Universitat de Lleida

Caracterización térmica dinámica de la transferencia de calor multidimensional en edificios

Dynamic performance assessment of multidimensional heat transfer in buildings

Roberto Garay Martinez

http://hdl.handle.net/10803/460756

Universitat de Lleida

TESI DOCTORAL

Caracterización Térmica Dinámica de la Transferencia De Calor Multidimensional en Edificios

Dynamic Performance Assessment of Multidimensional Heat Transfer in Buildings

Roberto Garay Martinez

Memòria presentada per optar al grau de Doctor per la Universitat de Lleida
Programa de Doctorat en Ingeniería y tecnologías de la información

Director/a
Daniel Chemisana Villegas

Tutor/a
Daniel Chemisana Villegas

2017

Acknowledgements

This work could not be possible without many of the people who is around me every day, and has helped me in my personal and professional evolution.

I would like to thank my colleagues at the Kubik test facility, for their support, and efforts in the design, set-up and operation of many experiments. We learned together about experimentation on building physics, sensors, construction techniques, and many other topics. I would like to specially thank Ines Apraiz, Amaia Uriarte and Fernando Fernandez, who were more directly involved in our initial experimental experiences, and with whom all our experimental procedures were tested and developed.

I would also like to thank all my co-authors, with whom I shared many discussions on experimentation on heat transfer on a set of different envelope systems. I always got positive feedback and contributions from their side.

This thesis would have been impossible without Dr Daniel Chemisana, who has helped me since our initial telephone conversations, briefed me into the administratives of a doctoral process, has cooperated in the definition of the mathematical formulation proposed in this thesis, and introduced me to other PhD candidates with whom we have made joint works, some of which are incorporated to this thesis.

Anyhow, my greatest gratitude is to my family. To my parents Roberto and Ana Rosa, and brother Joseba, who have always supported me. To Miren and our children Eneritz and Unai, with whom I settled and formed a household.

Agradecimientos

Esta tesis no sería posible sin las personas que me rodean cada día, y que me ayudan en mi evolución personal y profesional.

Me gustaría agradecer su apoyo y esfuerzo a mis colegas involucrados en la infraestructura experimental Kubik. En los últimos 6 años hemos diseñado, construido y operado numerosos experimentos. Aprendimos juntos sobre experimentación en térmica de la edificación, sensórica, tecnologías constructivas, y una gran variedad de temática asociada. Me gustaría agradecer especialmente su apoyo a Inés Apraiz, Amaia Uriarte y Fernando Fernández, con los que comparto el recuerdo de los primeros trabajos experimentales, y con quienes se desarrollaron nuestros procedimientos experimentales.

Me gustaría agradecer a mis co-autores la posibilidad de haber compartido múltiples conversaciones sobre enfoques experimentales, sobre una variedad de sistemas constructivos. Su respuesta ha sido siempre constructiva.

Esta tesis habría sido imposible sin la ayuda del doctor Daniel Chemisana. Él me ha ayudado desde nuestras conversaciones telefónicas iniciales, me ha guiado a lo largo del proceso doctoral, ha cooperado en la formulación matemática propuesta en esta tesis, y me facilitó la colaboración de otros alumnos de doctorado con los cuales hemos realizado trabajos conjuntos, dos de los cuales se han incorporado a esta tesis.

Pero sobre todo, mi mayor gratitud es hacia mi familia. Hacia mis padres Roberto y Ana Rosa, y hermano Joseba, que siempre me han apoyado. Y hacia Miren y nuestros hijos Eneritz y Unai, con los que me he asentado y he formado un hogar.

Esker Onak

Egunerokotasunean, nire inguruan daudenei zor diot tesi hau. Haiei esker eboluzionatu dut maila personal eta profesionalean.

Nire esker ona adierazi nahi diet KUBIK instalazio esperimentalean ditudan lankideei, haien iritzi eta lanagaitik bertan gauzatutako esperimentuen diseinu, eraikuntza eta operazioan. Elkarrekin bide interesgarria egin dugu eraikuntzako fisikaren esperimentazioan, sentsoreen hautakenta, eraikuntza tekniketan eta beste hainbat kontuetan. Nire esker ona bereziki eman nahi diot nite lankide Ines Apraiz, Amaia Uriarte eta Fernando Fernandori, denon artean prozedura esperimental interesgarriak diseinatu eta garatu genituelako.

Tesi honen baitan dauden artikuluetan nirekin batera egile direnei ere esker ona adierazi nahi diet. Elkarrizketa eta eztabaida ugari izan ditugu bero transferentziaren esperimentazioaren eta beste zenbait gairen harira. Beti jaso izan ditut ekarpen onak.

Tesi hau ezinezkoa izango zen Daniel Chemisana Doktorearen laguntzarik gabe. Hasierako telefono elkarrizketez geroztik beti izan dut lagun. Doktoretza prozesuaren arlo administratiboan aliatu perfektua izan da, tesian proposatutako formulazio matematikoa definitzen lagundu dit, eta bere beste zenbait ikasleren laguntzarekin lan kooperatibo oso interesgarriak egin ditugu. Lan hauetako batzuk tesi honen parte bihurtu direlarik.

Edonola ere, nire eskerrik beroena nire familiarentzako da. Nire gurazo Roberto eta Ana Rosa, eta Joseba anaiarentzako, beti nire ondoan egon direlako. Eta nola ez, Miren eta gure seme-alaba Eneritz eta Unairentzako. Haiekin egonkortu eta familia sortu nuen.

Summary

This work develops a suitable framework for the numerical and experimental assessment of transient multidimensional heat transfer in building envelopes.

A new method to integrate the thermal assessment of architectural junctions within monitoring and thermal assessment processes linked to building energy retrofit is presented. This method leads to more accurate assessment of baselines in such processes and precise analysis of potential retrofit alternatives. Calibrated models are used for the differential thermal assessment of the envelope retrofit with the base case.

In this process, advances are made in the formulation of heat transfer phenomena, and in experimental thermal assessment methods.

A generalized heat transfer formulation is derived from standards dealing with multi-dimensional heat transfer in buildings. The generalized formulation allows for the computation of transient thermal performance in architectural junctions. Applications of this new formulation to several disciplines such as experimental assessment, numerical calculation of harmonic properties, and integration into building energy software, are presented and discussed.

An experimental procedure for the assessment of heat transfer in architectural junctions is developed. This procedure makes use of calibrated numerical models, and allows reporting on the overall thermal field and heat transfer in junctions.

Thermal assessment processes are incorporated to this thesis, presenting critical thermal variables such as overall U-value increase due to thermal bridging, surplus heat transfer in thermal bridges, temperature factor and harmonic thermal properties.

Experimental thermal assessment processes are incorporated. One-dimensional thermal resistance measurements and differential thermal performance assessment of external thermal insulation systems are presented.

Overall, the methods presented in this work, cover all practical aspects dealing with multidimensional heat transfer in buildings, with innovations in the mathematical formulation and experimental performance assessment methods. To the authors' belief these novelties open a wide range of possibilities to researchers and practitioners to more detailed numerical experimental assessment methods in building envelopes where multidimensional heat transfer is relevant.

Resumen

Esta tesis tiene por objeto el desarrollo de un marco adecuado para el análisis numérico y experimental de la transmisión térmica dinámica multidimensional en las envolventes arquitectónicas.

Esta tesis presenta un nuevo método para integrar el análisis térmico en encuentros arquitectónicos. Este método está enfocado a su uso en procesos de monitorización y análisis térmico de edificios, para la mejor valoración técnica de alternativas de rehabilitación para la actualización de los niveles de aislamiento térmico en los edificios. El método presentado tiene por objeto conducir a la obtención de líneas base y estimación de ahorros energéticos en las propuestas de rehabilitación más precisas en estos procesos de análisis. El método propuesto permite análisis térmico diferencial entre el caso pre y post rehabilitación mediante modelos numéricos calibrados.

En el proceso, la tesis presenta avances en la formulación térmica dinámica de fenómenos multidimensionales y de métodos de análisis térmicos experimentales.

Se deriva una formulación generalizada de la transmisión de calor a partir de normativa técnica existente en el campo de la transmisión de calor multidimensional. Esta formulación generalizada permite el cálculo del comportamiento térmico dinámico en encuentros arquitectónicos. Se presentan y discuten aplicaciones diversas de esta formulación en campos tales como el análisis experimental, obtención de propiedades armónicas e integración en software de cálculo de demandas energéticas de edificios.

Se desarrolla un procedimiento experimental para la evaluación de la transmisión de calor en encuentros entre sistemas constructivos. Este procedimiento emplea modelos numéricos calibrados y permite el cálculo térmico dinámico del campo térmico multidimensional en estas uniones.

En esta tesis se consideran las variables críticas para el cálculo térmico en encuentros entre sistemas, tales como el valor de U global, transmisión de calor incremental, factor de temperatura y propiedades armónicas.

También se consideran los métodos de análisis térmico experimental. Se presentan cálculos estacionarios de resistencia térmica de sistemas constructivos y cálculos diferenciales para el análisis del comportamiento térmico de sistemas de aislamiento térmico exterior.

En general, los métodos presentados en este trabajo abordan la problemática de la transmisión de calor multidimensional en la edificación desde varios prismas, presentando además innovaciones en formulación matemática y procesos de análisis experimental. Para el autor, estas novedades generan varias posibilidades para investigación y aplicación futura de procesos de análisis térmico más precisos.

Resum

Aquesta tesi té per objecte el desenvolupament d'un marc adequat per a l'anàlisi numèric i experimental de la transmissió tèrmica dinàmica multidimensional en les envoltants arquitectòniques.

Aquesta tesi presenta un nou mètode per integrar l'anàlisi tèrmic en trobades arquitectòniques. Aquest mètode està enfocat al seu ús en processos de monitorització i anàlisi tèrmica d'edificis, per a la millor valoració tècnica d'alternatives de rehabilitació per a l'actualització dels nivells d'aïllament tèrmic als edificis. El mètode presentat té per objecte conduir a l'obtenció de línies base i estimació d'estalvis energètics en les propostes de rehabilitació més precises en aquests processos d'anàlisi. El mètode proposat permet l'anàlisi tèrmica diferencial entre el cas pre i post rehabilitació mitjançant models numèrics calibrats.

En el procés, la tesi presenta avanços en la formulació tèrmica dinàmica de fenòmens multidimensionals i de mètodes d'anàlisi tèrmics experimentals.

Es deriva una formulació generalitzada de la transmissió de calor a partir de normativa tècnica existent en el camp de la transmissió de calor multidimensional. Aquesta formulació generalitzada permet el càlcul del comportament tèrmic dinàmic en trobades arquitectònics. Es presenten i discuteixen aplicacions diverses d'aquesta formulació en camps com ara l'anàlisi experimental, obtenció de propietats armòniques i integració en programari de càlcul de demandes energètiques d'edificis.

Es desenvolupa un procediment experimental per a l'avaluació de la transmissió de calor en trobades entre sistemes constructius. Aquest procediment fa servir models numèrics calibrats i permet el càlcul tèrmic dinàmic del camp tèrmic multidimensional en aquestes unions.

En aquesta tesi es consideren les variables crítiques per al càlcul tèrmic en trobades entre sistemes, com ara el valor d'U global, transmissió de calor incremental, factor de temperatura i propietats armòniques.

També es consideren els mètodes d'anàlisi tèrmica experimental. Es presenten càlculs estacionaris de resistència tèrmica de sistemes constructius i càlculs diferencials per a l'anàlisi del comportament tèrmic de sistemes d'aïllament tèrmic exterior.

En general, els mètodes presentats en aquest treball aborden la problemàtica de la transmissió de calor multidimensional en l'edificació des de diverses òptiques, presentant a més innovacions en formulació matemàtica i processos d'anàlisi experimental. Per a l'autor, aquestes novetats generen diverses possibilitats per a investigació i aplicació futura de processos d'anàlisi tèrmic més precisos.

Table of Contents

1 Motivation

This work is targeted at developing a suitable framework for numerical and experimental assessment of transient multidimensional heat transfer in building envelopes.

With the evolution of building physics over the last decades, knowledge has been gained over most of the domains related to heat transfer in buildings. Similarly to any other domain in society, the evolution is impressive. The joint effect of the brains of thousands of researchers, and the evolution of information and communication technologies reflects on the knowledge, methods and tools available to practitioners and researchers today.

In the particular field of building envelopes, and their performance assessment, a lot has also been done. Today, numerical codes allow for the calculation of steady-state and transient performance. Envelope heat flows can be integrated into building energy simulation tools, which are capable of computing heat flows, temperature variations and energy balances comprising many energy sources in buildings (internal gains, HVAC, etc.).

Along the way, experimental processes related to energy performance of building and its components are more common today than never before. Both in research activities or related to Measurement and Verification (M&V) of energy saving measures, the digital age allows researchers to manage astounding amounts of experimental information, with data acquisition costs substantially lower than decades ago. Sensors have been democratized, data acquisition equipment is capable to manage large sets of sensors and store high resolution datasets, with minimal need of user intervention over long measurement campaigns. IT networks allow for telemetry, wireless and remote access to data.

When related to detailed assessment of heat transfer in building envelopes, experimental methods have already been developed for one-dimensional heat transfer problems. Different approaches are pursued for on-site assessments and for detailed experiments within experimental test-cells and facilities. Averaging methods for the calculation of the steady-state performance of walls have even been introduced in technical standards. System identification and transient assessment methods are relatively more complex, with its present use limited to the research community. However, these have already been available in the last 2 decades, with increasing popularity.

When related to the particular field of knowledge of thermal bridges, previous works are related to steady-state numerical assessment, with on-site works commonly limited to qualitative data such as local temperature measurement or Infra-red imaging of thermal bridges.

To my knowledge, similar works have not been conducted. An experimental study carried out by the University of the Basque Country, where a thermal bridge was experimented in a laboratory environment, and its transfer function calculated. Still, the present work differentiates from it substantially.

My particular concern related to thermal bridges was initiated with the initiation of the operation of the Kubik $_{\text{by Tecnalia}}$ test facility in 2010. This facility is targeted at the assessment of the realistic performance of building envelopes, and differs substantially from other experimental setups for the energy performance assessment of buildings.

Targeted at realistic performance assessments, thermal bridges should not be eliminated, or minimized. The assessment of their influence within the experimental setups is commonly one of the targets of the experimentation and the final result. In fact it is common, not only to assess its contribution to the heat balance of a specific test setup, but also its diferential performance when thermal bridge insulation is performed. Thus thermal bridge assessmen is commonly one of the main targets of experimentation.

Considering that this experimental facility is not primarily targeted at side-by-side testing, transient assessment needed to be developed in the context of sequential experimentation. With these models, the variability in indoor and outdoor boundary conditions is fed in calibrated or validated thermal models to latter project models from different experimental configurations to the same boundary conditions.

All this implied that we had to revisit numerical models and experimental assessment methods related to thermal bridges and multi-dimensional heat transfer to adapt these to our particular needs.

With increasingly insulated buildings, proper thermal design of envelopes reaches far beyond the calculation of one-dimensional U-value, into fields of moisture transfer, air and water-tightness…and thermal bridges. In any building, envelope systems need to meet each other, along with other architectural elements. In each of these junctions, multi-dimensional heat transfer occurs, and potentially relatively large amounts of heat can be transferred leading to thermal bridges. With envelope insulation values reaching limits as low as 0.2 W/m^2K across Europe, thermal bridges are potentially the most relevant heat transfer path in building walls.

This thesis presents part of my research activity in the field of thermal bridges in building envelopes, with particular emphasis on transient thermal performance assessment and experimental calibration of thermal models. The ultimate goal of these techniques is its application for a better envelope heat transfer analysis in building envelope retrofitting.

2 Structure

This thesis reports on research performed on new assessment methods related to transient multi-dimensional heat transfer in buildings. The thesis is structured by means of a collection of papers related to particular topics. These works are arranged in a logical sequence where the reader is initiated with state of the art analysis and methodological approaches, and is further introduced in numerical assessments. The last works are devoted to experimental assessment and numerical calibrations.

Most works have been developed specifically as independent, self-contained papers and published in international peer reviewed journals, and conferences. These papers are complemented with specific sections where consolidated information is introduced. The structure of this document is distributed as follows:

Section 3 presents the state of the art on heat transfer analysis in building envelopes. This section presents the overall status of this field, and consolidates particular state of the art analysis presented in other sections.

Section 4 presents a methodological approach to the assessment of building envelope retrofitting considering not only commonly used steady state and one-dimensional procedures, but also experimental multi-dimensional heat transfer analysis techniques developed within this thesis. This section is constructed based on the conference paper entitled *“Experimental assessment of thermal performance of building envelope retrofitting works”* presented within the EESAP7 conference.

Section 5 presents a numerical procedure for the disaggregation of one-dimensional and multidimensional heat transfer paths in the transient domain, particularly developed for harmonic boundary conditions, but generalizable for any other type transient thermal conditions. The content of this section is based on the journal paper entitled *“Disaggregation process for dynamic multidimensional heat flux in building simulation”* published in Energy and Buildings in 2017.

Section 6 presents the particularities of multidimensional heat transfer in a façade-floor slab architectural junction, and variations in the thermal field due to external envelope insulation. The performance of point thermal bridges is also introduced. Typical assessment parameters such as linear thermal transmittance and temperature factor are discussed, and the overall influence of thermal bridges over its representative surface area is evaluated. The content of this section is based on the conference paper entitled *“Estudio de transferencia de calor en los puntos de anclaje a forjado de una subestructura de fachada ventilada”* which was presented within the EECN conference. The original language of the paper (Spanish) is used in this section.

Section 7 presents experimental procedures for the assessment of steady-state one-dimensional thermal insulation performance. The content of this section is based on the journal paper "*Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale*", which was published in Energy and Buildings in 2016. In this work, averaging methods are used over experimental data and the thermal resistance value of an internal insulation system is delivered. This work also deals with high thermal resistance constructions and materials which are increasingly common in building energy retrofits.

Section 8 presents a procedure for the calibration of multidimensional heat transfer models based on experimental data, which characterizes the heat transfer in architectural junctions and delivers the differential heat transfer on this junction. This section is based on a journal paper entitled "*Performance Assessment of Thermal Bridge Elements into a Full Scale Experimental Study of a Building Façade*" published in Energy and Buildings in 2014.

Section 9 presents an experimental assessment of the differential thermal performance of an external thermal insulation system. This work is based on a conference paper entitled "*Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting*", presented in SBE16 Thessaloniki "*Sustainable Synergies from Buildings to the Urban Scale*" in 2016. In this work, the overall thermal transmittance of an externally insulated building envelope is obtained experimentally, and its thermal resistance compared with previous experimental assessments without the aforementioned external insulation system.

Sections 10 and 11 present the overall conclusions and opportunities for further research in the field of multidimensional heat transfer in architectural junctions.

This thesis is complemented with 2 annexes. In Annex 1, a review paper on the concept and activity of the KUBIK by Tecnalia test facility can be found. Annex 2 presents full bibliographic reference to the papers enclosed in this thesis.

3 State of the Art

3.1 Heat transfer in building envelopes

According to the Sustainable Building and Climate Initiative of the UN [1], and other sources [2-5], buildings are responsible for 40% of the global primary energy consumption. Aside from energy needs for appliances or Domestic Hot Water, a large amount of this is required for space conditioning (heating and cooling), to meet occupants comfort requirements. Intensive studies and development of techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings have been conducted during more than 50 years.

Within buildings, its envelopes -façades, roof, glazed areas…- are the main heat transfer path to the environment. Building envelopes are the physical interface between indoor and outdoor conditions, and their response to variations on these conditions such as temperature oscillations and incidence of solar radiation, substantially defines the heat dynamics of buildings. Roofs, façades, and glazed areas are responsible for over 60% of heat losses in conventional buildings.

Many of these losses occur through non-insulated walls, thus it is considered that there is a great heat flux reduction potential by incorporating additional insulation to building envelopes. Incorporation of thermal insulation can be performed on the outer and inner sides of the building envelope[6]. In some cases, injection of insulation in cavity walls is also possible.

In broad terms, External Thermal Insulation Composite Systems (ETICS) are increasingly favored over internal insulation approaches, due to a number of advantages like (a) lower disruption to occupants during retrofitting works, (b) no loss of internal space, (c) lower risk of surface or interstitial condensation as the existing substrate is kept close to internal temperature, and (d) more efficient thermal performance allowed by a continuous insulation layer that prevents thermal bridges at junctions with intermediate floors and walls.

In favor of the aforementioned insulation systems, many requirements are imposed in building codes to steady state thermal performance metrics of envelopes, to facilitate the introduction of building envelope insulation systems. In fact, along the last half of the past century, building energy codes have forced a trend towards more insulated building envelopes. This trend has been boosted by EU Energy Performance of Buildings Directives (EPBD) [4, 5], adopted by all EU member states. In this context, the relative relevance of thermal bridges has grown.

In developed countries in Europe, the building stock is already considered to be large when it is compared to demographic projections. It is even stated in [7] that population decline may eventually lead to an oversupply of housing in certain nations or regions. For this reason, the quest in energy performance improvement is mostly related to the already existing and ageing building stock, which will need to improve its thermal performance under the previously mentioned EPBD policies. This is recognized and supported by EU-level EPBC and Construction products Regulation (CPR) [8], and funding granted by the Horizon 2020 Framework Programme for Research and Innovation initiatives [9].

Among the aforementioned thermal insulation systems for building envelope, External Thermal Insulation Composite Systems (ETHICS) are one of the most commonly used alternatives. These systems potentially allow for a nearly complete avoidance of certain thermal bridges, but their practical implementation leads to performance uncertainties.

Although improving the thermal performance of building envelopes is a relatively expensive energy retrofit intervention, once the decision for the renovation of a Building is taken, incorporating additional thermal insulation is a robust solution. Thermal insulation layers increase 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).

Considering the present regulatory framework, all new buildings in the near future will be designed to achieve Nearly Zero Energy Building (NZEB) performance levels. The existing building stock will need to upgrade its performance by means of energy retrofitting at a slow but steady pace by means of the aforementioned energy retrofitting systems. NZEBs are characterized by a substantial improvement in envelope insulation levels compared with state of the art construction methods; along with reductions on heat losses at the ventilation system, and introduction of renewable energy systems.

3.2 Relevance of thermal bridges

A detailed analysis on the relevance of thermal bridges and how building codes deal with them in EU Member States was performed in [11]. The relevance of thermal bridges in the energy assessment of buildings was estimated in up to 30% of heating energy demand. This ratio is increased for highly insulated buildings. It was identified that although all building codes considered thermal bridges, these were commonly assessed through conservative default values. When dealing with renovation projects for already built buildings, the energy requirements for junctions are reduced or even not-imposed. The use of improved junctions compared to national default values was evaluated to improve the overall energy load by 15%.

[12] reviews calculation processes for thermal bridge assessment in the building codes. It is identified that, compared to the other aspects such as strict requirements for the thermal transmittance of the building envelope, the energy losses through thermal bridges are often not sufficiently taken into account. In most situations, the common practice is related to simplified approaches where calculations of thermal bridges are not required, or tabulated or default values in energy calculation software are used.

The same source indicates that for highly insulated buildings a correct thermal bridge accounting is evidently important and more attention is needed either to implement reliable simplified method or general calculation method. It is the opinion of this author that detailed calculations of thermal bridges are not more complicated than dynamic energy simulations, which is required in many countries.

In [13] a numerical and experimental work was carried out over a well-insulated steel-frame light construction similar to many commercially available insulation systems. In this work, thermal bridges were found to cause a 13-27% of increase in the one-dimensional heat transfer coefficient of a wall.

Furthermore, several previous works such as [14, 15], have identified that the thermal insulation level of building envelopes can be improved by up to 18%, with a correct design of junctions between envelope constructions.

In [16] several building envelope studies were reviewed, summarizing that the thermal performance of a wall reaches a 27%-44% of deviation from one-dimensional heat transfer analysis.

In [17], thermal bridges in several architectural junction details are studied, and thermal bridge coefficient values are positioned according to [18] in the range 0.59-1.02 W/mK for floor-wall junctions in several masonry wall configurations.

When distributed over a typical building with 3m slab-to-slab height, the lower figure (0.59 W/mK) provided in [18], is converted in a surplus 0.2W/m2K, which is in the same range of magnitude of many highly insulated contemporary building envelopes.

The evolution of various cases of thermal bridges before and after envelope insulation works is evaluated in [19, 20].

According to the cited works, within the new context with NZEBs, thermal bridges no longer are a minimal part of the heat balance of a building, but pay a significant role in it. However, it is common practice to define building envelope designs based on one-dimensional performance of insulation systems, disregarding multidimensional heat transfer paths such as window sills, slab-façade junctions, balconies, etc. In the process of neglecting these heat transfer paths leads to an infra-estimation of the overall envelope heat transfer is performed. To the authors' opinion, with the aforementioned relevance of multi-dimensional heat transfer in the total heat loss coefficient of a building envelope, more detailed assessment processes are needed.

Furthermore, there is increased awareness of the so-called 'performance gap' [21]. This performance gap is the mismatch between predicted and measured energy use in buildings, which is partially attributed to simplified energy modeling of building envelopes, defective workmanship and unrealistic design assumptions. This issue poses clear implication for strategic EU targets, especially considering that the underperformance tends to grow as technologies becomes more complex [22]. In order to find solutions for these shortcomings and improve our knowledge of their underlying causes, there is a critical need for in-situ tests of construction systems, as built and in service conditions.

3.3 Numerical Assessment procedures

The scientific community has conducted Intensive studies and developed techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings over more than 50 years. At present times, test and calculation methods are available. Specific methods, focused at various scales and approaches for the assessment of thermal performance of buildings are available, comprising from standardized material testing procedures to dynamic simulation software tools [23].

However, up to very recently the evolution of computational techniques for the assessment of energy consumption in buildings paid only marginal attention to multi-dimensional heat transfer. Along the development process of building simulation codes, one-dimensional heat transfer was prioritized. This prioritization was caused by two concurring reasons: With mostly poorly insulated buildings, one-dimensional heat transfer was highly predominant at that time, and at the same time, multi-dimensional heat transfer requires of comparably higher computational effort which was not available to most building simulation specialists until very recently.

Numerical modeling for multi-dimensional heat transfer is most commonly de-coupled from building simulation codes and performed under normalized steady-state boundary conditions [18]. Outcomes from these calculations can be introduced into building simulation codes by means of steady-state thermal performance parameters.

Normalized thermal bridge assessment procedures rely on the disaggregation of 1- 2- and 3-dimensional heat transfer processes in buildings. In its most simple modeling scheme, building envelopes are mainly characterized by one-dimensional (1D) heat transfer formulae. In these cases, the effect of heterogeneous elements (beams, window sills…) is neglected. However, thermal bridges are common in places where structural stresses are transmitted from façades to beam elements, or where different kinds of envelope constructions meet, etc. with variations in the geometry & materials among the different sides of the joint. In these areas, bi- or tri-dimensional (2D /3D) heat transfer phenomena are present, and 1D assumption cannot be applied.

3D heat transfer accounts for a small share of the total heat transfer in a building, as it is restricted to corners. However, although not addressed with sufficient depth in this thesis, 3D thermal bridges are common locations for cold spots where condensation and mold growth can occur.

In common practice, building envelope heat transfer is commonly approached as and equivalent 1D heat flow over the full envelope surface, considering an additional linear heat transfer, related to the length of the edge in which 2D heat flows occur, as formulated in (1).

$$\psi = L^{2D} - \sum U_j * l_j \quad (1)$$

Performance values of envelope constructions are most commonly provided through steady state approaches under standardized procedures: [24] for 1D & [18] for 2D/3D heat transfer.

Historically, 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 [25] are freely available to designers, but to the author´s 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 [26] cannot be applied and only qualitative assessments can be made by means of methods such as Infra-Red imaging.

In practical applications, thermal bridges are normally considered for the calculation of heating & cooling loads in buildings by means of simplified approaches. In ASIEPI [27] a detailed review of simulation software was performed and atlases [28-30] were published for building physicists. Thermal bridge atlases and best practice/accredited construction details are available in [31-33]. A review on normative compliance regarding thermal bridges in European countries [34] resulted in many compliance and assessment methods where various parameters such as temperature factor, lineal thermal transmittance… are used to assess the thermal quality of junctions. Overall, for each country, assessment methods may differ, commonly related to the application of thermal bridge atlases and default values.

Also, several reference dimensions are possible in the definition of geometries leading to multi-dimensional heat transfer. Methodological inconsistencies due to this and other factors are discussed in [20]. In [35], discrepancies in results attributed to different geometrical definition of the dimensions of thermal bridges are presented.

To the authors' belief, these simplified procedures should be amended. In this belief, it is considered that within highly insulated buildings, the sensitivity of the final result to the proper transient thermal modeling of thermal bridges is increased. This is also stated in some of the references suck as [12]

[36] performs a detailed numerical study on multi-dimensional heat transfer in many architectural details. It states that for the overall yearly heat transfer there is minimal difference between steady-state and transient models. However, deviations in the temperature factor are identified when dealing with transient boundary conditions.

Transient numerical models for architectural junctions have been developed in [37-40], where discretization methods such as finite element and finite difference methods are used. In [41], linear thermal bridges were modeled by a Boundary Element Model in the frequency domain. In [42, 43], a procedure for obtaining the z-transfer function of 3-dimensional thermal bridges is developed. In [40], harmonic heat flows for timber frame constructions are provided in terms of amplitude and phase shift parameters, under various modeling approaches. In the same work, it is identified that additional information rather than introducing equivalent parameters into the model for homogeneous walls is required to incorporate transient models into BES software in order to properly model thermal bridge elements. In equivalent-wall methods defined in [38], the architectural detail in the architectural junction is reduced to minimize the overlapping between the dynamics of the thermal bridge and the dynamics of the homogenous wall portions, when compared to standardized geometric requirements in [18]. Therefore, it could be concluded that the dynamics of a thermal bridge differs from that of the homogeneous walls, and that a specific disaggregation procedure for its dynamic modeling would be desirable.

In this process, it should also be considered the need for such methods in the context of dynamic behavior assessments of a full building/rooms. In most building energy simulation (BES) software, only 1D heat flow is calculated under dynamic boundary conditions. 2D/3D heat flow being incorporated as an increased value of 1D heat transfer, calculated under various simplifying approaches. Methods to implement time-varying 2D/3D heat flow into BES software have already been developed. In [44], a method for introducing dynamic 2D heat transfer in energy plus is developed, while in [38, 39, 45, 46], a transfer function of a 2D thermal bridge is obtained both through finite element & experimental techniques.

3.4 Experimental Assessment procedures

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.

Experimentation within building physics is commonly divided in on-site and laboratory assessment methods. Standardized assessment methods have been developed for both cases [26, 47]. As an intermediate step, several research facilities have been developed for on-site experimental assessment of energy performance under weather exposure conditions. In [48], a review on many available test facilities can be found. Assessment procedures in experimental facilities are more commonly focused on transient thermal performance metrics which are not commonly addressed by means of the aforementioned normalized assessments.

Anyhow, most experimental assessments performed in literature are related to one-dimensional heat transfer. On-site experiments [49] are commonly performed by means of temperature heat flux measurements. Measurements are performed for long periods, and the overall thermal resistance of the envelope construction is obtained by means of averaging processes.

Laboratory conditions allow for more sophisticated assessment methods So-called HOTBOX [47] devices perform one-dimensional heat transfer experimentation by means of guarded or calibrated setups where calorimetric assessments of the heat transfer are made.

Similar approaches are followed under transient ambient conditions within outdoor experimental test setups such as PASSYS/PASLINK test environments [50-57]. However, in experiments conducted in these facilities, assessment methods are substantially more advanced, and dynamic assessment methods are commonly used. The switch to dynamic assessment methods is related to the need to properly address the influence of solar radiation and other variable outdoor boundary conditions within the experiment.

In fact, dynamic assessment methods and tools such as LORD [58] and CTSM/CTRM-r [59] is increasingly common within the last decades in many experimental works such as [46, 58, 60, 61].

[62] compares characterization methods for the determination of the thermal resistance of building components from onsite data. It concludes that dynamic data analysis methods have an improved performance compared to semi-stationary methods. Dynamic methods are able to better cope with the influences of weather conditions. These methods are identified as sutiable even to deduce reliable thermal resistance from summer measurements, which are characterised by a large capacitive functioning of walls.

[63] applies ISO [24] & ASTM [64] 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 ontain satisfactory ressults from steady-state methods, while in others, campaign lengths up to 20 days are required. Dynamic methods perform substantially better, delivering robust ressults in 5 to 10 days.

In [45], a hotbox device was used to experimentally characterize the thermal performance of a construction comprising multi-dimensional heat transfer. In this particular case, the transfer function of the assembly and the configuration of an equivalent wall were calculated. With this exception made, experimental assessment of multi-dimensional heat transfer is commonly limited to the use of infra-red imaging technologies, or local measurement of temperatures in cold spots.

Some incipient approaches to quantitative thermographic assessments are provided in [65].

In recent years, infrastructures for the experimental assessment of building energy performance have increased in complexity. Since the beginning of the 21st century, several full scale experimental facilities have been constructed, consisting in multi-rise buildings where envelopes are constructed/installed on-site. In these sites, substantially greater attention is given to non-optimal test conditions, as multi-dimensional heat transfer, infiltration…and other phenomena are introduced in tests, not as inaccuracies, but as topics of experimentation themselves.

One of these facilities is the Kubik by Tecnalia research facility [66-81]. This is a research infrastructure located in Derio, Spain. KUBIK bridges the gap between laboratory testing and full scale market deployment of building envelopes, HVAC & ICT solutions for Energy Efficiency, where the full energy interaction between different elements is evaluated.

Figure 1: Kubik by Tecnalia research facility. General view (left) & specific façade used for the experiment (right)

In this test environment, large portions of the envelope are modified for each test, and architectural details, construction materials, and assembly processes are selected to match reality. In figure 1, a 2 story- high façade construction is shown where several architectural junctions with floor slabs were introduced on purpose. As expected these resulted in thermal bridges.

Under the particularities of these experiments, particular solutions need to be developed to experimentally assess the thermal performance of these junctions.

In [48] several additional facilities with similar ambitions are referred.

In [82, 83] a decision support methodology was developed to guide thermal analysts in the process of definition of test environments for the assessment of energy performance in buildings. In this work, it is assumed that it is difficult to provide generalist assessment methods under varying infrastructure and project scopes. Instead, the particular aims in each project for the measuring the thermal performance of buildings or building components are considered in the development of a methodology which guides informed decisions. The selection of most suitable methods and adaptation of methods and standards to the particular needs of the user is facilitated by the decision tree presented.

Underlying in all cited works and procedures, it is concluded that full scale testing requires quality on all topics within the experimental sequence: test infrastructure, test setup, assessment method, sensors, data analysis procedures, data acquisition systems, etc.

3.5 Integration into building simulation software

The dynamic performance of buildings is commonly assessed by means of simulation. In this field, Building Energy Simulation (BES) tools have been developed over the last decades with increasing accuracy. Software such as Energy plus [84] and TRNSYS [85] has evolved to a level of complexity, where its accuracy is commonly related to modeling assumptions and input data introduced by users of these tools rather than by the tools themselves. Strachan et al. [86] performed a comparative analysis of simulation output from many researchers on a very detailed validation experiment.

In relation with the introduction of multi-dimensional heat transfer, different approaches have been followed. In some cases, thermal bridges are simply neglected, or their influence estimated as a surplus heat transfer based on normative or bibliographic data. When the effect of thermal bridges is explicitly introduced, two main trends appear: The introduction of steady state heat transfer coefficients or the calculation of equivalent wall layers [41, 42].

Heat transfer coefficients are calculated by means of finite element software such as [23, 80], and then introduced as an additional coupling between indoor and outdoor ambiences. In this approach, it is assumed that the thermal bridge responds immediately to changes in its bounding temperature conditions.

Equivalent wall layers require of transient thermal modeling or experimentation in order to obtain a transient thermal model. This modeling is commonly achieved by means of transient finite element/difference software such as [44-46]. Transient thermal models are commonly expressed by means of transfer function or response factors. These models then are backward identified to equivalent wall constructions with similar thermal performance. An example of this can be foun in [91]

In backward identification, the definition of the equivalent homogeneous wall is performed by means of error minimization algorithms which target at minimal prediction errors in output heat flux or temperatures between the original heat transfer and the equivalent homogeneous wall. To the authors’ belief, this is an unnecessary step which at the same time is time consuming, requires relevant technical skills, and introduces a source of error. For this reason, a more direct path should be prioritized, where transient thermal models such as transfer functions, response factors, etc. would be directly introduced within BES systems. This of course would imply relevant efforts in the adaptation of building simulation software such as [84] but would more easily be implemented in programs where modeling is performed in a more open environment [85, 92].

3.6 Conclusions

The overall state of the art of thermal bridge assessment has been reviewed, with particular focus on transient modeling, experimentation and integration within Building Energy Software. Due to many factors, such as the historical limits of computer capacity, and relatively minor relevance of thermal bridges within poorly insulated buildings, assessment methods have not been sufficiently spread.

Overall, numerical assessment has been limited to steady-state calculations, and experimental assessments have mainly by-passed thermal bridging by mitigation in experimental design or avoidance to measure in influenced areas.

However, with the wave of modern building codes, nearly zero energy buildings, and full scale experimental research facilities, attention should be paid to every minimal detail. Thermal bridges should be integrated into thermal assessments, due to its increased relative relevance in the heat balance of buildings along with incremental thermal insulation of building envelopes.

It is critical to achieve advances in the transient thermal performance of thermal bridges both for numerical and experimental procedures. Advanced numerical procedures would lead to suitable dynamic models (e.g. response factor model) which would then be integrated in BES systems. Experimental assessment methods would enrich experimental performance assessment procedures to deliver more accurate baselines and intervention potentials within energy retrofits of building envelopes.

3.7 References

[1] United Nations Environment Programme – Sustainable Building and Climate Initiative, 2015. Retrieved from http://www.unep.org/sbci on 28/04/2016

[2] U.S. Department of Energy (DOE), 2008 Buildings Energy Data Book, 2008.

[3] Pérez-Lombard L., et al, A review on buildings energy consumption information, Energy and Buildings 40, 2008

[4] E.U., 2002/91/EC of the European Parliament and of the Council of 16th December 2002 on the Energy Performance of Buildings, 2002.

[5] E.U., 2010/31/EU of the European Parliament and of the Council, of 19 May 2010 on the Energy Performance of Buildings (recast), 2010.

[6] Dionysios I. Kolaitis, Emmanouil Malliotakis, Dimos A. Kontogeorgos, Ioannis Mandilaras, Dimitrios I. Katsourinis, Maria A. Founti, Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings, Energy and Buildings, Volume 64, September 2013, Pages 123-131, ISSN 0378-7788.

[7] Housing Statistics in the European Union 2010, Austria, Federal Ministry for Science, Research and Economy, https://www.bmwfw.gv.at/Wirtschaftspolitik/Wohnungspolitik/Documents/housing_statistics_in_the_european_union_2010.pdf (2017/05/15)

[8] Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products.

[9] European Commission, Energy-efficient Buildings (EeB), public private partnership http://ec.europa.eu/research/industrial_technologies/energy-efficient-buildings_en.html (2017/05/15)

[10] European Commission, HORIZON 2020, The EU Framework Programme for Research and Innovation, https://ec.europa.eu/programmes/horizon2020/ (2016/12/09)

[11] 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/ (2014/07/10)

[12] Kalle Kuusk, Jarek Kurnitski, Targo Kalamees, Calculation and compliance procedures of thermal bridges in energy calculations in various European countries, In Energy Procedia, Volume 132, 2017, Pages 27-32.

[13] Zalewski, L., Lassue, S., Rousse, D., & Boukhalfa, K. (2010). Experimental and numerical characterization of thermal bridges in prefabricated building walls. Energy Conversion and Management, 51(12), 2869–2877.

[14] Ge, H., McClung, V. R., & Zhang, S. (2013). Impact of balcony thermal bridges on the overall thermal performance of multi-unit residential buildings: A case study. Energy and Buildings, 60, 163–173.

[15] Hua Ge, Fuad Baba, Effect of dynamic modeling of thermal bridges on the energy performance of residential buildings with high thermal mass for cold climates, In Sustainable Cities and Society, Volume 34, 2017, Pages 250-263.

[16] Karambakkam, B. K., Spitler, J. D., & Leonard, C. M. (2003). A One-dimensional Approximation for Transient Multi- dimensional Conduction Heat Transfer in Building Envelopes, (1995).

[17] Larbi, a. Ben. (2005). Statistical modeling of heat transfer for thermal bridges of buildings. Energy and Buildings, 37(9), 945–951.

[18] EN ISO 10211:2007. Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations

[19] T.G. Theodosiou, A.M. Papadopoulos, The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy Build. 40 (11) (2008) 2083–2089.

[20] B. Berggren, M. Wall, Calculation of thermal bridges in (Nordic) building envelopes – risk of performance failure due to inconsistent use of methodology, Energy Build. 65 (2013) 331–339.

[21] De Wilde P. The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction 2008; Vol. 41, p. 40–49.

[22] Miles-Shenton D et al. LowCarb4Real: Developing Low Carbon Housing, Lessons from the Field, Leeds Metropolitan University; 2009.

[23] Clarke J.A. Energy simulation in building design. Butterworth-Heinemann, 2nd edition, Oxford (2001).

[24] EN ISO 6946: 2007. Building components and building elements – Thermal resistance and thermal transmittance – Calculation Method

[25] THERM, Two-Dimensional Building Heat-Transfer Modeling, LBNL, https://windows.lbl.gov/software/therm/therm.html (18/05/2016)

[26] EN ISO 9869-1:2014 thermal insulation –Building elements- In-situ measurements of thermal resistance and thermal transmittance – Part 1: Heat Flow Meter Method

[27] IEE SAVE ASIEPI Project, Assessment and Improvement of the EPBD Impact, "The final recommendations of the ASIEPI project: How to make EPB-regulations more effective? Summary report", 2010, Intelligent Energy Europe Programme, contract EIE/07/169/SI2.466278

[28] Schild, P.; Blom, P.: Good practice guidance on thermal bridges and construction details – Part 1: Principles. Information paper 188 (2010). http://www.buildup.eu/publications/8239

[29] Schild, P.: Good practice guidance on thermal bridges and construction details - Part 2: Good examples. Information paper 189 (2010). http://www.buildup.eu/publications/8241

[30] Tilmans, A. (2009). Software and Atlases for evaluating Thermal Bridges. Information paper 152. http://www.buildup.eu/node/5657

[31] IETcc, CEPCO & AICIA, Catálogo De Elementos Constructivos Del Cte, v 6,3, 2010.

[32] Accredited Construction Details (ACDs) for Part L. for England & Wales. 2007, http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/bcassociateddocuments9/acd#SteelFrameDetails (2016/02/26)

[33] Enhanced Construction Details (EDCs): Thermal bridging and Airtightness. Energy Saving Trust, UK. http://www.energysavingtrust.org.uk/sites/default/files/reports/CE302%20-%20ECD_thermal%20bridging%20and%20airtightness.pdf (2016/02/26)

[34] Citterio, M. et Al. (2009). Thermal bridges in the EBPD context: overview on MS approaches in regulations. Information paper 64. http://www.buildup.eu/publications/1449

[35] DA DB-HE /3, Documento de apoyo al Documento Básico DB-HE Ahorro de la Energía. Puentes Térmicos, Ministerio de Fomento, Spain 2014.

[36] Van Nieuwenhove, S., Numerical analysis of thermal bridges under dynamic boundary conditions, Master`s dissertation, University of Ghent, 2014.

[37] Al-Sanea, S. a. (2003). Finite-volume thermal analysis of building roofs under two-dimensional periodic conditions. Building and Environment, 38(8), 1039–1049.

[38] Martin, K., Erkoreka, a., Flores, I., Odriozola, M., & Sala, J. M. (2011). Problems in the calculation of thermal bridges in dynamic conditions. Energy and Buildings, 43(2-3), 529–535.

[39] Martín, K., Flores, I., Escudero, C., Apaolaza, A., & Sala, J. M. (2010). Methodology for the calculation of response factors through experimental tests and validation with simulation. Energy and Buildings, 42(4), 461–467.

[40] Viot, H., Sempey, a., Pauly, M., & Mora, L. (2015). Comparison of different methods for calculating thermal bridges: Application to wood-frame buildings. Building and Environment, 93, 339–348.

[41] Tadeu, a., Simões, I., Simões, N., & Prata, J. (2011). Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. Energy and Buildings, 43(12), 3685–3695.

[42] Kossecka, E., & Kosny, J. (2004). Two-Step Procedure for Determining Three-Dimensional Conduction Z-Transfer Function Coefficients for Complex Building Envelope Assemblies, 1–11. Retrieved from http://www.ornl.gov/sci/roofs+walls/staff/papers/new_075.pdf

[43] Kossecka, E., & Kosny, J. (2005). Three-dimensional conduction z-transfer function coefficients determined from the response factors. Energy and Buildings, 37(4), 301–310.

[44] García Gil, A., Modelado de Puentes Térmicos en la Simulación Térmica de Edificios, Departamento de Máquinas y Motores Térmicos ETSII, Universidad de Málaga, 2008.

[45] Martin K., 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).

[46] Martin, K. et al, Equivalent wall method for dynamic characterisation of thermal bridges, Energy And Buildings 55 (2012)

[47] ISO 8302:1991 Thermal insulation -- Determination of steady-state thermal resistance and related properties -- Guarded hot plate apparatus

[48] Janssens A, IEA EBC Annex 58, Report of Subtask 1a: Inventory of full scale test facilities for evaluation of building energy performances, KU Leuven 2016, ISBN: 9789460189906, http://www.kuleuven.be/bwf/projects/annex58/data/A58_Final_Report_ST1a.pdf (2016/11/30)

[49] Galliano, R.; Ghazi Wakili, K.; Stahl, Th.;Binder, B.; Baniotti, B.; Performance evaluation of aerogel-based and perlite-based prototyped insulations for internal thermal retrofitting: HMT model validation by monitoring at demo scale. Energy and Buildings 2016, 126, 275–286

[50] Norlén U. Estimating thermal parameters of outdoor test cells. Build Environ 1990;25(1):17-24.

[51] Madsen H, Holst J. Estimation of continuous-time models for the heat dynamics of a building. Energy Build 1995 3;22(1):67-79.

[52] Owen JL. Solar building—European Union Research and Development Programmes. Solar Energy 1996 0;58(1–3):127-135.

[53] Wouters P, Vandaele L, Voit P, Fisch N. The use of outdoor test cells for thermal and solar building research within the PASSYS project. Build Environ 1993 4;28(2):107-113.

[54] Vandaele L, Wouters P. The PASSYS Services: Summary report. BBRI & European Commission – Directorate - General XII, EUR 15113 EN, Brussels, 1994. .

[55] Van Dijk HAL, Van der Linden GP. The PASSYS method for testing passive solar components. Build Environ 1993 4;28(2):115-126.

[56] Development of the PASSYS Test Method, Research Report PASSYS Subgroup Test Methodologies. Ed. H.A.L. van Dick, TNO Building and Construction Research. CEC DG XII Brussels, 1993. EUR 15114 EN.

[57] Hahne E, Pfluger R. Improvements on PASSYS test cells. Solar Energy 1996 0;58(4–6):239-246.

[58] Gutschker, O.; Parameter identification with the software package LORD, Building and Environment, Special Issue: Outdoor Testing, Analysis and Modelling of Building Components, 2008, 43(2), 163–169

[59] CTSM-R Development Team, Continuous Time Stochastic Modeling in R. User's Guide and Reference Manual, 2015. http://ctsm.info/pdfs/ctsmr-reference.pdf (2016-06-14)

[60] Strachan, P.A.; Vandaele, L. Case studies of outdoor testing and analysis of building components. Building and Environment, 2008, 43(2), 129-142.

[61] Naveros, I.; Bacher, P.; Ruiz, D.P.; Jiménez, M.J.; Madsen, H.; Setting up and validating a complex model for a simple homogeneous wall, Energy and Buildings, 2014, 70, 303–317

[62] Deconinck, A.H., Roels,S., Comparison of characterisation methods determining the thermal resistance of building components from onsite measurements, In Energy and Buildings, Volume 130, 2016, Pages 309-320.

[63] Ioannis A. Atsonios, Ioannis D. Mandilaras, Dimos A. Kontogeorgos, Maria A. Founti, A comparative assessment of the standardized methods for the in–situ measurement of the thermal resistance of building walls, In Energy and Buildings, Volume 154, 2017, Pages 198-206.

[64] ASTM C1155 - 95(2013) Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data

[65] O'Grady, M., Lechowska, A., Harte, A., Infrared thermography technique as an in-situ method of assessing heat loss through thermal bridging, In Energy and Buildings, Volume 135, 2017, Pages 20-32.

[66] Tecnalia, "Kubik by Tecnalia", http://www.energiaenedificacion.com/kubik-by-tecnalia/ [d2014/07/07

[67] Tecnalia, "KUBIK by Tecnalia, Experimental Infrastructure for the Configuration of Zero Energy Buildings", http://www.tecnalia.com/en/sustainable-construction/infrastructure-a-equipment/infrastructure-a-equipment.htm, 2012.

[68] Estudio de investigación sobre eficiencia energética y viabilidad de la aplicación de fachadas ventiladas en soluciones de rehabilitación, Anexo 4: Caracterización dinámica de los elementos de frente de forjado, TECNALIA, ERAIKAL-12.

[69] Garay, R. et Al, Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, Energy and Buildings Volume 85, December 2014, Pages 579–591. http://dx.doi.org/10.1016/j.enbuild.2014.09.024

[70] Garay, R et Al, Energy efficiency achievements in 5 years through experimental research in KUBIK, 6th International Building Physics Conference, IBPC 2015, Torino, 2015

[71] Chica, JA et al, KUBIK: Open building approach for the construction of an unique experimental facility aimed to improve energy efficiency in buildings. Proceedings of the O&SB2010 "Open and Sustainable Building", ISBN: 978-84-88734-06-8

[72] Roberto Garay Martinez, Eunate Goiti, Gudrun Reichenauer, Shanyu Zhao, Matthias Koebel, Aitor Barrio: Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. Energy and Buildings 06/2016; 128.

[73] Peru Elguezabal, Roberto Garay: Experiences when employing different alternatives for envelope upgrading. 05/2015; 3(1). DOI:10.3233/FDE-150032

[74] Dionysios I. Kolaitis, Roberto Garay, Maria A. Founti: An experimental and numerical simulation study of an active solar wall enhanced with phase change materials. 05/2015; 3(1).

[75] Roberto Garay: Highly insulated systems for energy retrofitting of façades on its interior. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, Thessaloniki; 10/2016

[76] Roberto Garay: Hygrothermal assessment of a prefabricated timber-frame construction based in hemp. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, Thessaloniki; 10/2016

[77] Roberto Garay: Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, Thessaloniki; 10/2016

[78] Roberto Garay Martinez, Elguezabal Esnarrizaga, Julen Astudillo Larraz: Integrated Solar Thermal Systems for renovation of external walls. Advanced Building Skins 2016, Bern; 10/2016

[79] Idurre Fernandez, Roberto Garay, Raul Urrea, Amaia Aramburu, Igor Madariaga: New Sustainable Construction System With Hemp Fiber Insulation. REHABEND 2016, Burgos; 05/2016

[80] Roberto Garay, Amaia Uriarte: Superinuslation Solutions For The Internal Insulation In Energy Retrofitting. REHABEND 2016, Burgos; 05/2016

[81] Roberto Garay, Amaia Uriarte, Ines Apraiz: Calibration Procedures for Multidimensional Heat Transfer Models Based on On-site Experimental Data. 6th International Building Physics Conference, IBPC 2015, Turin; 06/2015

[82] Roels S, IEA EBC Annex 58, Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements

[83] Fletcher M., Optimising test environment and test set up for characterizing actual thermal performance of building components and whole buildings 6th International Conference on Building Physics for a Sustainable Built Environment IBPC 2015, Torino.

[84] EnergyPlus v8.4, EnergyPlus™ Documentation, Engineering Reference, https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf (23/02/2016)

[85] TRNSYS 16 Documentation, Volume 6, Multizone Building, http://web.mit.edu/parmstr/Public/Documentation/06-MultizoneBuilding.pdf (23/02/2016)

[86] Strachan, P., Monari, F., Kersken, M., Heusler, I., IEA Annex 58: Full-scale Empirical Validation of Detailed Thermal Simulation Programs, Energy Procedia 78 (2015), 3288-3293, 6th International Building Physics Conference, IBPC 2015

[87] TRISCO, Physibel, http://www.physibel.be/v0n2tr.htm (2016/11/30)

[88] ANSYS, Simulation Driven Product Development, http://www.ansys.com/ (2016/11/30)

[89] COMSOL Multiphysics, https://www.comsol.com/ (2016/11/30)

[90] VOLTRA, Physibel, http://www.physibel.be/v0n2vo.htm (2016/11/30)

[91] Kośny, J., Kossecka, E., Multi-dimensional heat transfer through complex building envelope assemblies in hourly energy simulation programs, In Energy and Buildings, Volume 34, Issue 5, 2002, Pages 445-454.

[92] Modelica, https://www.modelica.org/ (2016/12/09)

4 Methodology

Experimental assessment of thermal performance of building envelope retrofitting works

Roberto Garay Martinez

4.1 Abstract

On-site experimental thermal assessment procedures for building envelopes are commonly limited by one-dimensional heat transfer assessment by means of averaging processes. With the evolution of building envelope insulation systems reaching almost its technical limits in NZEB, thermal performance assessments need to focus on other architectural elements whose influence is increased within this context.

In this work, a methodological reformulation to the assessment of building envelope retrofits is performed, where other relevant heat transfer paths are studied. Particularly, and due to its relevance, structural in the façade-slab interaction are used as a case study. 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.

Heat transfer phenomena around these junctions are clearly multidimensional, and transient under outdoor exposure conditions. Experimental and numerical procedures are defined to tackle this complexity. The proposed approach includes the construction of a dynamic multidimensional heat transfer model where experimental boundary conditions are introduced and its thermal properties calibrated to match experimental observations.

Calibrated thermal models are later used to incorporate various envelope retrofit systems and evaluate performance metrics as defined by each particular project specification.

4.2 Introduction

Building envelopes are the main heat transfer path from buildings to its environment. Building envelopes – roofs, façades, and glazed areas- are responsible for over 60% of heat losses in conventional buildings. It is considered that 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 the basics of the improved performance is based on the thermal transmittance of the wall4.8, which is defined by the thermal conductivity and the thickness of the composing materials, where properties insulation material layers are critical.

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

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 [1] are freely available to designers, but to the author´s 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 [2] cannot be applied and only qualitative assessments can be made by means of methods such as Infra-Red imaging.

In this paper, a hybrid numerical and experimental procedure is proposed to assess the present thermal performance of an architectural junction and its performance under the feasible alternative retrofitting possibilities.

Ultimately, this allows for a more detailed assessment of the thermal performance of a retrofitting intervention.

4.3 Thermal assessment methodology

Thermal bridges are construction details where non.one dimensional heat transfer occurs. As such, heat flux in these locations cannot be measured directly by means of heat flow meters. A thermal assessment method is proposes which bases its assessment of the heat flow across architectural junctions based on several localized temperature and heat flow measurements, which are then used to calibrate a dynamic numerical thermal model which is later used to provide accurate heat transfer assessment of the present architectural junction and possible alternatives for the thermal retrofitting of the building envelope.

The ultimate 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 bibliographical means. 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.

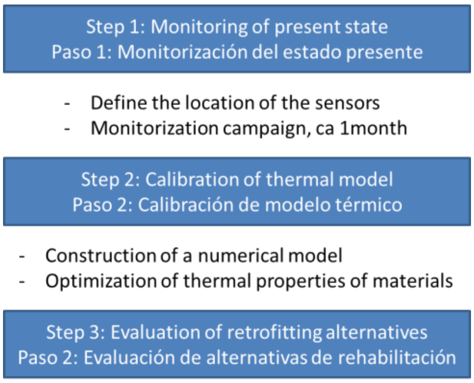


Figure 1: Thermal assessment sequence.

4.4 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. In figure 2, a monitoring scheme is proposed for a slab-façade junction.

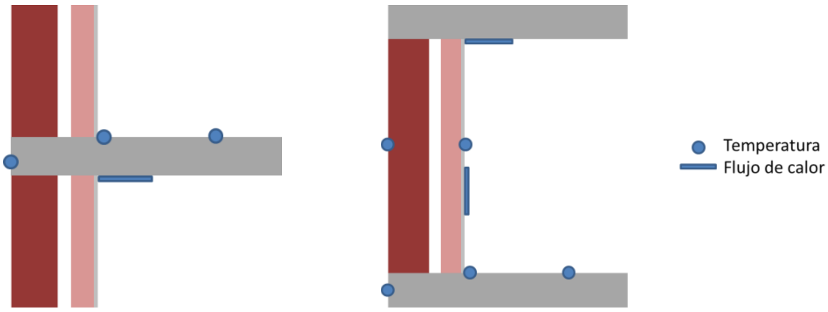


Figure 2: Monitoring scheme of a slab-façade junction (left), distribution of sensors in a multi-story monitoring (right).

In order to facilitate the experimental process, this step 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 monitoring 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).

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

4.5 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 [3, 4] 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.

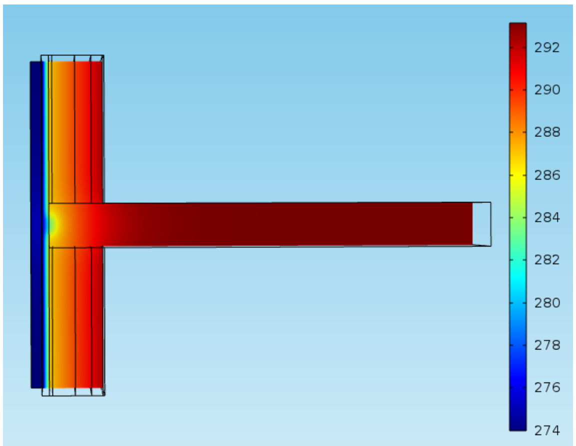


Figure 3: Thermal model of an architectural junction. [11]

Boundary condition data from the monitoring campaign is introduced in this model, and a dynamic thermal simulation is performed over the monitored period. In this activity, thermal properties of materials and modeling assumptions are varied to minimize de observed error in output variables when compared with monitored spots in the physical junction within the monitored campaign.

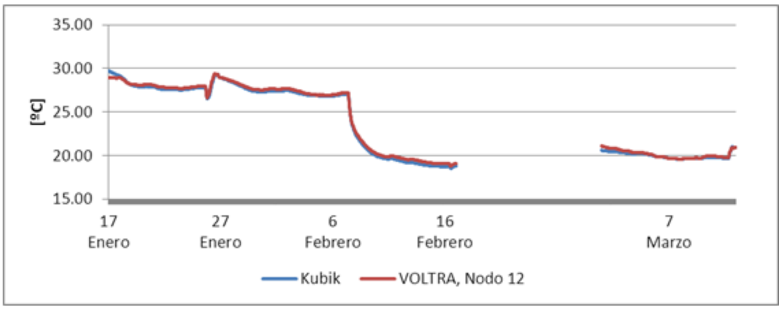


Figure 4: Calibrated output signal on a thermal model. [12][13]

At the end of this process, the thermal model is classified as “Calibrated”, and can be used for later assessment of retrofitting alternatives. 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, if the thermal state in all the monitored spots is correctly predicted with the thermal model, to the authors’ belief, it could be reasonable to accept that the calibrated thermal model can be used to predict the thermal performance of the full architectural junction.

4.6 Step3: Proposal of retrofitting 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 dynamic thermal model, which can be used to perform both dynamic 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 [5], but with calibrated thermal parameters for the baseline junction
- Contribute to the calculation of the overall coupling coefficient of the building envelope under standard [6]
- Calculate the dynamic thermal response of the architectural junction under harmonic boundary conditions similar to [7]
- Obtain transfer functions and response factors of the architectural junction by procedures such as [8]
- 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 [9]
- Perform heat transfer analysis of the architectural junctions for the verification of energy savings in energy performance contracts by means of IPMVP [10] 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.).

4.7 Discussion

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 monitoring market, it could be expected that the intrusiveness of the methodology could be further reduced by removing wires in the monitoring process.

4.8 Reference

[1] THERM, Two-Dimensional Building Heat-Transfer Modeling, LBNL, https://windows.lbl.gov/software/therm/therm.html (18/05/2016)

[2] EN ISO 9869-1:2014 thermal insulation –Building elements- In-situ measurements of thermal resistance and thermal transmittance – Part 1: Heat Flow Meter Method

[3] EN ISO 6946: 2007, Building Components and Building Elements - Thermal Resistance and Thermal Transmittance - Calculation Method

[4] Catálogo De Elementos Constructivos Del Cte, IETCC, 2010, http://www.codigotecnico.org/index.php/menu-catalogo-informatico-elementos-constructivos (18/05/2016)

[5] EN ISO 10211:2007: Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations.

[6] EN ISO 13790:2008: Energy performance of buildings. Calculation of energy use for space heating and cooling.

[7] EN ISO 13786:2007 Thermal performance of building components. Dynamic thermal characteristics. Calculation methods

[8] Martín, K., Flores, I., Escudero, C., Apaolaza, A., & Sala, J. M. (2010). Methodology for the calculation of response factors through experimental tests and validation with simulation. Energy and Buildings, 42(4), 461–467. http://doi.org/10.1016/j.enbuild.2009.10.015

[9] Gacía Gil, A., Modelado de Puentes Térmicos en la Simulación Térmica de Edificios, ETSII Málaga, 2008. https://es.scribd.com/doc/26313726/Modelado-de-Puentes-Termicos-en-la-Simulacion-Termica-de-Edificios (18/05/2016)

[10] IPMVP International Performance Measurement and Verification Protocol, Volume 1, EVO, 2012 http://evo-world.org/ (18/06/2016)

[11] BRESAER, BREakthrough Solutions for Adaptable Envelopes in building Refurbishment EU h2020 GA Nº 637186.

[12] Estudio de investigación sobre eficiencia energética y viabilidad de la aplicación de fachadas ventiladas en soluciones de rehabilitación, Anexo 4: Caracterización dinámica de los elementos de frente de forjado, TECNALIA, ERAIKAL-12.

[13] Garay, R. et Al, Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, Energy and Buildings Volume 85, December 2014, Pages 579–591. http://dx.doi.org/10.1016/j.enbuild.2014.09.024

5 Mathematical formulation of dynamic Multi-dimensional Heat Transfer

Disaggregation process for dynamic multidimensional heat flux in building simulation

Roberto Garay Martinez, Alberto Riverola, Daniel Chemisana

5.1 Abstract

Heat transfer across envelopes (façade, roof, glazed areas) represents a big share of the energy flow within the heat balance of buildings. This paper focuses on areas of the envelope where multi-dimensional heat transfer occurs. These areas are commonly defined as thermal bridges, due to a localized reduction of thermal resistance of constructions in these places. This paper reviews common standardized methods to assess heat transfer in buildings, under various modelling assumptions: one-dimensional, multi-dimensional, steady state and dynamic. Within presently developed modelling and assessment methods, a need for improvement has been identified over existing methods for the thermal assessment of multi-dimensional heat transfer under dynamic conditions. A phasorial approach to differential heat transfer in thermal bridges has been developed, which serves as the dynamic extension of steady-state thermal bridge coefficients. This formulation is applied to the junction of a masonry wall with a concrete slab.

5.2 Nomenclature

Variables		
A	Area	m2
C	Response factor (overall heat flow rate)	W/K
c	Response factor (partial heat flow density)	1D: W/m2K 2D: W/mK 3D: W/K
d	Thickness of a material layer	M
f	Decrement factor	-
L	Thermal coupling coefficient	3D: W/K 2D: W/mK
l	Length	m
N	Number of 1D components	-
Q	Heat flow rate	W
q	Density of heat flow rate	W/m2
R	Thermal resistance	m2K/W
T	Temperature	K
U	Surface thermal transmittance, Thermal transmittance	W/m2K
Y	Periodic thermal transmittance	W/m2K
λ	Thermal conductivity	W/mK
θ	Phase of vector	-
φ	Phase difference	hour
χ	Point thermal transmittance	W/K
Ψ	Linear thermal transmittance	W/mK

Subscripts	
BC	Boundary condition
e	External
ei	Exterior-interior
i	Internal
ii	Interior-interior
se	External surface
si	Internal surface
t	Time
tot	Total
1D	1-dimensional
2D	2-dimensional
3D	3-dimensional
1,2,3,…n	Individual layers in a 1D construction
i, j, k	Individual elements
y	Individual time step
^	Harmonic property
˙	Instantaneous value

5.3 Introduction

Up to 40% of primary energy consumption in developed countries is related to buildings [1] [2] [3] [4], where a large share is used for space heating and cooling, to meet occupants' comfort requirements. The scientific community has conducted Intensive studies and developed techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings over more than 50 years. At present times, various test and calculation methods are available, which focus on different scales and approaches for the assessment of thermal performance of buildings, from standardized material testing procedures to dynamic simulation software tools [5].

Heat transfer across building envelopes has a significant influence on the heat balance of buildings. Building envelopes are the physical interface between indoor and outdoor conditions, and their response to variations on these conditions, such as temperature oscillations and incidence of solar radiation, substantially defines the heat dynamics of buildings. For this reason, building codes impose many requirements on the steady state performance metrics of envelopes, such as maximum allowances on the thermal transmittance of envelopes, window ratio, overall heat loss coefficient, etc.

The dynamic performance of buildings is commonly assessed by means of simulation. In this field, Building Energy Simulation (BES) tools have been developed over the last decades with increasing accuracy. Software tools such as Energy Plus [6] and TRNSYS [7] have evolved to such a level of complexity that their accuracy is commonly related to modelling assumptions and input data introduced by users of these tools, rather than by the tools themselves. Strachan et al. [8] performed a comparative analysis of simulation outputs from several researchers on very detailed validation experimental campaigns.

However, some fields still remain where building simulation tools have not been fully developed or their use has not been fully introduced to the building simulation community. Simulation tools are in constant evolution to meet simulation needs imposed by new construction techniques, dynamic systems and highly insulated houses such as Nearly Zero Energy Buildings (NZEB).

NZEBs are characterized by a substantial improvement in envelope insulation levels compared with state of the art construction methods, along with reductions on heat losses related to ventilation & air infiltration and the introduction of renewable energy systems. Within such environments, thermal bridges are no longer a minimal part of the heat balance of a building, but may play a significant role in it. In [9] a numerical and experimental study was carried out over a well-insulated steel-frame lightweight construction, similar to many commercially available insulation systems. In this work, thermal bridges were found to cause an increase of 13-27% in the one-dimensional heat transfer coefficient of a wall.

In practical applications for the calculation of heating & cooling loads in buildings, thermal bridges are usually considered by means of simplified approaches. In ASIEPI [10] a detailed review of simulation software was performed and atlases [11-13] were published for building physicists. Thermal bridge atlases and best practice/accredited construction details are available in [14, 15, 16]. A review on normative compliance regarding thermal bridges in European countries [17] highlighted differing compliance and assessment methods, where various parameters were assessed, such as temperature factor, lineal thermal transmittance, etc. Overall, while assessment methods for each country may differ, most of them are based on the application of thermal bridge atlases and default values.

Several previous works such as [18] have identified that the thermal insulation level of building envelopes can be improved up to 18% with a correct design of junctions between adjacent envelope constructions. In [19] several building envelope studies were reviewed, summarizing that the multi-dimensional thermal performance of a wall reaches a 27%-80% deviation from one-dimensional heat transfer analysis. In [20], the thermal bridge of several architectural junction details is assessed, where thermal bridge coefficient values according to [21] are positioned in the range of 0.59-1.02 W/mK for floor-wall junctions in several masonry wall configurations.

The evolution of various cases of thermal bridges before and after envelope insulation works is evaluated in [22, 23].

In order to bring the aforementioned figures from [21] to the context of highly insulated envelopes, the lower figure (0.59 W/mK) is akin to the heat loss coefficient of a wall with a U-value of 0.2 W/m2K within a 3m slab-to-slab height configuration (0.6 W/mK).

For assessing multi-dimensional heat transfer, different reference dimensions can be taken. Methodological inconsistencies due to this and other factors are discussed in [23]. In [24], discrepancies in results attributed to different geometrical definitions of the dimensions of thermal bridges are presented.

Considering that the relevance of multi-dimensional heat transfer in building envelopes is increasingly impacting the heat balance of buildings in the path to NZEBs, new methods need to be developed for the proper computation and assessment of these areas. In this field, previous works have dealt with calibration and identification techniques of dynamic models for thermal bridges.

Up to very recently the evolution of computational techniques for the assessment of energy consumption in buildings paid only marginal attention to multi-dimensional heat transfer. In the development of building simulation codes, predominant energy paths (homogeneous walls, fenestration…) were prioritized, furthermore considering the comparably higher computational effort required to properly address multi-dimensional heat transfer.

Numerical modelling for multi-dimensional heat transfer is most commonly not covered by building simulation codes and performed under normalized steady-state boundary conditions [21]. Outcomes from these calculations can be introduced into building simulation codes by means of steady-state thermal performance parameters. To the authors' belief, these simplified procedures should be amended. In this belief, it is considered that within highly insulated buildings, the deviation of simplified steady-state assessments from a proper dynamic thermal modelling of thermal bridges is increased.

Dynamic numerical models for architectural junctions have been developed in [25, 26, 27, 28], where discretization methods such as finite element and finite difference methods are used. In [29], linear thermal bridges were modelled using a Boundary Element Model in the frequency domain. In [30, 31], a procedure for obtaining the z-transfer function of 3-dimensional thermal bridges is developed. In [28], dynamic heat flows for timber frame constructions are provided in terms of amplitude and phase shift parameters, under various modelling approaches. In this same work, it is concluded that additional information is required for incorporating dynamic models into BES software in order to properly model thermal bridge elements. This approach is preferred due to its accuracy when compared to the introduction of equivalent parameters into a one-dimensional heat transfer model for homogeneous walls. In equivalent-wall methods defined in [26], the architectural detail of the junction is reduced to minimize the overlapping between the dynamics of the thermal bridge and the dynamics of the homogenous wall portions, when compared to standardized geometric requirements in [21]. Therefore, it could be concluded that the dynamics of a thermal bridge differ from the dynamics of homogeneous walls, and that a specific disaggregation procedure for their dynamic modelling would be desirable.

Taking into consideration different dynamic performance of homogeneous walls and architectural junctions identified in [26] and the recommendation for developing specific models for architectural junctions in [28], a generalized geometrical and calculation procedure is needed to properly assess dynamic heat transfer in architectural envelopes. In order to integrate this procedure into the wide range of formulae used by researchers and engineers in the field of building physics, this calculation procedure should be based in commonly used and standardized definitions and calculation procedures [21, 32, 33, 34, 35]. In this generalized methodology, full compatibility of the formulae with geometrical dimensions in [21] and variables defining steady-state and dynamic performance in [34, 32] should be pursued.

Generalized formulae following this approach would avoid uncertainties in the calculation of dynamic thermal properties by methods such as [26], where the dynamically affected envelope area needs to be defined by calculation and inspection for each particular case, and thus the obtained heat transfer function is only applicable to that particular case. Furthermore, with the methodology in [26], the geometrical definition of building envelopes needs to be modified for each architectural junction within a building simulation model, requiring extensive effort in the process. Generalized formulae aligned with the geometrical definitions in [21] would substantially facilitate transitions between thermal assessment works at architectural junction level and full-scale building energy simulation.

In this paper, a mathematical formulation is developed, following the generalization criteria defined above, for the disaggregation of dynamic heat transfer phenomena in envelope areas with multi-dimensional heat transfer. This formulation provides the opportunity to differentiate the dynamic thermal performance of a thermal bridge from dynamic one-dimensional heat transfer in detailed numerical calculations – e.g. performed by means of finite element models. The proposed approach provides output which can later be introduced in BES tools for a coupled analysis within a full-building simulation.

5.4 Dynamic models for building envelopes

Building envelopes represent a relevant share of the heat exchange between the building and its environment. Envelopes are the physical boundary of buildings and are designed to shelter occupants from variable outdoor conditions. Due to the variability of these conditions, heat transfer across the envelopes is highly dynamic.

Regarding the energy behaviour of building envelopes, three main categories are identified:

- Fenestration systems, curtain wall elements, etc. These systems show a high permeability to solar radiation, along with a reduced thermal mass. For their characterization, two steady-state equations are used, describing short-wave energy input from the sun and thermal heat transfer with the environment (long wave radiative, convective, and conductive heat transfer). [36, 37]
- Lightweight insulated envelope systems, sandwich panels, etc. These systems are distinguished by a minimal thermal mass and relatively high thermal resistance. In such envelopes, thermal inertia is of little relevance, and useful thermal models can be obtained by means of one steady-state equation.
- Massive envelope systems, stonework, masonry, brickwork, etc. Thermal inertia in these constructions allows for a substantial smoothing and phase shifting of thermal effects caused by oscillating boundary conditions. In order to achieve a suitable characterization of these systems, several mathematical formulations can be used. Some of the most commonly used models are based on transfer functions and response factors.

In this paper, thermal performance calculations for massive construction elements are addressed. As stated above, the inertia of these systems provides a relevant smoothening of the response of walls to varying boundary conditions. For comparative calculations, wall performance is commonly assessed by means of the steady-state thermal transmittance value of a wall. This parameter provides the benefit of allowing its comparison with fenestration systems.

Although steady-state thermal transmittance is considered to be a good performance indicator for fenestration and lightweight insulated systems, the assessment of the thermal performance of massive walls requires further characterization of the dynamics of the wall.

For the dynamic thermal performance modelling of building envelopes, techniques such as discrete transfer functions, response factors, finite elements, finite differences and phasor approaches are used. Each of the mentioned alternatives is used in different contexts given its particular ratio between accuracy and computational cost.

BES software tools such as Energy Plus [6] and TRNSYS [7] perform (multi) yearly simulation of the energy performance of whole buildings, where the thermal response of walls and other thermal systems is computed at regular hourly or sub-hourly intervals. In this context, the computational effort required for the computation of each wall assembly is critical. Energy Plus bases its calculations in the so-called “Conduction Transfer Function”, while TRNSYS uses the Mitalas Transfer Function. In both cases, these functions model the heat transfer across a wall based on present and past values of surface temperature and heat flux of the wall.

One-dimensional models based on multi-element/difference discretization of a wall require much larger computational effort and are commonly disregarded for standardized calculations in BES systems, although these are implemented in optional algorithms [6].

For the dynamic performance assessment of building envelopes, EN 13786 [32] provides a calculation method in which the one-dimensional dynamic thermal performance of a wall under harmonic boundary conditions can be obtained.

In this work, a multi-dimensional generalization of [32] is provided, in which boundary conditions are defined similarly, but its heat transfer calculation method is substituted by a numerical method –i.e. finite element method. The selected numerical method provides an accurate modelling of the multi-dimensional heat transfer under similar geometrical modelling conditions as defined in [21], and an accurate modelling under dynamic conditions as to obtain the time-variant thermal response of the system through the output parameters in [32].

Under this approach, a dynamic generalization of parameters in [21] is achieved, compatible with the parameter definition in [32].

5.5 Relevant standardized procedures for thermal assessment

The proposed dynamic thermal assessment builds over several international standards, and generalizes the dynamic thermal assessment of multi-dimensional heat transfer by means of the hybridization of two standards [21, 32]. The relevant international standards for the topic of this paper are reviewed below.

In ISO 7345 [33], physical quantities and corresponding symbols and units used in the thermal insulation field are defined.

The method to obtain the thermal resistance and thermal transmittance of building components and elements is provided in EN 6946 [34]. It is important to note that this procedure excludes doors, glazed units, curtain walling, components which involve heat transfer to the ground, and components allowing air permeability. The method assesses the appropriate design thermal conductivity or thermal resistance of the materials considering their application. This calculation procedure applies to thermally homogeneous layers, including air layers and cavities. Relevant parameters defined [34] are thermal resistance (R) and thermal transmittance (U). The thermal resistance of a homogeneous material is defined in (1), the total thermal resistance of a building component is calculated in (2), and the thermal transmittance is obtained in (3).

$$R = \frac{d}{\lambda}\ (X) \quad (1)$$

$$R_T = R_{si} + R_1 + R_2 \ldots + R_n + R_{se} \quad (2)$$

$$U = \frac{1}{R_T} \quad (3)$$

Numerical calculation of heat flows and minimum surface temperatures in steady-state multi-dimensional heat transfer environments are defined in EN 10211 [21]. The specification for two-dimensional and three-dimensional geometrical models of thermal bridges is performed in this standard. Geometrical boundaries, model subdivisions, thermal boundary conditions and thermal values and relationships are incorporated within the specifications. In addition, the procedure for obtaining linear and point thermal transmittances and surface temperature factors is explained.

The thermal coupling coefficient $\mathrm{L_{3D}}$ between two different environments can be obtained from the total heat flow Q calculated three-dimensionally in (4).

The thermal coupling coefficient obtained from 2D calculation L_{2D} of the component separating two different environments can by derived from the heat flow, as defined in (5).

$$Q = L_{3D}(\theta_i - \theta_e) \quad (4)$$

$$Ql = L_{2D}(\theta_i - \theta_e) \quad (5)$$

Based on the definitions given in (3, 4 and 5), the linear thermal transmittance (Ψ) separating two environments is defined in (6), and the point thermal transmittance (χ) is defined in (7).

$$\Psi\,\mathrm{l} = L_{2D} - \sum_{j=1}^{N_j} U_i A_i \quad (6)$$

$$\chi = L_{3D} - \sum_{i=1}^{N_j} U_i A_i - \sum_{j=1}^{N_j} \Psi_j l_j \quad (7)$$

EN 13786 [32] provides methods to calculate the harmonic thermal behavior of a complete building component where one-dimensional heat transfer can be assumed. In this document, the periodic thermal transmittance ($\mathrm{Y_{mn}}$) and the decrement factor (f) are defined. In this method, the response of a wall to harmonic excitations is assessed.

The periodic thermal transmittance is defined as the complex amplitude of the density of heat flow rate through the surface ($\hat{\mathrm{q}}_\mathrm{i}$), divided by the complex amplitude of the harmonic temperature excitation ($\widehat{\mathrm{T}}_\mathrm{e}$). Magnitudes on opposite sides of the wall (m and n) are taken to define the transmittance.

The decrement factor (f) is defined as the ratio of the modulus of the periodic thermal transmittance to the steady-state thermal transmittance U.

$$Y_{e,i} = -\frac{\hat{q}_i}{\hat{T}_e} \quad (9)$$

$$f = \frac{|\hat{q}_i|}{|T_e| U} = \frac{|Y_{e,i}|}{U} \quad (10)$$

The phase difference (φ) measures the difference in hours between the peak excitation (maximum exterior temperature) and its response (peak heat density of heat flow rate at the interior surface).

When considering a phasorial approach to the phase difference defined in [32], this phase difference needs to be converted into an angular shift. In this operation, the magnitude of the phase difference is related to the period of the considered periodic boundary condition, as per equation (11).

$$\theta = \frac{\varphi}{Period} * 2\pi \quad (11)$$

5.6 Phasorial approach to dynamic thermal properties

According to [38], *"…a phasor… is a complex number representing a sinusoidal function whose amplitude (A), angular frequency (ω), and initial phase (ϑ) are time-invariant. …. The complex constant, which encapsulates amplitude and phase dependence, is known as phasor..."*

With a fully developed algebraic operation system, phasor operations can be used to perform addition or subtraction operations in dynamic linear systems such as building envelope systems, under uniform frequency conditions. Within a heat transfer equation, different phasors can be used to represent different heat flows in an architectural detail with multi-dimensional heat flow. This can be represented as shown in eq. (12.a, 12.b), which can be further transformed to meet the definitions in section 8.2 of [21], as shown in eq. (13.a, 13.b)

Equations (12.a, 13.a) show steady-state base formulation in [21] while in (12.b, 13.b) its phasorial variant is formulated. Furthermore, given the definition of Y in [32], eq. (13.b) is further converted in eq. (14) to harmonize it with [32].

$$Q_{tot} = \sum_{1D} Q_i + \sum_{2D} Q_j + \sum_{3D} Q_k \quad (12.a)$$

$$Q_{tot}\angle\theta_{tot} = \sum_{1D} Q_i\angle\theta_i + \sum_{2D} Q_j\angle\theta_j + \sum_{3D} Q_k\angle\theta_k \quad (12.b)$$

$$L_{3D}\angle\theta_{tot} = \sum_{1D}(U_i * A_i) + \sum_{2D}\left(\psi_j * l_j\right) + \sum_{3D}(\chi_k) \quad (13.a)$$

$$L_{3D}\angle\theta_{tot} = \sum_{1D}(U_i\angle\theta_i * A_i) + \sum_{2D}\left(\psi_j\angle\theta_j * l_j\right) + \sum_{3D}(\chi_k\angle\theta_k) \quad (13.b)$$

$$L_{3D}\angle\theta_{tot} = \sum_{1D}(Y_i\angle\theta_i * A_i) + \sum_{2D}\left(\psi_j\angle\theta_j * l_j\right) + \sum_{3D}(\chi_k\angle\theta_k) \quad (14)$$

The transition of eq. (12.b) and (13.b) is performed as a phasorial implementation of (4, 5), where given only one periodical boundary condition, $L_{tot}\angle\theta_{tot}$ can be calculated according to eq. (15):

$$Q\angle\theta = L_{tot}\angle\theta_{tot} * T_{BC}\angle 0 \quad (15)$$

For situations with multiple boundary conditions with the same oscillation periods in an architectural detail, $Q_{tot}\angle\theta_{tot}$ can be obtained with the phasor-equivalent method to the one stated in section 8.3 of (11), as shown in eq. (16).

$$Q_{tot}\angle\theta_{tot} = \sum_{BC}\left(L_{tot,BC\_n}\angle\theta_{tot,BC\_n} * T_{BC\_n}\angle\theta_{BC\_n}\right) \quad (16)$$

5.7 Calculation procedure of the phasorial assessment of differential heat transfer in thermal bridges

The application of phasor operators to the dynamic heat transfer analysis of a thermal bridge is reflected by means of eq. (14, 16). However these equations contain many heat transfer coefficients which need to be obtained in a hierarchized way. In this section, a stepwise approach for obtaining phasorial coefficients for an architectural junction is defined. This approach is applied to a case study in section 6.

Similarly to steady-state calculations under [21], the initial step is the construction of a multidimensional geometrical model, comprising all the architectural junctions to be assessed in the analysis. The main particularity in the scope of this model is its purpose to assess dynamic heat transfer; for this purpose, thermal conductivity/resistance of materials is complemented by material density and specific heat. The amplitude and phase shift of the heat flux on the inner surfaces of the model are obtained.

Additional models are constructed to obtain the heat flux across partial subsets of the architectural junction (e.g. 1D heat transfer for 2D architectural detail). Again, amplitude and phase shift of the heat flux are taken on the inner surface of the model.

In figure 1, heat paths in a 2D architectural detail are shown, along with their phasor representation.

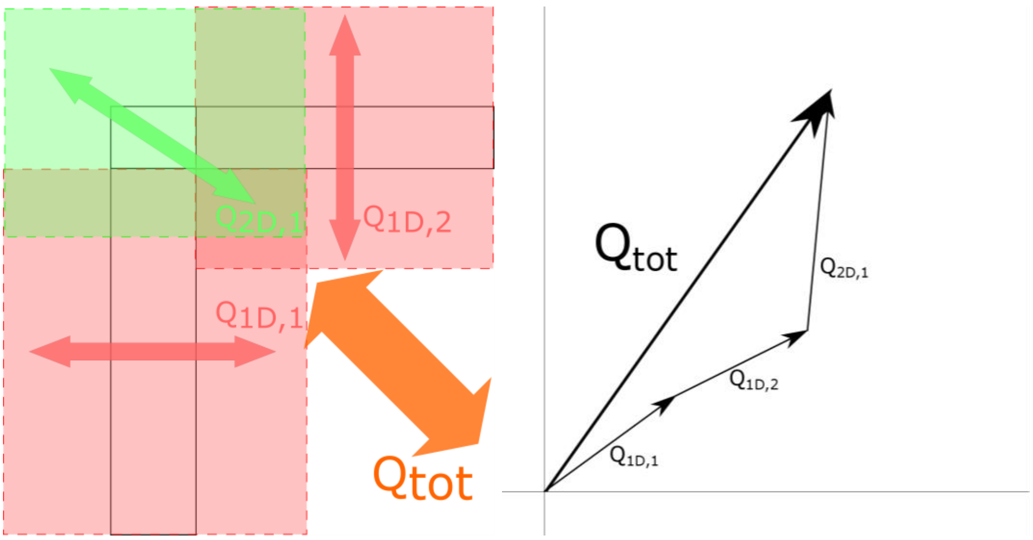


Figure 1: Sketch of an architectural junction with a geometrical thermal bridge (left), and its phasor representation (right).

In table 1, the calculation steps to obtain the required parameters in eq. (14) are provided. For 2D architectural models, only steps 1-3 will be required.

Table 1. Calculation steps to achieve all the required heat transfer data in eq. (14)

Step	2D	3D	Action	Obtained data
1	Yes	Yes	Construct 1D heat transfer models	$L_{1D}\angle\theta_{tot}$
2	Yes	Yes	Eq. (14) without 2D and 3D heat transfer	1D, all Y and θ parameters
3	Yes	Yes	Construct 2D heat transfer models	$L_{2D}\angle\theta_{tot}$
4	Yes	Yes	Eq. (14) without 3D heat transfer	2D, all ψ and θ parameters
5	n/a	Yes	Construct 3D heat transfer models	$L_{3D}\angle\theta_{tot}$
6	n/a	Yes	Eq. (14)	3D, all χ and θ parameters

This sequence needs to be followed for each particular oscillation frequence/period in the boundary conditions.

A graphical representation of the calculation procedure is provided in Figure 2. This sequence needs to be performed for each particular oscillation frequency study.

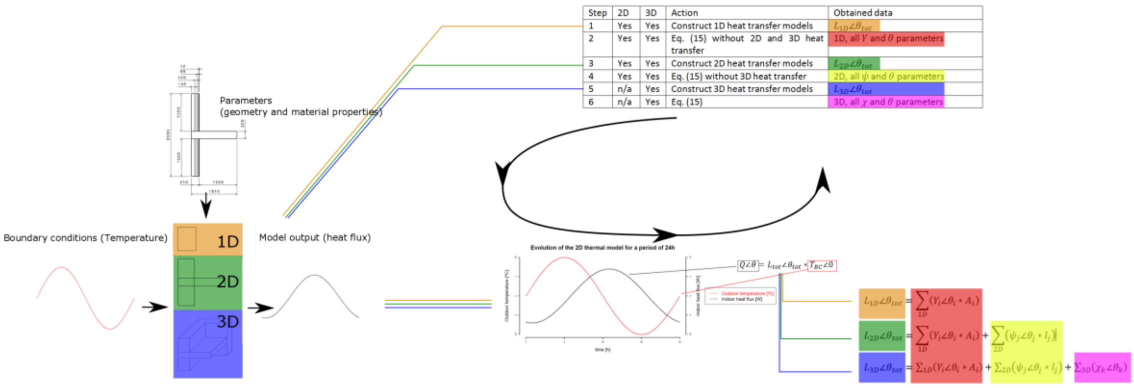


Figure 2. Calculation sequence and solving of equations (15) and (16) according to steps defined in Table 1.

In some particular cases, where the architectural model has been constructed in such a way where its edges are not affected by the junction, the heat flux of partial subsets can be obtained from the main model, by obtaining heat transfer data from cut planes at the edge of the model. However, this approach needs to be validated for each particular case and applied with caution.

5.8 Case study

In order to identify the relevance of dynamic phenomena in thermal bridges, and the outcomes of the defined methodology, a case study has been defined and solved. A junction of an external wall with an intermediate floor slab has been selected for this purpose. This junction is typical of masonry constructions in Spain and other South European countries, where thermal mass can have a relevant influence in the avoidance of overheating in summer periods.

A single-leaf ceramic masonry construction with internal insulation and internal plasterboard lining has been selected for the building envelope. This type of wall assembly is representative of typical construction details built in Spain after the 2006 Construction Building Code.

Following common construction details in Spain, this masonry construction is supported on the edges of a floor slab with structural properties. Considering this, the intersection is constructed in such a way that the slab is exposed to the external ambience. These construction details are well known causes of poor thermal performance of building envelopes.

This case study is a simple yet common construction detail in South European countries. This morphology is appropriate to illustrate the proposed methodology. The construction of the junction is relatively simple, avoiding unnecessary complexities in the description within the manuscript. Furthermore, due to the two-dimensional nature of this junction, the reader is provided of graphs and figures with more precise details compared to potential three-dimensional alternatives.

5.8.1 Geometry

The modelled façade-slab junction is defined by the dimensions and compositions indicated in Table 2.

Table 2: Composition of the model

Element	Thickness [mm]	Modelled distance from junction [mm]	Composition
Façade, above slab	310	1500	According to
Façade, below slab	310	1500	Table 3
Floor slab	300	1810	Concrete

The model height is set to 3.3 meters, where 3 meters correspond to the internal height of the external wall between slabs and 0.3 meters correspond to the height of the slab. All calculations refer to the 3.3 m model height (external dimensions of the façade). The wall thickness is 0.310 meters and there is a distance of 1.5 meters from the internal surface to the cut plane of the slab. This geometry is depicted in Figure 3.

For the calculation of linear thermal coefficients, this geometry results in an external height of 3.3m and an internal height of 3m for the considered model.

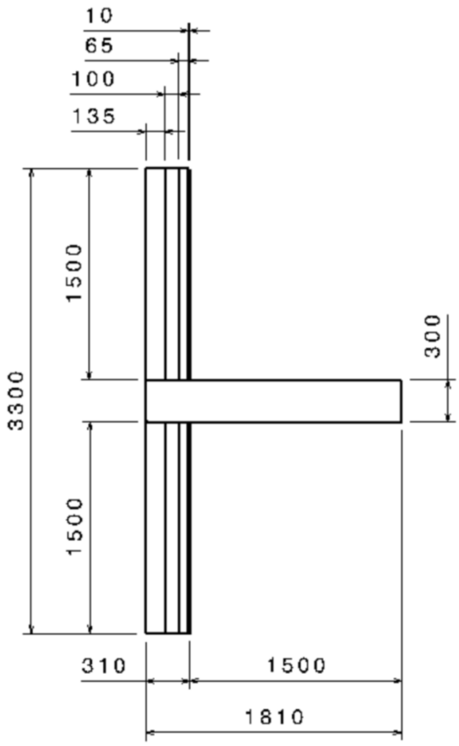


Figure 3: Model dimensions (in mm)

The composition and thermal properties of each assembly are shown in Tables 3 (masonry wall) and 4 (concrete slab).

Table 3: Thermal properties of the wall

Position	**Element**	**Thickness [m]**	**Thermal Resistance [m2K/W]**	**Thermal Conductivity [W/mK]**	**Density [kg/m3]**	**Specific Heat [J/kgK]**
Exterior	Brick	0.135	0.193	0.700	1600	850.0
	Extruded polystyrene	0.100	2.857	0.035	25	1470.0
	Air gap*	0.065	0.180	0.560	1.185	1004.4
Interior	Plasterboard	0.010	0.020	0.500	1300	840.0

Material data are taken from [28], while the thermal resistance of the air gap is taken from [39] for the case of horizontal heat flux.

Table 4: Thermal properties of the concrete slab

Element	**Thickness [m]**	**Thermal Conductivity [W/mK]**	**Density [kg/m3]**	**Specific Heat [J/kgK]**
Concrete	0.300	2.600	2300	930

5.8.1.1 Numerical model

The numerical assessment of this construction junction has been performed using a multi-dimensional finite difference method. Commercial software developed by PHYSIBEL [40] has been used. Within the same software suite, programs VOLTRA [41] (dynamic) and TRISCO [42] (steady-state) have been used to perform the required calculations.

Additionally to the dynamic study assessing dynamic thermal performance according to the mathematical formulation in (14), a steady-state thermal model was performed. In Table 5, the imposed boundary conditions for steady-state and dynamic analysis can be observed. In Figure 4, boundary conditions are depicted over the modeled geometry. Detailed dimensions and composition of each layer can be found in figure 4.

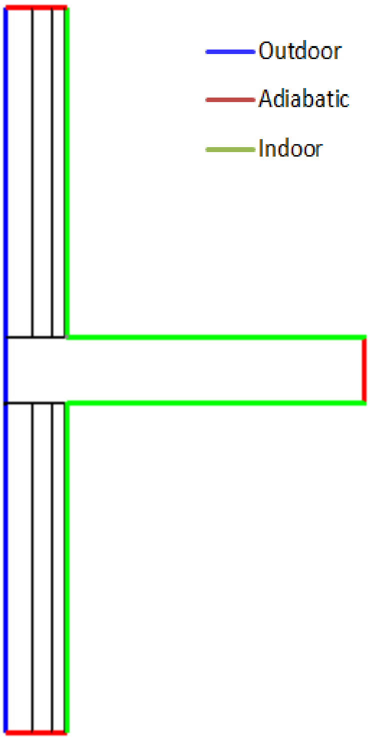


Figure 4: Geometrical definition of boundary conditions

Table 5: Boundary conditions

Assessment type	Position	Heat transfer Coefficient [W/m2K]	Mean temperature [°C]	Temperature amplitude [°C]	Period [h]
Steady-state	Outdoor	25	0	-	-
	Indoor	7.69	20	-	-
Dynamic	Outdoor	25	0	10	Variating, refer to Table 6
	Indoor	7.69	0	0	-

5.8.1.2 Steady-state performance

The case study resulted in an equivalent thermal transmittance of 0.696 W/m^{2}K. Considering that the one-dimensional thermal transmittance of the façade is 0.298 W/m^{2}K, the thermal bridge coefficient of the façade-slab junction, Ψ is calculated at 1.312 W/mK. In Figure 5, a vertical section of the temperature field is shown.

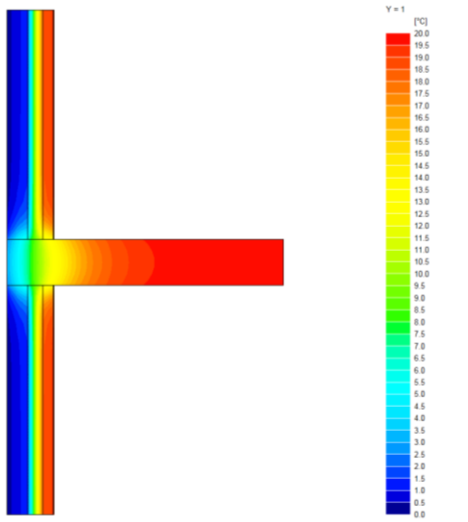


Figure 5: Temperature distribution [ºC]

Under the aforementioned steady-state approach, the 2-dimensional case shows a 134% increase in heat flow due to the wall-slab junction when compared to one-dimensional analysis of the external wall

For the modelled case, with a 3 m slab-to-slab height, this implies that the thermal bridge represents 57% of the total heat transfer across the external wall. Considering that the model height is representative of the building stock, the reduction in the insulation level observed in this steady-state analysis can be transposed to an equivalent increase in the thermal coupling coefficient of the whole wall.

5.8.1.3 Dynamic performance

The dynamic thermal performance was assessed for various oscillation periods of the external boundary temperature. For every case, evolutions of heat flow density and temperature were obtained. Simulation time was defined such as to allow for the stabilization of heat flow oscillations. In all cases, more than 10 periods were simulated to ensure the proper thermal initialization of the construction junction.

Oscillation periods in the range of 1 to 1728h were computed, with various intermediate resolutions. Simulation periods were spaced by 1h for periods shorter than 36h. For longer periods, the spacing was increased to 3h until 60h, 6h until 84h, 12h until 120h and 24h until 1728h. In Table 6, an excerpt of the results can be seen.

For each case, periodic thermal transmittance, decrement factor and phase difference (φ) were obtained according to ISO 13786. Output variables of the proposed methodology according to the process defined in Table 1 were calculated. All this information is presented in Table 6. In Figure 6, the evolution of temperature and heat flux is shown for the dynamic simulation of the system for a period of 24 hours.

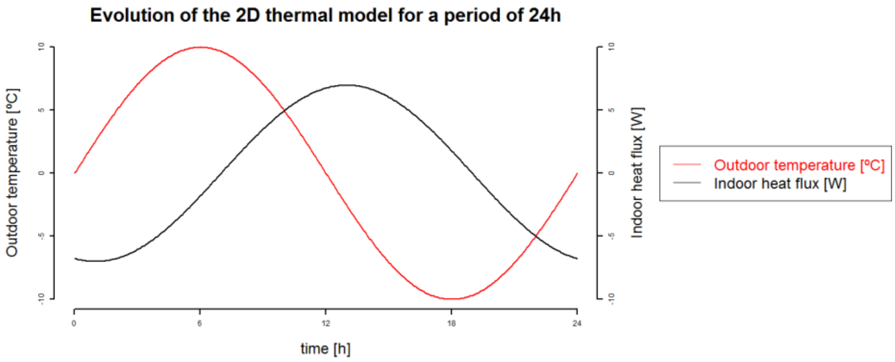


Figure 6: Dynamics of temperature and heat flow in the dynamic assessment of the external wall-intermediate slab junction for the period of 24h

Table 6: Dynamic properties

Time [h]	Amp q_{1D} [W]	Amp q_{2D} [W]	Time shift φ_{1D} [s]	Time shift φ_{2D} [s]	Y_{1D} $[\frac{W}{m^2K}]$	Y_{2D} $[\frac{W}{m^2K}]$	ΔY $[\frac{W}{m^2K}]$	Phase θ_{1D} [rad]	Phase θ_{2D} [rad]	Ang ΔY [rad]
3	0.08	0.08	9143	9150	0.008	0.008	0.000	1.69	1.69	-0.28
6	0.35	0.37	12180	12540	0.035	0.037	0.004	1.13	1.16	1.48
9	0.63	0.69	14400	15210	0.063	0.069	0.012	0.89	0.94	1.24
12	0.88	1.00	16200	17520	0.088	0.100	0.021	0.75	0.81	1.10
18	1.31	1.58	19080	21600	0.131	0.158	0.045	0.59	0.67	0.92
24	1.65	2.12	21120	25200	0.165	0.212	0.072	0.49	0.58	0.82
32	1.99	2.75	22800	29100	0.199	0.275	0.110	0.40	0.51	0.71
42	2.28	3.42	24300	33000	0.228	0.342	0.152	0.32	0.44	0.61
48	2.40	3.76	24900	34800	0.240	0.376	0.173	0.29	0.40	0.57
54	2.50	4.06	25500	36600	0.250	0.406	0.194	0.26	0.38	0.53
60	2.57	4.34	25800	38100	0.257	0.434	0.213	0.24	0.35	0.49
72	2.68	4.79	26400	40500	0.268	0.479	0.244	0.20	0.31	0.43
84	2.75	5.16	26700	42300	0.275	0.516	0.270	0.18	0.28	0.38
96	2.80	5.45	26850	43800	0.280	0.545	0.291	0.16	0.25	0.35
120	2.86	5.86	27150	45900	0.286	0.586	0.320	0.13	0.21	0.29
144	2.90	6.14	27300	47325	0.290	0.614	0.340	0.11	0.18	0.25
192	2.93	6.45	27450	48600	0.293	0.645	0.362	0.08	0.14	0.19
240	2.95	6.62	27450	49500	0.295	0.662	0.374	0.06	0.11	0.15
288	2.96	6.72	27450	49800	0.296	0.672	0.381	0.05	0.10	0.13
336	2.96	6.78	27600	50100	0.296	0.678	0.385	0.05	0.08	0.11
384	2.97	6.82	27600	50400	0.297	0.682	0.388	0.04	0.07	0.10
432	2.97	6.85	27600	50550	0.297	0.685	0.390	0.04	0.07	0.09
480	2.97	6.87	27600	50550	0.297	0.687	0.391	0.03	0.06	0.08

In Figure 7, one-dimensional and two-dimensional periodic thermal transmittance values are presented, along with the differential thermal transmittance associated with the thermal bridge. For short oscillation periods, the thermal mass in the construction isolates the indoor environment from oscillations in the outdoor environment, leading to negligible Y values. Also, due to the fast oscillations, the time shift exceeds the period of the oscillations, leading to phase shifts greater than 2*pi.

For longer oscillation periods, greater Y values are obtained, leading to pseudo-stationary behavior when the oscillation period substantially excedes the time constant of the system. In these cases, the phase shift is practically non-existent.

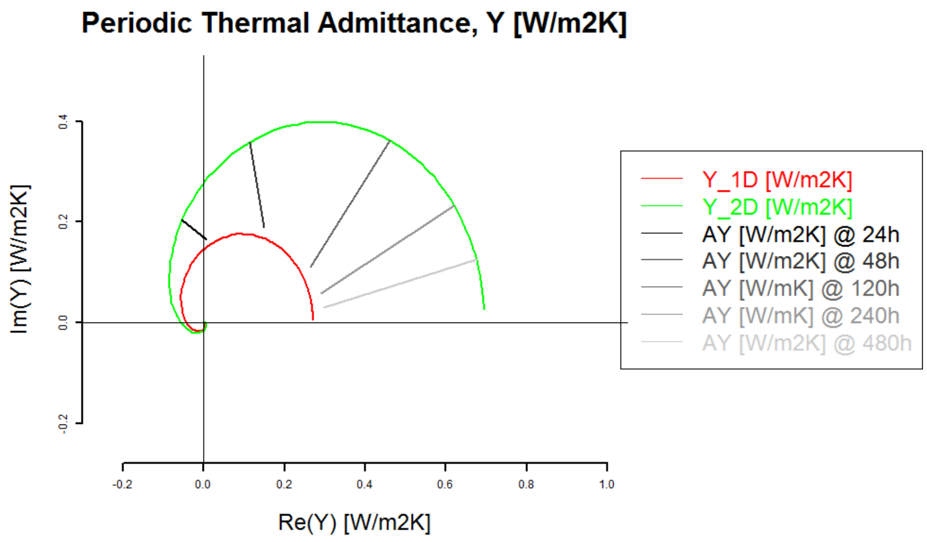


Figure 7: Phasor representation of the thermal response of the architectural junction

In Figure 8, the delay in the response is shown, in both phase and time shift. Maximum phase shift is observed for short oscillation periods. However, the maximum shift in time is observed for long oscillation periods. Maximum time shifts are observed for oscillation periods at 100h (1D) and 200h (2D), where time shifts of 7.7h (1D) and 14.25h (2D) happen.

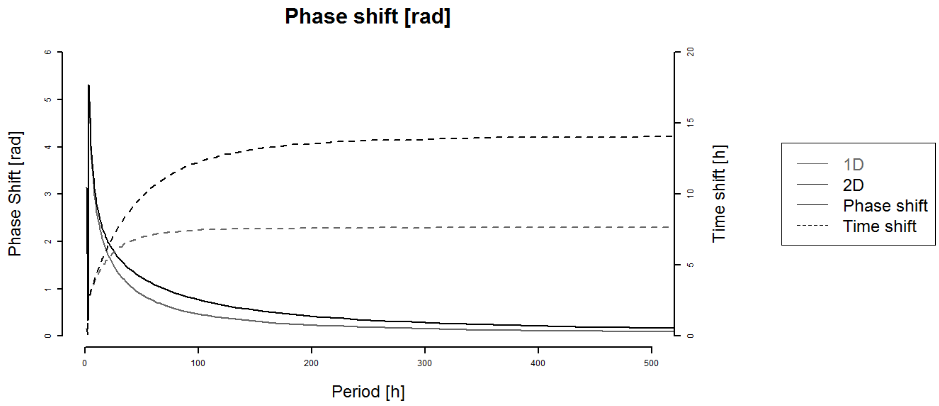


Figure 8: Dynamic thermal transmittance of the architectural junction for the evaluated oscillation periods.

In Figure 9, the dynamic thermal transmittance (Y) value is shown, indicating its evolution towards pseudo-stationary state for long periods. In the one-dimensional model, oscillation periods of 72h or above result in a Y value reaching over 90% of the U-value. In two-dimensional models, 168h are needed to reach such a state.

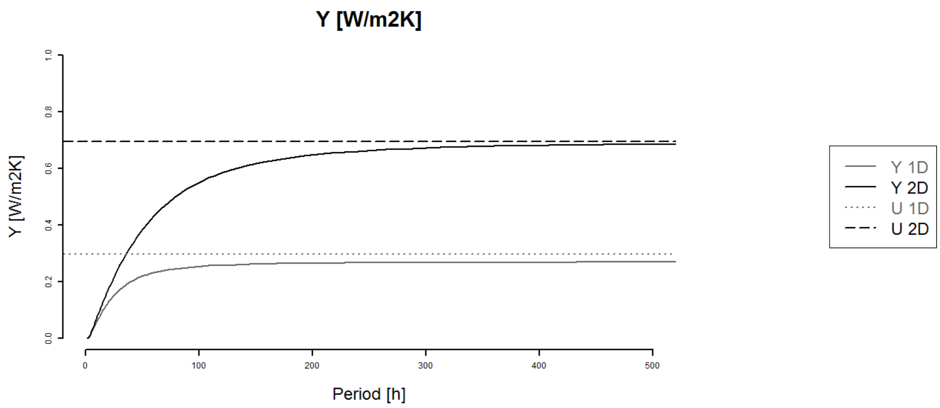


Figure 9: Phase shift of the architectural junction for the evaluated oscillation periods.

The previously mentioned evolution is better assessed with normalized parameters as shown in Figure 10. In this figure, the 1D to 2D normalized difference is shown in terms of periodic thermal transmittance. The difference between both normalized transmittances falls below 10% for oscillation periods greater than 132h.

The relevance of harmonic assessments for very short periods in terms of thermal transmittance can also be assessed. For periods shorter than 6h (1D) and 10h (2D), normalized periodic thermal transmittance is found to be below 10%.

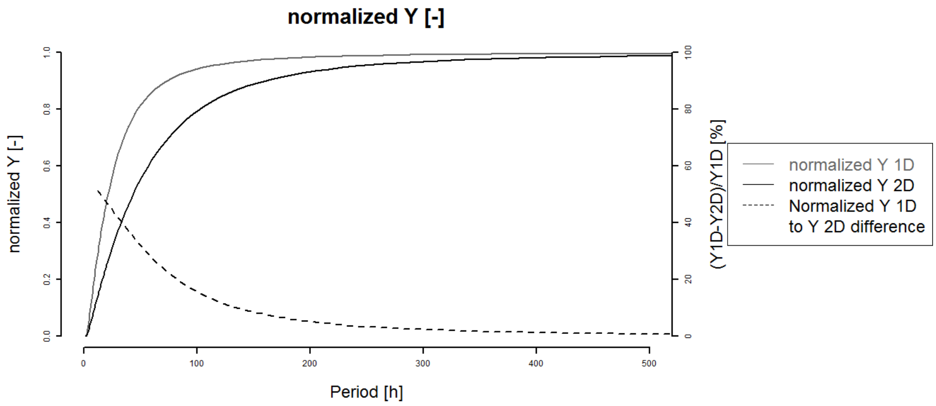


Figure 10: Normalized Y values and differences between 1D and 2D dynamic heat transfer assessments.

Figure 11 presents the harmonic linear thermal coefficient. The magnitude and phase of this phasor are shown. Due to the formulation in (14), the choice of geometrical dimension for the wall height impacts on the resulting parameters. External and internal wall dimensions deviate by 0.3 m over a total floor height of 3.3 m. As such, the harmonic linear thermal coefficient is also different for each considered geometrical criterion. The impact is more clearly seen in terms of magnitude than in terms of phase.

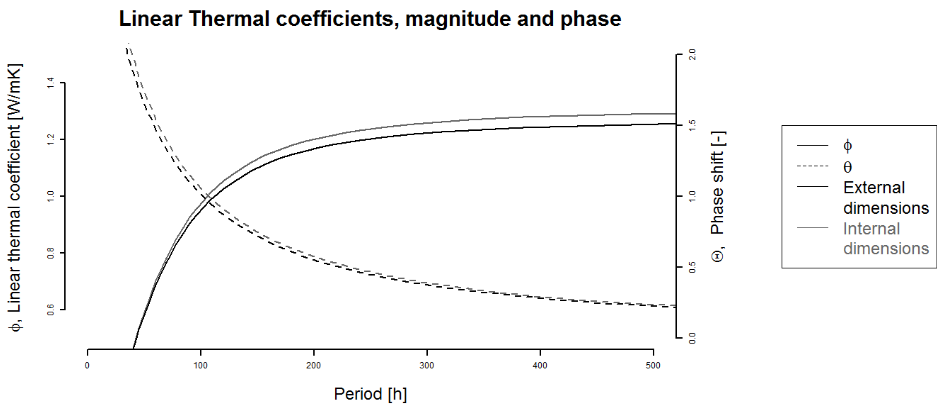


Figure 11: Harmonic linear thermal coefficient, magnitude and phase.

5.9 Discussion

Based on the outcomes of thermal models developed in this paper, the relevance of a dynamic multi-dimensional thermal assessment of architectural junctions can be assessed.

As it is already known, thermal bridges in architectural junctions are a relevant source of thermal coupling between indoor and outdoor ambiences. This can easily be derived from the steady-state assessment at long periods in Figure 9, where the overall U-value for a 3.3 m high model of an external wall is more than doubled by the architectural junction with an intermediate floor slab. While unsatisfactory, this is an expected behavior for the studied architectural junction. In fact, in many EU national building codes, steady-state thermal bridge calculation is mandatory within the thermal assessment of buildings.

Differences on the dynamic thermal response are observed on the time shift of the architectural junction, which is almost doubled for long oscillation periods.

For long oscillation periods, although the thermal response of 1D and 2D architectural details differs in dynamic thermal transmittance and time shift, the observed differences are relatively stable for oscillation periods greater than 200h. For very rapid oscillations, with periods shorter than 6h, the magnitude of the thermal response is very limited. In this case, although the angular shift may be large, the resulting thermal response is of reduced relevance. However, for intermediate situations, with periods larger than 6h but shorter than 200 h (not reaching quasi-steady-state situations), thermal responses of 1D and 2D cases are relevantly different.

Within the aforementioned range, the dynamic thermal response presents relevant amplitudes, while the dynamics of the heavyweight construction (floor slab) and lightweight construction (insulated façade) clearly differ. In Figure 10, the normalized difference between 1D and 2D cases is not stable and presents large differences, with variations for different oscillation periods. In Figure 8, the variation in phase and time shifts upon oscillation period also shows different behavior for 1D and 2D cases.

For this reason, the dynamic thermal performance of architectural junctions should be considered within the assessment of energy performance of buildings and their envelopes. This might be of a larger relevance in situations where thermal mass is exposed to both internal and external ambiences, such as the architectural junction in this study, and particularly for climates with highly variable outdoor conditions, in which the predominant heat path is substantially modified. These climatic situations are commonly found in Mediterranean climates in winter periods and in other European climates in summer periods, where indoor temperature is contained within the daily oscillation range of outdoor temperature.

As identified in [23] for steady-state analysis, obtained dynamic thermal bridge parameters differ for each of the geometrical reference systems. As expected, calculations with internal dimensions result in a larger linear thermal bridge coefficient. In the latter case, a smaller one-dimensional heat flow is assumed, which involves a larger correction in the linear thermal bridge coefficient that accounts for the non-one-dimensional heat transfer.

The phasorial analysis proposed in this work serves a dual purpose of analyzing the relevance of the need for dynamic thermal modeling methods for architectural junctions, while developing a suitable mathematical tool for the dynamic modeling of these junctions within a Fourier decomposition of indoor and outdoor boundary conditions.

5.10 Generalization

In this paper, a generalized formulation is proposed for the assessment of dynamic thermal performance of building envelopes under non-one-dimensional approaches. The presented formulation is valid for 2D and 3D cases, and is built over basic assumptions in the heat transfer analysis of buildings. The generalized formulation follows a similar approach to multidimensional heat transfer in [21], and is based on the linearity of thermal models and the principle of superposition.

Similarly to the approach in [21], all parameters in eq. (12.b, 14 and 16) can be obtained by means of partial models, constructed in such a way that only one particular coefficient is identified in each model according to eq. (16). The proposed formulation is also valid for the calculation of the total harmonic heat transfer of a building envelope, as a dynamic generalization of [35].

The relatively intense computational effort required to obtain the dynamic thermal response of architectural junctions by finite element or finite difference methods implies certain limitations to the present application of this method.

This method does not pretend to be used for the direct computation of the full procedure for all the excitation periods in each particular case. However, an approach similar to that pursued for simplified calculation of steady-state performance in architectural junctions could be feasible.

Atlases of pre-calculated parameters based on junction topologies are feasible, and phasorial formulations could lead to modified thermal parameters of equivalent walls for later use in prescriptive performance assessments.

For particular cases with heavy thermal integration of one-dimensional and multi-dimensional heat flow, the procedure presented in this work could be pursued for relevant excitation frequencies such as those defined in [32].

5.11 Mathematical application to BES tools

The phasorial formulation described could be developed on a suitable mathematical tool by means of Fourier decomposition of boundary conditions However, in the context of BES tools, mathematical approaches such as response factor [43] and z-transfer functions [30, 31] are most commonly used in the computation of heat transfer in building envelopes. Under this scheme, adaptations are possible where the phasorial approach is replaced by a response factor approach. Following the same process formulated and illustrated in sections 4 and 5 and considering the response factor definitions, included in [43], an equivalent formulation with a response factor approach can be achieved.

Equation (12.a) can be transformed into (17), where the instantaneous heat transfer is formulated as an aggregation of several 1D, 2D and 3D heat paths.

$$\dot{Q}_{tot} = \sum_{1D} \dot{Q}_i + \sum_{2D} \dot{Q}_j + \sum_{3D} \dot{Q}_k \quad (17)$$

In Eq.(18), heat transfer paths are defined as surface, linear and point heat flux densities applied over their representative areas and lengths.

$$\dot{Q}_{tot} = \sum_{1D}\left(\dot{q}_{1D,i} * A_i\right) + \sum_{2D}\left(\dot{q}_{2D,j} * l_j\right) + \sum_{3D}\left(\dot{q}_{3D,k}\right) \quad (18)$$

In (19-22), the dynamic response of the thermal model to its bounding temperatures is formulated. The overall heat transfer across the architectural junction, Eq.(19), and each of the 1D , 2D and 3D heat transfer densities are formulated (Eqs. 20-22).

$$\dot{Q}_{tot,t} = \sum_{y=0}^{\infty}(C_{ei,tot,y} * T_{ext,t-y} + C_{ii,tot,y} * T_{int,t-y}) \quad (19)$$
$$\dot{q}_{1D,i,t} = \sum_{y=0}^{\infty}(c_{ei,1D,i,y} * T_{ext,t-y} + c_{ii,1D,i,y} * T_{int,t-y}) \quad (20)$$
$$\dot{q}_{2D,j,t} = \sum_{y=0}^{\infty}(c_{ei,2D,j,y} * T_{ext,t-y} + c_{ii,2D,j,y} * T_{int,t-y}) \quad (21)$$
$$\dot{q}_{3D,k,t} = \sum_{y=0}^{\infty}(c_{ei,3D,k,y} * T_{ext,t-y} + c_{ii,3D,k,y} * T_{int,t-y}) \quad (22)$$

The relations of dynamic heat flux densities and the dynamic overall heat transfer in the architectural junction in Eq.(18) allow formulating Eqs. (23-24) in order to relate response factor in partial formulations Eqs. (20-22) and overall heat transfer, Eq.(19).

$$C_{ei,tot,y} = \sum_{1D}\left(c_{ei,1D,i,y} * A_i\right) + \sum_{2D}\left(c_{ei,2D,j,y} * l_j\right) + \sum_{3D}\left(c_{ei,3D,k,y}\right) \quad (23)$$
$$C_{ii,tot,y} = \sum_{1D}\left(c_{ii,1D,i,y} * A_i\right) + \sum_{2D}\left(c_{ii,2D,j,y} * l_j\right) + \sum_{3D}\left(c_{ii,3D,k,y}\right) \quad (24)$$

5.12 Conclusions

Heat transfer in building envelopes, although to be a dynamic phenomenon has traditionally been addressed by means of steady-state parameters. Dynamic energy assessment of building envelopes is commonly performed by means of numerical simulation in building energy simulation software, where one-dimensional heat transfer is computed. However, there is little background on the dynamic assessment of multi-dimensional heat transfer in architectural junctions. In this paper, a detailed analysis has been performed over a junction of an external wall with an intermediate slab, by means of a phasorial transformation of relevant parameters in the steady state and dynamic characterization of building envelopes. The outcomes of this analysis indicate a relevant mismatch between the dynamic thermal response of the one-dimensional wall and the two-dimensional wall-slab junction, in terms of both magnitude and time shift.

The phasorial decomposition proposed in this paper could be taken as a basis to develop a dynamic heat transfer assessment procedure, in which dynamic multi-dimensional heat transfer could be introduced into Building Energy Simulation by means of Fourier decomposition of boundary conditions. However, its present application is limited by the intensive computational time required for obtaining the required dynamic coefficients. Under this approach, the use of junction atlases with pre-calculated data would facilitate the use of this method within BES software.

The proposed approach is valid for mathematical transformations in which linear transformations are possible, such as the Laplace transform, response factor formulation, or Conduction Transfer Function. This roots mathematical applications in the field of heat transfer assessment of building envelopes.

5.13 Reference

[1] U.S. Department of Energy (DOE), 2008 Buildings Energy Data Book, 2008.

[2] Pérez-Lombard L., et al, A review on buildings energy consumption information, Energy and Buildings 40, 2008

[3] E.U., 2002/91/EC of the European Parliament and of the Council of 16th December 2002 on the Energy Performance of Buildings, 2002.

[4] E.U., 2010/31/EU of the European Parliament and of the Council, of 19 May 2010 on the Energy Performance of Buildings (recast), 2010.

[5] Clarke J.A. Energy simulation in building design. Butterworth-Heinemann, 2nd edition, Oxford (2001).

[6] EnergyPlus v8.4, EnergyPlus™ Documentation, Engineering Reference, https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf (23/02/2016)

[7] TRNSYS 16 Documentation, Volume 6, Multizone Building, http://web.mit.edu/parmstr/Public/Documentation/06-MultizoneBuilding.pdf (23/02/2016)

[8] Strachan, P. ; Monari, F.; Kersken, M. ;Heusler, I. ; IEA Annex 58: Full-scale Empirical Validation of Detailed Thermal Simulation Programs, Energy Procedia 78 (2015), 3288-3293, 6th International Building Physics Conference, IBPC 2015

[9] Zalewski, L., Lassue, S., Rousse, D., & Boukhalfa, K. (2010). Experimental and numerical characterization of thermal bridges in prefabricated building walls. Energy Conversion and Management, 51(12), 2869–2877.

[10] IEE SAVE ASIEPI Project, Assessment and Improvement of the EPBD Impact, "The final recommendations of the ASIEPI project: How to make EPB-regulations more effective? Summary report", 2010, Intelligent Energy Europe programme, contract EIE/07/169/SI2.466278

[11] Schild, P.; Blom, P.: Good practice guidance on thermal bridges and construction details – Part 1: Principles. Information paper 188 (2010). http://www.buildup.eu/publications/8239

[12] Schild, P.: Good practice guidance on thermal bridges and construction details - Part 2: Good examples. Information paper 189 (2010). http://www.buildup.eu/publications/8241

[13] Tilmans, A. (2009). Software and Atlases for evaluating Thermal Bridges. Information paper 152. http://www.buildup.eu/node/5657

[14] IETcc, CEPCO & AICIA, Catálogo De Elementos Constructivos Del Cte, v 6,3, 2010.

[15] Accredited Construction Details (ACDs) for Part L. for England & Wales. 2007, http://www.planningportal.gov.uk/buildingregulations/approveddocuments/partl/bcassociateddocuments9/acd#SteelFrameDetails (2016/02/26)

[16] Enhanced Construction Details (EDCs): Thermal bridging and Airtightness. Energy Saving Trust, UK. http://www.energysavingtrust.org.uk/sites/default/files/reports/CE302%20-%20ECD_thermal%20bridging%20and%20airtightness.pdf (2016/02/26)

[17] Citterio, M. et Al. (2009). Thermal bridges in the EBPD context: overview on MS approaches in regulations. Information paper 64. http://www.buildup.eu/publications/1449

[18] Ge, H., McClung, V. R., & Zhang, S. (2013). Impact of balcony thermal bridges on the overall thermal performance of multi-unit residential buildings: A case study. Energy and Buildings, 60, 163–173.

[19] Karambakkam, B. K., Spitler, J. D., & Leonard, C. M. (2003). A One-dimensional Approximation for Transient Multi- dimensional Conduction Heat Transfer in Building Envelopes, (1995).

[20] Larbi, a. Ben. (2005). Statistical modelling of heat transfer for thermal bridges of buildings. Energy and Buildings, 37(9), 945–951.

[21] EN ISO 10211:2007. Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations

[22] T.G. Theodosiou, A.M. Papadopoulos, The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy Build. 40 (11) (2008) 2083–2089.

[23] B. Berggren, M. Wall, Calculation of thermal bridges in (Nordic) building envelopes – risk of performance failure due to inconsistent use of methodology, Energy Build. 65 (2013) 331–339.

[24] DA DB-HE /3, Documento de apoyo al Documento Básico DB-HE Ahorro de la Energía. Puentes Térmicos, Ministerio de Fomento, Spain 2014.

[25] Al-Sanea, S. a. (2003). Finite-volume thermal analysis of building roofs under two-dimensional periodic conditions. Building and Environment, 38(8), 1039–1049.

[26] Martin, K., Erkoreka, a., Flores, I., Odriozola, M., & Sala, J. M. (2011). Problems in the calculation of thermal bridges in dynamic conditions. Energy and Buildings, 43(2-3), 529–535.

[27] Martín, K., Flores, I., Escudero, C., Apaolaza, A., & Sala, J. M. (2010). Methodology for the calculation of response factors through experimental tests and validation with simulation. Energy and Buildings, 42(4), 461–467.

[28] Viot, H., Sempey, a., Pauly, M., & Mora, L. (2015). Comparison of different methods for calculating thermal bridges: Application to wood-frame buildings. Building and Environment, 93, 339–348.

[29] Tadeu, a., Simões, I., Simões, N., & Prata, J. (2011). Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. Energy and Buildings, 43(12), 3685–3695.

[30] Kossecka, E., & Kosny, J. (2004). Two-Step Procedure for Determining Three-Dimensional Conduction Z-Transfer Function Coefficients for Complex Building Envelope Assemblies, ASHRAE, proceeding of Buildings IX: Thermal Performance Of Exterior Envelopes Of Whole Buildings.

[31] Kossecka, E., & Kosny, J. (2005). Three-dimensional conduction z-transfer function coefficients determined from the response factors. Energy and Buildings, 37(4), 301–310.

[32] EN ISO 13786:2007 Thermal performance of building components. Dynamic thermal characteristics. Calculation methods

[33] EN ISO 7345:1996 Thermal Insulation- Physical quantities and definitions

[34] EN ISO 6946:2007 Building components and building elements. Thermal resistance and thermal transmittance. Calculation method

[35] ISO 13789:2007 Thermal performance of buildings -- Transmission and ventilation heat transfer coefficients -- Calculation method

[36] EN 410:2011 Glass in building. Determination of luminous and solar characteristics of glazing

[37] EN 673:2011 Glass in building. Determination of thermal transmittance (U value). Calculation method

[38] Phasor, Wikipedia, https://en.wikipedia.org/wiki/Phasor {2016/03/22}

[39] CEN/TC 89 - Thermal performance of buildings and building components

[40] PHYSIBEL, SOFTWARE for thermal simulation, http://www.physibel.be/ (2017/01/31)

[41] VOLTRA, Computer Program to Calculate 3D & 2D Transient Heat Transfer inObjects Described in a Rectangular Grid Using the Energy Balance Technique,Version 6.3w, Physibel, 2009.

[42] TRISCO, Computer Program to Calculate 3D & 2D Steady State Heat Transfer in Rectangular Objects, Version 12.0w, Physibel, 2010.

[43] Mitalas, G. P.; Stephenson, D. G., Room thermal response factors, ASHRAE Transactions, 73, 1, pp. 1-10, 1967-11-01

6 Steady-state multi-dimensional heat transfer calculation procedures

Estudio de transferencia de calor en los puntos de anclaje a forjado de una subestructura de fachada ventilada

Beñat Arregi Goikolea, Roberto Garay Martinez, Alberto Riverola Lacasta, Daniel Chemisana Villegas

6.1 Resumen

Las fachadas ventiladas son una solución cada vez más utilizada debido a sus buenas prestaciones de durabilidad y eficiencia energética. En estas envolventes, la subestructura que soporta el acabado exterior interrumpe necesariamente la continuidad del aislamiento en los puntos de anclaje sobre la hoja interior. Este estudio analiza el impacto de estos puentes térmicos en la transferencia de calor y el riesgo de condensaciones superficiales, para una fachada ventilada que se instala sobre un edificio existente. El cálculo unidimensional simplificado se compara con simulaciones numéricas mediante elementos finitos, modelando el flujo de calor bidimensional en los frentes de forjado y el flujo de calor tridimensional en los puntos de anclaje a forjado de la subestructura.

6.2 Introducción

La diferencia entre rendimiento energético teórico y real constituye uno de los principales escollos en el camino hacia los edificios de consumo de energía casi nulo. Las fachadas ventiladas ofrecen una solución ventajosa frente a potenciales complicaciones como el sobrecalentamiento o las humedades, pero presentan un punto débil en los anclajes de la subestructura sobre la hoja interior que, al interrumpir necesariamente el aislamiento, constituyen puentes térmicos.

El procedimiento de cálculo simplificado en el Código Técnico de la Edificación (CTE) no contempla el impacto de estos anclajes. En este estudio se analiza la transferencia de calor y el riesgo de condensaciones superficiales en los anclajes de una fachada ventilada que se fijan sobre el frente de forjado de un muro existente.

6.3 Caso De Estudio

Se analiza la aplicación de una fachada ventilada sobre un edificio existente.

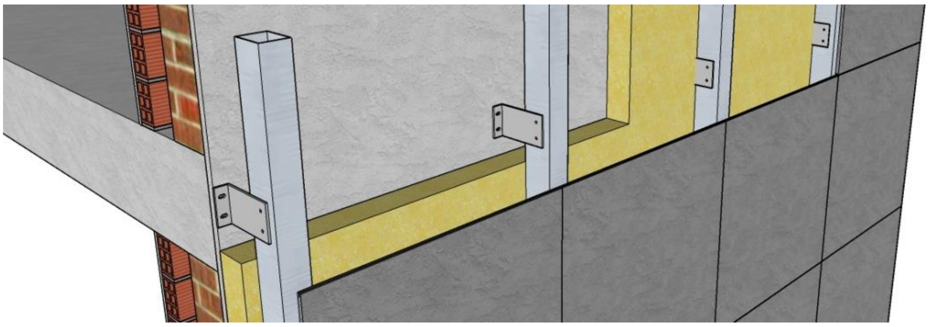


Figura 1: La subestructura de la fachada ventilada se fija a los frentes de forjado mediante anclajes de aluminio.

Para el muro original se plantea una construcción genérica de dos hojas de fábrica de ladrillo con cámara de aire intermedia, sin aislamiento térmico, revocado con cemento en su cara exterior y con un enlucido de yeso como acabado interior. Al apoyar la fábrica sobre los forjados de hormigón armado, estos últimos interrumpen la cámara y quedan expuestos al exterior con la única protección del revoco. Este detalle es un caso muy común de puente térmico.

Para la rehabilitación de esta envolvente se plantea una solución típica de fachada ventilada, fijando la subestructura a los frentes de forjado mediante anclajes de aluminio (figura. 1). Para el aislamiento se estima una conductividad térmica de 0,03 W/mK.

6.4 Metodología

Los cálculos se han realizado para el muro existente sin aislamiento y para su rehabilitación con fachada ventilada, considerando cuatro niveles de aislamiento en incrementos de 50 mm en el espesor del aislante.

Inicialmente se ha realizado un cálculo unidimensional simplificado, de acuerdo con la norma ISO 6946 y el Documento de Apoyo DA DB-HE/1 del CTE. Este cálculo no considera el impacto de los frentes de forjado ni los anclajes de la subestructura metálica de la fachada ventilada.

Posteriormente, con el objeto de cuantificar el impacto de los puentes térmicos, se han realizado simulaciones numéricas mediante elementos finitos siguiendo la norma ISO 10211. Para ello se ha empleado el software COMSOL Multiphysics:

- El flujo de calor adicional en los frentes de forjado se ha determinado calculando su transmitancia térmica lineal mediante una simulación bidimensional (figura 2 izda.).
- El flujo de calor adicional en los puntos de anclaje a forjado de la subestructura se ha determinado calculando su transmitancia térmica puntual mediante una simulación tridimensional (figura 2 dcha.).

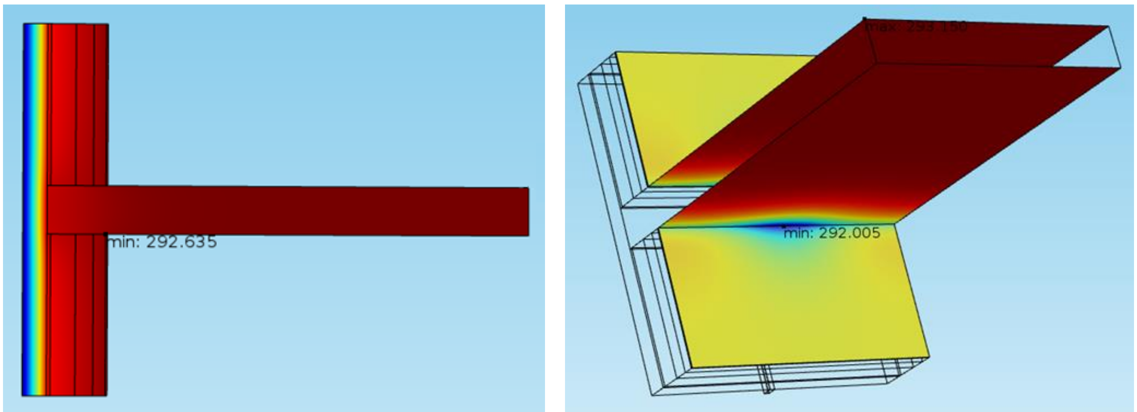


Figura 2: Modelización numérica bidimensional de un frente de forjado (izda.), y modelización numérica tridimensional de un anclaje metálico a forjado (dcha.).

Siguiendo el criterio de las normas ISO para cámaras de aire muy ventiladas, se han despreciado las resistencias térmicas del acabado exterior, la subestructura y la propia cámara de aire de la fachada ventilada, y las resistencias superficiales interior y exterior corresponden al aire en calma (0,13 m^2K/W). Los modelos se han sometido a temperaturas de contorno de 20 °C al interior y 0 °C al exterior.

Finalmente, para posibilitar una comparación directa de los flujos de calor obtenidos con los diferentes métodos de cálculo y simulación, se han traducido todos los resultados a su equivalente unidimensional.

Además del impacto en las pérdidas de calor, se ha evaluado también el riesgo de formación de condensaciones o mohos en las superficies interiores, empleando el método del factor de temperatura definido en la norma ISO 13788 y el Documentos de Apoyo DA DB-HE/3 del CTE. Los valores obtenidos mediante cálculos y simulaciones se han comparado con los valores límite definidos en el CTE para la zona climática de invierno E (la más severa).

6.5 Modelización térmica

6.5.1 Cálculo unidimensional de la fachada

Según los cálculos unidimensionales, los muros rehabilitados con solución de fachada ventilada cumplen las exigencias del CTE, tanto para evitar condensaciones superficiales (factor de temperatura) como para limitar las pérdidas de calor (transmitancia térmica). Las pérdidas de calor unidimensionales se reducen a medida que aumenta el nivel de aislamiento (figura 3 dcha.), aunque la efectividad decrece según aumenta el espesor del aislante (los primeros mm ofrecen un mejor rendimiento energético).

Tabla 1. Resultados del cálculo unidimensional de la fachada.

Espesor del aislamiento (mm)	**sin aisl.**	**50**	**100**	**150**	**200**
Temperatura superficial interior mínima, θ_{si} (°C)	17,27	19,01	19,39	19,56	19,66
Factor de temperatura de la superficie interior, f_{Rsi}	0,86	0,95	0,97	0,98	0,98
Densidad de flujo de calor a través del modelo (W/m²)	21,00	7,64	4,66	3,36	2,63
Transmitancia térmica, U (W/m²K)	1,05	0,38	0,23	0,17	0,13

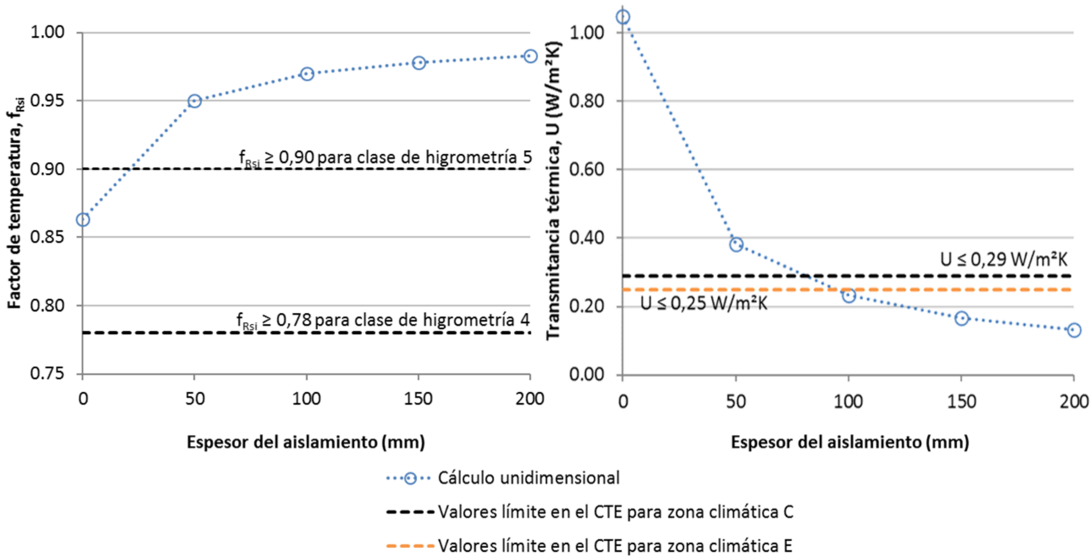


Figura 3: Factor de temperatura (izda.) y transmitancia térmica (dcha.) en función del espesor de aislamiento, obtenidos mediante cálculo unidimensional de la fachada.

6.5.2 Simulación numérica bidimensional del frente de forjado

Las simulaciones bidimensionales permiten cuantificar las pérdidas de calor adicionales en los frentes de forjado, que constituyen un puente térmico debido a la mayor conductividad del hormigón armado.

Los muros con aislamiento cumplen las exigencias del CTE para evitar condensaciones superficiales. El flujo de calor adicional debido al puente térmico viene dado por la transmitancia térmica lineal (figura 4 dcha.). Este valor se reduce drásticamente al incorporar el aislamiento, ya que el aislante pasa por delante de los frentes de forjado, aislándolos así del exterior.

Tabla 2. Resultados del cálculo bidimensional del frente de forjado.

Espesor del aislamiento (mm)	**sin aisl.**	**50**	**100**	**150**	**200**
Temperatura superficial interior mínima, θ_{si} (°C)	15,56	18,77	19,27	19,49	19,60
Factor de temperatura de la superficie interior, f_{Rsi}	0,78	0,94	0,96	0,97	0,98
Densidad lineal de flujo de calor a través del modelo (W/m)	57,18	18,45	11,05	7,89	6,14
Transmitancia térmica lineal, Ψ (W/mK)	0,44	0,04	0,02	0,01	0,00

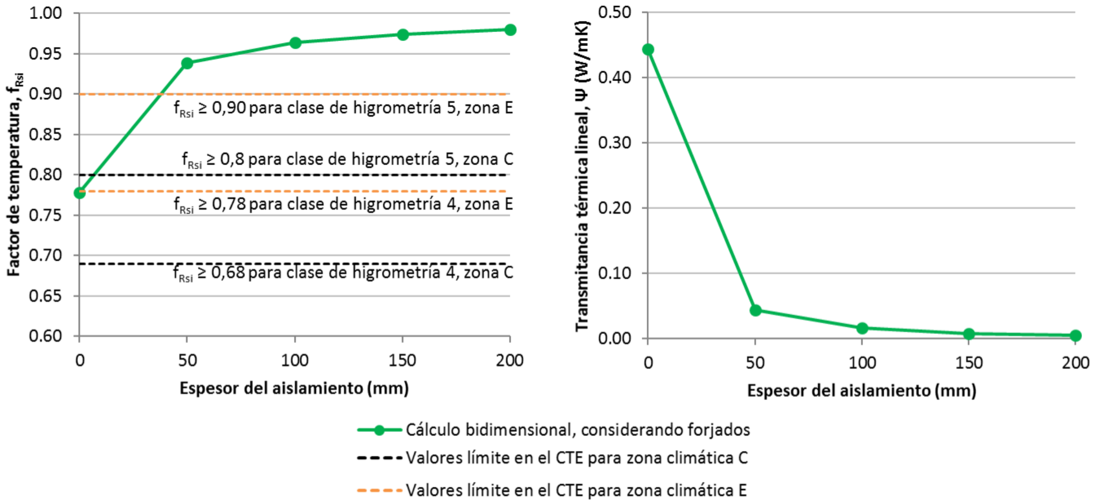


Figura 4: Factor de temperatura (izda.) y transmitancia térmica lineal (dcha.) en función del espesor de aislamiento, obtenidos mediante simulación numérica bidimensional del frente de forjado.

6.6 Simulación numérica tridimensional del anclaje a forjado

Además del impacto de los frentes del forjado, las simulaciones tridimensionales permiten cuantificar las pérdidas de calor adicionales en los anclajes a forjado, que constituyen puentes térmicos puntuales al interrumpir el aislamiento.

Los muros aislados cumplen las exigencias del CTE para evitar condensaciones superficiales. El flujo de calor adicional de cada anclaje viene dado por su transmitancia térmica puntual (Figura 5 dcha.). El impacto de este puente térmico se incrementa al aumentar el espesor de aislamiento; este incremento no es lineal, ya que depende de las dimensiones de los anclajes empleados en cada caso.

Tabla 3. Resultados del cálculo tridimensional del anclaje a forjado.

Espesor del aislamiento (mm)	**sin aisl.**	**50**	**100**	**150**	**200**
Temperatura superficial interior mínima, θ_{si} (°C)	-	18,26	18,77	18,86	19,00
Factor de temperatura de la superficie interior, f_{Rsi}	-	0,91	0,94	0,94	0,95
Flujo de calor a través del modelo (W)	-	39,91	25,21	19,76	16,11
Transmitancia térmica puntual, χ (W/K)	-	0,15	0,16	0,20	0,19

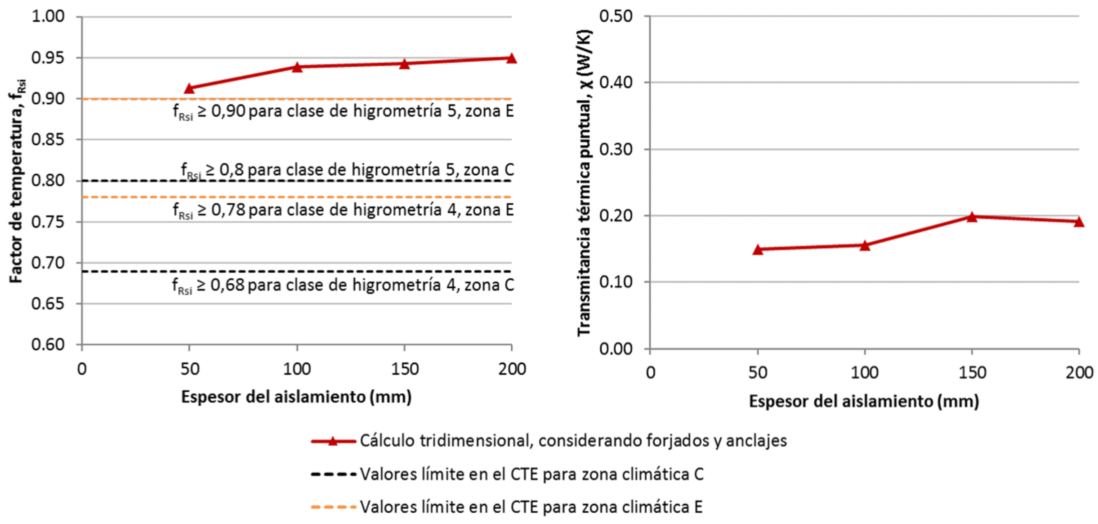


Figura 5: Factor de temperatura (izda.) y transmitancia térmica puntual (dcha.) en función del espesor de aislamiento, obtenidos mediante simulación numérica tridimensional del anclaje a forjado.

6.7 Resultados

Se presenta aquí una comparación de los factores de temperatura y las transmitancias térmicas medias, obtenidos mediante los diferentes métodos de cálculo y simulación arriba descritos.

Tabla 4. Comparación de factores de temperatura de la superficie interior.

Espesor del aislamiento (mm)	sin aisl.	50	100	150	200
Cálculo unidimensional	0,86	0,95	0,97	0,98	0,98
Cálculo bidimensional, considerando forjados	0,78	0,94	0,96	0,97	0,98
Cálculo tridimensional, considerando forjados y anclajes	-	0,91	0,94	0,94	0,95

Tabla 5. Comparación de transmitancias térmicas medias de la envolvente (W/m²K).

Espesor del aislamiento (mm)	sin aisl.	50	100	150	200
Cálculo unidimensional	1,05	0,38	0,23	0,17	0,13
Cálculo bidimensional, considerando forjados	1,18	0,39	0,24	0,17	0,13
Cálculo tridimensional, considerando forjados y anclajes	-	0,44	0,29	0,23	0,19

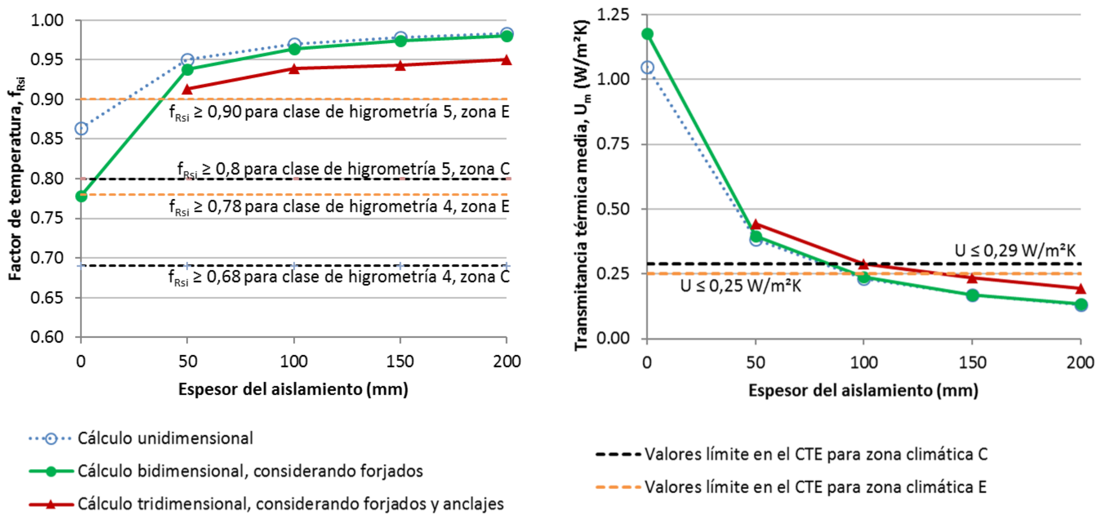


Figura 6: Comparación gráfica de factores de temperatura (izda.) y transmitancias térmicas medias (dcha.), en función del espesor de aislamiento, obtenidos mediante cálculos unidimensionales y simulaciones numéricas.

6.7.1 Riesgo de mohos y condensaciones en la superficie interior

Para la fachada sin aislamiento, el frente de forjado comporta una reducción importante del factor de temperatura (cálculo bidimensional en figura 6 izda.), pudiendo acarrear riesgo de formación de mohos en espacios con alta producción de humedad. La incorporación del aislamiento por delante de los frentes del forjado minimiza el impacto de este puente térmico lineal, si bien en este caso son los anclajes puntuales de la subestructura los que reducen el factor de temperatura (cálculo tridimensional en figura 6 izda.). Sin embargo esta reducción no compromete el cumplimiento de las exigencias del CTE, incluso para las condiciones más exigentes (clase de higrometría 5 en zona climática E). Esto es debido a que en las fachadas ventiladas el aislamiento se coloca por el exterior de la fábrica de ladrillo, aumentando así la temperatura del sustrato y proveyendo una seguridad adicional. Así pues, para las soluciones con aislamiento, el impacto de los puentes térmicos considerados en este estudio no es relevante en términos de riesgo de condensaciones y mohos en la superficie interior.

6.8 Transferencia de calor a través de la fachada

Para hacer posible la comparación directa de las pérdidas de calor, los flujos de calor multidimensionales en los puentes térmicos se han traducido a un flujo unidimensional equivalente, calculando en cada caso la transmitancia térmica media de la envolvente. A este efecto se ha asumido una distancia vertical entre forjados de 3,5 m y una distancia horizontal entre anclajes de 0,9 m.

- En la fachada sin aislamiento, el puente térmico lineal del frente de forjado incrementa en un 12% las pérdidas de calor obtenidas mediante el cálculo convencional (línea punteada en figura 6 dcha.). Al incorporar el aislamiento por delante de los frentes de forjado, estas pérdidas adicionales se reducen en gran medida. Así, los resultados de las simulaciones bidimensionales se acercan a los cálculos unidimensionales a medida que aumenta el espesor de aislante.
- Sin embargo, las pérdidas adicionales de los anclajes a forjado, que posibilitan la conducción de calor entre el forjado de hormigón armado y el ambiente exterior, solo pueden cuantificarse mediante la simulación tridimensional. Comparado con el cálculo unidimensional (línea punteada en figura 6 dcha.), el incremento en la transmitancia térmica calculado en este estudio es de entre un 16% y un 48%, para espesores de aislamiento de 50 y 200 mm respectivamente.

6.9 Conclusiones

En las fachadas ventiladas, la continuidad del aislamiento se interrumpe necesariamente en los puntos de anclaje de la subestructura a la hoja interior. Aunque no presentan riesgo de condensaciones superficiales, estos puentes térmicos pueden causar un incremento en las pérdidas de calor, especialmente a medida que aumenta el espesor de aislamiento.

En rehabilitaciones con fachada ventilada, es común que la subestructura de esta última se fije a los cantos o frentes de los forjados de hormigón armado existentes. Si el impacto de estos anclajes no se tiene en cuenta al realizar los cálculos energéticos, existe el riesgo de sobreestimar el desempeño térmico de la fachada rehabilitada, resultando en una infrautilización de la resistencia térmica del aislamiento y, en último término, un consumo energético superior al previsto.

Para optimizar la viabilidad de las fachadas ventiladas como una solución de bajo consumo energético en rehabilitación, se hace necesario mitigar el puente térmico en los anclajes a forjado, mediante un diseño específico que considere las solicitaciones térmicas además de las estructurales.

6.10 Reconocimientos

Este trabajo se ha desarrollado parcialmente dentro del proyecto de investigación BRESAER, financiado por el programa Horizon 2020 de la Unión Europea bajo el grant agreement Nº 637186.

6.11 Referencias

[1] Código Técnico de la Edificación (CTE). DA DB-HE / 1 Documento de Apoyo al Documento Básico DB-HE Ahorro de energía. Cálculo de parámetros característicos de la envolvente. (Febrero 2015)

[2] Código Técnico de la Edificación (CTE). DA DB-HE / 3 Documento de Apoyo al Documento Básico DB-HE Ahorro de energía. Puentes térmicos. (Mayo 2014)

[3] UNE-EN ISO 6946:2012. Componentes y elementos para la edificación. Resistencia térmica y transmitancia térmica. Método de cálculo. (ISO 6946:2007)

[4] UNE-EN ISO 10211:2012. Puentes térmicos en edificación. Flujos de calor y temperaturas superficiales. Cálculos detallados. (ISO 10211:2007)

[5] UNE-EN ISO 13788:2002. Características higrotérmicas de los elementos y componentes de edificación. Temperatura superficial interior para evitar la humedad superficial crítica y la condensación intersticial. Métodos de cálculo. (ISO 13788:2001)

7 Experimental Assessment of steady-state one-dimensional thermal insulation performance

Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale

Roberto Garay Martinez, Eunate Goiti, Gudrun Reichenauer, Shanyu Zhao, Matthias Koebel, Aitor Barrio

In the context of increasing energy costs and the need for global reduction of CO_2 emissions, the development of superinsulation materials for the construction sector allows the design of low-energy buildings. Since still being in an experimental or at early-commercial stage, R&D of these materials focused on its final application is required, to accelerate access to the market for renovation of the building stock where space is a critical metric.

In this paper, the experimental assessment of the thermal performance of a novel ambient pressure dried silica aerogel based composite is presented. In order to provide assessments at both, material and system levels, stress-strain tests, hot plate measurements, as well as full scale tests under realistic boundary conditions were conducted.

The overall results are that this material provides good insulation properties (thermal conductivity in the range of 0.015-0.018 W/mK), along with sufficient mechanical properties, and allows for the creation of super insulating assemblies even at small wall thickness.

7.1 Introduction

The development of cost-effective high thermal insulation performance products and systems can contribute to improve the energy efficiency of buildings and thus reducing CO_2 emissions. The majority of energy in a building is spent to satisfy heating and cooling demands accounting for 70% of the total final energy use. The energy performance of an average European building is rather poor, due to the fact that a high percentage of the European residential buildings were constructed before the 1960s, when energy building regulations were very limited, and have not undergone renovations to improve energy performance, meaning that these buildings have low insulation levels and their systems are old and inefficient [1].

One key method to improve the energy efficiency of buildings is to enhance the thermal resistance of the envelope. This can be achieved by: *a)* increasing the thickness of traditional insulation materials, something that is not always possible, as often, there are space limitations; *b)* decreasing the thermal losses at given insulation thickness by using materials with significantly lower thermal conductivity, for example super insulating materials such as aerogels. The use of Aerogel as an insulation material has been proven effective in several demonstration and retrofitting projects such as [2], the technical and economical optimization of façade insulation with Aerogel was studied in [3]. In [4] the design of an aerogel-filled sandwich panel was studied for building envelope integration.

Aerogels are open-porous, lightweight solids with densities ranging 3-350mg/cm^3 [5] consisting of an interconnected particle network structure with interstitial pores with a pore size typically <<1 µm [6, 7]. Such Nano porous structures make aerogels the materials with the lowest thermal conductivity at ambient conditions known in a solid (λ <0.012 $Wm^{-1}K^{-1}$) [8, 9].

Aerogels can be synthesized via a sol-gel process during which solid nanoparticles grow, crosslink and finally form a three-dimensional solid network with solvent filled pores. Since the silica aerogels comprise highly open structures in which the secondary particles of silica are connected to each other with only few siloxane bonds, the structure of native aerogels is too fragile to be handled. Aging processes are applied to strengthen the solid skeleton of silica [10].

Removal of solvent from the gel structure is essential for aerogel preparation, there are three typical routes to high performance aerogel-like materials: freeze drying [11], subcritical drying (or ambient pressure drying) [12, 13, 14] and supercritical drying [15, 16, 17]. Freeze drying is not popular for silica aerogel synthesis, since it is addressed as a time and energy consuming process [18], and the formation of microscopic crystals during freeze could degrade the gel structure. Supercritical drying is the traditional route [19], which was first based on alcohols and today primarily on CO_2, because of the latter system's greatly reduced process risks. Nowadays, ambient pressure drying of chemically modified gels results in materials with properties that are nearly indistinguishable from their supercritically dried analogs [20]. Thus, the supercritical and ambient pressure drying techniques tend to be applied for commercialization of aerogel materials. After drying, the nanosized pores in the system are filled with air leading to aerogels with a porosity greater than 90% [21].

Due to the exceptional properties of these materials they are excellent candidates for cases where the market demands products with strongly enhanced thermal insulation, better acoustic barrier and reduced weight properties [22].

Currently the main inhibitors that avoid spreading the use of super insulating aerogel materials are: *(i)* the high cost involved in their production and *(ii)* the poor mechanical properties of the associated current silica aerogel insulation products [23]. Cost reductions are mostly contingent on economical up-scaling and more efficient based on continuous and scalable production technologies. The largest savings which can be achieved from today's perspective are contingent upon a change of process technology from batch-type supercritical drying to a continuous subcritical ambient pressure drying process with complete solvent recycling and re-use.

The European Project AEROCOINs [24] has developed novel silica aerogel-based composite materials to improve the thermal insulation performance of the envelope of buildings aiming at maximizing their energy performance by reducing their energy demands. AEROCOINs has achieved the up-scaling of the formulations based on an ambient pressure drying process providing silica aerogel-based panels of 50 cm x 50 cm x 2 cm dimensions which are compatible with critical performance levels in building regulations (e.g. fire reaction class B was obtained according to the Construction Products Regulation [25]).

In the present work, the main objective is to validate the thermal performance of novel ambient pressure dried aerogel composite at building scale. In order to provide experimental assessments not only at system but also at material level, stress-strain tests, hot plate measurements, as well as full scale tests under realistic boundary conditions were conducted.

The present work bases its thermal assessment process at building scale on several previous experimental and data analysis procedures for the experimental assessment of the energy performance of buildings. In [26], a test was performed to calibrate a hygrothermal model of a wall with an insulating rendering based on silica-aerogels, for exterior thermal insulation applications. In [27] several envelope retrofitting solutions are tested, some of them comprising aerogel boards. The thermal transmittance of the system was assessed by different means: theoretical value, experimental by means of averaging and experimental by means of dynamic analysis with software LORD [28]. In this work, both experimental assessment methods are found to be in good agreement, although the theoretical transmittance of the wall is substantially lower- CA 20%- of the other two methods. Experimental assessments performed by dynamic methods based on system identification techniques such as those used by [28] and [29] are increasingly common within the last decades, in works such as [30] and [31].

In this particular work, the scope of the full scale experimental assessment was narrowed to the identification of the insulation properties of the aerogel material in the experiment. In order to better assess this performance, sensors were installed in close contact with both sides of these materials, on the inner side of a concrete wall-thus mitigating the effect of dynamic boundary conditions, and allowing for the correct application of averaging methods.

7.2 Preparation of Ambient-dried Aerogel composites

A pre-polymerized form of tetraethoxysilane (TEOS) containing 20% w/w SiO_2 in ethanol (PEDS-P_{75E20}, PCAS, France) was used as the silica gel precursor. The precursor was diluted with ethanol (F25-AF-MEK ethanol with 2% methyl ethyl ketone) yielding a silica sol with 6 % w/w SiO_2 content. After adding a 5.5 M solution of ammonium hydroxide (NH_4OH, Fluka, Germany) at 2 % v/v of the sol, the activated sol was quickly transferred into a mold where the nonwoven polyester fiber blankets had been placed.

Two Polyester fiber (PES) blankets were used: 5×5×1 cm^3 and 10×10×1 cm^3 for lab-scale samples, 50×50×2 cm^3 for pilot-scale samples. In both cases, delivered by Ridan Sp. z o.o, Poland.

Gelation of the silica resulted in the formation of a fiber reinforced gel composite. The aerogel composite board/ mat was obtained by surface modification (hydrophobization) of the aged gel by means of hexamethyldisiloxane followed by ambient pressure drying (APD) at 150°C for 3 hours in an oven. For comparison purposes, some aerogel composite materials were dried via supercritical drying (SCD) technique.

The impregnation of the PES blanket with the silica gel resulted in the air space between the fibers being filled out with a high porosity (>90%), high surface area (>600 m^2/g),and low density (0.08 – 0.12 g/cm^3) silica aerogel material. In this way, a superinsulating composite material was obtained.

The use of the fiber based blanket as reinforcing matrix for the silica aerogel improves the cohesion and mechanical properties of the aerogel material, giving it more flexibility and reducing fracture/ cracking which is essential for building insulation applications. A photographic image of 10cm x 10 cm composites is shown in figure 1.

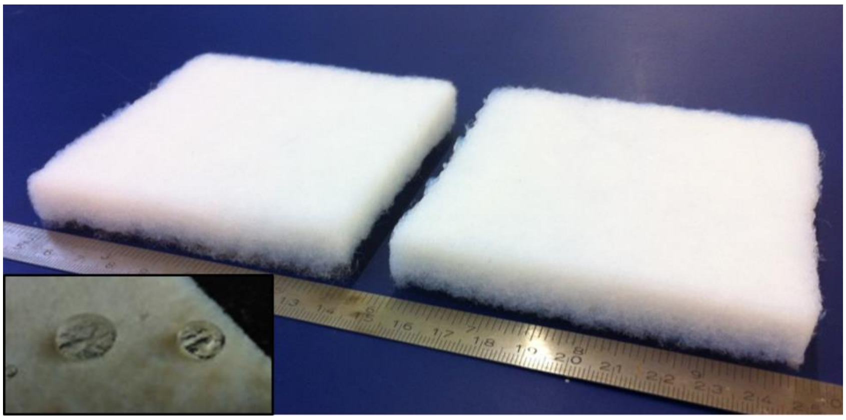


Figure 1: Digital photograph of the ambient dried PES-silica composite aerogels, inset shows the hydrophobicity of the composite

This synthesis process was followed at two different scales: Laboratory-scale and pilot manufacture plant scale.

At laboratory-scale, this process was assessed to be the most promising synthesis route for an up scaling process, and the pilot manufacture plant scale was the result of the up scaling of this process into a pre-industrial process.

Samples were referenced with the following naming structure: PS-L-X for laboratory scale produced PES silica composite, for a given X batch; and PS-P-X for pilot manufacture plant produced PES silica composite, for a given X batch.

The physical properties of both lab-scale and pilot-scale manufactured aerogel composites are listed in Table 1 and Table 2, respectively.

7.3 Characterization of the aerogel composites

7.3.1 Density and linear shrinkage

The bulk density ρ_{bulk} was calculated from the weight and envelope volume of the square, quasimonolithic tiles. The linear shrinkage *Ls (%)* upon drying was calculated from Eq. 1, based on the length of the wet L_{wet} and dried L_{dry} of aerogels:

$$L_S = \frac{L_{wet} - L_{dry}}{V_{wet}} \times 100. \qquad (1)$$

7.3.2 Thermal conductivity of lab-scale prepared composites

Thermal conductivities were determined for square plate specimens of monolithic aerogels using a custom built guarded hot plate device designed for small samples (guarded zone: 50×50 mm^2, measuring zone: 25×25 mm^2) of low thermal conductivity materials[32] at EMPA. The reliability of mentioned custom-built apparatus was verified by means of comparison with hot-wire measurement techniques at ZAE-Bayern.

The results of these tests are shown in Table 2. Compared with the reference silica aerogel at similar density prepared from PEDS-P_{75E20} (0.014 W $m^{-1}K^{-1}$) [33], the thermal conductivity of the respective composites, which are prepared under supercritical or ambient conditions, shows no significant changes with addition of PES fibers (from 0.0142 – 0.0160 W $m^{-1}K^{-1}$).

7.3.3 Mechanical property of the lab-scale prepared composites

Mechanical characterization of the laboratory scale composites PS-L-1 through PS-L-4 was performed on monolithic cylindrical samples using an universal mechanical testing setup (Zwick/Z010, Zwick/Roell, Germany), equipped with a 2kN force transducer (KAP-S, AST Gruppe GmbH, Germany) in a controlled environment (23°C, 50% relative humidity). Stress strain curves were measured in compression mode and elastic moduli were calculated from the linear regime of the curves which typically occurred at 4 ± 2 % strain. The samples were compressed with a constant deformation rate of 1 mm/min up to 80% strain or until the first buckling event (>50% loss of stress) occurred.

The strain-stress curves are shown in figure 2. In comparison to a pure, monolithic PEDS-P_{75E20} aerogel of identical density (100 kg/m^3, final strength ~2MPa, elastic moduli ~2MPa and strain at break ~ 65% but with buckling before break [33]), the PES-silica composites displays a much lower elastic modulus of 0.26 ± 0.13 MPa and low final compressive strength 0.5-0.7MPa but a very high fracture strain of more than 80%. This is due to the microfracturing which occurs during the ambient drying of the composites. Note that the super critically dried reference silica aerogel also features a relatively high fracture strain (65%) under laboratory conditions under a controlled compression rate, but is actually very fragile in real working conditions. As a result, the PES reinforcement not only facilitates ambient pressure drying, but also significantly improves cohesion of the fractured aerogel phase as well as flexibility and workability of the composite materials. The super critically dried composite PS-L-2 is slightly stronger than the ambient dried samples (figure 2, table 2), which is attributed to fewer cracks formed during the drying process.

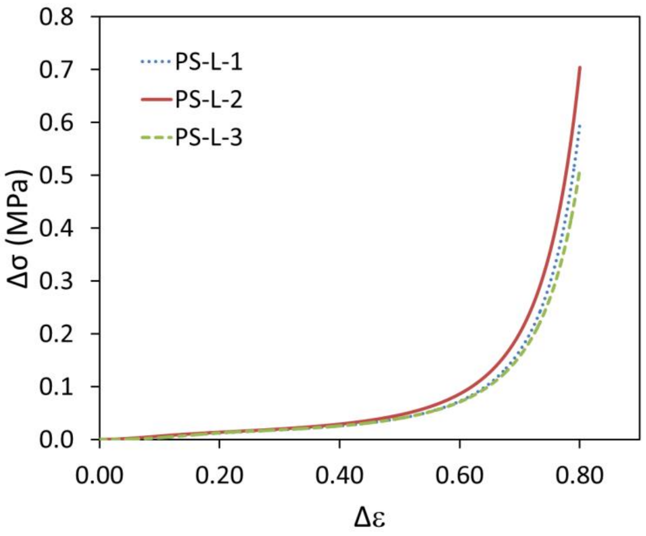


Figure 2: Strain-stress curve of the PES-silica composites.

7.3.4 Thermal conductivity of pilot-scale produced composites

Thermal testing of the pilot-scale produced silica aerogel composites was performed using two independent hot-plate measurement setups.

Boards with a size of 30 cm x 30 cm x 2cm where characterized in terms of their thermal conductivity using a Netzsch HFM 436/3/1E instrument. This instrument establishes a selected temperature difference across the sample and determines the corresponding heat flow via two integrated heat flow meters. All experiments were performed at a mean temperature of about 22.5 ° with a temperature gradient across the composite board of about 20 °C. To avoid dust release and contamination of the instrument, the samples were wrapped in household type plastic foil before introducing them into the instrument for thermal analysis.

Table 1 shows the results for two boards prepared under nominally identical conditions. In order to evaluate the possible effect of a mechanical deformation on the thermal performance of the silica aerogel based composites, the boards were exposed to a sequence of about four uniaxial compression cycles up to 20% strain before repeating the thermal conductivity measurement. The results reveal that no change in the thermal properties could be detected.

In addition, the same boards were analyzed again after being stored for one year in a laboratory environment (relative humidity RH < 60 %). Again, no change in the thermal properties was detected within the range of the accuracy of the instrument.

Table 1. Bulk density ρ_{bulk} and thermal conductivity λ of pilot-scale produced composite boards.

	pristine		**after 20 % mechanical compression**	**after storage for 1 year at ambient conditions**	
	density (kg/m^3)	thermal conductivity (W/(m K)	thermal conductivity (W/(m K)	thermal conductivity (W/(m K)	density (kg/m^3)
PS-P-1	94.0	0.018±0.001	0.018±0.001	0.017±0.001	103.6
PS-P-2	99.6	0.016±0.001	0.016±0.001	0.016±0.001	108.1

7.3.5 Mechanical properties of pilot-scale produced composites

Mechanical properties of ambient pressure dried composite boards were evaluated by means of compression tests that were performed using a Zwick Roell Z20 equipped with a 20 KN load cell. PS-P1 and PS-P2 composite boards cut to a size of about 24 cm x 27 cm and a thickness of about 2 cm where placed between two square plane parallel plates of 34 cm lateral length. While one of the plates was fixed, the other was movable with a centrally positioned ball joint to ensure that only axial forces were applied to the samples. Displacement and force were measured continuously with an accuracy of ± 0.5 mm and ± 1% (for loads > 60 N), respectively.

According to EU standard EN 826 (Determination of Compression Behavior of Thermal Insulation Products) [34] samples were placed centrally between the two plates, preloaded with (250±10) Pa and compressed with a constant rate of displacement of 5 mm/min. The zero deformation point was defined as the deformation at a stress of (250±10) Pa. In contrast to the standard, where deformations of 10 % are recommended for evaluation of elastic constants, the aerogel boards were compressed up to strain levels of 25%.

Only at very low deformation (< 2 %) and around 25 % strain a linear increase of the stress strain curve was observed (figure 3). This is a typical behavior found for aerogels, as they tend to soften after an initial Hooke's law dependence since relatively small deformations result in buckling of the backbone at the nanoscopic scale.

To quantify the respective Young's modulus, $E = \Delta\sigma/\Delta\varepsilon$, the derivative of the stress-strain curve was determined at two different deformations of 2% and 25%, respectively. $\Delta\sigma$ denotes the relative stress (pressure applied) and $\Delta\varepsilon = (\Delta d/d_0)$ the relative strain (i.e. relative change in sample thickness $\Delta d/d_0$) in the linear (elastic) regime. As compared to the traditional insulation [35, 36], the PES reinforced aerogel boards show a low compressive strength at 10 % strain and low Young's modulus, but relative higher ultimate compressive strength. Overall, such ambient dried silica aerogel composite with the reinforcement of PES blanket ameliorates both low thermal conductivity and improved ultimate compressive strength of the silica aerogels, giving more flexibility and adaptability of super insulating aerogel materials for building insulation applications.

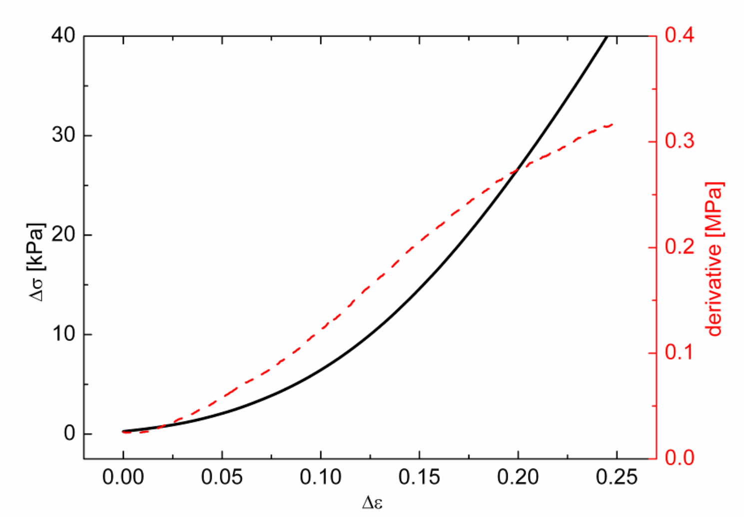


Figure 3. Black: Typical stress strain curve recorded for the silica composite boards. Red: corresponding derivative.

Table 2. Bulk density ρ_{bulk}, linear shrinkage L_s (Eq.1), thermal conductivity λ and elastic moduli E of the lab-scale produced composites

Samples	Drying method	Size (mm)	ρbulk (kg/m3)	Ls (%)	λ (W m-1K-1)	E (MPa)
PS-L-1	APD	50×50×10	114.0	3.2	0.0160	0.24
PS-L-2	CO2 SCD	50×50×10	100.0	2.3	0.0139	0.39
PS-L-3	APD	100×100×10	102.0	2.3	0.0145	0.14
PS-L-4	APD	100×100×10	103.0	2.5	0.0142	-

Table 3. Elastic moduli determined in different regimes of deformation for two pilot-scale silica composite boards.

	at 2% deformation	**at 25% deformation**
	E (MPa)	E (MPa)
PS-P-1	0.0150±0.0001	0.32±0.0005
PS-P-2	0.0250±0.00002	0.32±0.0007

7.4 Fire reaction characterization

The fire reaction characterization was carried out under construction European standard for euroclass fire classification EN13501-1:2007 [37]. According to this standard, the reaction to fire classification of a product for walls must be tested according to single burning item test (SBI) test [38] under the same installation conditions as those envisaged for the final applications. Hence, a sample of two wings (1,5m x 1,0m and 1,5m x0,5m) was built with prefabricated elements as defined in section 5.2. The joints were protected by gypsum plaster and the corner was mounted just by supporting the short wing with the long wing. This unprotected junction is the most unfavorable case because it allow the flame to reach the otherwise hidden part of the system.

Figure 4: Images of the sample before (left), during (center) and after SBI test (right).

The main parameters for the classification of the system are included in the following table:

Table 4. SBI main parameter results of prototype.

THR 600s [MJ]	FIGRA 0.2 W/s	FIGRA 0.4 W/s	TSP 600s [m^2]	SMOGRA [m^2/s^2]
0.85	20.560	6.182	49.658	6.192

These figures indicate that the combustible materials (plastic composite and insulation layers) were not affected by the flame and were protected by the plasterboard.

According to [38], the final performance of this system was classified as B-s1,d0. This classification is suitable for installation of the Aerogel-based internal insulation system in buildings, under all major construction regulations in Europe.

7.5 Full scale experiment

7.5.1 Experimental Environment

Building scale validation of the insulation performance of the composite boards PS-P-X was carried out in the adaptive Kubik $_{\text{by Tecnalia}}$ (hereinafter referred to as KUBIK) full-scale building test facility [39], which served at the same time as a technological demonstration environment, and as a full scale experimentation and validation testing environment for performance assessment of these composites under real-life conditions.

Figure 5: South-West view of the KUBIK test facility (left) and location of the test cell for testing of indoor insulation systems (right).

The KUBIK building is located in Derio, Spain (43°17'N 2°52'W), in the vicinity of the city of Bilbao, and approximately 12-15 km from the sea. KUBIK is a full scale experimental R&D infrastructure to demonstrate energy efficient technologies, focused on the development of new products and systems. The main distinctive feature of KUBIK is its capacity to create realistic scenarios for the quantitative determination of energy efficiency/ energy savings resulting from the interplay of constructive solutions, intelligent management of HVAC and lighting systems as well as non-renewable and renewable energy sources. The infrastructure is a building with a total floor area of 500 m^2 distributed over basement, ground floor and two upper levels.

To create an ideal test environment for the aerogel based composite insulation system, a subset of the KUBIK building was selected. The selected space consists of a relatively large test cell on the second floor of the KUBIK test building. This test cell provides two equally exposed façade modules, allowing the installation of insulation system. Indoor temperature control was achieved by means of a heating and cooling system. The system is composed of two fan-coil HVAC units installed at roof level, and a controller which delivers, on demand, heating & cooling to the test cell with the added functionality that dynamic control scenarios such as steps, ramps and schedules can be programmed. The homogeneity of ambient temperature inside the room is evaluated by means of a distribution of temperature sensors in various locations across the test cell: Two stands are distributed on the N-S axis, where three Pt-100 temperature sensors are placed at 10, 110 and 170 cm height, respectively.

This environment has been used for testing of various insulation materials and systems since its construction in 2014, as multiple systems can be tested at the same time in portions of the exposed wall. The Aerogel-based insulation system was installed in roughly ½ of the available surface, while other tests have been conducted in the remaining space. During the measurement phase and analysis process, several issues were inspected: 1-D heat transfer, 2-D thermal field on the installed support structure (plastic-composite profiles), and constructive details of the area in the vicinity of the window.

7.5.2 Definition of test samples

The prototypes used in the assessment consisted of a multi-layer assembly with the following components (see figure 5):

- Reflective foil (on the side facing the pre-existing wall)
- Two aerogel composite boards
- Plasterboard (on the side facing the room interior)

These elements were prefabricated in a plastic-composite frame providing mechanical stability to the system and allowing a dry construction process. These prototypes were manufactured by Acciona Infraestructuras, Madrid. Prototypes were delivered in two sizes: Small (50cm x 50cm) and Large (50cm x 100cm).

7.5.3 Assessment of 1-D heat transfer

The ambient dried Aerogel composite boards developed in this work are insulation materials which are characterized by their extremely low thermal conductivity as well as a comparatively low density and heat capacity. The utilization of insulation materials in the construction sector has the primary function to generate highly insulated building envelopes, while a reduced heat capacity is of little interest, and commonly disregarded in thermal calculations such as [40], furthermore considering that buildings are constructed with large quantities of materials such as concrete and bricks, with much greater heat capacity.

For this reason, the thermal assessment focused on the characterization of the on-site thermal resistance -R- of the tested aerogel based components. Along with the thermal transmittance, thermal resistance is used in the building and construction industry [41] as the most widely accepted reference parameter for the thermal insulation properties of materials, components and entire construction elements. Under uniform conditions the thermal resistance is the ratio of the temperature difference across a material (T_1-T_2) and the heat flux through it (Q) per unit area. Thermal resistance varies with temperature but it is common practice in construction to treat it as a constant value.

In order to obtain the R-value of the insulation system, temperature sensors were installed on both surfaces of the system:

- Directly on the internal surface of the pre-existing façade (outer surface of the insulation system),
- On the internal surface of the insulation system.

Heat flux sensors were installed on the internal surface of the render, in direct contact with the air in the test cell. This set-up was replicated along 4 selected measurement axes, where all variables were measured separately. These measurement locations were selected to account for the possible variability in the test outcome as a result of variations in the production process and unexpected temperature variations.

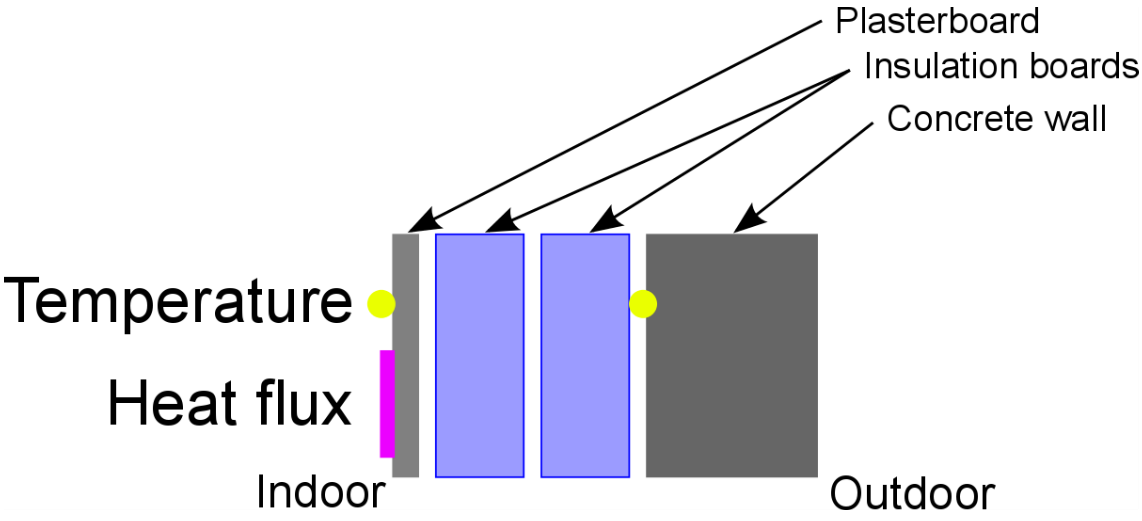


Figure 6: Location of sensors for the thermal resistance measurements

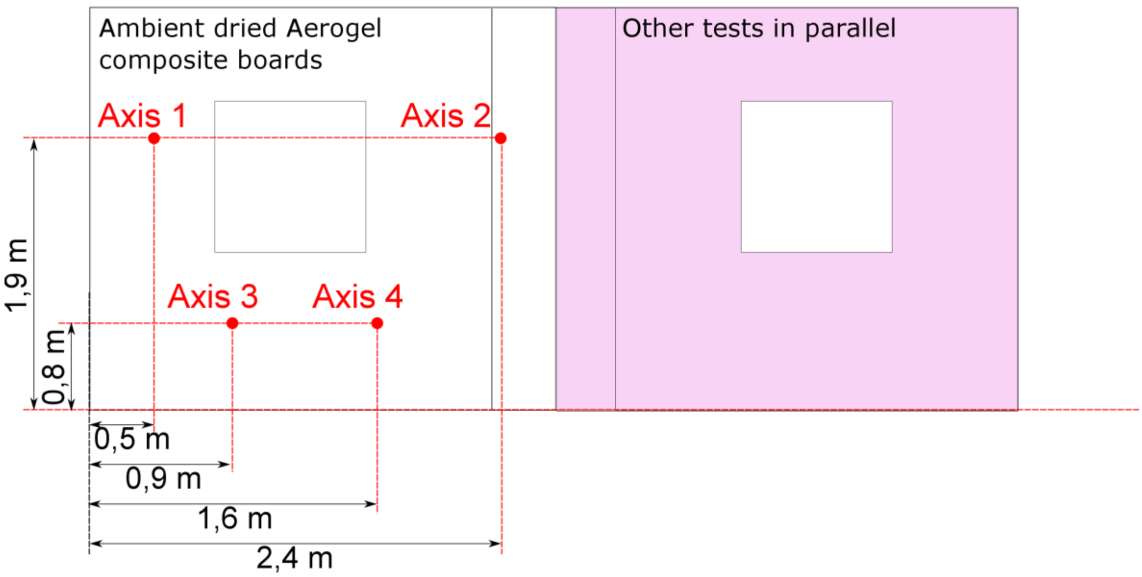


Figure 7: Internal view of the location of measurement axes in the test wall.

The R-value provides a steady-state characterization of the thermal insulation performance. As such steady-state characterization, R-value measurements must be performed under situations where the steady-state assumption can be guaranteed. For on-site measurements, reference [42] states that the stability should be addressed by ensuring that the daily averaged R-value does not deviate by more than 5% from that from the previous 24h. However, this criterion is established for on-site measurements, where heavy limitations on the campaign length are imposed by the construction process itself or the final handover of the building to the owner. Being a research facility, where the campaign length was not limited by such practical constraints and where the internal boundary conditions could be set specifically by means of the advanced control systems, the tests reported here were earmarked by a stability which was far better, i.e. deviations which were significantly lower than the reference 5% stated above.

7.5.4 Test campaign

The test campaign consisted on several test sequences in the period from November 2014 to April 2015. Sequences were almost consecutive with the exception of a period lasting approximately 6 weeks in January 2015, where the test was stopped due to maintenance and adaptation works in KUBIK.

Table 5. Indoor boundary conditions during the different tests conducted.

Id	Indoor temperature	Period	
1	30 ºC	14/11/2014	24/11/2014
2	30ºC	24/11/2014	01/12/2014
3	15 ºC/25ºC oscillation every 12h	01/12/2014	09/12/2014
4	15 ºC/25ºC oscillation every 6h	09/12/2014	16/12/2014
5	30 ºC	05/01/2015	02/02/2015
6	24h Sequence: 00:00 -> 27ºC 07: 00 -> 25ºC	19/02/2015	02/03/2015
7	24h Sequence: 00:00 -> 17ºC 07: 00 -> 25ºC	02/03/2015	06/04/2015
8	00:00 -> 27ºC 07: 00 -> 25ºC	06/04/2015	04/05/2015

7.5.5 Test campaign results

From the raw-series, surface-to-surface R-value calculations were made for each of the measurement axes. Overall, two sets of results are provided, namely:

- Daily averaged R-values (figure 8): Minutely logged signals were averaged on a daily basis (0h-24h). 1 R-value per day is provided.
- Cumulated R-value (figure 9): Minutely logged signals were cumulated (first data set onwards). The corresponding R-value is calculated for each point in time. The statistical confidence of this cumulated R-value increases with time.

In both cases, and due to its greater physical meaning, the thermal conductance (the inverse of the R-value) is plotted. The thermal conductance provides the direct heat loss across the construction for a given temperature gradient per unit surface area.

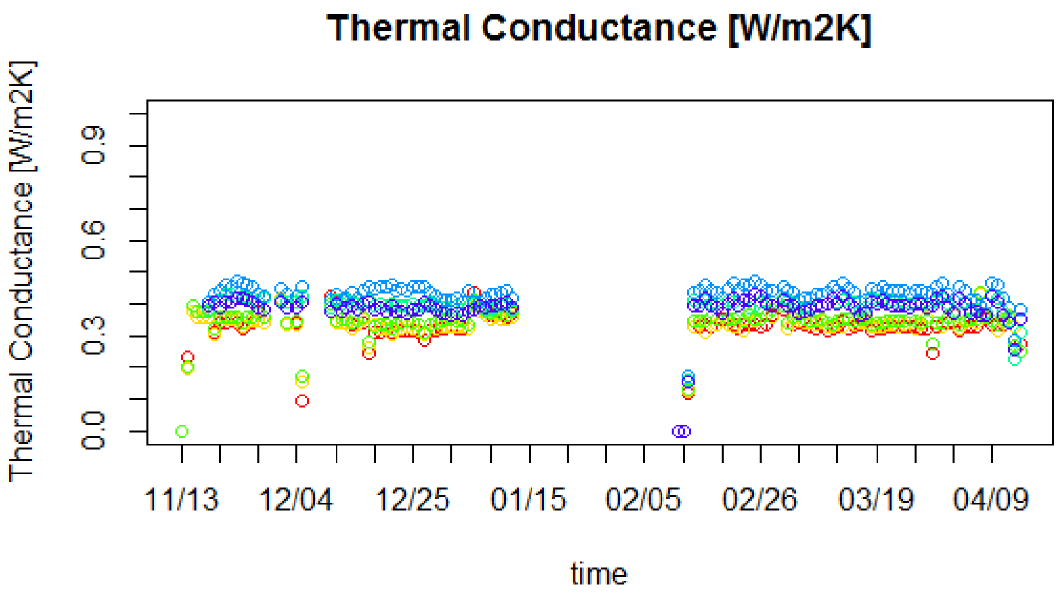


Figure 8: Daily coupling coefficients in the period 2014/11-2015/04.

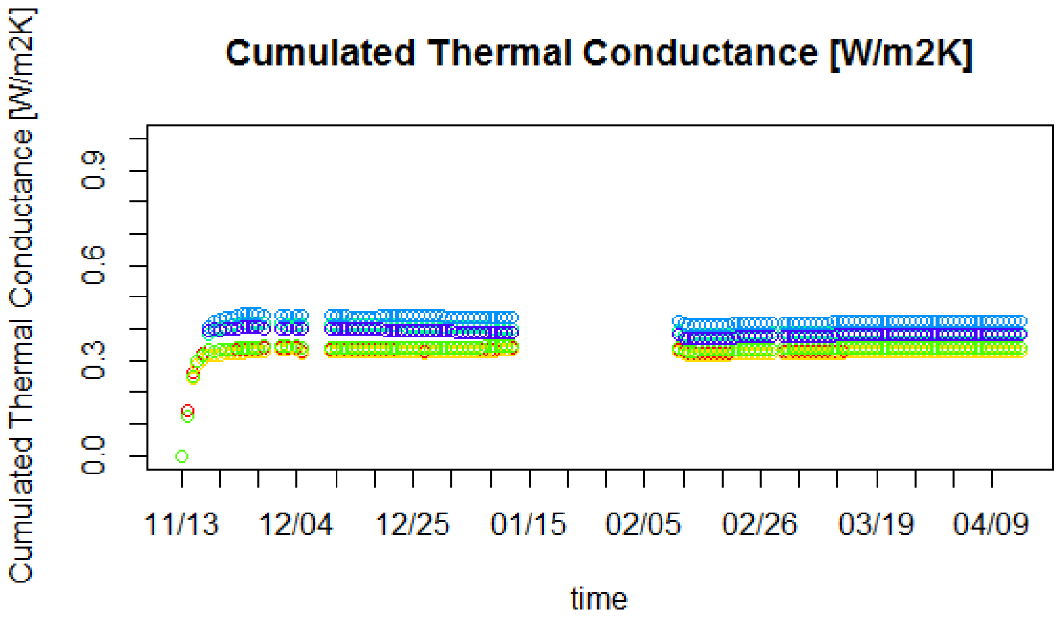


Figure 9: Cumulated coupling coefficients in the period 2014/11-2015/04.

As it can be directly observed from the above figures, there is a certain variation in the daily coupling coefficients, which is particularly relevant for certain peak days. A careful assessment of these outliers has shown that they have occurred on days, when data logger failure had occurred or only partial datasets of the full 24h cycle had been recorded. Another type of outlier was connected to a few single days where the internal boundary conditions had been changed as a result of switching between scenarios (e.g. indoor temperature is artificially increased from 15 ºC to 25ºC in sequences 3 & 4).

However, in the long term, the cumulated coupling coefficient calculation procedure proved to be very stable. Considering datasets from 100 days of measurements, sufficient inertia was included in the results to allow us to neglect any transient or momentary thermal storage effects of the building envelope itself.

Table 6. Experimentally determined coupling coefficients from the four axes.

Axis	**1**	**2**	**3**	**4**
Thermal Conductance [W/m²K]	0.308	0.327	0.328	0.341

Based on the reported values of the coupling coefficients, a reverse calculation was made to obtain the thermal conductivity of the ambient dried Aerogel composite boards (Table 7).

Table 7. R-value of Aerogel-based insulation system and estimated and thermal conductivity of the embedded Aerogel composites.

Axis	**1**	**2**	**3**	**4**
R-value [m2K/W]	2.872	2.688	2.676	2.561
Thermal conductivity [W/mK]	0.0139	0.0149	0.0149	0.0156

7.6 Conclusions

An efficient ambient pressure drying process has allowed the up-scaling manufacture of aerogel boards. Designing and fabricating a novel building component prototype based on the developed aerogel based reinforced composites has yield a component compatible with integration in internal insulation processes of building envelopes by means of conventional construction methods. This building component integrates low-conductive plastic-composite profiles and plasterboard renders within a multi-layer arrangement, and it has obtained the best fire classification for organic materials: B-s1,d0.

The thermal performance of the insulating component under real conditions has been demonstrated in a relevant construction environment. A monitorization campaign has been performed over roughly 6 months and the main conclusion of the full scale testing is that the aerogel board, when integrated into building envelope retrofitting activities performs as a superinsulation component, as several measurements provided thermal conductivities within the range of thermal conductivity measured at laboratory scale, thus, in the range of 0.015-0.017W/mK.

7.7 Acknowledgments

Research leading to these results was funded within the 7th EU Framework Program, under grant agreement no. 260141, AEROCOINS project.

7.8 References

[1] BPIE. Europe's buildings under the microscope. Executive summary, 2011. ISBN: 9789491143014

[2] K. Ghazi Wakili, B. Binder, M. Zimmermann, Ch. Tanner, Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building, Energy and Buildings (2014), 82, 237-242

[3] Erdem Cuce, Pinar Mert Cuce, Cristopher J. Wood, Saffa B. Riffat, Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings, Energy and Buildings (2014), 77, 28-39

[4]K. Chen, A Neugebauer, T. Goutierre, A. Tang, L. Glicksman, L.j. Gibson, Mechanical and thermal performance of aerogel-filled sandwich panels for building insulation, Energy and Buildings (2014), 76, 336-346

[5] AP Rao, AV Rao, GM Pajonk, Hydrophobic and Physical Properties of the Two Step Processed Ambient Pressure Dried Silica Aerogels with Various Exchanging Solvents, J Sol-Gel Scie Technol 2005, 36(3):285-292.

[6] H.-P. Ebert, Thermal properties of Aerogels, in: M.A. Aegerter, N. Leventis, M.M. Koebel (Eds.) Aerogels Handbook, Springer Science+Business Media, New York, 2011, pp. 537-564;

[7] JL Gurav, IK Jung, HH Park, ES Kang, DY Nadargi, Silica aerogels: synthesis and applications, J Nanomaterials 2010, 2010

[8] CJ Brinker, GW Scherer, (1990), Sol–gel science: The physics and chemistry of sol–gel processing. San Diego: Academic Press.

[9] Aerogels Handbook, Eds. MA Aegerter, N Leventis, MM Koebel, Springer, Heidelberg, (2011).

[10] S. Hæreid, M. Dahle, S. Lima, M.-A. Einarsrud, Preparation and properties of monolithic silica xerogels from TEOS-based alcogels aged in silane solutions, J. Non-Cryst. Solids 1995, 186: 96–103.

[11] J C Brinker, G W Scherer, Sol-Gel Science, The Physics and Chemistry of Sol-Gel Processing, ed. s. Edition. 1990, New York: Academic Press.

[12] M. Schmidt, F. Schwertfeger, Applications for silica aerogel products, Journal of Non-Crystalline Solids, 225 (1998) 364-368.

[13] V.D. Land, T.M. Harris, D.C. Teeters, Processing of low-density silica gel by critical point drying or ambient pressure drying, Journal of Non-Crystalline Solids, 283 (2001) 11-17.

[14] A. Parvathy Rao, G.M. Pajonk, A.V. Rao, Effect of preparation conditions on the physical and hydrophobic properties of two step processed ambient pressure dried silica aerogels, Journal of Materials Science, 40 (2005) 3481-3489.

[15] F Graser, A Stange, Preparation of aerogels. 1987, US Patents.

[16] C A García-González, M C Camino-Rey, M Alnaief, et al. Supercritical drying of aerogels using CO2: Effect of extraction time on the end material textural properties . The Journal of Supercritical Fluids, 2012, 66(0): 297-306.

[17] M J Bommel, A B Haan. Drying of silica gels with supercritical carbon dioxide . Journal of Materials Science, 1994, 29(4): 943-948.

[18] Y Liu, Y Zhao, X Feng. Exergy analysis for a freeze-drying process . Applied Thermal Engineering, 2008, 28(7): 675-690.

[19] MA Aegerter, N. Leventis, M.M. Koebel, (2011) Aerogels handbook., Springer.

[20] M.M. Koebel, L. Huber, S. Zhao, W.J. Malfait, Breakthroughs in cost-effective, scalable production of superinsulating, ambient-dried silica aerogel and silica-biopolymer hybrid aerogels: from laboratory to pilot scale, J Sol-Gel Sci Technol, 2016 1-11.

[21] A Emmerling, J Fricke, Scaling properties and structure of aerogels, Journal of Sol-Gel Sci Technol 1997, 8: 781-788.

[22] R Baetens, BP Jelle, A Gustavsen, Aerogel insulation for building applications: a state-of-the-art review, Energy and Buildings 2011, 43(4): 761-769.

[23] H Maleki, L Duraes, A Portugal, A new trend for development of mechanically robust hybrid silica aerogels, Materials Letters 2016, 179**:** 206-209,

[24] AEROCOINS, Aerogel-Based Composite/Hybrid Nanomaterials for Cost-Effective Building Super-Insulation Systems, EU FP7, GA 260141. http://www.aerocoins.eu (2015/11/16)

[25] Construction Products Regulation, Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC Text with EEA relevance

[26] Ibrahim, M.; Wurtz, E.; Biwole, P.H.; Achard, P.; Sallee, H.; Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering. Energy and Buildings 2014, 84, 241–251

[27] Galliano, R.; Ghazi Wakili, K.; Stahl, Th.;Binder, B.; Baniotti, B.; Performance evaluation of aerogel-based and perlite-based prototyped insulations for internal thermal retrofitting: HMT model validation by monitoring at demo scale. Energy and Buildings 2016, 126, 275–286

[28] Gutschker, O.; Parameter identification with the software package LORD, Building and Environment, Special Issue: Outdoor Testing, Analysis and Modelling of Building Components, 2008, 43(2), 163–169

[29] CTSM-R Development Team, Continuous Time Stochastic Modeling in R. User's Guide and Reference Manual, 2015. http://ctsm.info/pdfs/ctsmr-reference.pdf (2016-06-14)

[30] Strachan, P.A.; Vandaele, L. Case studies of outdoor testing and analysis of building components. Building and Environment, 2008, 43(2), 129-142.

[31] Naveros, I.; Bacher, P.; Ruiz, D.P.; Jiménez, M.J.; Madsen, H.; Setting up and validating a complex model for a simple homogeneous wall, Energy and Buildings, 2014, 70, 303–317

[32] Stahl, T.; Brunner, S.; Zimmermann, M.; Ghazi Wakili, K., Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. Energy and Buildings 2012, 44 (0), 114-117.

[33] Wong, J. C. H.; Kaymak, H.; Brunner, S.; Koebel, M. M., Mechanical properties of monolithic silica aerogels made from polyethoxydisiloxanes. Microporous Mesoporous Mater. 2014, 183 (0), 23-29.

[34] EN 826:1996. Thermal insulating products for building applications - Determination of compression behavior.

[35] Spitzner, M.H., Gellert, R., Pfundstein, M., Rodolphi, A. Dämmstoffe: Grundlagen, Materialien, Anwendungen, Walter De Gruyter, 2007.

[36] Gellert, R., Inorganic mineral materials for insulation in buildings. In Materials for Energy Efficiency and Thermal Comfort in Buildings, Woodhead Publishing, 2010, 193-228.

[37] EN 13501-1:2007+A1:2010. Fire classification of construction products and building elements. Part 1: Classification using data from fire reaction tests

[38] EN 13823:2010, Reaction fire tests for Building products. Building products excluding floorings exposed to thermal attack by a single burning item.

[39] Garay, R et Al, Energy efficiency achievements in 5 years through experimental research in KUBIK, 6th International Building Physics Conference, IBPC 2015, Torino, 2015

[40] EN ISO 6946: 2007. Building components and building elements – Thermal resistance and thermal transmittance – Calculation Method

[41] EN ISO 7345:1987 Thermal insulation -- Physical quantities and definitions

[42] EN ISO 9869-1:2014 Thermal insulation -- Building elements -- In-situ measurement of thermal resistance and thermal transmittance -- Part 1: Heat flow meter method

8 Experimental Assessment of dynamic multi-dimensional heat transfer in architectural junctions

Performance Assessment of Thermal Bridge Elements into a Full Scale Experimental Study of a Building Façade

Roberto Garay, Amaia Uriarte, Inés Apraiz

8.1 Abstract

In this paper, an experimental and numerical approach to the characterization of thermal bridges is presented. The need for this characterization was found within an experimental study in a 2 floor high façade. This façade was constructed with 3 concrete elements which were placed in it to produce a similar thermal bridge effect to the one created by floor slabs traditional building construction in Spain.

Commonly applied thermal assessments perform one-dimensional heat transfer analysis over planar elements such as the façades studied in this experiment. However, it is well known that thermal bridges are locations in buildings where one-dimensional heat transfer analysis can not be applied.

This problem was approached by creating a numerical 2D thermal model which was calibrated against experimental data from several temperature and heat flux sensors which were locate at specific points in the thermal bridge elements.

8.2 Introduction

Building energy consumption sums up to 40% of primary energy consumption in developed countries [1] [2] [3] [4]. Aside from energy needs for appliances or Domestic Hot Water, a large amount of this is required for space heating and cooling, to meet occupants comfort requirements. Intensive studies and development of techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings have been conducted during more than 50 years. Testing and calculation methods have been developed, ranging from standardized material testing procedures to dynamic simulation software tools [5].

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.

In the last half of the past century, building energy codes have forced a trend towards more insulated building envelopes. This trend has been boosted by EU Energy Performance of Buildings Directives (EPBD) [3] [4], adopted by all EU member states. In this context, the relative relevance of thermal bridges has grown.

Furthermore, in developed countries in Europe, the ageing building stock is involved into a thermal performance upgrade under the previously mentioned EPBD policies. Building envelope upgrade processes are being conducted with systems such as External Thermal Insulation Systems (ETHICS). These systems potentially allow for a nearly complete avoidance of certain thermal bridges, but their practical implementation leads to performance uncertainties.

A detailed analysis on the relevance of thermal bridges and how building codes deal with them in EU Member States was performed in [6]. The relevance of thermal bridges in the energy assessment of buildings was estimated in up to 30% of heating energy demand. This being more relevant within highly insulated buildings. It was identified that although all building codes considered thermal bridges, these were commonly assessed through conservative default values. When dealing with renovation projects for already built buildings, the energy requirements for junctions are reduced or even not-imposed. The use of improved junctions compared to national default values was evaluated at 15 %.

In this context, an experiment was carried out in order to assess the thermal performance improvement of one of such façade refurbishment methods.

This experiment was conducted in the Kubik $_{\text{by Tecnalia}}$ research facility [7] [8]. This is a research infrastructure located in Derio, Spain, focused on full scale testing of energy efficiency within the building sector. Its main goal being to bridge the gap between laboratory testing and full scale market deployment of building envelopes, HVAC & ICT solutions for Energy Efficiency, where the full energy interaction between different elements is evaluated.

Figure 1: Kubik $_{\text{by Tecnalia}}$ research facility. General view (left) & specific façade used for the experiment (right)

A 2 story- high façade was constructed in the Kubik $_{\text{by Tecnalia}}$ test facility and several thermal bridge elements were located in it. However, due to the need to assess heat transfer through these elements, a multidimensional heat transfer model was created and calibrated.

Building envelopes are mainly characterized by one-dimensional (1D) heat transfer formulae are applied, neglecting the effect of heterogeneous elements (beams, window sills…). However, thermal bridges are common in places where structural stresses are transmitted from façades to beam elements, or where different kinds of envelope constructions meet, etc. with variations in the geometry & materials among the different sides of the joint. In these areas, bi- or tri-dimensional (2D /3D) heat transfer phenomena is present, and 1D assumptions cannot be applied.

3D heat transfer accounts for a small share of the total heat transfer in a building, as it is restricted to corners. However, although not addressed in this paper, 3D thermal bridges are common locations for cold spots where condensation and mold growth can occur.

In common practice, building envelope heat transfer is commonly approached as 1D heat flow over the full envelope surface, considering an additional linear heat transfer, related to the length of the edge in which 2D heat flows occur, as formulated in (1).

$$\psi = L^{2D} - \sum U_j * l_j \quad (1)$$

Performance values of envelope constructions are most commonly provided through steady state approaches under standardized procedures: [10] for 1D & [11] [12] for 2D/3D heat transfer.

However, this approach lacks precision when the dynamic behavior of a full building/room needs to be evaluated. In most building energy simulation (BES) software, only 1D heat flow is calculated under dynamic boundary conditions. 2D/3D heat flow being incorporated as an increased value of 1D heat transfer, calculated under various simplifying approaches. Methods to implement dynamic 2D/3D heat flow into BES software have already been developed. In [13], a method for introducing dynamic 2D heat transfer in energy plus is developed, while in [14] [15] [16] [17], a transfer function of a 2D thermal bridge is obtained both through finite element & experimental techniques.

In the framework of the already mentioned testing of different façades under external weather exposure and internal dynamic conditions, such a dynamic 2D heat transfer method was required. This paper providing the procedure for the experimental calibration of 2D Finite Difference Model (FDM), used for the obtention of the dynamic heat transfer of the thermal bridge. This process involved the location of several sensor devices in the elements themselves, the construction of the 2D FDM, and the calibration of the models to meet experimental results.

However, as FDMs only accounted for a small fraction of the total geometry of the test cells, results coming from this FDM needed to be coupled with measured data from 1D heat transfer areas and HVAC systems.

In this framework, the results from the FDM were processed to convert them into a dynamic linear heat transfer transmittance, as it is further developed in chapter 8.

This process was found necessary not only because of its influence in the accuracy of the heat balance of the test cells, but also because one of the foreseen results was the thermal performance improvement of these elements, over the sequence of tested façades. This required of this experimental/numerical process being established to assess this improvement.

8.3 Process

The identification of 2D heat transfer through beam elements in façades was performed in a process which involved several steps.

- Definition of the mathematical integration frame for the assessment of the thermal bridges. (Section 3)
- Identification of suitable places for sensor placement (Section 5)
- Installation of sensors
- Experimental campaign (Section 6)
- 2D FDM modeling and calibration (Section 7)
- Integration of the calibrated models into the main room model (Section 10)

8.4 Integration Frame

Within a research project for the assessment of thermal improvement of building fabric through façade refurbishment, an experiment was conducted in which heat transfer through a building envelope was experimentally obtained.

This experiment was conducted in the Kubik $_{\text{by Tecnalia}}$ research facility, where a sub-sector consisting of two test-rooms in a vertical arrangement were conditioned for this test. A west-oriented test façade was constructed in these rooms, which comprised 3 beam elements, constructed in equivalent materials and thicknesses to those present in the Spanish building stock.

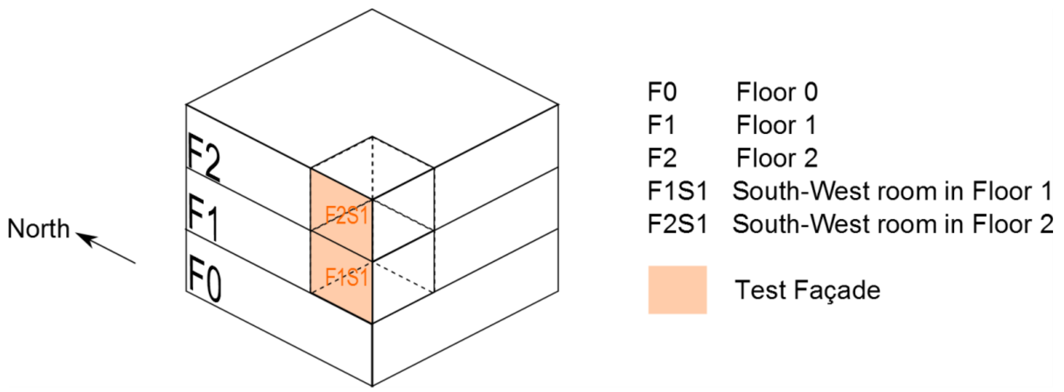


Figure 2: Scheme of test rooms

These 3 beam elements were located at slab level coincident with 1st, 2nd and roof level slabs in Kubik. All 3 elements were kept constant in the experiment, while a sequence of façades was experimented.

Thermal bridges in all 2D & 3D details were modeled in steady-state conditions during the architectural design of this test, and these results used to generate robust constructions details. These details achieved the goal of reducing relevant energy flows to only 1D and 2D heat transfer through concrete.

The experimental campaign was developed in three phases, where different façade constructions were placed in the same façade:

- Phase 0: Highly insulated sandwich façade
    - 20cm PU sandwich façade
    - Additional 10cm XPS placed internally
- Phase 1: Brick cavity façade
    - Internal brick wall: Mortar (1,5cm approx.) rendered hollow brick (7cm)
    - Cavity: 10cm air gap
    - External brick wall: 11cm perforated brick
- Phase 2: Ventilated façade refurbishment of brick cavity façade
    - Tiles: 1cm ceramic tiles
    - Cavity: 5cm, ventilated
    - Insulation: 5cm Mineral wool
    - Base wall: Pre-existing from Phase 1.

The configuration of each phase is shown in figure 3.

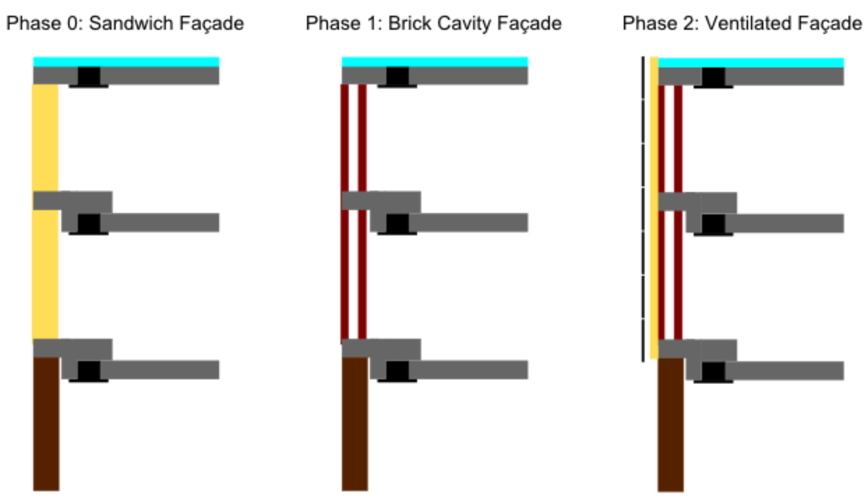


Figure 3: Vertical section of the west façade layout, for all experimental phases

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 shown in Eq 2.

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

Where:

- Q_{HVAC} represented the thermal output of the HVAC system
- $\sum_{1D} Q_{1D}$ represented the one-dimensional heat transfer through the building fabric
- $\sum_{2d} Q_{2D}$ represented the incremental two-dimensional heat transfer through the building fabric by the beam elements. All 2D heat transfer is neglected except that occurring through the beam elements.
- C represented an uncertainty value which also comprised all the non-considered heat flows.

This balance was formulated and solved for each of the test cells, considering the air volume enclosed in them as “well-mixed”. This approach was considered consistent as the HVAC system consisted on a fan coil system which provided a good air circulation in the test rooms.

The heat balance of the test cell was formulated in a dynamic way and solved for every considered time step (every hour). The heat balance is formulated over the enclosed air volume, whose thermal storage was neglected, the heat capacity and the oscillation of the temperature of this fluid being low, especially when compared with the heat transfer over the enclosing surfaces.

- Although several definitions of 1D and 2D heat flows are available, within this project the following definition was applied:
- Control volumes of test rooms were approached as hexahedral volumes limited by the internal surfaces of building elements.
- 1D heat flows were measured in clearly 1D heat flow zones and applied over the full corresponding surface of the test-room model.
- The additional heat flow generated by 2D heat flows in beam elements was calculated and introduced in the test-room model as a linear heat transfer in the corresponding edge.
- Convective and radiative heat exchange of the façade are jointly considered as a surface/boundary heat exchange.

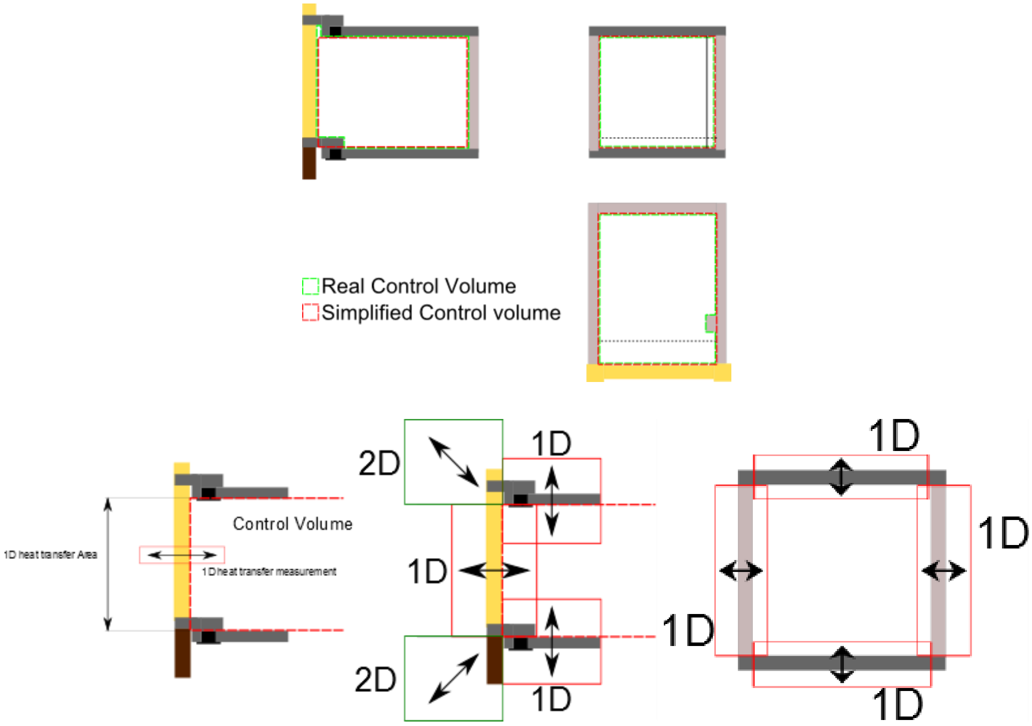


Figure 4: Definition of Control volume (Upper); Definition of 1D heat transfer measurement and application area (Lower left); 1D/2D heat transfer zones in the thermal model of the west façade (Lower center); Simplified 1D model of non-façade areas (Lower right)

The calculation of the additional 2D heat flow was calculated through a calibrated 2D FDM model. A measurement, modeling and calibration process was performed on each of these particular construction details, which is described in the following chapters.

The uncertainty value (C in Eq 2) is the only unknown value in Eq 2 as the other three heat flows are measured (Q_{HVAC} and $\sum_{1D} Q_{1D}$) or obtained through the calibrated model ($\sum_{2d} Q_{2D}$) which is developed in this paper. So the C value can be obtained by the application of Eq 2 and serve as a dynamic (time dependent) indicator of the uncertainty due to non-measured or modeled phenomena.

8.5 Joint surface Convective & Radiative heat transfer approach for internal surfaces

Internal heat transfer coefficients are identified from experimental data in the calibration process of the 2D FDM.

It is well known that wall surfaces exchange heat with their surrounding environment through convection and radiation processes. Roughly defined, convection is related with the temperature of the surrounding air, while radiation is related with the average radiant temperature of the surfaces enclosing this environment. In the case of rooms or test cells, this average radiant temperature is related to the temperature of wall/slab surfaces and the surface-to- surface view factor. In the case of external conditions, this is related to the temperature of the sky, the temperature of the surrounding earth/building surfaces, and again the view factor.

$$Q_{surf} = Q_{conv} + Q_{rad} = (h_{conv} * (T_{surf} - T_{amb}) + h_{rad}(T_{surf}{}^{4} - T_{rad\_env}{}^{4})) * S \quad (3)$$

Eq 3. Heat transfer in the internal surface of a wall

Where:

- Q_{surf} represents the overall surface heat transfer
- Q_{conv} represents the convective surface heat transfer
- Q_{rad} represents the radiant surface heat transfer
- h_{conv} represents the convective surface heat transfer coefficient
- h_{rad} represents the radiant surface heat transfer coefficient
- T_{surf} is the representative temperature of the surface
- T_{amb} is the representative temperature of the surrounding ambient air
- T_{rad_env} is the representative radiant temperature of the environment. For indoor cases it is obtained as a weighted average of the surrounding surfaces
- S is the Surface area

The original heat transfer equation can be substituted by a linear form according to [18], obtaining the following equation:

$$Q_{surf} = (h_{conv} * (T_{surf} - T_{amb}) + h_{rad}{}^{'}(T_{surf} - T_{rad\_env})) * S \quad (4)$$

Where $h_{rad}{}^{'}$ is the linearized radiant heat transfer coefficient

However, in the case of internal heat transfer, it was decided to join both heat transfer processes into one unique heat flux. This heat flux relative to the internal ambient temperature. It was considered that the simplification introduced through this approach was not very relevant in terms of model accuracy, as surface and ambient temperatures in this kind of test cells without windows were expected to be very similar.

$$Q_{surf} = h * (T_{surf} - T_{rad\_env}) * S \quad (5)$$

Where h is the overall heat transfer coefficient

The tested façade system does not comply with this assumption as it is more exposed to the external ambience and it is constructed with heavily inertial materials. However, this was not found problematic, as this system is part of the thermal model and not of its boundary conditions.

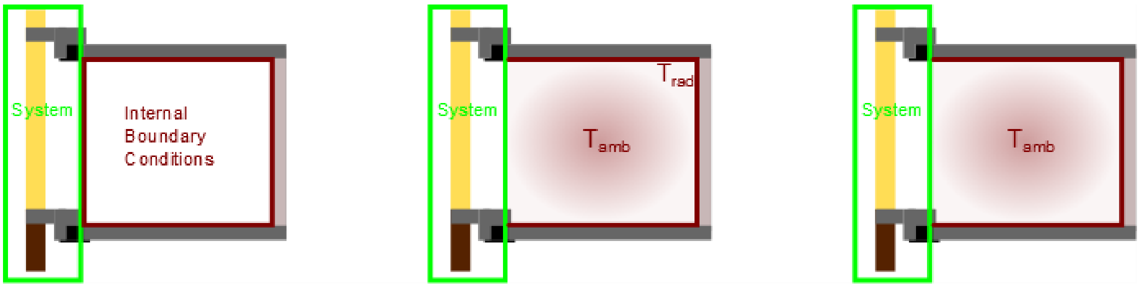


Figure 5. Left: Definition of internal boundary.
Center: Internal boundary conditions for segregated convective & radiative heat transfer.
Right: Internal boundary conditions for joint convective & radiative heat transfer.

The taken assumptions were verified with ambient & surface temperature data from the experimental campaign.

8.6 Identification of suitable places for sensor placement

8.6.1 Evaluation of the thermal field

The location of sensors requires of a careful study, to ensure that, once installed their signal will be accurate and representative of the measured variable. Within this study, a FDM analysis was performed in order to evaluate the expected thermal field in the thermal bridge area, and this information was used to select the most suitable places for the sensors.

Steady-state 2D thermal models of the three wall-slab junction details were made in order to find the most suitable places for sensor placement. The architectural details were modeled in TRISCO [19] and meshed according to [11]. Figure 6 shows the steady state result of one of the performed FDM analysis.

The selection of the location of sensors intended a balance between a reduced amount of sensors and the placement of sensors distributed across the architectural detail in order to provide sufficient data for the calibration of dynamic FDMs.

8.6.2 Feasibility of installation

Feasibility of the location was also evaluated, which was mainly related to weather-proofing. Sensors would have to be operative for several years. Outdoor locations with difficulties for sensors replacements had to ensure that sensors would not be damaged shortly after installation.

Due to weather-proof limitations, 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.

Furthermore, to avoid failure issues regarding failure of sensors in non-accessible locations, redundant sensors were located in external locations were replacement was estimated as difficultly achievable.

Due to the specific case of each of the slab-façade joints, not all internal locations where available in all joints:

- Floor 1: Only locations above the slab were possible
- Floor 2: All locations
- Roof: Only locations below the slab were possible

8.6.3 Selection of location

Suitability was defined with a series of specifications:

- Temperature sensors should be located at different isothermal zones, as they reflect areas differently influenced by internal or external boundary conditions in term of amplitude & phase-shift.
- Heat-flux sensors should be located at places with different heat flow densities.

Regarding the outer surface temperature, sensors were located in the center of the slab. In this case, redundant sensors were placed.

Regarding internal temperature measurements, 2D steady-state models showed that the surface temperature of the concrete elements had a relevant gradient perpendicularly to the façade, and sensors where placed in the coldest & hottest places of the element:

- Locations above the concrete element:
  - Concrete-façade corner
  - Upper-inner corner of the concrete element
- Locations below the concrete elements:
  - Concrete-façade corner
  - Centre of the steel beam

Regarding heat flux measurements, most divergent heat flux densities were found above the slab. Furthermore, no locations were found below the slab, as the highly conductive surface of the steel beam and the reduced exposed area of the concrete element were evaluated inappropriate.

The selected locations where the following:

- Upper surface next to the façade. Even if in this area the heat flux was not one dimensional, this location was selected because of being the area with the highest heat flux.
- Centre of the internal vertical surface: This location was the only area where pseudo-1D surface heat flux was present.

These can be seen in figure 6.

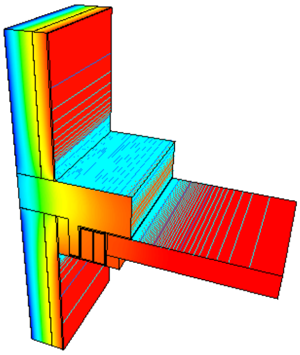
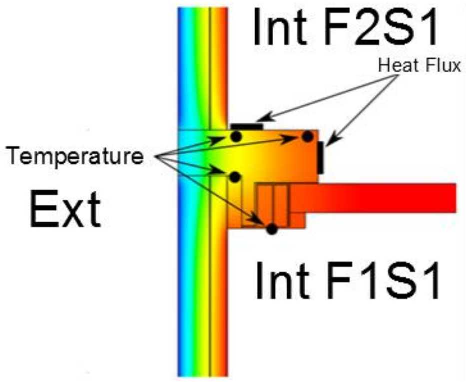



Figure 6: Thermal bridge on Floor 2 level: Steady-state model of (left). Internal sensor location (right)

The final sensor list and location can be found in Table 1.

Table 1. Sensor & location list

Beam Element	Type of measurement	Type of sensor	Format	Amount of sensors
Floor 1	Outdoor surface temperature	4-wire Pt100, 1/3 class B. Thermo Sensor	PVC Sealed for concrete-embedded applications.	2
	Indoor surface temperature			2
	Indoor heat flux	Heat flux tile. Phymeas.	Thickness: 1mm Size: 10cmx10cm	2
Floor 2	Outdoor surface temperature	4-wire Pt100, 1/3 class B. Thermo Sensor	PVC Sealed for concrete-embedded applications.	2
	Indoor surface temperature			4
	Indoor heat flux	Heat flux tile. Phymeas.	Thickness: 1mm Size: 10cmx10cm	2
Roof	Outdoor surface temperature	4-wire Pt100, 1/3 class B. Thermo Sensor	PVC Sealed for concrete-embedded applications.	2
	Indoor surface temperature			1

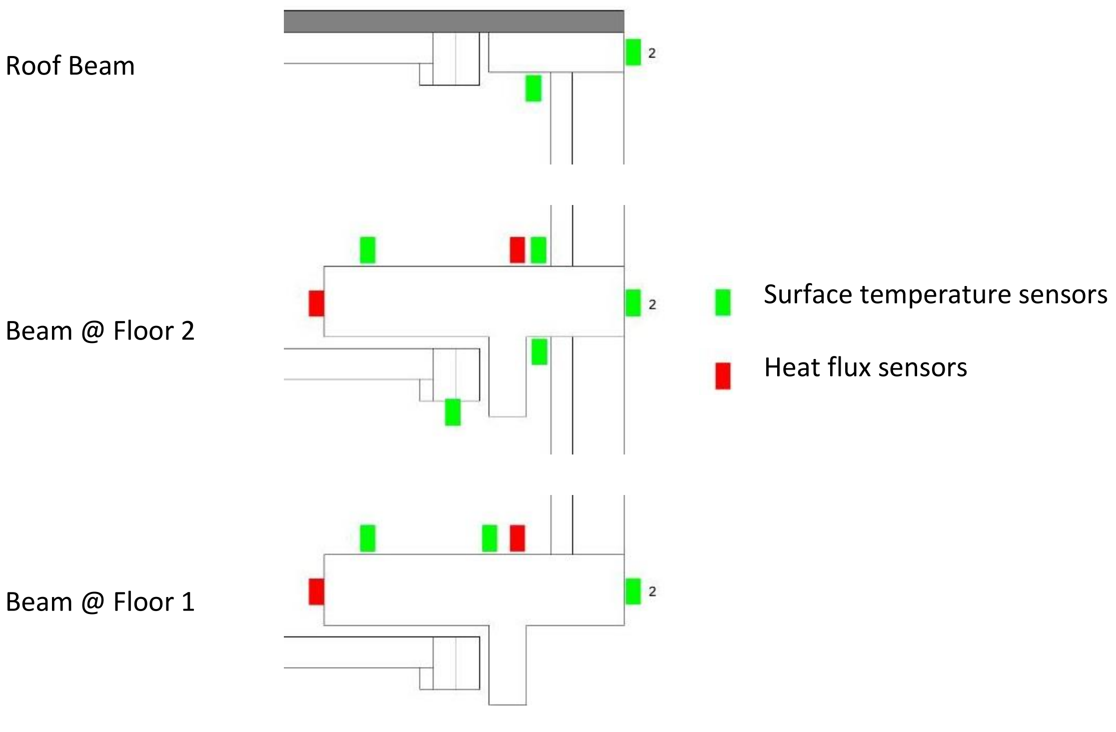


Figure 7: Location of sensors. Green: temperature. Red: Heat flux

8.7 Experimental campaign

The experimentation on the assessment of thermal bridges was conducted within the experimental campaign of the main project described in the integration frame. Depending on the experimental campaign, different façades were tested. Data provided in this paper was obtained during Phase 0 with the highly insulated sandwich façade construction.

In this campaign several temperature set point levels were established at each of the thermal zones. Data was divided in four datasets, which are indicated in Table 2.

Table 2. Experimental datasets for the highly insulated sandwich element

Dataset	**Period**	**Outdoor conditions**	**Indoor Temperature**	
			F1S1 (Floor 1)	F2S1 (Floor 2) + All neighbouring spaces in the building.
1	2012/I/19 – 2012/II/5	Winter period, average Temperature: 3-12 ºC	Constant, 29-31ºC	Constant, 29-31ºC
2	2012/II/6 – 2012/II/16	Winter period, average Temperature: 2-9 ºC	Constant, 20ºC	Constant, 20ºC
3	2012/II/17 – 2012/II/28	Winter period, average Temperature: 4-9 ºC	Highly variable, 20-30ºC	Nearly constant, 15-20ºC
4	2012/II/29 – 2012/III/11	Winter period, average Temperature: 6-12 ºC	Constant, 20ºC	Constant, 30ºC

1-minute raw experimental data was obtained from the experimental campaign and an hourly averaging process was conducted. As no data was missed in periods longer than 1h during the full experimental campaign, no data gaps needed to be solved. Daily average temperatures are shown in figure 8.

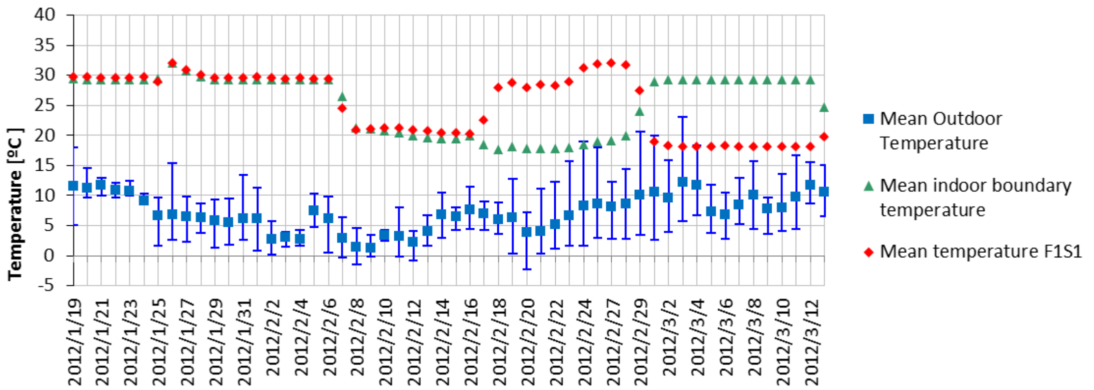


Figure 8: Daily average temperatures for the highly insulated sandwich element

During the design of the thermal bridge elements, attention was paid to minimizing 3D thermal bridging in corners and ensuring 2D heat transmission along the floor beams. This aim was verified by a thermographic study, which stated that, aside from 0.1-0.2m on each of the sides of the floor beams (which were 3,3m long), no 3D heat transmission processes were present in the floor beams, as a 2D thermal profile in the slab element is maintained in the full length of the element.

8.8 FDM modeling and calibration

The FDM modeling was conducted using VOLTRA [20], a transient 2D-3D heat transfer modeling software. In this software, the architectural details were modeled in 2D and meshed according to [11], and a parametric study was conducted to fix each of the thermal properties in the model. The calibrated parameters being the following.

- 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]

During the construction process, strong efforts were made to ensure the quality of the test set up, and no uncertainty was expected in the dimensions and shape of the architectural detail.

The calibration process was conducted in steps:

0. An initial model was constructed by using thermal properties from the Physibel database in VOLTRA [20].
1. Thermal conductivity of materials was fixed by using Temperature data from nearly steady state periods.
2. Thermal capacity of materials was fixed by using Temperature data from transient periods.
3. Surface heat transfer coefficients were fixed by using heat flux data from steady state periods.

At each step the effect of the modification of the calibrated parameters in previously calibrated parameters was studied. Details range of estimation, and bibliographic references on the imposed thermal parameters, as well as the finally validated result can be found in sections 9.3 and 9.4.

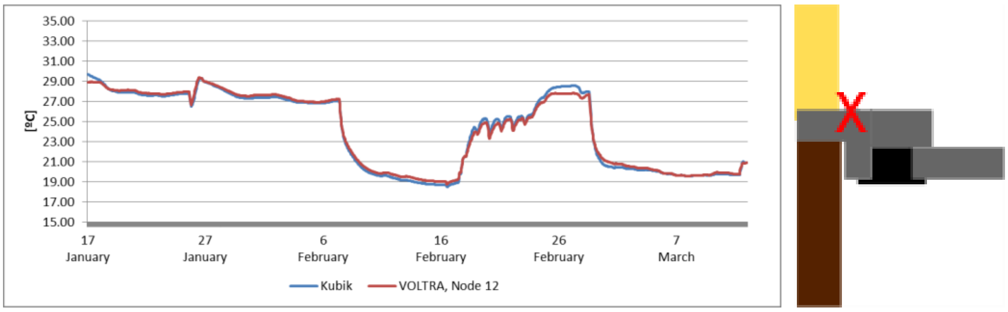
The following results were obtained:

- Façade constructions: These elements were constructed with 30cm of insulating materials. The resulting very insulating (U<0.2 W/m2K) and almost massless elements required only a fine tuning of thermal conductivity values.
- Concrete elements: Floor slabs and thermal bridge elements required minor conductivity and capacity tuning, as the final values were similar to initial estimations and data from material catalogues.
- Heat transfer coefficients were found to be most difficult to calibrate. Different coefficients were required for upwards and downwards heat flow. Additionally, reduced heat transfer coefficients were applied to corner areas.
- Dataset 3 presented highly unsteady conditions due to two situations. Firstly, as all the surrounding internal spaces where artificially cooled to generate a thermal gradient with the F1S1 room, as the heating system was found not able to meet the setpoint at all times. Additionally, when the setpoint was reached, a very strict deadband value produced short activation-deactivation osculation cycles of this system. Dataset 3 was not considered suitable for calibration due to a highly variable convection coefficient oscillation caused by:
    - The direction of the vertical convection was not always the same, as floor slabs were charged-discharged when indoor temperature oscilated.
    - The activation over short cycles of the fan coil heating system modified airflow around the indoor surface.

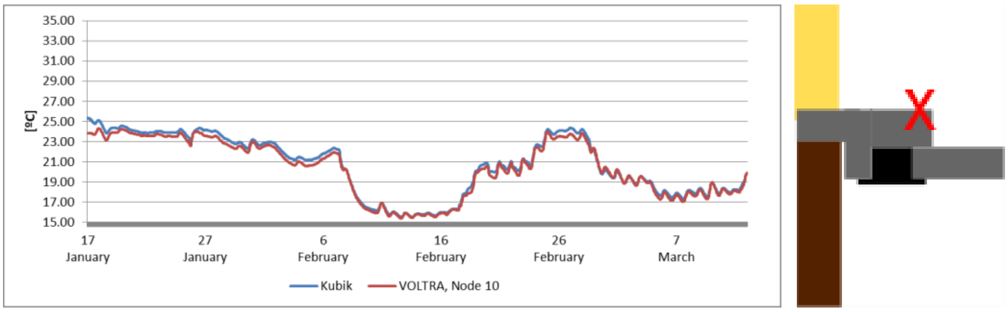
The final conclusion of this process is that material testing and precise construction of architectural details allows for a good control in heat transfer in solid materials, while convective processes need to be specifically verified prior to the estimation of the thermal behavior of a thermal bridge.

Instability of convective problems were mostly related to the HVAC system, which consisted on a fan-coil system located in the ceiling. The activation/deactivation cycles to keep setpoint temperatures in the test cells provided very different air velocities in the test cell. This problem should not be present, or at least be of lower relevance in test cells conditioned with different HVAC schemes.

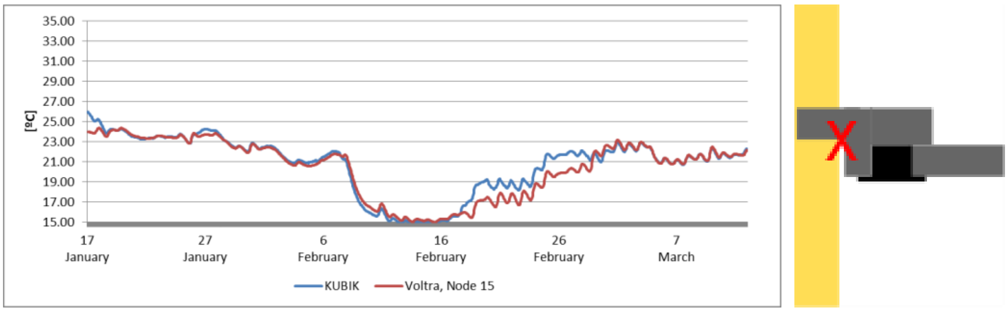
Floor 1. Concrete beam, upper surface temperature. Indoors, next to the façade



Floor 1. Concrete beam upper surface temperature. Indoors, opposite to the façade



Floor 2. Concrete beam, lower surface temperature.



Floor 2. Concrete beam, Heat flux, indoors, next to the façade.

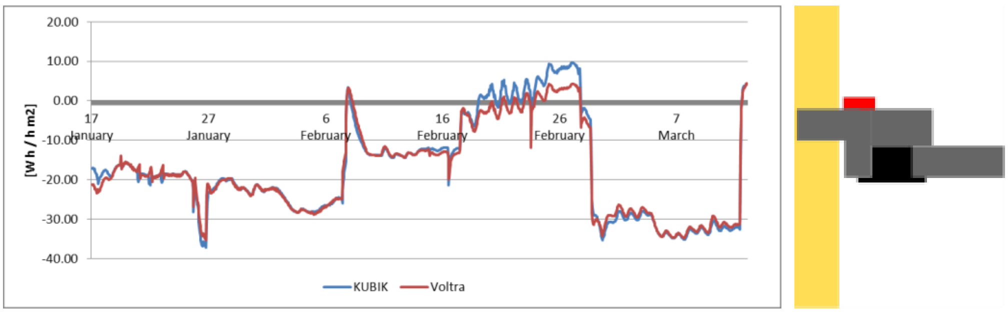
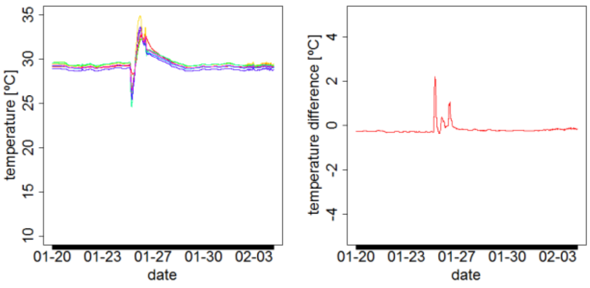


Figure 9: Comparison between experimental data and calibrated signals for selected temperature and heat flux signals.

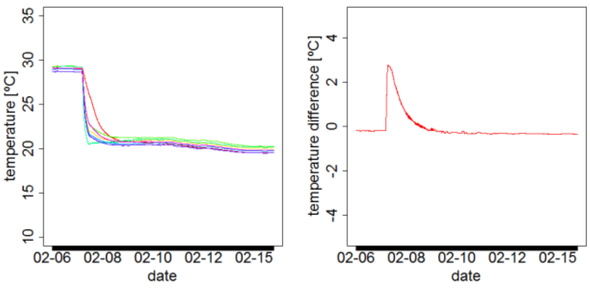
8.9 Verification of the joint convection-radiation approach

Data from the experimental campaign was used to verify that temperature differences between surface and air temperature were sufficiently similar as to perform a joint modeling of convection and radiation processes in the internal side of the façade elements. As it can be seen in the figure 10 , the difference between these temperatures was limited, except for those moments where heavy HVAC excitation was made, or where high temperature differences between test cells were present (Sequence 4).

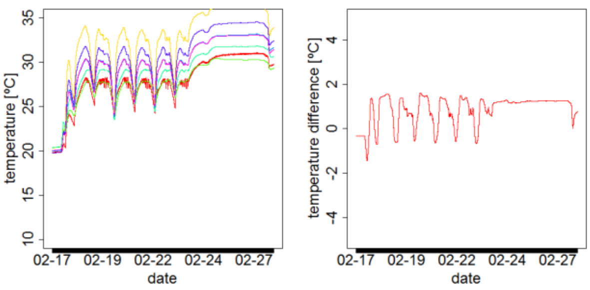
Sequence 1



Sequence 2



Sequence 3



Sequence 4

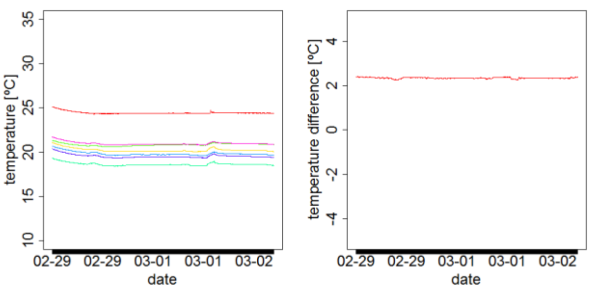


Figure 10.a: Surface, air and average temperatures (left)
maximum difference between individual signals to the average (right))

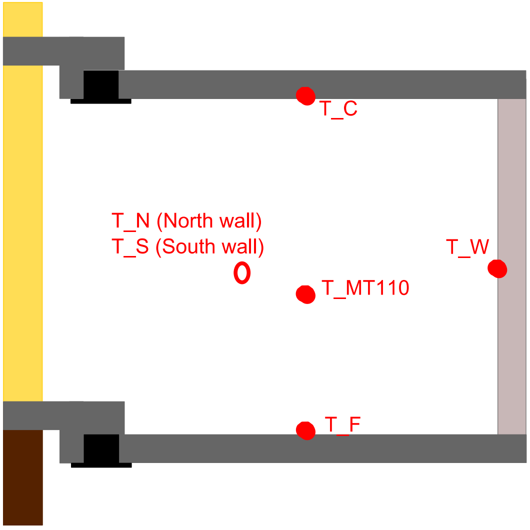


Figure 10.b: Location of sensors

The observed temperature differences were:

- Smaller than 0,5 ºC in steady states
- Around 1-3 ºC during the dynamic response when the HVAC system acts as full power.
- Stable at 2.2 ºC when a highly different temperature was present in a neighboring room. This situation was found specific to sequence 4, which is very specific to calibration purposes.

The observed differences due to highly HVAC fluctuating situations, and highly different surface temperatures due to opposed temperatures in neighboring test cells, were estimated specific to very seldom phenomena, and the inaccuracy introduced by the joint convection-radiation approach was assumed acceptable.

8.10 Modeling details of the FDM

8.10.1 Selected boundary conditions

The selected boundary conditions for each FDM account for the following:

- Outdoor: Surface temperature, measured at the concrete beam, average of signals (2-3 signals depending of the beam).
- Indoor: Indoor air temperature. Measured at three heights, 70, 110 and 170cm. The FDM uses the average of these three signals.

The selected boundary condition for the outdoor ambient was the surface temperature of the slab, as this temperature already accounted for the influence of solar radiation. This surface temperature was found very robust, as sensors placed in the same beam, produced nearly-identical signals. It is known that the surface temperature varies along the façade, as part of the 2-dimensional heat transfer phenomena, which is studied in this paper. However, when studying a case with highly insulated façade elements, it was found that although the considered boundary condition is not very representative of the surface temperature over the 1-dimensional areas, this did not produce significant differences in the surface temperature field inside the building.

8.10.2 Surface heat exchange model

The FDM was constructed based on the defined boundary conditions. In figure 11, a scheme of the surface heat transfer areas can be found. This heat exchange scheme was changed when an area with reduced heat transfer was required.

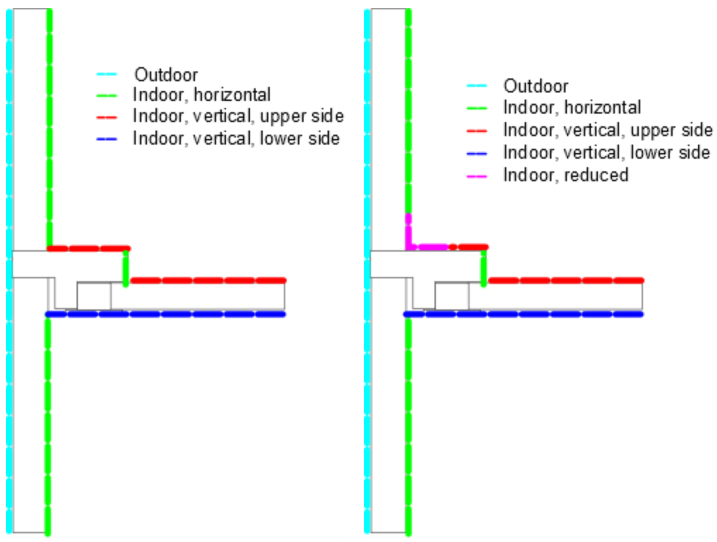


Figure 11: Surface Heat transfer scheme, initial approach (left) and modified approach with reduced heat transfer areas (right)

8.10.3 Material properties

Material properties were subjected to identification procedures. In Table 3, thermal parameters are provided. For each item, the range of estimation and a reference value from [21] are provided. Minimum and maximum values were established to the calibration of the parameters, based on experience of variation ranges for such elements.

As it can be seen in this table, Insulation materials, and metal elements did not require of parameter estimation, and only concrete, which was not a standardized material supply for this experiment required parameter estimations.

Table 3. Parameters of the FDM, materials

Material	**Parameter**	**Unit**	**Range**			**Calibrated**
			Min	Max	Estimation CTE[21]	
Concrete	Thermal conductivity	W/mK	2	2,6	2,6	2,2
	Density	Kg/m3	2000	2400	2300	2300
	Heat capacity	kJ/kg			930	
Steel beam	Thermal conductivity	W/mK			50	
	Density	Kg/m3			7800	
	Heat capacity	kJ/kg			930	
Poliurethane	Thermal conductivity	W/mK			0,028	
	Density	Kg/m3			25	
	Heat capacity	kJ/kg			1470	
XPS	Thermal conductivity	W/mK			0,035	
	Density	Kg/m3			25	
	Heat capacity	kJ/kg			1470	

8.10.4 Surface heat transfer coefficients

The calibration of the thermal model required of a fine tuning of the surface heat transfer coefficients. This heat transfer accounted jointly for convection and radiation phenomena. Initially, all surfaces where considered with one heat transfer coefficient, but then reduced values were provided for corner areas, and different coefficients were identified for up and downwards heat flux periods. The reduced heat transfer in corner areas is estimated to be produced/required as the air velocity in these areas is reduced, when compared to more exposed areas. And the difference between upwards and downwards periods is an already known issue, which is even reflected in standardized heat transfer calculations [10].

For each item, the range of estimation and a reference value from [10] are provided. Minimum and maximum values were established based on experience of variation ranges for such parameters.

Table 4. Parameters of the FDM, heat transfer coefficients

Item	Unit	Range			Calibrated
		Min	Max	Reference ISO [10]	
Inside, horizontal flux	W/m2K	3,5	7,7	7,7	4,0
Inside, horizontal flux, reduced	W/m2K	2	7,7	-	2,5
Inside, vertical, upward flux, Upper side	W/m2K	3,5	7,7	10	4,0
Inside, vertical, upward flux, Lower side	W/m2K	3,5	7,7	10	4,0
Inside, vertical, downward flux, Upper side	W/m2K	3,5	7,7	5,9	3,5
Inside, vertical, downward flux, Lower side	W/m2K	3,5	7,7	5,9	4,0
Inside, vertical, flux, reduced	W/m2K	3,5	7,7	-	3,5

8.11 Integration of the calibrated models into the main room model

The experimentation and calibration process which is described in this document was developed to produce a suitable thermal model of thermal bridges for its use in a thermal balance of a room.

From the calibrated model and according to the equation stated in section 3 (Integration Frame), the thermal influence of the thermal bridge was obtained. And used in the thermal balance of the room.

Aside from the previously used temperature and heat flux measurements, each model was defined to output dynamic inbound and outbound heat flow form the room. From the same model, the 1D heat transfer from façade and slab elements was calculated and applied to the corresponding surfaces. All additional heat was assigned to the "additional 2D heat transfer" term. Eq 6 was applied (which is a reformulation of that previously stated in Eq 2)

$$Q_{2D} = Q_{Constructive\_detail} - Q_{1D} \quad (4)$$

With the following Q_{1D} definition:

$$Q_{1D} = Q_{1D,Façade} * L_{Façade} + Q_{1D,Floor\_slab} * L_{Floor\_slab} \quad (5)$$

Where:

- All the heat transfer was referred to a reference room (F1S1 or F2S1 depending on the case), and heat flows were measured in the indoor surface/volume of this reference room.
- Q_{2D} was the additional heat transfer caused by the beam element
- $Q_{Constructive\_detail}$ was the heat gained/lost by the reference room
- Q_{1D} was the heat transferred through a 1D zone of the planar elements
- $Q_{1D,Façade}$ was the heat transferred through a 1D zone of the façade
- $Q_{1D,Floor\_slab}$ was the heat transferred through a 1D zone of the floor slab
- $L_{Façade}$ was the height of the façade modeled in the FDM model
- L_{Floor_slab} was the width of the floor slab modeled in the FDM model

Dimensions $L_{Façade}$ and L_{Floor_slab} were taken from the geometry modeled in Voltra, as shown in the following scheme:

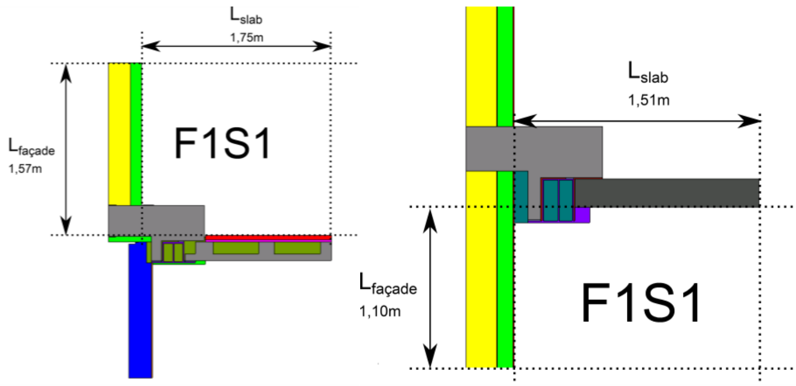


Figure 12: Sketch of the internal dimensions in the F1S1 room, in the FDM model for the beam-elements at floor 1 (left) and floor 2 (right) levels

All this process performed dynamically for each hourly time step.

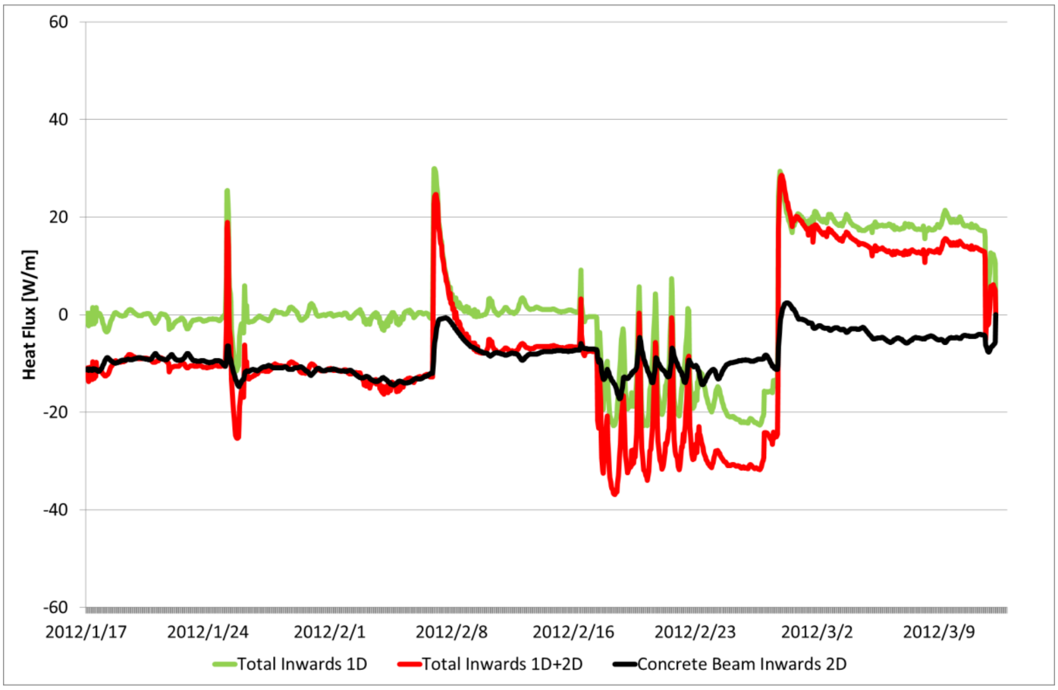


Figure 13: Concrete beam at floor 1 level. Hourly heat flows towards F1S1 zone in the modeled architectural detail.

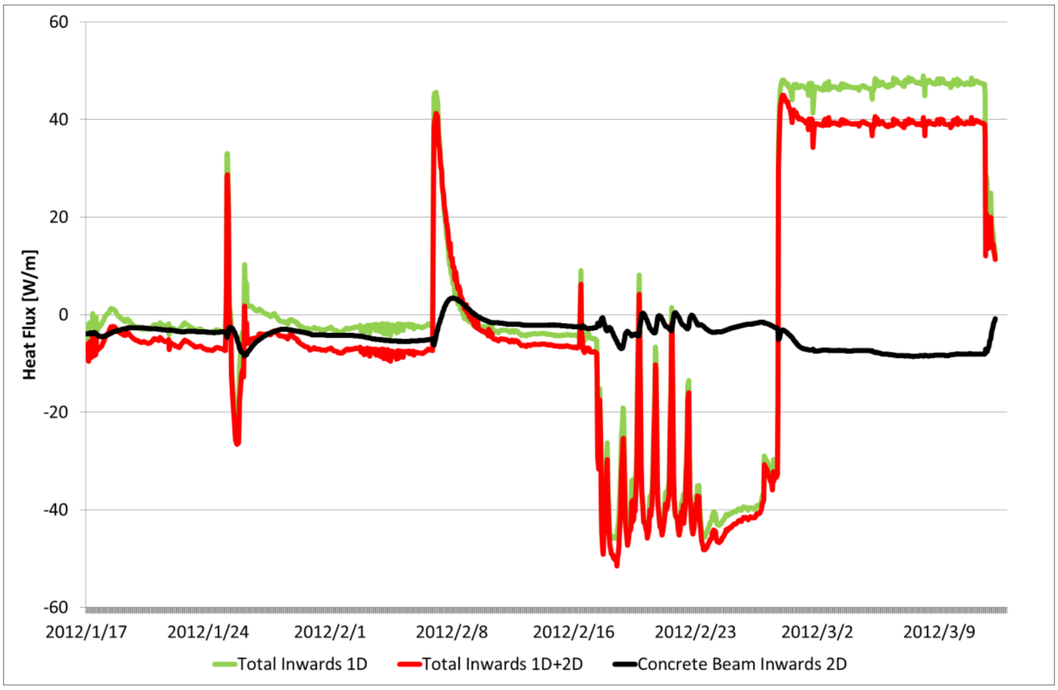


Figure 14: Concrete beam at floor 2 level. Hourly heat flows towards F1S1 zone in the modeled architectural detail.

The thermal influence of the concrete elements was found relevant, not only in terms of overall energy balance, but also in terms of short term response.

Depending on the boundary temperatures in each of the sequences, the additional heat transfer across the thermal bridge had different impact on the overall heat balance. In situations with small 1D heat transfer, heat transfer across concrete elements was far more relevant than 1D-heat transfer. This can be observed in situations such as sequences 1 & 2 of the concrete element at floor 1 level (figure 13), where 1D heat transfer could even be neglected, during pseudo-steady-state periods. In situations with larger heat transfer situations, the concrete element provided 10-20% of surplus/reduced heat transfer over the analyzed junction detail.

It was also noticed that the time-response of the slab was far slower than that of planar surfaces, as it was expected due to these elements being composed by bulk concrete, as opposed to insulation materials, void spaces… on planar surfaces.

8.12 Summary and Conclusions

Within a research project with further objectives, the energy performance of thermal bridges generated in several concrete beam elements has been studied. This assessment was performed through a dynamic 2D thermal model, which was calibrated against experimental data. The thermal flow in these elements was found clearly bi-dimensional, which states the need of such analysis methods. Furthermore, not only the thermal field was calculated, but its results were reformulated to fit into the heat balance calculation of several rooms.

The models were found to be extremely sensible to surface convection and radiation heat transfer, while were reasonably stable to thermal properties of materials. The geometric description was considered exact as craftworks were supervised to avoid uncertainties of this kind. The sensitivity to surface heat transfer coefficients was mainly observed in heat flux signals, while temperature signals did not divert significantly with heat transfer coefficients similar to the finally calibrated one.

It was found extremely relevant to include heat transfer across these concrete elements for a proper heat balance analysis of the experiment. 2D heat flows were found very relevant in some cases where 1D heat transfer was very low or even neglectable. Even in situations with large 1-dimensional heat transfer, 2D heat flow accounted for modifications in the range of 10-20% for the analyzed junctions. It should be noted that 2D heat flow did not necessarily have the same direction to the 1D heat flow, so that it would be difficult to deal with it as a linear factor of 1D heat flows. The magnitude of this heat flux is found coherent with previous works on heat transfer such as [6], where the influence of thermal bridges is estimated in 15%.

Within full scale testing of thermal performance of building elements with clearly non one-dimensional flow, it is considered that the use of methods such as the one exposed in this paper or others providing similar information is highly useful.

8.13 Acknowledgements

The authors would like to thank the Government of the Basque Country, who partially funded this work; and the University of Seville and Fraunhoffer IBP for their advice in the definition of the experimental set-up.

8.14 References

[1] U.S. Department of Energy (DOE), 2008 Buildings Energy Data Book, 2008.

[2] Pérez-Lombard L., et al, . A review on buildings energy consumption information, Energy and Buildings 40, 2008

[3] E.U., 2002/91/EC of the European Parliament and of the Council of 16th December 2002 on the Energy Performance of Buildings, 2002.

[4] E.U., 2010/31/EU of the European Parliament and of the Council, of 19 May 2010 on the Energy Performance of Buildings (recast), 2010.

[5] Clarke J.A. Energy simulation in building design. Butterworth-Heinemann, 2nd edition, Oxford (2001).

[6] 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/ (2014/07/10)

[7] Tecnalia, “Kubik by Tecnalia”, http://www.energiaenedificacion.com/kubik-by-tecnalia/ (2014/07/07)

[8] Tecnalia, “KUBIK by Tecnalia, Experimental Infrastructure for the Configuration of Zero Energy Buildings”, http://www.tecnalia.com/en/sustainable-construction/infrastructure-a-equipment/infrastructure-a-equipment.htm, 2012.

[9] EN ISO 14683:1999. Thermal bridges in building construction. Linear thermal transmittance. Simplified methods and default values.

[10] EN ISO 6946: 2007. Building components and building elements – Thermal resistance and thermal transmittance – Calculation Method

[11] EN ISO 10211-1:1995. Thermal bridges in building construction. Calculation of heat flows and surface temperatures. Part I: General calculation methods.

[12] EN ISO 10211-2:2001. Thermal bridges in building construction. Calculation of heat flows and surface temperatures. Part II: Linear thermal bridges.

[13] García Gil, A., Modelado de Puentes Térmicos en la Simulación Térmica de Edificios, Departamento de Máquinas y Motores Térmicos ETSII, Universidad de Málaga, 2008.

[14] Martin K., 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).

[15] Martin, K. et al, Equivalent wall method for dynamic characterisation of thermal bridges, Energy And Buildings 55 (2012)

[16] Martin, K. et al, Methodology for the calculation of response factors through experimental tests and validation with simulation, Energy and Buildings 42 (2010)

[17] Martin, K et al, Problems In The Calculation Of Thermal Bridges In Dynamic Conditions, Energy and Buildings 43 (2011)

[18] Alvarez, S. Análisis Dinámico del Comportamiento Térmico de Edificios, Universidad de Sevilla (1986).

[19] TRISCO, computer program to calculate 3D & 2D steady state heat transfer in rectangular objects, version 12.0w, PHYSIBEL (2010)

[20] 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. Physibel, 2009

[21] IETcc, "CTE, Código Técnico de la Edificación", "Catálogo De Elementos Constructivos Del CTE", v6.3, March 2010.

[22] ASHRAE Handbook – Fundamentals ASHRAE (2001).

[23] Ben-Nakhi A.E. Adaptive construction modeling within whole building dynamic simulation. Department of Mechanical Engineering, University of Strathclyde, Glasgow (1995).

[24] Blanusa P. et Al., Comparison between ASHRAE and ISO thermal transmittance calculation methods, Energy and Buildings 39 (2007)

[25] Blomberg, T., Heat Conduction In Two And Three Dimensions. Computer Modeling of Building Physics Applications, Department of Building Physics, Lund University, Sweden (1996)

[26] Carpenter, S., Advances in modeling thermal bridges in building envelopes. Enermodal engineering limited, Kitchener (2001).

[27] Citterio M., M. Cocco and H. Erhorn-Kluttig. Thermal bridges in the EBPD context: overview on MS approaches in regulations. ASIEPI Information paper (2008).

[28] EN ISO 13786:2007. Thermal performance of building components. Dynamic thermal characteristics. Calculation methods.

[29] EN ISO 13789:1999. Thermal performance of buildings -- Transmission heat loss coefficient -- Calculation method.

[30] Karambakkam B K., A One-dimensional Approximation for Transient Multi-dimensional Conduction Heat Transfer in Building Envelopes. Oklahoma State University, School of Mechanical and Aerospace Engineering.

[31] Mao G., Dynamic calculation of thermal bridges, Energy and Buildings 26 (1997)

[32] Martin, K. et al, Analysis of a thermal bridge in a guarded hot box testing facility, Energy And Buildings 50 (2012)

[33] Strachan P, Simulation support for performance assessment of building components. Building and Environment 43 (2008)

[34] Strachan P, et al. Thermal Bridge Assessments, Energy Systems Research Unit, University of Strathclyde, Glasgow, Scotland

[35] Tadeau, A, et al. Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. Energy and Buildings 43 (2011)

[36] Theodosiou T.G. eta Al., The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy and Buildings, 40 (2008)

[37] Thorsell, T., Advances in Thermal Insulation. A computer program to query an atlas of building details (2002)

9 Experimental assessment of external thermal insulation systems for building envelope energy retrofits

Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting

Roberto Garay, Beñat Arregi, Peru Elguezabal

9.1 Abstract

External Thermal Insulation Composite Systems (ETICS) are increasingly used for the energy-efficient retrofit of buildings.

This paper evaluates the in-situ thermal performance of a prefabricated composite panel made of PIR and concrete, by full scale testing of a prototype installed at the KUBIK test facility. Experimental results from measurement show a reduction in the thermal resistance of the ETICS assembly compared to theoretical design values. A number of phenomena have been identified causing multidimensional heat flow of conductive and convective nature, such as thermal bridges at floor slabs and anchors, and thermal bypass of the insulation causing airflow behind the ETICS.

9.2 Introduction

According to the Sustainable Building and Climate Initiative of the UN [1], buildings are responsible for 40% of the global energy needs, yet commercially available technologies can provide energy saving potentials between 30% and 80%. In a European context, considering its large building stock relative to demographic projections, the burden of reducing the energy demand of the built environment will largely lie in the energy efficient retrofit of existing buildings. This is recognized and supported by EU-level legislation such as directives on Energy Performance (EPBD) [2] and Energy Efficiency (EED) [3] of buildings, a harmonized Construction Products Regulation (CPR)[4], and funding granted by the Horizon 2020 Framework Programme for Research and Innovation initiatives.

Heat losses through the building envelope (walls, roofs, floors and glazed areas) account for over 60% of the energy use of conventional buildings. Many of these losses occur through uninsulated walls, thus the addition of thermal insulation is one of the most robust and efficient solutions for improving their energy efficiency. External Thermal Insulation Composite Systems (ETICS) are increasingly favoured over internal insulation approaches, due to a number of advantages like (a) lower disruption to occupants, (b) no loss of internal space, (c) lower risk of surface or interstitial condensation as the existing substrate is kept close to internal temperature, and (d) more efficient thermal performance allowed by a continuous insulation layer that prevents thermal bridges at junctions with intermediate floors and walls.

However, there is increased awareness of a 'performance gap' [5] resulting in a mismatch between predicted and measured energy use in buildings, which is often attributed to a combination of causes like occupant behaviour, defective workmanship and unrealistic design assumptions. This issue poses clear implication for strategic EU targets, especially considering that the underperformance tends to grow as the technology becomes more complex [6]. In order to find solutions for these shortcomings and improve our knowledge of their underlying causes, there is a critical need for in-situ tests of construction systems, as built and in service conditions.

This study evaluates the thermal performance of a prefabricated ETICS assembly in a retrofit application, by means of a prototype that was designed and built to be representative of a solution as implemented in the market. The thermal resistance expected from theoretical design values is compared to data from the experimental assessment, discussing possible causes for the variance between these.

9.3 Case study

This study measures in-situ thermal performance of a prefabricated ETICS solution that is mechanically anchored to existing floor slabs. The ETICS product, developed within the ETIXc project[7], is a composite panel comprised of PIR thermal insulation and a photo catalytic concrete external finish.

Figure 1: Test area at first floor of west-facing façade in KUBIK facility: (a) original brick wall before installation; (b) ETIXc prototype installed.

The test was carried out over a portion of the west-facing façade of the KUBIK test facility in Derio, Spain (43° 17′ N 2° 52'W). KUBIK by Tecnalia [8] is a full scale experimental infrastructure focused on research and development of new energy efficient products and systems. It has a total floor area of 500 m² distributed over basement, ground floor and two upper levels. The main distinctive feature of KUBIK is its capacity to create realistic scenarios for the quantitative determination of energy efficiency and energy savings resulting from the interplay of construction solutions, intelligent management of HVAC and lighting systems, and non-renewable and renewable energy sources.

A prototype of the ETIXc assembly was installed over a wall made of two brick layers with an uninsulated air layer in-between, representing a common Spanish construction from the 1970s (figure 1). This wall, erected in 2011, has since been used for testing a number of different thermal insulation systems.

9.4 Methodology

The experimental set-up and the data analysis were designed to obtain the thermal resistance of (a) the whole wall integrating the ETIXc solution and (b) the ETIXc component in itself.

9.4.1 Measurement method and materials

Pt100 temperature sensors by Thermo Sensor GmbH (precision ≤ ± 0.1 °C) and Phymeas heat flux sensors (precision ≤ ± 0.1 % of FSV) were used in the experiment, connected to a Beckhoff Automation PLC system, where data from measurements was recorded at 1 minute intervals.

In order to gather the data required for obtaining thermal resistance values for the different layers of the component, the sensors were placed over relevant points of the assembly:

- Layer 1, external surface of ETIXc panel: temperature sensor only
- Layer 2, internal surface of ETIXc panel: temperature sensor only
- Layer 3, external surface of existing brick wall: temperature and heat flux sensors
- Layer 4, internal surface of existing brick wall: temperature and heat flux sensors

These sensors give sufficient information for obtaining the following thermal resistance values:

- $R_{4\text{-}1}$, thermal resistance of the retrofitted wall
- $R_{4\text{-}3}$, thermal resistance of the original wall
- $R_{2\text{-}1}$, thermal resistance of ETIXc panel

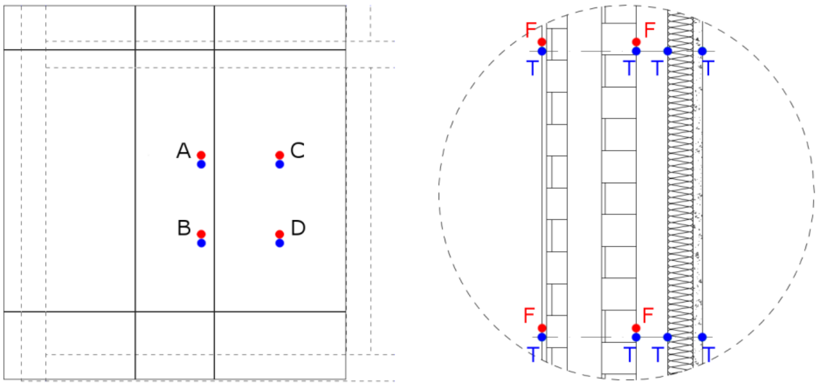


Figure 2: (a) wall elevation with location of four measurement axes; (b) location of heat flux (F) and temperature (T) sensors through wall section

This arrangement was replicated along 4 measurement axes, in order to assess the variability of the thermal resistance due to installation defects and thermal stratification conditions. So as to exclude the effect of thermal bridges, these measurement axes were deliberately placed in an intermediate zone between floors.

9.4.2 Calculation of thermal resistance

The characterization of the thermal properties of the system was performed by means of a procedure where the cumulated mean values of the required variables were computed. For one-dimensional heat transfer, thermal resistance is defined as the ratio of temperature difference and the heat flux between opposite faces of a material. Although thermal resistance is dependent on temperature, this variance is relatively small for applications in the construction sector, and thus is generally assumed to be a constant value.

The input variables (temperature and heat flux) vary over the course of the experiment. Despite a dominant daily cycle, changing weather conditions result in a high variability among different days. Therefore a normalised average method[9] has been used to filter out heat storage effects, where the obtained data is aggregated in order to reduce dynamic oscillations.

$$R = \frac{\sum_{j=1}^{n}(T_{si,j} - T_{se,j})}{\sum_{j=1}^{n} q_j} \qquad (1)$$

where:

- R is the surface-to-surface thermal resistance (in m²K/W)
- $T_{si,j}$ is the interior surface temperature (in °C or K) at time step j
- $T_{se,j}$ is the exterior surface temperature (in °C or K) at time step j
- q is the density of heat flow rate through the material (in W/m²) at time step j
- j is each of the time steps of the experimental sequence
- n is the number of time steps of the experimental sequence

When carried over a long enough period of time, there is a convergence to an asymptotical value that is close to the steady-state value. The test procedure requires a minimum duration of 72h and a deviation in thermal resistance below 5% when data for the last 24 hours is subtracted. As the experiment has been carried out over 63 days, this criterion is much improved in this particular case.

9.5 Baseline values

This experiment makes use of a previously experimented brickwork wall[10]. The values obtained by physical measurement are listed in Table 1. Table 2 presents the calculation[11] of the thermal properties of the ETIXc panel, based on design data.

Table 1. Thermal properties of original wall, based on previous measurements.

	Thickness d [m]	**Thermal resistance R [m²K/W]**
Original wall	0.295	0.53

Table 2. Thermal properties of ETIXc panel, from theoretical calculations based on design data.

	Thermal conductivity λ [W/mK]	Thickness d [m]	Thermal resistance R [m²K/W]
PIR insulation	0.03	0.080	2.67
Concrete	1.75	0.030	0.02
ETIXc panel		0.110	2.69

9.6 Results from experimental campaign

Minutely recorded data in the period from 1 November 2015 to 3 January 2016 was processed for this assessment. The cumulated averaging method was found very stable, furthermore considering that with 63 days of data, daily heat storage can be easily neglected.

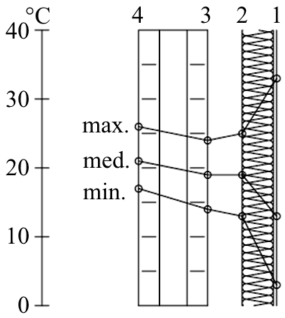
Results were obtained for each of the 4 measurement axes (figure 2). In order to achieve a robust and stable surface-surface conductance value, the signals were processed by generated cumulated mean values of each of the signals.

Quantitative results are portrayed in Table 3. A high variance can be observed in temperature and heat flux values recorded, especially for the outer surface of the façade (layer 1). This is due to a higher oscillation in temperatures compared to the internal environment, the effect of solar radiation heating the external surface, and long wave radiation emissions to a clear night sky cooling the surface.

Locations to the inner side of the insulation show lower variances, due to the insulation value of the PIR mitigating external oscillations and the thermal mass of the brickwork. The inner surface of the insulation (layer 2) and the outer surface of the original wall (layer 3) show a very similar performance, as the air layer that separates these locations has poor insulating properties, especially considering the higher relative thermal resistance of the insulation in the panels.

The room surface (layer 4) is also subjected to variances, caused by changes in internal room temperature and the operation of the HVAC system.

Table 3. Statistical distribution of experimental readings for temperature and heat flux density.



	Temperature T [°C]				Heat flux density q [W/m²]	
	T_1	T_2	T_3	T_4	q_3	q_4
Average	13.52	19.25	19.46	21.53	2.67	3.38
Maximum	33.14	25.32	24.62	26.59	9.08	20.14
Third quartile	16.26	20.63	20.69	22.64	4.16	5.07
Median	13.54	19.03	19.23	21.19	2.60	2.35
First quartile	10.24	17.71	17.97	20.22	1.36	1.32
Minimum	2.84	13.28	13.91	16.92	-4.94	-3.53

From the temperature and heat flux density values measured, thermal resistance values have been obtained for both the original wall and the ETIXc panel (Table 4):

- The overall thermal resistance of the insulated assembly has been measured at 2.73–3.00 m²K/W, a significant improvement from the value measured before insulation (0.53 m²K/W)
- The thermal resistance measured for the original wall substrate is increased after the application of insulation (0.53 m²K/W before insulation, 0.61–0.78 m²K/W after insulation)
- The thermal resistance of the ETIXc panel has been measured at 1.70–2.15 m²K/W, lower than its theoretical value (2.69 m²K/W)

Table 4. Overall and partial thermal resistances calculated from temperature and heat flux density.

	Temperature difference ΔT [°C]		Heat flux density q [W/m²]	Thermal resistance R [m²K/W]		
Layer 1	8.01	5.74	2.67–3.38	2.73–3.00	1.70–2.15	ETIXc panel
Layer 2						
Layer 3		2.07			0.61–0.78	Original wall
Layer 4						

9.7 Conclusions

9.7.1 Performance of the ETICS assembly

The thermal resistance measured in-situ for the ETICS assembly (1.70–2.15 m²K/W) is lower than its theoretical value from design data (2.68 m²K/W). A number of potential causes are identified below:

- Where the ETICS panels are anchored to the intermediate floor, thermal bridges occur. Reinforced concrete floor slabs are comparatively more conductive than the original wall substrate of perforated brick and air layer, creating a potential for lateral heat flow that is not accounted for by the one-dimensional calculation. While the quantification of their additional heat flow is outside the scope of this study, these could potentially contribute to the increase measured in the test.
- The presence of an air gap between the ETICS assembly and the original wall, in the case where the complete airtightness of this air layer cannot be guaranteed, can potentially result in infiltration of external air by natural or forced (wind-driven) convection. It constitutes a mechanism of open convective loop[12], which is a form of thermal bypass[13]. In the tested assembly, care was taken on site to seal all joints between panels. However, the extent of this phenomenon cannot be detected by conventional air pressure tests, as the air infiltration does not reach the indoor space.
- A high moisture content within the concrete and the PIR insulation could lead to an increase of their thermal conductivity above declared values. In the experimented façade, a water leakage test was carried out in order to prevent the risk of rainwater penetration at joints between concrete panels.
- In addition to the above mentioned factors, there could also be unidentified error sources originating from the experimentation.

9.7.2 Performance of the original wall substrate

The thermal resistance measured in-situ for the original wall substrate after incorporating the insulation (0.61–0.78 m²K/W) is higher than the previous in-situ measurement of the uninsulated wall (0.53 m²K/W).

- The thermal conductivity of brick has a strong dependence on moisture content. The installation of the ETICS assembly might have resulted in the drying of the original masonry substrate[14], thus lowering its thermal conductivity.
- The ETICS assembly offers additional protection to the wall substrate against weather, wind and air infiltration, which might result on an improvement of its thermal performance.

9.7.3 Overall conclusions about the assessed retrofit intervention

In general terms, the assessed ETICS assembly constitutes a successful retrofit intervention. As shown by full scale experimental testing, the application of the ETIXc solution results in a 5x increase in the thermal resistance of the wall (from 0.53 m^2K/W before insulation up to 2.73–3.00 m^2K/W after insulation).

The in-situ thermal performance of the prototype is slightly below the level predicted using design data. This underperformance can be attributed to differences between the theoretical model and the as-built prototype, such as those identified above.

Theoretical calculations assume perfect execution, which is rarely, if ever, possible on site. In order to minimise the gap between predicted and measured values, unrealistic design assumptions should be challenged, and the additional energy loss observed in-situ might need to be estimated and factored in energy calculations.

The authors believe that the workmanship in the tested assembly reflects general construction practice, and the experimental study is representative of the in-situ performance of a typical building, as built and in service conditions, retrofitted with the ETICS assembly studied.

Physical measurements of thermal resistance should be encouraged, which should ultimately lead to a better understanding of the factors that affect in-situ thermal performance by both designers and operatives.

9.8 Acknowledgements

The authors would like to thank the contribution and effort of the ETIXc project consortium, composed of Sociedad Financiera y Minera, S.A. FYM – HeidelbergCement Group[15] and Prehorquisa[16]. This research work has been aided by the EEA Grants[17] special funding from the Financial Mechanism of the European Economic Area (2009-2014).

9.9 References

[1] United Nations Environment Programme – Sustainable Building and Climate Initiative, 2015. Retrieved from http://www.unep.org/sbci on 28/04/2016

[2] Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast).

[3] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency.

[4] Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products.

[5] De Wilde P. The gap between predicted and measured energy performance of buildings: A framework for investigation, *Automation in Construction* 2008; Vol. 41, p. 40–49.

[6] Miles-Shenton D et al. *LowCarb4Real: Developing Low Carbon Housing, Lessons from the Field*, Leeds Metropolitan University; 2009.

[7] ETIXc: Precast external thermal insulation system for buildings with photocatalytic performance. Retrieved from www.i-labspain.es/en on 03/05/2016

[8] Garay R et al. Energy efficiency achievements in 5 years through experimental research in KUBIK, 6th IBPC Conference, *Energy Procedia* 2015; Vol. 78, p. 865–870.

[9] ISO 9869-1:2014 Thermal insulation – Building elements – In-situ measurement of thermal resistance and thermal transmittance – Part 1: Heat flow meter method.

[10] Garay R, Uriarte A, Apraiz I. Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, *Energy and Buildings* 2014; Vol. 85, p. 579-591.

[11] EN ISO 6946:2007 Building components and building elements – Thermal resistance and thermal transmittance – Calculation method.

[12] Harrje DT, Dutt GS, Gadsby KJ. Convective loop heat losses in buildings, *ASHRAE Transactions* 1985; 91(2): 751-760.

[13] Siddall M. The impact of thermal bypass, *Green Building Magazine* 2009; Vol. 19 No. 1.

[14] Künzel HM. Effect of interior and exterior insulation on hygrothermal behaviour of walls. *Materials and Structures/Materiaux et Constructions* 1998. Vol. 31, p. 99-103.

[15] FYM – HeidelbergCement Group (www.i-nova.net)

[16] Prehorquisa (www.prehorquisa.com)

[17] EEA Grants (eeagrants.org)

10 Conclusions

In this work, the overall state-of-the-art of thermal bridge assessment has been reviewed, with particular focus on dynamic modeling, experimentation and integration within Building Energy Software. Due to many historical factors, such as limits of computer capacity and the relatively minor relevance of thermal bridges in the context of poorly insulated buildings, assessment methods for thermal bridges have not been sufficiently developed and spread. Overall, thermal bridge assessment has been limited to steady-state calculations.

In experimental works related to heat transfer in building envelopes, the effect of thermal bridges has been envisioned not as a topic for study, but a source of error. Considering this approach, Experimental setups have been targeting at avoiding thermal bridge effects by mitigation in experimental design or avoidance to measure in influenced areas.

In the context of modern building codes, nearly zero energy buildings, and full scale experimental research facilities, attention should be paid to every minimal detail. This includes thermal bridges, whose relative impact in the heat balance of buildings is increasingly relevant with incremental thermal insulation of building envelopes. Furthermore, considering that thermal bridges in architectural junctions are a major heat loss path, and produce cold spots where surface condensation and mould growth is more likely to occur.

In *section 4* of this work, a procedure has been proposed for the assessment of envelope heat transfer which integrates multi-dimensional heat transfer, in the frame of on-site experimental heat transfer assessment, targeted at thermal retrofitting of building envelopes. The main innovations of this methodology are the formulation of transient multi-dimensional heat transfer in architectural junctions –section 5- and its capacity to integrate point measurements in the viccinity of architectural junctions in order to calibrate numerical models –section 8- which are later used to assess potential envelope retrofit alternatives.

This methodology integrates various thermal assessment methods. These methods are developed in this thesis in the field of numerical steady-state multi-dimensional heat transfer –section 6-, steady-state one-dimensional experimental heat transfer –section 7-, experimental calibration of multidimensional numerical models –section 8- and experimental assessment of the diferential heat transfer due to envelope retrofitting –section 9-.

In *section 5*, the generalization of the mathematical formulation of heat transfer in building envelopes to adapt it to dynamic multidimensional phenomena has been conducted. The formulation presented in section 5 is particularized for the case of harmonic excitation of bi-dimensional architectural junctions, but the underlying concept reaches far beyond. The same formulation is implicitly valid for any type of time-varying boundary condition, and 2- or 3-dimensional heat transfer. In fact, in section 8, the same approach is used to obtain a time-varying representation of multidimensional heat transfer in an experimental setup.

Within this section, the formulation of an adaptation of the mitalas transfer function into the multi-dimensional field is also performed. In the field of numerical modelling, adaptations such as the aforementioned Mitalas transfer function or response factors characterizing the architetural junction would bring the possibility to further integrate these outputs in Building Energy Simulation software.

In *section 6*, a numerical assessment of the multi-dimensional heat transfer in an architectural junction is presented, in this works, possible outputs of thermal assessments such as temperature factor –f-, Surface thermal transmitance –U-value-, linear thermal transmittance -Ψ- and point thermal transmitance – χ- are introduced. Steady-state numerical assessments performed in this section reflect that thermal bridges in the uninsulated architectural junction account for 12% of heat transfer in the model. Although the overall heat transfer is substantially reduced with external thermal insulation multidimensional heat transfer in lightwheight façade substructures account for 16-46% of heat transfer increase when compared with a simplified junction model.

In *section 7*, a one-dimensional experimental asessment of an internal insulation system is presented. This paper presents several research activities within the field of material formulation and upscaling. In the field of building physics, experimental assessment methods based on averaging methods are presented. The accuracy and repeatability of the processes are tested against laboratory measurements (accuracy) and several parallel measurement axes (repeatability). The ultimate conclussion is that these methods provide accurate and repeatible ressults within +-0.001W/mK in material thermal conductivity with systems with thermal conductances in the range of 0.3X W/m2K.

In *section 8*, a calibration procedure of a transient multi-dimensional heat transfer model is proposed as a way to by-pass difficulties on the direct experimental determination of the magnitude of heat transfer in architectural junctions.

The selected model is an analytic finite diference model which is calibrated in order to better match experimental observations of the heat transfer dynamics on various temperature and heat flux measurements in the architectural junction. None of these localized measurements provides the overall heat transfer across the architectural junction. However, these measurements, located in selected places around the junction provide tramsient data. The calibrated numerical model, in good agreement with experimental observations is used to perform detailed analysis of the architectural junction. Jointly with a transient formulation of multi-dimensional heat transfer in the junction the calibrated model is successfully used to allocate heat transfer across the envelope to one- and two-dimensional heat transfer.

The presented experimental case shows that the thermal field in cases such as façade-slab junctions is clearly multidimensional. Even in situations with large one-dimensional heat transfer, 2D heat flow accounted for corrections to the heat balance of the experimental building in the range of 10-20% for the analyzed junctions.

Experiences presented in section 8 are accumulated over the ressults provided in the numerical study presented in section 5, where clear differences are observed in the multi-dimensional heat transfer assessment of the architectural junction compared to one-dimensional heat transfer. All this states the need of advanced analysis methods such as those proposed in this thesis.

Together, the formulation deployed in section 5, one-dimensional experimental assessment procedures illustrated in section 7 and the calibration procedure defined in section 8 provide the tools required for the experimental transient thermal assessment of architectural junctions. This can latter be used as suggested in section 4 to define with better precission the thermal performance of alternative building energy retrofit solutions.

The methodology proposed would require of relatively long measurement campaigns, which should be performed at the same time than those performed for the assessment of one dimensional heat transfer. In section 7, one of such one-dimensional heat transfer procedures is shown. The proposed campaign would last for approximately 1 month but would not require human intervention in the process.

Overall, due to the relatively small amount of sensorization spots defined, and the lack of human intervention during the measurement campaign, the procedure outlined in section 4 is considered to be a minimally intrusive methodology. 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 and data acquisiton systems from dwellings in the monitorization process.

This methodology is capable of producing many possible outcomes, which should be defined based on the requirements of each particular case. In section 4, several output variables are presented. In sections 5 and 6 these output parameters are further defined and examples of possible analysis presented. In section 5, an asessment of the harmonic thermal properties of the architectural junction is presented. In section 6, the particular analysis on the steady-state performance of a façade-slab junction is performed by considering temperature factors, overall thermal transmitance, and heat transfer coefficients in thermal bridges, along with its variations with different insulation thickness. In both cases, the impact of the thermal bridge over a representative surface of the façade is estimated. In section 5, the overall envelope thermal transmitance of the presented case study is incremented in excess of 100% due to the introduction of thermal bridges. In section 6, temperature factors are reduced by 0.04 and overall U-values are increased by 0.06W/m2K. The aforementioned 0.06W/m2K represents an increase of 20% to 35% in the overall highly insulated architectural junction.

Again advanced methods such as those presented in this work are required to properly address such relevant discrepancies –when compared to neglection of the thermal bridge effect- in the case of otherwise highly insulated and well characterized building envelopes.

The calibration procedure defined in section 8 has been proven satisfactory to characterize the transient thermal performance of the architectural junction over time. Considering present energy audit techiques it is viable to obtain suitable geometric definitions of the architectural details for the construction of numerical models, reducing uncertainties in this field. Also, thermal properties of materials were found not to be especially critical in the calibration of the models, with only minimal tuning required. In all cases, most fit properties were within the ranges found in reference works.

Although relatively stable to geometric and thermal properties of materials, the calibration of numerical models was found to be sensible to surface heat transfer. The sensitivity to surface heat transfer coefficients was mainly observed in heat flux signals, while temperature signals did not divert significantly with heat transfer coefficients similar to the finally calibrated one. However, the main difficulties arising from the calibration of surface heat transfer coeffcients was caused by unstable convective effects such as those caused by convectors and fans. To the authors' opinion, the identified limitation is of minor relevance in most situations, but a suitable experimental procedure shoud define that sensors should not be installed near convective flows such as heat sources (e.g. wall-hung radiators) or fans.

The final output of the calibration procedure is a thermal model which is later reformulated to fit into the heat balance of a room. This reformulation is performed by means of the mathematical reformulation defined in section 5, particularized for the time domain.

As the final step in the proposed methodology, *section 9* presents an experimental assessment on the diferential thermal performance of an external thermal insulation system compared to the original wall. This assessment is performed by means of averaging method with a similar approach to that presented in section 7. However this analysis provides the diferential thermal performance provided to the building envelope by the addition of the external thermal insulation system, thus assessing the benefits of this type of systems.

The diferential assessment concludes that the in-situ measured thermal resistance of the external thermal insulation system is 20% lower than its design value. Its possible constructional causes are discussed. At the same time, the original brick wall improves its thermal resistance when compared to the measured value prior to the installation of the external thermal insulation system by 15-45%. This behavior is assumed to be linked to better thermal performance of a dry and weather-protected wall in the retrofit case.

Overall, this assessment concludes that the retrofit is successful with a 5x increase in the thermal resistance of the wall (from 0.53 m^2K/W before insulation up to 2.73–3.00 m^2K/W after insulation), although the assessment of the thermal performance of the insulation system slightly below the level predicted using design data.

11 Future work

This thesis presents several developments in the assessment of thermal performance of multidimensional heat transfer in architectural junctions. These developments build over pre-existing assessment methods in the field of heat transfer in buildings.

As in many other works, formulation, procedures and methods presented here need to be further developed for its wider adoption by the building physics, and thermal engineering community.

The generalized mathematical formulation of thermal bridges is based on existing formulation in relevant technical standards. As such, it could easily be considered as the basis for an extension of *EN ISO 13786 Thermal performance of building components. Dynamic thermal characteristics. Calculation methods*. The content of this standard is presently limited to the calculation of 1D harmonic heat transfer properties. Should it be considered suitable, additional calculation procedures based on section 5 of the present work could extent the scope of this standard for cases with multidimensional heat transfer.

The methodology for on-site thermal assessment of heat transfer in architectural junctions, and the calibration procedure of numerical models have only been applied over an experimental facility. Experimental works conducted over the Kubik test facility validate the overall concept, but further work is required to achieve a robust experimental procedure for its application over *real-world* buildings with limitations regarding factors such as the timespan of the experimental campaign, availability of architectural data, imperfections in sensor installations, etc. Extended experimental works over various types of buildings should be performed in order to assess the relevance of these factors, and define suitable procedures to overcome possible limitations imposed by these.

The application of the calibration procedure for numerical models presented in section 8 required of intensive manual work in the construction of numerical models and selection of parameters leading to minimal error when compared to experimental data. Furthermore, limitations have been identified regarding situations with heavy convective situations. With these considerations, two main works remain undone. A suitable automated parameter identification procedure should be implemented, reducing implementational work in the calibration procedure, and leading to reasonable costs for the implementation of the calibration methods in thermal audits in buildings. Furthermore, procedures for the bounding and mitigation of non-precise outputs associated with heavy convective situations need to be developed.

Within the field of building energy simulation (BES), two issues are considered critical. On one side, the mathematical formulation within BES would need to adapt for the inclussion of multidimensional heat transfer in envelopes. These adaptations would differ for each BES, based on the mathematical approach pursued by each.

However, the main limitation for BES lies in the computational effort required to calculate the transient thermal response of an architectural junction, which may be several times larger than that employed in BES to calculate the yearly energy loads of full buildings. In this case, databases of typical architectural junctions would need to be developed with pre-calculated transient characterization of architectural junctions, to by-pass current limitations in computational effort.

12 Bibliography

[1] Aegerter , MA. Et Al., Aerogels Handbook, Springer, Heidelberg, (2011).

[2] AEROCOINS, Aerogel-Based Composite/Hybrid Nanomaterials for Cost-Effective Building Super-Insulation Systems, EU FP7, GA 260141. http://www.aerocoins.eu (2015/11/16)

[3] Al-Sanea, S. a. (2003). Finite-volume thermal analysis of building roofs under two-dimensional periodic conditions. Building and Environment, 38(8), 1039–1049.

[4] Alvarez, S. Análisis Dinámico del Comportamiento Térmico de Edificios, Universidad de Sevilla (1986).

[5] ANSYS, Simulation Driven Product Development, http://www.ansys.com/ (2016/11/30)

[6] 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/ (2014/07/10)

[7] Atanasiu et al. Principles for nearly zero-energy buildings. Paving the way for effective implementation of policy requirements. BPIE. 2011. ISBN: 9789491143021

[8] ASTM C1155 - 95(2013) Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data

[9] Atsonios, I.A., et Al., A comparative assessment of the standardized methods for the in–situ measurement of the thermal resistance of building walls, In Energy and Buildings, Volume 154, 2017, Pages 198-206.

[10] Baetens, R. et al., Aerogel insulation for building applications: a state-of-the-art review, Energy and Buildings 2011, 43(4): 761-769.

[11] Berggren, B., Calculation of thermal bridges in (Nordic) building envelopes – risk of performance failure due to inconsistent use of methodology, Energy Build. 65 (2013) 331–339.

[12] Bommel, M J et al., Drying of silica gels with supercritical carbon dioxide . Journal of Materials Science, 1994, 29(4): 943-948.

[13] BRESAER, BREakthrough Solutions for Adaptable Envelopes in building Refurbishment EU h2020 GA Nº 637186.

[14] Brinker, CJ. Et Al., Sol–gel science: The physics and chemistry of sol–gel processing. San Diego, Academic Press, 1990

[15] CEN, TC 89 - Thermal performance of buildings and building components, https://standards.cen.eu/dyn/www/f?p=204:7:0::::FSP_ORG_ID:6072&cs=1838C2B207A6B7D88562A05376928F458 (2016/12/09)

[16] Chen, K. et al., Mechanical and thermal performance of aerogel-filled sandwich panels for building insulation, Energy and Buildings (2014, 76, 336-346

[17] Chica, JA et al, KUBIK: Open building approach for the construction of an unique experimental facility aimed to improve energy efficiency in buildings. Proceedings of the O&SB2010 “Open and Sustainable Building”, ISBN: 978-84-88734-06-8

[18] Citterio, M. et Al., Thermal bridges in the EBPD context: overview on MS approaches in regulations. Information paper 64, 2009, http://www.buildup.eu/publications/1449 (2016/12/09)

[19] Clarke J.A. Energy simulation in building design. Butterworth-Heinemann, 2nd edition, Oxford (2001).

[20] Código Técnico de la Edificación (CTE). DA DB-HE / 1 Documento de Apoyo al Documento Básico DB-HE Ahorro de energía. Cálculo de parámetros característicos de la envolvente. (2015)

[21] Código Técnico de la Edificación (CTE). DA DB-HE / 3 Documento de Apoyo al Documento Básico DB-HE Ahorro de energía. Puentes térmicos. (2014)

[22] COMSOL Multiphysics, https://www.comsol.com/ (2016/11/30)

[23] CTSM-R Development Team, Continuous Time Stochastic Modeling in R. User’s Guide and Reference Manual, 2015. http://ctsm.info/pdfs/ctsmr-reference.pdf (2016-06-14)

[24] Cuce, E., et Al., Optimizing insulation thickness and analysing environmental impacts of aerogel-based thermal superinsulation in buildings, Energy and Buildings (2014), 77 28-39

[25] Deconinck, A.H., Roels,S., Comparison of characterisation methods determining the thermal resistance of building components from onsite measurements, In Energy and Buildings, Volume 130, 2016, Pages 309-320.

[26] De Wilde P. The gap between predicted and measured energy performance of buildings: A framework for investigation, Automation in Construction 2008; Vol. 41, p. 40–49.

[27] Ebert, H.-P., Thermal properties of Aerogels, in: M.A. Aegerter, N. Leventis, M.M. Koebel (Eds.) Aerogels Handbook, Springer Science+Business Media, New York, 2011, pp. 537-564;

[28] Economidou et al., Europe´s building under the microscope. A country-by-country review of the energy performance of buildings, BPIE, 2011, ISBN: 9789491143014

[29] EEA Grants, http://www.eeagrants.org (2016/12/09)

[30] Efficiency Valuation Organization, IPMVP International Performance Measurement and Verification Protocol, Volume 1, EVO, 2012 http://evo-world.org/ (18/06/2016)

[31] Elguezabal, P. et al., Experiences when employing different alternatives for envelope upgrading. Journal of Façade Design and Engineering, 2015, doi:10.3233/FDE-150032

[32] Emmerling, A. et Al, Scaling properties and structure of aerogels, Journal of Sol-Gel Sci Technol 1997, 8: 781-788.

[33] EN 13501-1:2007+A1:2010. Fire classification of construction products and building elements. Part 1: Classification using data from fire reaction tests

[34] EN 13823:2010, Reaction fire tests for Building products. Building products excluding floorings exposed to thermal attack by a single burning item.

[35] EN 410:2011 Glass in building. Determination of luminous and solar characteristics of glazing

[36] EN 673:2011 Glass in building. Determination of thermal transmittance (U value). Calculation method

[37] EN 826:1996. Thermal insulating products for building applications - Determination of compression behavior.

[38] EN ISO 13786:2007 Thermal performance of building components. Dynamic thermal characteristics. Calculation methods

[39] EN ISO 13790:2008: Energy performance of buildings. Calculation of energy use for space heating and cooling.

[40] EN ISO 7345:1996 Thermal Insulation- Physical quantities and definitions

[41] EN ISO 9869-1:2014 Thermal insulation -- Building elements -- In-situ measurement of thermal resistance and thermal transmittance -- Part 1: Heat flow meter method

[42] Energy Saving Trust, Enhanced Construction Details (EDCs): Thermal bridging and Airtightness, UK, 2009, http://www.energysavingtrust.org.uk/sites/default/files/reports/CE302%20-%20ECD_thermal%20bridging%20and%20airtightness.pdf (2016/02/26)

[43] EnergyPlus v8.4, EnergyPlus™ Documentation, Engineering Reference, https://energyplus.net/sites/default/files/pdfs_v8.3.0/EngineeringReference.pdf (2016/02/23)

[44] ETIXc: Precast external thermal insulation system for buildings with photocatalytic performance. www.i-labspain.es/en (03/05/2016)

[45] European Commission, A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy, COM (2011) 21, 2011, http://ec.europa.eu/resource-efficient-europe/pdf/resource-efficient_europe_en.pdf (2016/12/09)

[46] European Commission, A Roadmap for moving to a competitive low carbon economy in 2050, COM(2011)112, 2011, http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52011DC0112 (2016/12/09)

[47] European Commission, Directorate-General for Energy, Consultation Paper – Financial support for Energy efficiency in buildings, 2012, https://ec.europa.eu/energy/sites/ener/files/documents/2012_eeb_consultation_paper_en.pdf (2016/12/09)

[48] European Commission, Energy –efficient buildings. Multi-annual roadmap for the contractual PPP under Horizon2020, 2013, ISBN: 978-92-79-31239-7

[49] European Commission, HORIZON 2020, The EU Framework Programme for Research and Innovation, https://ec.europa.eu/programmes/horizon2020/ (2016/12/09)

[50] European Parliament, Construction Products Regulation, Regulation, (EU) No 305/2011, 2011, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011R0305 (2016/12/09)

[51] European Parliament, Directive 2002/91/EC, Energy Performance of Buildings, 2002, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32002L0091 (2016/12/09)

[52] European Parliament, Directive 2010/31/EU, Energy Performance of Buildings (recast), 2010, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF (2016/12/09)

[53] European Parliament, Directive 2012/27/EU, Energy efficiency, 2012, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF (2016/12/09)

[54] EUROSTAT. Business enterprise R&D expenditure (BERD) by economic activity. 2005-2013

[55] Fernandez, I. et al., New Sustainable Construction System With Hemp Fiber Insulation. REHABEND 2016, Burgos; 05/2016

[56] Fletcher M., Optimising test environment and test set up for characterizing actual thermal performance of building components and whole buildings 6th International Conference on Building Physics for a Sustainable Built Environment IBPC 2015, Torino.

[57] FYM – HeidelbergCement Group, www.i-nova.net (2016/12/09)

[58] Galliano, R. et Al.; Performance evaluation of aerogel-based and perlite-based prototyped insulations for internal thermal retrofitting: HMT model validation by monitoring at demo scale. Energy and Buildings 2016, 126, 275–286

[59] Garay Martinez, R. et al., Integrated Solar Thermal Systems for renovation of external walls. Advanced Building, Skins 2016

[60] Garay Martinez, R. et al., Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. Energy and Buildings 06/2016; 128. DOI:10.1016/j.enbuild.2016.06.071

[61] Garay, R et al. Energy efficiency achievements in 5 years through experimental research in KUBIK, 6th IBPC Conference, Energy Procedia 2015; Vol. 78, p. 865–870.

[62] Garay, R et al., Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, Energy and Buildings 2014; Vol. 85, p. 579-591.

[63] Garay, R. et al. Superinuslation Solutions For The Internal Insulation In Energy Retrofitting. REHABEND 2016

[64] Garay, R. et al., Calibration Procedures for Multidimensional Heat Transfer Models Based on On-site Experimental Data. 6th International Building Physics Conference, IBPC 2015, Turin; 06/2015

[65] Garay, R., Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, 2016

[66] Garay, R., Highly insulated systems for energy retrofitting of façades on its interior. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, 2016

[67] Garay, R., Hygrothermal assessment of a prefabricated timber-frame construction based in hemp. International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16, Thessaloniki, 2016

[68] García Gil, A., Modelado de Puentes Térmicos en la Simulación Térmica de Edificios, Departamento de Máquinas y Motores Térmicos ETSII, Universidad de Málaga, 2008. https://es.scribd.com/doc/26313726/Modelado-de-Puentes-Termicos-en-la-Simulacion-Termica-de-Edificios (2016/05/18)

[69] García-González, CA. et Al., Supercritical drying of aerogels using CO2: Effect of extraction time on the end material textural properties. The Journal of Supercritical Fluids, 2012, 66(0): 297-306.

[70] Ge, H. et Al., Impact of balcony thermal bridges on the overall thermal performance of multi-unit residential buildings: A case study. Energy and Buildings, 2013, Vol. 60, p. 163–173.

[71] Ge, H. et Al., Effect of dynamic modeling of thermal bridges on the energy performance of residential buildings with high thermal mass for cold climates, In Sustainable Cities and Society, Volume 34, 2017, Pages 250-263.

[72] Gellert, R., Inorganic mineral materials for insulation in buildings. In Materials for Energy Efficiency and Thermal Comfort in Buildings, Woodhead Publishing, 2010, 193-228.

[73] Ghazi Wakili, K. et Al., Efficiency verification of a combination of high performance and conventional insulation layers in retrofitting a 130-year old building, Energy and Buildings (2014), 82, 237-242

[74] Graser, F. et Al., Preparation of aerogels. 1987, US Patent US4667417A

[75] Gurav, JL et Al., Silica aerogels: synthesis and applications, J Nanomaterials 2010, 2010

[76] Gutschker, O.; Parameter identification with the software package LORD, Building and Environment, Special Issue: Outdoor Testing, Analysis and Modelling of Building Components, 2008, 43(2), 163–169

[77] Hæreid, S. et al., Preparation and properties of monolithic silica xerogels from TEOS-based alcogels aged in silane solutions, J. Non-Cryst. Solids 1995, 186: 96–103.

[78] Hahne E, Pfluger R. Improvements on PASSYS test cells. Solar Energy 1996 0;58(4–6):239-246.

[79] Harrje DT et al. Convective loop heat losses in buildings, ASHRAE Transactions 1985; 91(2): 751-760.

[80] Ibrahim, M. et Al., Hygrothermal performance of exterior walls covered with aerogel-based insulating rendering. Energy and Buildings 2014, 84, 241–251

[81] IEE SAVE ASIEPI Project, Assessment and Improvement of the EPBD Impact, "The final recommendations of the ASIEPI project: How to make EPB-regulations more effective? Summary report", 2010, Intelligent Energy Europe programme, contract EIE/07/169/SI2.466278

[82] IETcc, CEPCO, AICIA, Catálogo De Elementos Constructivos Del Cte, v 6,3, 2010.Catálogo De Elementos Constructivos Del Cte, IETCC, 2010, http://www.codigotecnico.org/index.php/menu-catalogo-informatico-elementos-constructivos (18/05/2016)

[83] IREC, Integrated Regional Benchmark Analysis. MARIE project, Final Report, 2012. http://www.marie-medstrategic.eu (2016/12/09)

[84] ISO 13789:2007 Thermal performance of buildings -- Transmission and ventilation heat transfer coefficients -- Calculation method

[85] ISO 8302:1991 Thermal insulation -- Determination of steady-state thermal resistance and related properties -- Guarded hot plate apparatus

[86] Janssens, A., IEA EBC Annex 58, Report of Subtask 1a: Inventory of full scale test facilities for evaluation of building energy performances, KU Leuven 2016, ISBN: 9789460189906, http://www.kuleuven.be/bwf/projects/annex58/data/A58_Final_Report_ST1a.pdf (2016/11/30)

[87] Karambakkam, B. K., et Al., A One-dimensional Approximation for Transient Multi-dimensional Conduction Heat Transfer in Building Envelopes, (2005).

[88] Koebel, M.M. et al., Breakthroughs in cost-effective, scalable production of superinsulating, ambient-dried silica aerogel and silica-biopolymer hybrid aerogels: from laboratory to pilot scale, J Sol-Gel Sci Technol, 2016 1-11.

[89] Koebel, M.M., Aerogels handbook., Springer, 2011

[90] Kolaitis, D.I. et Al., An experimental and numerical simulation study of an active solar wall enhanced with phase change materials. Journal of Façade Design and Engineering, 2015, doi:10.3233/FDE-150027

[91] Kośny, J., Kossecka, E., Multi-dimensional heat transfer through complex building envelope assemblies in hourly energy simulation programs, In Energy and Buildings, Volume 34, Issue 5, 2002, Pages 445-454.

[92] Kossecka, E., & Kosny, J., Three-dimensional conduction z-transfer function coefficients determined from the response factors. Energy and Buildings 2005, 37(4), 301–310.

[93] Kossecka, E., & Kosny, J., Two-Step Procedure for Determining Three-Dimensional Conduction Z-Transfer Function Coefficients for Complex Building Envelope Assemblies, 1–11, 2004, http://www.ornl.gov/sci/roofs+walls/staff/papers/new_075.pdf (2016/12/09)

[94] Künzel HM. Effect of interior and exterior insulation on hygrothermal behaviour of walls. Materials and Structures/Materiaux et Constructions 1998. Vol. 31, p. 99-103.

[95] Kalle Kuusk, Jarek Kurnitski, Targo Kalamees, Calculation and compliance procedures of thermal bridges in energy calculations in various European countries, In Energy Procedia, Volume 132, 2017, Pages 27-32.

[96] Land, V.D. et al., Processing of low-density silica gel by critical point drying or ambient pressure drying, Journal of Non-Crystalline Solids, 283 (2001) 11-17.

[97] Larbi, a. Ben, Statistical modelling of heat transfer for thermal bridges of buildings. Energy and Buildings 2005, 37(9), 945–951

[98] Liu, Y. et al., Exergy analysis for a freeze-drying process . Applied Thermal Engineering, 2008, 28(7): 675-690.

[99] Madsen, H. et al., Estimation of continuous-time models for the heat dynamics of a building. Energy Build 1995 3;22(1):67-79.

[100] Maleki H. et Al., A new trend for development of mechanically robust hybrid silica aerogels, Materials Letters 2016, 179: 206-209,

[101] Martin K., 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).

[102] Martin, K. et al, Equivalent wall method for dynamic characterisation of thermal bridges, Energy And Buildings 55 (2012)

[103] Martin, K. et al, Methodology for the calculation of response factors through experimental tests and validation with simulation. Energy and Buildings 2010, 42(4), 461–467.

[104] Martin, K. et al, Problems in the calculation of thermal bridges in dynamic conditions. Energy and Buildings 2011, 43(2-3), 529–535.

[105] Miles-Shenton D et al. LowCarb4Real: Developing Low Carbon Housing, Lessons from the Field, Leeds Metropolitan University; 2009.

[106] Modelica, https://www.modelica.org/ (2016/12/09)

[107] Naveros, I. et al., Setting up and validating a complex model for a simple homogeneous wall, Energy and Buildings, 2014, 70, 303–317

[108] Norlén U. Estimating thermal parameters of outdoor test cells. Build Environ 1990;25(1):17-24.

[109] O'Grady, M., Lechowska, A., Harte, A., Infrared thermography technique as an in-situ method of assessing heat loss through thermal bridging, In Energy and Buildings, Volume 135, 2017, Pages 20-32.

[110] Owen JL. Solar building—European Union Research and Development Programmes. Solar Energy 1996 0;58(1–3):127-135.

[111] Parvathy Rao, A. et Al., Effect of preparation conditions on the physical and hydrophobic properties of two step processed ambient pressure dried silica aerogels, Journal of Materials Science, 40 (2005) 3481-3489.

[112] Pérez-Lombard L., et al, A review on buildings energy consumption information, Energy and Buildings 40, 2008

[113] Phasor, Wikipedia, https://en.wikipedia.org/wiki/Phasor {2016/03/22}

[114] Prehorquisa, www.prehorquisa.com (2016/12/09)

[115] Rao, AP. et Al., Hydrophobic and Physical Properties of the Two Step Processed Ambient Pressure Dried Silica Aerogels with Various Exchanging Solvents, J Sol-Gel Scie Technol 2005, 36(3):285-292.

[116] Roels S., IEA EBC Annex 58, Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements

[117] Schild, P. et al., Good practice guidance on thermal bridges and construction details – Part 1: Principles. Information paper 188 (2010). http://www.buildup.eu/publications/8239

[118] Schild, P., Good practice guidance on thermal bridges and construction details - Part 2: Good examples. Information paper 189 (2010). http://www.buildup.eu/publications/8241

[119] Schmidt, M. et al., Applications for silica aerogel products, Journal of Non-Crystalline Solids, 225 (1998) 364-368.

[120] Siddall M., The impact of thermal bypass, Green Building Magazine 2009; Vol. 19 No. 1.

[121] Spitzner, M.H. et al., A. Dämmstoffe: Grundlagen, Materialien, Anwendungen, Walter De Gruyter, 2007.

[122] Stahl, T. et al., Thermo-hygric properties of a newly developed aerogel based insulation rendering for both exterior and interior applications. Energy and Buildings 2012, 44 (0), 114-117.

[123] Strachan, P. et al., IEA Annex 58: Full-scale Empirical Validation of Detailed Thermal Simulation Programs, Energy Procedia 78 (2015), 3288-3293, 6th International Building Physics Conference, IBPC 2015

[124] Strachan, P. et al., Case studies of outdoor testing and analysis of building components. Building and Environment, 2008, 43(2), 129-142.

[125] Strachan, P., et al, Case studies of outdoor testing and analysis of building components. Building and Environment, 2008, 43(2), 129-142.

[126] Tadeu, A., et al., Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. Energy and Buildings, 43(12), 3685–3695.

[127] Tecnalia, "KUBIK by Tecnalia, Experimental Infrastructure for the Configuration of Zero Energy Buildings", http://www.tecnalia.com/en/sustainable-construction/infrastructure-a-equipment/infrastructure-a-equipment.htm, 2012.

[128] Tecnalia, "Kubik by Tecnalia", http://www.energiaenedificacion.com/kubik-by-tecnalia/ (2014/07/07)

[129] Tecnalia, Estudio de investigación sobre eficiencia energética y viabilidad de la aplicación de fachadas ventiladas en soluciones de rehabilitación, Anexo 4: Caracterización dinámica de los elementos de frente de forjado, ERAIKAL-12.

[130] Theodosiou, T.G. et al., The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy Build. 40 (11) (2008) 2083–2089.

[131] THERM, Two-Dimensional Building Heat-Transfer Modeling, LBNL, https://windows.lbl.gov/software/therm/therm.html (2016/05/18)

[132] Tilmans, A., Software and Atlases for evaluating Thermal Bridges. Information paper 152. http://www.buildup.eu/node/5657 (2016/12/10)

[133] TRISCO, Computer Program to Calculate 3D & 2D Steady State Heat Transfer in Rectangular Objects, Version 12.0w, Physibel, 2010, http://www.physibel.be/v0n2tr.htm (2016/11/30)

[134] TRNSYS 16 Documentation, Volume 6, Multizone Building, http://web.mit.edu/parmstr/Public/Documentation/06-MultizoneBuilding.pdf (2016/02/23)

[135] U.S. Department of Energy (DOE), 2008 Buildings Energy Data Book, 2008.

[136] UK Department for Communities and Local Government, Accredited Construction Details (ACDs) for Part L. for England & Wales. 2007, http://www.planningportal.gov.uk/uploads/br/accredconbk.pdf (2016/12/09)

[137] UNE-EN ISO 10211:2012. Puentes térmicos en edificación. Flujos de calor y temperaturas superficiales. Cálculos detallados. (EN ISO 10211:2007. Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations)

[138] UNE-EN ISO 13788:2002. Características higrotérmicas de los elementos y componentes de edificación. Temperatura superficial interior para evitar la humedad superficial crítica y la condensación intersticial. Métodos de cálculo. (ISO 13788:2001)

[139] UNE-EN ISO 6946:2012. Componentes y elementos para la edificación. Resistencia térmica y transmitancia térmica. Método de cálculo. (EN ISO 6946: 2007, Building Components and Building Elements - Thermal Resistance And Thermal Transmittance - Calculation Method)

[140] United Nations Environment Programme, Sustainable Building and Climate Initiative, 2015

[141] van Dick, H.A.L., Development of the PASSYS Test Method, Research Report PASSYS Subgroup Test Methodologies, TNO Building and Construction Research. CEC DG XII Brussels, 1993. EUR 15114 EN.

[142] van Dick, H.A.L., et al., The PASSYS method for testing passive solar components. Build Environ 1993 4;28(2):115-126.

[143] Vandaele, L. et al., The PASSYS Services: Summary report. BBRI & European Commission – Directorate - General XII, EUR 15113 EN, Brussels, 1994.

[144] Van Nieuwenhove, S., Numerical analysis of thermal bridges under dynamic boundary conditions, Master`s dissertation, University of Ghent, 2014.

[145] Viot, H. et al., Comparison of different methods for calculating thermal bridges: Application to wood-frame buildings. Building and Environment 2015, 93, 339–348.

[146] VOLTRA, Computer Program to Calculate 3D & 2D Transient Heat Transfer inObjects Described in a Rectangular Grid Using the Energy Balance Technique,Version 6.3w, Physibel, 2009. http://www.physibel.be/v0n2vo.htm (2016/11/30)

[147] Wong, J. C. H. et al., Mechanical properties of monolithic silica aerogels made from polyethoxydisiloxanes. Microporous Mesoporous Mater. 2014, 183 (0), 23-29.

[148] Wouters P. et al., The use of outdoor test cells for thermal and solar building research within the PASSYS project. Build Environ 1993 4;28(2):107-113.

[149] Zalewski, L. et al., Experimental and numerical characterization of thermal bridges in prefabricated building walls. Energy Conversion and Management 2010, 51(12), 2869–2877.

Annex

A1 KUBIK $_{\text{by Tecnalia}}$ research facility

Energy efficiency achievements in 5 years through experimental research in KUBIK

Roberto Garay, José Antonio Chica, Inés Apraiz, José M. Campos, Borja Tellado, Amaia Uriarte, Víctor Sanchez

Fundación TECNALIA, Edificio 700 Parque Tecnológico de Bizkaia, Derio (Bizkaia) 48160, Spain

A1.1 Abstract

The European construction sector (a fragmented SMEs dominated business with high economic and environmental impact and high technological inertia) faces a major challenge to reduce the emissions by almost 90% in 2050. This requires new innovative solutions and services to be rapidly implemented in the market. Research Infrastructures that give support for later-stage developments (high Technology Readiness Levels) can play a relevant role in both the technological development and market introduction of construction products for energy efficient buildings. The following paper describes such an infrastructure (KUBIK$_{\text{by Tecnalia}}$) located in Bilbao (Spain) and its major outcomes in the period 2011-2015.

A1.2 Introduction

The document “A Roadmap for moving to a competitive low carbon economy in 2050” [1] published by the European Commission in 2011 sets up a European scenario to keep climate change below 2ºC by reducing the greenhouse gas (GHG) emissions by 80-95% by 2050. The Europe2020 flagship initiative for a resource-efficient Europe [2] details the reduction of GHG emissions in the period until 2020 per sectors. Buildings in Europe generate 36% of GHG and 40% of total energy consumption, and therefore are key enablers of the 2050 decarbonisation goal [3]. The European Commission brings the 2050 decarbonisation strategy into Directives, which in the construction sector are the Energy Performance Building Directive (EPBD) and its recast [4], and the Energy Efficiency Directive. The EPBD-recast Directive enforces new buildings in Europe to be nearly zero energy buildings (nZEB) from 2019 onwards. The Energy Efficiency Directive [5] targets the retrofitting of public buildings (owned or occupied by the central governments) from 1 January 2014 to a minimum of 3% per year. This new set of Directives requires the European Construction sector to strength the innovation capabilities and to increase the market uptake of new developments.

But the construction sector is highly conservative and low-innovative (business enterprise R&D expenditure are very low [6] when compared with other sectors) with a high potential impact in the European economy and environment [7]. Among the identified barriers for market up-take of energy efficient new buildings and existing buildings' retrofitting, the most relevant is the considerable upfront funding required [8]. This makes risk diminishing activities critical to facilitate market introduction of any innovative product in the construction sector.

Moreover, the construction sector is very fragmented, not only in terms of size of companies (over 95% are SMEs) but also in terms of diverse typology of stakeholders in the value chain. These factors increase the complexity of introducing innovation making necessary strong alignments.

A1.3 Nearly Zero Energy Buildings "nZEB" and energy renovation in Europe

New buildings in Europe will be required to be nearly zero energy buildings from 2019. Research at an international level on building energy efficiency allows concluding that to achieve nZEB is necessary the resolution of a trinomial expression made up of [9]:

- Improvements of buildings thermal performance, through architectural or constructive solutions basically improving the envelope performance
- Energy consumption reduction through rational use for air conditioning, illumination and ventilation of living spaces, supported by intelligent management systems (BEMSs)
- Increasing energy generation based on renewable energies at building level and its proximity (distributed generation and multi-generation management) handing over partial responsibility to the building for the generation of the energy needed to supply its activities

It is the combination of activities in these 3 areas what makes buildings be nearly zero energy buildings. Innovation is required in the 3 dimensions to accelerate nZEB market uptake.

Figure 1: External view of the Kubik by Tecnalia test facility

With regard to existing buildings, an increased renovation rate and depth of the renovation (measured as % of energy saving) is crucial for achieving the Europe-2020 and -2050 decarbonisation targets. Existing buildings are renovated every 30 to 40 years [10] on average, and every 60 to 80 years in the Mediterranean countries [11]. Renovation rate in Europe today is between 1% and 2% per year [8]. Predictive models indicate the need to increase the renovation rate to a minimum average of 3% per year thus increase the depth of renovation to allow achieving decarbonisation targets.

Innovation is required to (1) improve the performance of the building envelope, (2) improve the management of energy equipment, and (3) improve the user acceptance thus reducing misuses.

A1.4 KUBIK aims and experimental capabilities: Research infrastructures as leverage factor

$KUBIK_{by\ Tecnalia}$ (hereinafter referred to as KUBIK) is a full scale experimental infrastructure for R & D + I on energy efficiency, focused on the development of new products and systems that provide energy consumption reduction for the building whilst improve user comfort and health indoor environment.

KUBIK has the experimental capabilities that allow the validation of innovative products and systems in service conditions that may accelerate their introduction to the market. The main distinctive feature of KUBIK is its capacity to create realistic scenarios for the investigation of energy efficiency resulting from the interaction of constructive solutions, the intelligent management of HVAC and lighting systems and non-renewable and renewable combinations of energy supplies.

The infrastructure is a building enclosing a maximum of 500 m^2 distributed over a basement, a ground floor and a further two levels. The supply of energy is based on the combination of conventional and renewable energies. The infrastructure is configurable in (1) its envelope (façades, windows, roof, shading systems), (2) its internal partitioning (open layout, large spaces, small spaces), (3) its HVAC system (type of diffusing system, ventilation, HVAC plant…), and (4) in the building management system [12].

KUBIK supports developments at high TRLs in products and services to be launched into the market, accelerating the uptake of new innovative solutions through their co-development with the relevant stakeholders in the construction sector under realistic use conditions.

KUBIK is an open research infrastructure to be used by the industry, research centers, public administrations and standardization bodies. New solutions can be shown to the market (different stakeholders in the value chain).

A1.5 KUBIK capabilities at a glance: FIEMSER and ReFaVent projects

Following is the description of the activities developed in KUBIK in the frame of two research projects: FIEMSER and REFAVEN.

A1.5.1 FIEMSER

FIEMSER system, an innovative Building Energy Management System (BEMS), was validated in KUBIK. Current BEMSs have several weaknesses: predefined energy control strategies, lack of integration of the local energy generation with the building energy consumption, lighting system decoupled from the HVAC system, wired control networks, limited interoperability, etc. FIEMSER system defines dynamic and holistic control strategies that take into account the current and future building operating conditions (building users activities, weather conditions, energy prices, etc.) and integrates the different energy related subsystems: HVAC, lighting, local generation and energy storage. FIEMSER system leverages on the Service-Oriented Architecture (SOA) paradigm with the definition of modular service interfaces. This paradigm provides the necessary flexibility to: (1) adapt the system to the different configurations, (2) integrate existing control protocols and emerging wireless ones, and (3) support different GUI (Graphical User Interface).

FIEMSER System is an innovative Building Energy Management System (BEMS) for existing and new residential buildings, which pursues the increase of the efficiency of the energy used and the reduction of the global energy demand of the building, but without penalizing the comfort levels of the users. In order to achieve this goal, two main strategies are followed:

- Minimizing the energy demand from external resources, through the reduction of the energy consumption in the building and the correct management of local generation and energy storage equipment to satisfy the energy demand of the building, and even provide the capability to export energy to the utilities when needed.
- Interaction with the building user, in order to increase the consciousness of the consumer about his energy consumption, providing hints to make punctual changes in his behaviour without major disruptions of his comfort conditions.

The deployment of the FIEMSER system in KUBIK represented an apartment that has its own connection (and meter) to the electrical grid and takes hot/cold water for air conditioning from communal services. Also RES are managed as communal services.

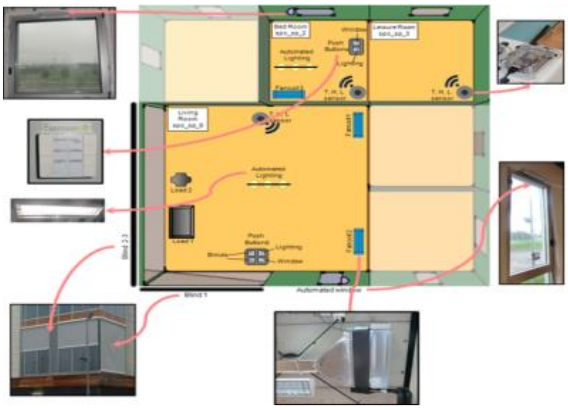


Figure 2: Building Automation equipment deployed in KUBIK for FIEMSER validation

The apartment was composed by six cells (testing minimal unit in KUBIK) in the 1st floor of the building was distributed configuring three rooms: living room (four cells), bedroom (1 cell) and leisure room (1 cell). These rooms were in the East, South and West facades.

Figure 2 shows the location of some components of the testing scenario, with photographs of the most relevant devices.

FIEMSER validation defined metrics, performance indicators and validations domains in order to have a proper picture of the overall FIEMSER project performance after the finishing the validation process.

- System wide validation domain: This validation domain covered verification of the appropriate operation of each of the installed systems (automated windows, blinds,..)
- Functionalities validation domain: The functionality validation domain covered the verification of the forecasts and operation schedules released by the FIEMSER.
- Energy validation domain: Top validation domain. Supported by the previous validation steps, covered the validation of FIEMSER in terms of energy savings and efficiency.

FIEMSER´s validation in KUBIK considered the reference model to be the simulation.

The achieved measured savings by implementing FIEMSER system were 26,5% for lighting, 8,7% for heating and 80,5% for cooling.

A1.5.2 REFAVEN

REFAVEN project investigated on the suitability of ventilated façades as external thermal insulation systems for the refurbishment of the building stock. Research was conducted on the modification of the heat transfer, not only through traditional brick façades, but also on the modification of the thermal field in thermal bridge areas such as those in façade-slab junctions.

For this purpose, a sub-sector of two test-rooms in a vertical arrangement was conditioned in KUBIK. A west-oriented test façade was constructed in these rooms, which comprised 3 façade-slab junction elements, constructed in equivalent materials and thicknesses to those present in the Spanish building stock.

Figure 3. Left: Building with brick façade, Center-left: Calibration façade test configuration in KUBIK (phase 0), Center-right: Brick façade test configuration in KUBIK (phase 1), Right: Ventilated façade solution in KUBIK (phase 2)

These elements were located at slab level coincident with 1st, 2nd and roof level slabs in KUBIK. A sequence of façades was tested:

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

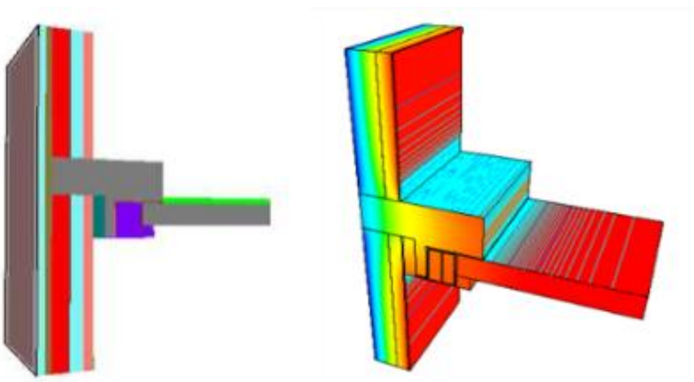


Figure 4: Finite difference models of the slab-façade junction at floor level 2

In all three phases, the effect of the building fabric within the thermal balance of the building was experimentally evaluated. Prior to experimentation, thermography and airtightness tests were performed to minimize uncertainties related to unexpected phenomena.

Heat flows (1- and 2-dimensional) were subjected to measurement and calibration. 1-D heat transfer was modeled through calibrated state-space models, and 2-D heat transfer through calibrated FDM. These models, jointly with a heat balance approach to the test set-up provided the backbone of the energy assessment needed for the REFAVEN project.

The outstanding conclusions of this study was that the selected ventilated façade reduced the overall heat flow across the façade by 50%, and that thermal bridges (which accounted for 20% of the overall energy flows) were minimized by 50%. Ventilated façades were also effective in reducing solar heat gains in summer period.

A1.6 KUBIK achievements in 5 years of operation

In the period 2011 to 2015, a total of 21 projects (7 on-going, 3 starting and 11 finished) have had KUBIK as research platform. The vast majority (18) of these projects is EU-funded, and only 3 of them were supported by the industry.

Most projects (16) involved the development of building components, 7 of them for retrofitting of buildings. In total 4 intelligent management systems (building-demand and on-site generation management) related project were implemented in KUBIK, whilst only 1 project tackled the management of distributed energy generation.

Table 1. Testing period in KUBIK

Period	Number of projects
1 to 1.5 years	9
6 months to 1 year	6
3 to 6 months	2
Less than 3 months	4

Two patents have been obtained in the frame of KUBIK activities: (1) Passive Solar Collector Module for Building Envelopes (09812437.3, EP 2520 870 A1), (2) Photovoltaic Module for Curtain Walls (PCT/ES2011/070902, WO/2012/089883 A2). In addition, one utility model has been developed: Prefabricated Façade (Utility Model application: U200930530, ES 1 071 274 U).

Regarding visitors to the infrastructure, a total of 1.138 people have visited KUBIK in the period 2011-2015, spread as follows:

Table 2. Number of visitors in Kubik

Period	Number of visitors
2011	109
2012	325
2013	321
2014	383
TOTAL	1.138

Table 3. Visitors per type

Type of visitor	%
Educational Centers	17.3
Research Centers	10.3
Industries	37.2
Consulting	7.1
Public administration	13.5
Architects	3.2
Platforms, clusters, associations, etc.	11.5

The typologies of industries visiting KUBIK are as follows:

Table 4. Type of visiting industries

Type of industry	%
Construction	39.3
Electr./Telecom.	4.9
Equipment	13.1
Renewables	4.9
Labs	3.3
Real Estate	4.9
Others	29.5

Table 5. Visitors per country of origin

Country	%
USA	1.3
Asia & middle east	3.3
Latin-America	11.2
Europe	84.2

The technical activity associated with deployments in KUBIK in the period 2011-2015 totalized 1.029.467€, equivalent to 3,3 Persons/Year.

A1.7 Conclusions

KUBIK provides the needed support to improve the energy performance at building level, as requested by the Energy Performance Building Directive (EPBD), and in a comprehensive way, the envelope, the demand and energy generation. KUBIK allows developing and validating innovative products and systems to optimize energy efficiency in buildings, from its conceptualization to its implementation.

The potential of KUBIK is to mobilize the stakeholders towards a more innovative and added-value business in the field of energy efficiency in buildings and urban areas. As the European Commission is forcing new buildings to reduce the energy consumption thus increase the share of energy generation from renewable sources, this is promoting new business models which are a starting basis for new companies (start-up) as well as for bringing innovation to the activity of existing ones towards what will be the future of the construction sector.

A1.8 Acknowledgements

KUBIK has been co-financed by the Spanish Ministry of Education and Science, the Spanish Ministry of Science and Innovation within the National Plan for Scientific Research, Technological Development and Innovation 2008-2011 Research (PID-5300000-2009-6) and the European Regional Development Fund (ERDF).

FIEMSER project has been funded by the European Union under the seventh Framework Program.

REFAVEN project has been partially funded by the Basque Government through the ERAIKAL Program.

A1.9 References

[1] COM(2011)112.http://eur-lex.europa.eu/resource.html?uri=cellar:5db26ecc-ba4e-4de2-ae08-dba649109d18.0002.03/DOC_1&format=PDF.

[2] COM (2011) 21. http://ec.europa.eu/recource-efficient-europe.

[3] Energy-efficient buildings: Multi-annual roadmap for the contractual PPP under Horizon 2020.
http://www.ectp.org/cws/params/ectp/download_files/36D2981v1_Eeb_cPPP_Roadmap_under.pdf

[4] Directive 2010/31/EU of the European Parliament and the Council of 19 May 2010. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF.

[5] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:EN:PDF

[6] EUROSTAT. Business enterprise R&D expenditure (BERD) by economic activity. 2005-2013

[7] Energy –efficient buildings. Multi-annual roadmap for the contractual PPP under Horizon2020. European Commission. 2013. ISBN: 978-92-79-31239-7

[8] Economidou et al. Europe´s building under the microscope. A country-by-country review of the energy performance of buildings. BPIE. 2011. ISBN: 9789491143014

[9] Atanasiu et al. Principles for nearly zero-energy buildings. Paving the way for effective implementation of policy requirements. BPIE. 2011. ISBN: 9789491143021

[10] Consultation Paper – Financial support for Energy efficiency in buildings. European Commission, Directorate-General for Energy. Brussels, February 2012.

[11] Integrated Regional Benchmark Analysis. Work in Progress within the MARIE project. IREC 2012. Final report. http://www.marie-medstrategic.eu

[12] Chica, JA et al, KUBIK: Open building approach for the construction of an unique experimental facility aimed to improve energy efficiency in buildings. Proceedings of the O&SB2010 "Open and Sustainable Building", ISBN: 978-84-88734-06-8

A2 Scientific publications included in this thesis

A2.1 Bibliographic reference

Section 4: Garay, R.; Experimental assessment of thermal performance of building envelope retrofitting works; EESAP7: 7º Congreso Europeo sobre Eficiencia Energética y Sostenibilidad en Arquitectura y Urbanismo, 7th European Conference On Energy Efficiency And Sustainability In Architecture And Planning; Universidad del País Vasco/Euskal Herriko Unibertsitatea (2016); ISBN: 978-84-9082-434-4

Section 5: Garay, R.; Riverola, A.; Chemisana, D.; Disaggregation process for dynamic multidimensional heat flux in building simulation; Energy and Buildings, Volume 147, August 2017, Pages 298-310, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2017.05.029.

Section 6: Arregi Goikolea, B.; Garay Martinez, R.; Riverola Lacasta, A.; Chemisana Villegas, D.; Estudio de transferencia de calor en los puntos de anclaje a forjado de una subestructura de fachada ventilada; III Congreso de Edificios de Consumo de Energía Casi Nulo (EECN); Grupo Tecma Red (2016)

Section 7: Roberto Garay Martinez, Eunate Goiti, Gudrun Reichenauer, Shanyu Zhao, Matthias Koebel, Aitor Barrio, Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale, Energy and Buildings, Volume 128, 15 September 2016, Pages 111-118, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2016.06.071.

Section 8: Roberto Garay, Amaia Uriarte, Inés Apraiz, Performance assessment of thermal bridge elements into a full scale experimental study of a building façade, Energy and Buildings, Volume 85, December 2014, Pages 579-591, ISSN 0378-7788, http://dx.doi.org/10.1016/j.enbuild.2014.09.024.

Section 9: Roberto Garay, Beñat Arregi, Peru Elguezabal, Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting, SBE16 Thessaloniki “Sustainable Synergies from Buildings to the Urban Scale”, Aristotle University of Thessaloniki, (2016)

Procedia Environmental Sciences, volume 38, 2017, Pages 155-161, ISSN: 1878-0296, https://doi.org/10.1016/J.PROENV.2017.03.097.

Annex 1: Roberto Garay, José Antonio Chica, Inés Apraiz, José M. Campos, Borja Tellado, Amaia Uriarte, Víctor Sanchez, Energy Efficiency Achievements in 5 Years Through Experimental Research in KUBIK, Energy Procedia, Volume 78, 2015, Pages 865-870, ISSN 1876-6102, http://dx.doi.org/10.1016/j.egypro.2015.11.009.

A2.2 Status and Journal metrics

Table 1: Status and journal metrics of scientific papers comprised in this thesis.

Chapter	Journal Conference	Status	Date	Jorunal metrics
4	EESAP 7	Presented / Published	July 2016	n/a
5	Energy and Buildings	Published	August 2017	Impact factor (2015): 2.973 5-Year Impact Factor (2015): 3.666 <u>Journal Citation Report (2015)</u> Q1 (6/60) in “Construction & Building Technology” Q1 (6/126) in “Engineering, Civil” Q2 (31/88) in “Energy & Fuels” <u>Scimago Journal Rank (2015)</u> SJR 2.073 Q1 in “Building and Construction” Q1 in “Civil and Structural Engineering” Q1 in “Electrical and Electronic Engineering” Q1 in “Mechanical Engineering”
6	EECN III	Published	June 2016	n/a
7	Energy and Buildings	Published	September 2016	Impact factor (2015): 2.973 5-Year Impact Factor (2015): 3.666 <u>Journal Citation Report (2015)</u> Q1 (6/60) in “Construction & Building Technology” Q1 (6/126) in “Engineering, Civil” Q2 (31/88) in “Energy & Fuels” <u>Scimago Journal Rank (2015)</u> SJR 2.073 Q1 in “Building and Construction” Q1 in “Civil and Structural Engineering” Q1 in “Electrical and Electronic Engineering” Q1 in “Mechanical Engineering”
8	Energy and Buildings	Published	December 2014	Impact factor (2015): 2.973 5-Year Impact Factor (2015): 3.666 <u>Journal Citation Report (2015)</u> Q1 (6/60) in “Construction & Building Technology” Q1 (6/126) in “Engineering, Civil” Q2 (31/88) in “Energy & Fuels” <u>Scimago Journal Rank (2015)</u> SJR 2.073 Q1 in “Building and Construction”

				Q1 in “Civil and Structural Engineering” Q1 in “Electrical and Electronic Engineering” Q1 in “Mechanical Engineering”
9	SBE16 Thessaloniki Procedia Environmental Sciences	Presented / Published	October 2016	SBE16: n/a Procedia Environmental Sciences: Scimago Journal Rank (2014), SJR 0.220
A1	IBPC 2015 Energy Procedia	Presented / Published	May 2015	IBPC 2015: n/a Energy Procedia: Scimago Journal Rank (2014), SJR 2.073

A2.3 Published versions

Below, the captions of the first page of the published versions are shown.

COMUNICACIÓN COMPLETA / FULL PAPER

7º Congreso Europeo
sobre Eficiencia Energética y Sostenibilidad
en Arquitectura y Urbanismo

Universidad del País Vasco/Euskal Herriko Unibertsitatea
Donostia-San Sebastian, Spain
4-6 julio 2016
www.eesap.eu

Please complete this template and email as an attachment to papers@eesap.eu

Experimental assessment of thermal performance of building envelope retrofitting works

Caracterización experimental del comportamiento térmico-energético de actuaciones de rehabilitación de envolventes por el exterior

Roberto Garay[1]

[1] *Tecnalia, División Construcción Sostenible / Sustainable Construction Division*
Parque Tecnológico de Bizkaia, C/Geldo s/n, Edificio 700, E-48160 Derio Bizkaia Spain
+34 667 178 958 Roberto.garay@tecnalia.com

Key Words:
Building envelope, Thermal insulation, Experimentation, Retrofitting
Envolventes Arquitectónicas, Aislamiento térmico, Experimentación, Rehabilitación

Abstract Resumen

Esta comunicación presenta el desarrollo de una meodología para la evaluación de la mejora en las prestaciones térmicas de las envolventes edificatorias tras la realización de actuaciones de rehabilitación. Particularmente, se focaliza en el comportamiento térmico de los elementos multidimensionales tales como el encuentro entre los forjados y las fachadas. Estos lugares presentan una transmisión de calor multidimensional que dificulta la evaluación experimental de la transferencia de calor. En este trabajo se propone una metodología según la cual se desarrolla un modelo térmico numérico del encuentro correspondiente, que se calibra mediante mediciones puntuales previas a la rehabilitación, y que se emplea con posterioridad para la evaluación de las distintas actuaciones de rehabilitación posibles.

1. Introduction Introducción

Building envelopes are the main heat transfer path from buildings to its environment. Building envelopes – roofs, façades, and glazed areas- are responsible for over 60% of heat losses in conventional buildings. It is considered that there is a great heat flux reduction potential by incorporating additional insulation to building envelopes.

eman ta zabal zazu
Universidad del País Vasco Euskal Herriko Unibertsitatea
CAMPUS OF INTERNATIONAL EXCELLENCE

UPV/EHU caviar
calidad de vida en arquitectura
quality of life in architecture

Figure 1: Experimental assessment of thermal performance of building envelope retrofitting works. Chapter 4.

Energy and Buildings 148 (2017) 298–310

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Disaggregation process for dynamic multidimensional heat flux in building simulation

Roberto Garay Martinez [a,*], Alberto Riverola [b], Daniel Chemisana [b]

[a] *Sustainable Construction Division, TECNALIA Research & Innovation, Parque Tecnológico de Bizkaia, C/Geldo s/n, Edificio 700, E-48160 Derio, Bizkaia, Spain*
[b] *Sección de Física Aplicada, Universidad de Lleida, Escuela Politécnica Superior, Jaume II, 69, E-25001 Lleida, Spain*

ARTICLE INFO

Article history:
Received 18 October 2016
Received in revised form 9 May 2017
Accepted 12 May 2017
Available online 17 May 2017

ABSTRACT

Heat transfer across envelopes (façade, roof, glazed areas) represents a big share of the energy flow within the heat balance of buildings. This paper focuses on areas of the envelope where multi-dimensional heat transfer occurs. These areas are commonly defined as thermal bridges, due to a localized reduction of thermal resistance of constructions in these places. This paper reviews common standardized methods to assess heat transfer in buildings, under various modelling assumptions: one-dimensional, multi-dimensional, steady state and dynamic. Within presently developed modelling and assessment methods, a need for improvement has been identified over existing methods for the thermal assessment of multi-dimensional heat transfer under dynamic conditions. A phasorial approach to differential heat transfer in thermal bridges has been developed, which serves as the dynamic extension of steady-state thermal bridge coefficients. This formulation is applied to the junction of a masonry wall with a concrete slab.

1. Introduction

Up to 40% of primary energy consumption in developed countries is related to buildings [1–4], where a large share is used for space heating and cooling, to meet occupants' comfort requirements. The scientific community has conducted Intensive studies and developed techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings over more than 50 years. At present times, various test and calculation methods are available, which focus on different scales and approaches for the assessment of thermal performance of buildings, from standardized material testing procedures to dynamic simulation software tools [5].

Heat transfer across building envelopes has a significant influence on the heat balance of buildings. Building envelopes are the physical interface between indoor and outdoor conditions, and their response to variations on these conditions, such as temperature oscillations and incidence of solar radiation, substantially defines the heat dynamics of buildings. For this reason, building codes impose many requirements on the steady state performance metrics of envelopes, such as maximum allowances on the thermal transmittance of envelopes, window ratio, overall heat loss coefficient, etc.

The dynamic performance of buildings is commonly assessed by means of simulation. In this field, Building Energy Simulation (BES) tools have been developed over the last decades with increasing accuracy. Software tools such as Energy Plus [6] and TRNSYS [7] have evolved to such a level of complexity that their accuracy is commonly related to modelling assumptions and input data introduced by users of these tools, rather than by the tools themselves. Strachan et al. [8] performed a comparative analysis of simulation outputs from several researchers on very detailed validation experimental campaigns.

However, some fields still remain where building simulation tools have not been fully developed or their use has not been fully introduced to the building simulation community. Simulation tools are in constant evolution to meet simulation needs imposed by new construction techniques, dynamic systems and highly insulated houses such as Nearly Zero Energy Buildings (NZEB).

NZEBs are characterized by a substantial improvement in envelope insulation levels compared with state of the art construction methods, along with reductions on heat losses related to ventilation & air infiltration and the introduction of renewable energy systems. Within such environments, thermal bridges are no longer a minimal part of the heat balance of a building, but may play a significant role in it. In [9] a numerical and experimental study was carried out

* Corresponding author.
E-mail address: Roberto.garay@tecnalia.com (R.G. Martinez).

http://dx.doi.org/10.1016/j.enbuild.2017.05.029
0378-7788/© 2017 Elsevier B.V. All rights reserved.

Figure 2: Disaggregation process for dynamic multidimensional heat flux in building simulation, Chapter 5.

ESTUDIO DE TRANSFERENCIA DE CALOR EN LOS PUNTOS DE ANCLAJE A FORJADO DE UNA SUBESTRUCTURA DE FACHADA VENTILADA

Beñat Arregi Goikolea, División de Construcción Sostenible, Tecnalia
Roberto Garay Martinez, División de Construcción Sostenible, Tecnalia
Alberto Riverola Lacasta, Sección de Física Aplicada, Universidad de Lleida
Daniel Chemisana Villegas, Sección de Física Aplicada, Universidad de Lleida

Resumen: Las fachadas ventiladas son una solución cada vez más utilizada debido a sus buenas prestaciones de durabilidad y eficiencia energética. En estas envolventes, la subestructura que soporta el acabado exterior interrumpe necesariamente la continuidad del aislamiento en los puntos de anclaje sobre la hoja interior. Este estudio analiza el impacto de estos puentes térmicos en la transferencia de calor y el riesgo de condensaciones superficiales, para una fachada ventilada que se instala sobre un edificio existente. El cálculo unidimensional simplificado se compara con simulaciones numéricas mediante elementos finitos, modelando el flujo de calor bidimensional en los frentes de forjado y el flujo de calor tridimensional en los puntos de anclaje a forjado de la subestructura.

Palabras clave: Fachada Ventilada, Anclaje a Forjado, Transferencia de Calor, Puente Térmico, Elementos Finitos, Transmitancia Térmica Lineal, Transmitancia Térmica Puntual, Factor de Temperatura

INTRODUCCIÓN

La diferencia entre rendimiento energético teórico y real constituye uno de los principales escollos en el camino hacia los edificios de consumo de energía casi nulo. Las fachadas ventiladas ofrecen una solución ventajosa frente a potenciales complicaciones como el sobrecalentamiento o las humedades, pero presentan un punto débil en los anclajes de la subestructura sobre la hoja interior, que al interrumpir necesariamente el aislamiento, constituyen puentes térmicos.

El procedimiento de cálculo simplificado en el Código Técnico de la Edificación (CTE) no contempla el impacto de estos anclajes. En este estudio se analiza la transferencia de calor y el riesgo de condensaciones superficiales en los anclajes de una fachada ventilada que se fijan sobre el frente de forjado de un muro existente.

CASO DE ESTUDIO

Se analiza la aplicación de una fachada ventilada sobre un edificio existente.

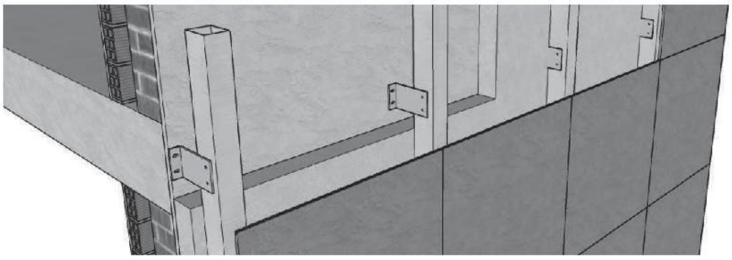


Figura 1. La subestructura de la fachada ventilada se fija a los frentes de forjado mediante anclajes de aluminio

Para el muro original se plantea una construcción genérica de dos hojas de fábrica de ladrillo con cámara de aire intermedia, sin aislamiento térmico, revocado con cemento en su cara exterior y con un enlucido

Figure 3: Estudio de transferencia de calor en los puntos de anclaje a forjado de una subestructura de fachada ventilada. Chapter 6.

Energy and Buildings 128 (2016) 111–118

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale

Roberto Garay Martinez [a,*], Eunate Goiti [a], Gudrun Reichenauer [b], Shanyu Zhao [c], Matthias Koebel [c], Aitor Barrio [a]

[a] Sustainable Construction Division, TECNALIA Research & Innovation, Parque Tecnológico de Bizkaia, C/Geldo s/n, Edificio 700, E-48160 Derio Bizkaia, Spain
[b] Bavarian Center for Applied Energy Research (ZAE Bayern), Magdalene-Schoch-Str. 3, 97074 Wuerzburg, Germany
[c] Building Energy Materials and components, Empa – Swiss Federal Laboratories for Materials Science and Technology, 8600 Dübendorf, Switzerland

ARTICLE INFO

Article history:
Received 16 November 2015
Received in revised form 17 June 2016
Accepted 23 June 2016
Available online 25 June 2016

Keywords:
Insulation
Aerogel
Superinsulation
Experimentation
Fullscale
Bulding envelope
In-situ

ABSTRACT

In the context of increasing energy costs and the need for global reduction of CO_2 emissions, the development of superinsulation materials for the construction sector allows the design of low-energy buildings. Since still being in an experimental or at early-commercial stage, R&D of these materials focused on its final application is required, to accelerate access to the market for renovation of the building stock where space is a critical metric.

In this paper, the experimental assessment of the thermal performance of a novel ambient pressure dried silica aerogel based composite is presented. In order to provide assessments at both, material and system levels, stress-strain tests, hot plate measurements, as well as full scale tests under realistic boundary conditions were conducted.

The overall results are that this material provides good insulation properties (thermal conductivity in the range of 0.015–0.018 W/mK), along with sufficient mechanical properties, and allows for the creation of superinsulating assemblies even at small wall thickness.

1. Introduction

The development of cost-effective high thermal insulation performance products and systems can contribute to improve the energy efficiency of buildings and thus reducing CO_2 emissions. The majority of energy in a building is spent to satisfy heating and cooling demands accounting for 70% of the total final energy use. The energy performance of an average European building is rather poor, due to the fact that a high percentage of the European residential buildings were constructed before the 1960s, when energy building regulations were very limited, and have not undergone renovations to improve energy performance, meaning that these buildings have low insulation levels and their systems are old and inefficient [1].

One key method to improve the energy efficiency of buildings is to enhance the thermal resistance of the envelope. This can be achieved by: *a)* increasing the thickness of traditional insulation materials, something that is not always possible, as often, there are space limitations; *b)* decreasing the thermal losses at given insulation thickness by using materials with significantly lower thermal conductivity, for example superinsulating materials such as aerogels. The use of Aerogel as an insulation material has been proven effective in several demonstration and retrofitting projects such as [2], the technical and economical optimization of façade insulation with Aerogel was studied in [3]. In [4] the design of an aerogel-filled sandwich panel was studied for building envelope integration.

Aerogels are open-porous, lightweight solids with densities ranging 3–350 mg/cm^3 [5] consisting of an interconnected particle network structure with interstitial pores with a pore size typically «1 μm [6,7]. Such nanoporous structures make aerogels the materials with the lowest thermal conductivity at ambient conditions known in a solid (λ <0.012 Wm^{-1} K^{-1}) [8,9].

Aerogels can be synthesized via a sol-gel process during which solid nanoparticles grow, crosslink and finally form a three-dimensional solid network with solvent filled pores. Since the silica aerogels comprise highly open structures in which the secondary particles of silica are connected to each other with only few siloxane bonds, the structure of native aerogels is too fragile to be handled. Aging processes are applied to strengthen the solid skeleton of silica [10].

* Corresponding author.
E-mail address: Roberto.garay@tecnalia.com (R. Garay Martinez).

http://dx.doi.org/10.1016/j.enbuild.2016.06.071

Figure 4: Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. Chapter 7.

Energy and Buildings 85 (2014) 579–591

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Performance assessment of thermal bridge elements into a full scale experimental study of a building façade

Roberto Garay*, Amaia Uriarte, Inés Apraiz

Tecnalia, Sustainable Construction Division Parque Tecnológico de Bizkaia, C/Geldo, Edificio 700, 48160 Derio, Spain

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form
11 September 2014
Accepted 13 September 2014
Available online 22 September 2014

Keywords:
Thermal bridge
Cold bridge
2-Dimensional heat transfer
Slab-façade junction
Full scale experiment
Dynamic model
Calibration
Thermal inertia

ABSTRACT

In this paper, an experimental and numerical approach to the characterization of thermal bridges is presented. The need for this characterization was found within an experimental study in a 2 floor high façade. This façade was constructed with 3 concrete elements which were placed in it to produce a similar thermal bridge effect to the one created by floor slabs traditional building construction in Spain.

Commonly applied thermal assessments perform one-dimensional heat transfer analysis over planar elements such as the façades studied in this experiment. However, it is well known that thermal bridges are locations in buildings where one-dimensional heat transfer analysis cannot be applied.

This problem was approached by creating a numerical 2D thermal model which was calibrated against experimental data from several temperature and heat flux sensors which were located at specific points in the thermal bridge elements.

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 is required for space heating and cooling, to meet occupants comfort requirements. Intensive studies and development of techniques for the assessment of heating, cooling and air conditioning energy consumption of buildings have been conducted during more than 50 years. Testing and calculation methods have been developed, ranging from standardized material testing procedures to dynamic simulation software tools [5].

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.

In the last half of the past century, building energy codes have forced a trend toward more insulated building envelopes. This trend has been boosted by EU Energy Performance of Buildings Directives (EPBD) [3,4], adopted by all EU member states. In this context, the relative relevance of thermal bridges has grown.

Furthermore, in developed countries in Europe, the aging building stock is involved into a thermal performance upgrade under the previously mentioned EPBD policies. Building envelope upgrade processes are being conducted with systems such as External Thermal Insulation Systems (ETHICS). These systems potentially allow for a nearly complete avoidance of certain thermal bridges, but their practical implementation leads to performance uncertainties.

A detailed analysis on the relevance of thermal bridges and how building codes deal with them in EU Member States was performed in [6]. The relevance of thermal bridges in the energy assessment of buildings was estimated in up to 30% of heating energy demand. This being more relevant within highly insulated buildings. It was identified that although all building codes considered thermal bridges, these were commonly assessed through conservative default values. When dealing with renovation projects for already built buildings, the energy requirements for junctions are reduced or even not-imposed. The use of improved junctions compared to national default values was evaluated at 15%.

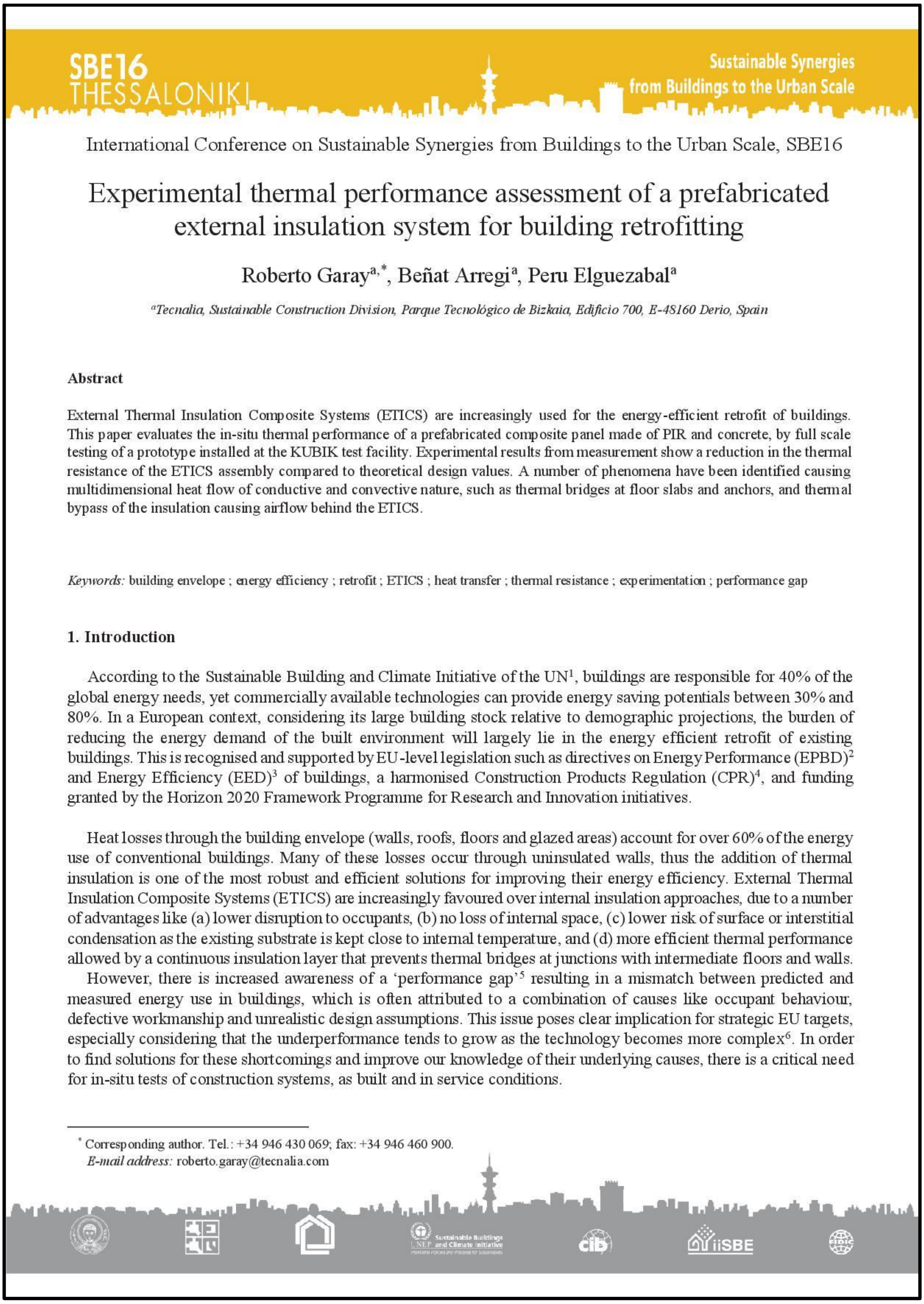
In this context, an experiment was carried out in order to assess the thermal performance improvement of one of such façade refurbishment methods.

This experiment was conducted in the KUBIK$_{\text{by Tecnalia}}$ research facility [7,8]. This is a research infrastructure located in Derio, Spain, focused on full scale testing of energy efficiency within the building sector. Its main goal being to bridge the gap between laboratory

* Corresponding author. Tel.: +34 667178958.
E-mail address: Roberto.Garay@tecnalia.com (R. Garay).

http://dx.doi.org/10.1016/j.enbuild.2014.09.024
0378-7788/© 2014 Elsevier B.V. All rights reserved.

Figure 5: Performance assessment of thermal bridge elements into a full scale experimental study of a building façade. Chapter 8.



International Conference on Sustainable Synergies from Buildings to the Urban Scale, SBE16

Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting

Roberto Garay[a,*], Beñat Arregi[a], Peru Elguezabal[a]

[a]*Tecnalia, Sustainable Construction Division, Parque Tecnológico de Bizkaia, Edificio 700, E-48160 Derio, Spain*

Abstract

External Thermal Insulation Composite Systems (ETICS) are increasingly used for the energy-efficient retrofit of buildings. This paper evaluates the in-situ thermal performance of a prefabricated composite panel made of PIR and concrete, by full scale testing of a prototype installed at the KUBIK test facility. Experimental results from measurement show a reduction in the thermal resistance of the ETICS assembly compared to theoretical design values. A number of phenomena have been identified causing multidimensional heat flow of conductive and convective nature, such as thermal bridges at floor slabs and anchors, and thermal bypass of the insulation causing airflow behind the ETICS.

Keywords: building envelope ; energy efficiency ; retrofit ; ETICS ; heat transfer ; thermal resistance ; experimentation ; performance gap

1. Introduction

According to the Sustainable Building and Climate Initiative of the UN[1], buildings are responsible for 40% of the global energy needs, yet commercially available technologies can provide energy saving potentials between 30% and 80%. In a European context, considering its large building stock relative to demographic projections, the burden of reducing the energy demand of the built environment will largely lie in the energy efficient retrofit of existing buildings. This is recognised and supported by EU-level legislation such as directives on Energy Performance (EPBD)[2] and Energy Efficiency (EED)[3] of buildings, a harmonised Construction Products Regulation (CPR)[4], and funding granted by the Horizon 2020 Framework Programme for Research and Innovation initiatives.

Heat losses through the building envelope (walls, roofs, floors and glazed areas) account for over 60% of the energy use of conventional buildings. Many of these losses occur through uninsulated walls, thus the addition of thermal insulation is one of the most robust and efficient solutions for improving their energy efficiency. External Thermal Insulation Composite Systems (ETICS) are increasingly favoured over internal insulation approaches, due to a number of advantages like (a) lower disruption to occupants, (b) no loss of internal space, (c) lower risk of surface or interstitial condensation as the existing substrate is kept close to internal temperature, and (d) more efficient thermal performance allowed by a continuous insulation layer that prevents thermal bridges at junctions with intermediate floors and walls.

However, there is increased awareness of a 'performance gap'[5] resulting in a mismatch between predicted and measured energy use in buildings, which is often attributed to a combination of causes like occupant behaviour, defective workmanship and unrealistic design assumptions. This issue poses clear implication for strategic EU targets, especially considering that the underperformance tends to grow as the technology becomes more complex[6]. In order to find solutions for these shortcomings and improve our knowledge of their underlying causes, there is a critical need for in-situ tests of construction systems, as built and in service conditions.

* Corresponding author. Tel.: +34 946 430 069; fax: +34 946 460 900.
E-mail address: roberto.garay@tecnalia.com

Figure 6: Experimental thermal performance assessment of a prefabricated external insulation system for building retrofitting. Chapter 9.

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2015) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

6th International Building Physics Conference, IBPC 2015

Energy efficiency achievements in 5 years through experimental research in KUBIK

Roberto Garay*, José Antonio Chica, Inés Apraiz, José M. Campos, Borja Tellado, Amaia Uriarte, Víctor Sanchez

Fundación TECNALIA, Edificio 700 Parque Tecnológico de Bizkaia, Derio (Bizkaia) 48160, Spain

Abstract

The European construction sector (a fragmented SMEs dominated business with high economic and environmental impact and high technological inertia) faces a major challenge to reduce the emissions by almost 90% in 2050. This requires new innovative solutions and services to be rapidly implemented in the market. Research Infrastructures that give support for later-stage developments (high Technology Readiness Levels) can play a relevant role in both the technological development and market introduction of construction products for energy efficient buildings. The following paper describes such an infrastructure ($KUBIK_{by\ Tecnalia}$) located in Bilbao (Spain) and its major outcomes in the period 2011-2015.

Keywords: Energy efficiency; R&D infrastructure

1. Introduction

The document “A Roadmap for moving to a competitive low carbon economy in 2050” [1] published by the European Commission in 2011 sets up a European scenario to keep climate change below 2°C by reducing the greenhouse gas (GHG) emissions by 80-95% by 2050. The Europe2020 flagship initiative for a resource-efficient Europe [2] details the reduction of GHG emissions in the period until 2020 per sectors. Buildings in Europe generate 36% of GHG and 40% of total energy consumption, and therefore are key enablers of the 2050 decarbonisation goal [3]. The European Commission brings the 2050 decarbonisation strategy into Directives, which in the construction

* Corresponding author. Tel.: +34-946-430-850.
E-mail address: roberto.garay@tecnalia.com

Figure 7: Energy efficiency achievements in 5 years through experimental research in KUBIK. Annex 1.