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Thermal Performance of Lightweight Composite Slabs: FEM and DOE Analyses

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Abstract

The aim of this work is to investigate the thermal performance of a new lightweight composite slab using advanced numerical methods based on nonlinear finite element models (FEM). Furthermore, the thermal optimization of the composite slab is done by means of the design of experiments (DOE) methodology. At present, this type of floor is very efficient in terms of energy saving and sustainability, due to its downward thermal transmittance and weight (or dead load) values. Six different lightweight composite slabs are modelled using a steel plate, lightweight concrete, inner layers made of expanded polystyrene and lightweight mortar insulation. In order to obtain the thermal properties of the different materials, a non-destructive test (NDT) system based on the modified transient plane source technique, following the ISO/DIS 22007-2.2, has been used. The convection and radiation in the cavities are modelled using an equivalent film coefficient from the UNE-EN-ISO 6946 Standard. Then, the nonlinear analysis for upward and downward fluxes in each different composite slab is solved. Based on the best slab configuration, an optimization using the DOE methodology is developed. The thermal transmittance value, for both upward and downward fluxes, is adopted as the objective function. The input variables considered are the composition and thickness of the lightweight concrete, the thickness and insulation properties of the lightweight mortar and the thickness and size of the inner expanded polystyrene. The DOE methodology provides the sensitivity analysis and response surface for each variable with respect to the objective function. In this way, the best configuration of the composite slab to obtain the best thermal behavior is reached. In summary, the methodology described in this research work can be applied to other composite slabs in order to optimize their thermal behavior.

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Keywords: energy efficiency; thermal insulation; DOE analysis; sustainability in construction; lightweight concrete; nonlinear simulation

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1. Introduction of composite slabs

The first use of composite slabs was in the USA in the 1930s. These structural elements are commonly used in commercial, industrial and residential buildings. They have significant benefits such as speed and safety of construction; reduction of weight; saving in transport, and high structural stability. Although there is no national standard regarding this structural system, it is widely used in Spain. Numerical studies of these composite slabs are very useful to provide better knowledge of this type of floors in terms of thermal behaviour.

General composite slabs are made up of cold-formed galvanized steel plate and concrete. This paper presents an innovative composite slab composed of steel (S), lightweight concrete (LWC), expanded polystyrene (EPS) and insulating lightweight mortar (LWM). This specific composition provides high thermal insulation.

Fig. 1 shows the main elements of the composite slab studied in this paper. The steel plate works as formwork as well as supporting the positive bending, while negative bending is supported by the lightweight concrete. Reinforcement bars are usually placed inside the concrete layer in order to support additional loads such as thermal stress or retraction.

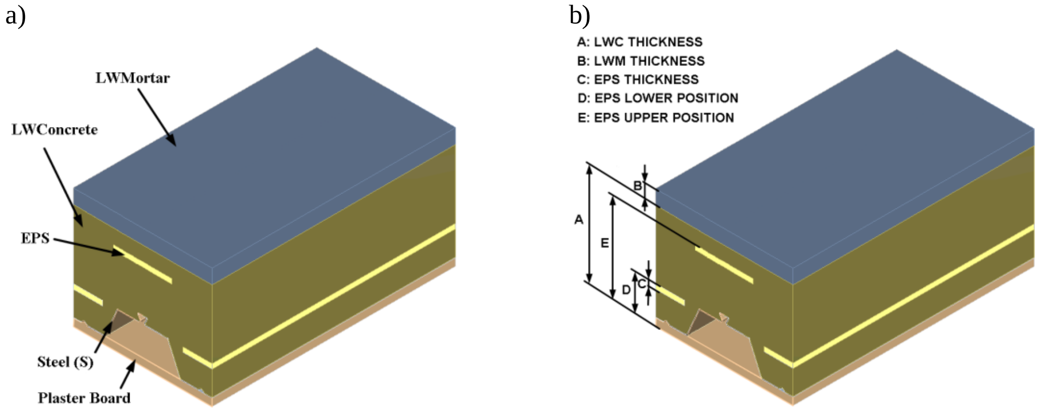

Fig. 1. 3D geometry of the composite slab: (a) main materials; (b) main geometrical parameters.

The latest update of the Spanish National Standard DB-HE “Energy Savings” is very restrictive in terms of energy efficiency. It differentiates between each climatic zone in Spain in terms of building heat transfer. In this paper, the numerical research identifies the optimum composite slab geometry, meeting the new energy efficiency requirements.

There is a lack of research into the thermal behavior of composite slabs [1], making this work a current and important contribution. The authors of this paper have solid experience in thermal studies using Finite Element Methods (FEM) [2] -[5].

Nomenclature

U	thermal transmittance (W/m^{2}K)
T	temperature (K)
q/A	heat flux (W/m^2)

2. Thermal properties

Thermal properties of materials are basic to numerical models. Accurate measurements of thermal properties are necessary for reliable results. For this reason, Non Destructive Tests (NDT) have been developed to obtain the thermal properties of each material. The equipment used in this work includes a thermal conductivity analyzer TCI by C-Therm. This system applies a transient and constant heat source to the specimen using an interfacial heat reflectance sensor. Using this technology, both conductivity and specific heat are measured quickly and directly, see Fig. 2.

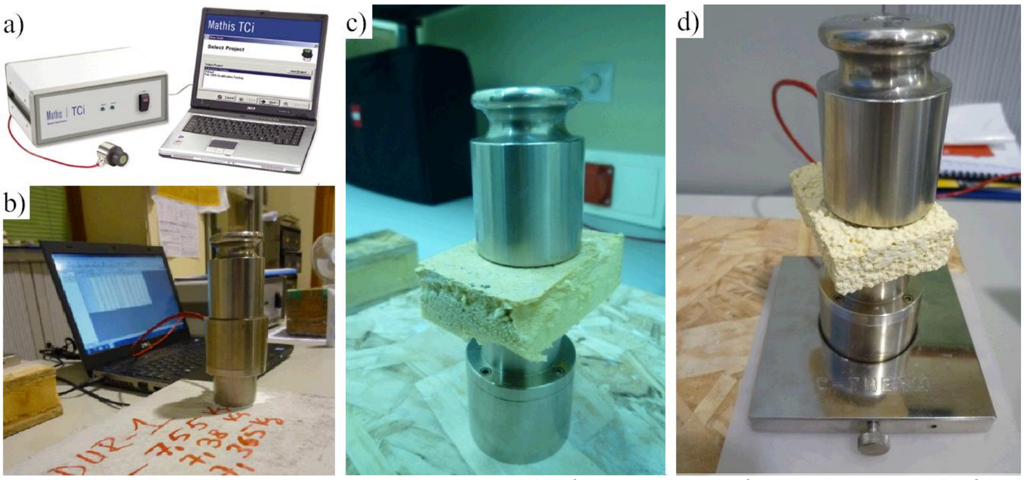

Fig. 2. Thermal conductivity measurements (a) TCI equipment; (b) of LWConcrete; (c) of EPS measurements; (d) of LWMortar

In addition, the density of all the materials used was measured in order to define their properties in the numerical model. The values of thermal conductivity and density of each one are shown in Table 1.

Table 1. Physical properties of materials of the composite slab.

Materials	Conductivity (*W/m·K*)	Density (kg/m^3)
Steel	60.5	7850
LWMortar	0.045	160
EPS	0.04	15
Plaster board	0.25	832
LWConcrete (structural-25)	0.70	1622
LWConcrete (non-structural-15)	0.39	1410

3. Numerical Model

Two numerical models have been studied in this work: the thermal behavior of an upward and a downward flux through the composite slab. The finite element mesh of the numerical model for both cases is shown in Fig. 3.

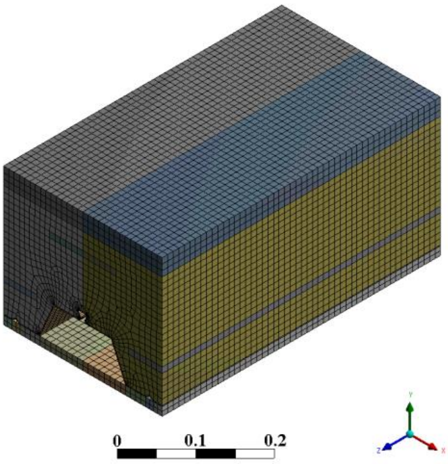

Fig. 3. Finite Element Mesh of the numerical model.

Boundary conditions of this thermal study have been established following the National Standard ISO 6946:2007, [6]. This National Standard stablishes the values of the convection coefficients depending on the heat flux direction. The input parameters considered are the following:

- Ambient temperature of 22 *ºC* (295 *K*)
- 10 W/m^2 heat flux for both cases studied, upward and downward fluxes.
- Convection coefficient of 10 $W/m^{2o}C$ for upward flux, and 5.88 $W/m^{2o}C$ for downward flux. Convection film is applied to the opposite surface with respect to the heat flux, Fig. 4.
- In order to simulate the convection and radiation heat transfer inside the cavities of the composite slab, an equivalent film coefficient is applied. The film coefficient is applied using a pilot node whose behavior governs the chosen surface selected.

The values of this equivalent film coefficient are shown in Fig. 4(a) for the upward flux and in Fig. 4(b) for the downward flux.

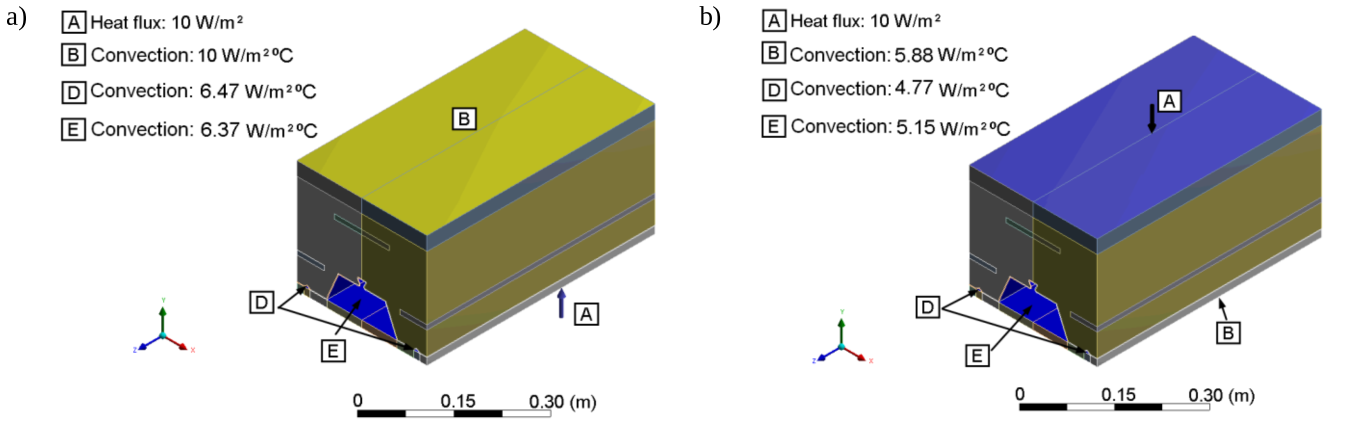

Fig. 4. Boundary conditions applied to the numerical model: (a) for the upward flux; (b) for the downward flux.

4. Results

The main results obtained in the numerical analysis show a temperature distribution throughout the composite slab for both cases studied: upward and downward fluxes. Temperature values and temperature distribution in both cases are very similar. Transmittance, which provides the thermal efficiency of these composite slabs, is obtained using equation (1).

$$U = \frac{q/A}{\Delta T} \qquad (1)$$

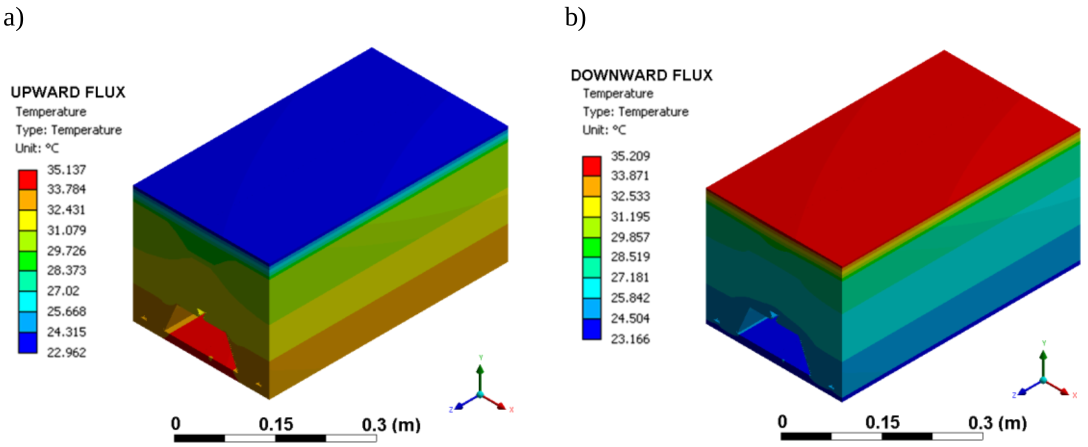

Fig. 5. FEM results: (a) for upward flux; (b) for downward flux.

Thermal transmittance obtained is 0.879 $W/m^2{}^oC$ for the upward flux model and 0.883 $W/m^2{}^oC$ for the downward flux model. The thermal efficiency of the composite slabs is similar for the upward and downward fluxes.

4.1. Design of Experiments methodology

Design of Experiments (DOE) analyzes the relation between input and output parameters. The aim of this DOE is to obtain the optimum geometrical design of the composite slab in order to achieve the best thermal behavior. This methodology determines the influence of several input parameters (see Table 2) on an output parameter which is the thermal transmitance. In this way, the DOE is able to identify the most influential parameters and optimize the geometry of these composite slabs.

The input parameters considered in this study and their values are shown in Table 2.

Table 2. Values of the input parameters.

Input Parameter	Min Value	Initial Value	Max Value
LWC thickness (m)	$1.80\cdot10^{-1}$	$2.00\cdot10^{-1}$	$2.20\cdot10^{-1}$
EPS thickness (m)	$9\cdot10^{-3}$	$1.0\cdot10^{-2}$	$1.1\cdot10^{-2}$
LWM thickness (m)	$2.7\cdot10^{-2}$	$3.0\cdot10^{-2}$	$3.3\cdot10^{-2}$
First EPS position (m)	$2.7\cdot10^{-2}$	$3.0\cdot10^{-2}$	$3.3\cdot10^{-2}$
Second EPS position (m)	$5.472\cdot10^{-2}$	$6.08\cdot10^{-2}$	$6.688\cdot10^{-2}$

The objective function is the thermal transmittance of the composite slabs in both upward and downward fluxes. The sensitivity analysis quantifies the influence of each input parameter on the objective function. Two different sensitivity analyses have been studied. Firstly, the influence of thickness on thermal behavior, taking into account the EPS, the LWC and the LWM thicknesses, see Fig. 6(a). Secondly, the influence of the position of the EPS inner layer as well as its thickness. These parameters are related to the thermal behavior of the composite slab, see Fig. 6(b).

a) b)

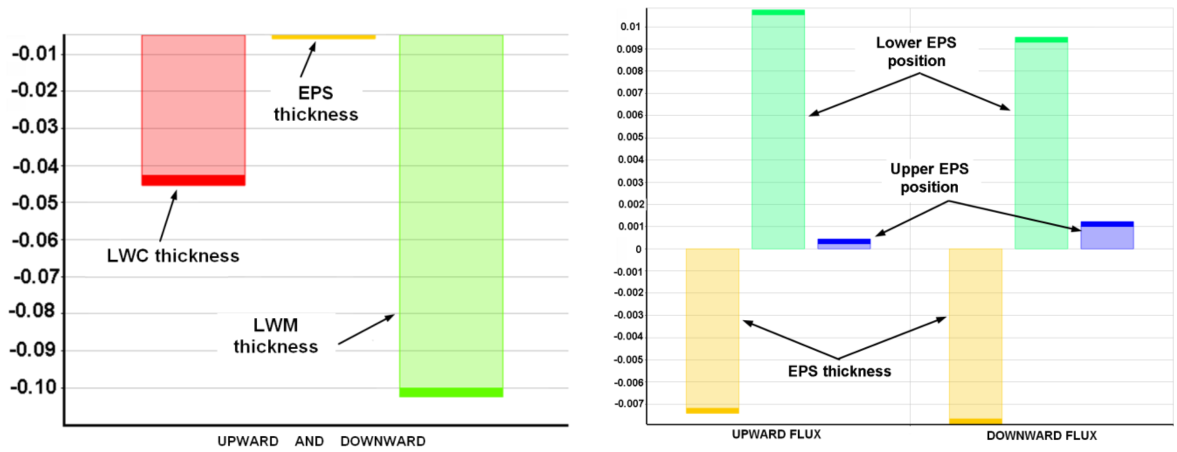

Fig. 6. Sensitivity analyses for upward and downward fluxes: (a) material thicknesses; (b) EPS layer position and thickness.

Figure 6 a) shows the influence of the thicknesses of LWC, EPS and LWM on the thermal transmittance of this composite slab. As it is shown in this graphic, the relation is an inverse relation which means that the increase in thicknesses provides a decrease in the thermal transmittance of the slab.

The sensitivity analysis determines the most influential parameters in the thermal transmittance of the composite slabs. The most influential input parameters are related using Response Surface Methodology (RSM). The RSM finds the optimum input values for the best thermal transmittance of the composite slabs.

a) b)

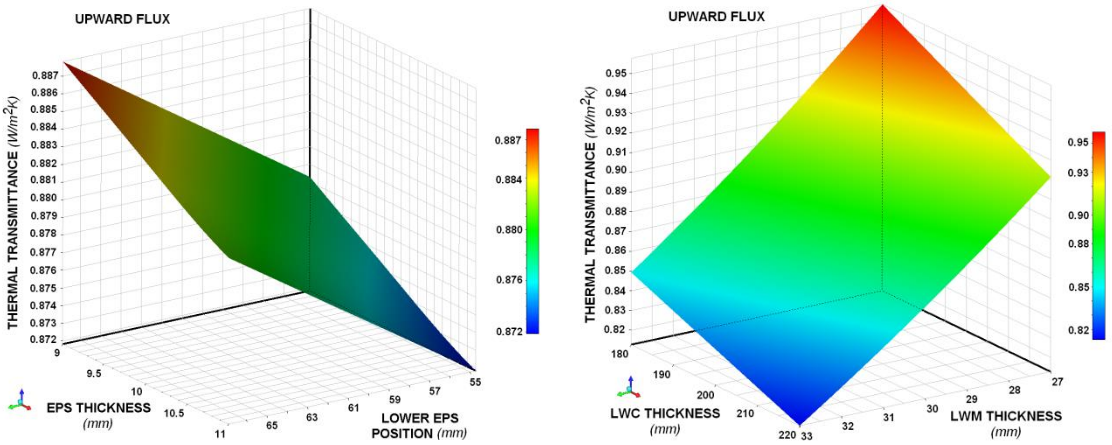

Fig. 7. Response Surfaces: (a) for EPS thickness and the lower EPS position; (b) LWC and LWM thicknesses.

5. Conclusions

The main results of this numerical analysis perfect the design of a thermal efficient composite slab. This study concludes that the most important parameters of these composite slabs are the thicknesses of the different materials; see Fig. 6(a). LWC and LWM thicknesses are more influential in the thermal transmittance results than EPS thickness (due to the very low thermal conductivity of the EPS). The influence of the LWM and LWC thicknesses on the thermal transmittance of the composite slab is an inverse relation, and the LWM thickness is more influential than the LWC one, see Fig. 6(a). The position of the EPS layers is also crucial. For this reason, the DOE analysis compares the upper and lower positions of the EPS layers and their thicknesses, see Fig. 6(b). The results show that the lower position is more influential on the thermal transmittance than the upper position for both upward and downward fluxes. This study provides the best arrangement inside the slab to improve the thermal insulating performance. With respect to the lower EPS layer, the closest position to the steel sheet provides the best thermal efficiency. At the same time, the thickest EPS layer provides the best insulating behavior. Finally, LWC and LWM are restricted by boundary conditions of the building but it was proved that in both cases, the thickest layer results in the highest thermal efficiency of the composite slab.

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