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THERMAL BRIDGE CHARACTERIZATION IN CROSS-LAMINATED TIMBER AND CONCRETE HYBRID CONSTRUCTIONS THROUGH 2D ANALYSIS: AN ANALYSIS PROPOSAL

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Thermal behaviour in a building depends not only on the main elements, such as the walls, slabs or floors, but also on how these elements connect geometrically and on the composition of the materials. In building envelopes existing zones where heat transfer cannot be considered to be one-dimensional. This phenomenon is called a thermal bridge (TB). In recent years, multiple hybrid constructions with wood–concrete or wood–steel composites have been developed, achieving innovative and efficient results; however, the existing literature does not yet include studies on the effect of TBs and the types of structural connections between building's elements in the heat transfer of hybrid structures. As such, the present work proposes an analysis that allows the characterisation of TBs in the structural connections of wall-CLT with slab-CLT and wall-concrete with slab-CLT, considering at the same time the effect of the main types of structural steel connectors. The analysis involves determining the linear thermal transmittance in steady-state temperature conditions using two-dimensional (2D) physical modelling based on International Organization for Standardization (ISO) standard 10211. With this approach, design decisions can be made that will consider the reduction of heat transfer in joints where connections have a higher heat transfer.

Keywords: timber; CLT; hybrid; thermal bridge; connector; building

CARACTERIZACIÓN DE PUENTES TÉRMICOS EN CONSTRUCCIONES HÍBRIDAS DE MADERA CONTRALAMINADA Y HORMIGÓN MEDIANTE ANÁLISIS 2D: UNA PROPUESTA DE ANÁLISIS

El comportamiento térmico en un edificio depende no solo de los elementos principales —paredes, losas o suelos—, sino también de cómo estos se conectan geométricamente y de la composición de sus materiales. En las envolventes de los edificios existen zonas donde la transferencia de calor no puede considerarse unidimensional. A este fenómeno se le denomina puente térmico (TB). Últimamente se han desarrollado múltiples construcciones híbridas compuestos por madera-hormigón o madera-acero, consiguiendo resultados innovadores y eficientes; sin embargo, la literatura existente aún no incluye estudios sobre el efecto de TB en la transferencia de calor por tipos de conexiones estructurales de estructuras híbridas. Así, el presente trabajo propone un análisis que permite la caracterización de TBs en las conexiones estructurales de muro-CLT con losa-CLT y muro-hormigón con losa-CLT, considerando al mismo tiempo el efecto de los principales tipos de conectores metálicos. El análisis involucra la determinación de la transmitancia térmica lineal en estado estacionario utilizando modelos físicos bidimensionales (2D) basados en la estándar 10211 de la Organización Internacional de Normalización (ISO). Con este enfoque, se pueden tomar decisiones de diseño que considerarán la disminución de transferencia de calor en uniones donde las conexiones tengan una mayor transmisión de calor.

Palabras clave: madera; CLT; híbrido; puente térmico; conector; edificio

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1. Introduction

Cross-laminated timber (CLT) has gained attention in recent years for a number of reasons, some of which are its technical capabilities and environmental properties, which allow the use of timber in a wider range of applications than was previously possible. CLT can be used as a structural panel on roofs, walls and floors. Its other main advantages are its high dimensional stability, high strength, high stiffness and ease of manufacturing (Abed et al., 2022). An evaluation of the structure of tall mass timber buildings showed that 55% feature hybrid constructions, distributed as follows: 35% concrete–timber, 12% concrete–steel–timber and 8% steel–timber (Council on Tall Buildings and Urban Habitat, 2022). As such, the preceding study showed that construction is not limited to the use of a single material; rather, a combination of materials and techniques is necessary to achieve better performance.

The most recent projections indicate that, by 2060, the energy demand in the building sector worldwide will increase by 30% if efforts are not made to develop energy-efficient solutions for building and construction (Dean et al., 2016). This demonstrates the need to continue improving the building standards related to energy efficiency as new construction technologies are adopted. The energy consumption of a building is strongly dependent on the characteristics of its envelopes (Schiavoni et al., 2016), including its external walls, floors, ceilings, roof coverings, windows and doors, as these determine the amount of energy needed for heating and cooling (Aslani et al., 2019). However, the repetitive structural elements and the connections between these different building components make possible the occurrence of thermal bridges TBs (Capozzoli et al., 2013). A TB is defined as a zone of the building envelope in which it is impossible to consider the heat transfer to be one-dimensional (1D); (Viot et al., 2015); consequently, this phenomenon affects the envelope's thermal response, increasing the thermal loads necessary for heating or cooling. Ilomets et al. (2017) asserted that TBs contribute up to 23% of the total transmission heat loss of apartment building envelopes (i.e., prefabricated concrete, brick, wood and autoclaved aerated concrete). Common approaches used to evaluate TBs include the equivalent U-value method, the equivalent wall method and the three-dimensional dynamic method. These are based on heat conservation equations and differ according to system state (i.e., transient vs. steady state) and thermal properties (Saied et al., 2022). The U-value method is based on International Organization for Standardization (ISO) standard 10211 (ISO, 2017) and involves calculating the effect of a TB with two specific transmission coefficients: the punctual thermal transmittance coefficient (χ) and linear thermal transmittance coefficient (Ψ). Chang et al. (2019) conducted a heat transfer analysis of TBs in different CLT structural joints, such as wall-to-wall and wall-to-roof joints, while also considering the connection method, including a self-tapping screw, metal bracket plus screw and engineered wood products (EWPs) plus a self-tapping screw. However, the investigation only analysed CLT solutions without considering possible hybrid combinations.

In more than 50% of all finished and under-construction tall mass timber buildings, CLT is not the only material used; instead, a combination of conventional materials, such as steel and concrete, is deployed to obtain better structural performance (Council on Tall Buildings and Urban Habitat, 2022). There is a lack of studies examining the thermal performance of CLT hybrids—specifically, the effect that TBs have on heat transmission through the envelope. To fill these gaps, the present study proposes an analysis proposal for characterising TBs in CLT hybrids through the Ψ-value, considering the effect of metallic structural connectors.

1. Materials and methods

To accomplish the study's objective, a methodological analysis is proposed. First, a theoretical explanation is provided of how the TB analysis was performed according to the limits established for the study. Later a justification of the analysis proposed is explained. Subsequently, the stages of analysis and study cases used to address the proposed methodological approach are explained.

1.1. TB theoretical analysis

TBs can be characterised in steady-state conditions by determining the linear thermal transmittance Ψ-value. To quantify heat loss through the envelope at TBs, it is common to use Eq. (1), which involves multiplying the Ψ-value by the length of the TB (*L*) and by the difference between the indoor temperature (T_{in}) and the outdoor temperature (T_{out}):

$$Q_{TB} = \psi \cdot \mathrm{L} \cdot (T_{in} - T_{out}) \tag{1}$$

One approach is presented on ISO 14683 (ISO, 2007b) consisting in determining the linear thermal transmittance using a basic system that involves catalogues with different general configurations. A more precise approach features heat transfer equations based on ISO 10211 (ISO, 2017). The ISO 10211 procedure calculate the thermal coupling coefficient (L^{2D}) in two-dimensional (2D) expressed in (W/mK), as Eq. (2) shows:

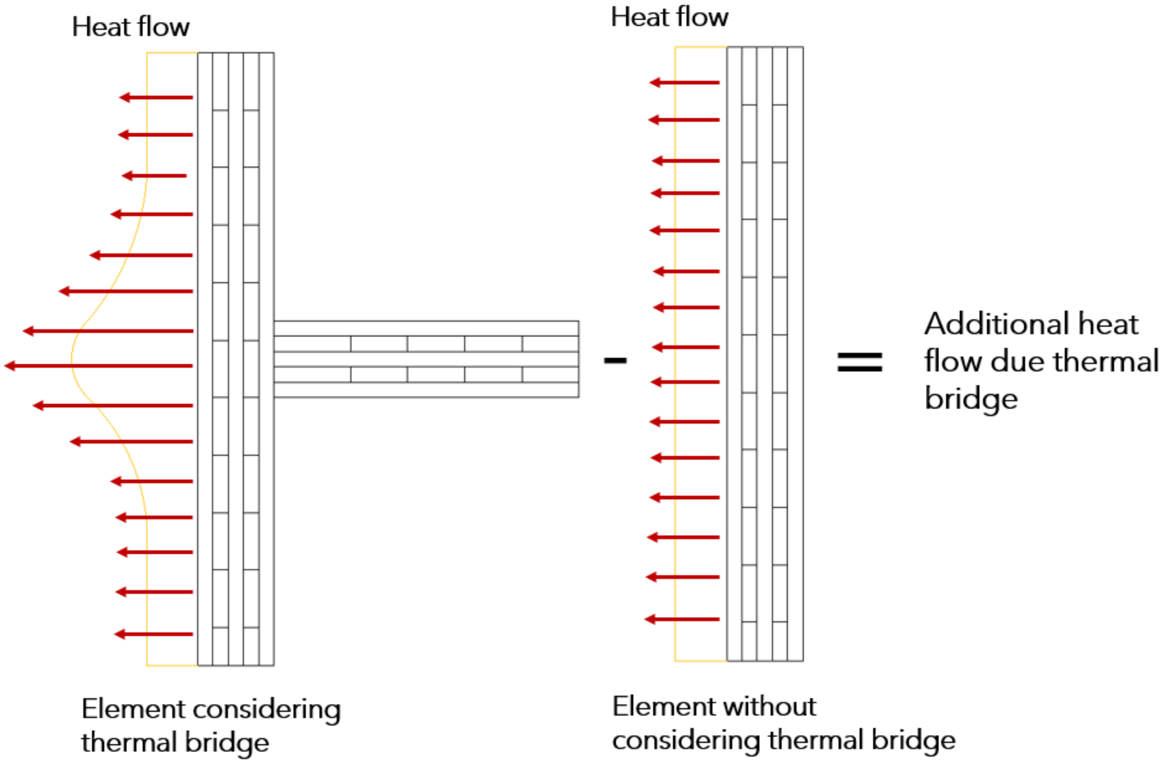
$$L^{2D} = \frac{q}{(T_{in} - T_{out})} \tag{2}$$

where *q* is the heat flow per meter length, while T_{in} and T_{out} are the internal and external temperatures, respectively. Subsequently, the Ψ-value is used to represent the heat flow influence of a linear TB on the total 2D heat flux, expressed as Eq. (3):

$$\psi = L^{2D} - \sum_{i=1}^{N} U_i \cdot l_i \tag{3}$$

where U_i is the thermal transmittance (W/m^2K) of the 1D component *i* separated in two environments, and l_i is the length over which the Ψ-value applies (Martin et al., 2011). Finally, the heat flux due to the TB is calculated by evaluating the difference between the heat flow crossing the whole element and the flow crossing the element without the TB (Viot et al., 2015), as Figure 1 shows.

Figure 1: Conceptual perspective of TB effect

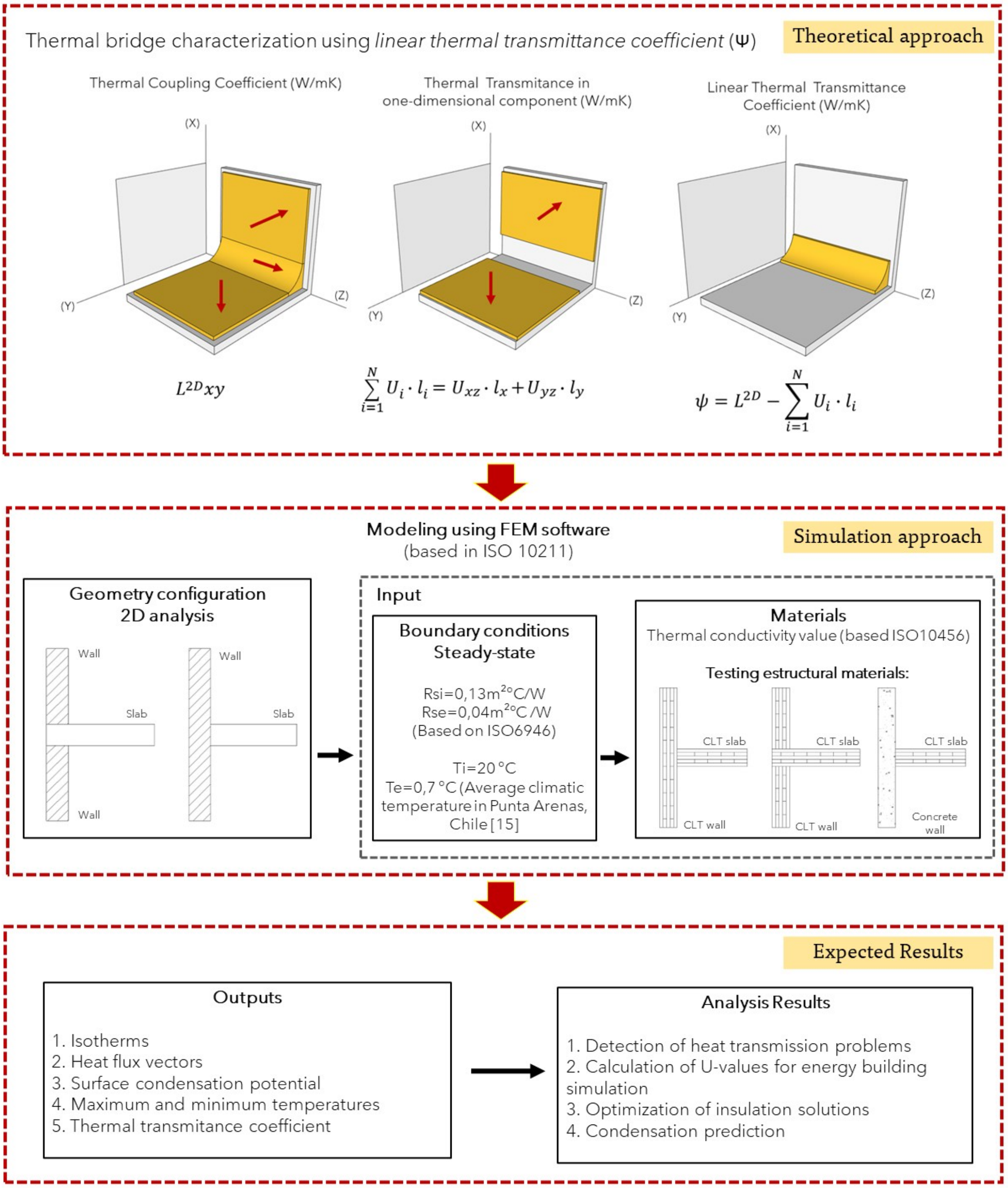


The purpose of this study is to achieve a preliminary understanding of the behavior of thermal bridges in hybrid constructions considering the effect of connectors. To achieve this objective, the methodology proposed by ISO 10211 (ISO, 2017) will be used because there is no catalog of configurations for connectors in timber hybrid elements to be calculated under ISO 14683. On the other hand, the results are a first approximation to evaluate TB in hybrid timber connections that can evolve in the study of the effect of heat transfer in the dynamic regime for TB or the analysis of the hybrid timber TB in a 3D approach.

1.2. Case study and simulation approach

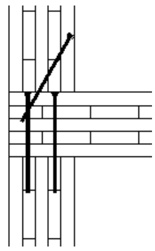
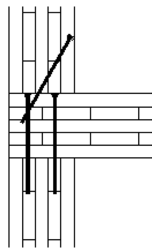
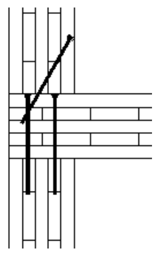
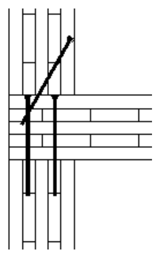
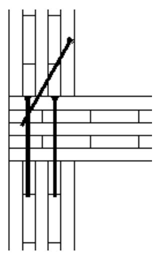
The heat lost in the envelope by walls and roofs represent 35% and 25% of the total heat loss, respectively (Saied et al., 2022). Structural wall-to-floor joints are precisely determinant in terms of the envelope's heat transfer. As such, for multi-story structures, wall-to-floor connections are of vital importance, as they occur more often than do other joint types, such as wall-to-roof and wall-to-foundation joints. Tall buildings and hybrid structures tend to present more TBs in their wall-to-floor joints, meaning that they are of particular interest in this study. The analysis is thus performed in a 2D steady state using the finite element method (FEM). The analysis approach is shown in Figure 2—essentially, the effect of the TB is determined by the difference in the heat flux to the outside of a point of the envelope where the TB is located with respect to the same envelope without TB.

Figure 2: Methodological Approach based on ISO 10211



In relation to wall-to-floor element connections, two types of geometric configurations have been considered based on the different solutions in the literature, corresponding to CLT and CLT–concrete configurations. As such, for these building materials, different building connections are compared. The main cases that have been previously identified include CLT walls with CLT floors, and concrete walls with CLT floors, taking their thermal conductivity values from ISO 10456 (ISO, 2007a). Considering the materials and geometric configurations, different connection solutions are considered, as shown in Table 1.

Table 1: Case studies considering different connections solutions

Geometric configuration	Material Configurations		Connections type	Cases	Diagram
Floor cross wall	CLT-wall	CLT-floor	Screws	W-F-1	
	CLT-wall	CLT-floor	Screws + steel angle bracket	W-F-2	
	CLT-wall	CLT-floor	Slotted-in steel plates	W-F-3	
Floor top wall	CLT-wall	CLT-floor	screws + steel angle bracket	W-F-4	
	Concrete-wall	CLT-floor	Steel collector plate bracket	W-F-5	

The indoor and outdoor boundary conditions for the heat transfer analysis are set based on ISO 6946 (ISO, 2017), determining the surface resistance values to be R_{si} = 0.13m²°C/W and R_{se} = 0.04m²°C/W. The outdoor temperature is set at 0.7°C, corresponding to the average climatic temperature in Punta Arenas—a city in southern Chile that experiences an extreme winter climate (MINVU, 2018)—while the indoor temperature is set at 20°C.

2. Expected results

The objective of the following article is to analyze the thermal bridge on timber hybrid connections and determine the heat flow rate in a static regime considering the effect of types of connectors. In this sense, particularly where a connector is located, the heat flux along a linear thermal bridge will be greater than the rest of the cross-section of the joint type. In the proposed case studies, higher values of Ψ-value are expected in those types of joints that are exposed to greater contact with the indoor environment.

The case studies that would imply a greater thermal bridge would be those that use screws and steel angle brackets, being a more considerable effect in the hybrid case of concrete wall and CLT slab. Steel collector plate brackets embedded in the concrete wall are expected to present higher heat fluxes due to the lower thermal conductivity of the concrete material in which the connector is inserted.

3. Limitations

The presented study has specific limitations. Although the choice of the case studies presented is justified, the constructive solutions only respond to wall-slab joints, ignoring other types of encounters that could determine amounts of heat flux like in wall–ceiling, wall–wall and wall–slab floor. Regarding the connections, a limited number of solutions are also presented, largely determined by the type of union and materials that are selected. Finally, the narrow framework of study of hybrid solutions is recognized, framed only to consider the union of a CLT slab element with a concrete wall, as well as other possible variants of materials to be used such as steel and other variants in wood.

4. Conclusions and further research

By determining the linear thermal transmittance coefficient in constructive solutions of hybrid structures, it is possible to evaluate the potential for heat loss in such solutions and, thus, to make more appropriate insulation design decisions to reduce these losses. With the analytical approach and modelling, it is also possible to determine the most critical heat flow vectors and to create temperature diagrams that can be considered during the decision-making process, to avoid surface and interstitial condensation risks. The heat transfer in a static regime for 2D geometric solutions has the potential to incorporate the effect of TB in the energy simulations through the determination of an equivalent thermal transmittance value.

In future, this study proposes expanding the scope of constructive solutions for typical hybrid CLT–concrete–steel projects in the future. At the same time, the effect of thermal inertia in some materials is a parameter that introduces the study of the dynamic behavior of thermal bridge, and represents an opportunity to investigate the effects of TBs changes in a specific time frame. A 3D approach for hybrid solutions should be considered to quantify all the potential connector effects in TB along the building element unions.

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