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# Hybrid composites in reusable space vehicles wing structures

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**Abstract.** The study is dedicated to the solution of a complex problem – development of an optimal thermal design of the tourist class reusable space vehicle (RSV TC) wing structure. The complexity of the problem resides in the necessity to consider critical factors of the suborbital flight and in a number of nesting tasks, that need to be solved. The authors implemented a multiscale modeling approach covering design of hybrid composite material thermal properties (i.e. mesoscale level), determination of thermal loads and thermal state analysis of a composite wing (i.e. macroscale and structural scale levels). Analysis of thermal fields demonstrated the necessity of thermal protection (TP) application for the wing structure. Consequently, optimal from the weight efficiency point of view TP thicknesses were determined. Summing up, the results of a RSV TC wing structure development are presented in the current paper.

## 1. Introduction

Space tourism has become a subject of particular interest during the last few decades. The facts that facilitate this interest reside in a vast experience in spacecraft development, a number of successful flights of non-professional astronauts to the International Space Station (ISS), and high potential interest of business in this field [1]. Nowadays two variants of space tours are technologically feasible – orbital and suborbital. The last one implies ballistic trajectory flight beyond the Karman line (100 km above sea level). Due to some technical, financial and medical reasons suborbital flights are now much more attractive for both business and customers. The potential high demand of suborbital flights is proved by the results of market research provided by IPSOS Group (France) conducted by the order of EADS Astrium [2]. Duration of the proposed suborbital tour will not exceed 80 min with the exposure to weightlessness of 3-5 min. The ticket price will lie in the range of 150-200 ths. USD. For commercial feasibility of such flights RSV development is a question of essential importance [3]. Recently, a number of private companies all over the world are involved into the space tourism activity. The examples of suborbital RSV projects could be RocketplaneXP (Rocketplane Kistler, USA, 2005), New Shepard (Blue Origin, USA, 2006), Space Plane (EADS Astrium, France, 2007), Lynx Mark (XCOR Aerospace, USA, 2008), SpaceShipTwo (Virgin Galactic, USA, 2010), Oduvanchik (Bauman MSTU, Russia, 2007), Reusable Suborbital Space Complex (Cosmocourse, Russia, 2014) and others.

Weight efficiency together with high service security are the key issues in RSV TC design. Therefore, polymer composite materials that can meet mentioned requirements and have proved their reliability for structural application in aerospace for decades are the right choice for RSV load bearing structures (fuselage, wings, spars, etc.). Due to the demand of economic feasibility of RSV, stipulated by its tourist application, hybrid polymer composites, that contain two or even more types of the reinforcement (herein after hybrid composites), have great opportunities. Combination of expensive carbon fibers

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(CFs), that demonstrate high strength-to-weight performance, with cheap but lower in mechanical properties glass fibers (GFs) allows to achieve optimal design solution from technical and economical positions.

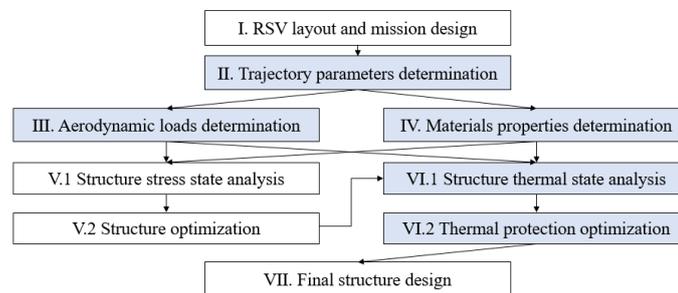
However, design of suborbital RSV TC is a complex problem, that involves a number of nesting tasks, i.e. trajectory parameters and flight loads determination, materials choice and optimal structure development, etc. Modern engineering design approach implicates a wide use of Finite Element Analysis (FEA) methods for all mentioned subtasks, thus reducing the development time and cost [4]. The type of the analysis, that literally covers the design in micro-, meso-, macro- and structural levels, is referred as a multiscale analysis. Micro-, meso- and macro-scale types belong to the modeling of material and aims to diminish numerous laboratory tests, while structural level is responsible for the global structure modelling, thus reducing full-scale trials costs.

Consequently, current work aims to develop an optimal design methodology for suborbital RSV TC load bearing structures. The implementation of the mentioned methodology is demonstrated via the design of a hybrid composite wing for the suborbital RSV, engineered in Bauman MSTU [5].

The reminder of this paper is organized as follows. Section 2 describes the design procedure; in Section 3 we report the results of the solved nesting tasks; Section 4 concludes the paper.

## 2. Development of the design procedure

Design of the RSV TC is a complex task that requires solving of a certain number of separate engineering problems. The general scheme of RSV design is presented at Figure 1. Our previous study covers the structural optimal design of the RSV wing structure [5], and the current study is mostly concentrated on the thermal design, that includes the following stages: trajectory parameters evaluation, materials thermal properties definition, aerodynamic thermal loads modelling, structure thermal analysis and TP optimization.

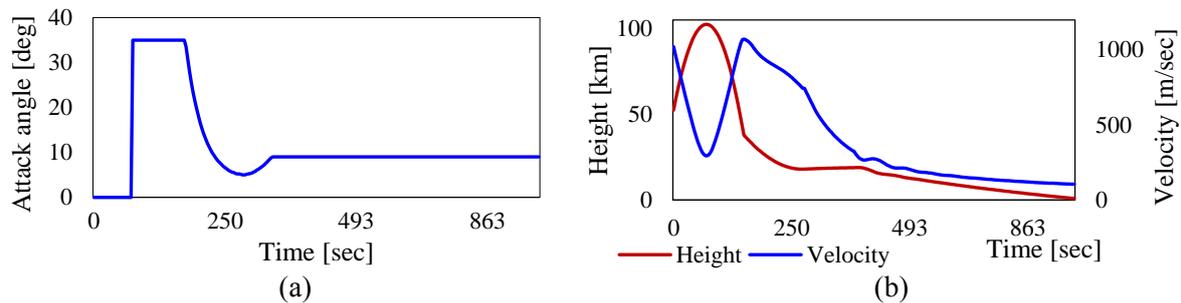


**Figure 1.** Principal scheme of RSV design.

## 3. Solving of the formulated tasks

### 3.1 Trajectory parameters determination

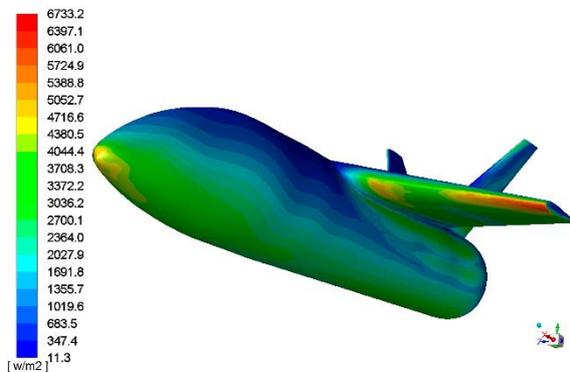
Two phases could be distinguished during the suborbital flight, namely active and passive. Active phase involves acceleration and injection of RSV either with a rocket booster or with an aircraft up to the certain height. Passive phase includes ascent of RSV to the height of 100 km, staying at zero-gravity conditions for 3-5 min following by the glide descent in the atmosphere and return to the landing point. In current study trajectory parameters (i.e. flight altitude, attack angle, RSV velocity, etc.) were defined by means of special program, developed in NPO Molniya, that simulates RSV center-of-mass motion [6]. Due to the economic requirements the velocity at the end the active phase should be minimum but enough to reach the desired height with holding-up at this point for not less than 3 min. Therefore, trajectory slope to the horizontal plane at the beginning of the passive phase is rather high. For the considered suborbital RSV, the flight passive phase starts from 46 km altitude with the velocity of 3.8M and trajectory angle of 56°. It is worse to mention that the value of the side overload is limited by 4.5g, that is acceptable for trained space tourists. Some results of the trajectory parameters determination are presented at Figure 2. This data is used as the input parameters for the next design stage.



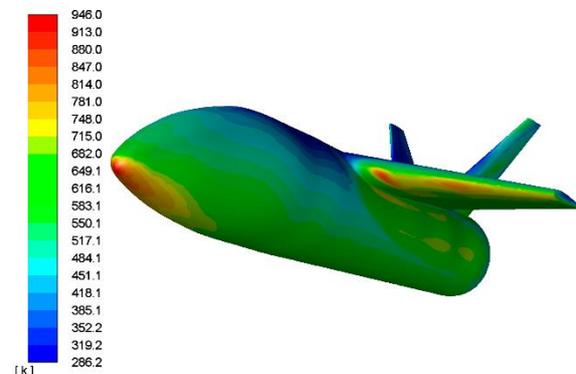
**Figure 2.** Trajectory parameters of the suborbital RSV TC:  
(a) attack angle vs. time; (b) flight height and RSV velocity vs. time.

### 3.2 Aerodynamic loads determination

Modelling of RSV aerodynamic flow was performed by means of Fluid Flow module of FEA-package ANSYS Workbench. 3D-model of RSV was enclosed into a gaseous medium with the total volume of almost 100 000 m<sup>3</sup>. Such volume was large enough to leave out medium disturbance bringing by the side areas. Flow direction and velocity were assigned on the hemisphere frontal area of the gaseous medium, while on the back flat area free outflow conditions were applied. Modelling was conducted for the most critically loaded trajectory interval – RSV reentry in a dense atmosphere with the high values of attack angle. The resulting heat flow from the gaseous medium to the RSV surface distributes unevenly (Figure 3) and moreover changes each second. However, critical regions of the wing surface could be distinguished, e.g. the leading edge and neighboring section in the windward side of the wing are subjected to the highest temperatures influence. Thus, the gaseous temperature close to these regions could reach 945 K (Figure 4).



**Figure 3.** Total heat flux from the gaseous medium to the RSV surface [W/m<sup>2</sup>].



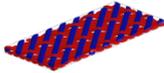
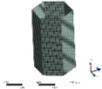
**Figure 4.** Temperature of the gaseous medium close to the RSV surface [K].

### 3.3 Determination of the material thermal properties

The wing skin consists of a laminated composite combining layers reinforced with GFs and CFs, and a lightweight core made of Kevlar®. Thermal conductivity of such hybrid structure depends on numerous variables, i.e. nature and thermal properties of both reinforcement and matrix materials, reinforcement content, defects in composites, reinforcement architecture, etc. Moreover, thermal conductivity of laminated composites has a certain anisotropy and varies with the temperature. Such a big number of variables leads to a great amount of possible combinations, and as a result each material exhibits unique thermal response. Thus, it is wise to utilize FEA-analysis to determine hybrid composite thermal properties. In this study we implemented Digimat and ANSYS Workbench software to solve this task utilizing reference data about thermal properties of composite distinct constituents (fibers and matrix) [7-9].

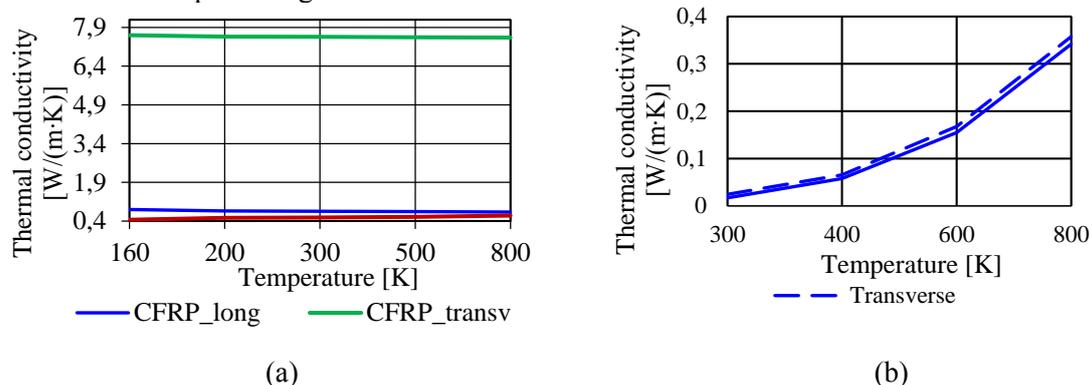
The thermal properties of each component of a hybrid composite were defined separately. Consequently, three different models (for CF reinforced plastic (CFRP), GF reinforced plastic (GFRP) and Kevlar® honeycomb) were developed. The parameters and assumptions of each model are presented in Table 1.

**Table 1.** Parameters of the computational models for determination of materials thermal properties.

Parameter	CFRP	GFRP	Kevlar® honeycomb
Software	Digmat	Digmat	Ansys WB
Reinforcement architecture/type	UD tape/ AKSA A-49 24K4	Satin fabric 8/3 /T10	Satin fabric/Kevlar
Representative material volume (RMV)			
RMV dimensions [mm]	0.04 x 0.04 x 0.4	4 x 2.2 x 0.24	$h = 10, d = 3, \delta = 0.085$
Fiber diameter [ $\mu\text{m}$ ]	6	6	-
Reinforcement volume fraction [vol.%]	60	60	60
Density [ $\text{kg}/\text{m}^3$ ]: reinforcement/matrix	1 790/1 300	2 520/1 300	1 435/1 300
Heat transfer	Conductive	Conductive	Combined

The important issue of the described problem is the character of heat transfer in each material model. Whereas thermal conductivity is inherent for CFRP and GFRP, honeycomb, due to its peculiar structure, exhibits more complex heat transfer. Thus, heat transfer in honeycomb is carried out via conductivity, air convection inside the cell and radiation of the cell walls (with the emissivity factor equal to 0.9). By applying different temperatures for the opposite cell faces the aggregated heat flow coming through the cell was simulated, following by the evaluation of the effective honeycomb thermal conductivity.

The modelling results indicate, that CFRP demonstrates downward temperature dependency in transverse and longitudinal directions, while GFRP – upward (Figure 5 (a)). Note, that due to isotropic nature of GFs the thermal conductivity of the respective composite was investigated only in one direction. At the same time the effective heat transfer of the honeycomb shows non-linear rise with the temperature increase. This fact could be explained by the incremental contribution of the radiative heat transfer with the temperature growth.

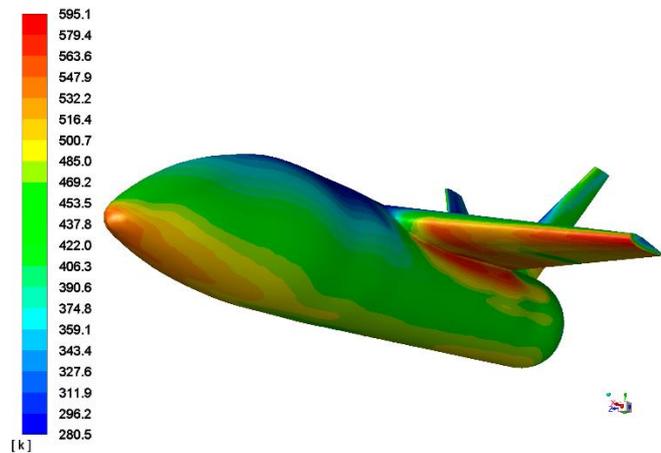
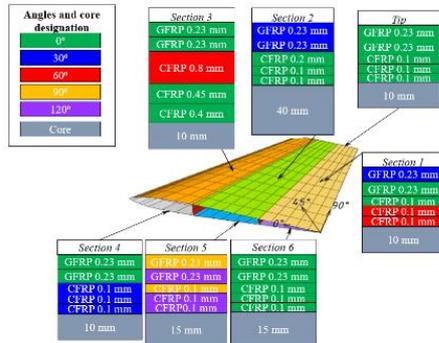


**Figure 5.** Thermal conductivity of hybrid composite constituents:  
(a) CFRP (transverse and longitudinal) and GFRP; (b) Kevlar® honeycomb.

### 3.4 Modeling of the wing thermal state

At a previous design step described in the study [5,10] an optimal structure of the hybrid composite wing skin was determined, so here we present only the resulting wing structure (Figure 6). Next, thermal state of the wing under the applied thermal loads was simulated in ANSYS WB. In addition to aerodynamic heat, radiative heat transfer between the inner wing walls and outer surface with the ambient medium were considered. The resulting temperature distribution on the wing skin surface demonstrates that maximum temperatures are localized in the leading edge and could exceed 600 K (Figure 7). So, in order to withstand the thermal loads, hybrid composite wing needs additional TP. However, it is not wise to apply TP to the whole wing surface, as it will increase the structural mass

enormously [11]. Therefore, the optimization of the TP thickness and its positioning on the wing surface was carried out.



**Figure 6.** Optimized hybrid composite wing skin.

**Figure 7.** RSV surface temperature at 50 km altitude (210 sec of passive phase) [K].

### 3.5 Optimization of TP of the wing

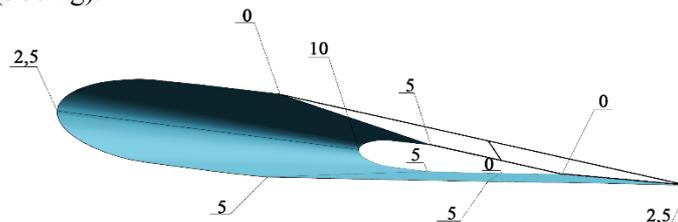
Some wing sections are exposed to the influence of the temperatures, that exceed the allowable service temperature for polymer composites. Thus, the maximum service temperature for polyimide resin does not exceed 530 K. Therefore, the leading edge as well as parts of the windward and leeward sides of the wing needs to be thermally protected. Needless to say, that as the temperature distribution is uneven within the wing surface and thereby it is reasonable to apply different thicknesses of the TP layer on the different sections. Hence, it's necessary to find an optimum distribution of the TP within the RSV wing surface. In our previous work we have proved the feasibility of using this material for RSV wing TP [12]. However, parametric optimization of the TP thickness is necessary [13]. Such optimization could be conducted by means of introduction of the set of line-segment functions with apexes, which are coincident with the borders of the root and tip wing chords. Between this borders the TP thickness varies linearly in both directions – along the chord length and along the wing span. Therefore, the optimization problem was formulated as follows:

$$W = \int_0^{S_{wing}} \rho \cdot \delta(x, y) dS \rightarrow \min, \quad (1)$$

$$T(x, y) \leq T_{max}, (x, y) \in S_{wing}, \quad (2)$$

where  $W$  is the TP mass, kg;  $\rho$  – TP density, kg/m<sup>3</sup>;  $\delta$  – TP thickness, mm;  $S, S_{wing}$  – TP and wing surface area respectively, m<sup>2</sup>;  $T, T_{max}$  – calculated and maximum allowable temperature respectively, K.

Maximum TP thickness was taken to be equal to 20 mm, while discretization step – equal to 2.5 mm. The additional constraint was the equivalence of the TP thickness in the borders of the wing sections. Genetic algorithm was chosen for optimization. The resulting distribution of TP thickness is presented in Figure 8. The modelling results demonstrate that wing excluding Sections 1 and 2 need additional TP with the thicknesses from 0 up to 10 mm. The total mass of such TP will be 68 kg, that not exceed 20% of the total wing mass (380 kg).



**Figure 8.** Results of the TP optimization: wing TP thicknesses excluding Sections 1 and 2 [mm].

#### 4. Conclusion

An optimal design methodology for suborbital RSV TC load bearing structures was developed in this study. The feasibility of the developed methodology was illustrated with the example of a hybrid composite wing for RSV TC. The results of the solution of several distinct engineering problems were presented, e.g. trajectory parameters determination, aerodynamic flow modelling, material properties simulation, and TP optimization.

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