planes methods provide upper and lower limits, respectively, for the test result. The parallel-path method is least accurate for the base cases (A.1 and B.1), where the thermal bridging effect occurs over the largest area. The addition of insulated sheathing reduces the effective area of the thermal bridge, which makes the parallel-path assumption more representative of the actual heat flow. At the same time, the insulated sheathing is also more isothermal because of its low conductivity, so the isothermal-planes method also becomes more accurate as additional sheathing insulation is added. In general, then, these assemblies are a combination of the parallel-path and isothermal-planes cases, and the true result must reflect some combination of the two methods (as is suggested in *Fundamentals*).

For these assemblies, it appears that the ISO/DIS 6946-1 approach is more accurate than the NEC method, although the NEC method is more precise (and tends to provide more conservative results). In other words, the NEC results are more consistent from specimen to specimen but do not agree as closely with test results. The NEC results were determined using the NEC-recommended value of 430 Btu-in./(h·ft^2·°F), or 62.1 W/(m·K), for the thermal conductivity of the steel components. Using the measured conductivity of the steel, which was 481 to 495 Btu-in./(h·ft^2·°F), or 68.4 to 71.4 W/m·K, would result in a much less accurate result.

The simplifications introduced by the BRANZ method make the results less accurate and less precise. On the other hand, they err on the conservative side and are much easier to do as a hand calculation method. All of the calculational results are easily adapted to a spreadsheet calculation (except the actual computer simulation method, of course), so the simplifications in the BRANZ method are not an advantage unless the user does not have access to a computer spreadsheet program.

The method described in ANSI/ASHRAE 90.1 is quite accurate and precise for these assemblies, as should be expected (the method was empirically derived from physical tests of steel-framed wall assemblies). It is also extremely simple to use, as it is a table of values for various stud spacings and thicknesses and various insulation levels. It is not, of course, applicable to any thermal bridging situation other than the specific steel-stud walls that are covered by the table in ANSI/ASHRAE 90.1. Moreover, the tabulated results do not account for the effects of framing around windows, doors, and other construction features, so the method may slightly overpredict the thermal resistance of a typical steel-framed wall. In general, however, the tabular approach provides a good estimate of wall performance.

The zone method is intended for use with simple two-dimensional analyses, and application to a three-dimensional problem requires a great deal of care in assigning thermal resistances to the appropriate zones. As shown in Figure 5, however, it does not provide any additional accuracy or precision over the ISO or NEC methods that it is intended to replace. The adjustments suggested by the modified zone method improve the precision somewhat, as shown in Figure 5, but it is still not as accurate as the ISO method for the specimens evaluated in this study (although the modified zone method requires less effort than the ISO method).

Computer simulation appears to have the greatest precision and accuracy of all methods evaluated. Although this approach can model many situations other than steel-framed walls and is quite accurate, it does require a higher level of effort and some training (it also requires use of a personal computer).

None of the calculational methods shown in Figure 5 includes contact resistance except the second computer model (labeled "FVM, CR") and the ANSI/ASHRAE 90.1 method (as it is based on empirical results). The zone and modified zone methods do not lend themselves to including the effect of contact resistance, but it would be relatively simple to include in the parallel-path and isothermal-planes methods. Based on the computer simulation results, accounting for contact resistance between the metal studs and the wallboard increases the overall thermal resistance of the specimens by 3% to 9%, with a similar increase in accuracy relative to the test results. This is probably not a large enough improvement to justify the additional calculational effort, especially where insulated sheathing is used (in which case contact resistance is less important).

CONCLUSIONS

Adding insulated sheathing to a metal-framed wall produces a greater increase in the overall thermal resistance than the additional R-value of the sheathing itself. The difference is probably due to the reduction in the effective area of the thermal bridge.

Insulated sheathing also reduces the warm-side surface temperature depression caused by thermal bridging. There appears to be a law of diminishing returns at work in that adding more insulated sheathing does not produce an equivalent reduction in the thermal bridging effect. Therefore, it should not be difficult to determine a cost-optimal level of insulated sheathing for a given application.

Neither the parallel-path nor the isothermal-planes method should be used exclusive of the other. These are, and were always intended to be, complementary methods that provide the upper and lower limits of the actual result.

Based on the accuracy and precision of the various methods shown in Figure 5, a hierarchy of preferred methods can be established.

1. Where the time and facilities exist, a physical test is the preferred method, as long as the test specimen

provides an accurate representation of the wall to be analyzed.

2. If a physical test is not possible, computer simulation provides the next most accurate results, assuming the equipment is available and the user is proficient in the operation of the computer program. Computer simulation can also provide information on surface temperature distribution, which may be important for evaluating ghosting and condensation-related problems. The results should be within ±5% of the test result, if contact resistance between the studs and the sheathing is included.
3. Specifically for steel-framed walls, the tabular data in ANSI/ASHRAE 90.1 give accurate results, assuming relatively little additional framing for windows, doors, etc. The results should be within 10% of a physical test result and slightly conservative.
4. In general cases where neither physical testing nor computer simulation is available, the method described in ISO/DIS 6946-1 (i.e., the arithmetic mean of the parallel-path and isothermal-planes methods) should be used. This source also contains a good description of the calculations used in the parallel-path and isothermal-planes methods. The results should be within ±10% of test.
5. The modified zone method provides a reasonably accurate result and is easily adapted to a spreadsheet application. A recent source (Kosny and Christian 1995) provides a good description of this procedure.

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