DESIGNING PRO-COMPOSITE AIRCRAFT CONCEPTS AND LAYOUTS TO MAXIMIZE POTENTIAL BENEFITS OF HIGH SPECIFIC STRENGTH OF CFRP

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Abstract

The main problems of weight saving for composite airframes of civil aircrafts were considered and substantiated. New program complex for fast and confident composite structure weight estimation on the basis of multilevel approach was described. Relationship between composite aircraft structure weight and physical characteristics of resins was obtained on the basis of numerical and experimental results. Investigation of alternative "Black metal" and "Frame" structure concepts for Flying Wing aircraft has shown that "Frame" concept has more potential in weight saving for current resins.

1 Introduction

Structure weight of an aircraft is the key parameters which directly impacts not only on technical parameters and level of comfort for passengers, but also on transport efficiency of the aircraft, because transport efficiency is a complicated enough function of many parameters, and manufacturing and direct costs of the aircraft are the main ones. On Figure 1 the graph illustrating tendency of transport efficiency of civil aircrafts for all period of aviation development is presented. This graph was prepared on the basis of materials presented in open publications in frame of FP6 NACRE project [1]. The transport efficiency was estimated as a value 1/c, where c is the cost of transportation of a one passenger on 1 km, at corresponding level of comfort, safety requirements and ecology demands. The relative value of transport efficiency is shown on the graph.

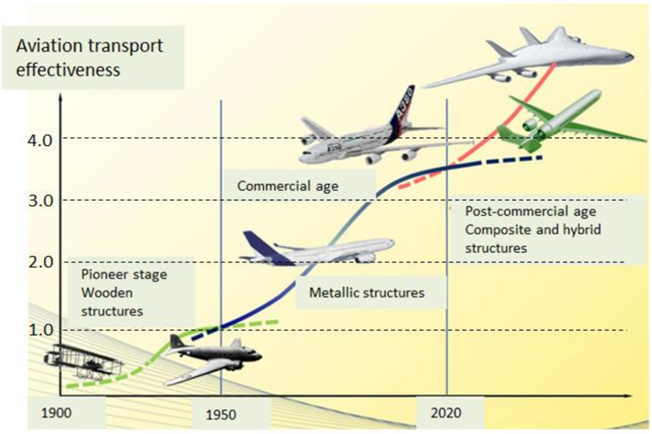

Fig. 1 – Main stages of civil aircraft development

The figure shows that now metallic structures, having passed a way of 60-year-old evolution have reached the maximum of their efficiency mainly because of no real progress in structure weight saving. Further increase of weight efficiency (and, consequently, transport efficiency) is connected with new fibrous composite materials (CM) having high values of stress characteristics. For example, ultimate stress of current carbon fibers exceeds value $\sigma_{ul.tension}$=500 kgs/mm^2 that approximately 10 times more than those for modern aluminium alloys, whereas specific weight of fibres two times less. Composite materials are now widely used in aircraft secondary structures, but as for the primary (load-bearing) ones, no real success in weight saving have been reached so far.

The experience which has been gained in TsAGI in frame of international and Russian projects has shown that the main difficulties in weight saving of composite aircraft structures are connected with essential misbalance between ultimate values of relative deformations of resins and fibers. This misbalance does not allow carbon fibers to realize their high potentials in composite skin packages having orthogonal monolayers. For this reason in frame of “Black metal” composite structure concept, which has metallic design concept and layout, it is very difficult to get high weight (and transport) efficiency of composite primary structures, becaus this design concept and layouts were created to realize maximally potentials of metallic alloys, but not of composite materials.

The history shows that change of a constructive material inevitably leads to new design concepts and layouts and consequently, for the further progress of composite airframes it is necessary to search new design concepts and new layouts optimal for these concepts. This problem was a subject of research in the European project FP6 NACRE, in Russian project CM-fuselage and in Collaborative project FP7 ALaSCA. Search of so-called "pro-composite" concepts, i.e. the concepts allowing to realize high potential advantages of composite materials more efficiently than in frame of “Black metal” concept, is now considered by many scientific schools as one of perspective and promising directions in development of the next generation of airframes and space structures [2-4].

In the present paper the approach and the method for searching rational concepts and layouts are described. This approach allows designers to take into account main problems concerning development of composite primary structures in forming new stress/strain criteria, manufacturing constraints and optimization algorithms for non-conventional composite structures, and also to estimate the impact of different design parameters on a structure weight of an airframe at the initial stage of designing.

2 The Main Problem of Weight Saving in Composite Airframes

To define the main directions of search of pro-composite airframes it is necessary to analyze the main disadvantages of "Black metal" composite concepts applying to current composite materials [5]. Experience gained in TsAGI shows that the main disadvantage of “Black metal” concept is that for current composites it is impossible to create high-effective composite panel similar to metallic one, i.e. the structure consisting of a thin skin and a thin-walled supporting set. Such type of an airframe structure element can realize almost all potential advantages of current metallic alloys first of all in:

-harmonious combination high strength and high deformation properties;

-high level of ultimate shear strain.

It is worth to say that the thin-walled supported panel is the top of evolution of metallic structure details in current airframes, such as panels, walls, ribs and frames. Due to the high deformation ability the metal skin is a good in bearing impact loads, and also allows designers to realize so-called postbuckling effect [6, 7]. This effect is used to increase the weight efficiency of thin metallic skin panels without losing their safety characteristics. Furthermore, the thin-walled, supported panel in metallic airframe is a hi-tech type of a structure both from manufacture and repair viewpoints.

As for composite panels in frame of «Black metal» composite concept, unfortunately, they have not got any advantages mentioned above as there is no industrial technology so far performing strong bonding between fibers, similar to welding of steel reinforcements in reinforced concrete, and consequently, carbon fibers can be bonded in a uniform structure only by the means of binding (resin). This is the root of many problems of using composite materials in airframe primary structure. One of them is that in frame of quasiisotropic and other orthogonal packages current resins do not allow carbon fibers to realize fully their high strength characteristics. Due to very small value of ultimate tensile strain a carbon fiber in these packages can be loaded not more than by 25-

30% of their ultimate stress.

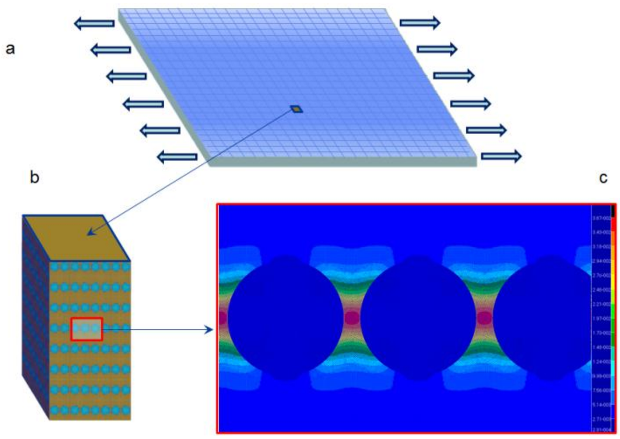

Fig. 2 - Picture of deformation of resin in 90^o layers of composite package.

The analysis of stress-strain state of the resin inside the package on the boundaries of layers with different angles of orientations of fibers, carried out using results of the numerical-experimental investigation has shown that the level of critical stress concentration in the resin depends mainly on the following parameters:

1. Relative angles of fiber orientation of two adjacent layers.
2. Direction and magnitude of the vector of tensile strain of the package.
3. Percentage of fibers in the package.
4. The value of ultimate tensile strain of the resin.

The most critical case for such kind of package is the one when relative orientation of two adjacent layers equals 90^o and the direction of vector of ultimate tensile deformation of the package coincides with the orientation of one of these layers (Fig.2).

The most favorable case when two adjacent layers are oriented $\pm 10^o$ relative to the vector of ultimate tensile strain of the package (see Fig. 4).

Experimental investigations of strength of resin in composite packages [8] showed that one of the main parameters that impacts on the strength of composite package is ultimate tensile strain $\varepsilon_{\text{ultimate tensile resin}}$ (Fig. 3). For current resins the maximum value of this parameter is $\varepsilon_{\text{ultimate tensile resin}} \leq 2.7\%$[1].

For example results of experimental testing for definition of beginning of delamination of monolayers ($0/90^o$) have shown good coincidence with numerical investigation both for brittle and more viscous resins.

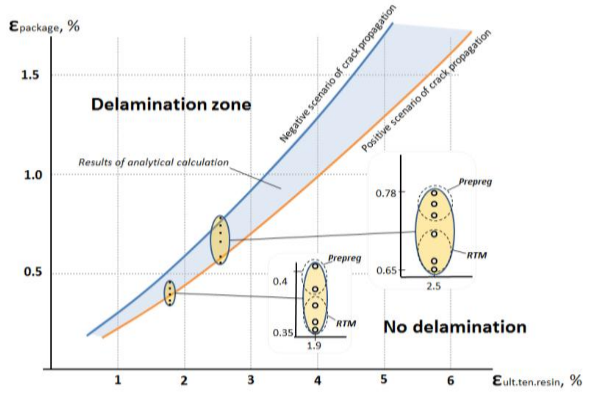

Fig. 3 – Relationship between relative strain of the orthogonal package and ultimate relative tensile strain of resin.

On the basis on these investigations the database on deformation criteria for strength of composite skin have been created. Using this database for analysis of strength of skin under tension allowed to reduce significantly time needed to estimate the composite structure weight on the basis of general (manufacturing) FEM model.

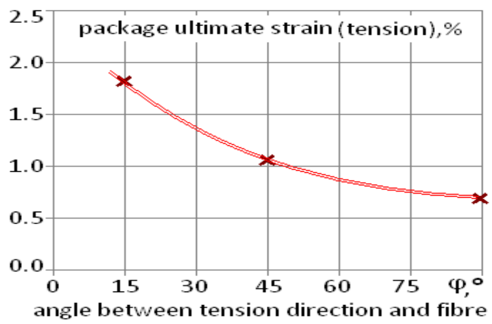

Fig.4 – Relationship between ultimate tensile strain of the composite package and angle of relative orientation of monolayers.

Results represented on Figures 3 and 4 show that in order to get the maximum strength of fibers, angles between fibers should be minimized.

[1] On condition that $\sigma_{\text{ult tens.resin}} \geq 6\text{-}8 kg/mm^2$.

3 Alternative Concepts of Composite Primary Structures

The graphs on Fig.3 and Fig. 4 illustrated that composite skin having orthogonal monolayers (quasiisotropic) is a rather poor primary structure element. It should be noted that because of low value of $\varepsilon_{ult.ten.resin}$ current composite packages are very bad also in taking impact strength. So it is difficult to expect to get high weight efficiency in frame of "Black metal" concept if the resin with good strength/strain characteristics: stress $\sigma_{ult.ten.resin} \geq$ 8-9 kg/mm^2 and strain $\varepsilon_{ult.ten.resin} \approx$ 5-6% will not be created.

As the significant improvement of properties of resins is not expected in the near future, the authors suggests to focus the attention on searching new airframe structure concepts where the composite skin would not be loaded by high-level tension\compression forces, so it (skin) would be not a primary structure element. What about primary structure elements, they should consist of unidirectional fibers. Such pro-composite structure concepts exist and they are built on the basis on the "Frame" and the "Lattice" concepts.

Fig. 5 - Rocket structure composite unit.

The new approach to design of rocket structures applied when designing "Proton-M" rocket, has allowed scientists and engineers from CRISM, Khotkovo [9-12] to create lattice composite structures of the rocket units with weight saving from 28 to 50 %. The structure of a rocket unit made using the lattice composite technology is shown on Figure 5. Primary structure elements in this structure are lattice ribs having unidirectional placement of carbon fibers. Weight saving of this unit was more than 50% with respect to metallic (aluminium) prototype.

There are also a number of examples of successful application of composite materials in high-loaded airframes. As a rule, all the concepts differ from traditional ("Black metal") ones. In frame of conventional concept with cylindrical fuselage the pro-composite "Frame" concept could be realized when fuselage structure is close to lattice structure concept and wing structure is close to beam structure concept with high value of aspect ratio. But more favourable pro-composite aircraft concept is considered to be "Flying wing" concept. Wing and fuselage in frame of this concepts are well integrated that allows to decrease the number of high-loaded joints in the primary structure.

But in order to obtain high efficiency for "Flying wing" structure concept a rather difficult problem of interaction between the upper composite panels and aerodynamic flow should be solved.

Skins of these panels under internal pressure loads are being deformed and started to impact on aerodynamic characteristics (first of all on a drag force) of the airplane. The additional primary structure weight needed to reduce the deformations out of the plane of the panels.

To estimate the potential of weight saving in frame of "Flying wing" concept two alternative structure concepts ("Black metal" and "Frame") were compared on the base of the multilevel approach. In frame of the "Black metal" structure concept the skin bears this transverse and compression loads through bending. It is not good method to bear these loads and it would be more preferable for skin to bear these loads through tension. But for the composite skin consisting of monolayers with different fiber orientation and small values of ultimate relative tensile strain of resin it is impossible to realize this idea.

To bear the tensile loads the skin should buckle without failure. Postbuckling behavior of a structure was studied well enough for the metal panels, and numerous results of the investigations showed that as a rule, at external loads P>Pcr, where Pcr is buckling force for skin the panel was not being destroyed because a redistribution of internal loads between the skin and stiffeners allowed keeping the load-carrying capability of the structure at a sufficient level with some degradation of structure's rigidity.

As for composite panels this paper illustrates the real absence of possibility of using this effect in frame of conventional fuselage panel (Figure 5). On the Figure 6 the deformation of the composite skin in postbuckling state is shown. The postbuckling state corresponded to the external loads on panel equal $\lambda = P_{cr}/P_{ult} = 0.8$ (not high postbuckling level), where P_{cr} is the critical load of skin buckling. Figure 6 illustrates that the skin after buckling was in tensile strain state and the real general tension strain of the skin in 90^o monolayers was more than 0.5%. It means taking into account the investigation described in Chapter 1 that internal deformed state of this monolayer is close to failure (delamination). For this reason postbuckling effect is not permitted in conventional composite panels.

The relationship between the weight and thickness of composite panel with quasiisotropic skin is shown on Figure 6.

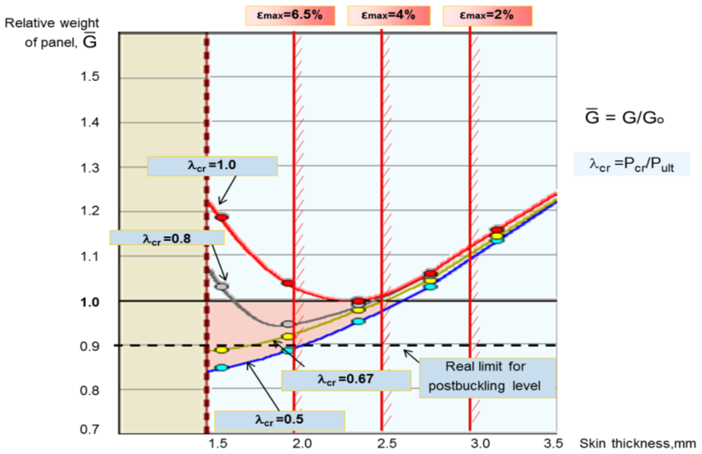

Fig. 6 - Relationship between thickness and weight of composite panel

The relationship has been obtained on the basis of the analytical method which had been validated in frame of FP6 ALCAS and FP7 MAAXIMUS EU projects. This relationship indicates that of "Black metal" concept using of postbuckling effect can't give any advantages for $\varepsilon_{ult.ten.resin} < 5\%$. Therefore the concept when skin is a primary structure element it is impossible to realize the idea to bear pressurized loads through tension of skins.

As for frame (lattice) concepts stiff and strong ribs made from composite material with unidirectional carbon fibers can bear all general loads (excluding external and internal pressure). As for the skin in this concept, it can be made from another structure material. The skin can be made from an elastic material, i.e. a viscous resin and high value of $\varepsilon_{ult.ten.resin}$ and low one of $\sigma_{ult.ten.resin}$ can be used. This skin will be good at bearing tension stresses. On Figure 8 difference in principles of bearing external loading between "Black metal" and "Frame" (lattice) concepts are shown.

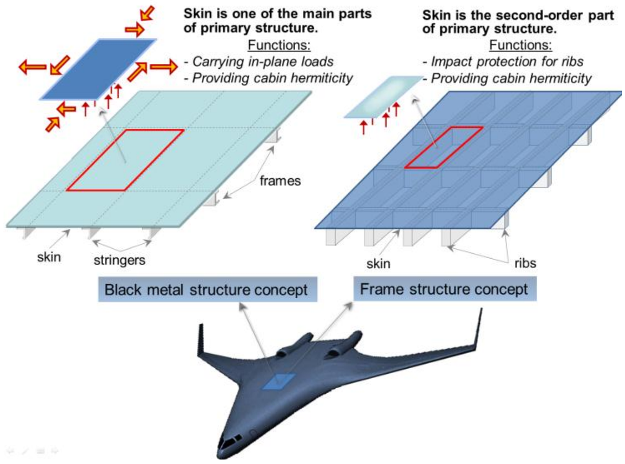

Fig.7 - Alternative structure concepts of Flying Wing composite aircraft.

Investigations presented in this chapter allowed author to simplify significantly the procedure of weight estimation of two alternative composite concepts mentioned above (Fig.7) and use simplified FEM models for the whole aircraft structure, as the problem of skin buckling should be excluded from the consideration for these two concepts. What about "Black metal" concept, it is caused by large value of thickness needed to bear the internal pressure through bending. As for "Frame" concept - due to absence of compression stiffness of elastic skin. This allowed to decrease significantly the labor input to numerical investigations for weight estimation of composite aircraft composite structure at the initial stage of design.

The special approach to stress-strain analysis of composite ribs was developed and validated in order to investigate stress-strain state inside ribs. The main feature of this approach is that the real rib is modelled by a alternative set of "boxes", which consist of membrane finite elements (see Fig. 8).

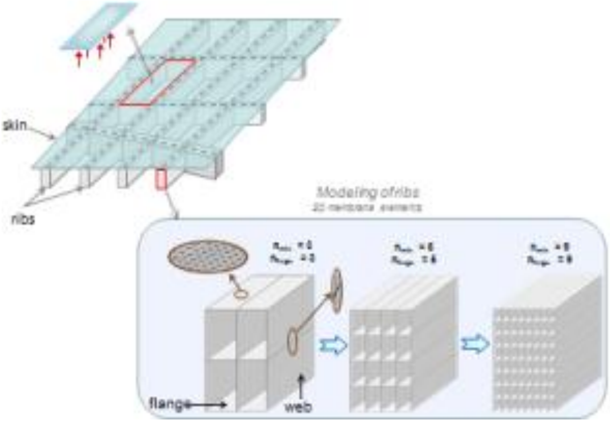

Fig. 8 – Modelling of ribs by the means of 2D membrane elements

This approach to modelling allowed to avoid using 3D elements for stress-strain analysis and consequently it could reduce significantly time of the analysis at the same time keeping the needed level of accuracy. In order to define the needed level of accuracy the corresponding parameters of rib models were automatically chosen. On Figure 9 the procedure of defining of rational parameters of rib model is shown.

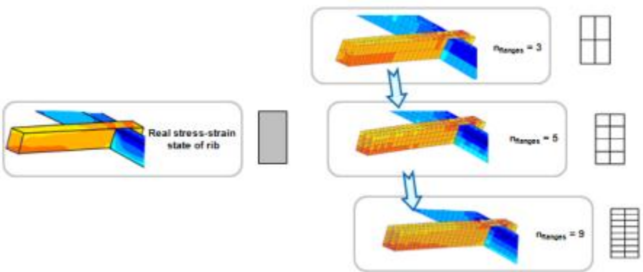

Fig. 9 – Procedure of definition of rational rib FE model taking into account level of accuracy and constraints on maximum size of FEM model.

4 Alternative Concepts of Composite Primary Structures

The task of weight saving of composite airframes is one of the main problems in designing new generation aircraft structures. Taking into account the investigations described in Chapter 2 and 3, this task can be solved on the basis of the program complex on the basis of multilevel approach [5] to multidisciplinary design similar to weight estimation of metallic aircraft structures. Two main problems which prevented from fast and confident estimation have been removed and this removal was substantiated.

The multilevel approach for designing new aircraft concepts was developed and validated in TsAGI to solve multidisciplinary tasks of finding optimal airframes at the initial stage of design. One of the main features of this algorithm is fast and confident procedure of weight estimation of aircraft structures.

The procedure (approach) is based on the universal parametrical principle of forming four computational research models of different level of detailing (geometrical, mass, manufacturing and strength) in frame of the special database for the airplane structure. In Chapter 1 strength and manufacturing models were used to calculate stress/strain parameters of structure elements. Two more models (geometrical and mass) are used in this procedure to calculate aerodynamic characteristics and dynamic behaviour of aircraft structures [13] respectively. The special database was created in accordance with the real procedure of creating airframes. The special database contains:

- statistical parameters of prototypes, including manufacturing constraints and weight parameters of secondary structure;
- stress/strain criteria and constraints on geometrical parameters.

The database includes 4 main blocks, which are responsible for corresponding level of structure modeling (see Figure 10).

Block 1 is responsible for manufacturing module which contains the information concerning the main structural elements of airframes (panels, frames, walls, attachments etc.). It is also responsible for the relationship between Strength and Manufacturing modules. Database of this block corresponds to the computational model of the Manufacturing level; in frame of this model by means of internal programs of Block 1 the main structural elements (panels, walls, ribs etc.) of the airframe are formed.

Block 2 is responsible for the mass module which contains the information concerning the main units of the airframe. It is responsible for the relationship between Manufacturing and Mass modules. Database of this block corresponds to the computational model of the Mass module; in frame of this model by means of internal programs of Block 2 the main units (structure boxes) of the airframe are formed.

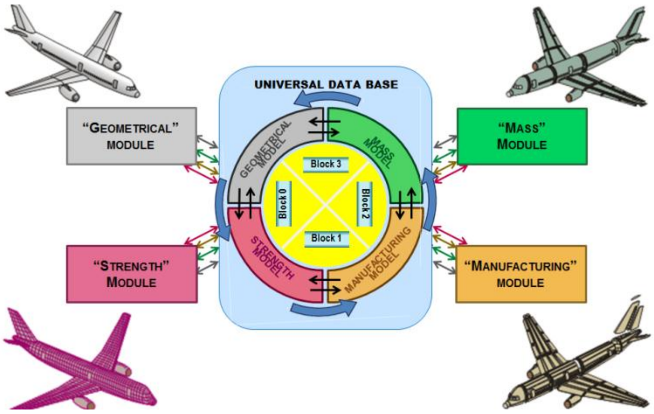

Fig. 10 - Block-scheme of the multilevel algorithm.

Block 3 is responsible for the geometrical module which contains the information concerning the entire airframe. It is responsible for the relationship between Mass and Geometrical modules. Database of this block corresponds to the computational model of the Geometrical module; in frame of this model by means of internal programs of Block 3 the entire airframe is formed.
Block 0 is responsible for the relationship between Geometrical and Strength modules and allows to realize redesign procedure.
Generally, the procedure of weight estimation consists of 4 stages. At the stage 1 on the basis of design parameters the weight of FEM strength model is calculated. This is the initial level for airframe weight parameters, because this weight is enough to bear all general load cases. At the stage 2, weights of all structure elements (panels, walls, frames) are under calculation. During this procedure by the means of database block 1 the primary weight is précised. At the stage 3. weights of all structure units (fuselage barrels, wing boxes etc.) are under calculation. During this procedure by the means of database block 2 in addition to weight of primary structure units, weights of secondary structure of units are added. And finally, by the means of database block 3 some weight corrections are performed at the level of the whole aircraft.

The estimation of structure weight (G) for two alternative Flying wing concepts ("Black metal" and "Frame", having take-off weight 150 t) has been carried out using the multilevel approach and the parametrical relationship between G and $\varepsilon_{ult.ten.resin}$ of resin was obtained (see Figure 11). The results indicate that it is difficult to have the weight benefits of composite structure related to metallic structure for current resins in frame of "Black metal" concept. As for "Frame" concept, there is a possibility to have weight saving up to 8-10%. But real benefits could be obtained only for higher values of $\varepsilon_{ult.ten.resin}$ close to 8%. In this case we can see no difference between these concepts. In this calculation the value of maximum tensile stress for resin was taken not less than 7 kg/mm^2.

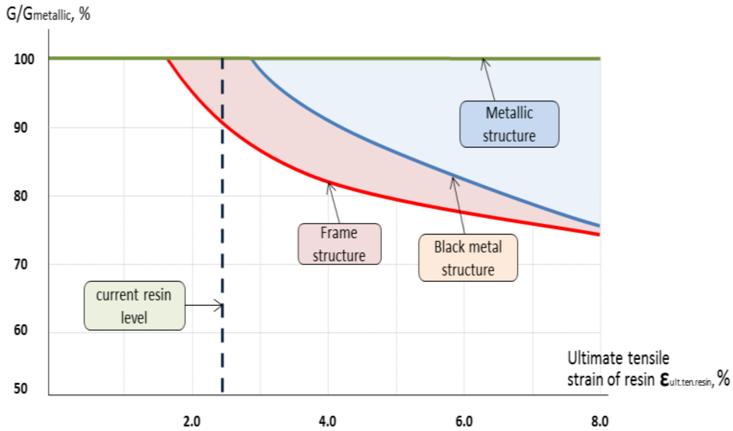

Fig. 11 - Procedure of structure weight estimation in frame of the four-level algorithm

5 Conclusion

The results of the investigation of composite aircrafts presented in the paper have shown that using current composite materials containing current carbon fibers and resin has given no real benefits in structure weight saving. The main reason is rather low stress/strain physical characteristics of current resins, which are usually used in composites as binders.

It was shown that in order to have significant weight benefits the value of ultimate tension strain of resin must be at least two times more than for current resins (keeping values of resin ultimate tension stress at the same level about 6-

8 kg/mm^2).

Investigation of non-linear behaviour of composite skin (“Black metal” concept) have shown that using of postbuckling effect can’t give any advantages for $\varepsilon_{ult.ten.resin} < 5\%$.

New “Frame” structure concept for Flying wing with elastic skin was suggested to solve the problem of favourable interaction between skin and aerodynamic flow without losing weight efficiency.

Results of weight estimation of alternative “Black metal” and “Frame” structure concepts presented in the paper has shown that “Frame” concept can have more potential in weight saving even for current resin and for the resin with $\varepsilon_{ult.ten.resin}$ close to 8%.

Short description of the approach of modelling pro-composite structure elements for fast and confident estimation of non-conventional airframe weight at the initial stage of designing was included in the paper.

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