DEVELOPMENT OF STRUCTURE ELEMENTS BASED ON ARCHITECTURED MATERIALS FOR PERSPECTIVE CIVIL AIRCRAFTS

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Abstract

The present work is dedicated to study of effective applications of architectured materials (metamaterials) in aircraft structures. Recent advances in additive manufacturing made it possible to make metallic details consisting of a small cells with a characteristic size of elements about 10^{-3}-10^{-4}m. The structure parameters of such architectured cells (and thus their performance) can be defined by the designer, making a highly-customized structure, which can be adapted to a concrete demands.

In this work an application of architectured metamaterials to creation of lightweight metal-composite joints and load-bearing skins for aircraft structures are considered and a preliminary assessment of their potential in weight saving is given.

1 Architectured Materials Based on Metallic Alloys

Evolution of load-bearing structures in various branches of mechanical engineering is always focused on improvement of structure weight, cost, reliability and other important characteristics. For any kind of structure these characteristics are driven mainly by their structural efficiency on different levels of detailing. These levels can be classified as follows:

– Level 1 - Internal structure of material (level of crystal lattice, dimension: < 10^{-6}m);
– Level 2 – Elementary cell (level of meso-structure, dimension: 10^{-5}-10^{-3}m);
– Level 3 – Structure element (level of detail, dimension: 10^{-3}-10^{-1}m);
– Level 4 – Structure (level of aggregates, dimension: >10^{-1}m).

Improvement of performance of any metallic structure presumes enhance of its structural efficiency simultaneously on all of these levels. On level 1 this is realized by creation of new allows with better properties, on level 3 – by improvement of metal-working technologies, on level 4 – by increasing of assembling quality and technical solutions.

What about level 2 (level of material cells), structural efficiency on that level is remaining considerably low up to now. The only available method of its improvement is creation of foam materials, which have almost random (and so not optimal) layouts of cells.

Recent advances of Additive Manufacturing (3D-printing) of metallic structures made it possible to reach two important characteristics, which can have a considerable influence on structural efficiency on the level of cells. These characteristics are:

- High mechanical properties of materials of printed details [1] (almost equal to conventionally manufactured ones);
- High resolution of 3D printing [2] (thickness of layer less than 0.05mm).

Capability of layer-by-layer building of high-strength structures with a very small characteristic size of elements makes it possible to perform detailed design of structures on the new dimensionality (corresponding to level 2). The capability to make small and well-ordered cells from high-strength material can give great opportunities of creation of brand new type of aircraft structures, based on so-called "architectured materials" (or "mechanical metamaterials"). Architectured material is a term describing a micro-cell with pre-defined internal structure layout, which can be considered (on an upper level of detailing) as a material, having a certain combination of mechanical properties (Fig.1).

A structure based on architectured materials can be considered as if it is built of a vast number of various materials. Every unit cell of such structure can be considered as a material, as it has its own combination of mechanical properties due to its own internal layout. As every zone of such structure can have various mechanical properties, architectured materials can become a unique instrument allowing "customization" of local properties at every local zone of the structure, making it highly anisotropic and better adapted to a certain boundary conditions and loads.

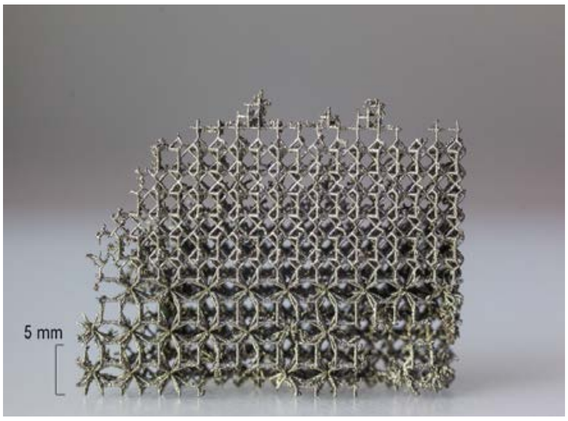

Fig. 1 – Fragment of a technological specimen made of metallic architectured materials

This capability of architectured materials can be used not only to decrease the weight of existing metallic details, removing the material from low-loaded zones, but also to create the brand new metallic details, which are in the best way adapted to a certain conditions of exploitation. By forming the distribution of mechanical properties through the volume of a detail, the designer can accurately pre-define the shape change of the detail under a certain external loading. This can lead to sufficient change of well-proven design solutions currently used in different types of structures.

2 Feasible applications of architectured materials to aircraft structures

Metallic structure details based on architectured materials, having higher exploitation characteristics as compared to analogues, can have effective applications in space, aircraft, ship, automotive and other structures, for which weight effectiveness is a one of the main factors.

What about aircraft structures, the investigations, carried out in this work have indicated the following feasible applications of architectured materials:

- Small attachment details (brackets, corbels etc.);
- Impact absorbing panels;
- Skins with cooling from inside;
- Adaptive wing elements;
- Lightweight metal-composite joints;
- Load-bearing skins subjected to buckling.

For first two applications the main feature of architectured materials used is a capability to create low-density zones with high-ordered structure. For skins with cooling from inside the main feature is high total surface area of elements of an architectured material.

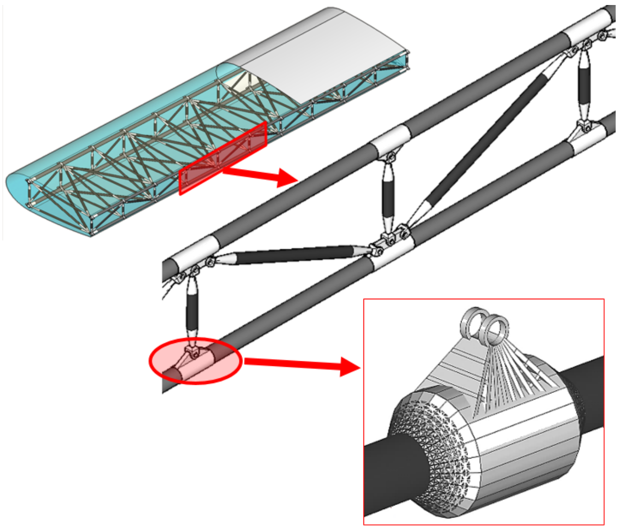

Fig. 2 – Metal-composite joint for frame composite structures

Development of adaptive wing elements can be based on a specific type of architectured materials – auxetic materials, having negative Poisson ratio.

What about metal-composite joints based on architectured materials (Fig.2), the main specific feature here is a capability of a smooth change of stiffness characteristics of the metallic part.

3 Metal-composite joint based on harmonization principle

Creation of lightweight and reliable metal-composite joints is a complex task even for low-loaded structure elements, while for high-loaded ones it becomes critical. The main problem of development of weight effective metal-composite attachment is caused by a significant difference between metal and polymer resin – the component of composite material, defining its strength characteristics.

In conventional composite airframes with "black metal" layouts metallic parts of attachments are, as a rule, loaded very slightly, far less ultimate values. At the same time, composite parts are often overloaded, that cause early local failure of resin. That means that the load transfer in such attachments is organized not rationally.

As stiffness characteristics of metallic alloys are a lot higher that corresponding characteristics of resin, crumpling of resin occurs at a very low level of loading of metallic parts. This problem is solved by decreasing specific loading of attachments, that leads to a considerable decrease of its weight efficiency. As a result, composite structures require a lot more weight expenses for organization of joints (Fig.3) as compared to metallic structures.

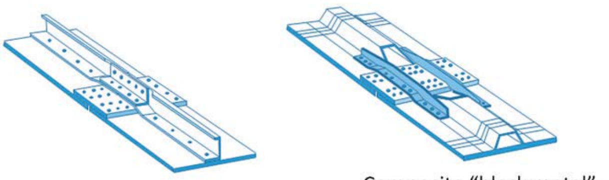

Fig. 3 – Principal schemes of joints in metallic and "black metal" composite structures

Investigations carried out in this work are aimed to find approaches to decreasing weight of metal-composite attachments by the means of creation of rational layouts for metallic parts of joints based on harmonization principle. According to this principle, local mechanical properties of metallic and composite parts should be almost equal in the contact zones. Harmonization presumes smooth reducing of stiffness properties of metallic part in the zones of contact. That can be realized only by creation of special architectured material, having low "density" (and correspondingly, low stiffness) in the zones of metal-composite contact. Away from the zone of contact, this "density" slowly increases up to "solid" metallic alloy.

Metal-composite joints based on harmonization principles have been a topic of a number of researches carried out in TsAGI in the recent years [3]. The two main structure concepts were proposed. The first one, called "hard" concept presumes harmonization of strength properties by the level of metal. According to this concept, in the zone of contact resin is maximally removed from composite package, providing extra-high fiber volume ratio and thus enhancing stiffness of the package in this zone.

The second concept, based on application of metamaterials is called "soft" concept, as the stiffness of metallic part is reduced in the zone of contact down to the properties of resin. This leads to a significant increase of contact area in order to provide suitable conditions for loading of composite part of the joint. As a consequence, of size of the join is also increasing. For "solid" material that would mean corresponding increase of weight, but for highly porous architectured materials that is a lot more effective.

For designing of "soft" joints the approach to design of metallic structures based on beam elements was proposed. Weight efficiency of the such joints can be illustrated on a simple modeling task.

In this task a simple structure of the joint is considered. The structure is located in space between two parallel planes A and B (Fig. 4) and limited by the following surfaces:

- surface S0, lying in the plane A and corresponding to the part of the structure made of "solid" material,

- surface S1, lying in the plane B and corresponding to the part of the structure to the part of the structure made of architectured material with low "density",
- side surface S2, defining the shape of the joint.

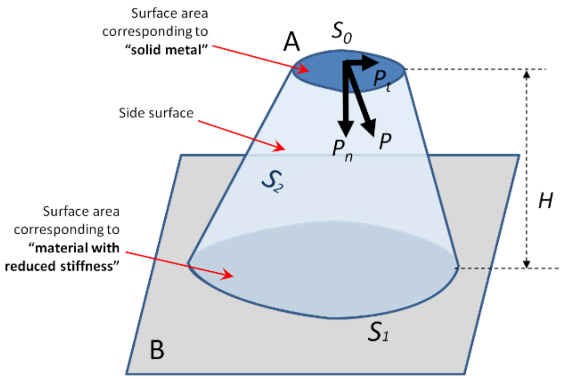

Fig. 4 – Principal scheme of load transfer in "soft" metal-composite joint

Taking into account mechanical properties of metallic and composite materials used in aircraft structures, the main requirements to the structure of the considered joint can be formulated as following:

- structure of the "soft" joint should provide transfer of the load from metallic part of the structure with Young modulus E ~ 70-120 GPa (E_1 = 70 MPa – Young modulus of an aluminum alloy, E_2 = 120 GPa – Young modulus of a titanium alloy)to the composite part with Young modulus E_{resin}= 5 GPa(Young modulus of resin);
- in the zone of contact stiffness of the metallic part should be maximally close to the stiffness of resin;
- normal and shear stresses transferring through the contact area should not cause crumpling of the composite package.

For preliminary assessment of weight efficiency of "soft" joint concept, the considered joint structure was a rod structure, limited by triangle surfaces S_0 and S_1 and side surfaces, which forming lines are located of sides of the triangular surfaces (Fig. 5).

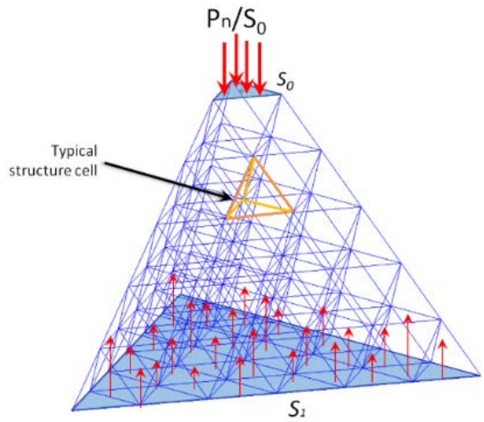

Fig. 5 – Truncated tetrahedron with rod structure layout

In this task, architectured material was modeled by 1D finite elements. Several load cased on compression and shear loads were considered. The results have shown that the total volume of the joint is only about 13-15% from the weight of the solid tetrahedron made of the same metallic alloy.

This example have shown that architectured materials are effective for load transfer between the structures, made of materials with sharp distinctions in mechanical properties.

4 Metallic skin with metamaterial filament

One of promising structural applications of architectured materials (also called metamaterials) is load-bearing skins subjected to buckling. The proposed concept of skin structure is three-layered, consisting of two "solid" layers and a layer made partly from metamaterials (Fig.6).

The idea of this concept is quite simple: increase of a buckling load of skin is reached due to increase of its total height, at the same time removing material from low-loaded zones from inside of skin allows to keep it lightweight. Depending of the demands, either the buckling load of skin ay can be increased at keeping the same weight, or the weight can be decreased keeping the same buckling margins.

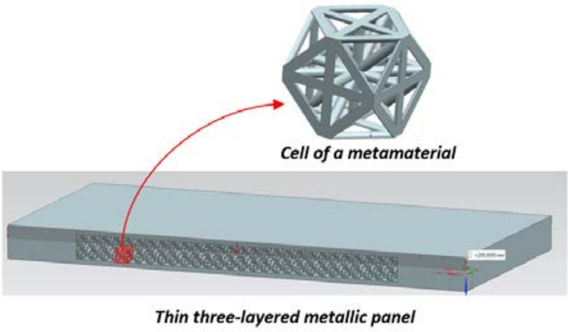

Fig. 6 – Application of metamaterials to thin skin elements

This concept may seem to be close to a honeycomb structures, as the principle used here is almost the same. But the metamaterial skin concept has a number of important advantages as compared to honeycomb skins:

- Distribution of stiffness properties can be smooth and optimized, giving better weight efficiency;
- Connection of metamaterial skin to metallic structures (or structure elements) with conventional layouts is easy to organize.

The second advantage is illustrated on Fig.7, where the connection of metamaterial skin with typical stringer is shown. The layout of the metamaterial layer becomes more dense while approaching to the zone of connection, where the solid material is used. As the change of stiffness parameters is smooth, no concentrations occur in the zone of connection. This is an important feature of this concept, unlike the honeycomb structures, where organization of attachments can be a very complicated task.

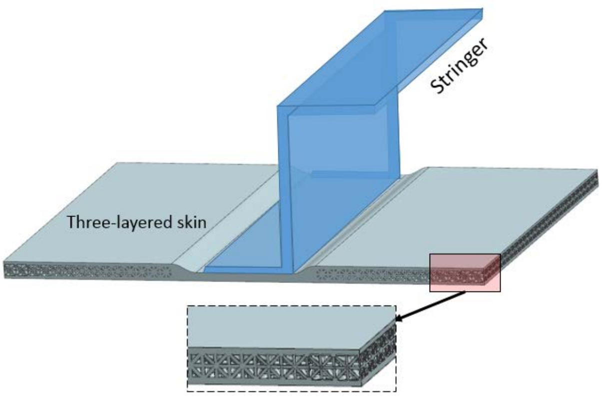

Fig. 7 – Zone of attachment of three-layered skin and stiffener

In this work a parametric study of the metamaterial skin concept was made, aiming to make a preliminary assessment of weight effectiveness of the concept.

For that scope, a model task was considered for a flat and thin plate subjected to buckling under compression loading. Two variants of the plate made of the same material (steel) were analyzed for various combinations of parameters of external geometry: solid plate and three-layered plate with a metamaterial layer. Fig. 7 shows an example of buckling mode and a stress-strain state picture of the three-layered plate.

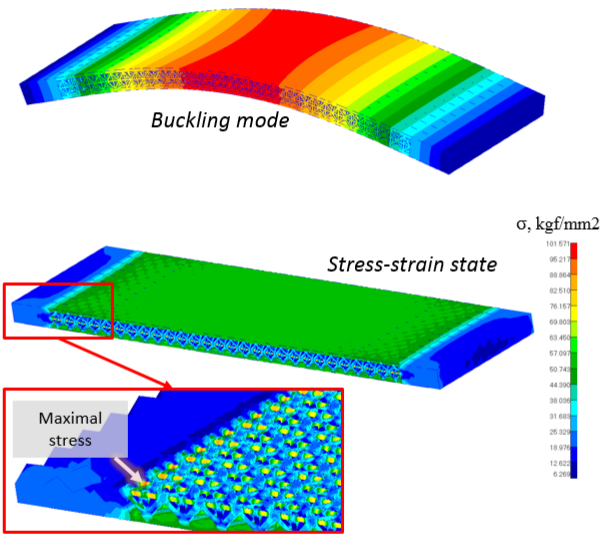

Fig. 7 – Results of buckling analysis of a metamaterial plate

The results of the investigations have shown that the weight of three-layered plate is from 15% to 35% lower in comparison with solid plate for different geometries of the flat plate. This allows to make a conclusion that three-layered metamaterial skin has a considerable potential in weight saving for elements of aircraft structures for which buckling is an active design constraint.

References

[1] Zheng, Xiaoyu, Howon Lee, Todd H. Weisgraber, Maxim Shusteff, Joshua DeOtte, Eric B. Duoss, Joshua D. Kuntz, Monika M. Biener, Qi Ge, Julie A. Jackson, Sergei O. Kucheyev, Nicholas X. Fang, and Christopher M. Spadaccini. Ultralight, ultrastiff mechanical metamaterials, *Science*, 20 June 2014.

[2] Tobias A. Schaedler and William B. Carter. Architected Cellular Materials. *Review in Advance*, April 21, 2016.
[3] E Dubovikov, V Fomin, I Kondakov , A Shanygin and D Vedernikov. *Development of rational hybrid fuselage structure for prospective civil aircraft.* Proc IMechE Part G: J Aerospace Engineering, DOI: 10.1177/095441001878550, 2018.

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