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Review

FEM Analysis: A Review of the Most Common Thermal Bridges and Their Mitigation

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Abstract: The necessity to improve the energy saving potential of buildings is now a duty. European and national policies are being implemented to address the important decisions being made on this subject. For these reasons, several studies focus on this relevant topic. This paper review not only focusses on it but studies it in-depth. A commercial 3D simulation software was used to design a building sited in Palermo estimating the thermal losses before and after external envelope insulation. In particular, all the thermal bridges (TBs) were analysed with the finite element method (FEM) and mitigated with rock wool insulation. The paper shows the linear thermal transmittance difference and heat flux loss before and after TB mitigation. The results confirm the importance of installing an external insulation layer in the old building envelope. The linear thermal transmittance of TBs and the associated heat flux loss often decrease by more than 50%.

Keywords: thermal bridges; thermal bridges mitigation; FEM analysis; building energy saving

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1. Introduction

Today, the topic of energy consumption in the civil sector is much discussed. In particular, research and actions are focused on trying to decrease heat losses in buildings [1]. Many action plans have been put into place, for example, in the European context we talk about the Energy Performance of Buildings Directive (EPBD), which promotes the improvement in the energy performance of buildings within the European Union, taking into account outdoor local and climatic conditions, as well as indoor climate and cost-effectiveness requirements [2]. European studies estimate that the energy consumption of public buildings accounts for approximately 10% of the total annual energy consumed in Europe [3]. In Italy, policymakers have put into place a recovery plan called "PNRR", the "National Recovery and Resilience Plan" [4]. These economic support measures are aimed at reviving the country's economy, which has been hit hard by the pandemic. Part of the allocated funds are intended for the restoration of residential and non-residential buildings. The citizens can deduct the costs of renovating their house under certain guidelines and financial ceilings. In this way, the aim is to reduce the thermal losses of buildings [5–7]. In this context, the proposed article will study the contribution of thermal bridges in the heat losses in a civil home located in Sicily, listing and studying them with the "FEM" analysis (Finite Element Method). In addition, a comparison will be made between the values obtained from the simulations and those tabulated in the national atlases of thermal bridges tabulated in the standard UNI EN ISO 14683 [8]. There are many studies in the literature on this subject, analysing its nature or its impact on the overall heat loss of a house; this is carried out by laboratory, numerical or FEM modelling studies.

Davide Borelli et al. have implemented a bi-dimensional steady state FEM model to simulate the wall to floor thermal bridge. With the regression algorithm, the value of linear transmittance ψ has been carried out for a lot of different node configurations [9].

Seohoon Kim et al. have studied the heat loss coefficient of an envelope considering thermal bridges with the heat flow meter method. The result of the study shows that the thermal bridges account for 16.98% of total heat loss [10]. In a similar analysis, Stefano Bergero and Anna Chiari studied the heat losses of an envelope considering the contributions of thermal bridges. They compared the heat losses using the numerical and abacus calculations of thermal bridges. The result is that the contribution of the numerical approach is approximately eight times the weight of the abacus [11]. Justas Terentjevas et al. have studied, with the use of bi and three-dimensional numerical analysis, the linear thermal transmittance of the thermal bridges in a window installed in a different position inside the wall and with and without window fasteners. Among the results, they found that insulating the window frame reduces the thermal bridge value by an order of magnitude [12].

M.J. Romero et al. have proposed a study based on thermal bridges connected to three different building envelope improvements. The results show that installing insulation on the outside of the façade and on the joints necessary to support the insulating panels reduces thermal bridge transmittances by 20% and 63.4%, respectively [13]. Sara Aghasizadeh et al. have studied thermal bridges related to the balcony–wall connection. They have studied three different kinds of connection: Concrete–concrete, concrete–steel, and steel–steel. The better solutions in each case are based on the installation of an EPS insulating layer between the exterior and interior structure. In this way, the EPS interrupts the heat transfer. The results of the 3D simulations show that the linear transmittance is higher in the concrete–concrete connection, medium in the steel–steel and lower in the concrete–steel connection. In the end, the thermal bridge insulations with EPS reduced the heat losses by 12.2% [14]. Xinwen Zhang et al. have studied the balcony thermal bridge apartments. Their research, using the TRNSYS simulator, have shown the importance of wall insulation for thermal bridge mitigation. In fact, this practice reduced linear thermal transmittance by 60% and heating energy demand by 8% [15]. Jan Ge et al. focused the thermal performance of wall-to-floor TBs. They implemented the same formula to carry out the insulation performance for this kind of TB. They proved that installing an insulation layer outside the wall reduces the thermal losses connected to TB [16]. Zaccaro et al. studied the importance of thermal bridges in term of thermal losses. In their opinion, they play an important role in the manufacturing of the building component. If the fixing of the structures is carried out carefully, thermal bridges will have less impact on heat losses [17]. Essam al Ayed et al. studied the thermal bridges in Arabian houses. They proved that the concrete structural elements increase the TBs by approximately 60%. For this reason, according to Arabian standards, a 55 mm of external insulating reduces the exterior wall transmittance by 79% [18].

This paper investigates the most common thermal bridges, TBs, generated in building structures and their mitigations. These TBs will be studied with a commercial finite element method (FEM). The linear thermal transmittance of the thermal bridge in a simple brick structure will be studied, followed by the installation of insulating material capable of reducing the thermal dispersion of the envelope and, therefore, the linear thermal transmittance of the TBs. As shown in the results and discussion section, the values of thermal bridge linear transmittance and heat loss are likely due to the results found in the studies cited before. In fact, linear transmittance with external insulation installation decreases by the same order of magnitude as found in the studies by Romero et al.

Authors' Contribution

The analysis of thermal bridges has historically relied on the use of tabulated values found in standards. This approach has always involved the use of linear thermal transmittance estimates using empirical equations. Therefore, the theoretical study and practical implementation could be affected by any approximations that the tabulated values cause. In Italy, the legislation since 2008 only considers the tabulated values. Moreover, it does not analyse all possible cases of thermal bridge mitigation. In the last decade, thanks to 3D modelling software and finite element studies, it is possible to investigate and create ad hoc models of any thermal bridge you wish to study. For this reason, this review article aims to simulate a real case study to list all possible thermal bridges in a house, evaluating at the same time TB theory simulation and practical applications. The device used made it possible to model individual thermal bridges by choosing all the materials and their respective dimensions (e.g., window frame dimensions), which could not be performed with atlases. The simulations made it possible to study thermal bridges before and after their mitigation by demonstrating that it is possible:

- to decrease their linear thermal transmittance and associated heat losses;
- to evaluate with isotherms the temperature distributions in all areas of the TB;
- to identify any anomalies and hot spots.

The latter two points can be analysed using FEM analysis.

2. Case Study

The linear thermal transmittance simulations of TBs depend on the geometrical and structural characteristics of the envelope. For these reasons it is important briefly describe these aspects.

- External wall

The technical characteristics of the materials making up the external walls are described in Table 1.

Table 1. External wall characteristics.

Layer	Description	Thickness (mm)	Conductivity (W/my)	Thermal Transmittance (W/m^2 K)	Vapour Resistance	Specific Heat (J/kgK)
	Internal conductance	0		7.7000		
1	Lime and gypsum plaster	20	0.7000	35.0000	10.7222	1000
2	Tuff blocks	260	0.5500	2.1154	100.0000	1000
3	Lime and gypsum plaster	20	0.7000	35.0000	10.7222	1000
	External conductance	0		25.0000		

Total thickness = 300 (mm). Global thermal transmittance = 1.4291 (W/m^2 K). Global thermal resistance = 0.6997 (m^{2}K/W). Periodic thermal transmittance = 0.34 (W/m^2 K). Attenuation factor = 0.24 (-). Phase shift = 10.76 (h).

- Internal wall

The technical characteristics of the materials making up the internal walls are described in Table 2.

Table 2. Internal wall characteristics.

Layer	Description	Thickness (mm)	Conductivity (W/mK)	Thermal Transmittance (W/m^2 K)	Vapour Resistance	Specific Heat (J/kgK)
	Internal conductance	0		7.7000		
1	Lime and gypsum plaster	15	0.7000	46.6667	10.7222	1000
2	Hollow brick	80	0.5500	4.2553	9.3826	1000
3	Lime and gypsum plaster	15	0.7000	46.6667	10.7222	1000
	External conductance	0		25.0000		

Total thickness = 110 (mm). Global thermal transmittance = 2.2335 (W/m^2 K). Global thermal resistance = 0.4477 (m^{2}K/W). Periodic thermal transmittance = 2.03 (W/m^2 K). Attenuation factor = 0.91 (-). Phase shift = 2.46 (h).

- Floor on ground and internal floor

The technical characteristics of the materials making up the floor on ground are described in Table 3 and internal floor in Table 4.

Table 3. Floor on ground characteristics.

Layer	Description	Thickness (mm)	Conductivity (W/mK)	Thermal Transmittance (W/m^2 K)	Vapour Resistance	Specific Heat (J/kgK)
	Internal conductance	0		7.7000		
1	Lime and gypsum plaster	50	0.7000	14.0000	10.7222	1000
2	Stone masonry	750	2.2800	3.0400	100.0000	1000
3	Lime and gypsum plaster	50	0.7000	14.0000	10.7222	1000
	External conductance	0		25.0000		

Total thickness = 850 (mm). Overall thermal transmittance = 1.5584 (W/m^2 K). Global thermal resistance = 0.6417 (m^{2}K/W). Periodic thermal transmittance = 0.03 (W/m^2 K). Attenuation factor = 0.02 (-). Phase shift = 19.66 (h). Floor and roof ceiling.

Table 4. Inter-floor and roof ceiling characteristics.

Layer	Description	Thickness (mm)	Conductivity (W/mK)	Thermal Transmittance (W/m^2 K)	Vapour Resistance	Specific Heat (J/kgK)
	Internal conductance	0		25.0000		
1	Concrete substrate	100	1.4000	14.0000	74.2308	1000
2	Flat concrete slab	210		1.9048	10.1579	1000
3	Interior plastering	10	0.7000	70.0000	10.7222	1000
	External conductance	0		10.0000		

Total thickness = 850 (mm). Overall thermal transmittance = 1.5584 (W/m^2 K). Global thermal resistance = 0.6417 (m^{2}K/W). Periodic thermal transmittance = 0.03 (W/m^2 K). Attenuation factor = 0.02 (-). Phase shift = 19.66 (h). Windows.

- Windows

The technical characteristics of the materials making up the windows are described in Table 5.

Table 5. Windows characteristics.

Window Single Layer Glass and Frame without Thermal Break	
GLASS Glass type = Single Thermal transmittance = 5.40 W/m^{2}K	FRAME Frame type = metal without thermal break Thermal transmittance = 2.20 W/m^{2}K
Total window thermal transmittance 3.4872 W/m^{2}K	

3. Methodology

The object of the study is based on a 3D simulation of a building sited in Palermo (Italy). The methodology followed involves studying winter heat loads and the linear thermal transmittance of the TBs. This procedure will be carried out following an energy refurbishment of the building envelope, on which an 8 cm rock wool thermal insulation will be installed. It will be installed in such a way as to reduce the linear thermal transmittances of thermal bridges. The rock wool characteristics are shown in Table 6.

Table 6. Rock wool characteristics.

Thickness (mm)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)	Compressive Strength (kPa)
80	0.035	90	1030	0.10

In Figure 1 is shown the building object of the simulation.

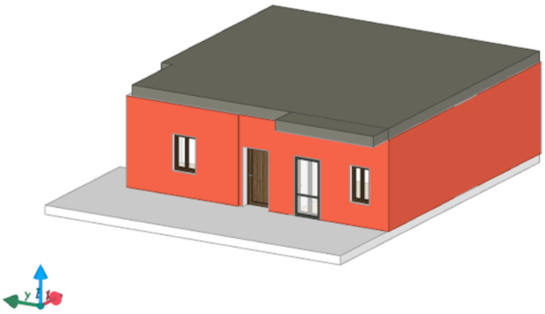


Figure 1. 3D building simulation.

FEM Theory

This section will show the energy and thermal bridge simulations of the building before and then the energy requalification. With the envelope and window characteristics, the thermal heat load in the starting situation is shown in Table 7.

Table 7. Thermal heat loads.

Thermal Heat Loads		
Winter design outdoor temperature	5.00	°C
Maximum dispersion through transmission	5876.01	W
Maximum dispersion through ventilation	585.84	W
PROJECT heat load (transmission + ventilation + recovery factor)	6461.85	W

To consider the impact of TBs on annual energy consumption, it is necessary to take into account the primary energy demand for heating, which amounts to 5976.07 kWh. The primary energy consumption of 536.18 kWh is attributed to thermal bridges. This represents 9% of the total.

The finite element calculation method, according to UNI EN ISO 10211, makes it possible to obtain the linear thermal transmittances and surface temperatures of the simulated structures [19]. It is based on the following assumptions: all physical properties are independent of temperature and there are no heat sources inside the building element. The numerical method used is validated in accordance with Appendix A of the standard, as it provides the temperatures and heat flows, allows for the calculation of temperatures and heat fluxes at positions other than those indicated in the standard, calculates the sum of the absolute values of all heat fluxes twice, for n nodes (or cells) and for 2n nodes (or cells). The difference between these two results is always less than 1%. By iterating the calculation until the sum of all heat fluxes (positive and negative) entering the object and dividing by half of the sum of the absolute values of all these heat fluxes, it is less than 0.0001.

4. Results and Discussions

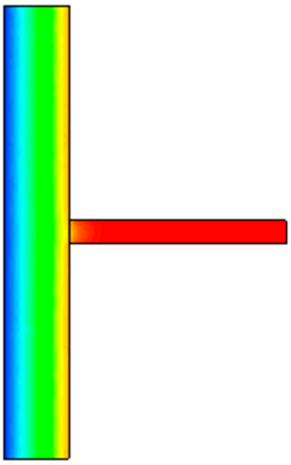
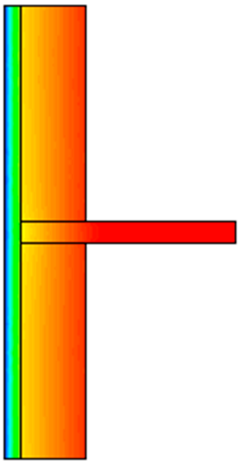
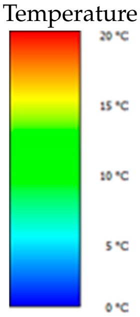
4.1. TBs FEM Analysis

In this section, the most common TBs encountered in the 3D simulation, with the starting and corrected condition (achieved with the rock wool insulation), are listed in a table. The TBs are represented with discretized temperature curves every 0.25 °C.

- IW: internal wall

The thermal bridge regarding internal walls is generated when there is an intersection between a partition and the external wall. In this condition, the possibility of considering the flow with one-dimensional models and studying them, at least in 2D analysis, is lost. From the results obtained in both simulations, it is shown that insulating the external wall with a thermal coat decreases TB transmittance by 75% and heat flow loss by 71%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 8.

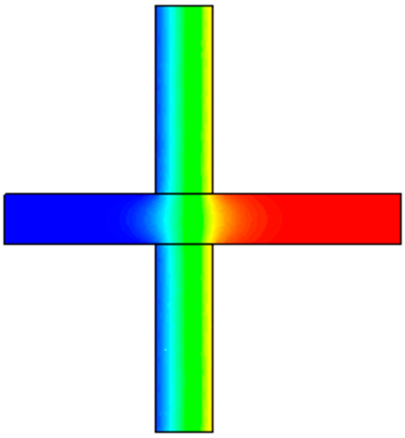
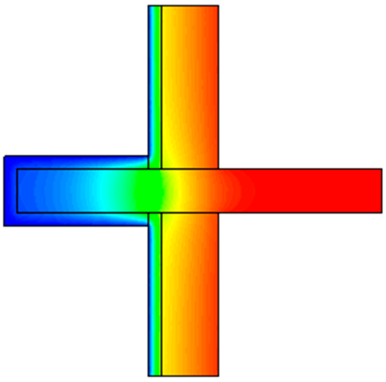
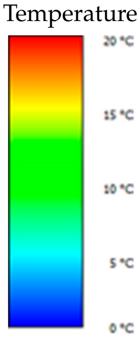
Table 8. IW Thermal bridges.

	Not Mitigated TB	Mitigated TB	Temperature Scale
			
Linear thermal transmittance-kl	0.12	0.03	(W/mK)
Total thermal flux-F	48.41	14.19	(W/m)

- B: Balcony

A TB near a balcony occurs in the intersection of two different structures: one, the balcony, made of reinforced concrete and the other, the wall, made of tuff. In this junction there are geometric and thermophysical discontinuities, due to the different thicknesses and thermal conductivity. The thermal insulation installed all around the balcony mitigates the thermal flux loss. The isothermal lines show that the temperature structures internal to the insulating layer are hotter. In this case, the TB linear thermal transmittance decreases by 44% and thermal flux loss decreases by 77%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 9.

Table 9. B Thermal bridges.

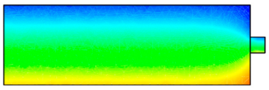
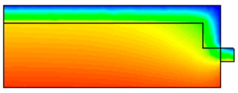
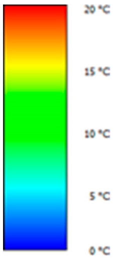
Not Mitigated TB		Mitigated TB	Temperature Scale
			
Linear thermal transmittance-kl	0.23	0.13	(W/mK)
Total thermal flux-F	66.53	15.85	(W/m)

- W: Windows

A TB near the windows or window frames, in general, is due to the geometric discontinuity between the wall and the frame, but, above all, to the different materials between the wall and the frame and, therefore, the thermal conductivity is very different. The mitigation of a TB near the window has been considered in the insulating layer in the external wall that curves and touches the frame of the window. This adopted insulating has been chosen because the frame considered is installed in the middle of the wall. If the window is installed in line with the external face of the wall it would be sufficient to install the insulation up to the frame, without making the curve. In this case, the linear thermal transmittance does not change significantly but the thermal flux loss decreases by 65%.

The values related to this thermal bridge in the starting and correction conditions are shown in Table 10.

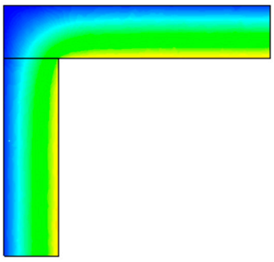
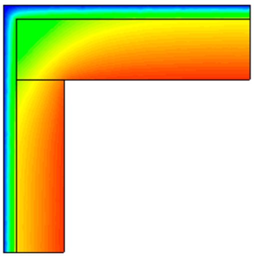
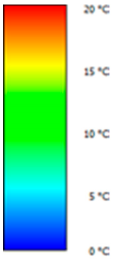
Table 10. W Thermal bridges.

	Not Mitigated TB	**Mitigated TB**	**Temperature Scale**
			Temperature 
Linear thermal transmittance-kl	0.19	0.14	(W/mK)
Total thermal flux-F	35.89	12.79	(W/m)

- R: Roof

The intersection between the roof and external wall creates a TB due to the geometry discontinuity creating a 90° corner. The materials are different because the roof is composed of a concrete structure and the wall is composed of tuff. The optimum mitigation for this kind of thermal bridge is to provide the installation of a continuous insulating layer starting at the wall and covering all of the roof surface. In this case, the TB linear thermal transmittance does not change significantly but the thermal flux loss decreases by 75%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 11.

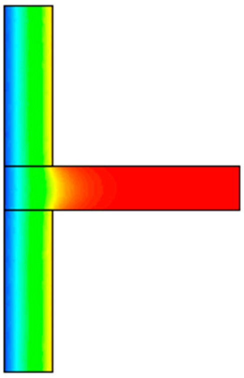
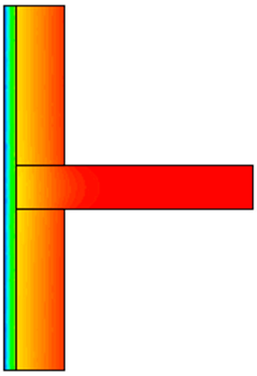
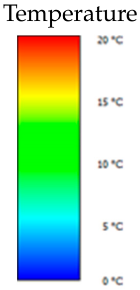
Table 11. R Thermal bridges.

	Not Mitigated TB	**Mitigated TB**	**Temperature Scale**
			Temperature 
Linear thermal transmittance-kl	0.17	0.15	(W/mK)
Total thermal flux-F	70.17	17.48	(W/m)

- IF: Internal floor

The internal floor TB is similar in condition as the internal wall one because it occurs at an intersection between the external wall and internal floor, characterised by geometrical and material discontinuity near the intersection. The insulation of the external wall is the best solution to mitigate this TB. In fact, the linear thermal transmittance decreases by 72% and the thermal flux loss decreases by 78%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 12.

Table 12. IF Thermal bridges.

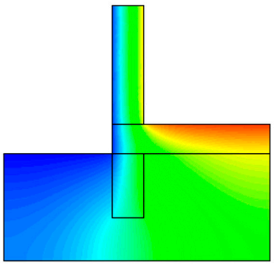
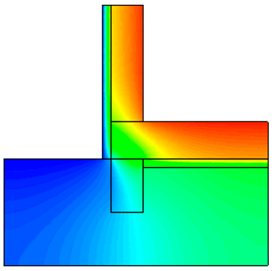
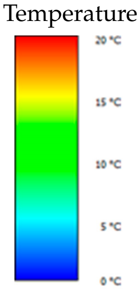
	Not Mitigated TB	**Mitigated TB**	**Temperature Scale**
			
Linear thermal transmittance-kl	0.32	0.09	(W/mK)
Total thermal flux-F	68.39	15.36	(W/m)

- GF: On ground floor

The on ground floor TB is the most complicated to study and to solve. In this case, there are interactions between the ground, internal floor, external wall and building foundations. Large thermophysical and geometric discontinuities constitute a large thermal bridge. This TB mitigation is the most complicated to perform. The solution is to use underfloor insulation: the floor and screed are demolished, the floor is waterproofed with a bitumen sheath, a layer of non-woven fabric is laid, followed by insulating panels (preferably moisture-resistant) on which the new screed and floor are built. The linear thermal transmittance is pratically halved and the thermal flux loss is decreased by 66%.

The values related to this thermal bridge in the starting and correction conditions are shown in Table 13.

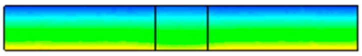
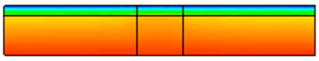
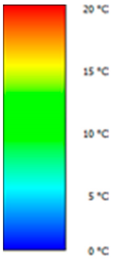
Table 13. GF Thermal bridges.

	Not Mitigated TB	**Mitigated TB**	**Temperature Scale**
			
Linear thermal transmittance-kl	0.21	0.10	(W/mK)
Total thermal flux-F	48.40	16.80	(W/m)

- P: Pillar

TBs due to the interaction between a pillar, load-bearing element and an external wall occurs when a building consists of a reinforced concrete load-bearing structure and an infill of other material. In this case, the pillar has the same thickness of the external wall. A simple mitigation of this TB occurs by installing a continuous insulating layer that covers the pillar and the external wall. In this way, the TB is practically eliminated, and the thermal loss decreases by 79%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 14.

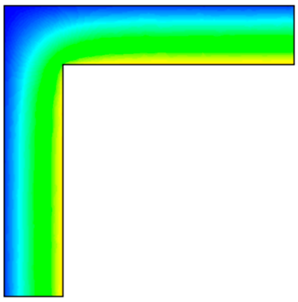
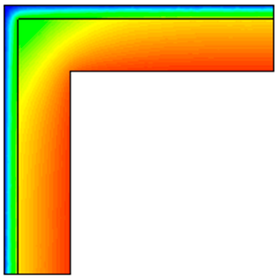
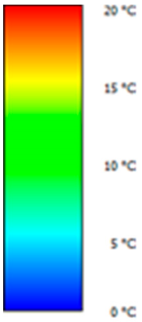
Table 14. P Thermal bridges.

	Not Mitigated TB	Mitigated TB	Temperature Scale
			Temperature 
Linear thermal transmittance-kl	0.20	0.01	(W/mK)
Total thermal flux-F	76.69	16.25	(W/m)

- C_m: External bridges

In this TB, the discontinuity is essentially geometrical. The curve of the external wall distorts the heat flux lines. In the same way of other mitigation, to solve the TB corner it is possible to cover the envelope corner with a continuous insulating layer. Linear thermal transmittance decreases by 22% and thermal flux loss is 74%. The values related to this thermal bridge in the starting and correction conditions are shown in Table 15.

Table 15. C_m Thermal bridges.

	Not Mitigated TB	Mitigated TB	Temperature Scale
			Temperature 
Linear thermal transmittance-kl	0.19	0.15	(W/mK)
Total thermal flux-F	76.31	18.94	(W/m)

4.2. FEM Analysis Validation

Simulations with FEM software made it possible to study the behaviour of thermal bridges before and after their mitigation. The percentage values calculated for each intervention show that it is possible to reduce the heat loss of a building envelope by using insulating material. It has also been shown that some TBs are easier to control than others. For example, solving thermal bridges on corners or pillars is easier than solving thermal bridges on the floor against the ground. To simplify the reading of the results, in Table 15 have been listed all the percentages of kl and F reductions. The linear thermal transmittance calculated with the FEM analisys are compared with the values carried out by tables of UNI EN ISO 14683 considering the same TB mitigation [8]. This comparison is shown in Table 16. The values extracted from the UNI abacus compared to the FEM return only a numerical value. For this reason, the FEM analysis is preferred because it underlines with the isolation temperatures and the possible hot spots on which to focus. The finite element method is more accurate and can be used for all types of thermal bridges as opposed to the pre-calculated abacus evaluation. The FEM approach has the advantage of allowing a study without geometric limitations and of performing a calculation in terms of the thermal coupling coefficient, thermal flux and lineal thermal transmittance returning numerical and graphical results. The biggest advantage is the study of isotherms, as already mentioned. This thermal distribution makes it possible to visually intercept any critical points in the structure. It is evident from the simulations carried out that external insulation allows for higher temperatures inside the insulating layer. The wall without insulation has temperatures on the inside surface of approximately 15 °C that decrease towards the outside. In the post-insulated situation the internal temperatures are clearly higher. The 15 °C temperature moves from the inner surface towards the middle of the wall and beyond. This condition justifies the decrease in heat loss due to the thermal bridge.

Table 16. Mitigation TB summary.

TB	kl Reduction	F Reduction	Kl FEM Simulation (W/mK)	Kl UNI Abacus (W/mK)
IW	75%	71%	0.03	0.10
B	44%	77%	0.13	Not present
W	27%	65%	0.14	0.10
R	Minimum variation	75%	0.15	0.75
IF	72%	78%	0.09	0.10
GF	50%	66%	0.10	0.8
P	95%	79%	0.01	Not present
C_m	22%	74%	0.15	0.15

In the end of the study, a simulation with the installation of a continuous insulating layer in the external wall and external roof has been conducted. At the same time, all thermal bridges have been mitigated following the rules listed in this paper. In Table 17 are shown the results of this ultimate simulation. Comparing the values it is possible to underline the heat load decreasing by 17%. As in the pre-intervention situation, the impact of thermal bridges on the total primary energy demand in a year is considered. This energy demand is equal to 4867.41 kWh and the TBs weighing a total of 420 kWh. Their relationship does not change and is equal to 9%. This result depends on the installation of the insulation layer that has the aim to mitigate the thermal loss and, at the same time, the TBs. This means that the installation of wool rock covers the double aim at the same time.

Table 17. Thermal heat loads after envelope insulation.

Thermal Heat Loads after Envelope Insulation		
Winter design outdoor temperature	5.00	°C
Maximum dispersion through transmission	4705.60	W
Maximum dispersion through ventilation	632.90	W
PROJECT heat load (transmission + ventilation + recovery factor)	5338.51	W

4.3. Correct Installation of Thermal Insulation

The theory behind the study of thermal bridges on which this paper is based should be used as a starting point for the correct design and execution of building envelope improvements. Unfortunately, implementing the insulation measures simulated with the tool is not so easy. In order to achieve the linear thermal transmittance reduction values of TBs and the associated thermal energy losses, care must be taken when installing the insulation. When laying the coat, it is necessary to check that the substrate is suitable. For this reason, it is necessary to visually check the surface and carry out a dusting of the surface. It is important that the operator who installs the coat is trained and knows how much glue is needed to glue the panel, as an insufficient quantity does not guarantee the adequate adhesion of the panel to the support, compromising the result of the installation of the thermal coat. The mechanical fixing must counteract horizontal forces due to the action of the wind and ensure the stability of the system over time. The dowels must be long enough to cross the thickness of the insulation and penetrate the masonry behind until a mechanically reliable and solid layer is achieved. They should also be specifically designed for fixing thermal insulation systems and applied after the mortar has hardened. The next step is to apply the skim coat to the 5 mm thick insulation boards. This must be performed with adhesive mortars with high vapor permeability. For skimming to be effective, the adhesive/smoothing agent must penetrate between the surface fibres of the panel. While the mortar is still wet, the reinforcing mesh is applied and then the second coat of levelling compound is applied so that the mesh is embedded in the levelling compound. The edges must be protected with angles applied with adhesive. The last layer is the external finish, which must be resistant to weather and temperature changes. It must also be impermeable to water but permeable to vapor from inside the building, in order to dispose of vapor production inside the house [20].

5. Conclusions

The aim of this paper is to highlight the importance of thermal insulation on the building envelope to reduce heat loss and mitigate the impact of thermal bridges. The FEM analysis carried out on the various types of TBs with the consequent description of the correct laying of the thermal insulating layer makes it possible to give a general theoretical and practical overview of the subject under study. According to the results of this and other works, listed in the introduction section, the possibility of TB mitigation is real.

- The percentage incidence of TBs on the total heat loss in this study is approximately 10%, whereas the incidence of the study by Sara Aghasizadeh et al. is estimated at 12%;
- There are also contrasting results, as in this study the values calculated using the FEM method and those of the national atlas are comparable. In the Stefano Bergero and Anna Chiari study, however, the atlas values are eight times lower than the calculation ones.

Linear thermal transmittance can be reduced significantly, such as thermal flux losses. It is necessary to note that there are several possible interventions of TB mitigation, but the research team focused on the most common cases. Future works will be based on the TB FEM analysis considering the possibility of mould formation. This is another relevant topic related to thermal building insulation.

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Nomenclature

B	Balcony
C_m	External corner
C_n	Internal corner
EPBD	Energy Performance of Buildings Directive
EPS	Sintered expanded polystyrene
FEM	Finite element method
Fig.	Figure
GF	On ground floor
IF	Internal floor
IW	Internal wall
P	Pillar
PNRR	National Recovery and Resilience Plan
TB	Thermal bridge
W	Window

Appendix A Definitions

Being able to calculate the heat loss of a building means estimating the ability of the envelope to insulate the internal environment from the changing conditions of the outside. The calculation procedure is based on the following steps [21]:

- Determination of the design based on the outdoor temperature, and annual average temperature of the area in which the building is located;
- Distinction between heated and unheated spaces and their internal temperatures;
- Dimensional characterisation of all building elements;
- Calculation of heat loss through transmission;
- Calculation of heat loss through ventilation;
- Calculation of the heating capacity, i.e., the additional capacity required to compensate for the effects of intermittent heating;
- Calculation of the total heat load.

As mentioned above, the envelope tends to disperse thermal energy in the form of heat due to the temperature difference between the indoor air-conditioned environment and the outdoor environment. The UNI EN ISO 12831 lists the different ways to conduct energy transmission to the outdoors [21]:

- Transmission heat loss to the outside through the envelope, (W/K);
- Transmission heat loss to the unheated space, (W/K);
- Transmission heat loss to the ground, (W/K);
- Transmission heat loss to a heated space at a different temperature, (W/K);
- Ventilation heat loss, (W/K).

Heat loss is influenced by the presence of thermal bridges. TBs are a part of the building envelope characterised by a large difference in thermal conductivity between envelope elements, change in envelope thickness and the difference between the areas of the surfaces, internal and external, of a wall, as in the edges between wall, ceiling, and floor. A distinction is made between linear and point thermal bridges. The former have a uniform cross-section in one direction. The latter have no uniform cross-sections in any direction. The incidence of a linear thermal bridge is estimated by linear thermal transmittance measured in [W/m^2K], steady-state heat flow divided by the length and temperature difference between the rooms on each side of the thermal bridge [8]. In the following Figure A1 are shown the most common TBs in a building envelope.

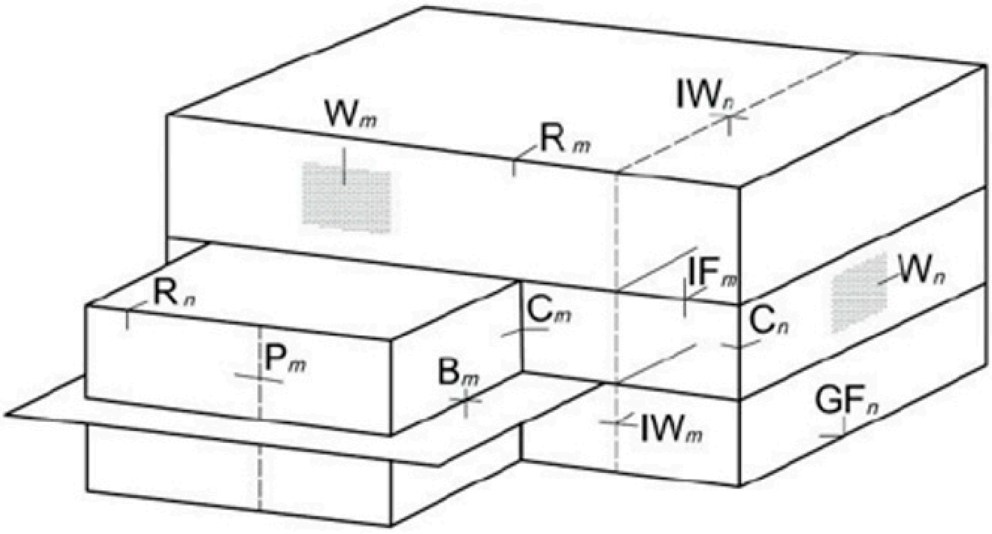

Figure A1. Schematic representation of thermal bridges in a building envelope.

The acronyms refer to the following thermal bridges:

- IW: internal wall;
- B: balcony;
- W: window;
- R: roof;
- IF: internal floor;
- GF: on ground floor;
- P: Pillar;
- C_m: external corner;
- C_n: internal corner.

Linear thermal bridges may occur at joints between external walls, between joints of internal walls with external walls and roofs, between joints of intermediate floors with external walls, between pillars built into external walls, and around windows and doors. The length of the linear thermal bridge may refer to the internal dimensions measured between the internal faces of each zone of the building, or between the internal faces of the external elements of the building. Finally, it can be referred to as the external dimensions measured between the external faces of the envelope.

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