LOAD COMPOSITE STRUCTURE IN AERONAUTICAL ENGINEERING

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Summary

This paper presents selected design issues related to new generation passenger aircraft projects with high share of composite materials. Among projects being now in progress there are a Blended Wing Body configuration (BWB) and a number of classical configuration characterised by very high comfort for passengers. Advantages and disadvantages of composite material being used in aircraft structures have been discussed.

1. INTRODUCTION

Composite materials are widely used for many years in aeronautical engineering. They are applied both in civil and even more extensively in military sector. Steady growth of composite materials in structures of combat aircraft is very well known [1]. As an example the percent of structural weight of different loaded and no loaded elements for F-18 (Hornet aircraft) is presented in Tab. 1.

Tab. 1. Percent of structural weight for aircraft F-18 C/D and F-18 E/F 1 [1]

	F-18 C/D	F-18 E/F
Aluminium	49	31
Steel	15	14
Titanium	13	21
Carbon Epoxy	10	19
Other	13	15
Sum	100	100

It follows from Tab.1 that share of Carbon Epoxy has increased almost two times during a few years and that it happen due to decreasing of Aluminium Alloy. In general Aviation and in Unmanned Aviation the share of composite materials is even higher. In these aircraft among the elements being manufactured of not composite materials there are engines, sometimes landing gears (it is not the rule!) and on-board systems, Fig.1-2. Such a situation has of course both positive and negative consequences. Manufacturing the structures made of composite materials need a very careful quality control and unfortunately, if these high demands requirements are not fulfilled, can results in failures, catastrophic events and death of people. Using prepreg technology it makes possible to manufacture the aircraft structure sometimes by amateurs and people without professional knowledge and understanding the safety problems.

In various comparisons between application of aluminium alloys (traditionally used in aeronautical engineering for years) and carbon fibre (used longer in combat and passenger aviation, and relatively shorter in general aviation) there are usually discussed 4 groups of factors, i.e. weight, performance, purchase cost and maintenance cost. Drivers for composite materials to be applied in Aerospace engineering and comparison between carbon epoxy and aluminium alloys are presented in Tab.2 and Tab.3

Tab. 2. Advantages coming from application of advanced new materials in aerospace engineering [1]

• Weight reduction ○ Increased range ○ Reduced fuel cost ○ Higher payload ○ Increased maneuverability	• Improved performance ○ Smoother aerodynamic shape ○ Special aeroelastic properties ○ Increased temperature capability ○ Improved damage tolerance ○ Reduced delectability
• Reduced acquisition cost ○ Reduced fabrication cost ○ Improved "fly-to-buy" ratio ○ Reduced assembly costs	• Reduced through-life support cost ○ Resistance to fatigue and corrosion ○ Resistance to mechanical damage

Tab. 3. Comparison of carbon/epoxy and conventional aluminium alloys for airframe application [1]

• Weight reduction ○ Saving 15-20% compared with aluminium alloys ○ Cost of reduction \$60-\$100 per 1 kg ○ Reduction in number of joints	• Acquisition cost ○ Material cost increase ○ Reduction due to high conversion rate (low fly-to-buy ratio) ○ Reduction due to reduction in joints ○ Fabrication cost generally increases
• Performance ○ Smoother, more aerodynamic form ○ Improved aeroelastic properties ○ More resistant to acoustic environment ○ More resistant to service environment ○ Improved fire containment ○ Improved crash resistant ○ Improved stealth properties	• Repair costs ○ Fatigue resistant, reduction ○ Corrosion immune, reduction ○ Fretting resistant, reduction ○ Impact sensitive, increase ○ Prone to delamination, increase

Composite materials used to-day in aerospace technology have more advanced stiffness characteristics and higher ultimate stress level than even a few years ago. Bellow there are selected carbon fibres (CFRP) strength characteristics, routinely applied in European Aerospace Industry for loaded structures of passenger airplanes [2,3,4,5,6,7].

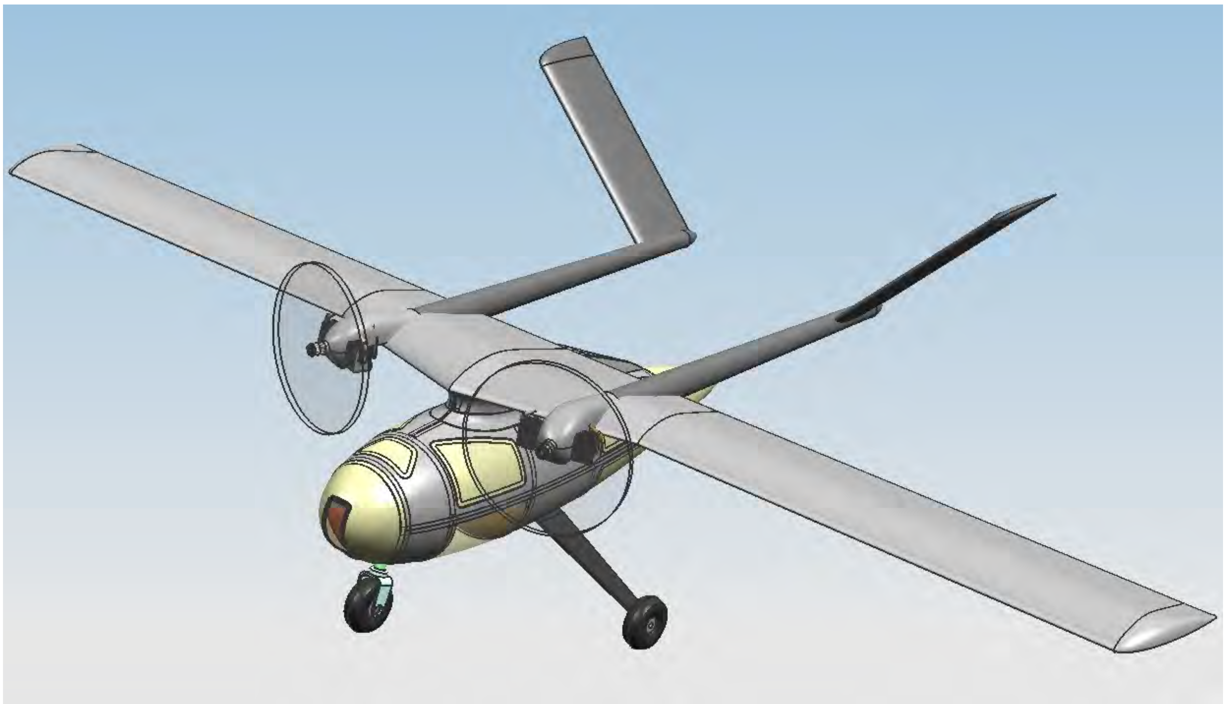

Fig. 1. Unmanned surveillance aircraft SAMONIT designed and planned to be built at Warsaw University of Technology

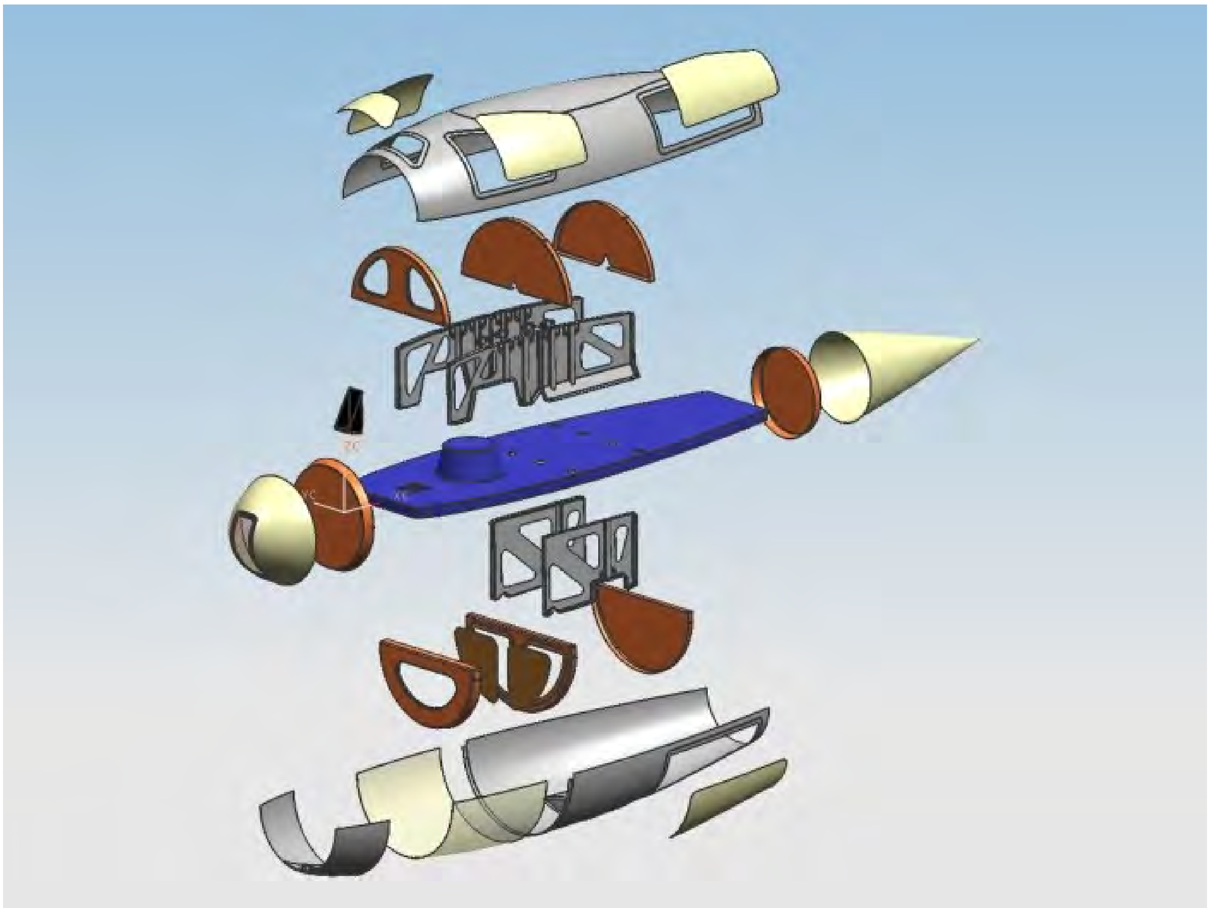

Fig. 2. Sensor's container made of CFRP for SAMONIT aircraft [3]

Tab. 4. Strength properties of the CFRP T300/HY917/60 70/30/00 traditionally used for rowing [2]

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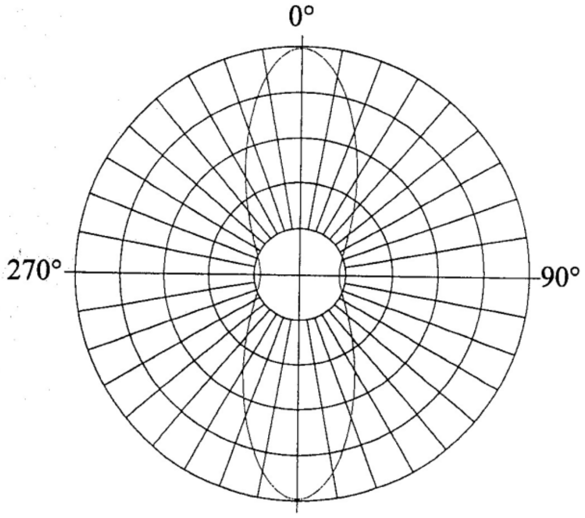
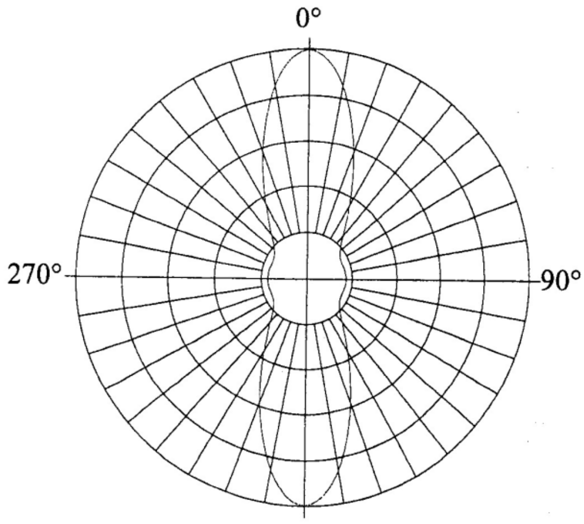
<td>

Young's modulus E</td>
<td>

Poisson's coefficient ν</td>
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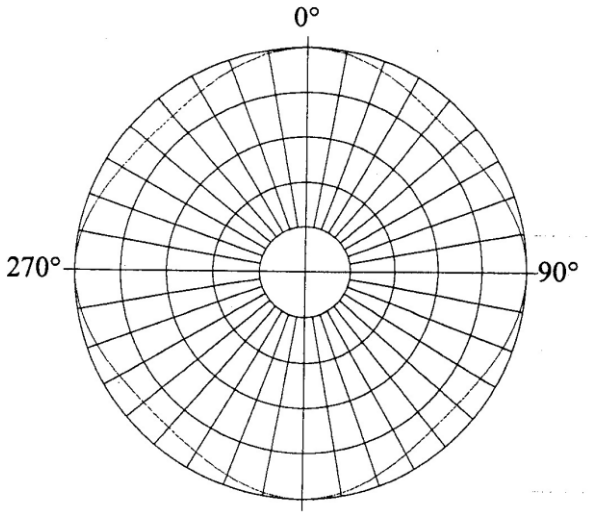
<td>

Kirchoff's modulus G</td>
<td>Values of important material's constants:
E_{11} = 104.11 GPa
E_{22} = 18.026 GPa
ν_{12} = 0.60219
G_{12} = 14.483 GPa
Re_{max} = 520 MPa
ρ= 1.562 g/cm^3</td>
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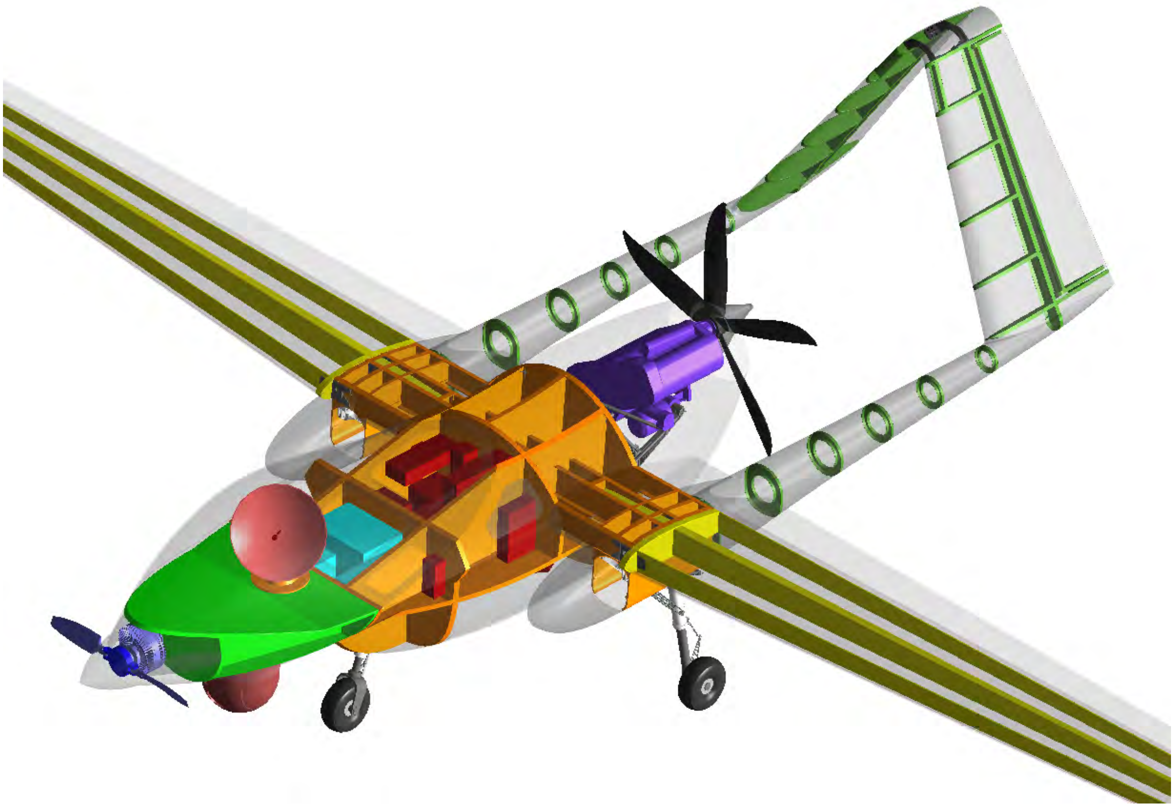


Fig.3. Loading structure of PW-103 aircraft [4]

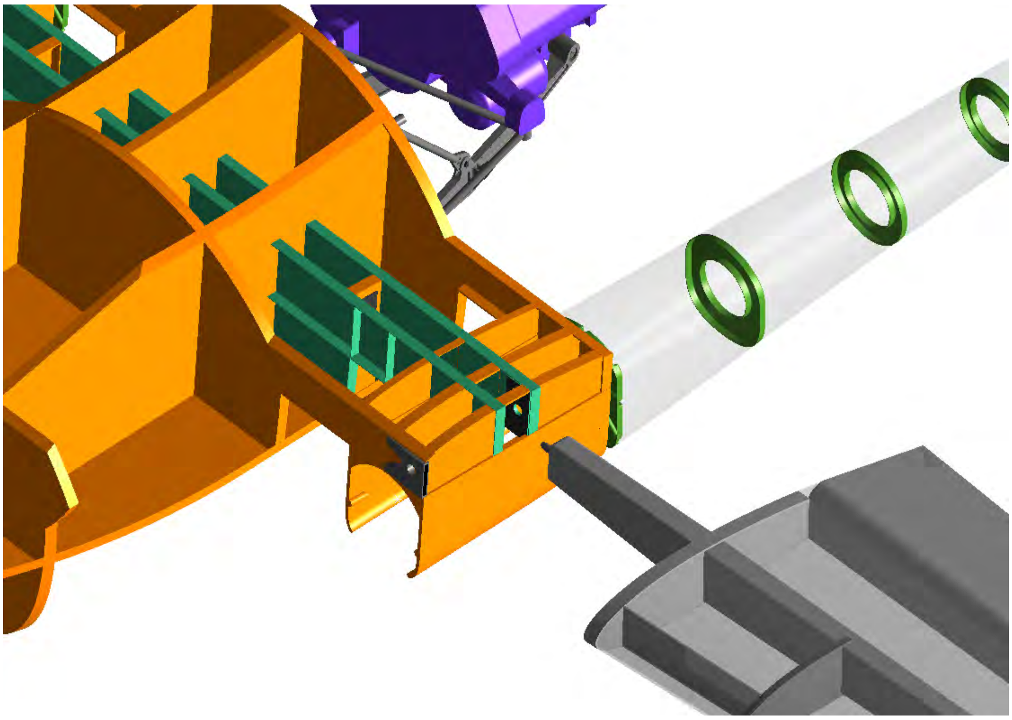


Fig. 4. Wing – body and tail-beam – body attachment [4]

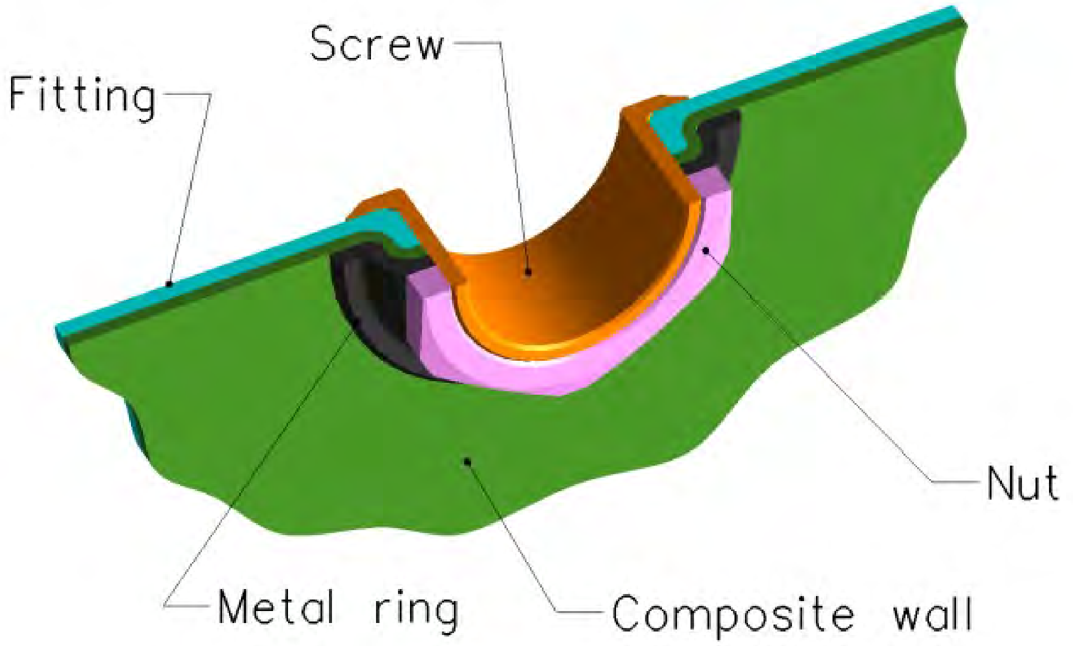


Fig. 5. Attachment of a composite single wall wing spar with metal fitting by the so-called „single wall lock type fitting" consisting of the metal ring, screw and nut (In Polish language „zamek kompozytowy"), [4]

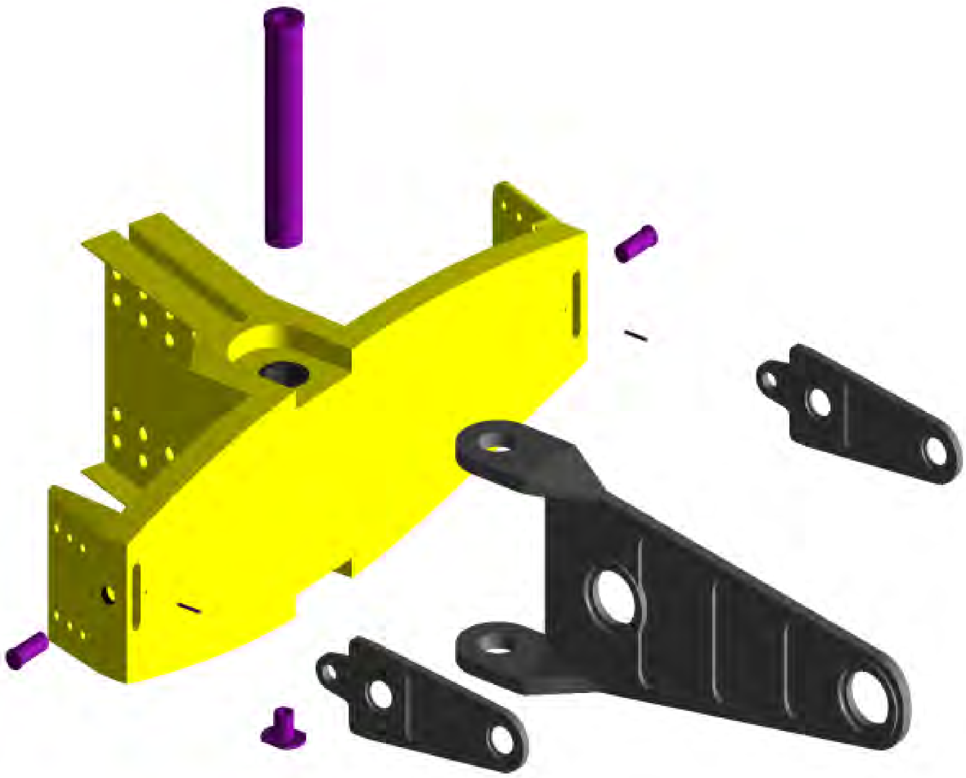
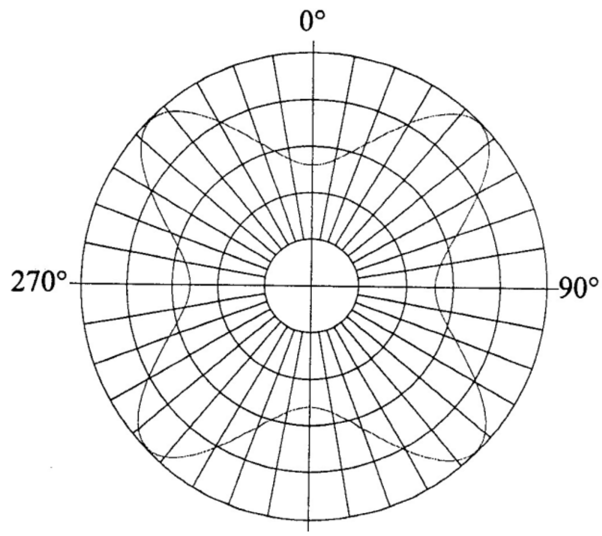
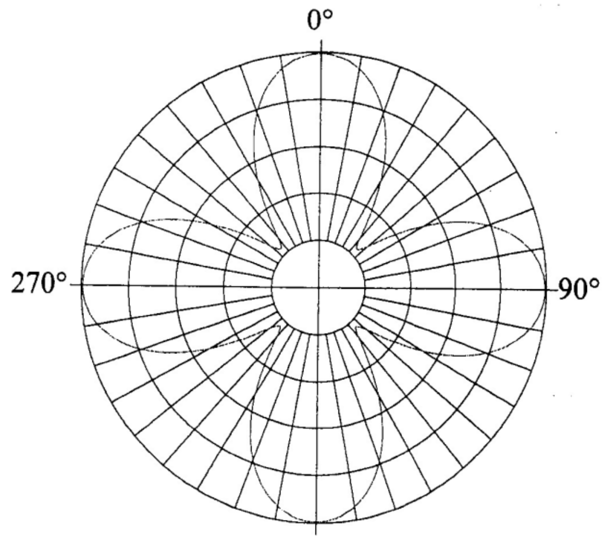
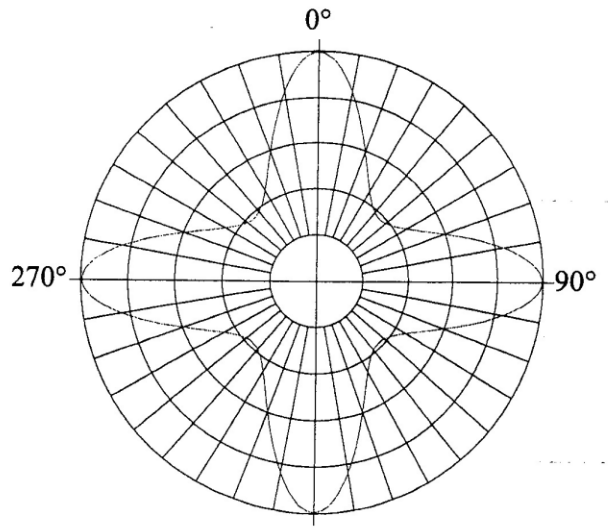


Fig. 6. Wing – body attachment designed for PW-114 aircraft. This external rib shown at the figure acts as an integral fitting [4]

Tab. 5. Strength properties of the CFRP T300/HY917/60 10/80/10 traditionally used for external shells [2]

 Young’s modulus E	 Poisson’s coefficient ν
 Kirchoff’s modulus G	Values of important material’s constants: E_{11} = 35.117 GPa E_{22} = 35.117 GPa ν_{12} = 0.54171 G_{12} = 29.865 GPa Re_{max} = 260 MPa ρ= 1.562 g/cm^3

2. PROJECT OF FULLY COMPOSITE STRUCTURE FOR BWB PASSENGER AIRCRAFT

Design process of very large passenger aircraft (for more than 600 passenger on board) meets many obstacles and barriers to be overcome. These obstacles are not only engineering in their nature but come mainly from the area of psychology, safety (including the evacuation issues) and adjustment to existing airport facilities (including width and ultimate loading of landing run and length of wind-sock). A-380 just entering into service possesses the traditional configuration, where the passenger cabin is located in fuselage, being clearly distinguished from the wing. However, since a few years one had came to the conclusion that further economical improvement in passenger transport will need non orthodox airplane configuration, including flying wing. Because such a project means extremely high financial risk even for biggest industrial players (Airbus and Boeing), so it is extremely important to analyze it carefully even before entering into the preliminary design phase. Many things must be checked, including functionality, aerodynamics, performances, stability, controllability and selection of material for loaded structures. Fig.7,8 show one of such project, traditionally called Blended Wing Body (BWB) and being in progress under the umbrella of FP6 within NACRE project [5,6,7]. Important point is that even the bulkheads and fuselage spars will be made of CFRP – the case never realized before in any passenger airplane. Only landing gears and engines will be made of traditional metallic materials. Selected subsystems with their estimated weights are shown in Tab. 6. For comparison, selected data for two biggest passenger airplane being to-day in service are shown in Tab.7.

Tab. 6. 29 % of maximum take-off weight consists of composite structure

Subsystem	Version with under-the-wing engines	Version with over-the- fuselage engines
Wing	58.997	66.615
Fuselage	131.642	131.642
Horizontal tailplane	2.116	2.116
Vertical tailplane	3.111	0
Landing gear	23.903	23.903
Nacelles	6.726	3.090
• **Whole structure**	**226.495**	**227.366**
Power unit	36.897	36.901
On-board systems	25.974	25.974
Furniture	25.974	25.974
Operating Empty Weight	**349.178**	**357.059**
Passengers	70.000	70.000
Fuel	290.000	290.000
• **Maximum Take-Off Weight**	**700.000**	**717.000**

Tab. 7. Main design and in-service parameters

Parameter	A-380	B-747-400ex
Wing span [m]	79.8	64.4
Body length [m]	72.7	70.7
Wing reference area [m^2]	845	541
MTOW [tons]	560	413
Wing loading [kg/m^2]	663	763
Thrust loading [kg/kG]	4.41	3.62
Passengers	555	416
Fuel volume [litres]	310 000	241 000
Max payload [tons]	150	113
Range [km]	15 000	14 200

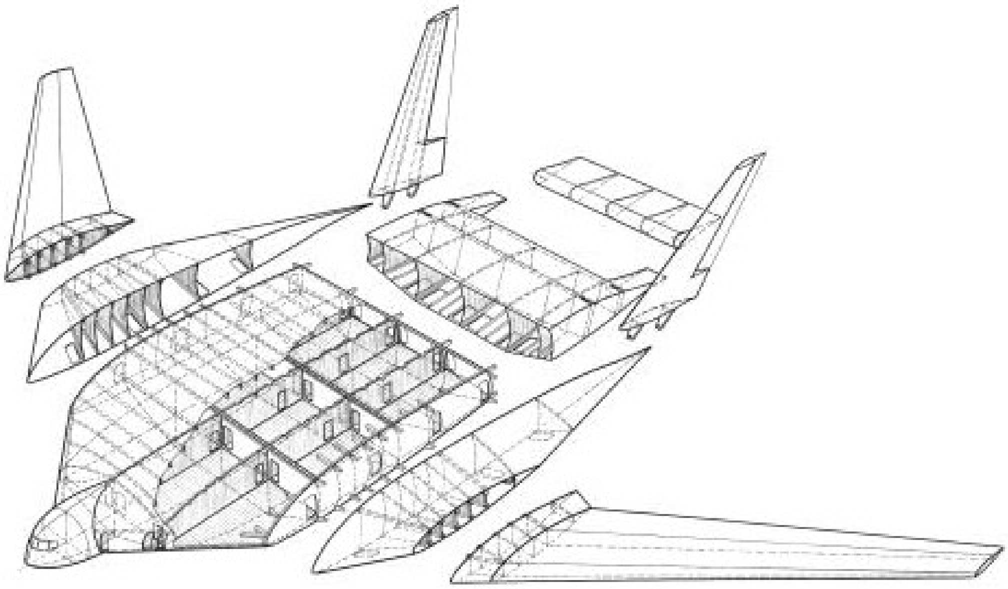


Fig. 7. Selected components of loaded structure and fuel system is designed in WUT [5]

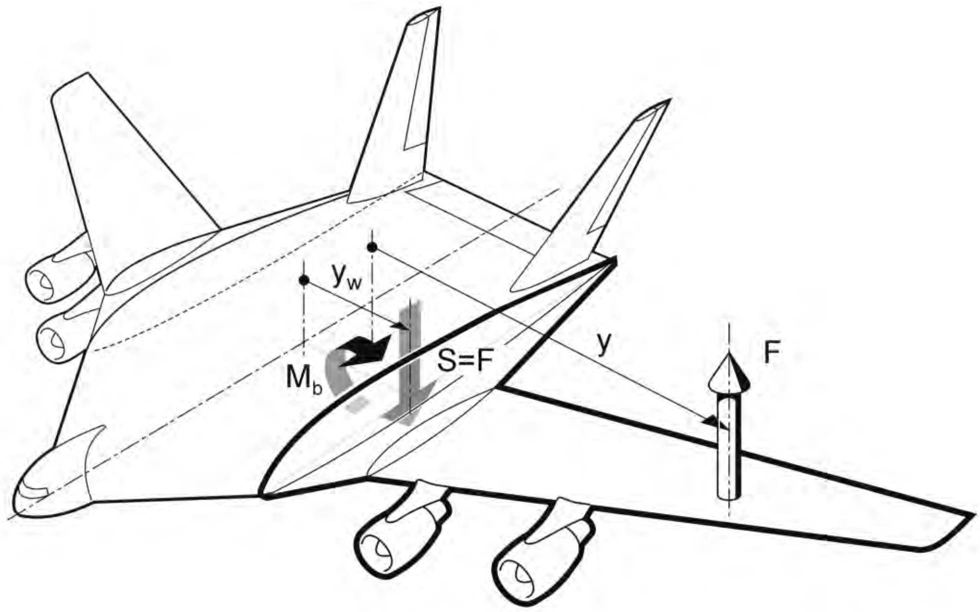


Fig. 8. Fuselage structure (BWB) loaded by forces acting on wing [5]

3. PROJECT OF AN AIRCRAFT CHARACTERISED BY EXTREMELY HIGH PASSENGER CABIN COMFORT

Another interesting design within the NACRE FP6 project is the aircraft offering to future passengers the increased comfort of travelling in single, double and quadruple compartments, (fig.9). These compartments have convertible beds, direct access to toilet and shower. Each passenger compartment has its window. This airplane can take 120 passengers, will have big shopping and restaurant area (150 m^2). Range of this airplane must exceed 12 000 km and maximum take-off weight will be 800 tons. Load structure and a computational model of main bulkhead to be used for strength analysis are shown in Fig.10-11.

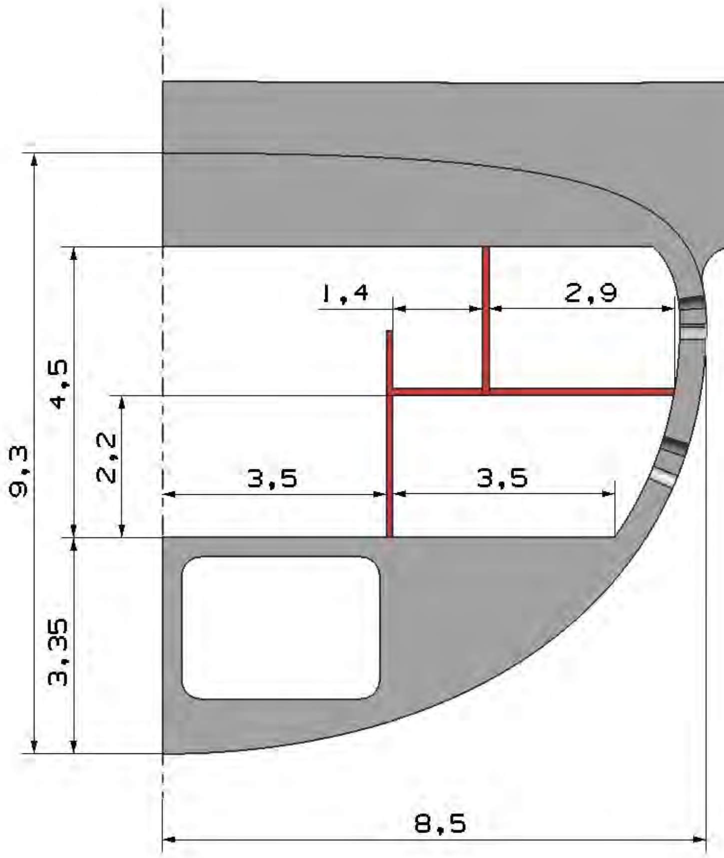


Fig. 9. Fuselage main dimensions in passenger section

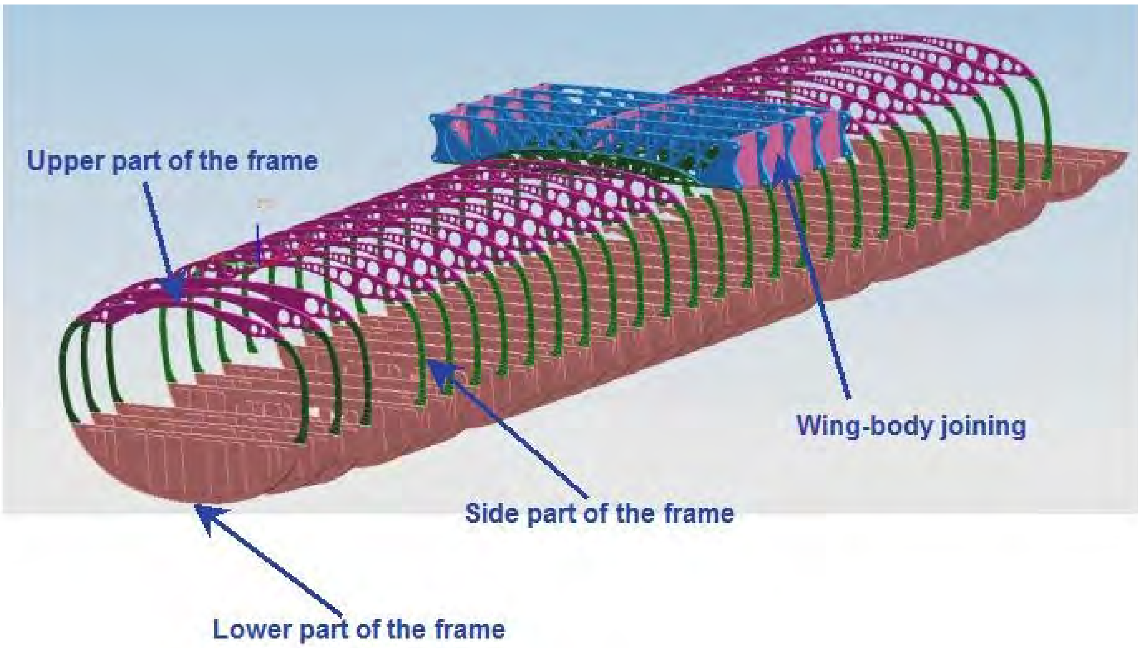


Fig. 10. Loaded structure of fuselage, made of carbon fibre

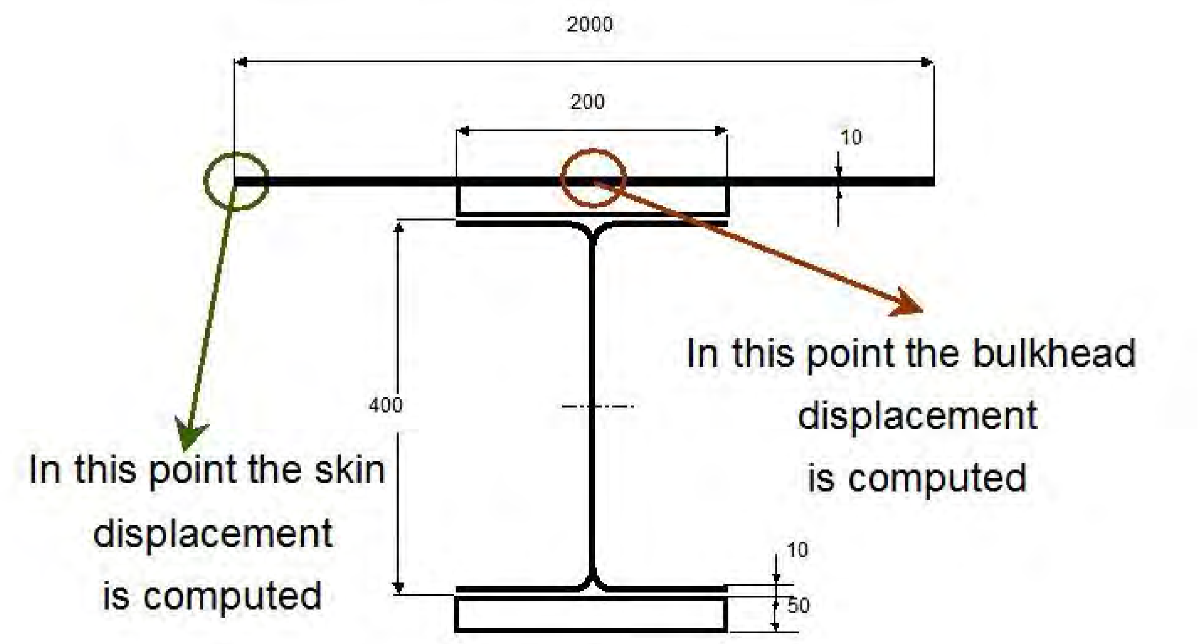


Fig. 11. Computational model of main bulkhead and a strip of external shell attached to the shelf of this bulkhead

Passenger aircraft fuselage is not only under the maneuverable loading but also under internal pressure loading, which in same cases can decide about strength-dependent dimensions. Contrary to conventional more or less circular aircraft fuselage designs, the given “H-Cylinder”, “V-Cylinder”, and “V-Lens” configurations imply a non-circular shape of the fuselage cross-section in order to follow the preset contour and to minimize drag [8]. With a potentially aerodynamically favourable elliptical contour, however, bending stresses are introduced into skins and frames resulting from the internal pressure – in contradiction to lightweight design principles, Fig. 12. Necessarily special lightweight design concepts have to be developed .

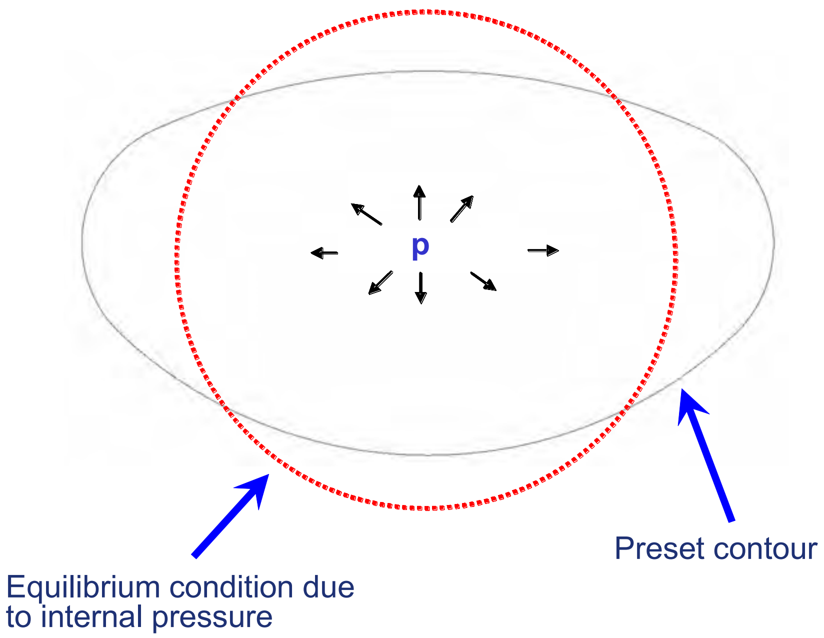


Fig. 12. Pressurised structure [8]

As similar problems have already been faced, when dealing with large transport or passenger aircraft, multi-bubble concepts with several circular shaped areas and straight-lined interfaces have been developed. With these configurations, the internal pressure only causes tensile stresses in skins and frames and tensile or compression stresses in the straight elements connecting the bubble segments (biaxial or membrane stress conditions only) (like in an inflatable mattress).

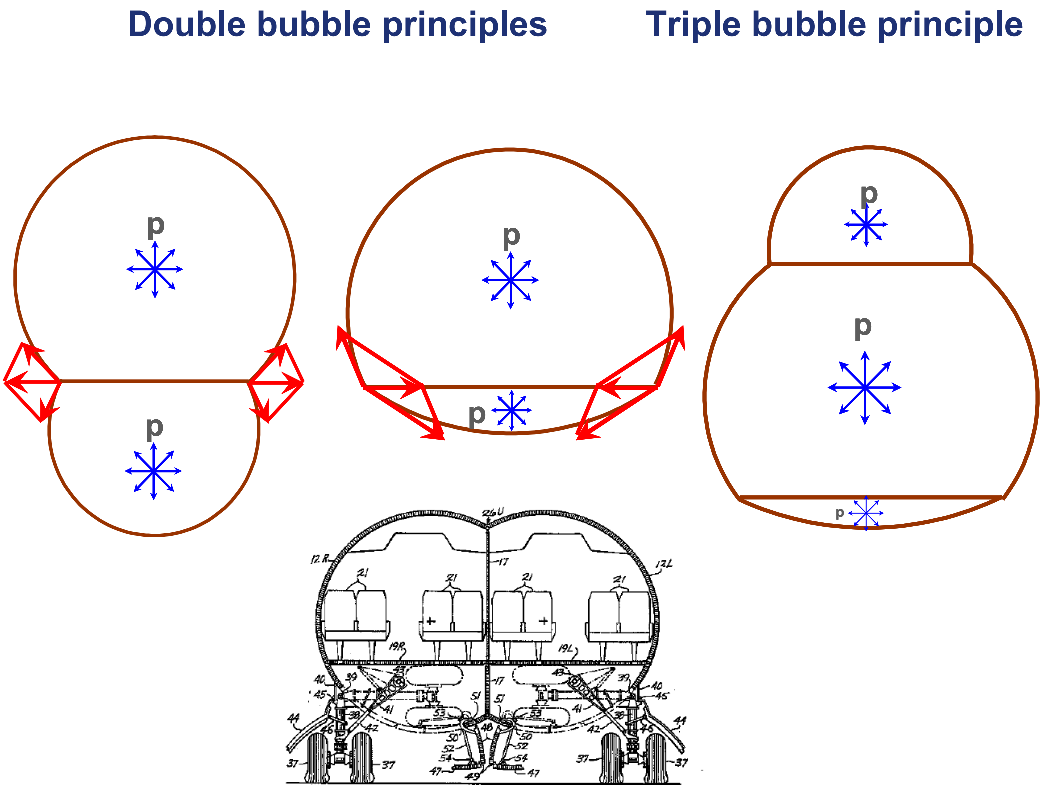


Fig. 13. Mechanical principle behind double and triple bubble concepts currently being or having been used for different kinds of military or civil aircraft [8]

One of the important project tasks was strength analysis for main bulkheads and external skin. This skin and bulkheads must carry-on the so-called reduced internal pressure loading (the difference between real internal pressure and external, atmospheric pressure at the cruising flight altitude). The reduced internal pressure is precisely defined by airworthiness requirements and in this project was assumed to be 0.12 MPa. Fig.14 shows external loading coming from the reduced internal pressure and Fig.15 shows the displacements of external shell. This external shell displacement must be limited by the condition of maximum allowable shell bulging (being from the other hand admissible from external flow point of view). Allowable shell bulging can generally be regulated due to changing of the structure stiffness (by changing the number of vertical and lateral pillars and changing of the bulkhead dimensions and its stiffness).

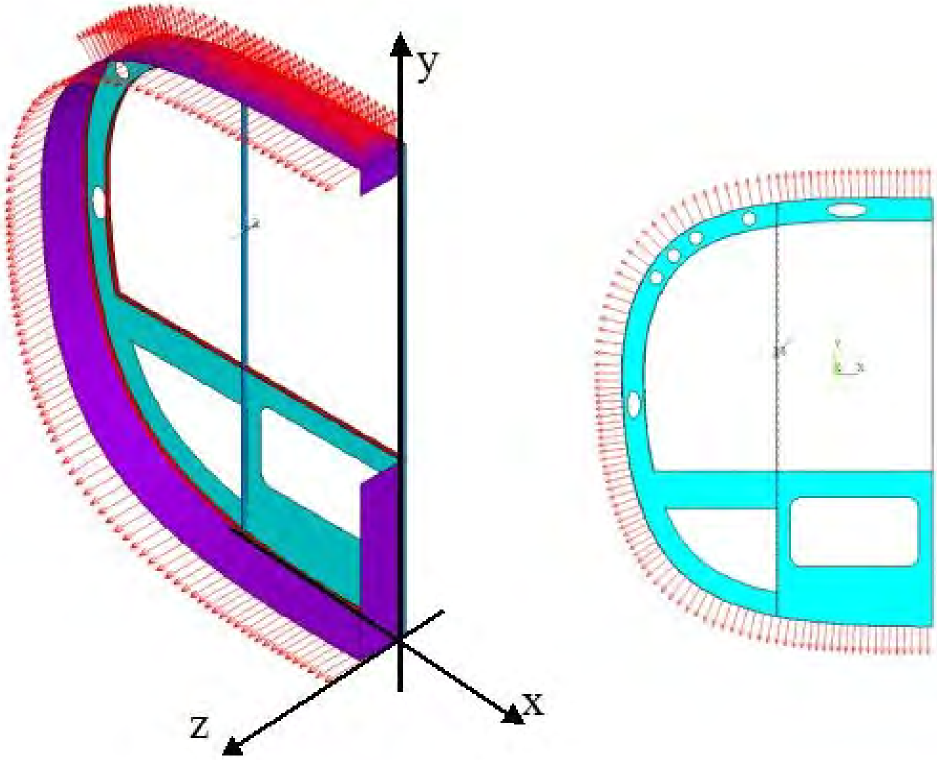


Fig. 14. Boundary conditions & loading of the „unit cell"

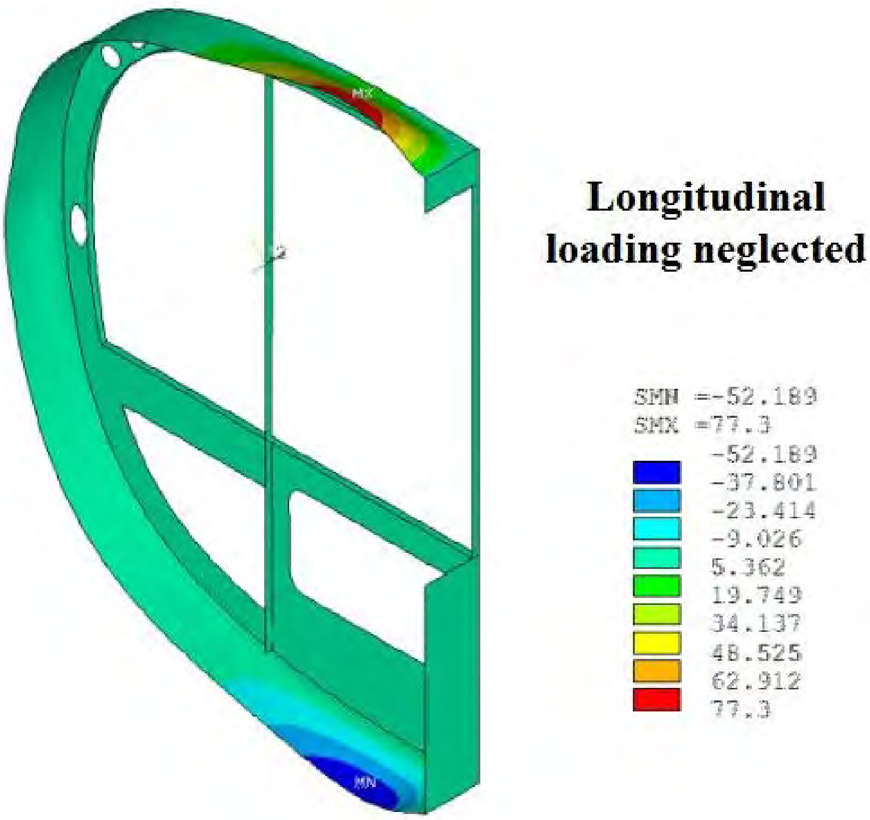


Fig. 15. Skin displacement in y direction

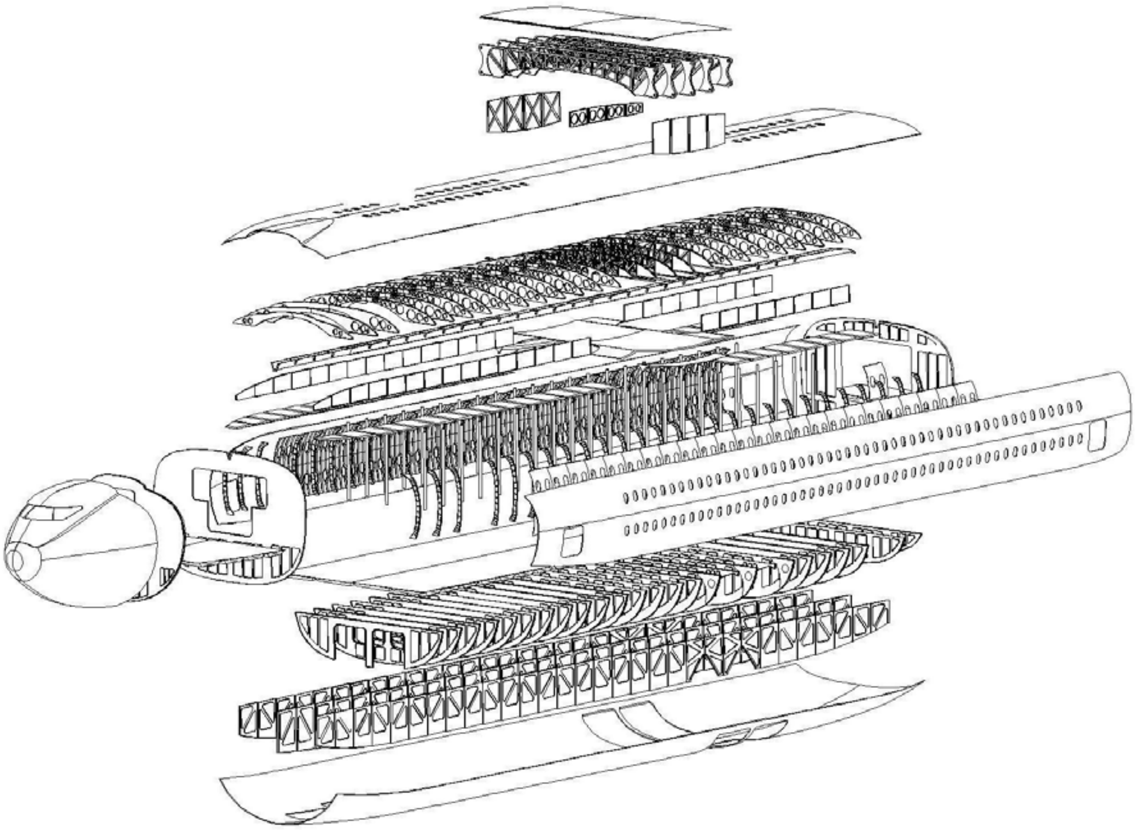


Fig. 16. Components of fuselage structures

Before numerical simulations the following assumptions have been made:

1. The only one external loading comes from internal cabin pressure and is equal to 0,1234 Mpa;
2. Distance between successive frames (bulkheads) is constant and equal to 2 m;
3. Vertical pillars are placed in the plane of airplane symmetry and on the walls of passenger compartments;
4. Frequency of pillars is changing. Three different models are considered: 1 bulkhead per one pillar, 2 bulkheads per one pillar and 3 bulkheads per one pillar (it means that per one pillar one has either one bulkhead, or 2 bulkheads, or 3 bulkheads). The abovementioned condition relates to main pillars only. Lateral pillars (located on the walls of passenger compartments) are placed at every one bulkhead;
5. In stress and strain analysis it was assumed that loaded structure consists only of main pillars and the main longitudinal spar (see Fig.17). No bulkheads, no skin, lateral pillars, longerons etc. (because number of these structural elements and their dimensions do not change and in consequence their weight do not change too);
6. For each case we assume that maximum vertical displacement of bulkhead element is less than 25 mm and that the weight of this bulkhead is minimised for this maximum displacement;
7. Maximum skin displacement can be limited due to increasing the number of longerons and is not analysed here in details;
8. Obtained results are relative, not absolute. It means that one can not estimate any total fuselage weight, one can only say how the weight of partial loaded structure (main pillars and the main longitudinal spar) will be increased when pillars frequency is decreased.

Loaded structure of aircraft fuselage consists of many parts (Fig.16), sometimes they have very complicated geometry. It is not possible to build one integrated FEM model which can include all details of real aircraft structure. Model presented in this paper is limited to main bulkhead (dispersed along fuselage at 2 m distance), lateral pillars (Fig.17) – 2 at the each main bulkhead cross section – and the so-called main vertical pillars, located at the chosen bulkhead cross section. The fuselage having an oval cross section (height equal to 9 m, width equal to 17 m) needs many vertical pillars (to increase its stiffness), however their number also must be limited, otherwise they can decrease the functionality of restaurant area. This leads to trade-off studies between stiffness and functionality (good functionality means less vertical pillars, desirable stiffness means more vertical pillars). Fig.18-19 show two different computational models: (1) each bulkhead has its main pillar and (2) every third bulkhead has its main pillar (in this second model between these two bulkheads with pillars there are two bulkheads without pillars). Different pillar's frequency leads also to changing the design and weight of bulkheads and longitudinal spar. It is due to the assumption that total displacements of the points located at the vertical axis of the bulkhead can not be greater than 25 mm. Design details and dimensions of bulkheads and longitudinal spar are shown at Fig.18-19, both for Aluminium Alloy 2024 and T300/HY917/60 10/80/10. Fig.20-21 show the weight of fuselage strip of unit length. Numerical results show that the most desirable situation correspond to the case when pillars are made of carbon fibres and are located as dense as possible (one pillar at every one bulkhead, i.e. 1 by 1). However, because of the functionality of restaurant area it was decided that vertical pillars will be placed every three bulkheads (it means every 6 m). It means that loaded structure will be 6 time heavier (Fig.19) what is equivalent that main pillars together with longitudinal spar will have 10 tons in total (1 pillar weights 300 kg, longitudinal spar 7500 kg, 1 meter of spar weights 150 kg, weight of main pillars per one meter is 200 kg). If vertical pillars were located at every one bulkhead then 1 meter of fuselage (bulkheads, longitudinal spar and main vertical pillars only, no skin, floor etc.) would weight only 33 kg (i.e. 6 time less).

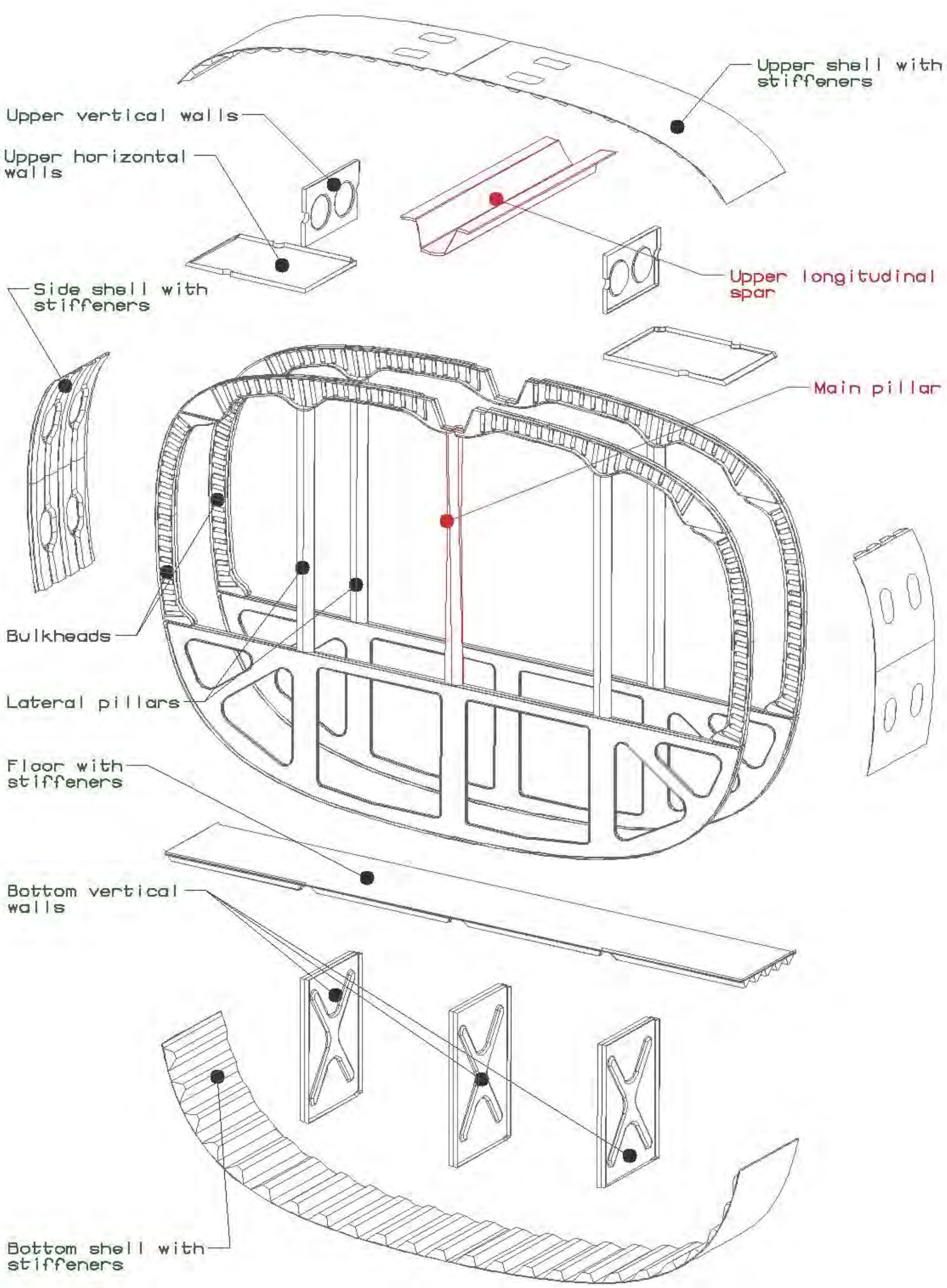


Fig. 17. Main components of loaded fuselage structure (their weight depends on the frequency of main vertical pillars)

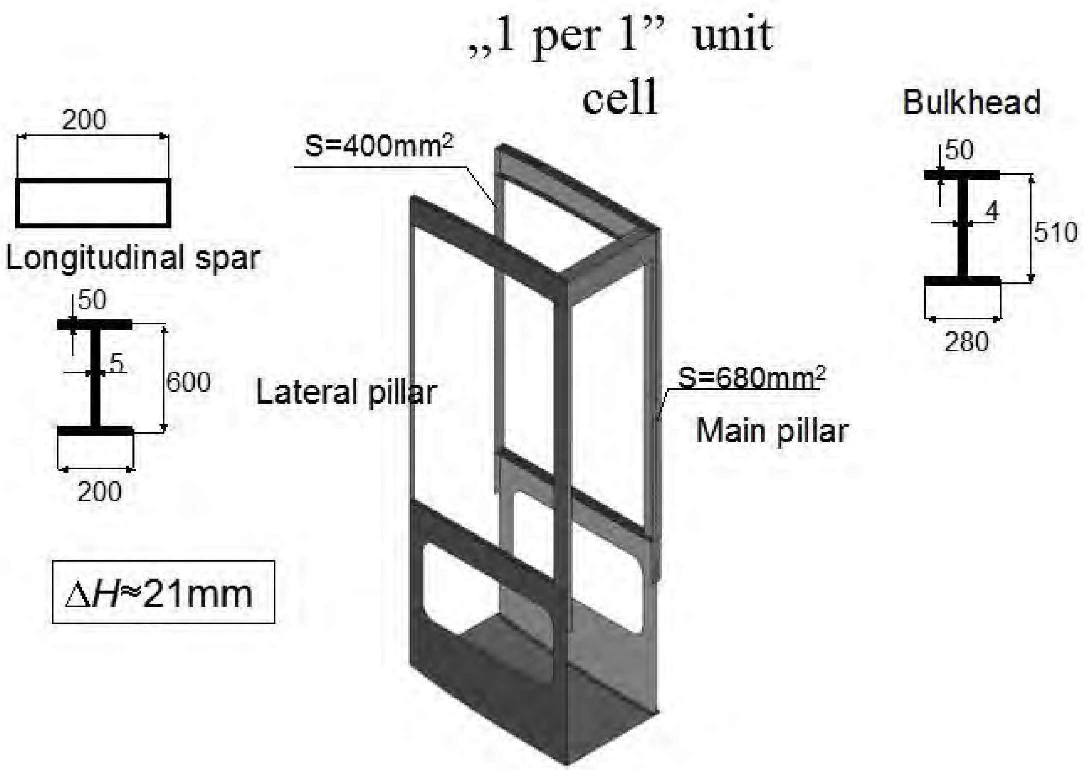


Fig. 18. Dimensions of computational model consisting of main pillars, lateral pillars and longitudinal spar (frequency 1/1)

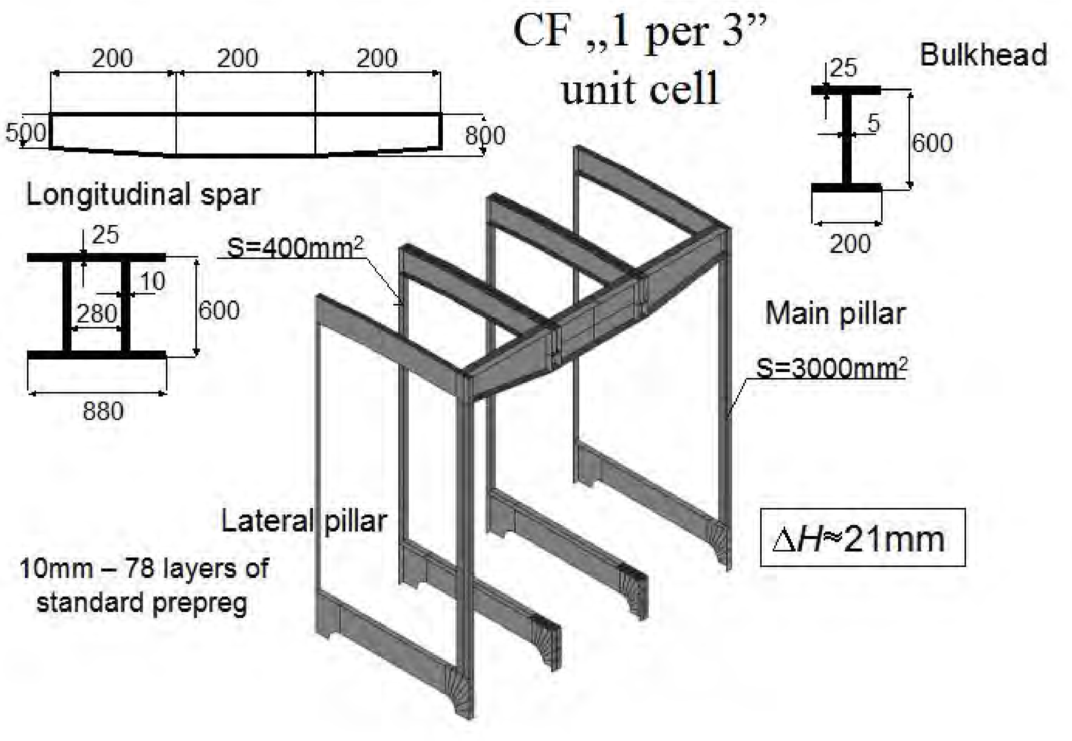


Fig. 19. Dimensions of computational model consisting of main pillars, lateral pillars and longitudinal spar (frequency 1/3)

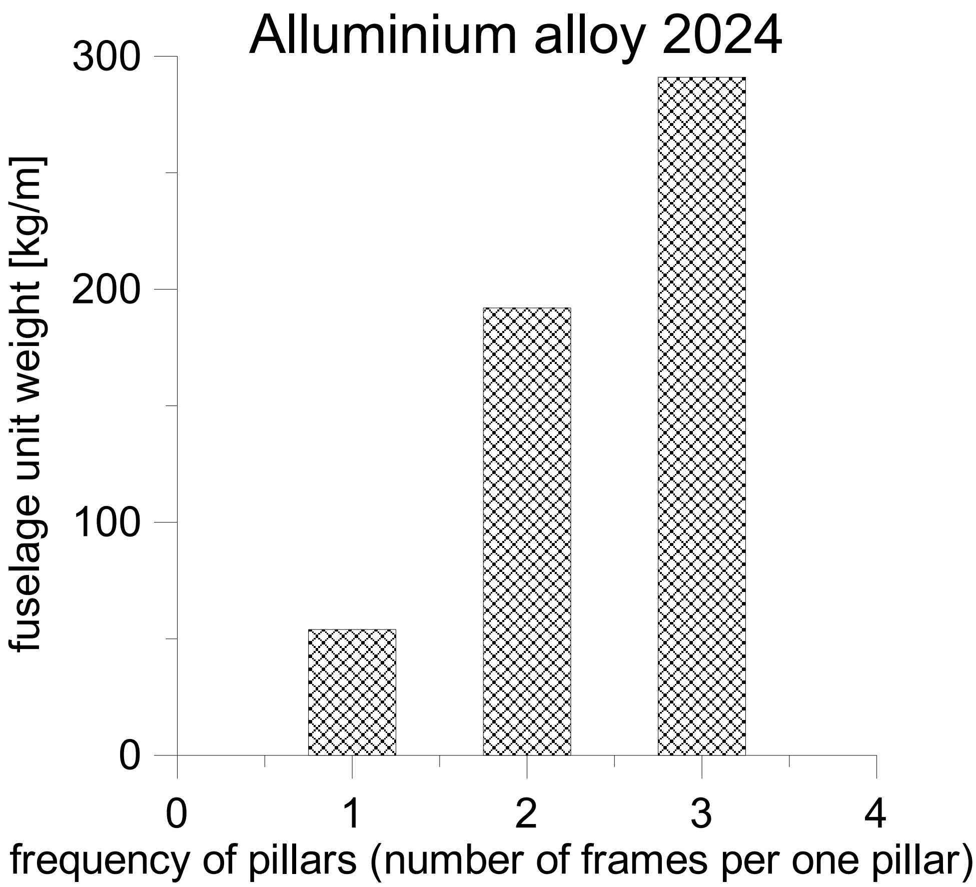


Fig. 20. Fuselage weight: influence of frequency of pillars

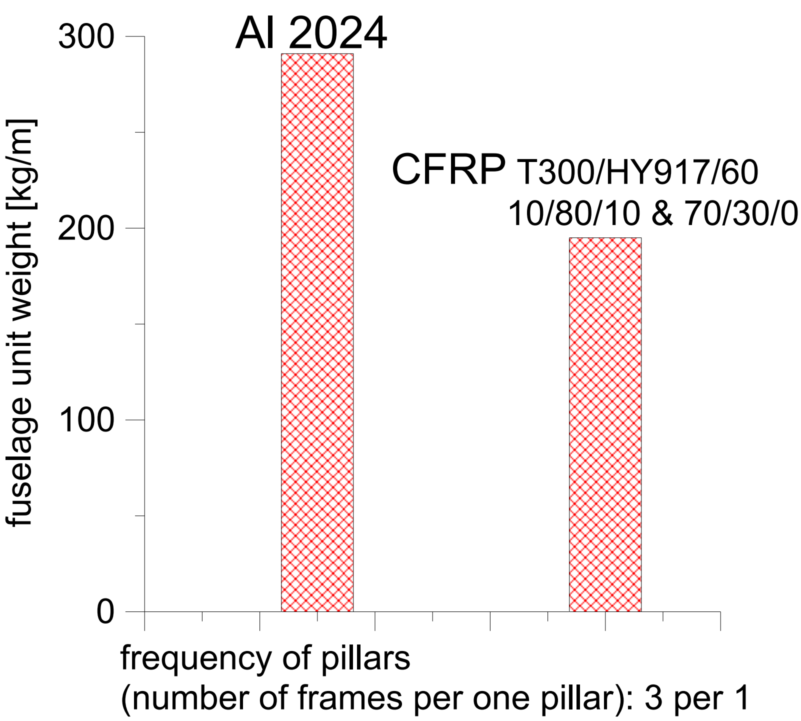


Fig. 21. Fuselage weight comparison: Al versus CFRP

Tab. 8. Main elements of loaded fuselage structure, either computed from the reduced internal pressure condition (bulkheads, main pillars and main longitudinal spar) or assumed (these elements they must be numerically analysed). Analysis was done based on composite material T300/HY917/60 10/80/10)

Part of structure	weight [kg]
External shell with stiffeners	40.250
Floor with stiffeners	10.950
Lateral walls	6.600
Vertical upper walls	2.000
Horizontal upper walls	3.000
Bulkheads	30.840
Main pillars (1 / 3)	2.500
Main longitudinal spar (1 / 3)	7.500
Weight of loading structure	**103.640**

4. CONCLUSION AND RECOMMENDATION

Composites (carbon fibres first of all) are very important materials in passenger and military aircraft structures built to-day and being designed for the future. They entered into general aviation and manned aviation a number years ago and now are used routinely. Loaded structures made of composite materials are much lighter (even on 50 %) and are relatively easy to be optimised in respect to functionality, strength and weight with combination to aircraft aerodynamics and performances. The new era in passenger airplane design will come soon when the loaded structure will be fully done from carbon fibres (i.e., when main spars, bulkheads and stiffeners will be made from composites).

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Z. Goraj

STRUKTURY KOMPOZYTOWE W LOTNICTWIE

Streszczenie

Przedstawiono wybrane zagadnienia związane z projektowaniem samolotów pasażerskich nowej generacji z dużym udziałem materiałów kompozytowych. Pokazano elementy projektu koncepcyjnego samolotu klasy BWB (latające skrzydło) oraz kilka konfiguracji klasycznych samolotów charakteryzujących się powiększonym komfortem kabin pasażerskich. Przeanalizowano zalety zastosowań materiałów kompozytowych w porównaniu do tradycyjnie stosowanych stopów aluminiowych.

З.Горай

КОМПОЗИТНЫЕ СТРУКТУРЫ В АВИАЦИИ.

Резюме

Представлены избранные вопросы связанные с проектированием пассажирских самолетов нового поколения с большой долей композитных материалов. Показаны элементы концепционного проекта класса ВДВ (летающее крыло), а также несколько классических конфигураций самолетов характеризующихся увеличенным комфортом пассажирских кабин. Обсуждены преимущества применения композитных материалов по отношению к традиционно применяемым алюминиевым сплавам.