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CONCEPTUAL DESIGN OF CIVIL AIRPLANE COMPOSITE WINGBOX STRUCTURES

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Abstract

The object of research in work is a wing of civil aircraft with take-off weight m_0*=65000 kg and the following aerodynamic parameters: aspect ratio* $\lambda=11,5$*, ¼ chord sweep* $\chi=25^\circ$ *and wingspan 35 m.*

The work presents analyzes of existing and new civil airplanes composite wingbox structures in which the problem of selection and verification of stress allowable for wing design is emphasized. Several basic design concepts of composite wingbox and wing-root splice joints are shows.

As was shown that the majority of airframe manufactures uses traditional structural schemes for composite wings that were used on metal wings for a long time. It is rational desire to reduce the technical risk and increase the spectrum of using well-known procedures for wing certification even if it's made of composite materials.

As shown in work the stress allowables for wing design depend not only on characteristics of composite materials but also mechanical and thermal loading, design of irregular zones, certification requirements and damage scenarios during manufacturing and operation must be considered at all design stages.

The effect of using composite materials is significantly small by all this factors in compare with metals. One way to increase potential weight effects is to increase impact resistance of composite structures by using matrix systems with higher interlaminar fracture toughness or introduce the fiberglass crack stoppers to the wing design.

Several design concepts and structural schemes of civil aircrafts composite wing is shown in work: multi ribs structure with stringer stiffened panels, multi spars structure with flat panels without stringers, sandwich panels' structure. Advantages and disadvantages of each design approach and structural schemes were emphasized. Also work shows several variants of wing-root splice joints for different composite wings design and discuss the problems associated with each splice design. An algorithm of rational design of the composite wing structures is developed.

Introduction

The minimal mass of airframe`s construction is one of the basic criteria determining the perfection of the airplane construction. Its implementation depends on the correct choice of materials, construction of the composite material units and their parameters.

This paper dwells upon the main demands which should be taken into consideration when designing the wing construction from composite materials for trunk route airplane, views the concepts of composite wingbox construction and wing-root splice joints with wing center-section, and describes the algorithm of designing wingbox in regular zone and zone of joints with wing center-section.

The paper aims at:

1) Analyzing the existing constructions of composite wingbox for civil airplanes.
2) Defining the specifics of verification of design stress allowables for composite airframe structures.
3) Examining basic concepts of the wings structure layouts of a civil airplanes and wingbox root splice joints.

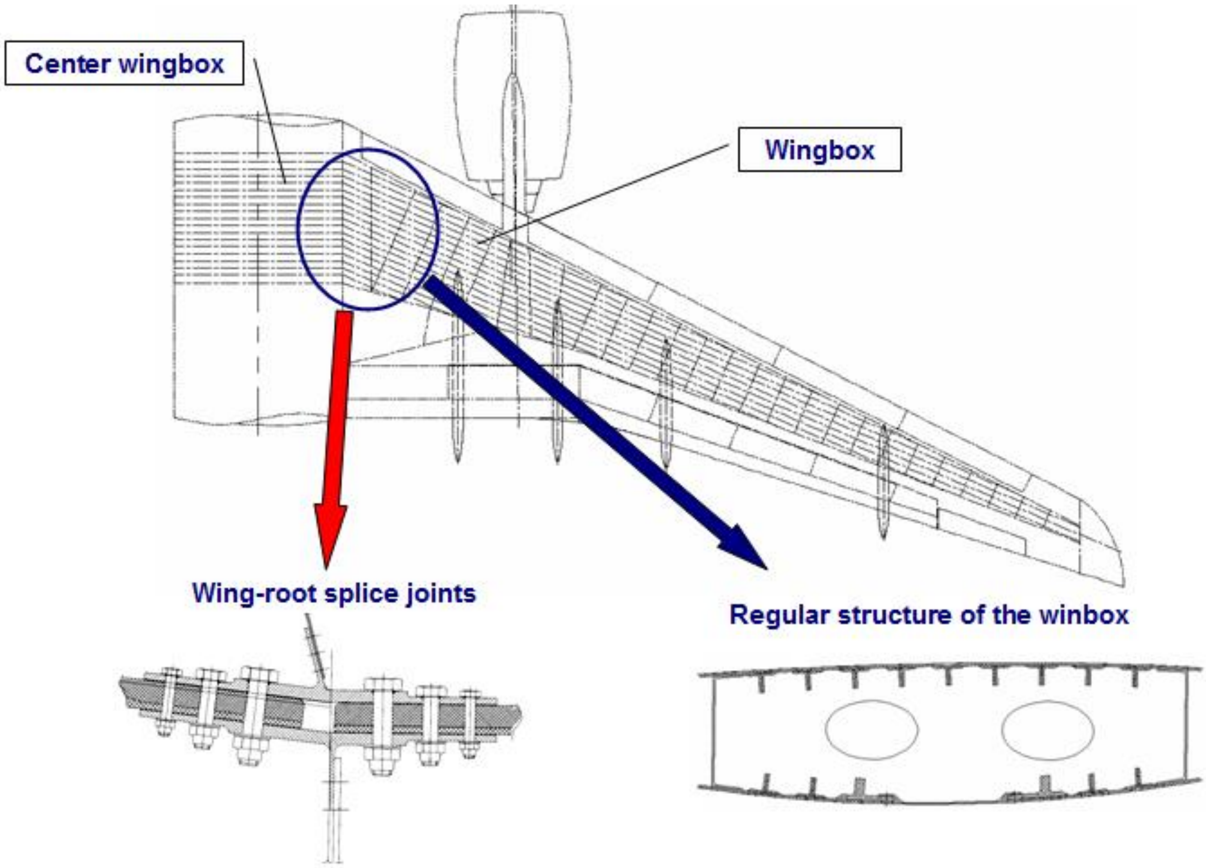


Fig.1. The object of research – a wingbox of a medium-range aircraft (regular zone of the structure and the root splice joint zone with wing center section)

4) Working out the methodology of the wingbox structural design in regular zone and root splice joints.

1. Analysis of the existing composite materials wing structures of the trunk route aircraft

The Boeing Company has developed a family of long-range widebody aircraft Boeing 787 Dreamliner which broadly uses composite materials in the construction of the airframe. By now the tests have been completed and the commercial exploitation of the aircraft has begun. The Boeing 787 wing is manufactured by the Japanese company Mitsubishi Heavy Industries.

The wing of Boeing 787 is a monobloc two-spar wing designed within the multi rib structural layout. The top and bottom panels with I-shaped cross-section stringers and spars are made of composite materials by autoclave molding process. The ribs are made of aluminum alloy. Fig. 2 shows photograph of wing root section shows the refined design of the upper wing skin stringer ends which form part of the side of body structural join with the center wing box. The wingbox and center wing section are spliced together through tapes of the inboard ribs with metal plates on the upper and lower wing surfaces and with metal fittings on the top panel stringers by means of mechanical fasteners. In order to prevent stringer delamination due to abrupt drops in stiffness, on the basis of the test results, the decision has been made to produce them with U-shaped cutouts in the stringers. [9].

Fig.2. Wingbox root section of Boeing 787 Dreamliner [11]

The Airbus Company is implementing a project of long-range Airbus A350 aircraft family with a broad usage of composite materials. The wing of Airbus A350 is a two-spar wing designed within the multi rib structural layout. (Fig.3). Panels with T-shaped stringers and spars are made of composite materials. The ribs are made of aluminum-lithium alloy [8]. In the joint zone of the outer wing with wing center-section the stringer`s wall is being dropped, going into the thickness of the panel.

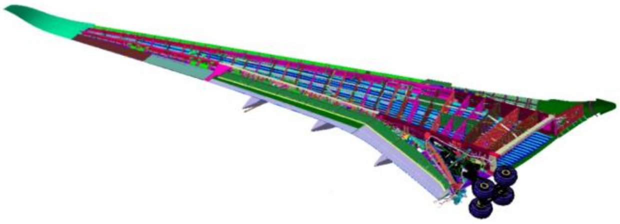


Fig.3. Airbus A350 wing CAD-model [8]

Russian Aircraft Corporation Irkut is developing a family of medium-range MS-21 aircraft. The MS-21 wing will be manufactured with a broad usage of composite materials. The wing is being designed by the company CJSC AeroComposite in cooperation with the company Fischer Advanced Composite Components AG. At the present moment a prototype of MS-21 wingbox has been designed and manufactured.

The MS-21 wingbox structural layout comprises two spars, top and bottom composite stringer panels and the ribs. T-shaped stringers of the top and bottom panels have the same pitch and are parallel to the conditional reference plane. In the joint zone of the outer wing with wing center-section the stringer`s wall is being dropped, going into the thickness of the panel.

Fig.4. MS-21 wingbox prototype [10]

2. Verification of design stress allowables for the composite structural design

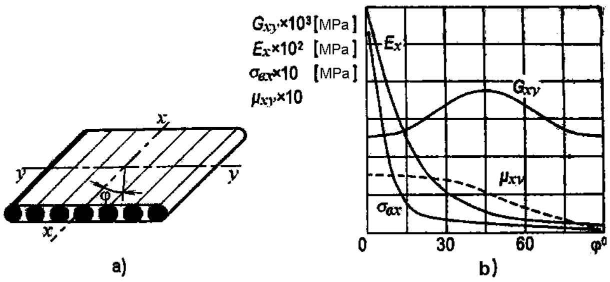


Fig.5. Interrelation between the composite materials characteristics and the direction of the fibers [7] (*a* - location of unidirectional fibers, *b* - effect of angles φ to the characteristics of the fibers)

Composite materials achieve the highest values of mechanical characteristics in the process of loading along the unidirectional fibers (φ = 0 °, Fig. 5a). When the armor angle shifts the material characteristics are changed (Fig. 5b). [7]

Design stress allowables is the values of the characteristic of the material, which are determined by the results of tests on the level of a multilayer material or a layer on probability basis and are used in design and calculation of the composite construction durability.

The choice of design stress allowables for a wing (Fig. 6) is a rather difficult task, because its value depends not only on the mechanical characteristics of the construction material, but also on the nature of external influence (loading), the existence of local construction irregularities, local stress concentrators and

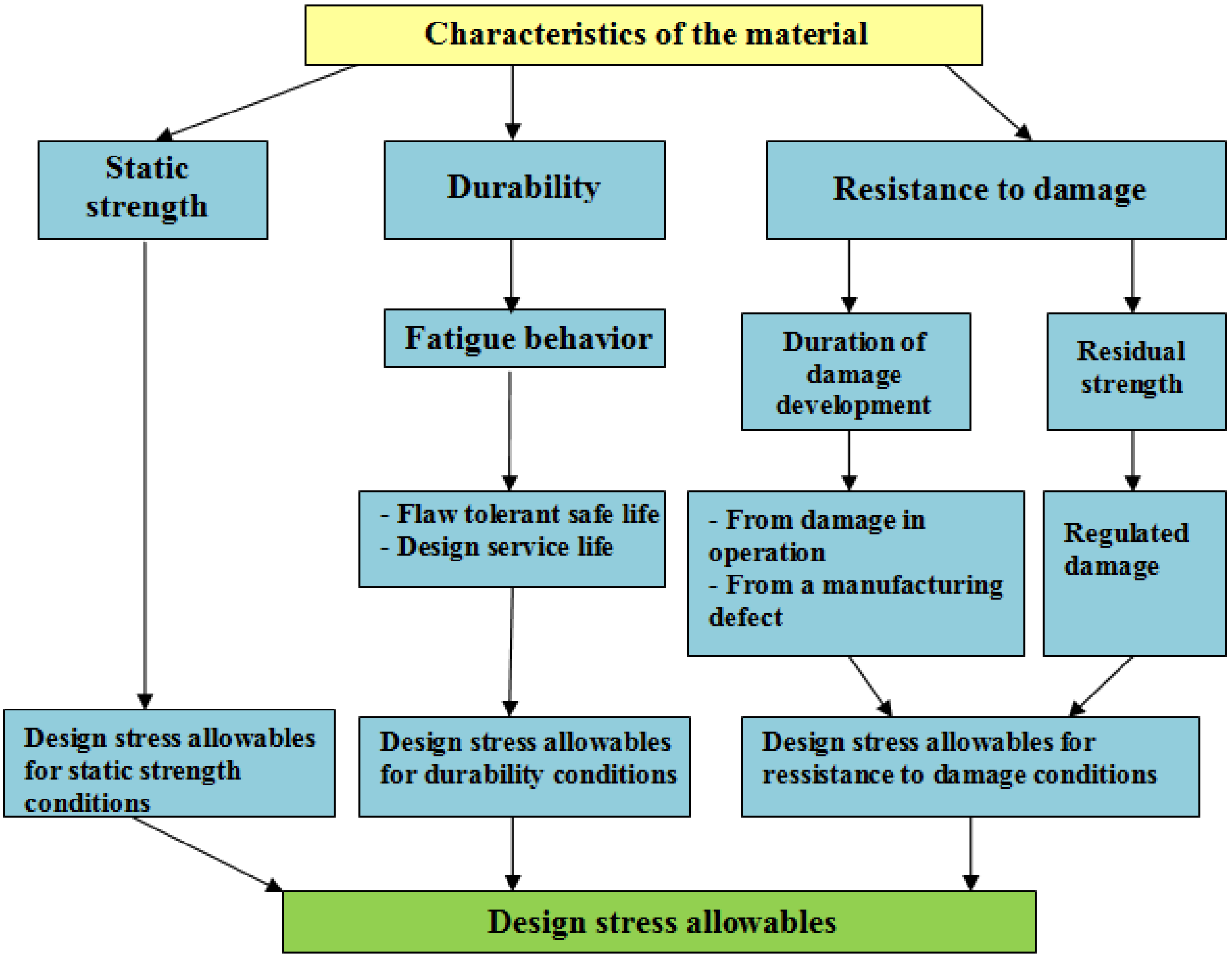


Fig.6. Criteria for choosing design stress allowables

damage caused in the process of manufacturing and operating of the construction [1]

The maximum level of strain compression for the material is set to $\varepsilon = 0{,}3\%$. This level of compression is chosen for the demands of providing construction durability after hitting, moisture saturation, fatigue and survivability requirements.

For the top panel the critical cases are compression after hitting and compression of laminate (package) with free orifice. For the lower panel, the possible option is stretching with both free and filled orifice. It is also advisable to consider the possibility of increasing the strain compression for the composite package for the lower wing panels to the level of $\varepsilon = 0{,}4\%$. In the process of designing it should be considered that the overall and local buckling for the composite construction is not allowed for calculated stress.

In the absence of sufficient amount of experimental works and the reliable strength characteristics at the initial stages of designing additional reducing safety indexes for the composites are being used.

For the basic strength elements of the construction the durability criteria are being introduced, which assess the level of allowable calculated stress σ, derived from the overall strength calculations.

As such criteria for a wing structure the following conditions may be considered (by groups of strength elements).

For wing composite coverings:

a) stretched zone - $\sigma \le [\sigma]$, where $[\sigma]$ is set by the requirements of static durability, endurance and survivability in view of deterioration of the mechanical characteristics at moisture saturation, exposure to temperatures, possible damage caused by technological nature and emerging in the process of exploitation;

b) compressive zone - no general or local buckling is allowed for this zone up to the level of calculated loads $\sigma_{cr} \geq \sigma$;

c) the level of relative deformations of the construction must not exceed the value of 0,4% under the calculated loads.

For the walls of spars and ribs no general or local buckling is allowed for this zone up to the level of calculated loads $\sigma_{cr} \geq \sigma$.

For the belts of ribs and shelves of spars:

a) stretched zone - $\sigma \leq [\sigma]$, where $[\sigma]$ is set by the requirements of static durability, endurance and survivability;

b) compressive zone - no general or local buckling is allowed for this zone up to the level of calculated loads $\sigma_{cr} \geq \sigma$.

A possible variation of mechanical characteristics set within 10% from the average values, and the decrease of maximum values as a result of exposure to environmental conditions (up to 20%) is included by introducing an additional safety index in calculation of the real safety margins.

3. Concepts of the composite wingbox structural layout

To strengthen the upper wing panel, operating mainly in compression, stringer reinforcement can be used (Fig. 7, Table 1), a multi-wall structure (Fig. 8, Table 2) or a three-layer structure with the cells (Fig. 12, Table 3).

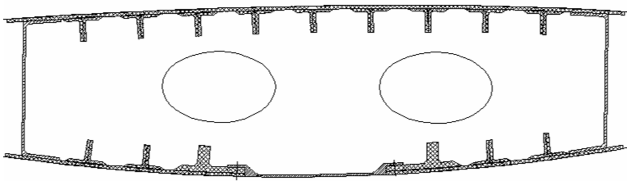


Fig.7. Composite multi-rib structural layout with reinforced panels

Table 1

Advantages and disadvantages of multi-rib structural layout with reinforced panels

Advantages	Disadvantages
-The possibility to produce the panels without the autoclave process and RTM; - It can be manufactured in one production cycle, if the stringer has a T-shaped cross-section; - A traditional structural layout, tried-and-true on metal wings; - There is a possibility to splice different systems (hydraulic, fuel, etc.) to the stringers; - There are composite analogues, and the level of technical risk is the lowest;	- The complexity of sealing ribs; - Complex configuration of the panels; - The complexity of manufacturing the panels in one production cycle, if the stringer has a I-shaped or more complex cross-section.

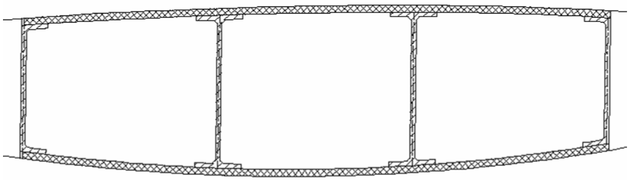


Fig.8. Composite multi-spar structural layout with monolithic panels without reinforcement

Table 2-

Advantages and disadvantages of multi-spar structural layout with monolithic panels

Advantages	Disadvantages
- Ease of manufacturing the panels; - Simple design and ease of ribs` sealing; - Increased stiffness of the outer wing panel, which is especially important when using composite materials for the designed structure; - Rational technological spacing of manholes at the bottom panel due to the small number of ribs; - The opportunity to	- Larger specific weight of regular zones of the panels (compared to the stringer design) due to the greater thickness of the coverings necessary for their sustainability; - In the root zone of the rear spar there are areas difficult to reach for building the wingbox, installation and maintenance of the zone systems; - No analogues for long-range aircraft, high level of technical

move to an integrated wingbox design and "no-center-section" wing with the joint of the outer wing panel at the surface of the aircraft symmetry;	risk. - In order to prevent thick panels from buckling the walls must possess significant stiffness

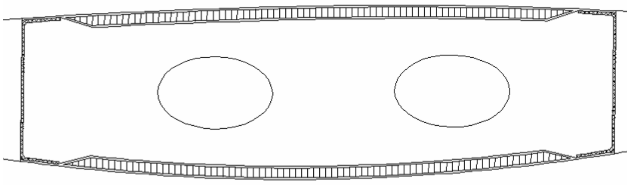


Fig.9. Sandwich skin panels structural layout

Table 3- Advantages and disadvantages of sandwich skin panels structural layout

Advantages	Disadvantages
- It is possible to reduce the weight of the wing panels in comparison with other structural layout; - Possibility of manufacturing the panels with a honeycomb filler in one production cycle using combined technologies; - Ease of manufacturing the panels.	- It is difficult to determine the place of unsticking of the covering from honeycomb filler as a result of hitting or in the process of exploitation; - Potential problems with accumulation of moisture in the honeycomb filler when the airtight covering is damaged; - Inability to produce panels with honeycomb filler through RTM technology; - The necessity to use autoclaves in manufacturing the panels.

With the use of honeycomb sandwich structures in a primary airframe construction a problem emerges which is related to the difficulty of ensuring the quality control of gluing covering and cells throughout the period of service of the construction. Using of the panels with a regular set of stringers and ribs allows employing the ideology of strength maintenance applied in the existing metal aircraft.

With the increased load the constructive upper limit on the height of the filler leads to the fact that the mass of the panel increases faster than the carrying capacity, and thus three-layer sandwich panels are less effective than reinforced panels or than stringer panels; with the further increase of the loading the latter must be strengthened with cross-cut ribs in order to prevent buckling, and therefore they become waffle-structured.

The panels reinforced by linear elements under the other equal conditions have another positive feature - a more predictable fracture pattern; moreover, when produced in an appropriate way they are technologically more reliable. Therefore, in modern aircraft strength panels of the wing covering, empennage, and fuselage represent a smooth covering, reinforced by a structured system of longitudinal ribs (stringers), which run in the direction of the prevailing loading (along the span of the wing, empennage, and alongside the fuselage). The technological aspect of the panels` effectiveness results from the fact that for the production of stringers highly effective technological processes can be applied – such as winding and pultrusion, ensuring the best implementation of the composite materials characteristics and significantly reducing the amount of laying out and cutting operations.

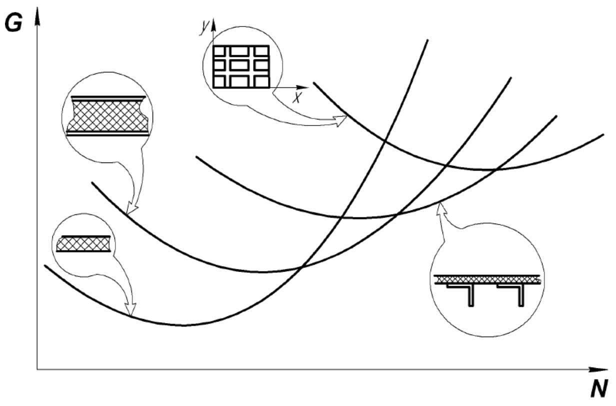


Fig.10. Dependence of the mass of the panels level loads and structural and technological solutions [5]

4. Description of the wingbox composite structures design algorithm

The structures of the airframe units (wing, empennage, and fuselage) are usually formed by thin wall panels representing a covering reinforced by ribs or a transverse wall with spars and ribs with struts. When operating within the structure the panels are in any case being loaded by a biaxial stretching - compression and shear.

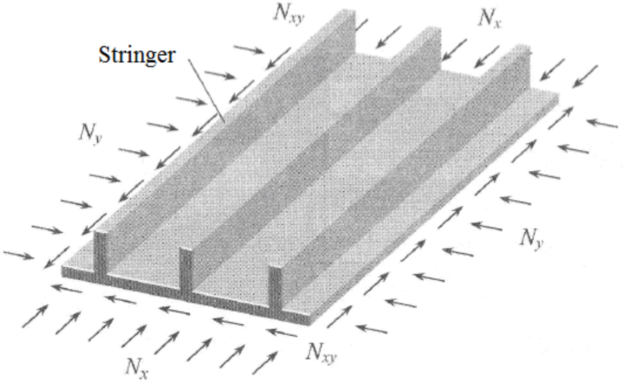


Fig.11. Wing panel reinforced by ribs and the action of axial and shear stress on it

When choosing the initial parameters of the elements (initial sizes and layer stacking schemes) it can be considered that the longitudinal and transverse stress fully perceive with stacking layers in the directions of 0 ° and 90 °, and shear stress – with layers of ± 45 °.

After selecting a scheme of laying and thickness the calculation of elastic and strength characteristics of the elements and panels is being made, and the required thickness (number) of layers is being determined regarding the conditions of durability, local and general stability in accordance with the techniques described in the following sections. Minimum required thickness of each of the described groups of elements` layers is calculated in accordance with the condition of ensuring the strength of the element at a given stress on the panel.

The construction parameters of the panel elements are selected by an iterative method. The iterative process goes on in the direction of bringing all the coefficients of strength and stability of the structural elements to a value close to unity, but not less than one. The thickness of panel elements is chosen regarding the condition of ensuring durability and preventing local buckling, and the height of the elements – regarding the conditions of preventing overall buckling panel [3].

Flow diagram of wing panels design algorithm in regular zone of wingbox is presented at the Fig.12.

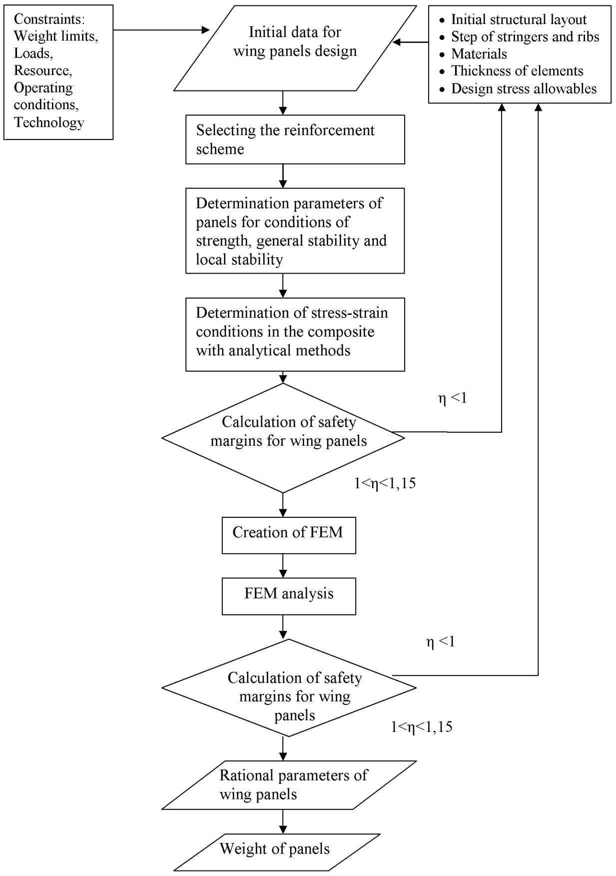


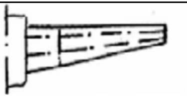
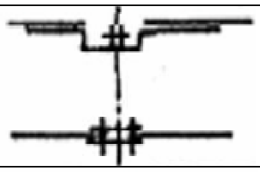
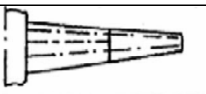
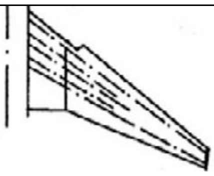
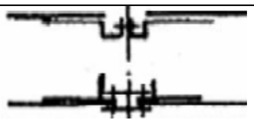
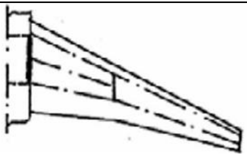
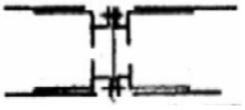
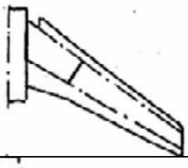
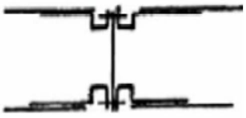
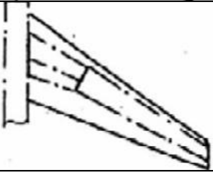
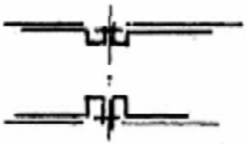
Fig.12. Flow diagram of wing panels design algorithm

5. Analysis of wing-root splice joints structures

The joint area is the most responsible area of composite structure design. When the joints are designed irrationally the entire gain in weight from the use of composite materials in the regular zone can be lost. Creating a splice is a complex multidimensional task.

Due to the requirements (constructive, technological, operational) the wings of large transport aircraft were often produced with a split seam contour (Table 4), which spliced the panels and wingbox spars and the center-section. At that flanged joints and joints with overlays were used.

Table 4-
Flanged type root splice joint

Airplane	Wing layout	Joint type
Il-14		
Il-18		
Il-62		
Il-76		
Tu-104		
Tu-154		

Despite their simplicity flanged joints are being rarely used today because of their larger weight and a big number of stress concentrators.

In the modern wings structures the transverse joints of separate outer wing panels between themselves and the joints of outer panels with the center-section are produced as integral (technological) (Table 5) [6]. For such joints it is typical to possess a special splice profile of variable cross-section, which connects the coverings of outer wing panels and center-section, as well as to have fittings connecting stringers or ribs of monolithic panels. Another feature is characterized by changes in the thickness of panel covering and splice profile used for a more equal loading of the fasteners and a reduced concentration of stress.

There is a tendency to reduce the transverse joints. Thus, the wings of DC-10, Boeing-747, Il-96-300 airplanes do not have transverse joints of outer wing panels and possessing only the joints of outer wing panels with center-section.

Table 5 -
Technological (shear type) root splice joints

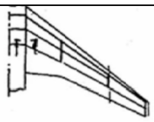
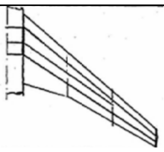
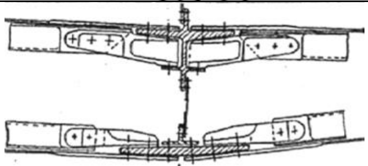
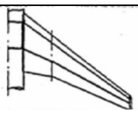
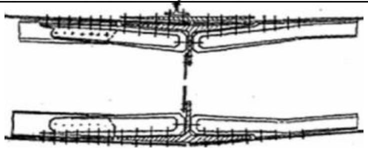
Airplane	Wing layout	Joint type
Il-86		
B-747		
DC-10		

Fig.13 shows a civil aircraft joint of detachable part with center-section. The joint is organized on a board rib, which matches the joint with the fuselage. All metallic parts of the joint (board rib belts, bands, fittings) are made of titanium alloys. The panels consist of covering with I-stringers.

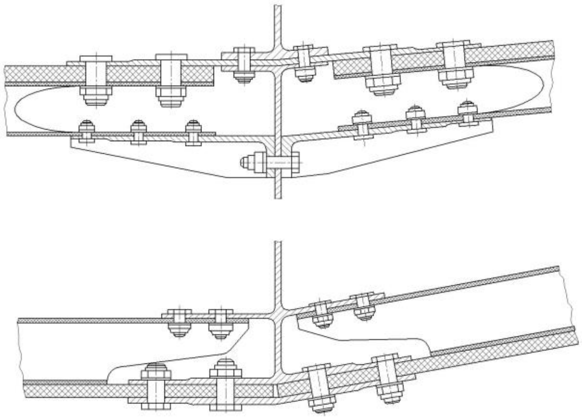


Fig.13. Splice joint of a composite wingbox with panels reinforced by I-shaped stringers

The structure of the root splice joints presented in Fig.14 differs from the previous one, due to different design of the wingbox panels – the covering and T-stringers are of small height which prevents the bolts to "catch" the edge of the stringer rib without providing the necessary jumpers on the composite materials.

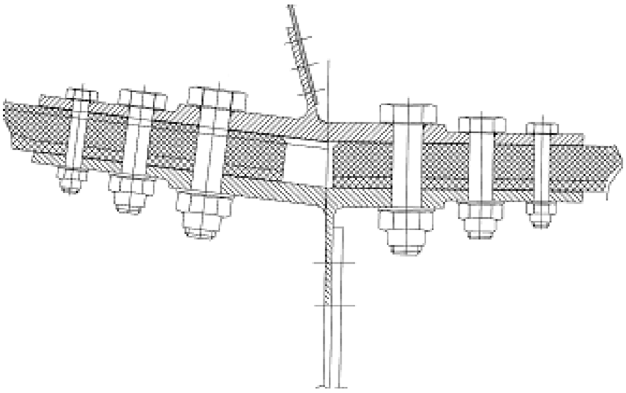


Fig.14. Splice joint of a composite wingbox with panels reinforced by T-shaped stringers

Composite top and bottom panels of the detachable part and center-section are sandwiched between the belts of board rib and the pads cut on the chord. The thickness of the rib belt and pads is symmetrically identical in order to ensure the symmetry of double-shear joint with the panels.

For the purpose of splicing the board ribs with fuselage covering a square is used which is set along the upper chord under the belt joint bolts.

6. Description of the wing-root splice joints design algorithm

The development of the structure of the joint of a detachable part with center-section of a passenger aircraft begins with collecting of the basic data:

a) geometry of board ribs (construction height)
b) length of the joint along the chord (the point of intersection between board ribs with the spars of the detachable parts and center-section)
c) layout of the zone
d) loading
d) availability of fuel
e) resource and resource stress allowables
g) operating conditions
h) design (presumable) of the detachable parts and center-section (step of the stringers, ribs, spars` design, weight limit and other elements in the process of linking).

When the finite element method (FEM) is used for the calculation of joints with numerous bolt or rivet connections it is advisable not to break the body of the bolt into the elements - it would significantly increase the dimension of the problem, instead it is preferable to find the coefficients of stiffness (compliance) of the bolt on the basis of analytical or experimental dependencies and to sum them with stiffness coefficients of major parts of the construction [3].

Flow diagram of wing-root splice joints design algorithm is presented at Fig.15.

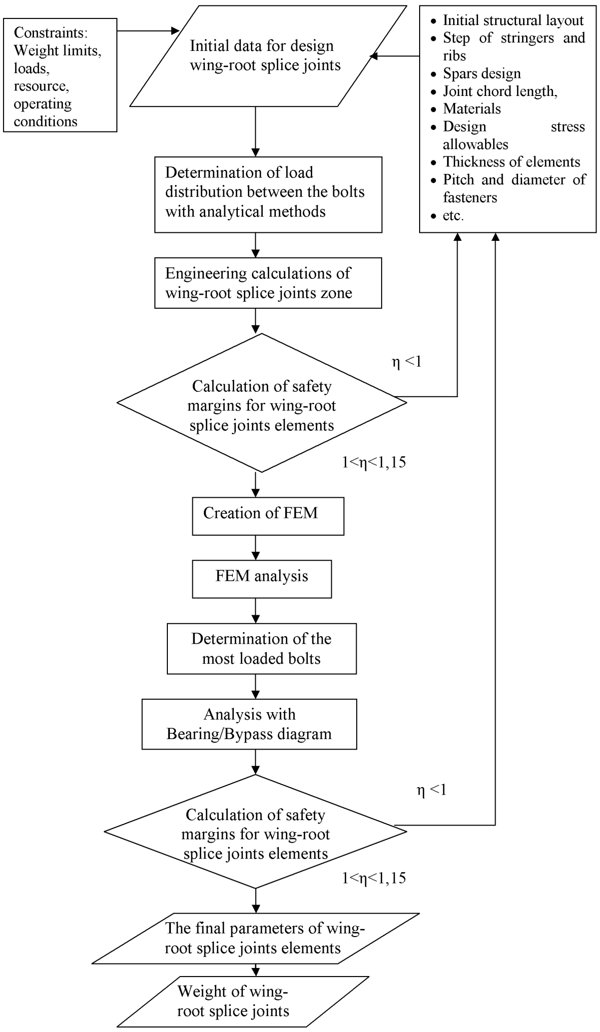


Fig.15. Flow diagram of wing-root splice joints design algorithm

The analysis of the element of the designed structure of a double-shear joint was performed. Electronic models of the designed structure were created in the CAD-system CATIA v5, structural analysis by the finite element method (FEM) was conducted in the CAE-system MSC Nastran. The results of FEM calculation are presented at the Fig.16

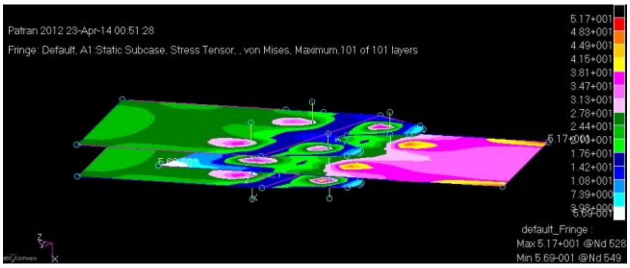


Fig.16. Stress tensor for element of double-shear root splice joint of composite wingbox

Conclusions

1) The analysis of structural design of composite wings, existing and developed long-range aircraft are shows.

2) The stress allowables for wing design depend not only on characteristics of composite materials but also mechanical and thermal loading, design of irregular zones, certification requirements and damage scenarios during manufacturing and operation must be considered at all design stages.

3) Several design concepts and structural layouts of civil aircrafts composite wing is shown in work: multi ribs structure with stringer stiffened panels, multi spars structure with flat panels without stringers, sandwich panels' structure. Advantages and disadvantages of each design approach and structural schemes were emphasized.

4) Shows several variants of wing-root splice joints for different composite wings design and discuss the problems associated with each splice design.

5) An algorithm of rational design of regular zone and root splice joint of the composite wing structures is developed.

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