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Light steel-frame walls: thermal insulation performances and thermal bridges.

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Abstract

This paper deals with the evaluation of thermal insulation performance of metal framed lightweight walls. This technology, more and more popular also in Italy, offers interesting advantages, but available commercial documentation lacks in reliable information about the real thermal insulation performance of the whole building envelope taking into account all the details and related thermal bridges. In other countries the available knowledge has been completed after long time and the recent growth of insulation performances requires something more than a simple Italian translation. In this paper the main envelope solutions are identified. The thermal transmittance has been calculated using a specialized freeware FEM application (THERM [1]) and the results checked with a commercial HAM application (WUFI [2]). The existing simplified methods have been extended in order to take into account also the most recent solutions proposed and realized, for a simple assessment of the real (corrected) average thermal transmittance, far from singular points. Finally the main thermal bridges have been analyzed, optimized and used to calculate the average thermal transmittance of a standard façade module comparing it with the non-corrected U-value.

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Keywords: lightweight walls, metal frame, U-value, FEM, thermal bridges.

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1. Introduction and simplified methods

In recent years lightweight walls, already used abroad, have become more and more widespread also in Italy because of advantages they offer such as a quick realization time, the integration of systems in walls thickness, the

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reduction (and recyclability) of wastes during the construction phase and the reduction of loads (and consequently costs) on bearing structures.

These walls are made with gypsum or cement plasterboards fixed on C or U-shaped steel frame profiles of 6/10 mm thickness and can potentially incorporate a high thickness of thermal insulation materials. So the thermal conductivities of materials in light steel frame walls are more heterogeneous than in a traditional wall, made of blocks and mortars. In fact the thermal conductivity of insulation layers is about 0.04 W/(mK) while for steel frames is about 1000-1500 times higher (50 W/(mK)). Actually, metal studs are important thermal bridges.

This topic has been already dealt abroad by American [3] and British standards as BRE Digest 465 [4] as well as by light wall manufactures associations as [5], assessing also the acoustics and fire safety performances. The first one proposed the Zone Method for metal stud walls with insulated cavities in order to consider thermal anomalies around metal studs (depending on the depth of studs, on the ratio between thermal resistivity of sheathing material and cavity insulation and on the thickness of sheathing materials) through an equivalent electrical circuit. The accuracy of that method has been verified for over 200 simulated cases of metal frame walls with insulated cavities. For all configurations considered, the discrepancy between results was within ± 2%.

In Italy light steel frame constructions are little practiced because traditional masonry or reinforced concrete ones still remain in the know-how of building companies. As a consequence the most of lightweight buildings are made of concrete load bearing structures and non-bearing light steel frame walls. Thus actors in the building industry (manufactures, builders, designers) often don't have the proper knowledge of these systems (in particular on building physics issues) partially due to a lack of regulations. In fact there is no standard which allow evaluating thermal performances while the only standard currently used, involves the realization in site [6].

Collecting and analyzing some Italian manufacturers data it was noted that they was often lacking ignoring the thermal effect of metal frame calculating the thermal resistance of walls in a current section (between metal studs). So it leads to an overestimation of thermal resistance by up to 200% depending on the construction details (number, position, frequency and organization of metal studs) as will be shown later in the paragraph 4.

The international standard ISO 6946 [7] purpose a simplified method to calculate the thermal resistance of walls with heterogeneous layers but explicitly it doesn't allow to calculate the thermal performance of a wall with an insulation layer crossed by metal studs because the ratio between the upper and the lower limits of thermal resistance is higher than 1.5. The limits are defined as follow: a minimum thermal resistance R_{min} when layers are exposed to the same temperature difference (parallel isothermal lines); a maximum thermal resistance R_{max} when heterogeneous layers are independent as they would be separated by adiabatic boundaries. The real thermal resistance should be an average value but it is true for little differences in thermal conductivities of materials.

M. Gorgolewsky (whose work forms the basis of the BRE Digest 465 standard) in [4, 8] adjusted the ISO 6946 proposing simple corrections in the normal U-value calculation method. The real thermal resistance is no longer the average value between R_{min} and R_{max} but a weighted *R'-value* was proposed (Equation 1) as a function of a *p* factor that includes the frequency *s*, and sizes *w* and *d* of metal studs (Equation 2). The finite element technique of ISO 10211 [9] was used to assess the real heat flow through steel framed constructions and results was compared (finding correlations) with predicted values obtained with the simplified method. The mean error was estimated lower than 3% for a range of 52 simulated cases.

$$R' = p \cdot R_{\max} + (1-p) \cdot R_{\min} \tag{1}$$

$$p = 0.8 \cdot \frac{R_{\min}}{R_{\max}} + 0.44 - 0.1 \cdot \frac{w}{40mm} - 0.2 \cdot \frac{600mm}{s} - 0.04 \cdot \frac{d}{100mm} \tag{2}$$

Three different construction types was considered: warm frame wall with all the insulation outside the steel frame, cold frame construction with insulation only between the steel studs and hybrid construction.

This paper would at first extend the number of cases analyzed by Gorgolewsky, calculating systematically the thermal performances of walls, drawing up some organized forms with simulated U-values for different wall configurations as a simple guide for designers and finding new correlations between simulated values and ones in a current section for double metal frame walls.

Nomenclature

i	studs frequency of the external wall
i’	studs frequency of the internal wall
n	number of coupled metal profiles
R	thermal resistance
s	thickness of external studs
s’	thickness of internal studs
s_{ISO}	thickness of external insulation
s'_{ISO}	thickness of external insulation
U	thermal transmittance without considering metal frame
U’	thermal transmittance considering metal frame
λ	thermal conductivity

2. U-value calculation with finite elements method.

A light steel frame wall feature is the presence of metal studs organized with a certain frequency usually of about 400-600 mm one to each other. To calculate with accuracy the U-value considering metal elements it is necessary at first to identify a regular and modular sequence in the wall section representative of the whole façade. For a wall with two layer of non aligned studs and a frequency of 600 mm the module is 600 mm every two studs (Fig. 1). As suggested by the standard ISO 10211 [9] the cut-off plane in the section it should be made at least 1 m far from calculation zone. Boundary conditions are set for external and internal environment: an external temperature equal to -5°C and a convective surface heat transfer coefficient h_e=25 W/(m^{2}K) and an internal temperature of 20°C and h_i=13 W/(m^{2}K) as stated in [7]. In calculation of U-values (without metal studs) air cavities are modeled using an equivalent thermal resistance following the ISO 6946 pre-calculated values. In finite element models air cavities have been modeled using the ISO 15099 [10] Cavity Model (already implemented in THERM for NFRC 100 [11] simulations). The radiation model is simplified and the software automatically calculates emissivities, surface cavity temperatures, the Nusselt number, the heat flow direction and the equivalent thermal conductivity of cavity. The heat flow direction depends on the gravity vector set before launching simulations. In Fig.1 is represented a double cold frame wall filled with mineral wool MW (λ=0.04 W/(mK)) with external studs of 50x150 mm (130 mm of MW), an air cavity of 100 mm and internal studs of 50x100 mm (80 mm of MW) and four gypsum plasterboard panels (λ=0.25 W/(mK)) (external, intermediate and two internal). The thickness of metal flanges is equal to 0.6 mm. From Table 1 it’s clear that without consider the metal frame the thermal transmittance is underestimated (about 67-74%).

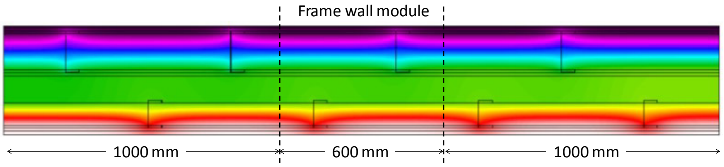


Fig. 1. Wall section calculation with Fem software THERM [1].

Table 1. U-values: different calculation methods.

Calculation method	U [W/(m^{2}K)]
Without frame	0.160
ISO 10211	0.279
Simplified method	0.267

A sensitivity analysis has been made changing the position of the internal (lower) studs from an aligned position with the external (upper) ones (600 mm frequency) to an average position (300 mm frequency). The alignment leads to a percentage growth of thermal transmittance of about 5%. In addition it is necessary to consider the real exposition of walls to climate conditions. The thermal conductivity of insulation materials depends on temperature and humidity. The change from dry to wet condition has been assessed using both the standard ISO 10456 [12] method and the dynamic software WUFI [2]. Thermal transmittance grows of about 1% compared to the dry value as shown in Fig. 2a. The effect of solar radiation on the contrary leads to a reduction of the U-value as shown in Fig. 2b, so it has been neglected in dynamic simulations.

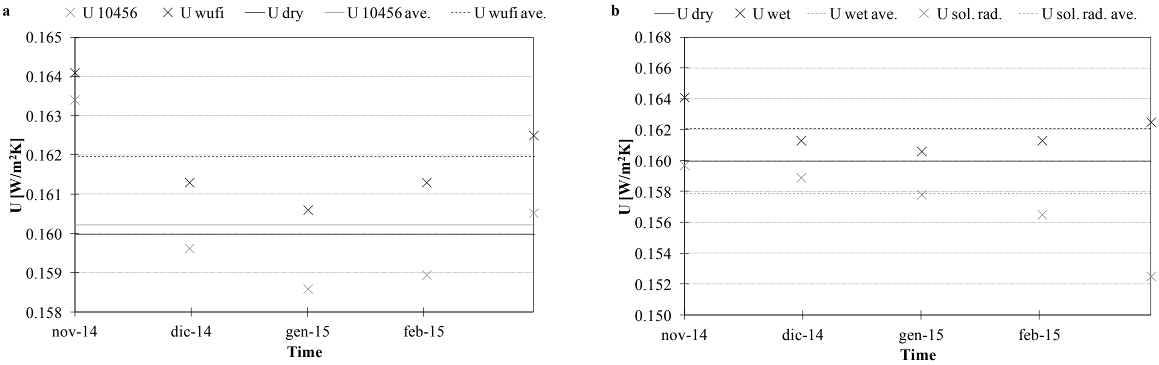


Fig. 2. A comparison between dynamic U-values calculated (a) using two different methods and (b) different climate conditions.

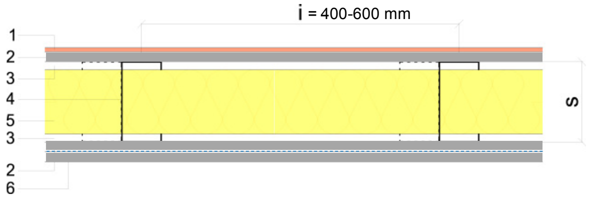
3. Wall types and classification

In this paragraph a classification of light steel frame walls is purposed on the basis of the organization, the frequency and the thickness of studs and the position of insulation layers. Five types of walls are defined: 1. Simple cold metal frame with insulation layer between the steel studs; 2. Double cold metal frame with insulation layer between the steel studs and interior wall non insulated; 3. Double cold metal frame with insulation layer between the steel studs; 4. Double cold metal frame with insulated cavity; 5. Hybrid construction with insulation between steel studs and outside. In the following part these cases are presented organized into forms showing U'-values.

Table 2. Variables of wall configurations.

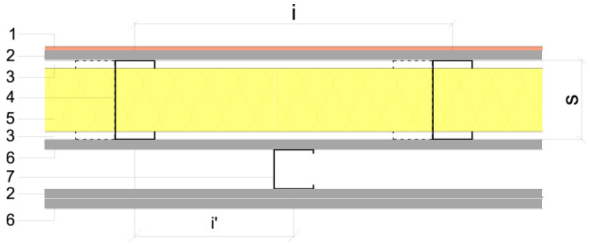
i	External studs frequency	400 – 600 mm	n	Number of coupled studs	1 - 2
i'	Internal studs frequency	0 – i/2	λ_{INS}	Thermal conductivity of insulation	0.04 W/(mK)
s	Thickness of external studs	100 – 150 mm	s_{INS}	Thickness of insulation between studs	100 – 150 mm
s'	Thickness of internal studs	50 – 100 mm	s'_{INS}	Thickness of insulation in cavity	40 – 80 – 120 mm

1.Simple cold metal frame, insulation layer between the steel studs



1 Plaster 5 mm, λ=0.43 W/(mK);
2 Gypsum plasterboard 12.5 mm, λ=0.25 W/(mK);
3 Air cavity 10 mm;
4 Steel studs C-shaped 50x100/150 mm;
5 Thermal insulation in mineral wool;
6 Gypsum plasterboard 12.5 mm with vapor barrier.

2.Double cold metal frame, insulation layer between the steel studs and interior wall non insulated



1 Plaster 5 mm, λ=0.43 W/(mK);
2 Gypsum plasterboard 12.5 mm, λ=0.25 W/(mK);
3 Air cavity 10 mm;
4 Steel studs C-shaped 50x100/150 mm;
5 Thermal insulation in mineral wool;
6 Gypsum plasterboard 12.5 mm with vapor barrier;
7 Steel studs C-shaped 50x50 mm.

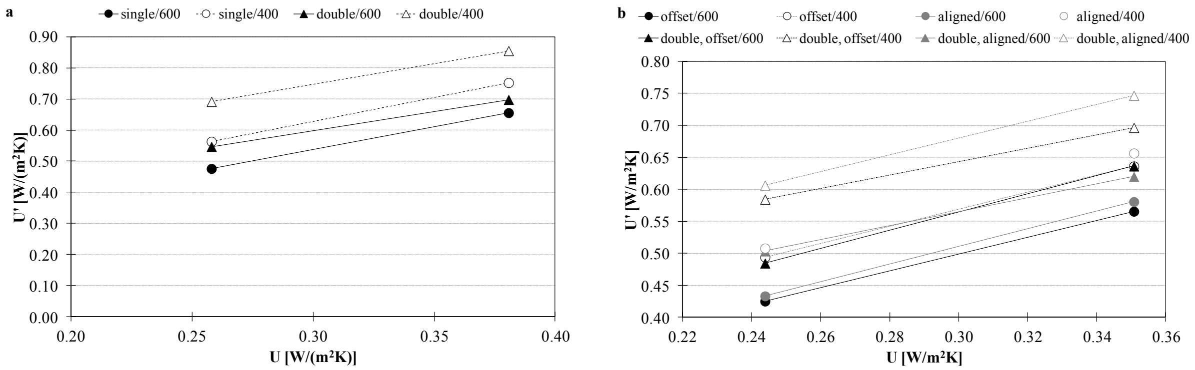
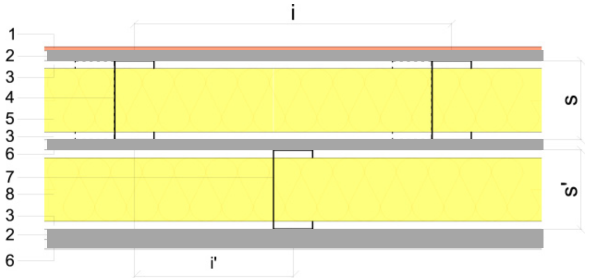


Fig. 3. U'-values for (a) simple (case 1) and (b) double (case 2) cold metal frame walls plotted against U-values. U-values depend on the thickness of thermal insulation equal to 130 mm for left points and 80 mm for right ones.

3.Double cold metal frame, insulation layer between the steel studs



1 Plaster 5 mm, λ=0.43 W/(mK);
2 Gypsum plasterboard 12.5 mm, λ=0.25 W/(mK);
3 Air cavity 10 mm;
4 Steel studs C-shaped 50x100/150 mm;
5 External thermal insulation in mineral wool;
6 Gypsum plasterboard 12.5 mm with vapor barrier;
7 Steel studs C-shaped 50x100/150 mm;
8 Internal thermal insulation in mineral wool.

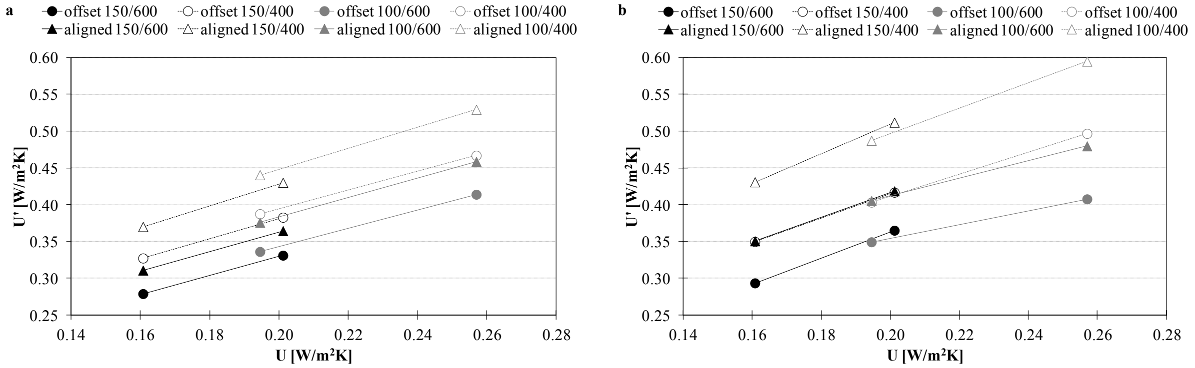


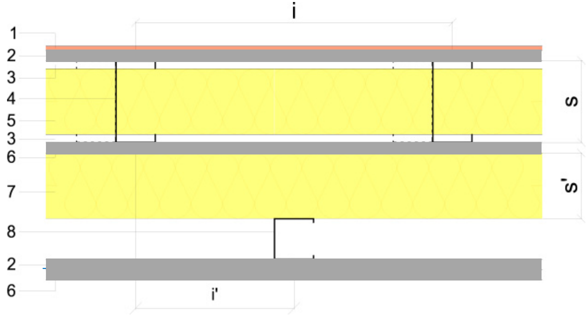
Fig. 4. U'-values for (a) single and (b) double studs plotted against U-values. Looking linked points, left ones represent the thickness of internal insulation equal to 130 mm while ones on the right the thickness of 80 mm.

From results it is clear that the most significant parameter is the thickness of insulation layers because the correct thermal transmittance growth of about a 35% in cases 1 and 2 while in case 3 (Fig. 4a) U'-values grow of about 20-25% changing the thickness of only an insulation layer (internal or external). Changing it in both layers the difference is about 50-55% (extreme left points compared with extreme right points).

The alignment and the frequency give, more or less, the same contribution of about 15-20%. Where the internal cavity is not insulated the alignment does not vary the result (Fig. 3b).

Following graphs (Fig. 5 and 6) show that only the interruption of the heat flux by means of an intermediate or external insulation layer (which works as a "thermal break") leads to a relevant limiting of U'-values. It is about a 25-30% more than starting U-values using the greater insulation thickness equal to 12 cm compared to 68% in best cases below. Solutions 4 and 5 may be considered equivalent.

4.Double cold metal frame with insulated cavity



48 cases

1 Plaster 5 mm, λ=0.43 W/(mK);
2 Gypsum plasterboard 12.5 mm, λ=0.25 W/(mK);
3 Air cavity 10 mm;
4 Steel studs C-shaped 50x100/150 mm;
5 External thermal insulation in mineral wool;
6 Gypsum plasterboard 12.5 mm with vapor barrier;
7 Internal thermal insulation in mineral wool;
8 Steel studs C-shaped 50x50 mm.

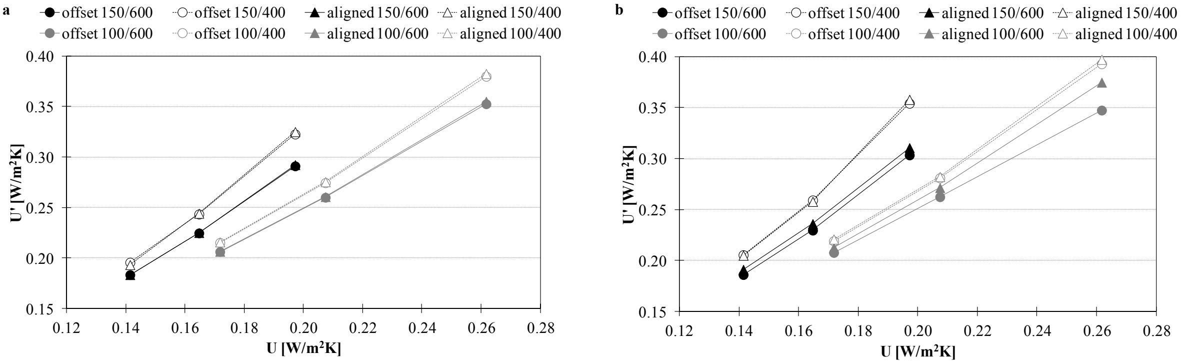
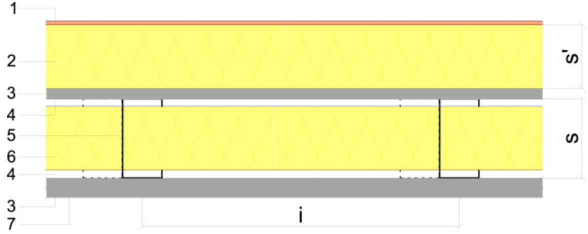


Fig. 5. U'-values with (a) single and (b) double studs plotted against U-values. Linked points differs one to each other for the thickness s' of thermal insulation equal to (from left) 12 – 8 – 4 cm.

5. Hybrid construction, insulation between steel studs and outside



24 cases

1 Plaster 5 mm, λ=0.43 W/(mK);
2 External thermal insulation in EPS
3 Gypsum plasterboard 12.5 mm, λ=0.25 W/(mK);
4 Air cavity 10 mm;
5 Steel studs C-shaped 50x100/150 mm;
6 Internal thermal insulation in mineral wool;
7 Gypsum plasterboard 12.5 mm with vapor barrier;

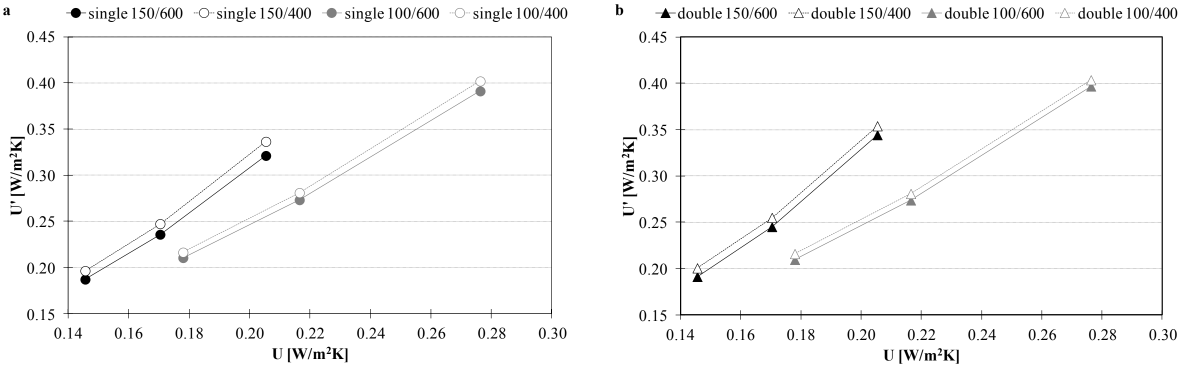


Fig. 6. U'-values for (a) single and (b) double studs, plotted against the U-values.

4. Results

Calculating for each solution and variation the U'-value with simplified methods it is possible to see how these methods fit the curve of the corresponding values calculated by modeling. The results are represented in graphs with simplified R'-values (y-axis) plotted against modeled R'-values (x-axis). Results for double cold metal frame walls are not reliable because equations they proposed were intended for single cold/hot frame and hybrid walls. Applying the simplified method of BRE Digest 465 [4], the mean error is high in both two cases respectively equal to 18% and 5%. It will be necessary to find a new equation for coefficient p_{mod} between 0 and 1 that has been calculated using the modeled values of the thermal resistance R'_{mod}.

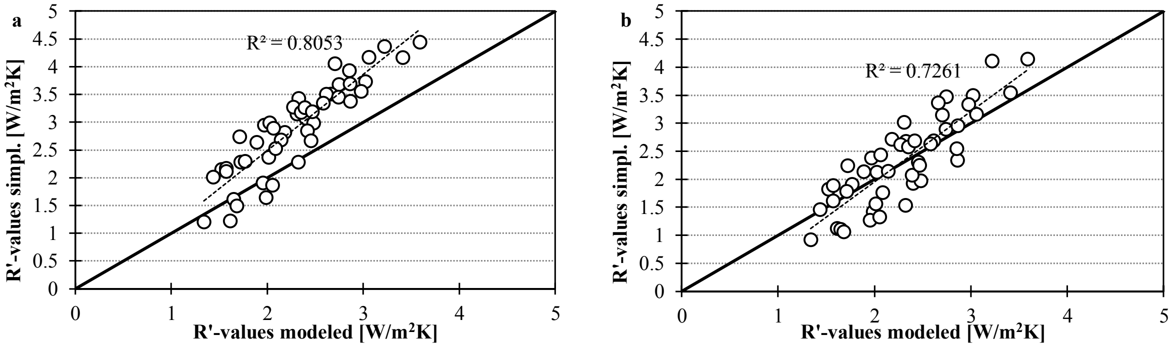


Fig. 7. The R'-values as predicted by (a) ISO 6946 and (b) Gorgolewsky methods, plotted against that obtained by finite elements modeling.

$$p_{mod} = \frac{\left(R'_{mod} - R_{min}\right)}{\left(R_{max} - R_{min}\right)} \tag{3}$$

New *p* coefficients have been assessed through linear multiple regressions, as a function of the frequency, the number and the depth of external steel studs, the depth of internal studs and the ratio between R_{min} and R_{max}:

$$p_a = -0.0003 \cdot i + 0.6216 \cdot n - 0.0005 \cdot s - 0.00005 \cdot s' + 1.7288 \cdot \left(\frac{R_{min}}{R_{max}}\right) - 1.0048 \tag{4}$$

$$p_b = 0.0011 \cdot i - 0.1836 \cdot n - 0.0020 \cdot s + 0.0003 \cdot s' - 2.6068 \cdot \left(\frac{R_{min}}{R_{max}}\right) + 1.1688 \tag{5}$$

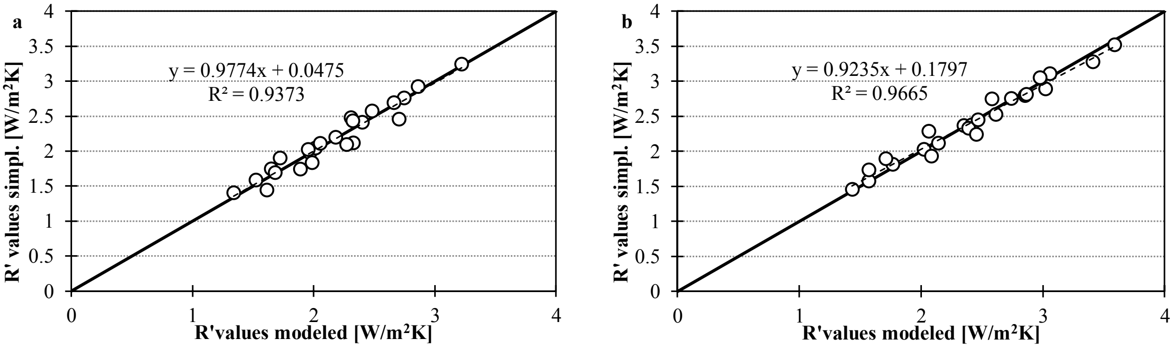


Fig. 8. The R'-values as predicted by simplified methods (a) for aligned and (b) non aligned steel studs.

4.1. Method 1

If the simplified method [4] seems too complicate another relation has been found between the modeled R'-values and the R-values of walls without consider the steel studs. The calculation of R_{min}, R_{max} and p is not required and results (R''-values) are functions of the frequency, the depth and the number of external steel studs, R-value and the depth of internal studs. The results are expressed by linear equations (5) and (6):

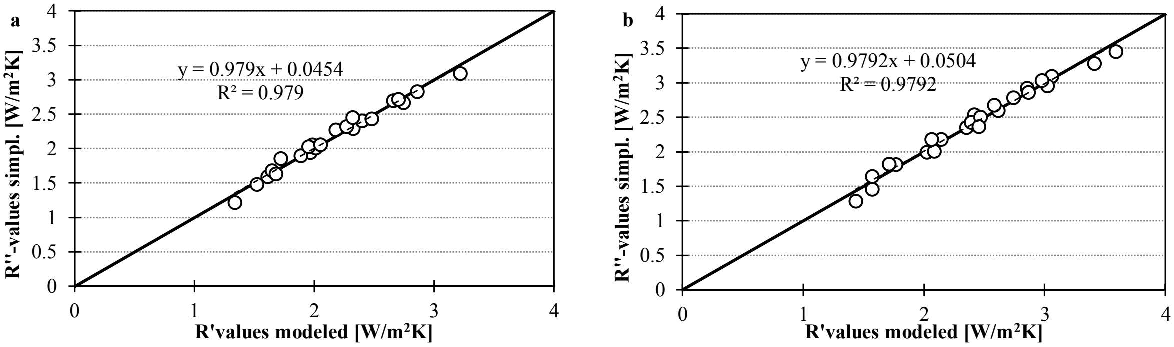


Fig. 9. The R''-values as predicted from thermal transmittance without metal frame (a) for aligned and (b) non aligned steel studs, plotted against the thermal resistances obtained by finite elements modelling.

$$R_a^{''} = 0.4004 \cdot R + 0.0019 \cdot i - 0.2637 \cdot n - 0.0007 \cdot s - 0.0015 \cdot s^{'} - 0.0019 \quad (6)$$

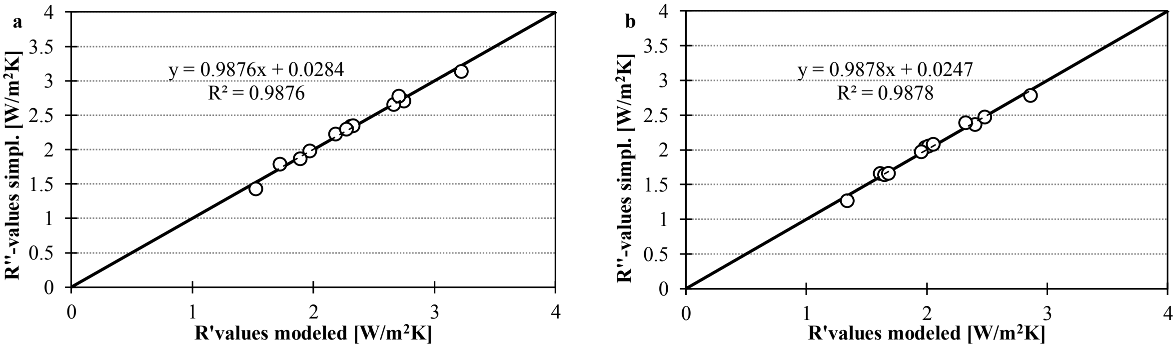
$$R_b^{''} = 0.6947 \cdot R + 0.0018 \cdot i - 0.1722 \cdot n - 0.0066 \cdot s - 0.0075 \cdot s^{'} - 0.0328 \quad (7)$$

This second way to assess the real thermal transmittance of walls considering the metal frame is more reliable than the first because of the higher R^2 values of fitting lines and the average error that is equal to 0.01% compared with the previous, equal to 0.32%.

4.2. Method 2

In the method 1 the variable n could be considered as a constant since it assumes values equal to 1 or 2 depending on the number of studs in the external layer. This data is declared by designer in choosing a wall solution.

It is possible to write four equations that differ one to each other depending on the alignment and the number of metal studs. The coefficient of determination of the linear regression R^2 grows from 0.98 to 0.99 and the average error is equal to 0.04%.



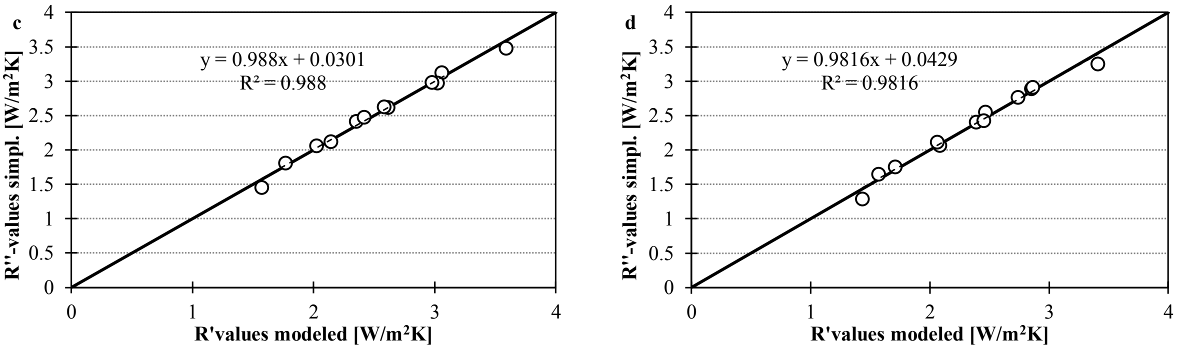


Fig. 10. The R''-values as predicted from thermal transmittance without metal frame for (a) single-aligned, (b) double-aligned, (c) single-non aligned, (d) double-non aligned steel studs, plotted against the thermal resistances obtained by finite elements modelling.

$$R''_a = 0.4211 \cdot R + 0.0018 \cdot i + 0.0005 \cdot s - 0.0019 \cdot s' - 0.4472 \quad (8)$$

$$R''_b = 0.3797 \cdot R + 0.0020 \cdot i - 0.0020 \cdot s - 0.0011 \cdot s' - 0.3478 \quad (9)$$

$$R''_c = 0.6411 \cdot R + 0.0018 \cdot i - 0.0039 \cdot s - 0.0059 \cdot s' - 0.4015 \quad (10)$$

$$R''_d = 0.7484 \cdot R + 0.0018 \cdot i - 0.0094 \cdot s - 0.0090 \cdot s' - 0.1807 \quad (11)$$

5. Construction details and thermal bridges

In realizing metal frame walls it is fundamental the design of construction details as connection with load bearing structures (beams and pillars), windows, roof, balconies, etc. and the control of thermal losses through thermal bridges. The Italian standards doesn't taking at all into account the contribution of thermal bridges in light steel frame walls so it is not possible to calculate thermal bridges using the tabulated values of EN ISO 14683 [13] so they have been assessed by a 2D finite element modeling. It is necessary to point out that steel frame constructions are characterized by some point thermal bridges (i.e. joints between horizontal and vertical metal profiles, joints between beams and pillars, etc.). To consider these situations a 3D analysis would be made. Thermal bridges have been added to the effect of metal frames previously calculated leading to a reduction of the whole thermal performance of a façade. This contribution has been assessed for four types of walls considering a reasonable standard façade module with RC load bearing structures. Construction details have been optimized to minimize the linear thermal transmittance. Results have been represented as a percentage increasing of the thermal transmittance without consider metal studs.

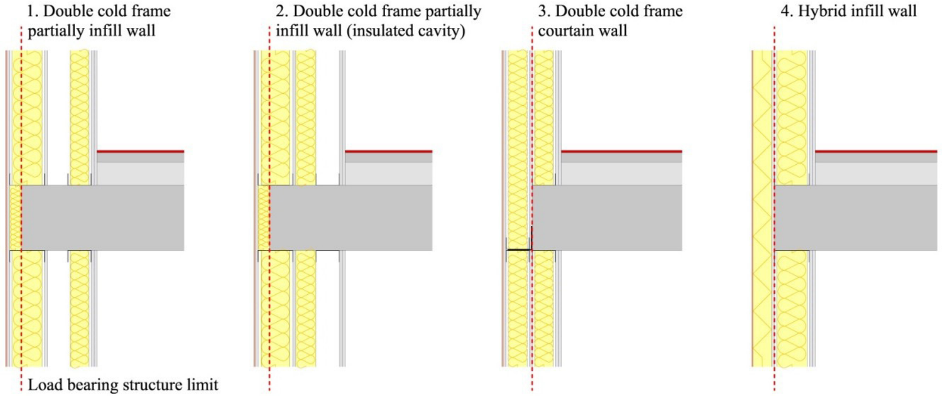


Fig. 11. Construction details of the four steel frame walls and their relationship with the load bearing structures.

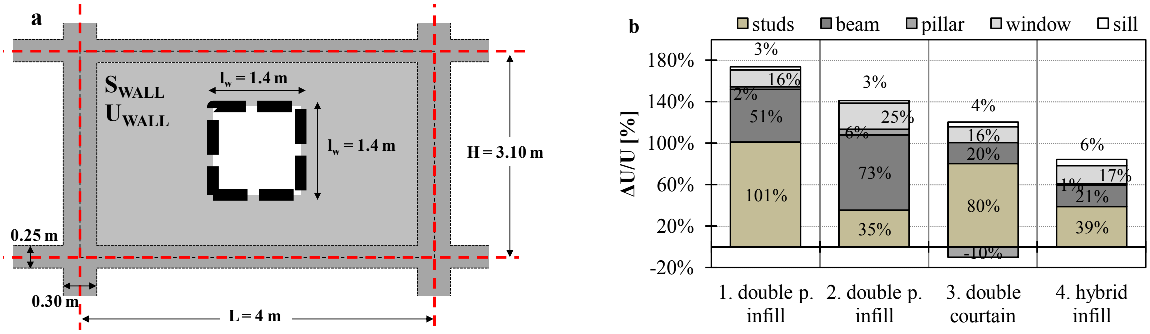


Fig. 12. (a) The standard facade module; (b) percentage increasing of thermal transmittance considering metal frame and thermal bridges.

6. Conclusions

From results it is possible to conclude that the correct evaluation of thermal performances of light steel frame walls requires more complex and detailed analysis than ones necessary for RC and masonry constructions, calculating real thermal performances including all construction details and metal studs. The heterogeneity of materials and the high frequency of metal studs may lead to an overestimation of thermal resistance using available technical data from manufacturers. To consider metal frames, the English standard [4] proposes a simplified method based on the international standard ISO 6946 with a good agreement with modeled results using finite element software for single cold/hot metal frame and hybrid walls. For double cold metal frame walls new simple algorithms have been found with a good agreement with modeled results. Despite of results' reliability, simplified methods are still very complex so in this work they were abandoned. Some new algorithms have been found relating real thermal resistances R' to declared values R. This method is very simple and suitable for U-value calculation software. To fill up lacks of Italian technical standards and manufacturers data it would be useful to: 1) update the existing standard [7] integrating the simplified method to assess the thermal resistance of walls with insulation layers crossed by metal elements as it has been already made in the British standard BRE Digest 465; 2) develop a software that allows designers to calculate in a simple way the real thermal resistance both for double and single light steel frame walls (the cases analyzed should be extended to consider different thermal conductivities of insulation layers while cases analyzed in [4] should be extended considering the double studs). Lastly the use of a simple and freeware finite elements software is recommended both for real U'-values and thermal bridges assessment.

Acknowledgements

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