MULTILEVEL APPROACH FOR STRENGTH AND WEIGHT ANALYSES OF COMPOSITE AIRFRAME STRUCTURES

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Abstract

A new approach to composite aircraft structure analysis at the initial stage of designing is considered. The approach is based on multilevel modeling of airframes which includes four parametrical FEM-models (levels) of different dimensionality basing on unified data base. Each FEM-model is built up for solving a specific task required for analyzing strength, weight and cost parameters of composite structures.

The use of such approach enables:

- *to improve accuracy of stress/strain parameters and weight predictions at the initial stages of designing;*
- *to reduce significantly labor content and duration of works required for researches;*
- *to carry out correct parametric investigations of airframe weight dependence on different constructive parameters.*

The program algorithms using such approach demonstrated high effectiveness in designing of non-conventional aircraft structures and in solving quite complicated stress/strain tasks. This approach was validated in frame of many domestic and international projects including projects of 6th European Program.

Introduction

The problems of safety improving, environmental friendliness and competition aspects imply considerable increase of aircraft weight. Numerous studies show the following: to accomplish all test requirements, while keeping aircraft performance, the airframe weight must be by 15-20% less as compared with the state-of-the-art. Such improvement in the weight effectiveness/efficiency may only be achieved through novel approaches to structural design of new-generation aircrafts. So, environmental and economic issues force future aircraft designs to maximize weight and cost efficiency to keep air transport competitive and safe.

As metal designs have reached a high degree of perfection today, and extraordinary weight and cost savings can hardly be expected, further potentials are especially seen to be connected with fiber reinforced composites which became apposite in aircraft structures. It forces the aviation and mainly civil aviation to go to the new stage of its development when the main parts of aircraft structures will be created of new composite materials. But new problems and difficulties appeared while the first steps in this direction were being made. And now it is obvious that a progress in developing modern aircraft structures is possible only if experts will have found novel solutions in the areas of

- developing new designing methods,
- preparing advanced materials,
- formulating the novel manufacturing processes, etc.

This article is focused on the first issue of this list which is considered by the authors to be the most difficult and important subject. The authors tried to use all their experience and skills to develop new approach to creation a program algorithm which would be able to satisfy new challenges.

Designing of airframe in general, and composite structures in particular always means careful considering material, structural and manufacturing aspects in a closed-loop process chain for reasons of their close interaction. To simulate correctly a composite design of modern airframe the following main features of composite structure and manufacturing process should be under consideration:

- Continuous fibers without any interruption (structural mechanics, material).
- Integral construction, none or very low number of joints / fitting elements (structural mechanics, manufacture).
- Fully automated manufacture yielding high output (manufacture).
- Design, tolerant to damages by providing redundant load paths around area of destruction (structural mechanics).

Only program algorithms which take into account these subjects will be able to provide correct solutions in investigation potentials of composite materials in frame of new pro-composite aircraft structures (often non-conventional) .

The procedure of optimizing non-conventional aircraft structures is usually multi-disciplinary iterative process which includes: determination of load cases; analysis of strength and stiffness; choice of manufacture process; estimation of cost and weight. TsAGI has experience in developing such methodologies [2, 3, 4, 5] which were validated in frame of domestic and international projects [6, 7, 8].

1 Airframe weight and aircraft’s cost

Effectiveness of airframe weight and aircraft’s cost are among the most important aircraft parameters dictating other aircraft performance data. In turn, the airframe weight (fig. 1) is a generalized function of the following global parameters: aircraft geometry, airframe concept, structure materials, manufacturing process. What about aircraft’s cost effectiveness it is a function of the same global parameters plus maintenance and repair. In this consideration the cost of a fuel was included in the frame of maintenance.

Geometrical parameters define relationship between weight/cost effectiveness and dimension of aircraft, while concept ones identify layout impacts on weight/cost characteristics. Characteristics of structure materials itself impact significantly on airframe weight/cost but they have also great influence on other global parameters. Manufacturing process is responsible for quite big part of weight components in airframe and it is the main global parameter in a cost of airframes.

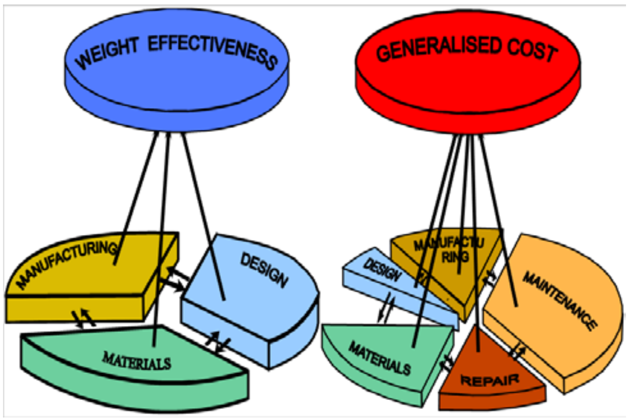

Fig. 1. Global components of airframe weight and aircraft’s cost effectiveness

In spite of the fact that the aircraft’s cost effectiveness is the main parameter which indicates the real quality of aircrafts this factor wasn’t as a rule being taken into account in designing airframes of conventional aircrafts at the initial stage of designing. It could be seen on a diagram (fig. 2) which illustrates relationship between airframe weight/cost effectiveness.

The curve in the diagram corresponds to the current technological level and subdivides the field into two areas: above the curve is the real technology domain, while the advanced domain is located below the curve.

In turn, the real technology domain may be subdivided into three zones along the “Airframe weight” axis. The right-hand one represents unpractical solutions in respect of both weight and cost. In this case, the airframe has excessive weight. The high cost is caused by the big fuel consumption due to a poor technical performance. This zone contains improper solutions and the only method for leaving this area will be the minimization of the structural weight.

The central zone corresponds to rational (optimal) solutions regarding weight & cost. This zone includes the most airframes of state-of-the-art airplanes.

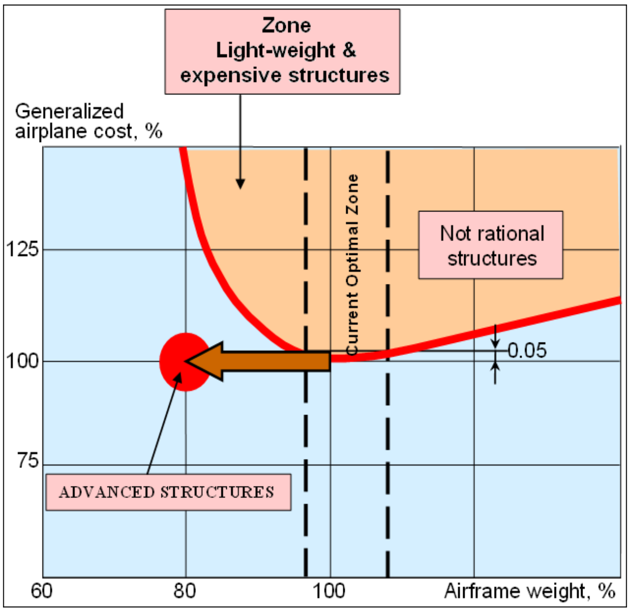

Fig. 2. Scaled aircraft's cost & airframe weight effectiveness

This zone features the insignificant sensitivity of the aircraft's cost effectiveness to the airframe weight, so it explains the fact that the main criterion in designing airframes was the weight of this airframe.

Taking into account the mentioned above needs (15-20% of reducing airframe weight) that could cover the new challenges it wouldn't be difficult to find in the diagram (fig. 2) the main direction of researches and the main destination of a design of the future aircrafts. It is the red circle. It is obvious that in this case the weight saving will be connected with aircraft's cost effectiveness mainly due to the increasing of the manufacturing cost. So, to reduce airframe weight by 20% and to keep the same cost level of the future aircraft the manufacturing cost should be at least reduced by 35-40%.

It means at least two general criteria (airframe weight and aircraft's cost effectiveness) must be taken into account in designing new generation aircraft structures already at the initial stages of designing. It not only complicates designing process seriously but also changes the approach itself to designing of aircraft structures.

So, the following main problems have to be solved for creation of a new program algorithm for designing of modern composite airframes at the initial stages:

1. new (stress/strain and others) criteria for composite materials and simulation models which are more complicated in comparing with metallic ones;
2. novel airframes which should be suitable and more effective for new structure materials;
3. new constraints (especially manufacturing ones).

It is clear that solving these problems increases labour input of designing significantly, and it in turn requires constantly searching for the new approaches.

2 Multilevel approach to designing composite structure

Numerous researches have shown an inefficiency of use of one simulation (FEM) model for solving the mentioned above multidisciplinary designing problems. However, use of several simulation models for research of problems of strain/stress, weight, cost and others add the new complexities connected with correct link of one model with other ones.

A new approach to composite aircraft structure analysis at the initial stage of designing was considered to satisfy new challenges and to reduce significantly labor input regarding preparations, solutions and analysis.

The approach is based on multilevel modeling of airframes which includes four parametrical FEM-models (levels) of different dimensionality basing on unified data base. The data base was developed taking into account the following demands:

- conventional form of inputting structure parameters for any aircraft structure;

- convenient interface which was designed to reduce significantly effort of users and possible mistakes;
- time economy by means of fully automatic procedure of creations of simulation models and getting the solution;
- possibility of using simultaneously several simulation models with different level of complexity of physical modeling.

The data base consists of four main parts each of them is responsible for its own level of simulation.

Each FEM-model is automatically built up for solving specific tasks required for analyzing strength, weight and cost parameters of composite structures (fig. 3). For each aircraft these models are created by means of conventional parameters of real aircraft. Thus, the given algorithm allows creating universal parametrical FEM models of a structure.

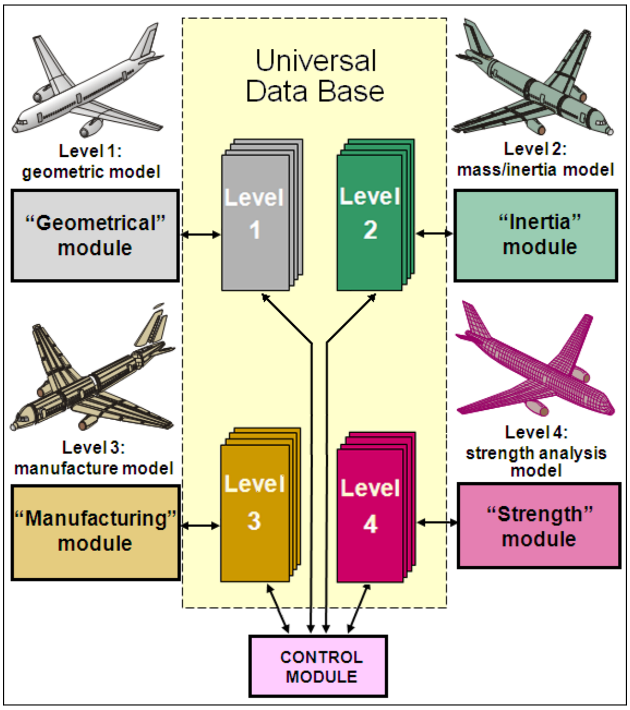

Fig. 3. Block diagram of the algorithm

At the first level the parameters defining geometry of the flying machine and forming the basic modules of a design are set. At the second level the parameters characterizing each of generated compartments, and forming constructive elements of each of compartments are set. At the same level within the limits of the generated compartments a large number of inertial parameters for all flying machine are set. At the third level the parameters characterizing each constructive element are set, and also the basic technological parameters and restrictions are set. At the fourth level the parameters characterizing the basic FEM-model, responsible for calculation of the general durability are set.

The program algorithms using such approach demonstrated high effectiveness in designing of non-conventional aircraft structures and in solving quite complicated stress/strain tasks. This approach was validated in frame of many domestic and international projects including projects of 6th European Program.

In order to find rational or compromise (weight & cost) parameters of airframe one could resort to the minimum-weight optimization algorithm relying on the specialized database with finite-element models which allow for features of manufacturing.

The block diagram (fig. 3) of the algorithm demonstrates the principal differences from the traditional minimum-weight optimization algorithms.

1. Four different basic finite-element models are used simultaneously:

- for creating geometry parameters and analyzing external loading factors,
- for outlining the critical load conditions,
- for analyzing manufacturing process parameters,
- for providing strength analysis.

2. The algorithm and essentially all the analytical models rely on the specialized database that contains statistical parameters of prototype structures.

3. All the analytical models for the algorithm are formed and processed automatically that significantly reduces time consumption.

This version of the algorithm may be the basis for establishment of versatile algorithm aimed at defining of the optimal (weight & cost) airframe parameters, and it enables efficiency of advanced structural materials to be estimated.

3 Examples of using the approach

One of the important problems of reducing an airframe weight is to research the possibility of skin local buckling during the structure loading. An experience shows that providing of this possibility enables a designer to reduce significantly the structure weight. This effect is usually realized in metal fuselage panels when the skin local buckling is allowed at a relatively low level of external load $P_{cr} = \lambda_{cr} \cdot P_{ult}$, where P_{ult} is the ultimate load for the given panel, λ_{cr} is a coefficient ($\lambda_{cr} = 0.3 \div 0.35$ for many metallic fuselage structures).

Postbuckling behavior of a structure was studied well enough for the metal fuselages, and numerous results of the investigations showed that as a rule, at external loads P, $P_{cr} < P < P_{ult}$, the structure 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 to composite fuselage structures, experimental data on buckling of composite fuselage section elements show that an airframe structure weight saving also could be possible if postbuckling behaviour of the section’s skin is allowed and the additional criteria of failure for the composite skin are satisfied [9].

But unfortunately insufficient number of results of experimental and analytical researches of a non-linear stress-strain state of modern composite structures does not give us a possibility to define reliably what combination of the structure parameters and the values of λ_{cr} would be realizable for practical using of the postbuckling effect, and a lot of special analytical and experimental researches should be carried out to use this effect actually.

This paper illustrates one of the possible ways of the practical investigation of this quite complicated phenomenon (non-linear postbuckling behavior of composite fuselage structures). In frame of the proposed algorithm this problem can be correctly enough solved with the minimum labour even at a stage of preliminary designing. Block scheme of the investigation procedure in frame of the algorithm is illustrated in fig. 4.

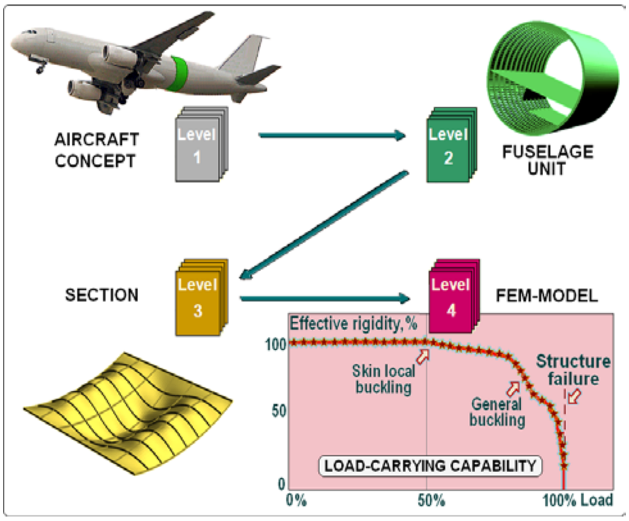

Fig. 4. Scheme of calculations procedure in frame of the algorithm

As an example of working capacity of this algorithm the results of parametrical researches are presented in fig. 5 for a composite panel of fuselage units of the middle-range aircraft with conventional layouts (fig. 6).

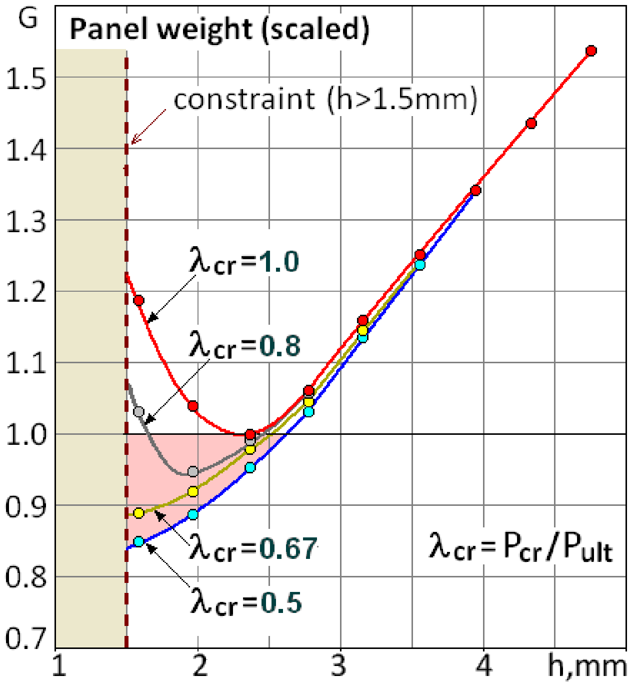

Fig. 5. Dependences of panel weight on skin thickness for different values λ_{cr}

These results show that the weight of the composite fuselage panels may be reduced due to the postbuckling effect if a certain combination of the structure parameters is realized. The diagram in fig. 5 shows that the reduction of the panel structure weight will be possible if the thickness *h* of composite skin belongs to the interval 1.5mm<h<2.7mm.

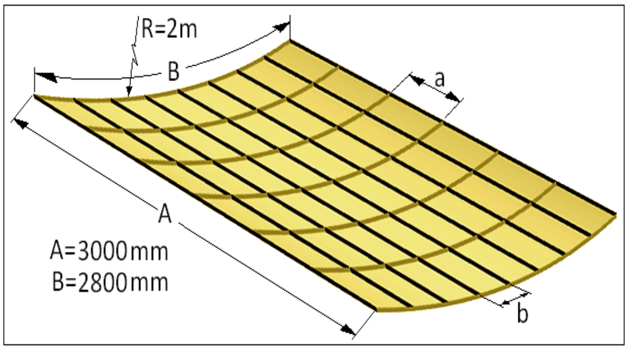

Fig. 6. Stiffened panel of composite fuselage

The composite material 977-2 IM was chosen (at the level 4 of the universal data base, fig. 4) as the main structure material for skin and stiffeners (taking into account degradation of the material's characteristics). Five loading cases were selected (at the level 2) from the full spectrum of the aircraft loading (level 1).

The following structure parameters were varied (level 3) at determining the dependence of the panel weight on skin thickness: layout and sequence of layers in skin and stiffeners; a shape and sizes of elements of stringer and frame; stringers and frames steps. Different values of λ_{cr} (from 0.5 to 1.0) were considered.

The following constraints were used:

- failure of at least one lamina of a composite skin or stiffener element (stringers, frames) at $P < P_{ult}$;
- general buckling of stiffened panel as a whole at $P < P_{ult}$;
- geometrical constraints.

The performed researches showed that the complicated nonlinear problem of designing composite section structure had been solved with small labour input and high level of accuracy at use of FE-model of large dimension. The example has illustrated high efficiency of the algorithm at solving complicated multidisciplinary problems at the initial stage of designing.

The other important problem that is under consideration in this paper was the task of weight saving for non-conventional fuselage structure in frame of Flying Wing's concept.

Usually such kind of aircraft concept has flat panels loaded by internal pressure, and the deformations of these panels can impact on aerodynamic characteristics significantly. Therefore in addition to general criteria the new criterion has to be introduced in the designing procedure for this structure concept. So to find the optimal solution concerning structure parameters, a complicated multidisciplinary investigation has to be carried out.

Authors have some experience of solving similar problems, so the results presented in this paper reflect the main features concerning the investigation procedure of minimization of Flying Wing structures.

The hypothetic Flying Wing aircraft in frame of composite structure concept using conventional layouts was considered (fig. 7).

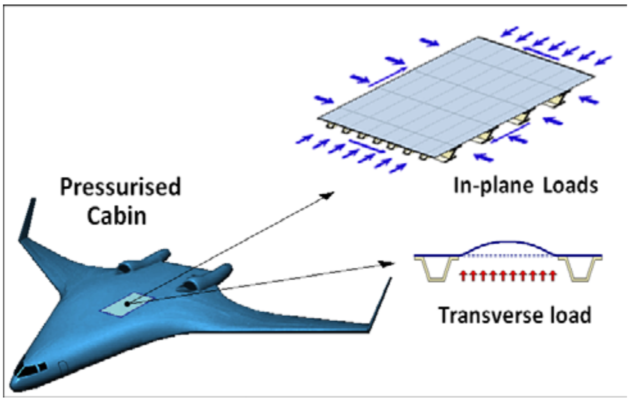

Fig.7. Hypothetic Flying Wing with pressurized cabin's panels

The main structure elements of this concept are the flat pressurized cabin's panels which have a distinctive feature in its loading due to a quite big level of bending moment because of out-of-plane loads (internal pressure). So the cabin's panels are under complicated loading factors. In additional to this phenomenon the pressurized panels can impact on re-distribution of aerodynamic pressure due to the specific deformations of the flat panels under external combined loading (fig. 8).

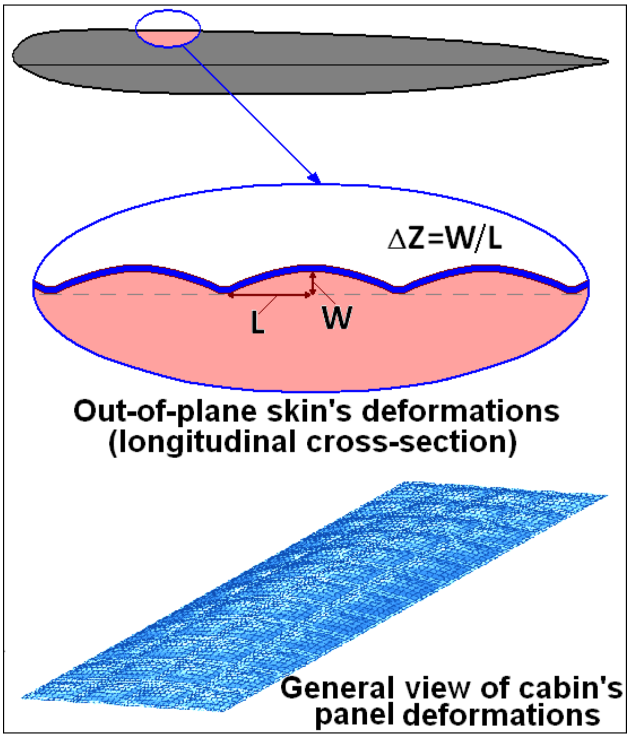

Fig. 8. Out-of-plane deformations of skin

If not to take into account the impact of the panel's deformations on the aerodynamic characteristics the problem of the structure weight minimization is being solved in frame of the mentioned above algorithm (fig. 4). The full spectrum of the aircraft loading was determined at the level 1. Then the critical loading cases were selected at the level 2. The structure parameters were varied at the level 3 to determine optimal layouts and to investigate buckling and non-linear behavior of the cabin panels (fig. 9). General and local stress-strain states of the structure were analyzed at the level 4.

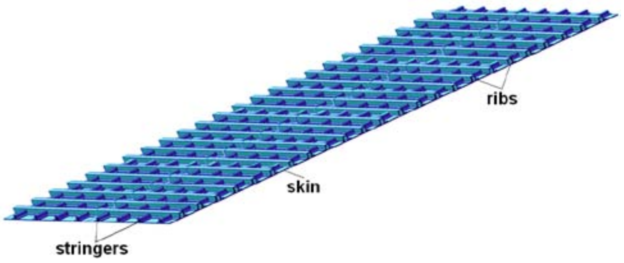

Fig. 9. Cabin's panel structure

For these composite structure parameters relative value of the structure weight (per unit of area) obtained in the optimization was $G_0 = 26.2\,\text{kg/m}^2$. This value was taken as a relative weight unit. The skin thickness ranged between 4 and 5 mm. The transverse ribs and longitudinal stringers had a “hat” shape (fig. 9). Results of the panels designing showed considerable influence of non-linear effects on the structure weight (the difference between results of linear and non-linear calculations was about 37%).

Analysis of strain state of the pressurized cabin panels showed existence of considerable out-of-plane deformations of the skin in the loading cases (fig. 8).

To investigate an influence of the skin deformations on the aircraft aerodynamic characteristics, the full computational fluid dynamic (CFD) analysis of the aircraft structure was carried out using "FLO-22" program of A. Jameson. It can be noted that the mentioned above universal data base comprises unified data for using both in strength and aerodynamic analyses. Results of CFD analysis showed that the skin deformations led to arising of local supersonic zones near the cabin surfaces (see a distribution of local Mach number in the neighbourhood of deformed panels, fig. 10). It resulted in increase of a drag coefficient. In particular, loss of aerodynamic efficiency (lift-to-drag ratio) was nearly 0.5 for the structure (and skin deflections) obtained by the designing without using a constraint on the skin deformations. For this reason an additional (aerodynamic) constraint on a function of skin deflections $\Delta z = W/L$ has been introduced into procedure of the structure optimization (fig. 8).

To investigate an influence of the aerodynamic constraint on the structure model weight, the parametrical calculations were being carried out regarding dependence of the structure weight on maximal allowed value of $\Delta z = W/L$. The results of these calculations (fig. 11) showed an significant influence of aerodynamic constraints on the structure weight.

The dependence of loss of aerodynamic efficiency on relative amplitude Δz of the cabin surface deflections is presented in the same diagramme (fig. 11). This dependence was obtained as a result of the structure designing (and the strain analysis of the structure) for corresponding aerodynamic constraints.

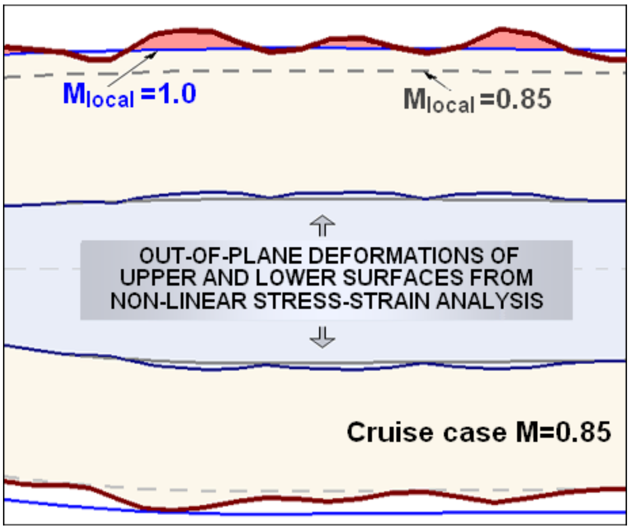

Fig. 10. Influence of skin deflections on local Mach number

Results of this investigation showed that the optimum solution for such kind of problems represents the compromise between increase in weight and reduction of aerodynamic efficiency.

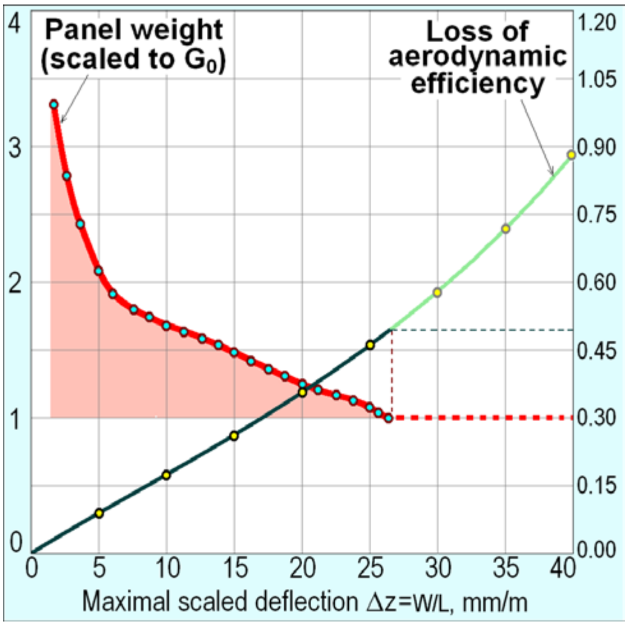

Fig. 10. Dependence of structure weight on aerodynamic constraint.

The examples showed that the algorithm enables a designer to solve very complicated multidisciplinary problems taking into account non-linear effects at the early stages of designing.

Summary

A new approach for analyses of airframe structure strength and weight at initial stage of designing was considered. The approach is based on a general-purpose principle of multilevel modeling of airframe structure. It allows automatic generation of four parametrical FEM-models of different dimensionality (level) basing on unified data base. Each FEM-model is built up for solving a specific problem required for analyzing strength and weight of composite structures and can be connected with specially adapted analytical models. Each level can be represented as a level of detailing at the correspondent stage of designing. On the other hand each level is responsible for investigation of certain set of structure parameters. This idea allows simulating the online procedure which goes sequentially through all the initial stages of aircraft designing within a single program.

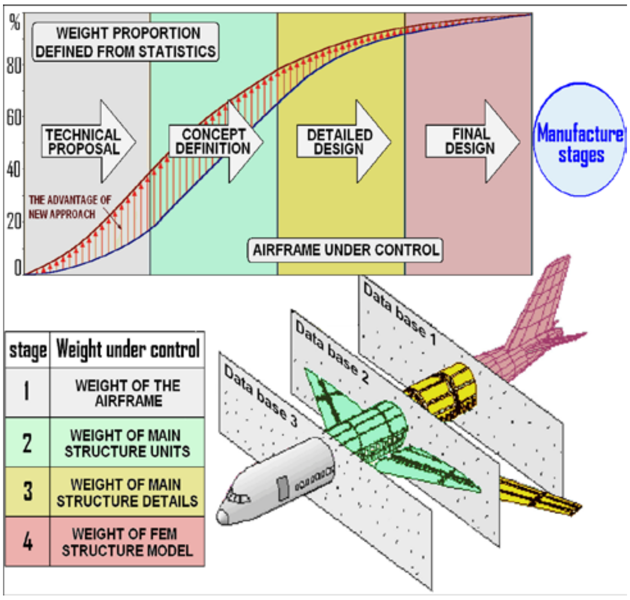

Fig. 12. Methodology of structure weight estimation in frame of the new approach

The use of such approach enabled:

- to improve considerably an accuracy of strength and weight prediction at the initial stages of designing (fig. 12);
- to reduce significantly labour input and work duration at pre-design researches;

- to carry out correct parametric investigations of airframe weight dependence on different combinations of constructive parameters;

to solve quite complicated multidisciplinary tasks concerning weight estimation taking into account new constraints (aerodynamic and aeroelasticity demands, conditions of postbuckling behaviour, cost limits, and others) in frame of standard FEM models.

Program algorithm created on the basis of the multilevel approach was successfully validated for many advanced structure layouts of domestic and foreign aircrafts. The algorithm demonstrated high effectiveness in designing of non-conventional layouts, e.g. Flying Wing and others. The authors performed such researches in frame of NACRE-project of 6th EC Program. The multilevel approach was effective in analyzing influence of postbuckling behavior of thin composite skin on structures weight (TsAGI's task in project ALCAS of 6th EC Programs and also in series of Russian projects).

The report comprises results of weight analyses for advanced layouts for new passenger aircrafts as well as the results of parametric investigations.

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