Thermal Resistance Measurements of Two-and Three-D Thermal Bridges Using an ASTM C177-based Apparatus

John Straube, PhD, P.Eng. **Joe Simonji, M.A.Sc.** **Chris Schumacher, M.A.Sc.**
Member ASHRAE

ABSTRACT

Thermal bridges, localized areas of building enclosures that allow higher heat flow, are recognized as an important source of heat loss/gain. Computer models are now widely used to quantify the impact of thermal bridges. However, few full-scale measurements of heat flow through thermal bridges have been undertaken to confirm and validate computer models. To allow for the measurement of specimens with complex 2D and 3D heat flows (i.e. thermal bridges) a special large-scale guarded hot plate apparatus based on ASTM C177 was designed and constructed. This apparatus is capable of accepting specimens measuring 4 ft (1219mm) by 4 ft (1219mm) and up to 16 inches (406mm) thick. This paper describes the apparatus, its design, and the results of commissioning tests.

Computer modelling was used to estimate heat flow errors describing the characteristics and limitations of the apparatus. Once constructed, the apparatus was validated against a heat flow meter calibrated using a NIST-traceable calibration specimen. The capability of the guarded hot plate to measure layered specimens with thermal bridges was demonstrated through the measurement of three specimens resembling typical wall assemblies. Measurements from the apparatus were compared against results from computer models and good agreement was found.

INTRODUCTION

When heat flows at a much higher rate through one part of an assembly than through another part, the term *thermal bridge* is used to reflect the fact that the heat has bridged over or around the thermal insulation. Thermal bridges are inevitable in most enclosures and due to increasing concerns about energy consumption codes and standards increasingly require designers to account for them when judging compliance.

Thermal bridges become important when:

- they lead to cold spots within an assembly that might impact performance (e.g., surface condensation, durability) or result in comfort problems; or
- they are either large enough or intense enough (highly conductive) to meaningfully increase the total heat loss through the enclosure.

In practice, thermal bridging can routinely reduce the thermal resistance of some enclosure systems (e.g., steel stud framing with batt insulation) by 30-50%, sometimes even more.

The International Energy Conservation Code and ASHRAE Standard 90.1 provide tables of common enclosure

John Straube an Associate Professor in the Faculty of Engineering, University of Waterloo, Waterloo, Canada, supervised Joe Simonji who took the primary role of conducting the work. He is now a building science engineer at RDH Building Science, Vancouver, Canada. Chris Schumacher, a Senior Specialist with RDH Building Science Labs Waterloo, Canada, provided technical review, instrumentation expertise, and advice.

assemblies with continuous insulation as one compliance path intended to limit thermal bridging. Calculations of overall heat transfer coefficients and full-scale ASTM C1363 hot-box testing are alternate paths for more complex and non-tabulated assemblies. Estimates of the actual overall heat transfer coefficients of each enclosure assembly in a building are also required if whole building energy modeling is used. For some European jurisdictions and Passive House projects linear and point transmittance values are required (e.g. ISO 10211 and ISO 14683).

Although the overall heat transfer coefficient of some enclosure systems can be calculated using simple one-dimensional assumptions, two-dimensional details such as solid slab balcony penetrations, solid parapets, and framing systems will often require at least two-dimensional calculations, such as finite-element computer calculations or even parallel path and isothermal planes methods. Some thermal bridges must inevitably be modeled in three-dimensions: cladding attachment, structural beam and column penetrations, and service piping and ductwork are all inherently three-dimensional. There are many three-dimensional finite volume computer programs available to aid thermal analysis which are increasingly being deployed to calculate the thermal impact of 3D details.

Despite the increasing prevalence of three-dimensional calculations to support design and code compliance, few physical measurements [Martin 2012, Prata 2017] of the thermal performance of specific building details have been tested to validate the computer models. Phenomena such as contact resistance, convection, and radiation can cause appreciable errors in some of these models and require judgement and experience to properly incorporate into a model. The lack of physical measurements limits the pool of information which could help validate such choices.

The need that the research outlined in this paper is intended to address is the development of a test apparatus and methodology able to physically measure, with reasonable accuracy, a range of building-scale thermal bridges and thereby allow for the verification and validation of computer models.

MEASURING THERMAL PERFORMANCE

Researchers may use a number of techniques and a range of apparatuses to measure the thermal performance of building enclosures and materials. The most common apparatus used to measure the thermal conductivity of materials is a heat flow meter: ASTM C518 [ASTM 2017] compliant equipment with specimen dimensions of 300 to 600 mm square are the most common in North America. Full-scale enclosure assembly performance, with a specimen size of about 1.8 x 2.4 m or larger, is routinely measured by a guarded hot box apparatus such as the ASTM C1363 [ASTM 2011]. A guarded hot plate, following ASTM C177 [ASTM 2013] represents a useful middle ground between these two apparatuses.

Guarded hot plates allow for the testing of specimens that are too thick (over 8" or 200 mm) or large (over 600 mm by 600 mm) for a heat flow meter but provide better accuracy and lower cost than a guarded hot box. A guarded hot plate also has the advantage that it is an absolute method of measuring the thermal conductivity of specimens unlike heat flow meters which are calibrated to a reference standard. As such they have a long history of being used to set national thermal conductivity standards [Zarr 2001]. An ideal apparatus should also allow for the measurement of specimens oriented in a horizontal, sloped, or vertical orientation with heat flow in the same direction and of the same magnitude as expected in a building application. This capability is critical for testing multi-layer glazing systems and highly air permeable penetrations (e.g., hollow tubes) which may allow natural convection.

The objective of the work described below was to design, construct, commission, and validate a rotatable guarded hot plate apparatus for measuring the thermal conductivity of thick insulation specimens and complex thermal bridge assemblies.

This paper briefly describes the apparatus developed and presents early results used to validate the accuracy of the measurements.

Apparatus Description

The single-sided guarded hot plate apparatus was developed to be an ASTM C177-13 compliant. The basic operating methodology can be found in the Standard and a series of ASTM Symposia (ASTM STP 544 1974, ASTM

STP 660 1983 ASTM STP 879 1985, ASTM STP 1116 1991, ASTM STP 1320 1997, ASTM STP 1426 2002) and will not be reviewed here.

A specimen size of 1.22 m x 1.22 m with a maximum thickness of about 400 mm was selected as the best compromise: a larger size would increase the effort of constructing and handling specimens while smaller sizes limit the possibilities to allow for a central full-scale thermal bridge to be measured accurately with reasonable edge losses. A meter area of about 405 mm square (16 in) was selected to ensure a size representative of most thermal bridges.

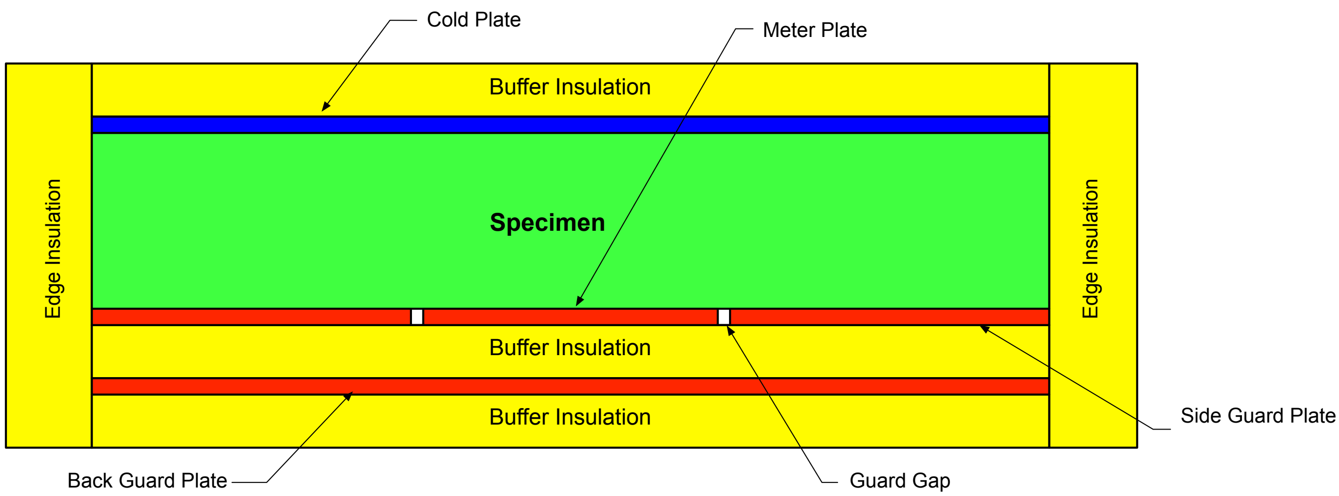

Figure 1: Schematic cross-section of apparatus.

Control of the test temperatures across the specimen close to actual service temperatures can be important for accurate and meaningful results [Schumacher & Straube 2017] because of temperature-dependent radiation, convection, and gas-conductivity impacts. The slope of the specimen and direction of heat flow can play an important role whenever natural convection may play a role [Lecompte 1990]. Hence, it was decided both to allow the rotation of the entire apparatus and to control the temperatures of both the hot and cold side over a wide range. The plates are returned to a horizontal position during specimen installation and removal to make

The hot plate and cold plate were comprised of 3 mm (1/8 in) and 6mm (1/4 in) thick aluminum plates respectively, both 1219 x 1219 mm in size. The hot side was the metered side and contained a separate square 404.8 mm (15 15/16 inches) meter plate from which the actual heat flow through the specimen was measured. The temperature of the entire hot plate (meter and side guards) was maintained by custom nickel-chrome electric resistance heaters. The heater was sized to cover the range of expected specimen conductances (0.1 to 2.0 W/m^2K). The maximum design temperature was limited to 65 °C to prevent damage to polymeric insulators and insulations, but this is close to the highest temperature experienced by most enclosure assemblies.

The cold side temperature was maintained by pumping a heat transfer fluid through 3/8 in (9.5 mm) diameter copper tubing mechanical pressed to the plate and bonded with thermally conductive epoxy. By connecting the fluid to a circulating bath chiller, very tight (+/-0.2 °C) temperature control over a range of -40°C to over 60°C was achieved. This is close to the lowest temperature likely to be experienced by most enclosure assemblies. However, cold temperature operation below the dewpoint of the laboratory air requires care to avoid condensation: the cold plate and back guard plate are insulated with insulation that has a vapor impermeable and airtight aluminum foil facer which is sealed in an airtight manner to the sides to limit condensation.

A Campbell Scientific measurement and control logger embedded control logic and collect the signals from the 45 thermistors and voltage drop across power sense resistors. Control algorithms use the spatial average of numerous sensors to improve accuracy.

The hot-plate temperature was controlled using a PID algorithm and time-proportional controlled solid-state power relays (i.e., Pulse Width Modulation). Power was measured using an array of precision resistors.

Edge Insulation

A significant amount of calculations and simulations were undertaken to understand the impact of edge insulation on accuracy. Edge insulation is an important part of the guarded hot plate as it helps guard the entire specimen and plate stack from ambient temperatures. The mean temperature of the test is also important (Bode, 1985, Dubois & Lebeau, 2013, Eguchi 1985, Peavy & Rennex 1986), as it defines the difference between the test specimen and the laboratory temperature. Given the desire to test materials and specimen at a wide range of hot and cold plate temperatures (to mimic in-service temperatures) the impact of mean temperature on accuracy is also important. Using Therm 7.3, a series of simulations were conducted with a 406 mm (16 in) thick specimen, a temperature difference of 40°C, and a laboratory temperature of 20°C.

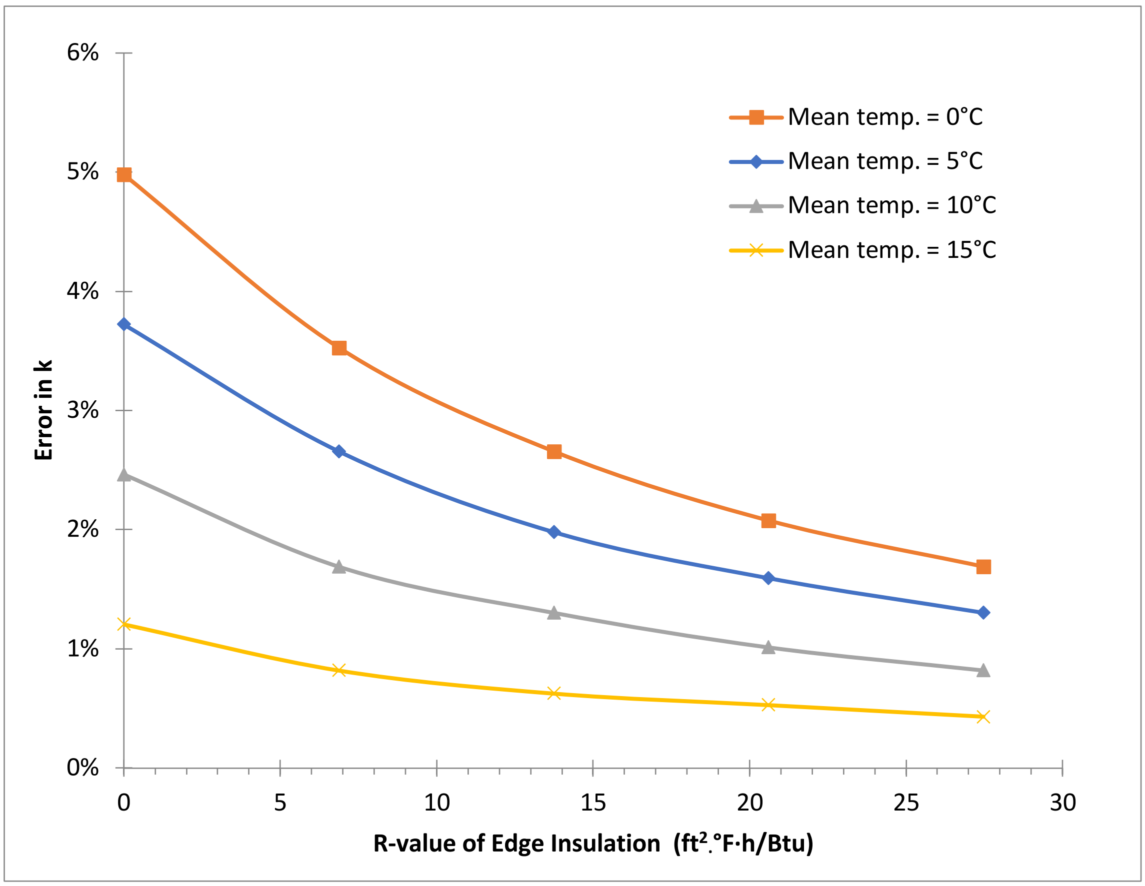

Figure 1 Predicted impact of mean temperature and edge insulation on accuracy.

The results (Figure 1) show that thick insulation specimen with even R-20 (RSI3.50) edge insulation will have over 2% error when the mean temperature is as low as 5°C. An edge insulation thickness of 3 in (76 mm) with a ½ in plywood casing was chosen with an R-value of about R-12 (RSI2.11) with the understanding that thinner insulation specimen will have much lower errors. When accuracy is needed and temperature effects are small, the testing should be conducted at a mean temperature of close to the ambient laboratory temperature. This may involve placing the entire apparatus in a conditioned chamber held at the desired mean temperature.

Material Validation Measurements

As part of the commissioning process insulation specimen of three thicknesses were measured and compared to results in a calibrated heat flow meter. A 3 in (76mm), 6 in (162mm), and 9 in (229mm) thick specimen comprised of layers of 3 in (76mm) thick nominal 64 kg/m[3] (4 pounds / cubic foot) density stonewool were tested in the new apparatus at different temperature conditions and compared to the results of an ASTM C518 heat flow meter calibrated to a NIST specimen (and hence presumed to be accurate to better than about 2%). The 6 in (152mm) and 9 in (229mm) thick specimens were created by stacking two and three layers, respectively, on top of one another. All of the specimens were created from the same three pieces of the stonewool insulation measuring 4 ft(1219mm) square. As these specimens are too large to test in the heat flow meter apparatus (HFM), 12" by 12" (305mm by 305mm) sections were cut from the center of each piece and tested individually in the heat flow meter. The thermal conductivity was recorded in the HFM for a range of mean temperatures and used to produce a temperature-dependent thermal conductivity relationship. The conductivity of the specimen tested were then adjusted to provide a result at the same mean temperature.

Table 1. Guarded Hot-plate versus Heat Flow Meter Comparison.

Test No.	Cold Plate Temp. (°C)	Hot Plate Temp. (°C)	Meter Plate Power (W)	Conductivity from HFM (W/m·K)	Measured C177 (W/m·K)	Difference	% Difference
3A	-14.38	23.32	3.0071	0.03695	0.03658	-0.00036	-0.98%
3B	10.02	37.820	2.3549	0.03889	0.03886	-0.00004	-0.09%
3C	29.43	57.220	2.4615	0.04083	0.04063	-0.00021	-0.50%
6A	9.980	37.820	1.1994	0.03904	0.03978	0.00074	1.89%
6B	29.431	57.220	1.2648	0.04099	0.04202	0.00103	2.52%
9A	9.937	37.820	0.80717	0.03903	0.03971	0.00068	1.75%
9B	29.444	57.220	0.85765	0.04097	0.04236	0.00139	3.39%

The results in Table 1 (where the test number prefix is thickness in inches) suggest good agreement for the 3 in (76 mm) specimen and reasonable agreement for the thicker specimen. It is expected that error at mean temperatures much different than the lab temperature would increase (see above), but the size of the increase was larger than expected. Subsequent assessment suggests that the thickness measurement in the large-scale format plays an important role, as it is difficult to accurately measure the specimen thickness in the middle of the assembled specimen over the meter plate and to ensure proper contact of the layers over the entire 1.44 m^2 (15.5 ft^2) specimen area.

MEASUREMENT OF THERMAL BRIDGES

Guarded hot plates are not typically designed to test specimens that are non-homogenous such as specimens containing thermal bridges. Non-homogenous specimens mean non-uniform heat flow which is traditionally avoided in guarded hot plate apparatuses. Non-uniform heat flow means that specimen temperatures at the surface of the plates are not uniform causing the task of accurate temperature measurement to be difficult (Larson 1985). Ideally, thermistors would be placed at the locations of average hot or cold side temperature, but this is very difficult to implement due to the complexity of three-dimensional thermal bridges.

In service, the surface temperature at a thermal bridge will vary from the adjoining assembly. Figure 2 schematically plots the temperature for the case when it is colder on the exterior. This surface temperature difference would be eliminated by a perfectly functioning C177 device, as the design attempts to ensure that the entire plate experiences the same temperature via the use of thick highly conductive aluminum plates and closely spaced and regulated temperature heater wires and chilling tubes. When calculating heat transfer it is common to apply a heat transfer coefficient to the interior and exterior of the entire enclosure surface to capture the resistance to heat flow from the air and room/outdoors to the adjoining enclosure by convection and radiation. When modeling thermal bridges, the heat transfer coefficient is often assumed to be constant and equal to standard values [ASHRAE 2017, ISO 2017] although larger and more significant thermal bridges will have different, and often slightly larger coefficients (because radiation and convection transfer does not increase linearly with temperature difference).

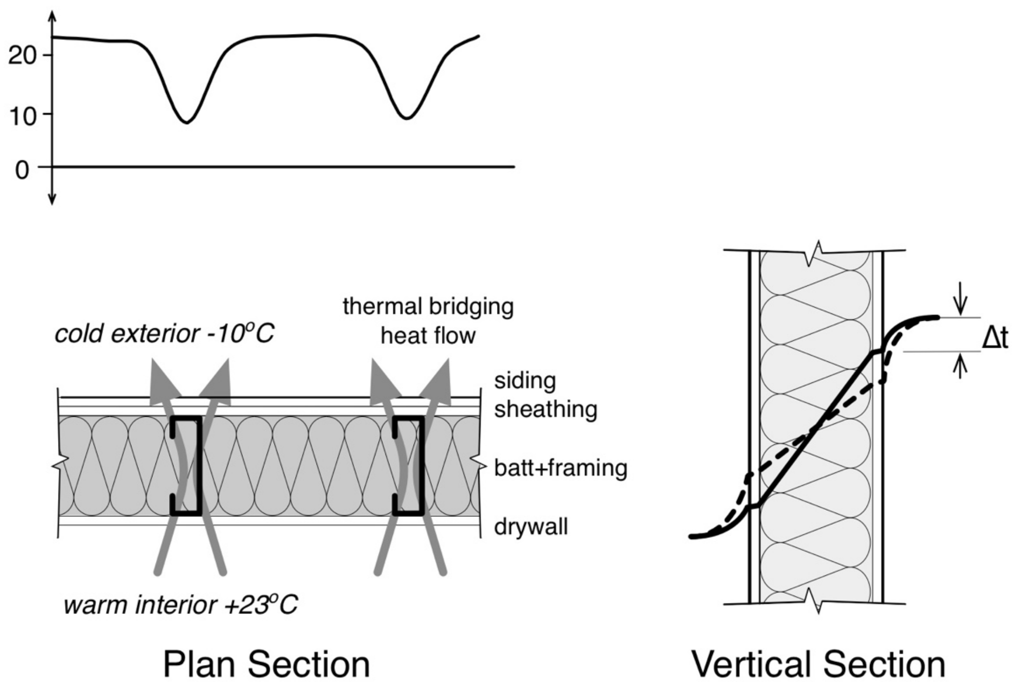

Figure 2: Example surface temperature variation at thermal bridge in plan and section (Straube & Burnett 2005).

To physically represent the airfilm resistance in the C177 apparatus, a thin layer of closed-cell polyethylene foam sheet was used. By measuring a stack of specimen using an ASTM C518 heat flow meter (HFM) apparatus it was found that two layers of commercially-available 3/32 in (2.4mm) closed-cell polyethylene foam had an RSI-value of 0.10 m^2K/W (R-0.58 hr·ft^2·°F/Btu). Hence, two layers have a resistance close to the interior air film resistances in service, and one layer of foam was used to represent the exterior film. Modelling and measurements showed that this level of resistance will approximate the realistic temperature drop experienced at the interior of thermal bridges while also maintaining uniform temperatures of the hot and cold plates. A surface-to-surface U-value can be calculated by subtracting the thermal resistance of the foam, and thicker layers of foam can be added to test lower surface heat transfer coefficients.

Another issue to be resolved in two-dimensional (linear) thermal bridges is the size of the thermal bridge in the test specimen relative to the size of the meter plate. One researcher suggests that the thermal bridge specimen should equal in size to the meter area with the guard sections composed solely of insulation of equivalent thickness (Salmon, 2001). This approach does reduce edge losses but does not provide a useful measurement of a thermal bridge since the heat flow at the boundaries of the meter area are not consistent with the heat flow in the middle of the meter area. A better solution is to extend the thermal bridges outside of the meter area to ensure heat flow conditions are as uniform possible within the meter area but not too far that edge loss errors become a concern. Three-dimensional (point) thermal bridges can be simply centered on the meter plate (provided of course that the bridge is smaller).

Thermal Bridge Test Validation

An initial test of the apparatus was devised to confirm the measurement ability of the apparatus (Figure 3). Three variations were tested. The test specimens replicate a wall section with gypsum board on the interior (k=0.1465 W/m·K), plywood on the exterior (k=0.0874 W/m·K), and insulation in the stud cavity. Three specimens were tested: an assembly with a wood stud (k=0.1351 W/m·K), an assembly with a steel Z-girt (assumed k=50 W/m·K), and an assembly with no thermal bridge penetrating the main insulating layer. The same materials were used in each test with the exception of the steel or wood.

The gypsum board and plywood measured 32 in (813mm) square and the wood stud was 32 in (813mm) long. This created a 32 in (813mm) square specimen surrounded with 8 in (406mm) of guard insulation. The wood stud was cut down to 3 in x 1.5 in (76mm x 38mm) so that it could be placed within the same insulation specimen from the validation testing. The perimeter used stonewool insulation as a guard.

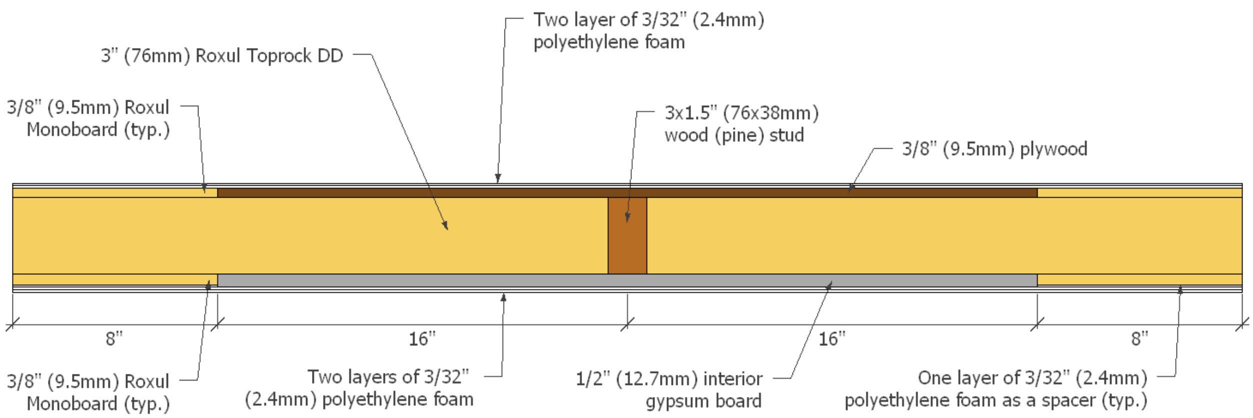

Figure 3: Linear thermal bridge specimen, showing wood stud.

The steel Z-girt specimen was identical to the wood stud specimen but incorporated a 20-gauge Z-girt (3 in or 76mm) web and 1.5 in (38mm) flanges in place of the wood stud. A steel Z-girt was used instead of a steel stud because it is easier to implement without the complexity of air voids caused by C-shapes.

For comparison of the measured results to modelling the three tests specimens were modelled in THERM 7.3 and their total thermal conductance was calculated.

To create a representative model, the materials in the specimens were measured in the heat flow meter to provide accurate values for the thermal conductivities for the materials in the models (listed above). The thermal conductivities of the materials are temperature dependent and the thermal conductivity of each material was reported based on the average temperature it experienced during the guarded hot plate testing. The specimens used to measure the thermal conductivity of the foam, gypsum board, and plywood in the heat flow meter consisted of multiple layers of each material for better measurement. The wood stud was measured in the heat flow meter by gluing multiple studs together to form a block of wood.

The results from the guarded hot plate tests and the predicted thermal conductivities for the specimens from THERM 7.3 are presented in Table 2.

Table 2 – Thermal Bridge Testing Results Compared to Computer Models.

Specimen	Meter Plate Power (W)	Predicted U THERM(W/m²K)	Measured U (W/m²K)	Difference (%)
no thermal bridge	1.963	0.430	0.434	1.06
w/ wood stud	2.285	0.493	0.507	2.60
w/ steel Z-girt	2.894	0.657	0.639	-2.73

From Table 2, it is shown that good agreement is observed between the measured and modelled thermal conductance of this simple thermal bridge. The measured thermal conductance for the specimen without a thermal bridge was closest to the predicted value (within about 1%) which was anticipated as it has no thermal bridge. The measured conductance for the steel Z-girt specimen was less than predicted. This observation is also explicable as the steel Z-girt is more influenced by contact resistances than the wood stud and the presence of contact resistances against the steel Z-girt is expected to cause a small underestimation in the thermal conductivity.

Subsequent work has investigated numerous cladding attachments and point thermal bridges. One such project is reported in these proceedings [DiPlacido et al 2019]. Future projects will investigate thermal bridges with air gaps (e.g. tubes) that may result in natural convection influences.

CONCLUSION

The design and manufacture of an ASTM C177-compliant guarded hot plate apparatus has been described. The apparatus was intended to allow for the measurement of two- and three-dimensional thermal bridges as well as solid material specimens. Physical measurement of thermal bridges is important for validation of computer models (for which many assumptions must be made). Computer models and measurements defined the error that could be expected from the new apparatus due to mean temperature deviations from laboratory temperature and thick material specimens.

Measurements verified that the apparatus was capable of good accuracy when measuring previously characterized insulation specimens of 76 mm (3 in) to 229 mm (9 in) thickness.

A methodology was developed to test thermal bridges in the lab. An interior and exterior insulation layer is applied to the specimen to represent the surface film resistance and thereby allow for realistic temperature deviations at the surfaces of the thermal bridge. Two simple linear thermal bridges were tested and compared to two-dimensional models and showed excellent agreement.

Future work will investigate point thermal bridges, and those with air gaps that may result in natural convection influences.

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