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Calibration procedures for multidimensional heat transfer models based on on-site experimental data

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Abstract

An experimental and numerical approach to the characterization of thermal bridges is presented, based on on-site taken measurements. Commonly on-site applied numerical thermal assessments perform one-dimensional heat transfer analysis over planar elements such as façades. However, it is well known that within thermal bridges in a building one-dimensional heat transfer analysis cannot be applied.
A procedure is proposed, based on the creation of a numerical 2D thermal model which is calibrated against experimental data from several temperature and heat flux sensors which are located at specific points in the thermal bridge elements. Results of one particular implementation of this method are discussed.

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Keywords: "Thermal bridge; Calibration; Heat transfer; Multidimensional;2-D model; Experimentation;"

1. Introduction

Building energy consumption sums up to 40% of primary energy consumption in developed countries [1-4]. Aside from energy needs for appliances or Domestic Hot Water, a large amount of this energy is required for space heating and cooling, to meet occupants' comfort requirements, where the heat transfer through building envelopes is one of the main terms in the heat balance of buildings, and special attention is paid on them to ensure a proper thermal insulation level.

Building envelopes are commonly assessed through one-dimensional (1D) formulae [5, 6]. However, this approach is not valid for locations where junctions between architectural elements are located, requiring bi- or tri-dimensional (2D /3D) heat transfer assessments [7-11]. These locations are commonly identified as the most

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thermally-weak places in the building envelope, especially considering that building energy codes have forced a trend towards more insulated building envelopes, increasing the relative relevance of thermal bridges [12].

Among building envelope upgrade systems which allow for nearly complete avoidance of thermal bridges, External Thermal Insulation Systems (ETHICS) can be found. This paper presents the calibration procedure followed on thermal bridge elements present in a full scale study to assess the overall performance of such façade refurbishment solution.

Nomenclature

Q_{HVAC}	Thermal output of the HVAC system
Q_{1D}, $\sum_{1D} Q_{1D}$	1D heat transfer through building fabric. Aggregation of all 1D heat transfer terms.
Q_{2D}, $\sum_{2D} Q_{2D}$	Incremental heat transfer through the building fabric generate by the beam elements. Aggregation of all 2D heat transfer terms.
C	Uncertainty value which also comprises all the non-explicitly considered heat paths
$L_{Façade}$, L_{Slab}	Characteristic length of Façade and slabs in the FDM model

2. Process

The identification of 2D heat transfer through beam elements in façades was performed in a process which involved several steps, which are further detailed in the following pages.

- Definition of the mathematical integration framework for the assessment of the thermal bridges.
- Identification of suitable places for sensor placement.
- Experimental campaign.
- Construction and calibration of a 2D thermal Finite Difference Model (FDM).
- Integration of the calibrated models into the main room model.

3. Integration Frame

The present calibration procedure was performed as part of an experimental research project for the assessment of thermal improvement of building fabric through façade refurbishment. This research was conducted in the Kubik by tecnalia [13-14] test infrastructure, where two test-rooms in a vertical arrangement were conditioned for it. A west-oriented test façade was constructed in these rooms, where 3 beam elements were intentionally placed to generate thermal bridges, with materials and thicknesses commonly used in slab and beam elements in the Spanish building stock.

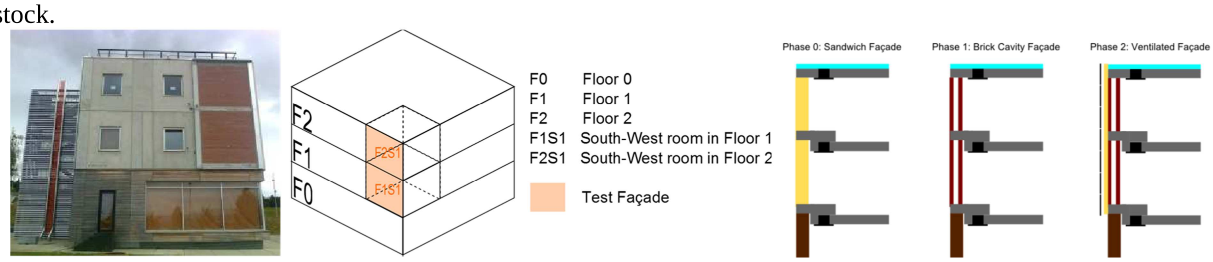

Fig. 1. Left: Brick façade test configuration in Kubik (2012), center: Scheme of test rooms, right: Configuration of each experimental phase

These 3 beams were located adjacent at 1st, 2nd and roof slab level in Kubik, and were kept constant in the experiment. 3 different envelopes were constructed along the experimental phases of the project (figure 1-right):

- Phase 0: Highly insulated sandwich façade
- Phase 1: Brick cavity façade
- Phase 2: Ventilated façade refurbishment of brick cavity façade

In all three phases, the effect of the building fabric within the thermal balance of the building was experimentally evaluated. The heat balance of each test-room was formulated as in equation 1.

$$0 = Q_{HVAC} + \sum_{1D} Q_{1D} + \sum_{2D} Q_{2D} + C \qquad (1)$$

1D heat flows were measured in clearly 1D heat flow zones and applied over the full corresponding surface (full test-cell height,…). The additional heat flow generated by 2D heat flows in beam elements was calculated as a linear heat transfer term, as illustrated in figure 2.

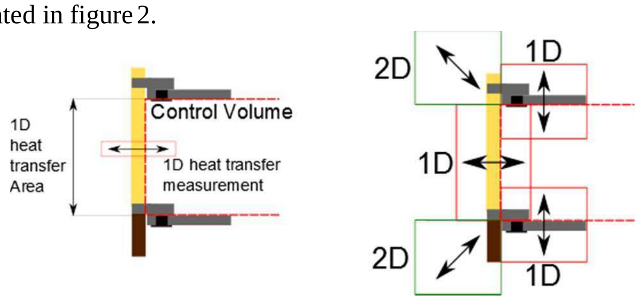

Fig. 2. Definition of Control volume, 1D heat transfer areas and additional 2D heat transfer

The calculation of the additional 2D heat transfer term was calculated through a calibrated 2D FDM model.

3D thermal bridges were not specifically accounted for, as attention was paid to minimizing 3D thermal bridging during the design phase. This was verified by a thermographic study in the test phase.

All non-explicitly measured or modeled phenomena were introduced in C, which accounted for issues such as minor 3D thermal bridges, infiltration, measurement uncertainty, etc.

4. Identification of suitable places for sensor placement

Steady-state FDM models were conducted in TRISCO [15] on the three wall-slab junction details for the definition of sensor locations. Due to weather exposure issues, no heat flux meter was installed outdoors, and temperature sensors were embedded in concrete, which in turn provided more stable temperature signals. Due to the stability of this solution, when possible, indoor temperature sensors were also embedded in concrete. Figure 3 shows the steady state result of one of the performed FDM analysis, and the selected locations for the installation of sensors.

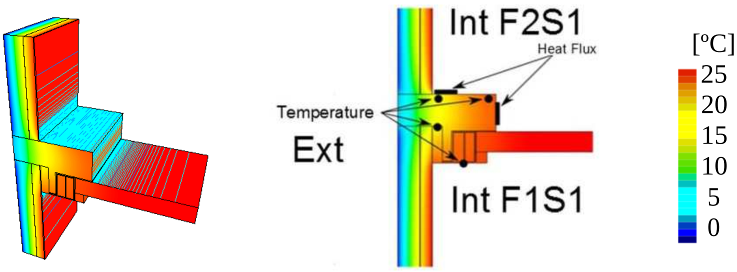

Fig. 3. Thermal bridge on Floor 2 level: Steady-state model of (left). Sensor location (right)

5. Experimental campaign

The experimentation on the assessment of thermal bridges was conducted in various phases. In this paper data from Phase 0 (highly insulated sandwich façade) was used. Phase 0 was divided in 4 periods; in which different internal boundary temperatures were imposed, as indicated in table 1.

Table 1. Experimental periods for the highly insulated sandwich element

period	Dates	Outdoor conditions (season, daily average temperature)	Indoor Temperature	
			F1S1 (Floor 1)	F2S1 (Floor 2) + other boundary areas in the building.
1	2012/I/19 – 2012/II/5	Winter, 3-12 ºC	30ºC	30ºC
2	2012/II/6 – 2012/II/16	Winter, 2-9 ºC	20ºC	20ºC
3	2012/II/17 – 2012/II/28	Winter, 4-9 ºC	20-30ºC	15-20ºC
4	2012/II/29 – 2012/III/11	Winter, 6-12 ºC	20ºC	30ºC

For constant boundary temperature set points, 1ºC dead band was used, while for variable conditions, free-floating was bounded between a maximum and minimum limits.

In this campaign 4-wire Pt100, 1/3 class B temperature sensors and 10cm X 10cm Phymeas Heat flux tiles were connected to a Beckhoff data acquisition system. The impact of these measurement devices was estimated at +-0.2ºC in temperature and +-5% in heat flux.

Data was acquired with a frequency of one minute and processed through 60-minute moving average processes. Data loss shorter than 10 minutes was corrected through linear interpolation, while longer gaps were not corrected.

6. FDM modeling and calibration

Dynamic 2D FDM modeling was conducted using VOLTRA [16], according to geometrical and discretization requirements in [7]. A parametric study was conducted in this model, where thermal properties of materials and heat transfer coefficients were varied within pre-defined ranges. These ranges were based on reference data from [6, 17], and the following parameters were varied within the optimization:

- Surface heat transfer coefficients, h [W/m2K]
- Thermal capacity (Specific Heat * Density) of materials $c_p * \rho$ [kJ/m3K]
- Thermal conductivity of materials λ [W/mK]

In the calibration process, the main source of inaccuracy was found to be related to heat transfer coefficients, while only minor tuning was required to material properties.

The calibration of internal heat transfer coefficients required a precise discretization of the internal surfaces, resulting in different heat transfer coefficients for upwards and downwards heat flows, and reduced values for corner areas. Furthermore, highly unsteady conditions in period 3 due to oscillations in the HVAC controller made it unsuitable for calibration. This was due to variations in the vertical convection direction and on/off cycles in the fan.

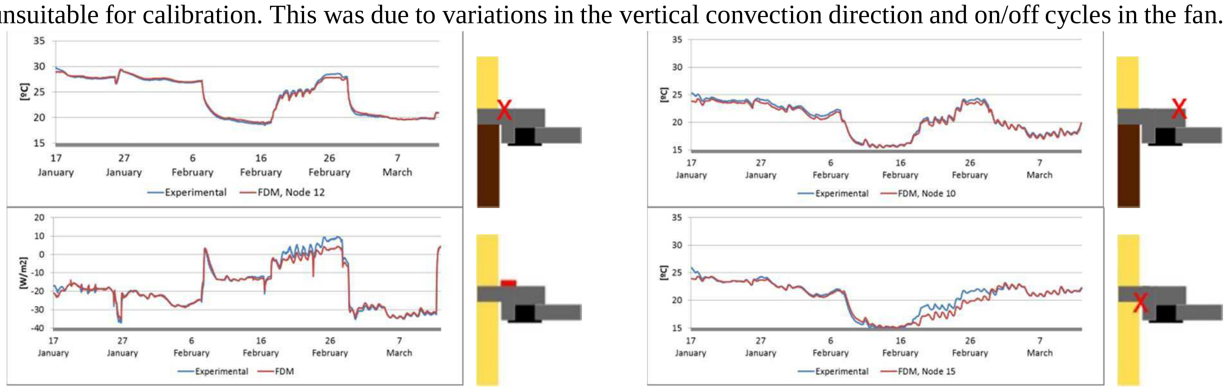

Fig. 4. Comparison between calibrated finite difference model and experimental data.

Figure 4 shows the outcome of the calibrated model when compared to experimental data, for specific locations. In fig 4 above, the temperature of the upper side of the concrete beam is shown, for two locations. In fig 4-bottom-left, the surface heat flux on the upper side of the concrete is shown, while in fig 4 bottom-right, the temperature of the inner side of the concrete beam is shown. A detailed definition of the calibration process can be found in [18].

Although a detailed error analysis was not carried out, the estimated measurement error (Temperature:+-0.2ºC, Heat flux: +- 5% of measured value) is considered to be within reasonable bounds as, along the experiments, temperature signals varied in a much greater magnitude (temperature: 7 - 12ºC, heat flux: -10 - 100%) than the measurement error. In relation to heat flux measurements, a high variation in heat flux level occurred with even reversed heat flux, while the models followed the shape and magnitude, not showing relevant deviation which might have been attributed to measurement equipment.

As it can be seen in figure 4, the only model-experimentation divergence is found in period 3 (17^{th} to 28^{th} February), where the model proved to be inaccurate under heavily oscillating indoor boundary conditions.

It was concluded that material testing and precise construction of architectural details allows for a good control in heat transfer in solid materials, while convective processes need to be specifically verified prior to the estimation of the thermal behavior of a thermal bridge.

7. Integration of the calibrated models into the main room model

The calibrated models were defined to output the overall energy flow in the model. 1D heat transfer from façade and slab elements was obtained from the boundaries of the FDM, were 1D behavior was verified. The "additional 2D heat transfer" term was calculated according to equations (2,3).

$$Q_{2D} = Q_{Junction} - Q_{1D} \tag{2}$$

$$Q_{1D} = Q_{1D\,,\,Façade} * L_{Façade} - Q_{1D\,,\,Slab} * L_{Slab} \tag{3}$$

All thermal models were constructed as 2-dimensional models, and the formulation was defined to refer heat flows per length of the thermal bridge element. Dimensions of architectural elements were taken from the geometry modeled in FDMs. All this process performed dynamically for each hourly time step.

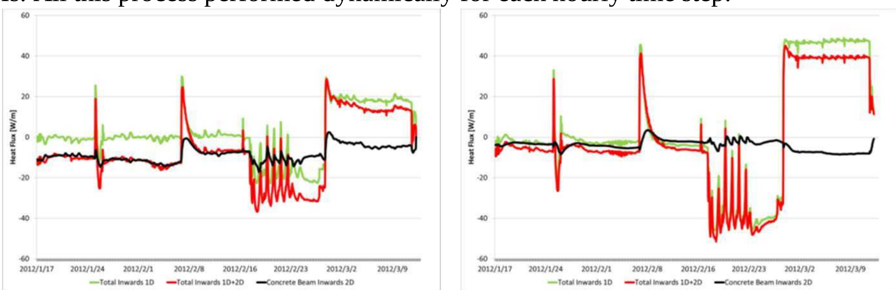

Fig. 5. Hourly heat flows towards F1S1 zone in the modeled architectural detail. Concrete beams at floor levels 1 (left) and 2 (right)

8. Summary and Conclusions

In this paper, a procedure for the calibration of dynamic thermal bridge models has been presented. This procedure has been applied on data from a full scale outdoor exposure test, where dynamic 2D models for several beam elements have been calibrated against experimental data.

The thermal flow in these elements was found clearly bi-dimensional, which justified the need of such analysis methods. Output of the calibrated models provided the instantaneous heat flux through thermal bridges, which allowed accounting for it in the heat balance calculation of several rooms.

The calibration of material properties in the models required minor tuning of thermal conductivity and capacities, resulting in a relatively straightforward process. However, output of the models was found to be very sensitive to surface heat transfer coefficients. The geometric description was considered exact as craftworks were supervised to avoid uncertainties of this kind. The mentioned sensitivity to surface heat transfer was mainly observed in heat flux signals, while temperature signals did not divert significantly with heat transfer coefficients similar to the finally calibrated ones.

Within full scale testing of thermal performance of building elements, it is common that areas with clearly non one-dimensional behavior appear. In most of present test environments, the trend is to minimize the influence of these elements in the test environment [19], avoid measurements in the area of influence of thermal bridges [20], and/or perform calorimetric tests in which the overall performance [19, 21] of building envelopes is obtained. However, in cases such as the one exposed in this work, where thermal bridges are a substantial part of the research, and the exposed procedure, or similar approaches are highly useful.

References

[1] U.S. Department of Energy (DOE), 2008 Buildings Energy Data Book, 2008.
[2] L. Pérez-Lombard, et al., A review on buildings energy consumption information, Energy and Buildings 40 (2008) 394–398.
[3] E.U., 2002/91/EC of the European Parliament and of the Council of 16thDecember 2002 on the Energy Performance of Buildings, 2002.
[4] E.U., 2010/31/EU of the European Parliament and of the Council
[5] EN ISO 14683:1999. Thermal bridges in building construction – linear thermal transmittance – simplified methods and default values.
[6] EN ISO 6946:2007. Building components and building elements – thermal resistance and thermal transmittance – calculation method.
[7] EN ISO 10211:2007. Thermal bridges in building construction. Heat flows and surface temperatures. Detailed calculationshods.
[8] EN ISO 10211-2:2001. Thermal bridges in building construction – calculation of heat flows and surface temperatures. Part II: Linear thermal bridges.
[9] K. Martin, Caracterización del comportamiento de los puentes térmicos en régimen estacionario y dinámico mediante ensayos y cálculo. Su influencia en la demanda energética de edificios de viviendas, Department of Thermal Engineering, University of the Basque Country, Bilbao, 2009.
[10] K. Martin, et al., Equivalent wall method for dynamic characterization of thermal bridges, Energy and Buildings 55 (2012) 704–714.
[11] K. Martin, et al., Problems in the calculation of thermal bridges in dynamic conditions, Energy and Buildings 43 (2011) 529–535.
[12] ASIEPI, WP4, An Effective Handling of Thermal Bridges in the EPBD Context –Final Report of the IEE ASIEPI Work on Thermal Bridges, http://www.asiepi.eu/(accessed 07.10.14).
[13] Tecnalia, KUBIK by Tecnalia, http://www.energiaenedificacion.com/kubik-by-tecnalia/ (accessed 05.05.15).
[14] Garay, R. et Al, Energy efficiency achievements in 5 years through experimental research in KUBIK, 6th International Building Physics Conference, 2015
[15] PHYSIBEL, TRISCO, computer program to calculate 3D & 2D steady state heat transfer in rectangular objects, version 12.0w, 2010
[16] PHYSIBEL, VOLTRA. Computer program to calculate 3D & 2D transient heat transfer in objects described in a rectangular grid using the energy balance technique, version 6.3w., 2009
[17] IETcc, CTE, Código Técnico de la Edificación, Catálogo De Elementos Constructivos Del CTE, v6.3, March 2010.
[18] Garay, R. et al., Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, Energy and Buildings 85 (2014) 579–591
[19] BBRI, The Passys Test Cells. A Common European Outdoor Test Facility for Thermal and Solar Building Research, 1990
[20] ISO 9869-1:2014. Thermal insulation -- Building elements -- In-situ measurement of thermal resistance and thermal transmittance -- Part 1: Heat flow meter method
[21] G. Bauwnes, et al. Co-heating tests: A state-of-the-art, Energy and Buildings 82 (2014) 163–172.