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CARBON FIBER COMPOSITE AIRPLANE FUSELAGE: CONCEPT AND ANALYSIS

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1. Introduction

The leading European and American aircraft concerns are standing nowadays on the verge of creating all-composite carbon fiber fuselages for big passenger airplanes. This intention is aimed at the breakthrough in technology to result in considerable reduction in weight (up to 30%) and cost (up to 40%) of the most material- and labor-consuming airplane unit, fuselage, against the traditional aluminum variant, the so called "standard body" [1]. The estimated effect of implementing the new technology in "$\Delta_{mass} - \Delta_{cost}$" coordinates are shown in fig. 1.

Fig. 1. Estimated effect of implementing the new technologies [2]

This is obvious that the high potential of reducing the weight of airframe structure is determined by the use of carbon fiber with specific properties different from those of metals. This is the reason why simple replication of metal variants by using composite materials does not fully provide the appropriate advantage of composite components due to the unique strength and rigidity characteristics of unidirectional carbon fibers. This is necessary therefore to develop special load-bearing structures to conform to special properties of these materials [3], [4].

The weight of passenger airplane fuselage makes approx. 12–15% of the maximum takeoff weight of the airplane and 40% of airframe weight [5]. Thus the use of carbon fibers as the construction material for such a resource-demanding unit as fuselage allows the considerable reduction in weight of the passenger airplane fuselage on the whole.

The paper addresses one of the concepts of carbon fiber fuselage for a big passenger airplane, "Lampassenkonzept" proposed by the Institute of Structural Mechanics of the German Aerospace Center (DRL, Braunschweig) within the research program assigned by Airbus, Germany. The proposed concept along with the weight/cost reduction issues addresses the possibility of meeting the additional requirements to carbon fiber plastic fuselages of big airplanes of tomorrow. The paper contains the analysis and comparison of above concept with the aluminum variant of "standard body", as well as the results of carbon fiber fuselage project in "Gondelkonzept" implemented by above Institute within the national German HGF-Project "Black Body".

2. Carbon Fiber Fuselages. Issue State

2.1 *Peculiar properties of carbon fibers as construction materials*

Carbon fibers have the uniquely high fatigue strength characteristics as well as the high strength (including the specific one) for strain and constriction. They are corrosion-proof. All this gives them the advantage over the traditional aluminum alloys. However they have rather low shear and contortion properties as compared with the latter [6]. When increasing the percentage of unidirectional layers they become more sensitive to the presence of cutouts and lose their strength advantages in bolt joints. Apart of this, carbon fibers display high sensitivity to impact loads [7] and this is accompanied by reduction of strength characteristics and requires a higher inspection cost during operation.

2.2 Basic Requirements to Carbon Fiber Fuselage of Tomorrow

Below are the present basic requirements [8] for fuselages of future passenger airplanes developed in Europe:

- 30% reduction of construction mass;
- 40% reduction of its manufacturing cost
- increase of passengers safety in conditions of impact and crash loads;
- reduction of inspection activities;
- insensitivity to cyclic loads;
- corrosion resistance
- flexibility when performing transportation tasks;
- increase of passengers fire safety
- proximity of technical solutions to present implementation, etc.

The chart of impact scenario for a passenger airplane fuselage is shown on fig. 2 [9], [1]. Based on the assumption that carbon fiber is rather sensitive to impact loads as it was mentioned above and the fuselage is presented by a thin-walled construction operating under the surplus internal pressure, it can be concluded that impact possibility is one of the critical points when designing carbon fiber fuselages of passenger airplanes.

2.3 Carbon Fiber Fuselages Today

Carbon fiber fuselages of light passenger airplanes with seating capacity of 8 up to 12 are well known. However carbon fiber fuselages for big passenger airplanes with container compartments and seating capacity over 100 people do not exist today.

The light passenger airplane Starship by company Beechcraft, USA, has carbon fiber shell of sandwich type with cell filling Normex produced using the prepreg technology

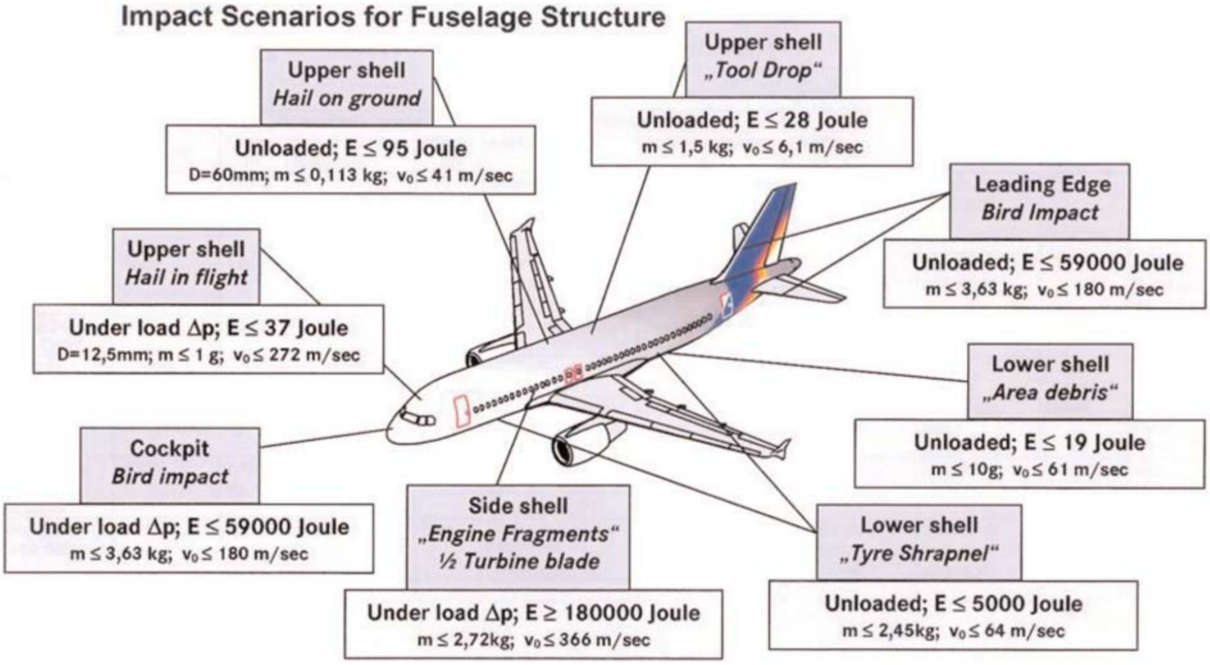


Fig. 2. Impact scenario chart for passenger airplane fuselage

Fig. 3. Carbon fiber fuselage of the light passenger airplane Premier I

or 'crude' winding [4], [10]. Fuselage weight saving following the use of carbon fiber is estimated to around 18%.

Anothher other light airplane Premier by company Raytheon Aircraft, USA, also has a sandwich-type fuselage with carbon fiber shell and cell filling though produced using the prepeg winding method [11] (Figure 3). In this case fuselage weight economy is estimated to around 20%.

One of the recent developments of light passenger airplanes with carbon fiber fuselages is represented by the collection of airplanes by Adam Aircraft, USA, Adam 500 and Adam 700 [12] where fuselage construction and tail booms is mainly a sandwich with carbon fiber shell and cell filling made by panel method based on prepreg technology.

2.4 *Specific Properties of Standard Metal Fuselage Construction*

Standard aluminum fuselage of a big passenger airplane is a semi-monocoque construction with shell, stringers and frames. The fuselage contains a cockpit and passenger compartment, both sections experiencing surplus internal pressure i.e. hermetic.

The lower bearing panel of this fuselage experiences loads caused by global impact of bending moment, torque, intersecting force as well as the surplus internal pressure. It contains rather big cutouts (fig. 4): front pit (1), pits for primary landing gears (2) and wing/fuselage juncture, as well as the baggage-and-cargo hatches (3). The biggest cutout for landing gear pit and wing/fuselage juncture is located in the area of largest bending moments (4) [13].

These cutouts weaken the lower panel construction, which operates mainly in constriction and experiences the danger of losing steadiness, and generate strain concentration. Flat panels limiting landing gear pits, and cockpit floor in the area of primary landing gears and wing juncture are loaded with surplus internal pressure and experience bend impact. Hence the standard fuselage in the lower panel area is not an optimal 'light' construction from the point of view of structural mechanics, and arrangement of pits and cutouts in load-carrying structure requires the increased mate-

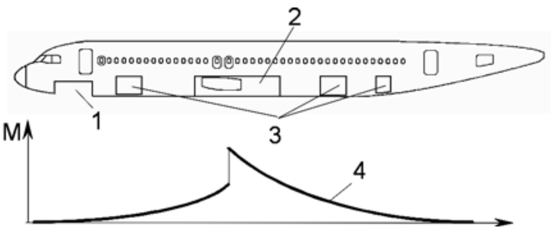


Fig. 4. Big passenger airplane – “standard body”

rial consumption. Practically all big passenger airplanes of leading aircraft world companies such as Airbus, Boeing, Tupolev and Ilyushin have similar fuselage constructions.

2.5 Present European Research Programs for the Development of Carbon Fiber Fuselage of a Big Passenger Airplane

The development of carbon fiber fuselage of a big passenger airplane in Europe is nowadays implemented within the two programs: TANGO and LUFO [14]. TANGO is the international program with seven European countries involved and based on composite materials technologies and load-bearing structures of modern fuselages. LUFO is the national German program and pursues the development of new composite materials technologies and load-bearing structures of carbon fiber fuselages. Airbus and German research organizations participate in the development of LUFO concepts.

2.5.1 TANGO Fuselage

TANGO fuselage is designed as an A321 fuselage section with a 4 m diameter and 6.4 m length located behind the primary landing gears pit. The section has cutouts for windows and temergency exit and presents a rather regular construction without big cutouts for landing gear pits and baggage hatches. The load-bearing structure of TANGO fuselage is conceived as a traditional semi-monocoque construction (fig. 5) [14].

As a result TANGO fuselage is a totality of connected panels made using different technologies. For example, Airbus makes panels based mainly on impregnation technologies, the hardened stringers and shell being joined by paste-like glue [14]. TANGO fuselage will be put to the strength test, the surplus internal pressure taken into account.

2.5.2 LUFO Concept of Airbus Carbon Fiber Fuselage

The following two concepts of carbon fiber fuselage are studied by Airbus within LUFO programs: VeSCo and SoFi [15], [16], [17]. Both concepts purpose to search and investigate the design of load-bearing panels for carbon fiber fuselage and do not consider general configuration of fuselage taking it as traditional [15], i.e. “standard body”. Concepts will be embodied as full-scale panels to be tested within the next LUFO III EMIR program [14], [16].

Both concepts are based on the principle of combined functions. At the same time they solve the tasks of structural mechanics, thermo-isolation, absorption of impact energy, acoustic damping, etc. [17]. Panel fabrication is based mainly on the prepreg technology [16].

2.5.2.1 VeSCo Panels

VeSCo panels [17] do not have stringers and represent a sandwich with a polythick shell, the inner shell perceiving the most part of load. VeSCo panels are specific due to ventilated filling between two shells (fig. 6,*a*). This is achieved, for example, by making filling in the form of folded structures [18]. There are frames inside the panels.

2.5.2.2 SoFi Panels

SoFi panels [17] as against VeSCo panels have stringers but also have sandwich

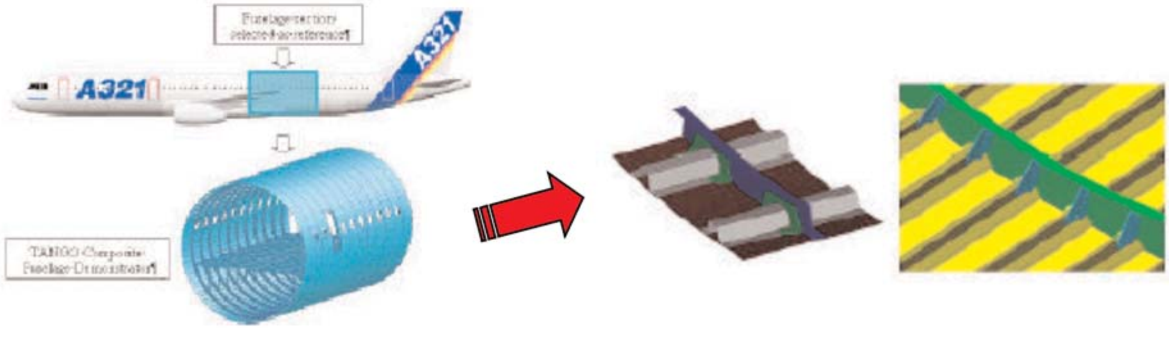
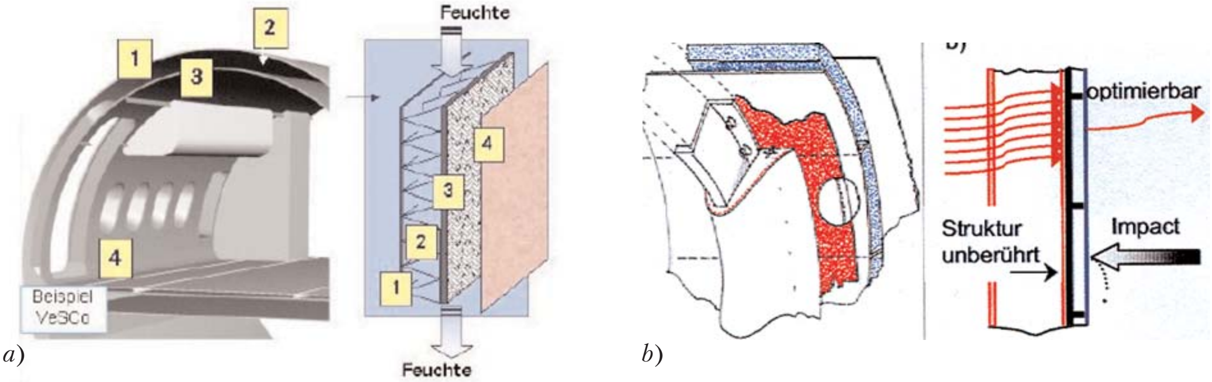


Fig. 5. General view of TANGO fuselage and load-bearing panels [14]



a) *b*)

Fig. 6. Principle of VeSCo (a) [17] and SoFi (b) [15] panels

structure with polythick shelld. The inner shell together with stringers located outside the panel perceives the most part of load. A thin outer shell functions as aerodynamic surface (fig. 6,*b*). The panels are distinguished by stringers and frames located on different sides of inner shell.

3. DRL Concepts of Carbon Fiber Fuselage

The Institute of Structural Mechanics of German Aerospace Center (DRL, Braunschweig) proposed two concepts of carbon fiber fuselage of a big passenger airplane: Lampassenkonzept [19] developed on the instructions of Airbus within LUFO II program, and Gondelkonzept [20] implemented with the national German HGF project “Black Fuselage”.

The following starting points were accepted to generate the load-bearing designs: 1) type of requirements to fuselage of tomorrow (see 2.2); 2) modern “standard body” from aluminum alloys as a prototype (see 2.4) and 3) specific features of carbon fiber as a construction material (see 2.1) [21].

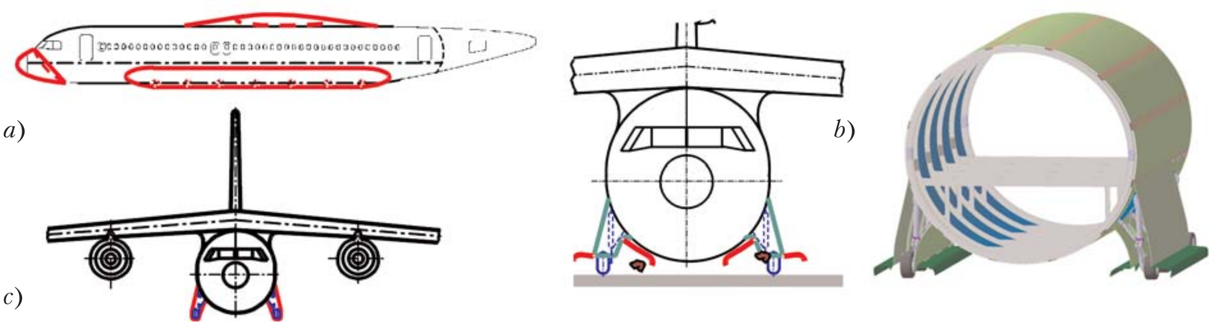
The analysis of 'standard body' and specific features of carbon fiber proved the efficiency of implementing requirements to fuselages of tomorrow provided that new non-standard load-bearing designs will be found. Unlike above concepts TANGO, VeSCo and SoFi, there were two ways of solving the problem – both global way of searching the general fuselage configuration and local one of searching designs of load-bearing elements (panels, etc.).

DRL concepts attempt to satisfy a part of requirements to fuselages of tomorrow by selecting its general configuration.

3.1 Lampassenkonzept

3.1.1 Fuselage Configuration Within the General Airplane Design

General airplane design for the carbon fiber fuselage in a Lampassenkonzept variant is a high-wing monoplane [19]. The fuselage is a relatively regular construction without big



a) *b*) *c*)

Fig. 7. General fuselage configuration in Lampassenkonzept

cutouts in the lower load-bearing panel for baggage-and-cargo hatches and pits for front and primary landing gears and the wing and fuselage juncture. The distinctive feature of general scheme of this concept is landing gears distributed along and for the both fuselage boards, without pronounced front and primary landing gears, as well as the access hatch of a baggage-and-cargo compartment located in the front part of the fuselage (fig. 7,*a*).

In emergency cases landing gear can be fixed or partly fixed with equal and rather simple structural elements and have the pronounced and rather thin cowls (fig. 7,*b*) equipped with folds opening in process of takeoff and landing (fig. 7,*c*). Landing gear distributed along the fuselage can be equipped with shake absorbers with special spring valves or membranes which snap into action when only compression force in shake absorber exceeds some critical value (when hitting against the ground). This allows the additional dispersion of energy in crash situation (fig. 8). Shake absorber cylinders can be made from composite materials with a special structure providing high energy absorption in case of destruction. A fixed or partly fixed landing gear makes the construction simpler, reduces the weight and increases passengers safety in crash situation.

Thus, in this design there is an attempt to give landing gear an extra function of passengers safety in crash situation and use it as potential crash elements distributed along the fuselage rather than to use it for takeoff and landing only. Such combination of landing gear function can help to avoid introduction of special crash elements into fuselage of tomorrow in order to improve passengers safety, i.e. make fuselage construction simpler and cheaper and increase functional importance of landing gear having the weight of 3.3 up to 5% from the maximum takeoff weight of airplane [5].

Positioning and extension of distributed landing gears as well as the form and dimensions of its cowls, takeoff and landing issues, etc. are the compromise questions of optimization and coordination from aerodynamics point of view first of all.

Folds of landing gear opening in process takeoff and landing (fig. 7,*c*) provide the protection of fuselage lower panels and wings from potential impacts such as crushed stone coming from under the wheels, or any other objects on a runway. The folds belong to nonpower structure elements and can function as a detector or victim structure in impact situation protecting with its relatively small surface rather big planes of fuselage and wing and thus reducing inspections of planes. Impact load on unprotected lower bearing carbon fiber panels can cause the reduction of their bearing capacity and following destruction of fuselage in the air similar to destruction of the well-known airplane Comet by de Havilland company.

Relatively thins cowls of landing gear distributed along the fuselage can probably serve stabilizing aerodynamic ridges (fig. 7,*b*) and opened folds of landing gear (fig. 7,c) as air brakes when landing.

The presence of baggage-and cargo access hatch located in the bow (stem) of the

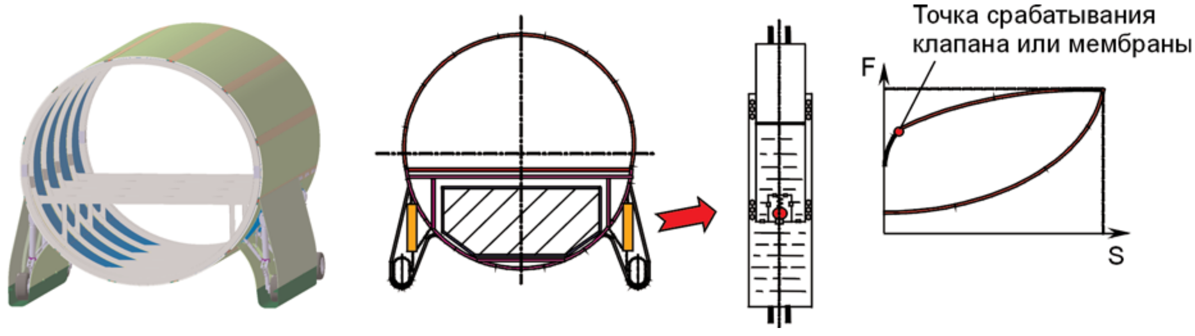


Fig. 8. Landing gears as crash elements distributed along the fuselage

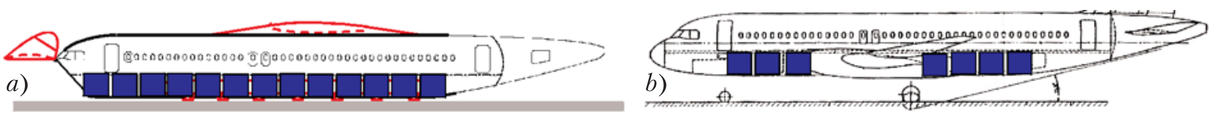


Fig. 9. Cargo bays in: (a) Lampassenkonzept and (b) “Standard Body"

fuselage in the high-wing monoplane design (fig. 7,*a*) provides higher flexibility of cargo and passenger transportation both owing to most containers (almost twice as many) placed in the cargo compartment (fig. 9,*a*) as compared with the “standard body”, and possibility of placing non-standard long-length cargo.

3.1.2 Fuselage Load-Bearing Design as a Totality of Load-Bearing Elements

Fuselage structure as a totality of lifting elements in Lampassenkonzept variant can be rather diverse. This paper presents and addresses the so called differential load-bearing design. According to this, the fuselage consists of rather numerous identical load-bearing elements. The purpose of this concept is highly automated and hence cheaper manufacture of basic load-bearing elements of fuselage structure in mass production conditions.

In this case the fuselage is a totality of three load-bearing structural groups (fig. 10): 1 – continuous (along the fuselage) side-members, the so-called 'stripes' (Lampassen); continuous (circumference) frames and 3 – panels between them. The latter can be of different discrete length or be continuous along the fuselage like 'stripes'.

Continuity of elements in each of the three groups allows to reduce the quantity of junctures and hence the weight of articles, as well as to decrease the scope and cost of assembly. Ideally, from the point of view of production and decrease in value of articles, all elements within the group can of be equal type and size, or comprise the minimum of subgroups with equal type and size. This is certainly a question of optimization and compromise settlements lying in “weight reduction (structural mechanics) – cost reduction (manufacture)” axes.

'Strips' (Lampassen) in this load-bearing design are sparsely disposed powerful stringers receiving the total bending moment and panels receiving mainly intersecting force and torque loads.

Configuration of panels and 'strips' investigated within the concept under consideration is shown on Fig. 11. For the reasons of simplicity and low production cost the panels represent an asymmetric stringer-free sandwich with load-bearing and hence thicker inner shell 1. The outer thin shell 2 also functions as certain mechanical protection of inner load-bearing shell and detector in case of the crash impact on the panel. Foam materials with closed pores are taken as filling 3. These pores also protect inner load-bearing shell from blows (of hail or tools for example), as well as for the acoustic and thermal protection of a passenger cabin (the principle

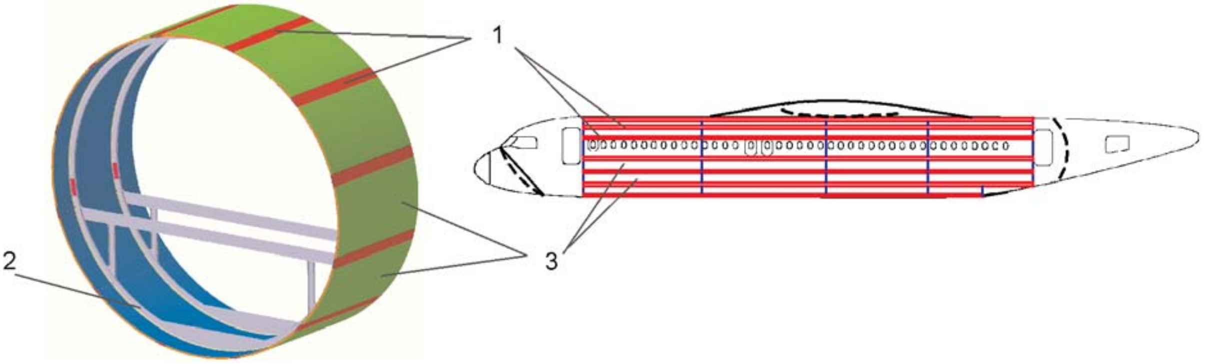


Fig. 10. Differential load-bearing design of fuselage in Lampassenkonzept

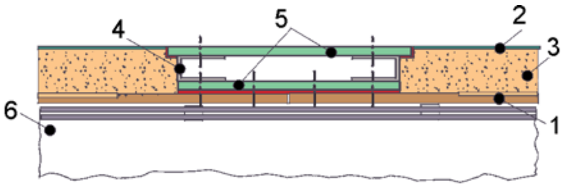


Fig. 11. Configuration of panels and 'strips'

of combined functions). For the reason of stability 'strips' have the form of box-shaped cross-section blocks consisting, for example, from two channel bars 4 with two cover plates 5. For the reason of weight economy, this is possible to track changes of bending moment along the fuselage varying the thickness of 'strip' cover plates 5. Frame 6 can also have a box-shape cross-section form for the reason of steadiness.

The rated strength evaluations of the considered fuselage structure assume the material of carbon fiber panels with ±450 primary disposal of layers; the material of channel bars and 'strip' cover plates – with primary disposal of layers along the fuselage. As a material for 'strip' cover plates the titanium carbon fiber with primary disposal of carbon fiber layers along the fuselage was also analyzed. This structure provides high strength and bending rigidity in axial direction of fuselage and relatively high contortion strength [22] (due to the titanium layers) in cross-section direction to re-join the panels.

Strength analysis and weight evaluation of the fuselage in Lampassenkonzept option were performed for the compartment located between sections 1 and 2 considering the cowls of distributed landing gear, i.e. practically for the whole passenger-and-cargo cabin of the fuselage (Fig. 12).

Geometric and loading calculation prototype was a ~ 4 m fuselage of A320 airplane. The cross section of carbon fiber fuselage was represented by twelve equally disposed 'strip' blocks and accordingly twelve panels with equal width of ~1 m. All panels were considered as being of equal cross section both in transverse and longitudinal directions of the fuselage, i.e. of the same size. It allows the mass and low cost production of panels, for example by method of pultrusion. 'Strip' blocks were represented by three subgroups, each of them containing four equal blocks, i.e. of the same type and size, with a varied thickness of 'strip' cover plates along the fuselage. Distance between the frames was assumed similar to that in a A320 prototype.

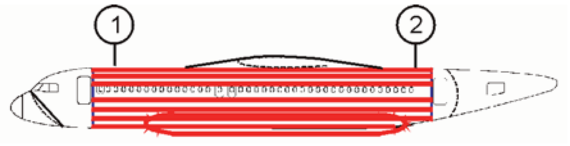


Fig. 12. Fuselage section under evaluation

Strength of carbon fiber fuselage within the preliminary design was evaluated analytically. Weight estimation of the composite fuselage in Lampassenkonzept option proved that with flexural and torsion rigidities almost equal to those of A320 aluminum fuselage, the weight can be reduced by ~29.9%, with maximum level of normal strain (around 415 MPa) in 'strip' cover plates made from titanium carbon fiber. The weight of wing and fuselage juncture was not taken into consideration in process of calculation.

The most dangerous calculation case for 'standard bodies' is the case of 'tough' landing on primary landing gears accompanied by considerable bending moments impacting the fuselage in the location of these gears (Fig. 4). For this reason the Lampassenkonzept option contains the probability of reduction in bending loads on the fuselage due to the landing gear distributed configuration, and accordingly of even greater weight advantage. Some potential fuselage weight reduction in this concept can be achieved by the increase of distance between the frames owing to sandwich panels.

3.2 Gondelkonzept

3.2.1 General Fuselage Design and Load-Bearing Panels

Airplane general design of carbon fiber fuselage in Gondelkonzept option is a low-wing monoplane [20].

The basic variant of load-bearing design (Fig. 13) has the following peculiarities: the

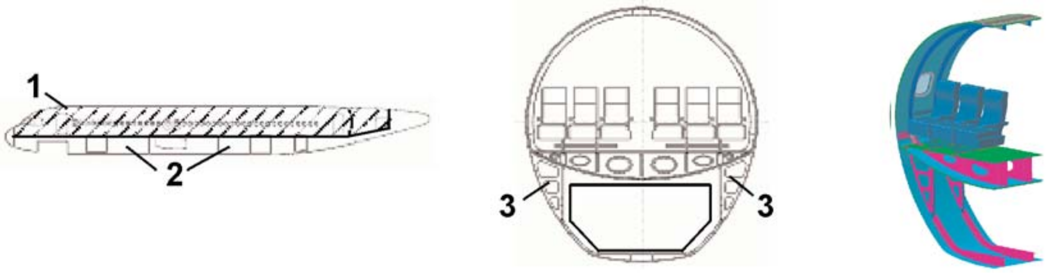


Fig. 13. General fuselage configuration in Gondelkonzept option

passenger cabin 1 experiencing the surplus internal pressure is the primary load-bearing structure of the fuselage for perceiving global loads; the cargo bay 2 comprises the secondary non-hermetic GONDEL structure perceiving local loads due to baggage only and accordingly not participating in fuselage general operations.

The passenger cabin construction consists of three load-bearing circular panels: two side panels and one lower. The latter contains sections for attaching seats and floor panel and they also function as load-bearing elements and participate in fuselage general operation in perceiving global loads. The lower panel radius is about twice as wider than that of side ones. Panel length is equal to the passenger cabin length. There are stringers, frames and local reinforcements integrated in the panel. Thus, unlike the Lampassenkonzept variant, the load-bearing structure of this fuselage is highly integrated and contains two cross-section and three longitudinal joints only: this leads to reduction of weight and assembly cost. In respect of the structural mechanics this is a regular load-bearing structure without big cutouts and drops of rigidity like in Lampassenkonzept variant.

The fuselage load-bearing panels in Gondelkonzept option can have most various load-bearing designs. SOFI type panels (Stringer Outside, Frame Inside) were under consideration in strength calculations and demonstrator of this fuselage given below. These panels have the same principle as SoFi modification of Airbus (see 2.5.2.2) where stringers are located in a so-called 1½ sandwich with foam multifunctional filling. Load-bearing panel shells are bolted through the titanium carbon fiber cover plates (mainly with unidirectional carbon fiber) which combine jointing and reinforcing functions like in Lampassenkonzept option.

The basic variant of GONDEL baggage-and-cargo compartment has service platforms suspended from the lower panel of passenger cabin. Since the constructional depth of the fuselage load-bearing structure is knowingly reduced, GONDEL can have the supporting continuous load-bearing beams 3 (fig. 13) which increase the constructional depth, participate in perceiving of global loads by fuselage, and with primary landing gears in the removed position located between them. Service platforms are made in modules and do not participate in fuselage general operations. All GONDEL elements perform the protection function for passenger cabin and are 'victim' structures, the perforating destruction of those as a result of impact loads not causing depressurizing of passenger cabin and its possible destruction in the air. They also perform the function of absorbing energy in case of crash loads and may have additional crash elements. GONDEL outer surface plays the role of detector in impact situation, and in the absence of damage or non-perforating damage allows to reduce considerably inspection activities performed for the load-bearing lower panel. There are the derived variants of Gondelkonzept [20], for example, without service platforms and light folds installed instead of them. Containers can be suspended from the lower load-bearing panel, etc.

In case of non-hermetic GONDEL compartment it's possible to vary its form [20] appropriate for non-standard cargo and track

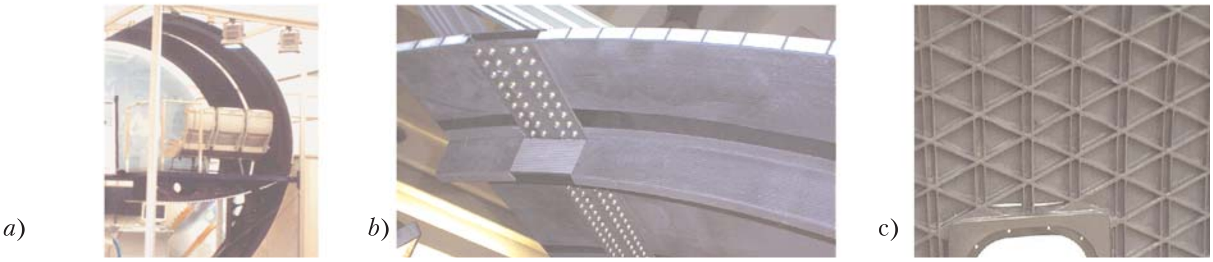


Fig. 13. General fuselage configuration in Gondelkonzept option

the ''barometer' of passenger operations more flexibly. Non-hermetic version of GONDEL compartment reduces the air-proof volume of fuselage and respectively assembly and maintenance cost, as well as the capacity of supercharge systems, i.e. for passenger cabin only. Containers of GONDEL may be air-proof too and this is not the best weight solution.

Weight estimate of carbon fiber fuselage in Gondelkonzept option proved that at the bend rigidity equal to that of a A320 fuselage, up to 25,5% weight reduction can be achieved at the maximum normal strain level in titanium carbon fiber cover plates (about 260 MPa). Strength reserve allows further reduction of fuselage weight if there are no bend rigidity limitations. Some potential weight reduction is also possible by increasing the distance between the frames owing to the presence of sandwich panels. This potential will be determined when performing optimization analysis.

3.2.2 Full-scale Fuselage Demonstrator

Some constructive ideas of Gondelkonzept option were implemented by the example of a natural-size demonstrator shown at ILA 2002 in Berlin and in 2004 on the conference SAMPE in Paris (fig. 14,*a*).

Load-bearing panels of the demonstrator shown by fig. 14,*b* were fabricated by SLI method (Single Line Injection) [23] developed by the Institute of Structural mechanics of German Aerospace Center (DRL, Braunschweig) and distinguished by high quality of product comparable with the prepreg technology. This method provides low pore level and probable varying of fiber content due to the pressure changes of autoclave and injection.

The full-scale load-bearing lattice structure was represented as a part of this demonstrator (fig. 14,*b*) [24]. This panel was designed and produced by the Russian research institute (CRISM – Central Research Institute for Special Machinery, Khotkovo) within the cooperation with the Institute of Structural Mechanics of German Aerospace Center.

4. Summary

1. Some basic requirements to the carbon fiber fuselage of passenger airplane of tomorrow can be fulfilled by investigation of its general configuration. General fuselage configurations in the considered Lampassenkonzept and Gondelkonzept allow rather efficient reaction to passenger safety demands in impact and crash aspects, as well as the demands of inspection activities reduction and flexibility of transportation tasks.

2. The analysis of general fuselage configuration allows getting the co-called regular load-bearing structure, i.e. without big cutouts thus providing a simpler construction and lower production cost, as well as the efficient solution of structural mechanics tasks such as reduction of weight.

3. Both presented concepts demonstrate that the purpose of reducing the weight of carbon fiber fuselage is up to 30% real as compared with a “standard body” variant.

4. The fuselage of a big passenger airplane is one of the biggest constructional units of the airplane and as it is shown in this paper the analysis of its load-bearing design can touch upon the questions of general design of the whole airplane. The two proposed concepts knowingly consider some boundary

points of the considered conceptual field and the most acceptable solutions lie somewhere within this field. For this reason, continuation of work is conceived as complex optimization analysis of configuration, strength and weight to find compromise settlements for the composite fuselage, considering the requirements not only to the fuselage only but to the airplane on the whole. This means that aerodynamics, designs of landing gear and engine, takeoff and landing issues, etc. should be also taken into consideration.

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