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Theoretical and Experimental Studies on Heat Transfer in Multi-Layer Composite

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Abstract

This paper presents an experimental system used for the measurement of heat developed at the interfaces of layers that form the stacked combination (between two and six layers), with the aid of appropriately positioned thermocouples. Temperatures curves are envisaged together with thermal gradients and corresponding processing to establish the fourth degree polynomial functions and maximum and minimum temperature deviations and thermal gradients. Finite element numerical modeling led to the determination of the deformations and stresses developed under the effect of heat in the plate being tested (in this case, for example, a six-layers plate). The temperature values between layers were established theoretically and were compared with the experimental values and then used in the numerical analysis.

Keywords: *laminated composites, thermal experiment*

Introduction

From the analysis of the technical data provided by literature and presentations of scientific or specialized companies, it results an important dispersion for materials characteristics of laminated composite used in multi-layer composites. Laminated composite plates are made by superposing two or more layers of composite material, different from the geometrical point of view and/or structure. They are manufactured and designed to be used as exterior insulation, in buildings as interior walls, walls sound insulation and accessories for roofs, walls and other thermo for industrial buildings. Composite materials used in these plates are usually extruded or expanded polystyrene, polyurethane, cork, thermo-plastic, which are consumer goods market as plates.

Thirty years ago, sandwich plates were a problem for engineers, architects and specialists regarding production costs and their design [1]. Multi-layers offered a spectacular dimension, proving to be a sustainable solution, fast and economic. Use of multi-layer composites is viable in many technical fields, in general, in the equipment industry, in particular - pipelines, pressure vessels with or without mixing systems fluids, vibration damping of dynamic machines (screens, centrifuges, crushers, vibrating mills etc.), both thermal and acoustic insulation.

Purpose of the Experiments

This paper aims to determine, through appropriate experimentation, the temperature range developed by a heat source in a multi-layer composite wall with elastic/pseudo-elastic structure. For example, to take into account the two combinations of layers of material relatively close to the point of view of thermal characteristics, but with different positioning. It was considered the case with required/known temperatures inside and outside the wall, or if the present value of heat flow, internal temperature and the ability to set the maximum external temperature. Thermal gradient values require optimal organization of structure/layers composites multilayer. The experimental methodology could be recovered in the plastic matrix composites, metal or ceramic plates and various natures and configurations.

Materials Used in Tested Laminated Composites

Considering the maximum temperatures for which the composites materials can keep their structure, a first layer comprising a reflective film of aluminum which adds sequentially to the other layers can be inserted.

Polystyrene

Polystyrene is highly resistant to mildew, abrasion, keeps its shape well over time, easy to clean and dry [2]. There are four important types of foam polystyrene commonly used in the residential building isolation, commercial, and used in various industrial applications, and others. These are the expanded polystyrene (EPS) [3], the extruded polystyrene (XPS), the polyurethane (PUR) and the polyisocyanurate (PIR).

Each of these materials has individual characteristics, certain advantages and disadvantages for the specific engineering applications [3]. Expanded polystyrene foam (EPS) is a plastic material which has special properties due to its structure. Made up of individual cells from low density polystyrene, EPS - is very light. Because its cells are not interconnected, the heat can not easily penetrate, so it is a good thermal insulator.

It was found that sounds do not easily cross the polystyrene plate which leads to the conclusion: EPS is a good insulator in terms of sound. It is also used in flotation devices, insulation, egg cartons, meat and so on, to produce disposable tableware, and in order to obtain the necessary sandwich boards in various utilizations [5]. Thanks to its basic characteristics, EPS is used more often by civil engineers, mechanical engineers and other categories, in order to obtain the desired results with a very low cost. The cost quality ratio ensures to all producers a better sale of these products.

Sandwich - s / sandwiches made from different materials, with different compositions, combined with polystyrene plates are much lighter, giving maximum efficiency at low cost. EPS preserves the physical properties even if it is combined with other materials, as shown in countless experiments. It is a recyclable material [6].

Extruded polystyrene foam (XPS) is composed of solid polystyrene crystals. The crystals, together with particular additives and the blowing agent are fed into an extruder. Inside the extruder, the materials are mixed and melted under controlled conditions of high temperature and pressure, turning them into a viscous fluid. In the flow sheet, this mixture is introduced in a mill, from which comes out in the form of foam, which is to be cooled. The result obtained from the extrusion process is a unique product with uniform structure foam and with closed cells with smooth surface. XPS, due to the consistency, has a high resistance to moisture, providing outstanding benefits for most applications, both in construction and in engineering in general.

Like any product, it also presents drawbacks. One of these would be that, although it is treated with (fireproof material) additives, it is preferable not to be near sources of heat, open flame or other ignition sources during transportation, storage, installation and practical usage.

Advantages are given by the material characteristics, such as low-value long-term conductivity, excellent mechanical strength, lack of capillary resistance, durability to the freeze - thaw, high resistance to vapor diffusion, light weight and ease of handling, easy cut with simple tools, resistance to deterioration under the action of weathering, clean, odorless and non-irritating to skin.

Cork

It consists of the outer bark of cork oak (Quercus suber L. and Quercus occidentalis) [7, 8] component from the forests of the Mediterranean, with mild winters comparative with normal oak from the center of the European continent [9]. It is harvested from trees without damaging the bark thereof. The first harvest of cork is done in about 20 years, and then every 9-10 years is repeated when its bark is regenerated until the tree is about 200-250 years [9]. After this age, the tree is removed and a sapling is planted, ensuring thus a raft continuously.

Oak forests are found in Portugal, Spain, Southern France, Italy and North Africa. Today, more than half of the raw material is from Portugal [9]. Harvesting of the bark from the cork oak is a very delicate operation. The expanded and agglomerated cork is very interesting to be used in industry [10, 11].

Presentation of the Experimental Facility

For experimentation, the following methodology has been used:

- A cubical box with sides x 500 mm x 500 mm (fig. 1) was made;
- Wall tested was designed in such way that the different layers are attached by welding to each other with a special adhesive (Universal Kebler) that does not “melt” on the polystyrene;

Fig. 1. Overview of the Test [12]

<u>Note</u>: The two “combinations” used for layered walls are the following:

Combination I: The type of combination of layers:

$$a = \sum_{1}^{2} j;\; b = \sum_{1}^{3} j;\; b = \sum_{1}^{3} j;\; c = \sum_{1}^{4} j;\; d = \sum_{1}^{5} j;\; e = \sum_{1}^{6} j;\; f = \sum_{1}^{7} j\;, \tag{1}$$

where j is the number of the layer considered.

Materials: 1 – aluminum foil and expanded polyester (δ = 3 mm), 2 – expanded polystyrene (δ = 20 mm), 3 – extruded polystyrene (δ = 12 mm), 4 – expanded polystyrene (δ = 20 mm), 5 – Cork (δ = 3 mm), 6 – polystyrene (δ = 20 mm), 7 – Polyvinyl Chloride (PVC) - Protex light (δ = 3 mm).

Combination II: To store the same type of combination of layers as described above.

Materials: 1 – Aluminum foil (bubble [13]) and expanded polyester (cell sheet) (δ = 3 mm), 2 – extruded polystyrene (δ = 20 mm), 3 – extruded polystyrene (δ = 12 mm), 4 – expanded polystyrene (δ = 20 mm), 5 – cork (δ = 3 mm), 6 - expanded polystyrene (δ = 20 mm) 7 - polyvinyl Chloride (PVC) - Protex light(δ = 3 mm).

- On the opposite wall of the tested box, in the experimental box, the heat source (fig. 2) was positioned, producing around it a maximum temperature of approximately 100 C;
- Every time the temperature was measured on the outside layer, made by means of thermocouples placed properly (fig. 3), in order to establish an average value on that surface, given the specific of the experimentation; in this regard it was used a device PICO PURPOSE TC - 08/usb with software acquisition and processing PICO SOFT related on a computer, the device was connected to thermocouples set; thermocouples with numbers 1, 2, 4, 6 and 7, read the temperatures outside the plates, while the thermocouple with number 5 read the temperature inside the wall;
- The data are acquired and are processed; interpretation of averages and practical proposals.

Fig. 2 . The heat source positioning [12]

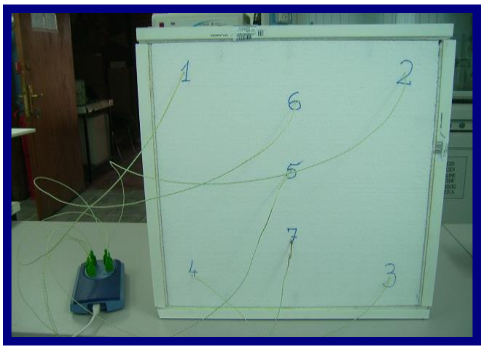

Fig. 3. The location of the transducers on the outer surface of the plate test [12]

Data Acquisition and Processing of Experimental Data

Current values of temperatures recorded by thermocouples (TM1, TM2, TM3, TM4, TM5, TM6, TM7 and TM8 - placed near the heat source) were recorded for the six layers of composite laminated plates tested. With these values it was then obtained the corresponding polynomial functions. The same methodology was undertaken for thermal gradients that define the eight thermocouples.

In the followings, by way of example, but also of practical interest, only some characteristic results are included, for the case with six plates multi-layer from the two combinations mentioned above (the current recorder temperature graphs for the four thermocouples: combination I – figs. 5-7; combination II – figs. 8-11).

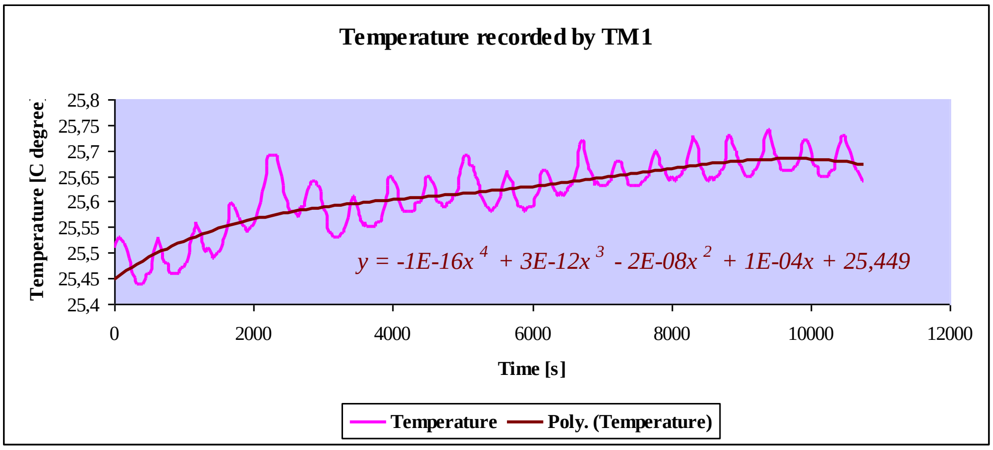

Fig. 4. Temperature recorded by TM1 and corresponding polynomial function [12]

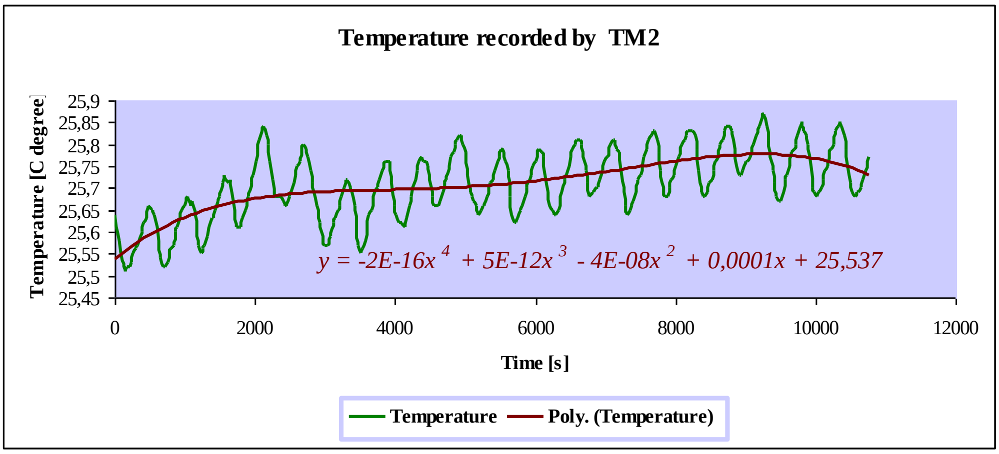

Fig. 5. Temperature recorded by TM2 and corresponding polynomial function – combination I [12]

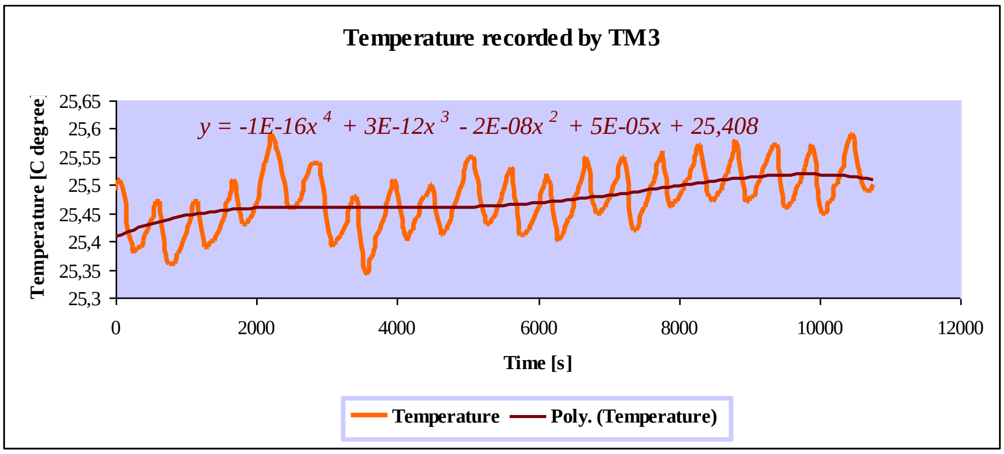

Fig. 6. Temperature recorded by TM3 and corresponding polynomial function – combination I [12]

Observations on the experimental results and their processing

1. Analyzing the form of the variation of the temperatures recorded by the eight thermocouples, there is in the first portion an (relatively) ascending trend that shows the transition to a portion of the Heat transfer (relatively) stabilized.

2. Transition areas are different as a way of changing the values of temperature, on one hand, by the position shown on the thermocouples, as well as due to the unstable intensity of the supply current source, on the other hand.
3. Modes of variation of the temperatures recorded by thermocouples are conditioned by the heat transfer by convection and conduction, on one hand, but also by the possible imperfections in the contact between layers, , on the other hand, which were not analyzed in the present experiments.

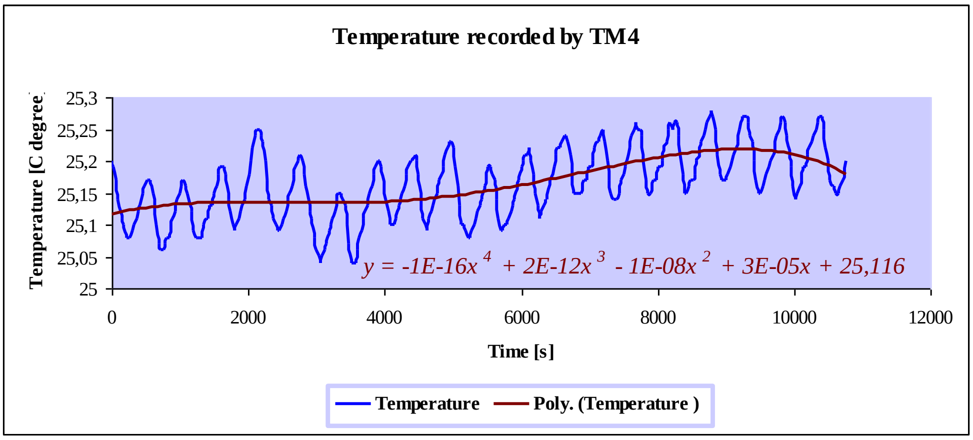

Fig. 7. Temperature recorded by TM4 and corresponding polynomial function – combination I [12]

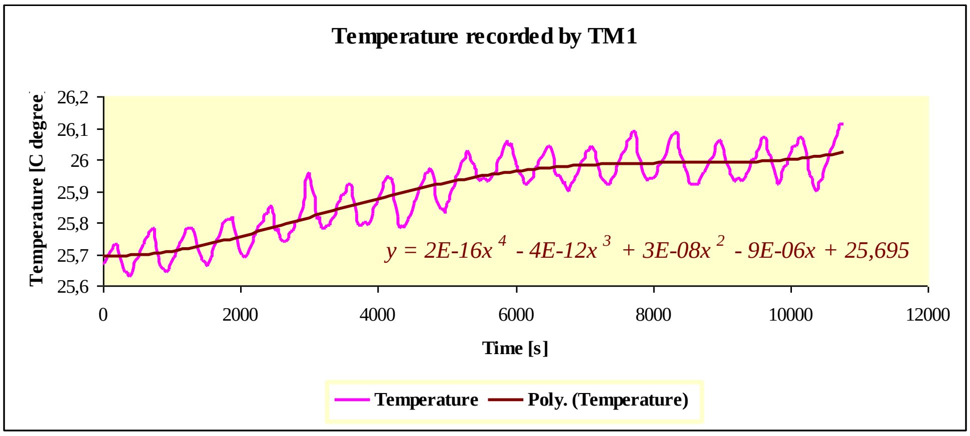

Fig. 8. Temperature recorded by TM1 and corresponding polynomial function – combination II [12]

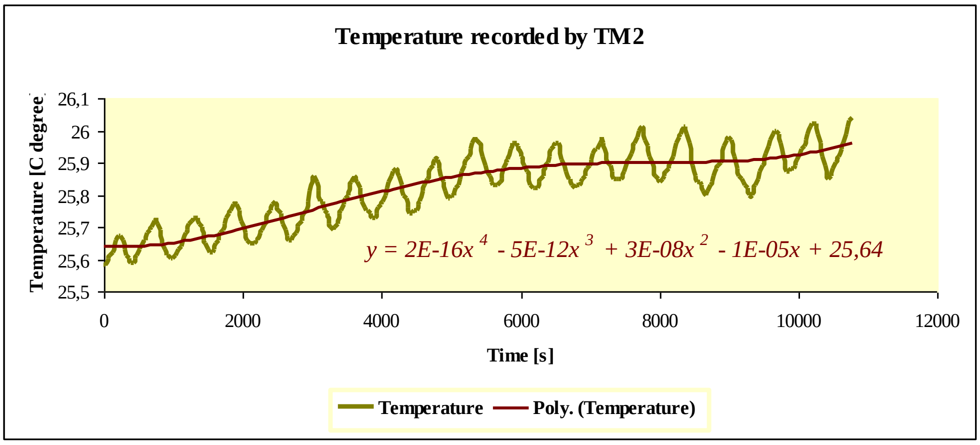

Fig. 9. Temperature recorded by TM2 and corresponding polynomial function – combination II [12]

4. "Real" curves representing the variation of the measured temperatures were analyzed using Excel software, setting the fourth degree polynomial functions used for mediate current values.
5. Deviations – minimum and maximum – set between the values of polynomial functions and the actual/measured values are specified, detailed in [12].

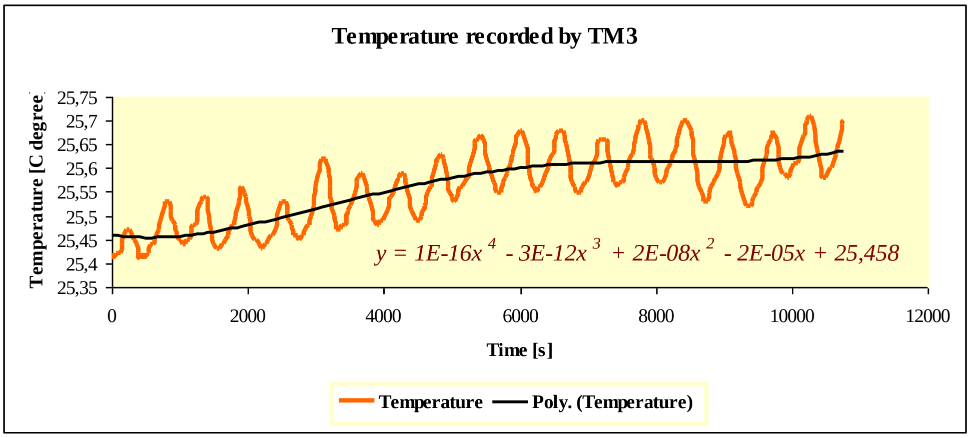

Fig. 10. Temperature recorded by TM3 and corresponding polynomial function – combination II [12]

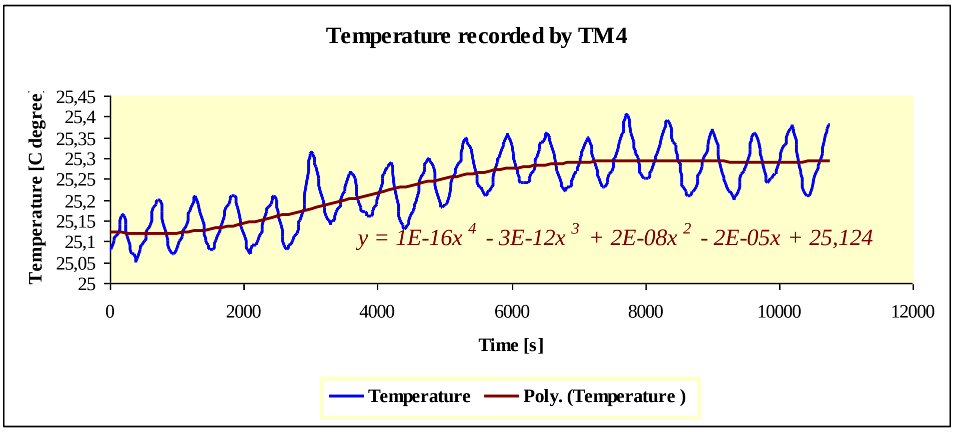

Fig. 11. Temperature recorded by TM4 and corresponding polynomial function – combination II [12]

Numerical Analysis of Thermal Stresses in Multilayer Plates Tested

Note: In the following, plates made of six layers are analyzed. For example, the results of the characteristics combination I – the multilayer wall consisting of six layers – are presented. To analyze the stresses and strains intermediate temperature values between the layers were used, based on the methodology specified in [12, 14, 15] and measured experimentally.

The 3D model was made using Autodesk Inventor and using physical and mechanical characteristics of the materials present in multilayer structures. Given the symmetry of the box tested (cubic form), in the analysis it was used only a quarter of its volume (fig. 12) by imposing the appropriate conditions in the analysis.

For thermal analysis, we have used a mesh with 559 404 nodes and 275 821 finite element, as shown in Figure 12, and the temperature distributions in the wall thickness are presented in Figures 13 and 14.

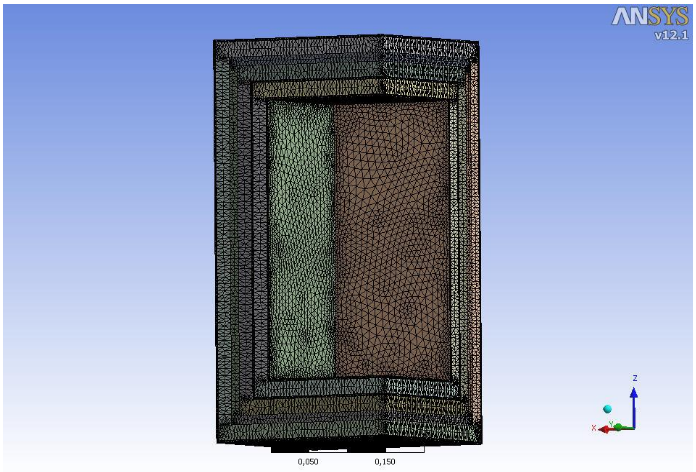

Fig. 12. Meshing 3D model of a quarter of an experimental box with six walls. [12]

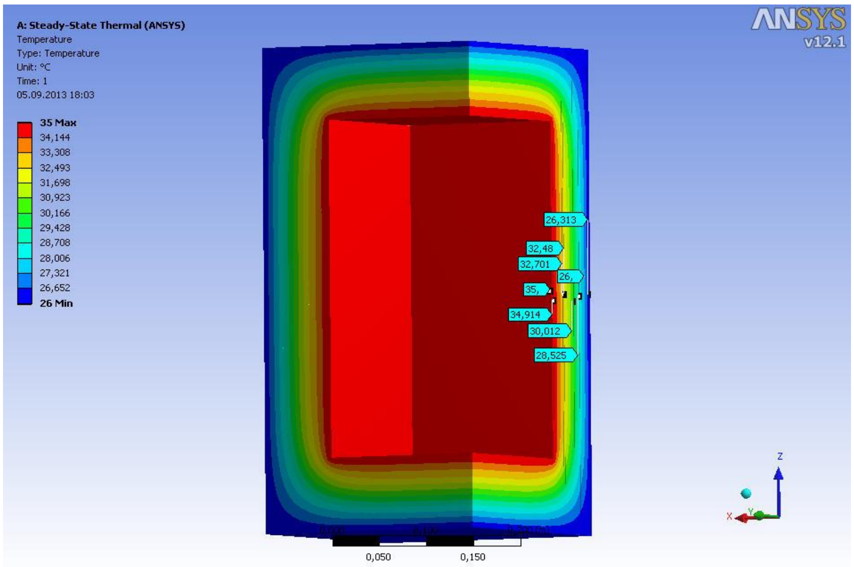

Fig. 13. Temperature distribution of the wall thickness (a) – [12]

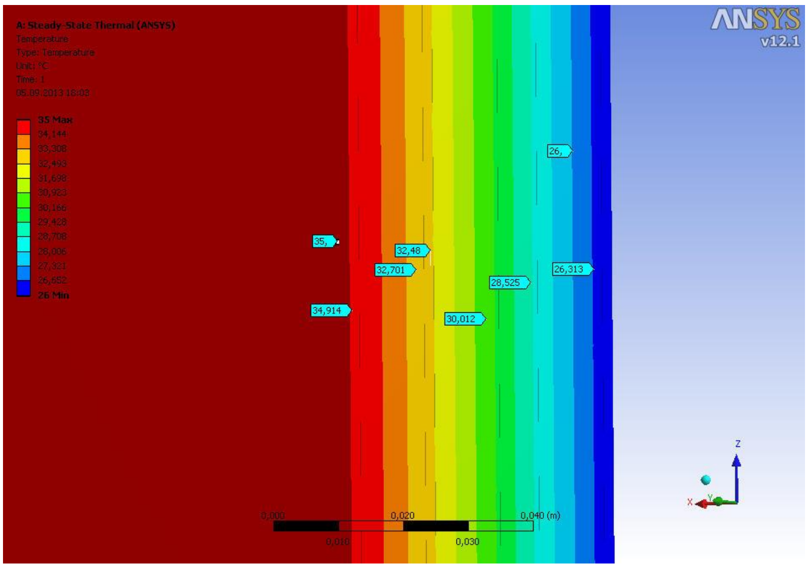

Fig. 14. Temperature distribution of the wall thickness (b) – [12]

Thermal stresses are shown in Figure 15 and the deformation of the multilayer box is presented in Figure 16.

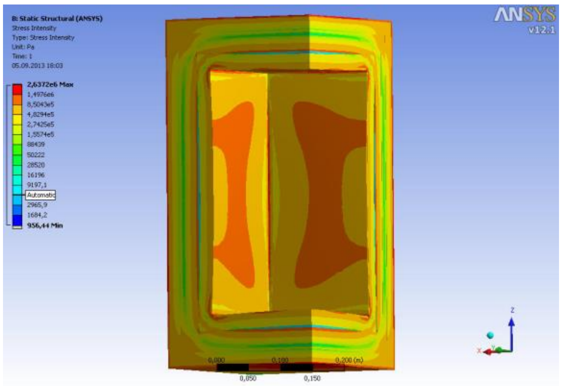

Fig. 15. The distribution of the thermal stresses in the walls of the tested box, six layers [12]

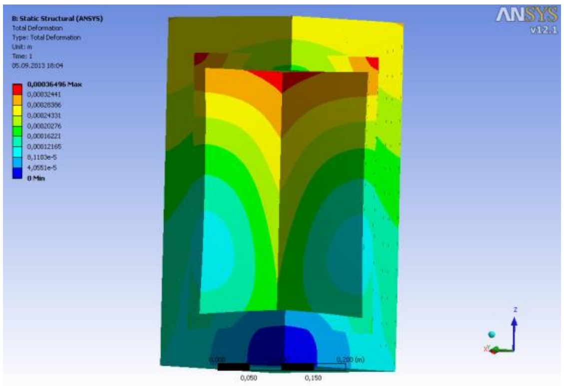

Fig. 16. The deformations of the box tested [12]

Conclusions

In the thermal analysis presented above, in view of the temperatures measured by thermocouples placed in such a way as to allow the plates surface temperature mediation to be tested, we were able to determine the values of heat flows in W/m^2, shown in Table 1 for each structural combination. The difference between the respective values can be explained through the electrical power supply inconsistency, some imperfections of contact between adjacent layers and exterior temperature changes (in the test laboratory) by personnel entering and leaving from the workspace.

Table 1. Heat flow values in experimentation laminated plates [12]

Combination	**a**	**b**	**c**	**d**	**e**	**f**
Combination I						
Heat Flux [W/m^2]	3.326	6.288	5.186	5.645	4.244	4.205
Combination II						
Heat Flux [W/m^2]	4.359	4.802	5.742	5.558	4.195	4.156

For a later stage, an adequate assessment can be considered for the states of stress (strain and stress) of multilayered plates under thermal influence, considering various ways to support the contours of the plates (boundary conditions – simple support, articulation ...). In this case, the case of the experimental box presented can be considered similar with an experimental test plate with an articulation in the whole contour or an elastic fitting.

The values of equivalent stresses σ_{ech} and total strains w, determined by numerical analysis performed using the finite element method are acceptable technically:

Plate with two layers (not specified in the present work, [12]):

$$\sigma_{ech} \approx (3.87\ldots7.65)\cdot10^5 \text{ Pa} \approx (0.387\ldots0.765) \text{ N/mm}^2 \;\; ; \;\; w \approx (0.463\ldots0.595) \text{ mm}, \qquad (2)$$

present, as expected, on the perimeter of the plate.

The multilayer plate with six layers (figs. 15 and 16):

$$\sigma_{ech} \approx (8.50\ldots26.37)\cdot10^5 \text{ Pa} \approx (0.85\ldots2.637) \text{ N/mm}^2 \;\; ; \;\; w \approx (0.284\ldots0.365) \text{ mm}, \qquad (3)$$

and time is on the perimeter of the plate.

By comparing the values given by the expressions (2) and (3), lower values result for stresses and the deformation (arrow) in the case of the six-layer plate, in comparison with the plate constructed with two-layers. The explanation is given by the greater flexibility of the box with wall from two layers, in relation to the box with wall from six layers.

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Cercetări teoretice şi experimentale privind transferul termic în compozite stratificate

Rezumat

Lucrarea prezintă instalaţia experimentală utilizată pentru măsurarea valorilor temperaturilor dezvoltate la nivelul interfeţelor straturilor care au format combinaţiile structurilor stratificate (de la două la şase straturi), cu ajutorul termocuplurilor poziţionate adecvat. Se au în vedere curbele temperaturilor şi gradienţilor termici, precum şi prelucrarea corespunzătoare pentru stabilirea funcţiilor polinomiale de gradul patru şi a abaterilor maxime şi minime pentru temperaturi şi gradienţii termici. Modelarea numerică cu elemente finite conduce la determinarea deformaţiilor şi a tensiunilor dezvoltate sub efect termic în plăcile testate (în cazul de faţă, pentru exemplificare, placa cu şase straturi). Valorile temperaturilor interfaciale au fost stabilite şi pe cale teoretică, comparate cu cele experimentale şi valorificate în cadrul analizei numerice efectuate.