GLOBAL ANALYSIS OF THE AIRCRAFT STRUCTURE AND ITS APPLICATION TO THE PRELIMINARY DESIGN STAGE

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Abstract. Modern aircraft safety depends on sufficient strength and rigidity of the structure. This must sustain with lightest possible weight, because any excess mass has not only detrimental effect upon the performance but also is significant economic factor. The most rational way to achieve the proper structure seems to be global analysis commenced in the preliminary design stage already. The analysis outcomes provide base for local analysis of the details led parallel. Any revisions more or less relevant can be made in the numerical model with very expensive prototype changes avoiding.
The paper illustrates efficiency of the airframe structure global analysis. As examples the aircrafts still in service but designed without computer application were chosen. The finite elements numerical model of each was created and some critical in-flight load cases were simulated.
The result obtained were a ground for evaluative opinion on the applied solutions and pointed zones with high stress gradients that could be redesigned eventually.

Keywords: aircraft, structure, finite element method, stress, global analysis.

Introduction

Almost every flying vessel designed recently looks like very complex system consisted of progressive materials, elevated aerodynamic shape and electronic equipment. Diversity in missions commenced by modern military aircraft or requirements not only for safety, but also aeronautics comfort of airliners cause that new aircraft creation sometimes exceeds beyond one corporation or even a country possibilities so it is the effect of cooperation between huge staff engaged in multidiscipline tasks. Complexity mentioned and size of designed construction cause the necessity of rational design methods formulation. The wide enforcement of numerical methods into design process has eliminated laborious calculation works and therefore unavoidable simplifications usage. The only one limitation at this time is potential computer power and what's more programmers talent. Trend observed is to provide full compatibility and data transfer between different design and calculation systems applied in every stage following the design process. The next step is creation of integrated CAD systems that allow engineering the whole object in one programme radius. An adequate example could be the family of MSC software, including full FEM solvers and some additions to fatigue or aeroelasticity analysis or CATIA system designed by Dassault. Some of corporations are proud of the fact that their aeroplanes were created only in electronic memory without any pencil sketch.

Concerning the background introduced above, creation of new airplane, belonging to the light general aviation, does not stand-alone. These category constructions, if they are not by-products of large corporations, they usually come into existence by cooperation of scientific institutes or academic centres, having the proper staff and experience [2, 8]. Light aircraft design needs only the small group of specialists, therefore it is in grasp of enthusiasts or students.

Regardless the size of the task, the principles formulated by design theory are holding true and the design process consists of the same stages. Furthermore the tendency to reliability, durability and safety increasing of flying construction, with minimizing project costs simultaneously involves optimization of many parameters at the preliminary stage of new subject creation [12]. It seems to be intentional to put into practice numerical methods in wide range at the very start.

Far simple structure does not demand high computation power and the whole design process can be executed with even personal computer assistance. However as far as application of CAD systems is very common, insomuch calculation tools are engaged in very late phases of the project, despite the software background disposal. It takes place, general, with respect to particular details. Whereas the initial stage of light general aviation is based on certain elaborated procedure outlines as an effect of empiric knowledge to some extent. The general idea of the airframe structure is verified with progressive computational tools hardly ever.

Finite Element Method calculation enforcement between the final part of preliminary design and full-scale design realisation in a wide range warrants avoidance of every imperfection following with notches of stress concentrations or overdimensioned parts, thus excessive mass [13, 10]. The simple algorithm, showed below, complying the remarks described is proposed in this paper. Tracking the sequent steps the engineer can make essential corrections that would be missed sometimes. Any change, later on, when the mistake was discovered during static or in-flight tests, would procure huge amount of problems or would be simply impossible [1].

1. Global analysis

At the preliminary design stage we do not know exactly the details of individual airframe elements (Fig 1). There is only general shape coming off the aerodynamic configuration already chosen. Nevertheless connection of this factor with the structure composition mustn't be neglected. It affects on airplane mass and its distribution. Thus even at this design phase we have to define assumptions about the carrying structure and its main joints. The airframe should secure proper strength and stiffness when possible failure appeared, what's more this failure could not propagate. These conditions are to stand its duty with the minimum total mass of the structure [3].

Despite the some kind of optional latitude in airframe design there is main line imposed already and it allows creating first approximation of numerical model based on Finite Elements Method, used mainly for introductory strength calculations. So-called the global analysis is commenced on this model. The results of this analysis create boundary conditions as starting point for local analysis of particular details, fitting joints or notches first of all [4]. The software within easy rich enables to create expanded, high-complicated models consisted of parts differential in its geometry and stiffness. Creation of complete designed airplane structures could be in grasp. That gives the wide point of view on the structure as a whole and localises possible neuralgic zones where corrections of the design should be made to eliminate errors unavoidable during the preliminary design.

In this paper creation and analysis of aircraft structure global models is presented considering two examples diversified not only in the essential structure but also in roles attended in service.

2. Epitomes of application

Among thousands of light airplanes of general aviation every type of structure is applied practically. Frameworks are very popular, just as sophisticated fibre reinforced polymer monocoque structures. However as type, as complication level determines global computational model complexity, nevertheless assuming essential simplifications there is possibility to create complete structure model without exerted work and wide staff involving.

The structure designing approach proposed in this paper is illustrated with two examples:

a) ultra light aircraft LM-2X-2P with fuselage metal framework structure fabric covered and metal spar wing;
b) wooden SZD-30 aerobatic sailplane with semi-monocoque plywood structure.

Both of them were designed with classic methods without procedures based on numerical methods. Thus we can assume their structures as an effect of preliminary design, accepted to accomplishment in metal or wood without any significant corrections.

The numerical models in FEM approach were created for both, concerning all of main structure sections. Flight-loads spectrums were obtained according to requirements obligatory nowadays. As the first step of proposed algorithm the static analysis was made. Results pointed some neuralgic zones with stress gradients and concentrations qualified to correction in the preliminary stage already. Any change of them in the real structure would involve expensive devices.

3.1. Numerical model of light aircraft

As an object of analysis the ultra-light airplane LM-2X-2P was taken into account (Fig 2). This type is a far evolution of very popular, produced in thousands Taylorcraft series of late 40's. Entanglement of the structure reduced to very minimum allows building it with not very demanding conditions. Also pending all of the service years failure frequency reported has kept at

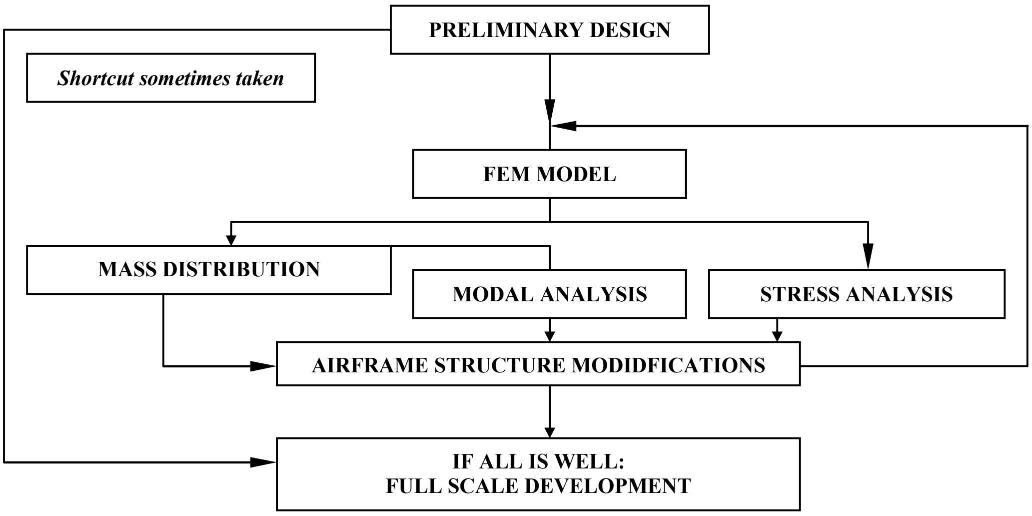

Fig 1. Algorithm of numerically supported preliminary design

low level. The airplane has become a charming subject of academic analysis due to easy anticipation of results [8, 11].

The fuselage is built as 3D framework. Every truss is connected to each other with gussets riveted and glued simultaneously. The horizontal and vertical empennage has flat-plate airfoil section, fixed straight to fuselage stringers and braced up. The wing has front and rear spar with aileron attached to the last one. Between spars is fitted framework instead of torque box. Ribs are made as flat frameworks of duralumin angles. Wing – fuselage connection is statically determined. Articulated joints merge spars with carrying beams of fuselage structure. The wing is supported with V-brace.

Fig 2. LM-2X-2P light airplane

Creating FEM numerical models of fuselage frameworks ideal approximation of articulations between trusses is considered most. Following this scheme the model should be made of *truss* type elements having simple shape function [13]. In this paper we have resigned of such approach and every truss of the framework has rigid connection likewise in classic frame what simulates reality better. The *beam* elements applied with dense mesh allow observing stress distribution not only in truss as whole but also along its span. The empennage and the wing were modelled in the same manner. *Truss* elements were used to create joints and braces and *shell-plate* to spar walls. The model has been created with MSC/Patran™ pre-processor and is presented below in Fig 3 [9].

The flight-loads were calculated according to JAR-VLA requirements and maneuvering envelope was obtained to identify limiting flight cases [6]. Continuous spectrum was discretised and fixed to the numerical model. FEM simulation was run with MSC/AdvancedFEA™ solver.

The results presented below are reduced to one of the cases analysed – point *D* in the envelope – with the highest loads, which is sizing for the structure thus. At first magnitudes of displacements were checked to verify stiffness of the airframe. The wing deformation reached about 20[cm] what is comparable value to ones manifested during exploitation. The picture below presents displacements mentioned above Fig 4.

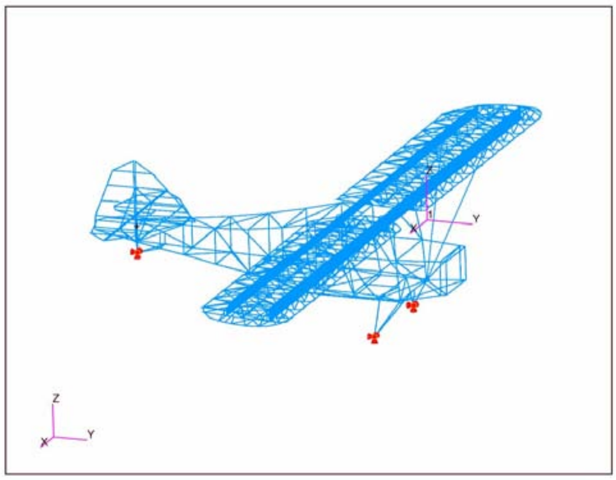

Fig 3. The numerical model of light airplane structure

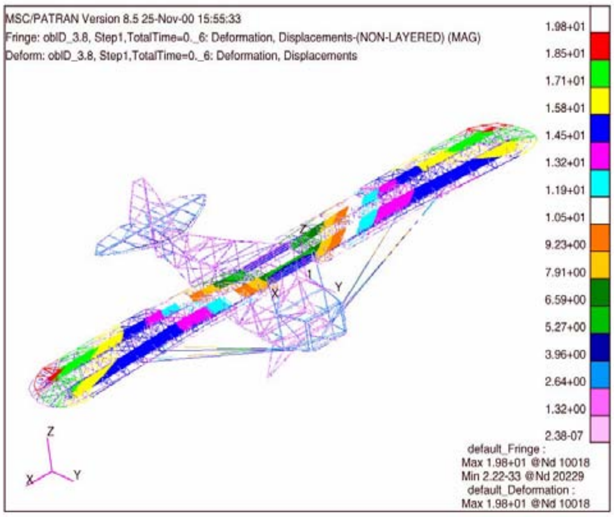

Fig 4. Displacement magnitudes caused by overload in point *D*

Zones with the highest stress gradients appeared in the main spar between wing-fuselage joint and V-brace connection. Bottom spar strips are tensiled with stress at the level of 350[MPa], close to the limit stress. The similar situation took place in carrying beams in the fuselage between main joints. In point *C* conditions stress mentioned is at the level of 100[MPa]. It suggests that point *D* cannot be realized in service, and practically it never happens. The neuralgic zones described above are presented in Fig 5 and 6.

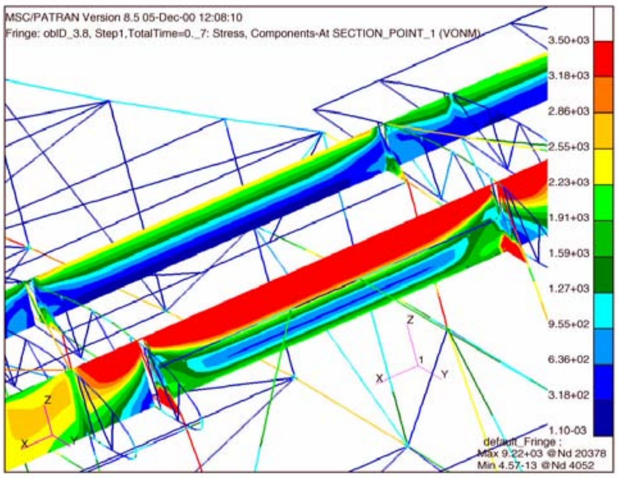

Fig 5. Effective stress in carrying beam of the fuselage (von Misses). Notice compression of upper strips with 350[MPa]

3.2. Numerical model of aerobatic sailplane

The next analysed example was a wooden aerobatic sailplane SZD-30 designed almost forty years ago in Polish Glider Experimental Workshop (Fig 7). The aircraft is one-seat, cantilever, upperwing, with T-shape empennage [7].

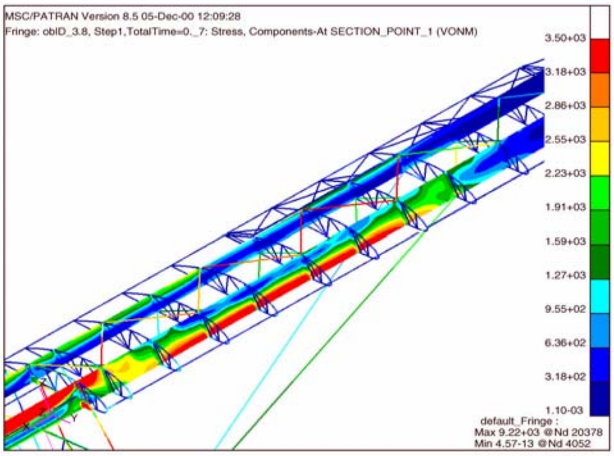

Fig 6. Effective stress in main spar (von Misses). Tension of bottom strips at level of 350[MPa]

Fig 7. SZD-30 sailplane towed by the winch

The fuselage has half-monocoque structure with four main girders covered with 1.5[mm] plywood. The wing consists of three segments. The centre wing is multistringer structure without spars and the torque box is made of double plywood layers. Outer segments of the wing are one spar structure with rear spar for aileron. Stabiliser is integral part of the fuselage. The elevator has one spar and ply cover.

Creation of the numerical model was similar to the one presented above. As pre – processor MSC/Patran™ was applied [9]. Two types of finite elements were used: *beam* for 1D and *plate-shell* for 2D details. The procedure of model creation was started from the sailplane framework consisted of fuselage frames connected by stringers and wing ribs set on spars. Modelling the structure some simplifications in details were made, e.g. in joints and fittings that could be rather a subject of a local analysis. In the next step plywooden covering of the airframe and cloth skin of steering surfaces were made. Hinge connections of an elevator and a stabiliser to the empennage were simulated by *bar-beam* elements. Similar intervention was applied to the wing – fuselage connection. The ailerons and canopy were omitted likewise nosetip made of laminate, because they are not integral structure elements. The model is presented in Fig 8.

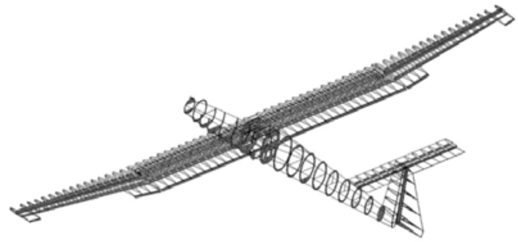

Fig 8. The sailplane geometry (covering is not shown)

On the grounds of this geometrical model the numerical one was created. During the meshing the whole airframe was divided into two – node *beam* elements and four – node *shell-plate* elements.

Several cases, including towing by the plane, were calculated as in previous example, but according to JAR-22 requirements what gave a wide representation of flight – loads [5]. Figure 9 shows simulation of symmetrical steady flight as a case example.

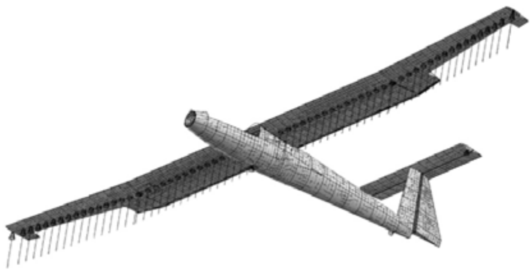

Fig 9. Forces and constrains simulating symmetrical steady flight

Static analysis of the sailplane structure exposed several neuralgic zones with high stress gradients. We present short comparison of identified zones to the real solutions designed.

The stress distribution on the covering of the wing segments according to von Misses criterion is presented in the Fig 10. This map exposes existence of zones with relatively high stress gradients. It particularly relates to the connection of the centre – wing section with the attached wing tips.

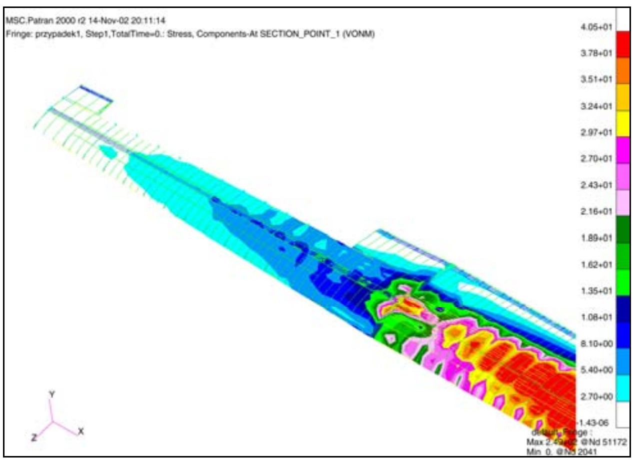

Fig 10. Effective stress concentration (von Misses) around wingtip and centre wing connection

Such high stress gradients zones generation is an occurrence of abnormal cooperation between the monocoque centre – wing structure and the wing tip designed as a fully spar structure. This kind of solution favours the generation of low load level zones, obviously not without influence on useless mass increment. Too high stress gradients appearance in the centre – wing section covering may suggest to bring about some proper corrections in the range of proportions of stringers section to the covering thickness. Pictures below present joint solution applied in the real structure (Fig 11).

Fig 11. Joints between wing segments. Centre-wing left, wing tip right

As we can notice, force of wing tip spar is directly transferred via main joint to centre-wing, without any force redistribution. We may anticipate, the centre-wing covering works not proper therefore.

The next zone identified is connection between elevator and vertical stabilizer (Fig 12).

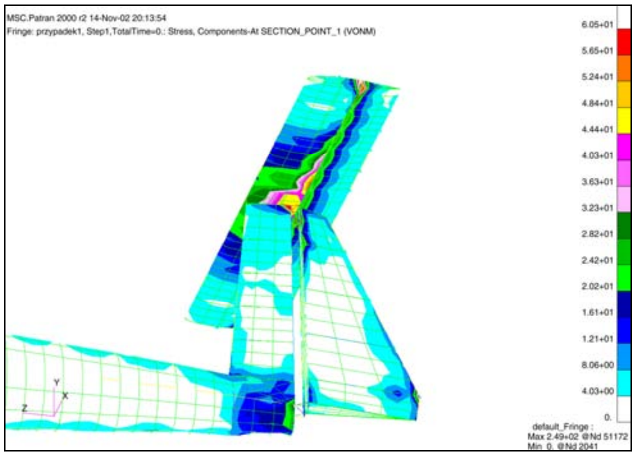

Fig 12. Effective stress concentrations (von Misses) in empennage connection

High gradients are not only origin of overload conditions, but also simplified numerical model. In the next two pictures we can see solution applied in the glider, a kind of beam, distributing force along elevator span (Fig 13-14).

Fig 13. Beam joint on vertical stabilizer

Fig 14. Relief for the beam and vertical pilot bar mounted into the stabilizer spar

This time designed joint seems to be more accurate than the one before.

As the last example main fuselage – wing joint is presented. It is four-point connection of two frames with pins assistance. The calculations identified high stress gradients in the frames circuits. In the real construction the force is distributed as in the model.

The pictures below present stress distribution and views of joint (Fig 15-17).

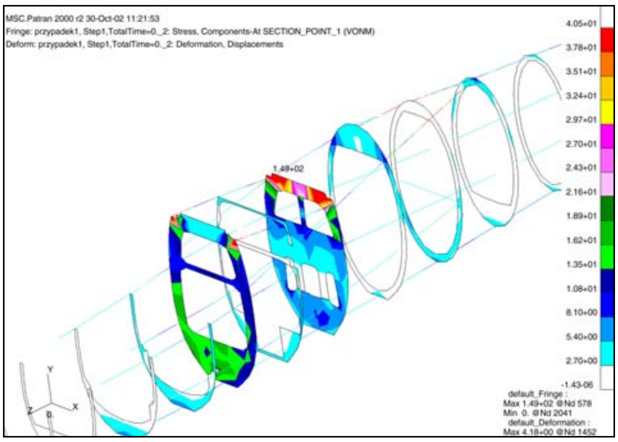

Fig 15. Effective stress distribution (von Misses) in fuselage carrying frames in fuselage – wing joints

Fig 16. Clasps for attaching pins in fuselage centre section

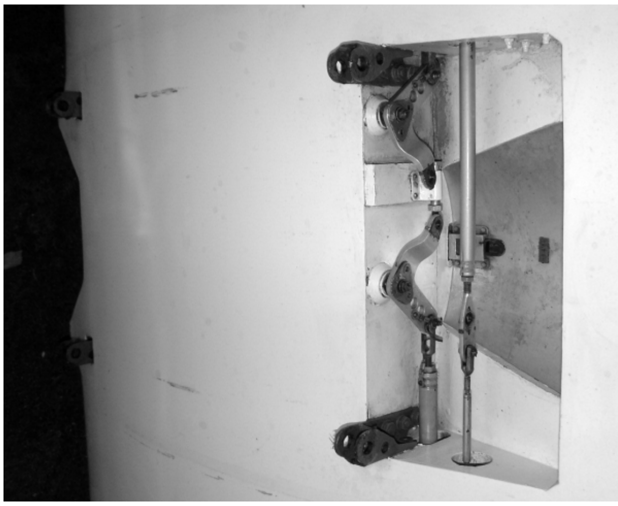

Fig 17. Four-point joints in centre wing

Conclusions

Obtained results proved the global analysis of simplified airframe structure model allows locating main neuralgic stress concentration zones in the forthcoming airplane. The models can be modified easily and any change of strength properties is observed practically on-line.

Epitomes presented are the first approximation obviously. Only linear analysis was proceeded. At first mesh modifications are desired. In the next step non-linear analysis should be commenced and buckling analysis also. The last mentioned is desirable due to high shear-stress gradients observation in sailplane wing covering. Also modal and aeroelasticity analysis could be made. As the last fatigue analysis to estimate preconditions of structure lifetime is necessary. Every step is possible within the same software family. It only depends on software possessed and hardware computational power.

But even this analysis showed some improper solutions that demand to correct. The comparison to the real structure designed proved that sometimes engineers experience is not sufficient to avoid errors. Stress distributions obtained in global analysis are the boundary conditions for local analysis of neuralgic zones, the connection zones in this example.

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