Optimization of the curing modes of three-layer honeycomb panels

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Abstract. In this paper, a method of determining rational regimes of the process of curing structures made of polymer composite materials and honeycomb filler was developed. The subject of the study was a three-layer panel where the top and bottom layers were made from carbon fiber, while the honeycomb filler was made from aluminum foil. The filler was bonded to the top and bottom layers with epoxy film adhesive. Using numerical simulation, temperature state, curing degree, and heat generation rate of all the elements of the three-layer panel were determined. The simulations revealed that the process of curing the considered honeycomb structure was uneven due to uneven temperature distribution. The optimal process modes ensuring the gradients of the degree of cure were established.

Keywords: honeycomb filler, curing process kinetics, degree of cure, composite structure.

1. Introduction
Composite structures made of three-layer panels with honeycomb filler (HF) are widely used as load-bearing elements in aviation (fairings of helicopters and planes, fuselage panels, longerons, frames, etc.) and space (re-entry vehicles of rockets, head shield, shells of compartments, solar battery frames, etc.) industries. The total stability of such constructions is much greater than that of its elements. These structures also enjoy good heat- and soundproofing properties, high fatigue strength, low mass, and so on [1-3].

In such three-layer structures, as a rule, the sheets are made from glass- and fiber plastics based on epoxy adhesives cured at the temperature range up to +200°C [4-6]. For investigation of properties of composite materials, experimental [7-14] and theoretical methods [2, 3, 15, 16] have been extensively used to optimize process regimes. The longest operation of the manufacturing process is curing, and it is known [9, 12] that the curing regimes (temperature and time) are determined by the chemical origin and composition of the adhesive, while the parameters of the heating up to the set curing temperature are influenced by dimensions of the parts made from polymer composite materials (PCM) and physical-thermal properties of reinforcement fillers.

The main method of assembling three-layer panels with honeycomb fillers is bonding the top and bottom sheets with the honeycomb filler; the quality of the finished panel is ultimately determined during the curing process. The main parameters of the curing process are the temperate, heat-up rate, and dwell time [5, 6]. Manufacturers of binders used to make the sheets of three-layer panels and adhesives used to bond the honeycomb filler with these sheets only specify the temperature and during of the curing process and do not elaborate on the number of heat-up steps, heat-up rate, and dwell time on each heat-up step.

The goal of this paper is to develop a rational process of curing a three-layer panel with honeycomb filler.

2. Study subject and methods
The study comprised an experimental and a theoretical stage. In the experimental stage, the amount of heat generated during the curing process, as well as thermo-physical characteristics of the carbon fiber and adhesive, were determined. In the theoretical part, thermal simulations using FEM were conducted.
For investigating the kinetics of the curing process for the panels, the assumptions were as follows: thermo-physical characteristics of the adhesive are only determined by the degree of cure, the curing process happens without shrinkage, the honeycomb filler is considered as a one-dimensional structure with the change of temperature, and the simulation only considered the amount of heat emitted during the curing of the binder and the adhesive film.

For analyzing the heat exchange processes during curing, this study used a non-stationary heat transfer equation with an internal heat source [17, 18]. During the curing of the epoxy binder, its stage changes first from a liquid state to a gel-like state and then to a solid state. The values of thermophysical properties with respect to the curing degree (see Table) were determined according to the method described in [19].

The total amount of heat emitted in a unit mass during the curing process $H_r$ was determined using the method of differential scanning calorimeter as 325 kJ/kg [14]. Thermophysical properties of the honeycomb filler were determined using the method described in [20]; the heat conductivity of the aluminum alloy was 240 W/(m·K). Thermal and physical properties of the carbon fabric (Aspro-A80 grade) and honeycomb filler used are given in Table 1. Kinetic parameters of the curing process were determined by the method presented in [19].

Table 1. Thermo-physical characteristics of the materials used

|                        | In the plane of the glass fabric | Perpendicular to the plane of the glass fabric | In the plane of the honeycombs | Perpendicular to the plane of the honeycombs |
|------------------------|---------------------------------|-----------------------------------------------|-------------------------------|------------------------------------------|
| Carbon fabric heat capacity, J/(kg·K) | 600                             |                                               |                               |                                          |
| Carbon fabric heat conductivity, W/(m·K) | 15                              |                                               |                               |                                          |
| Honeycomb filler heat capacity, J/(kg·K) | 900                             |                                               |                               |                                          |
| Honeycomb filler heat conductivity, W/(m·K) | 1,06                            |                                               | 1,4                           |                                          |
| Binder heat conductivity, W/(m·K) | Liquid state: 1980              | Gel state: 1800                               | Solid state: 1300             |                                          |
| Binder heat capacity, J/(kg·K)   | Liquid state: 0,08              | Gel state: 0,2                                | Solid state: 0,27             |                                          |

As a study object, we used a conventional three-layer panel structure (Figure. 1), with 10 mm thick sheets made out of carbon fiber and 400 mm wide and 100 mm thick aluminum alloy honeycomb filler. For manufacturing the carbon fiber panels, we used a carbon fiber pre-preg and epoxy adhesive with a volume fraction of 40%. As the binder, we used a composition of epoxy resin ED-20, isomethyltetrahydrophthalic anhydride, and diethylene glycol. To bond the carbon fiber sheets to the honeycomb filler, we used epoxy film adhesive of similar chemical composition with the thickness of the adhesive line of 1 mm. The honeycomb filler was made out of the grade 5056-6-23 HEXCEL aluminum foil. Such structures are typically used in the aviation industry to manufacture nose fairings, ailerons, wing, and floor panels.
For the convenience of studying the temperature kinetics during curing, three probing points were made in the structure contour, Figure 1. Point 1 is the center of the carbon fiber sheet of the upper part, while Points 2 and 3 are the center of the adhesive line of the right and upper parts. The curing of the honeycomb structure was done in a step-wise manner, Figure 2, to the temperature of 160°C for 300 minutes. To make the analysis of the obtained results more convenient, let us highlight several characteristic stages of the curing process, Figure 2: I – stage of heat-up to the gelling temperature, II – dwell stage at the gelling temperature, stage III – heat-up to the set curing temperature, IV – dwell stage at the set temperature. All calculations were made with the heat-up rate of 3 °C/min at stages I and III.

3. Results and discussion
A special feature of the considered three-layer panel, Figure 1, is the large difference of thermophysical characteristics of the panels, adhesive, and honeycomb material. Therefore, the paper only studies the temperature values in the heat-up process at three points shown in Figure 1 and not in the whole area and volume of the three-layer panel. The points are in the center of the carbon fiber of the upper sheet and in the center of the adhesive line on both sides of the honeycomb filler (right and upper parts). As a result of modeling, the paper determined the temperature state, curing degree, and heat generation rate.
Figures 3, 4, 5 show the time histories of the temperature state, curing degree, and heat generation rate. The temperature state in the center of the carbon fiber layer of the right and upper parts are fully identical, so the paper only shows the results for Point 1, Figure 1, located in the upper part of the carbon fiber sheet.

**Figure 3.** Time histories of the temperature in the center of the carbon fiber layer of the upper part (1), in the center of the adhesive line of the right part (2), in the center of the adhesive line of the upper part (3) and in the center of the honeycomb filler (4)

**Figure 4.** Time histories of the heat generation rate in the center of the carbon fiber layer of the upper part (1), in the center of the adhesive line of the right part (2), in the center of the adhesive line of the upper part (3)
By analyzing the obtained results, we can conclude the following. The simulations revealed that the temperature distribution in the structure volume is uneven. The kinetics of the heat-up process differs significantly for the material of the honeycomb filler (curve 3, Figure 3), adhesive line (curves 2, 3, Figure 4), and the upper panel (curve 1, Figure 3). For example, the maximum temperature gradient between the carbon fiber sheet in the upper part and the filler reaches 117 ºC in 67 minutes. The maximum temperature gradient in the carbon fiber sheet and the adhesive line (between Points 1 and 3) at the upper part of the structure reaches 52 ºC in 40 minutes.

The emergence of such a large temperature gradient is related to different thickness values of the honeycomb filler in the central and side parts of the three-layer panel and, consequently, different heat-up rates during curing. The heat-up rate in Point 2 (see Figure 1) is higher than in Point 3. Thus, the heat generation rate during curing is higher.

In this structure, carbon fiber takes up 10% of the total volume. So, the heat flux caused by heat generation in the binder has no significant influence on the overall temperature state, Figure 5. The maximum heat generation rate of the carbon fiber in the upper part (Point 1 in Figure 1) is 168 W/(kg·K), the maximum heat generation rate of adhesive at the upper part (Point 3 in Figure 1) is 59 W/(kg·K) (Figure 4).

So, the temperature of the carbon fiber is higher than that of the honeycomb filler and the adhesive line, so the curing process of the carbon fiber starts earlier and happens faster (Figure 5). The simulations revealed that when the upper carbon fiber sheet reaches the curing degree of 100%, the curing degree of the adhesive in the upper part (Point 3 in Figure 1) is less than 15%. Such a large gradient of the curing degree may cause defects in the process of forming the structure.

To ensure a more even curing, especially between the upper carbon fiber sheet and the adhesive, it makes sense to reduce the heat-up rate. We conducted simulation for the heat-up rate reduced to 1 °C/min and established that it leads to the increase of the adhesive curing degree from 15% to 40% (upon the upper carbon fiber sheet reaching the curing degree of 100%). So, the proposed heat-up regime reduces the curing degree gradient between carbon fiber and adhesive in the upper part of the structure (Points 1 and 3) by 28%.

Figure 5. Time histories of the curing degree in the center of the carbon fiber layer of the upper part (1), in the center of the adhesive line of the right part (2), in the center of the adhesive line of the upper part (3)
4. Conclusion
This paper considered a structure of a three-layer panel comprised of upper and lower carbon fiber layers and honeycomb filler bonded to these layers with epoxy film adhesive. Thermal regimes of heating the structure were simulated under the assumption that the chemical composition of the binder and epoxy adhesive were identical.

As a result of the simulations conducted, we established that the curing process is characterized by uneven heat-up throughout the structure volume, leading to uneven distribution of the curing degree and uneven heat generation rate. The adhesive temperature in the left and right parts is higher than that on the adhesive in the upper part, leading to an increased curing rate. The cause of the significantly higher curing rate of carbon fiber sheets is their higher thermo-physical properties, in particular, heat conductivity. It was established that the highest temperature gradient of the curing degree takes place between adhesive and carbon fiber in the upper part of the structure (between Points 1 and 3). To reduce the gradients of the curing degree by around 30%, it is proposed to reduce the heat-up rate to 1 °C/min.

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