Hybrid numerical and experimental performance assessment of structural thermal bridge retrofits

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Abstract

A methodological approach to the multi-dimensional heat transfer assessment of building envelopes is performed. The proposed method is particularly focused on thermally weak points in envelope-structure junctions and the assessment of envelope retrofit alternatives. Thermal performance in these spots is seldom assessed in energy audit processes, although it is one of the main heat loss paths in many insulated façade solutions. An envelope-slab junction case is presented, where multi-dimensional heat transfer occurs. The present paper proposes a methodology which allows for a hybrid experimental and numerical performance assessment in such circumstances. A numerical model is calibrated against experimental data, which is then modified to reflect various envelope retrofit solutions. Several possible analysis procedures are proposed, based on the capacities of transient thermal models.

Keywords

Building envelope; Experimental assessment; Thermal bridge; Finite Element; Envelope retrofitting

1 Introduction

1.1 Heat transfer in building envelopes & envelope retrofitting

According to the Sustainable Building and Climate Initiative of the UN (UNEP 2016), and other sources (DOE 2008) (Pérez-Lombard, Ortiz, & Pout 2008) (EU 2002) (EU 2010), buildings are responsible for 40% of the global primary energy consumption. Within buildings, envelopes – roofs, façades, and glazed areas- are the main heat transfer path from buildings to its environment. (ECOFYS 2007) studied the techno-economical optimum insulation level for building envelopes. In this study, optimal thermal transmittance levels were found to be substantially below the current insulation levels in building envelopes. Thus, there is a great heat flux reduction potential by incorporating additional insulation to building envelopes.

Once the decision for the renovation of a Building is taken, incorporating additional thermal insulation is a robust solution, as it increases the overall thermal resistance of the building envelope. Commonly, this measure is the first energy efficiency measure taken in most buildings, and combined with other energy efficiency measures, provides for medium-long-term Return of Investment (ROI).

There are various technical solutions such as External Thermal Insulation Systems (ETIC), Ventilated façades, cavity wall insulation, and internal insulation systems. The basic approach of all these systems is to improve the thermal transmittance of the wall, by means of the addition of insulation materials. In this context, the thickness of the insulation material and it insulation capacity are key variables (Elguezabal Garay, 2015).

1.2 Thermal bridges. Relevance & calculation procedures

Commonly retrofitting design decisions are made based on one-dimensional performance of insulation systems. Multidimensional heat transfer paths such as window sills, slab-façade junctions, balconies, etc. are disregarded. These items account for a relevant share of the heat loss coefficient of a building envelope.

Several sources such as (ASIEPI, 2010) show that the relevance of thermal bridges within the heat balance of a building is up to 30% of heating energy loads due to these elements. This ratio is considered to increase for highly insulated buildings. The correct design and improvement of junction details is estimated to reduce the same ratio to 15%. For this reason, adequate thermal bridge calculation methods for highly insulated buildings are needed (Kuusk, Kurnitski & Kalamees, 2017).

One of the reason to avoid multidimensional heat transfer in the assessment procedure of a building envelope retrofitting lies on the complexities of numerical models and the lack of robust experimental procedures to conduct such assessments.

Regarding numerical models, multidimensional heat transfer codes such as Therm (LBNL, 2018) are freely available to designers, but to the authors knowledge, these are only seldom applied on construction projects. When related to the on-site experimental assessment of the thermal performance of architectural junctions, standard methods such as (EN ISO 9869-1:2014) cannot be applied and only qualitative assessments can be made by means of methods such as Infrared imaging.

In (Garay, Uriarte & Apraiz, 2014), numerical and experimental works were conducted over a 2-dimensional thermal bridge. In this work, it was observed that steady-state numerical models did not correctly match the dynamics of the thermal bridge. This same source showed that for cases with unknown thermal properties, models failed to correctly identify the steady-state and transient aspects of thermal bridges.

In recent dates, works such as (O'Grady, Lechowska & Harte, 2017) have studied the possibility to integrate thermal imaging as a quantitative source of information for thermal bridge assessment. However, their applicability is yet to be further demonstrated.

1.3 Experimental processes for building envelope assessment

Experimental heat transfer assessment procedures in building envelopes have traditionally been focused on one-dimensional heat transfer assessment. In fact, it is common to find instructions to avoid the influence of thermal bridges in experimental setups within standardized assessment procedures.

Experimental procedures for the on-site of heat transfer in buildings are standardized under (EN ISO 6946:2007) (ASTM C1155 – 95, 2013). Although these standards integrate transient assessment methods, they are primarily focused on steady-state performance metrics. Their most common implementation is performed by means of averaging processes, which filter-out the dynamics of building envelopes.

Within the research community, there is an increasing awareness of the need for transient assessment methods which has led to specific transient methods (Gutschker, 2008) (Strachan & Vandaele, 2008) (Naveros, Bacher, Ruiz, Jiménez & Madsen, 2014). Anyhow, all this experience remains in the one-dimensional domain.

(Atsonios, Mandilaras, Kontogeorgos & Founti, 2017) applies (EN ISO 9869-1:2014) & (ASTM C1155 – 95, 2013) procedures over datasets from field experiments on building envelopes with various levels of insulation, at different periods of the year. For each case, the required campaign length is identified. In some cases, it is impossible to obtain satisfactory results from steady-state methods, while in others, campaign lengths up to 20 days are required. Transient methods perform substantially better, delivering robust results in 5 to 10 days.

The methodology presented in this paper does not intend to substitute experimental methods to assess one-dimensional heat transfer. It will complement existing procedures with a novel system for the assessment of multi-dimensional heat transfer, which to date is out of the scope of experimental procedures.

1.4 Goal and limitations of the proposed methodology

In this paper, a hybrid numerical and experimental procedure is proposed to assess the present thermal performance of an architectural junction. The procedure allows to assess building envelope retrofit systems. Ultimately, this allows for a more detailed assessment of the thermal performance of a retrofitting intervention.

The methodology is illustrated by means of a 2-dimensional façade-slab junction. The presented calculation method is also suitable for 3-dimensional heat transfer. The 2-dimensional heat transfer case is presented due to its larger representativity of the performance gap illustrated in this section.

Singular 3-dimensional thermal bridges are known to be less-relevant in terms of heat transfer, but critical in terms of cold-spots, and potential locations for mould growth. Users trying to replicate this methodology for repetitive 3-dimensional thermal bridges such as cladding anchors may experience difficulties in doing so. For these cases, users are encouraged to deal with this phenomena by means of pseudo-2D models. Specific adaptations of the present methodology may need to be developed. Reference on multi-dimensional heat transfer in architectural junctions may be found in (Atsonios, Mandilaras, Kontogeorgos & Founti, 2017).

2 Thermal assessment methodology

Thermal bridges are construction details where multi-dimensional heat transfer occurs. As such, heat flux in these locations cannot be measured directly by means of heat flow meters.

The proposed assessment method bases its assessment of the heat flow across architectural junctions on several localized temperature and heat flow measurements. Point measurements are used to calibrate a transient numerical thermal model. Once calibrated, the model can be used to provide accurate heat transfer assessment of the present architectural junction. The impact of envelope retrofit alternatives on the heat transfer across the junction can be calculated with the calibrated model. In table 1. The method is presented in a stepwise approach.

TABLE 1. Thermal assessment sequence.

Step	Activity
Monitoring of present state	- Define the location of sensors - Monitorization campaign, ~1month
Calibration of thermal model	- Construction of a numerical model - Optimization of thermal properties of materials
Evaluation of retrofitting alternatives	- Parametric study of retrofit possibilities vs performance indicators

The goal of this methodology lies on the identification of thermal and geometrical properties of an already constructed architectural junction based on insufficient data. Although geometrical details are commonly known in buildings constructed in the last 60 years, many thermal properties lie unknown and their determination is commonly performed by means of bibliographical research.

This method allows for the determination of critical information in the assessment of thermal bridges such as the effective thermal conductivity of insulation layers and air cavities, specific heat and density of concrete and brick constructions, etc.

This proposed hybrid methodology is complemented by state of the art one-dimensional heat transfer assessment techniques as shown in figure 1.

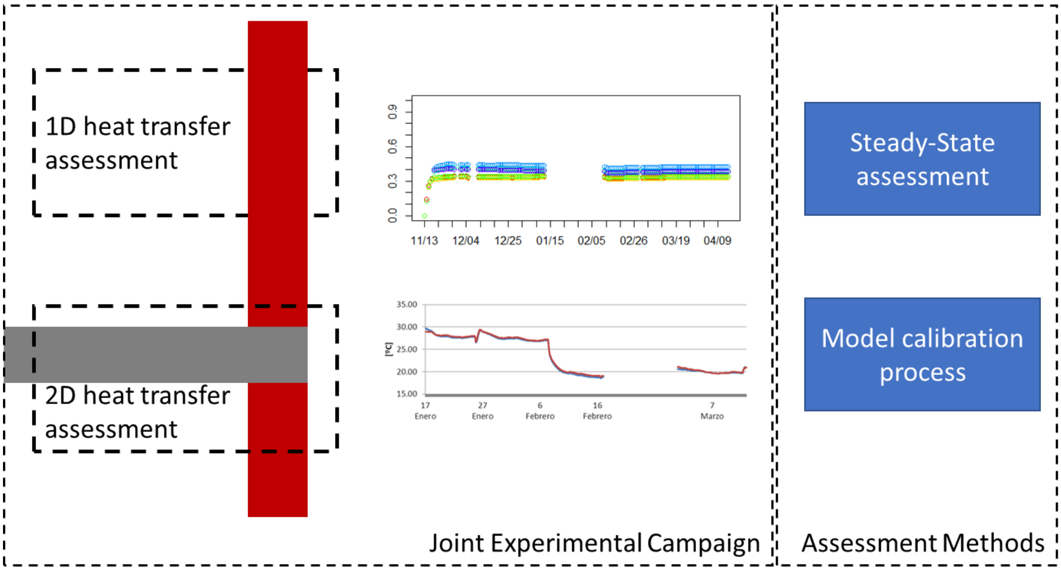

FIG 1. integration of assessment methods in a joint experimental campaign for on-site works

3 Step 1: Monitoring

In this step, the geometrical detail is defined, and several spots are selected for the installation of sensors. Commonly, 3-4 sensors are sufficient to provide a detailed thermal map of the architectural junction. In the selection of the sensor location, sensors should be located in such a way as to allow the mapping of the architectural detail in all its relevant internal surfaces.

The particular location of sensors will depend on each architectural junction, and the feasibility for some of the locations to integrate sensors. In (Garay, Uriarte & Apraiz, 2014), steady-state thermal models are used to identify suitable locations for sensor placement. By doing so, better experimental conditions are achieved. Alternative processes such as thermal imaging are also possible means of identification for suitable sensor location. The goal is to achieve spatial and transient representativity of the measurement scheme:

- Spatial representativity is achieved by means of sensor placement across the architectural junction, some of them mostly exposed to the external ambience, others in contact with indoor environment, and some of them in between.
- Transient representativity implies that sensors are positioned in such a way that they are exposed to different dynamics. Sensors in contact with insulation materials will deliver faster responses than those in contact with concrete and other capacitive materials.

The number of sensors to be placed needs to be defined based on the scope of the selected assessment. Considering that standardized one-dimensional heat transfer assessment procedures (EN ISO 9869-1:2014) incorporate ambient and surface temperature sensors and at least one heat flow sensor, this amount should be increased to achieve good representativity. Good practice should incorporate the following sensors:

- 1 ambient temperature sensor for each of the boundary conditions of the thermal bridge
- 1 surface temperature sensor for the coldest spot on each of the boundary conditions
- 1 heat flux on each of the internal boundary conditions
- 1 additional surface temperature sensor for planar systems not instrumented for (EN ISO 6946:2007)
- External weather conditions need to be measured, comprising, outdoor ambient temperature, wind speed & direction, and solar radiation over the façade.

For the application presented, Pt100 temperature sensors and PHYMEAS heat flux sensors are identified as suitable devices.

In figure 2 a monitorization scheme is proposed for a slab-façade junction. In this figure, meteorological sensors are not shown.

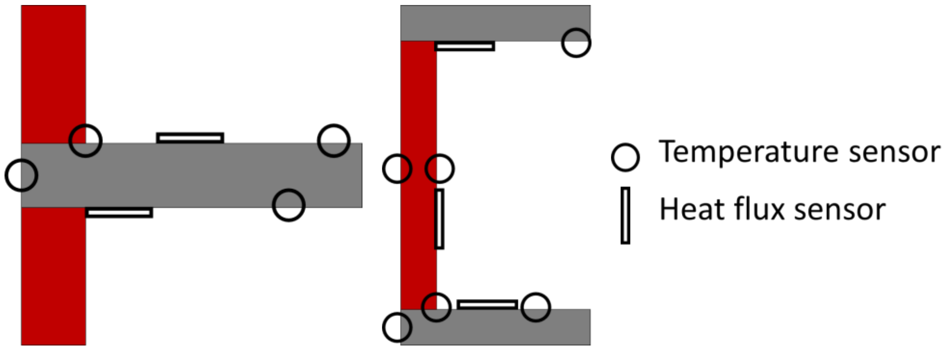

FIG 2. Monitorization scheme of a slab-façade junction (left), distribution of sensors in a multi-story setup (right)

To facilitate the experimental process, the experimental campaign should be coordinated with the installation of other sensors for the one-dimensional assessment of the thermal performance of walls. This would allow for the common utilization of data loggers. In the same figure, the monitorization spots are redistributed, to allow for the installation of the data acquisition system within one floor in a multi-rise building. The presented experimental setup would only be valid in a multi-rise building where boundary effects caused by foundations and roof can be neglected (i.e. central floor in a 7 story-high building).

In figure 3, the detailed location of sensors in an architectural junction can be seen.

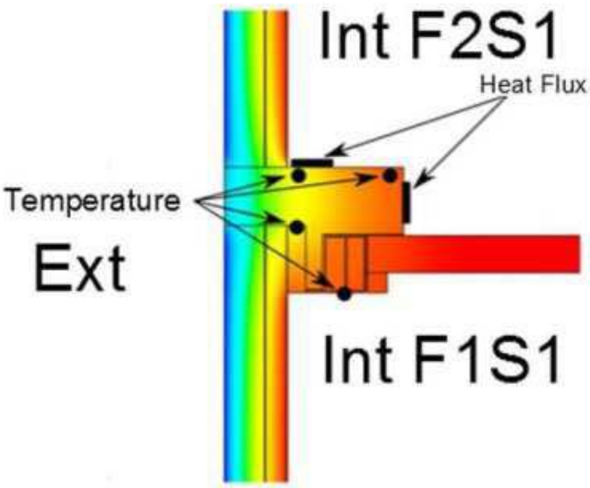

FIG 3. Location of temperature and heat flux sensors in an experimental assessment of the heat transfer in a façade-slab junction (model height: 2,77m) (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

Depending on the existing boundary conditions (i.e. indoor-outdoor temperature gradient), the insulation level of the construction, etc. the length of the monitorization campaign may divert. However, it is reasonable to assume that a proper result can be achieved in 3 to 5 weeks of experimental campaign.

In (Atsonios, Mandilaras, Kontogeorgos & Founti, 2017), one-dimensional heat transfer assessment was performed by means of identification processes over various wall assemblies. Different climatic conditions, envelope compositions and assessment methods resulted in variable campaign length requirements to deliver a result. When transient methods were applied, campaign lengths in the range of 10-20 days were required to achieve good identification of the system. In the proposed methodology, longer experimental campaigns are required to properly address heat dynamics in massive elements, such as concrete slabs. Anyhow, the prescribed campaign length is still inductive.

4 Step 2: Calibration

A thermal model of the architectural detail is constructed based on the available information of the junction. Commonly tabulated data from sources such as (EN ISO 6946:2007) and (Ministerio de Fomento, 2013) are taken to complete project-specific data. It should be considered that, in most cases, retrofitting projects are performed over relatively old buildings, with non-professional owners (e.g. individual owners/dwellers, not involved in the construction process), with only minimal architectural data available.

The definition of architectural dimensions needs to cover the influence area where multi-dimensional heat transfer occurs. General criteria established in (EN ISO 10211:2007) suggest that 1m of one-dimensionally homogeneous wall/slab length shall be modelled. The readers should consider that secondary criteria such as symmetry planes and wall thickness may modify this length.

Figure 4 shows a thermal model of a façade-slab architectural junction.

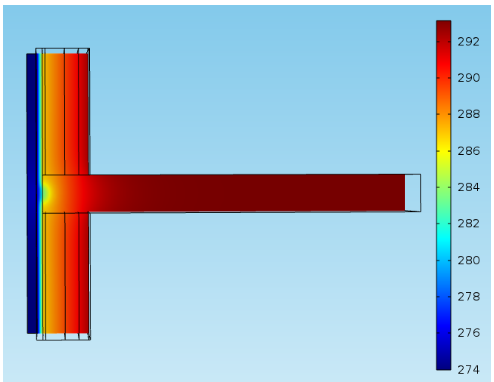

FIG 4. Thermal model of an architectural junction. (BRESAER)

Boundary condition data from the monitorization campaign is introduced in this model, and a transient thermal simulation is performed over the monitored period. The boundary conditions incorporated into the model are ambient temperature (in all surfaces) and solar radiation (for external surfaces only).

Thermal properties of materials and modelling assumptions are varied to minimize de observed error in output variables when compared with monitored spots in the physical junction within the monitored campaign.

In Figure 5, output data from a calibrated model in VOLTRA (PHYSIBEL, 2009) is compared to experimental data taken from a façade-slab junction constructed in the KUBIK experimental building (Garay, Chica, Apraiz, Campos, Tellado, Uriarte & Sanchez, 2015).

Error minimization needs to be achieved simultaneously in all point measurements. The comparison of the calibrated model against experimental data for all sensors installed in the junction can be found in (Garay, Uriarte, & Apraiz, 2014) and (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015).

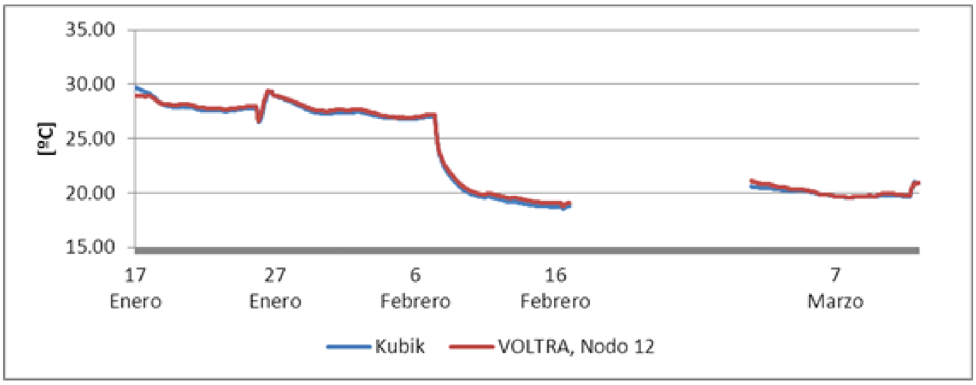

FIG 5. Calibrated output signal on a thermal model. (Garay, Uriarte, & Apraiz, 2014) and (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015)

In (Garay, Uriarte, & Apraiz, 2014) and (Garay Martinez, Uriarte Arrien & Apraiz Egaña, 2015), the model was parametrized to incorporate thermal capacity and conductivity of materials (concrete, steel, polyurethane and XPS). It was found that minor tuning was required to identify the parameters of concrete. Concrete density and conductivity were varied in a range of 2000-2400kg/m3, and 2-2.6 W/mK respectively. The model best fit to experimental data was achieved with 2300kg/m3 and 2.2W/mK.

This same model resulted to be more sensible to internal convective heat transfer phenomena. Separate heat transfer coefficients were required for horizontal, vertical upward and vertical downward heat transfer. Additional coefficients were required for corner areas. All of them resulted in surface heat transfer coefficients in the range of 2.5-4 W/m2K, substantially lower than reference values in (EN ISO 6946:2007). Full details on the calibration process can be found in (Garay, Uriarte, & Apraiz, 2014).

At the end of this process, the thermal model is classified as “Calibrated”, and can be used for later assessment of retrofitting alternatives. In (TECNALIA, 2013), visual inspection was used to identify the model which best fit experimental data, but this process can be improved by using error minimization techniques simultaneously over all measurement spots. As it can be seen in figure 4, the model was able to predict surface temperature within +- 0.2 ºC from experimental data.

The calibration is performed based on punctual sensor locations, none of these is sufficiently reliable as to fully represent the thermal performance of the architectural junction. However, Considering the good agreement of the calibrated model with experimental data, it is reasonable to accept that the calibrated thermal model can be used to predict the thermal performance of the full architectural junction.

5 Step3: Evaluation of retrofit alternatives

The calibrated model from the previous section can be used to predict the thermal performance of architectural junctions targeting at various performance figures. The model by itself is a transient thermal model, which can be used to perform both transient and steady-state calculations of the architectural junction for various purposes such as the following:

- Calculate thermal bridge coefficients and temperature factors of various alternative designs, based on calculation criteria and boundary conditions in (EN ISO 10211:2007), but with calibrated thermal parameters for the baseline junction
- Calculate the overall coupling coefficient of the building envelope under standard (EN ISO 13790:2008)
- Calculate the transient thermal response of the architectural junction under harmonic boundary conditions similar to (EN ISO 13786:2007) and (Garay Martinez, Riverola & Chemisana, 2017).
- Obtain transfer functions and response factors of the architectural junction by procedures such as (Martín, Flores, Escudero, Apaolaza & Sala, 2010).

- Obtain equivalent one-dimensional thermal models for its integration into energy simulation programs by means of system identification techniques, stochastic procedures, etc. as proposed by (Gacía Gil, 2008).
- Perform heat transfer analysis of the architectural junctions for the verification of energy savings in energy performance contracts by means of IPMVP (EVO, 2012) or equivalent methods.

Overall, the proposed models allow for a detailed assessment of the architectural junction, with many relevant output parameters, which should be defined on a case-by-case basis, along with the particularities of each project from its many perspectives (architectural constraints, expected performance levels, engagement of contractors in the final performance, etc.).

In the following paragraphs a case study on the assessment process for building energy retrofits is presented. The model for the façade-slab section presented in figure 3 is taken as baseline, and façade retrofit is performed by means of a ventilated façade system. This system is a closed joint ventilated façade cladding system (ULMA Architectural, 2018) based on vertical profiles and point anchors to the edge of concrete slabs (BRESAER).

The presented study was performed by means of multi-dimensional modeling of the junction. The ventilated façade model is parametrized to incorporate insulation thickness as the main variable. Anchor thickness is a dependent variable, as this parameter is required to be increased when the cladding is separated from the façade to meet mechanical criteria. The suitability of each alternative is assessed by means of surface, linear and point heat transfer, and temperature factor is obtained. Figure 6 shows the architectural detail and temperature field of the studied junction.

FIG 6. Architectural detail and thermal field in the cross-section of the slab-façade junction

The U-value of the façade evolves from 1.05 W/m^2K (Uninsulated) to 0.13 W/m^2K (20 cm of insulation). The achieved insulation levels are compared with normative requirements in Spain (Ministerio de Fomento, 2013).

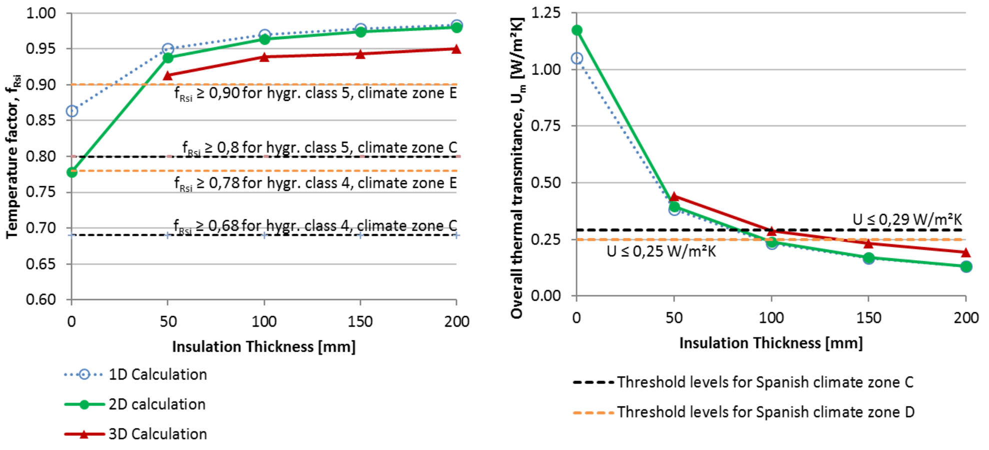

FIG 7. Temperature factors and thermal transmittance values. (Arregi Goikolea, Garay Martinez, Riverola Lacasta & Chemisana Villegas, 2016)

In figure 7, the evolution of thermal transmitance and temperature factors is shown for varying thermal insulation levels. For the uninsulated case, a 12% surplus heat transfer due to the 2D heat transfer over the 1D study. When adding insulation over this junction, the 2D surplus heat is substantially mitigated. However, 3D heat transfer introduced by mechanical anchors becomes a relevant part of the heat transfer across the façade. This surplus heat increases from 16% (5cm) to 48% (20cm) when the façade is insulated externally. The surplus 3D heat transfer is stable in absolute terms for all cases, but its relative relevance increases substantially.

The method results in a more precise assessment, where calculation errors due to 3D heat transfer are detected and corrected. As a result, the façade system is selected for compliance with the Spanish requirement of overall façade U-value (0.25 W/m^{2}K). In this correction, insulation thickness is increased from 10 to 15 cm of mineral wool.

6 Conclusions

With the increasing thermal performance levels required by national building codes in developed societies, steady-state thermal performance of one-dimensional sections of envelopes are not sufficient to guarantee the thermal performance of architectural envelopes. The need for detailed assessment is increasingly relevant in retrofitting projects, where architectural information and design alternatives face relevant constraints. Under such schemes, advances in design and assessment procedures are necessary, furthermore considering that thermal bridges in these junctions are major heat loss paths, and cold spots where surface condensation and mould growth is more likely to occur.

The proposed methodology provides a minimally intrusive methodology for the robust assessment of thermal performance of architectural junctions with many possible outcomes, which could be defined based on the requirements of each case. Considering the rapid adoption of wireless technologies in the sensor and monitorization market, it could be expected that the intrusiveness of the methodology could be further reduced by removing wires in the monitorization process.

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