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Stationary and transient heat conduction in multilayer non-homogeneous stratigraphy

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Abstract

The tendency to speed up the building process and reduce its capital costs is bringing to the increased use of semi-finished products in constructions. One frequent characteristic of those elements is the use of non-homogeneous layers of materials, possibly affecting their thermal properties. In addition to this, the gradual increase in the thickness of insulation layers in buildings is also shifting the focus from the heating loads to the cooling loads, especially for hot climates such as southern Europe, raising the necessity to evaluate the transient properties of construction elements, alongside with the most common stationary properties. The aim of this paper is to correctly evaluate both stationary and transient heat conduction properties of strongly non-homogeneous multi-layered constructions and evaluate the impact of the non-homogeneities. The evaluation of those properties are based on the definitions detailed in the EN ISO 13786 directive, for dynamic thermal characteristics, and in the EN ISO 6946 directive, for stationary thermal characteristics. The stationary thermal transmittance is the parameter considered for the stationary analyses; for transient analyses transient thermal transmittance, time shift and attenuation factor are evaluated. The methodology provided inside the respective directives is applied in order to estimate the parameters. Following, a finite elements model is implemented in the COMSOL Multiphysics software and the same properties are calculated through a finite element analysis performed based on the conditions detailed in the physical definitions of those properties in the respective directives. Each parameter assessed based on the respective directives, EN ISO 13786 and EN ISO 6946, is then compared with the results of the finite elements analyses. Based on those comparisons the impact of the non-homogeneities in the construction for the calculation of its thermal properties are evaluated and conclusions on their relevance in the identification of the thermal properties are given, also the ability of describing non-homogeneous constructions through the directive's methodology is discussed.

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Nomenclature

U	Stationary thermal transmittance	Y_{12}	Complex periodic thermal transmittance
R_{si}	Thermal resistance of the inside surface	$\hat{\Phi}_s$	Amplitude of the inside specific heat flux
R_{se}	Thermal resistance of the outside surface	$\hat{\theta}_e$	Amplitude of the outside temperature
λ_s	Equivalent conductivity of the layer	f	Decrement factor
α_n	Volumetric percentage of the n material	Δt_f	Time lag
λ_n	Thermal conductivity of the n material	T	Period of the variations
U_{din}	Periodic thermal transmittance		

1. Introduction

In recent evolution of the building sector, a constant increase in the use of semi-finished components is rapidly changing the building process. This change can be traced back to the various advantages this kind of building process can offer compared to traditional processes, from lower costs, higher quality control, shorter construction times cleaner and smaller construction sites to, if used correctly, lower environmental impact [1]. It is common, for semi-finished elements, to present more complex structures compared to traditional buildings. This is due to the optimization of their design and manufacturing procedures. One consequence is the presence inside those components of inhomogeneous material layers, compared to the typical homogeneous layers of traditional structures, resulting in the appearance of thermal bridges, typically complex and multi-dimensional. Due to the complexity of those elements the necessity of correctly evaluating the thermal properties of those elements, where assumptions made for simplified methods are therefore not valid anymore and more complex methods could be needed.

Another phenomena of recent years is the progressive shift of thermal energy demand from the heating season to the cooling season due, between other reasons, to the recent tendency of super insulation of building envelope, greatly reducing heating needs but frequently negatively impacting energy needs during summer. This shift in energy loads requires the design and evaluation of building performances to focus on different performance parameters [2] if during the heating season stationary thermal transmittance of the envelope is enough to identify its performances, during the cooling seasons transient properties becomes more important [3,4], requiring the application of more complex models for their calculation. The rising importance of transient properties and summer conditions is also testified by various researches focused on providing tools to evaluate those properties and implement them in the design process of building [5,6]. Those simplified methods and tools are best suited to describe constructions made by homogeneous layers, due to assumptions on which the models are base, not solving the need of performance evaluation of complex in-homogeneous components. The paper evaluates this need by applying both simplified methods, completely or partially neglecting the in-homogeneity, and complex methods and discussing the results.

2. Method

For the purpose of this study, a highly inhomogeneous semi-finished construction component was selected, it is important to note that it is a commercially available component, not an hypothesis. Object of the study is a semi-finished vertical wall composed by an outside insulation layer mad of expanded polystyrene and an inside layer made of precast concrete for structural purpose. Thickness of the structural layer is constant and equal to 6 cm, while the thickness of the insulation layer can vary and comes in 3 different sizes, defining the three analysed components; Component 1 has an insulation thickness of 6 cm, Component 2 totals a 8 cm insulation and lastly Component 3 insulation layer equals 10 cm. The inhomogeneity of the component is generated by the presence of a triangular steel cage inserted between the two layers for structural and production reasons. The cage interests both the insulation and structural layer for a depth of 3 cm each, has a complex and tri-dimensional shape and is not suited for simplification.

The prefabricated panel is directly positioned on the structure to create the envelope of the building and completed on-site with the application of plaster and finishing, not considered in this study. To perform the thermal analyses, a detailed finite element model is developed and implemented in the COMSOL modelling software; an example can be seen in Figure 1. Detailed simulations, both stationary and transient, are performed based on those models. Single panels have an height of 3 m and a variable length up to 3m, to avoid unnecessary modelling the case study is reduced to a 0.5x0.5 m portion of the component with one steel cage, appropriate verifications were made to ensure this simplification would not impact the results, resulting in errors lower than 3 %.

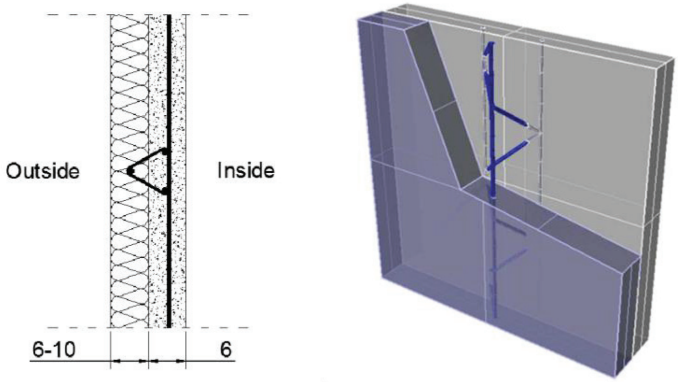

Fig. 1. (a) Section; (b) 3D model of the case study.

To enable comparisons between different calculation methods of both stationary and transient properties of each construction here different calculations methods are applied, and subsequently detailed. First the methodology detailed by the relevant ISO directive, identified from now on “Method A”; second, a variation to the directive methodology to partially consider the effect of inhomogeneity is applied and identified as “Method B”. Lastly, a detailed finite element analysis based on the definition of the single properties in the corresponding directive, is presented and identified as “Method C”.

2.1. Stationary properties evaluation

For the evaluation of stationary properties directive EN ISO 6946 is taken as a reference. Stationary thermal transmittance is the only stationary thermal property considered for the comparison. For Method A the procedure defined in the directive is applied directly resulting in the following formula:

$$U = \frac{1}{R_{si} + R_1 + R_2 + \ldots + R_n + R_{se}} \tag{1}$$

The formulation is based on various simplifications hypotheses, the most relevant for this study is the definition of the various layers of the building component as thermally homogeneous and surfaces between layers have to be planar and parallel. Those hypotheses does not apply in case of inhomogeneous components, therefore for Method A the presence of the reinforced steel cage, cause of the inhomogeneity, is neglected.

The directive suggests a solution for inhomogeneous layers, however it still require a mono-dimensional definition of the component, therefore is not suitable for complex constructions such as the ones under analysis. In Method B, to consider the presence of the steel cage but still apply Formula (1), equivalent homogeneous layers are obtained through the application of Formula (2) to obtain an equivalent conductivity of the layer.

$$\bar{\lambda} = \left(\frac{\alpha_1}{\lambda_1} + \cdots + \frac{\alpha_n}{\lambda_n}\right)^{-1} \tag{2}$$

Method C is based on the stationary thermal simulation of the finite element model previously shown with imposed boundary conditions imposed as defined by the directive: constant temperature of the two spaces on both sides of the component, inside and outside surface resistances according to the temperatures and adiabatic surfaces on the other four sides of the modelled component. Total heat flux is calculated from the simulation and, knowing temperatures and surface area, equivalent thermal transmittance of the component is obtained.

2.2. Transient properties evaluation

As suggested by the reference directive, EN ISO 13786, three different performance indicators are evaluated for transient analyses. Method A directly applies the procedure indicated in the directive, first indicator is the dynamic thermal transmittance represent the ratio of the complex amplitude of the density of the heat flow rate through the surface of the component adjacent to the internal zone to the complex amplitude of the temperature in external zone, as shown in the following equation:

$$U_{din} = |Y_{12}| = \left|\left(\frac{\hat{q}_s}{\hat{\theta}_e}\right)_{\hat{\theta}_s=0}\right| \tag{3}$$

Another frequently used performance indicator is the decrement factor, representing the dampening of the thermal heat wave when passing through the component compared to the stationary transmittance, shown in the following equation:

$$f = \frac{U_{din}}{U} = \frac{|Y_{12}|}{U} \tag{4}$$

Lastly, the time lag is calculated by the following equation, being Y a complex number, and represents the time delay between the outside and inside thermal waves.

$$\Delta t_f = \frac{T}{2\pi} \arg(Y_{12}) \tag{5}$$

As detailed in the directive, those parameters are obtained through the solution of various matrixes of complex numbers; a Matlab program was written to correctly solve the mathematical problem. Due to the system only considering homogeneous layers, as for stationary analysis, the presence of steel cage is neglected in Method A.

Similarly, to stationary analysis, Method B still applies the directive procedure but using equivalent homogeneous layers, all the input properties of the layers are therefore calculated based on the materials included in the single layer. A dynamic thermal simulation of the finite element model is used for Method C, setting the boundary and starting conditions in accordance with the directive with a fixed temperature for the internal zone and a sinusoidal function determining the external temperature as a function of time. Results of the simulation, time series of temperatures and heat fluxes, are elaborated to obtain the performance indicators as described above.

3. Results

Results of the evaluation of the stationary thermal transmittance are reported in Table 1 for the different component. As expected, for all methods applied, increasing the thickness of the insulation layer reduces the thermal transmittance of the component. Differences in results between Method A, neglecting the inhomogeneity, and Method B, using equivalent homogeneous layers, are minimal and lower than 1 %. Differences between Method A and Method C are instead more consistent, ranging from 4.3 % to 7.7 %, worsening the thermal performances of the element. Also, the results prove the strong influence of the thermal bridge inside the component, not simply function of the presence of a different material inside the layers but of its special positioning, changing the problem from mono-dimensional, as hypnotized in the directive, to fully tri-dimensional. Another interesting result is how the difference between Method A/B and Method C lowers by increasing the thickness of the insulation layer, reducing the effect of the thermal bridge as expected, therefore the more the thermal bridge is relevant the more the directive is unable to describe the real thermal performances of the component.

Table 1. Stationary thermal transmittance results.

	Thermal transmittance U *[W/(m²K)]*			Percentage difference *[%]*		
Component	Method A	Method B	Method C	A - B	A - C	B - C
1	0.606	0.607	0.658	0.188	7.928	7.754
2	0.470	0.471	0.498	0.146	5.660	5.522
3	0.384	0.385	0.402	0.119	4.463	4.349

Moving on to the transient properties, Table 2 shows the results in term of transient thermal transmittance of the analysed components. Results are similar to what seen for stationary properties. Method A and Method B gives similar results, confirming how the detrimental effect of the thermal bridge is not given by the simple presence of a different material, steel, but more by its geometry and spatial position. Differences between the directive, Method A, and the finite elements model, Method C, are similar as previously seen for stationary thermal transmittance ranging from 4.9 % to 8.4 % and decreasing with the increase in thickness of the insulation layer. For all methods, increasing the thickness of the insulation layer decreases the value of transient thermal transmittance, improving the thermal properties of the component.

Calculations concerning the decrement factor, reported in Table 2, shows different results, suggesting no major differences in the evaluation of the decrement factor between the three methods A, B and C. This is due to the definition of the decrement factor itself as a ratio between stationary thermal transmittance and transient thermal transmittance. As the two transmittances shows similar differences between the various methods they tend to cancel each other when calculating their ratio, as a result decrement factor evaluation shows similar results for all methods. It is also interesting to note how the decrement factors does not vary significantly with the increase of the insulation thickness, meaning the impact of this increase is nearly equal on both stationary and transient thermal transmittance.

Table 2. Transient properties: transient thermal transmittance results.

	Transient thermal transmittance U_{din} *[W/(m²K)]*			Percentage difference *[%]*		
Component	Method A	Method B	Method C	A - B	A - C	B - C
1	0.416	0.416	0.454	0.000	8.451	8.451
2	0.318	0.317	0.337	-0.095	5.757	5.846
3	0.256	0.256	0.269	-0.156	4.796	4.944

Table 3. Transient properties: decrement factor results.

	Decrement factor f *[-]*			Percentage difference *[%]*		
Component	Method A	Method B	Method C	A - B	A - C	B - C
1	0.687	0.685	0.690	-0.188	0.485	0.672
2	0.675	0.674	0.677	-0.241	0.225	0.465
3	0.667	0.665	0.670	-0.276	0.503	0.777

Lastly, results for the evaluation of Time Lag are shown in Table 4. As for stationary and transient transmittance Method A and Method B shows similar results, with differences of the order of 1 %; Method C on the other hand shows higher differences ranging from 13.4 % and 21.1 %. First thing to note is those differences are significantly higher than the ones registered previously, always lower than 8.5 %. Also interesting is how, increasing the insulation layer thickness increases the differences in this case, compared to the previous ones where increasing the thickness tended to reduce the differences between methods. As for the other properties, for all methods, increasing the insulation thickness improves the performances of the component by increasing the time lag between heat waves.

Table 4. Transient properties: time lag results.

Component	Method A	Time lag Δt_f [h] Method B	Method C	Percentage difference [%] A - B	A - C	B - C
1	3.560	3.603	4.160	1.188	14.423	13.394
2	3.780	3.827	4.670	1.228	19.058	18.051
3	4.020	4.077	5.170	1.391	22.244	21.147

4. Conclusions

Semi-finished components and constructions are becoming more and more diffuse in the modern building sector due to various advantages compared to standard technologies. Nonetheless those elements presents various critical issues, one of which is the typical use of inhomogeneous and complex stratigraphies, making the thermal properties difficult to evaluate and going against simplifications used by current directives on the matter. Also, due to current tendency in insulation and climatic changes, cooling loads and summer conditions are becoming always more important, requiring the evaluation of more complex transient thermal properties. To highlight the criticalities

Results of the analyses shows how the use methodologies suggested in the directives for the evaluation of both stationary and transient thermal properties result in significant differences compared to the evaluation of the same properties with a finite element model based on their definition. Differences for the analysed case studies vary from 4 % to more than 21 % depending on the thermal property analysed. All the properties shows significant differences with the exception of the decrement factor which does not shows differences between the directive method and the finite element model. Obtained results tend to advice against using the methods suggested in the directive to evaluate thermal properties of components while significant in-homogeneities are present inside the layers, or at least the use of significant safety coefficients. This is due to the fact directive methods are based on the assumption of homogeneous layers of material, therefore the more the in-homogeneities are significant inside the component the more the methods become inaccurate.

Increasing the thickness insulation tends to reduce the differences for stationary thermal transmittance and transient thermal transmittance, while the differences in time lag tends to increase by increasing the thickness. Depending on the parameter how need to me evaluated, the directive methods could be used with an adequate accuracy if insulation thickness is large enough. In conclusion the use of simplified methods for the evaluation of stationary and thermal properties of construction components, while accurate and useful for components with homogeneous layers, should be avoided when analysing in-homogeneous stratighaphies, using detailed finite elements models instead, as differences can be significant as shown in this paper.

References

[1] Aye L., Ngoa T., Crawford R.H., Gammampila R., Mendis P. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. Energy and Buildings, Volume 47, April 2012, Pages 159–168

[2] Aste N., Angelotti A., Buzzetti M.. The influence of the external walls thermal inertia on the energy performance of well insulated buildings. Energy and Buildings 41 (2009) 1181–1187

[3] Di Perna C., Stazi F., Ursini Casalena A., D'Orazio M. Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy and Buildings 43 (2011) 200–206

[4] Al-Sanea S.A., Zedan M.F., Al-Hussain S.N. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. Applied Energy 89 (2012) 430–442

[5] Gasparella A., Pernigotto G., Baratieri M., Baggio P.. Thermal dynamic transfer properties of the opaque envelope: Analytical and numerical tools for the assessment of the response to summer outdoor conditions. Energy and Buildings 43 (2011) 2509–2517

[6] Ballarini I., Corrado V. Analysis of the building energy balance to investigate the effect of thermal insulation in summer conditions. Energy and Buildings 52 (2012) 168–180