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SKEW BENDING OF AIRCRAFT FUSELAGE PANELS WITH "L" AND "C" STRINGERS MOUNTED BY HYBRID JOINT

UKOŚNE ZGINANIE POSZYCIA SAMOLOTU Z USZTYWNIENIAMI TYPU "L" I "C", MOCOWANYMI ZA POMOCĄ ZŁĄCZA HYBRYDOWEGO

A section of fuselage skin with dimension 30 x 200 mm was subjected to numerical study and loaded by skew bending (Fig. 3). The thickness of the skin was 0,6 mm, the length of a leg of an angle "L" profile stringer was 12 mm with 1mm thickness. The angle of inclination α of the load plane to the skin plane varies in the range from 10° to 90° with 10° increment. The elastic – plastic material model of D16T aluminum alloy was used in simulations of the fuselage skin as well as for "L" and "C" profile stringers. In the material model description damage of aluminum alloy was taken into account. An adhesive layer with thickness of 0,1mm was modeled using cohesive elements with the failure mode depending on the shear strength and the tensile strength.

The paper presents a comparative analysis of the considered structural elements with application of the unsymmetrical "L" profile or the symmetrical "C" profile with the same cross section area.

All numerical studies were performed in Abaqus program. Finally, one can conclude that the stiffness of the structural element with application of the symmetrical "C" profile stringer is stronger, whereas the mechanical response of both versions of the hybrid joint significantly depends on the angle of load inclination α.

Keywords: skew bending of hybrid joint, deformation processes, FEA (finite element analysis)

Badaniom numerycznym poddano wycinek poszycia o wymiarach 30x200mm, który następnie poddano obciążeniu poprzez ukośne zginanie, Rys. 3. Grubość blachy poszycia wynosiła 0,6 mm, długość ramienia kątownika równoramiennego 12 mm i grubość ramienia 1mm. Kąt nachylenia α płaszczyzny obciążenia w stosunku do płaszczyzny poszycia zmieniał się w granicach od 10° do 90° z przyrostem co 10°. W symulacjach zastosowano model sprężysto – plastyczny materiału dla poszycia i kształtownika jakim był stop aluminium D16T. W opisie modelu materiału uwzględniono także uszkodzenie stopu aluminium. Warstewka kleju o grubości 0,1 mm była modelowana z wykorzystaniem elementów kohezyjnych, dla których także uwzględniono uszkodzenie przyjmując dane producenta, takiej jak wytrzymałość na ścinanie oraz na rozciąganie.

W pracy przedstawiono analizę wpływu zmiany obecnie stosowanego niesymetrycznego kształtownika (kątownik), kształtownikiem symetrycznym (ceownik) o takim samym polu przekroju poprzecznego.

Wszystkie badania numeryczne przeprowadzono w programie Abaqus.

1. Introduction

Development of modern aircrafts requires implementation of new different composites with excellent mechanical and thermal properties, significantly lighter in comparison to conventional structural materials. These new materials are particularly important for creation or joining of critical aircraft parts, e.g. elements of engines, wings, fuselage, joining of structural elements by application of innovative methods etc. A relatively new idea in creation of the modern composite materials relies on introduction of gradation of thermo-mechanical properties to produce functionally graded materials - FGM (e.g. [1-8]). The modern composites can be manufactured as materials with internal interfaces made of different components (e.g. [9-17]). Other type of multi-phase composites are joined by adhesive layer adherends (e.g. [18-23]) or thermal barrier coating layers protecting the turbine blades against the thermal shock failure (e.g. [24-27]), etc. The modern adhesive layers can contain particles in the form of nano-particles or carbon nano-tubes, which reinforce composites in aerospace technology (e.g. [28, 29]). One can conclude that mixing of different phases in materials with application of the proper production technology leads to creation of new and stronger composite or structural element joints with higher durability and reliability.

The above ideas are the basis for improvements of joining technologies of structural parts in aerospace. Instead of using single joining technique as: riveting, spot welding, clinching or adhesive bonding a hybrid joining technique (e.g. [30, 22]) can be applied by combination of two simple ones, e.g.: riveted-

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bonding (e.g. [31, 32]), spot welded-bonding (e.g. [33, 34], clinched-bonding (e.g. [35-42]), etc.

The paper presents application of the hybrid joint (spot weld – adhesive) used in the construction of aircraft skin produced by PZL Mielec.

The fuselages skins (shells) of aircraft structures, due to the weight criterion, have a small thickness in the range of 0,6 - 1mm [43 - 45]. The use of such thin structures would not be possible among others, due to the phenomenon of stability loss under the influence of aerodynamic loads associated with flight mechanics and own loads. Therefore, the stiffeners of skin structures are used in the longitudinal direction or as longitudinal and transverse to the axis of the whole structure. The stiffeners are often aluminum profiles produced by extrusion. Profiles, depending on the construction, can be mounted to the skin by: riveting, spot - welding, adhesive or more often by laser welding [46 - 48]. Each of the above mentioned methods has its advantages and disadvantages, so in order to improve working between the stiffener and skin, the hybrid joints are also used eg. spot - welding - adhesive joints. The hybrid joints have a number of advantages, such as increased strength and rigidity, a two - stage damage model, which results in a much higher energy required to destruction of the connection in comparison to the pure mechanical or the adhesive joints.

The aim of this study is to perform a numerical model of the hybrid joint for an angle bar with the skin fuselage, and which is subjected to complex state of load. The obtained results indicate that the change of currently used angle bar as the stiffener improves load capacity of the connection.

2. The methods for stiffeners mounting, their cross sections and loading methods.

For mounting of skin stiffeners, almost all commonly used joining techniques are applied. The first and oldest one is riveting. The advantage of this method is not only the simplicity of technology, but also the greater energy absorption in relation to the welded structure [49]. The disadvantage is the possibility of crack initiation at the edges of the holes due to stress concentration. These cracks are difficult to detect at the initial stage of their development, because they are initiated on the inner surface of the sheets or in the inner layers of the multilayer connection. An additional difficulty in detecting cracks are rivet heads which cover a crack in the initial phase of development.

The second primary method used in joining aircraft structures for more than 50 years is adhesive bonding [46]. The main advantage of adhesive bonding is lack of stress concentrations in the joint. To increase load capacity as well as the amount of energy required for joint damage, hybrid (riveted - adhesive) joints are used. A detailed analysis of the work of these connections can be found in the papers [31, 48, 50, 51]. Connection parameters of hybrid adhesive - riveted joints may also be modified by the prestress [52] or use of appropriate holes tolerances [53]. More and more often, laser welding method is used to connect stiffener with skin [47, 43, 49]. Although laser beam welding minimizes heat impact on joint, there is a loss of alloying elements from weld zone which reduces the hardness and strength properties. The welding process can also cause a skin deflection, so-called Zeppelin effect, and requires complicated and large equipment.

For joining of aircraft structures a clinching technique could also be applied, which is used among others in Mercedes-Benz cars of S-Class. These connections are widely discussed in papers [54, 55].

In PZL Mielec aircraft plants a hybrid technique using adhesive bonding is also applied to connect stiffeners, but in this case mechanical joint is realized by spot weld. Numerical and experimental research, in particular on fatigue, also proved that hybrid joints have more advantages than pure adhesive or mechanical connections [44, 45, 56].

The most popular and simplest stiffener cross section is an angle bar (isosceles or non – isosceles) [47, 57, 43]. Using adhesive bonding or riveting, the angle bar is connected to the skin by one of the arms (Fig. 1a).

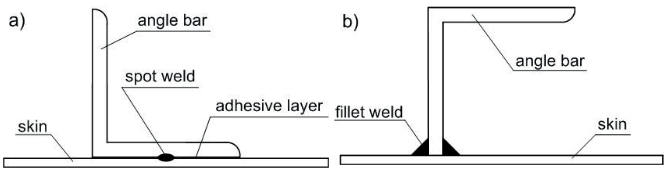

Fig. 1. Mounting of angle bar by using: a) spot welding and adhesive bonding, b) laser welding

On the other hand, using laser welding, the angle bar can be mounted as shown in Fig. 1b. In this position the bending rigidity is more than 2,5 times higher.

Orifici and others [58] subjected to research the skin with T-shaped stiffeners. The damage on contact with the skin after buckling was analyzed. They performed 71 experiments with anti – symmetrical and symmetrical configuration subjected to pull and push forces. The total damage of the joint was identified as the first drop of the force. The authors described four different types of damage modes due to complex stress states in the composite material. Numerical simulations were also carried out taking into account the arrangement of fibers for both the shell segment and for the whole panel, specifying the critical force causing local buckling. Complex stress states (compression with shear) were used by authors in [59]. It should be underlined, that the very important criterion in the designing and certification processes is the local and global buckling. Bertolini et al. [60] used in research "omega" stiffeners. Four point bending tests for stiffening beams were performed both for numerical studies as well as real tests. The damage appearance on contact between stiffeners and skin was analyzed. In [61] the mechanical response of the skin and stiffeners joints were investigated under impact loading. The effect of geometry influence on different stiffeners distributions wit double "T" cross section and various skin thicknesses was analyzed. Low velocity impact loads are very important, particularly during take-off or landing of an airplane and possible collisions with birds. Therefore international certification regulations require making tests for fuselage panels in terms of birds impact [62]. Chintapalli et al. [63] performed optimizing of "Z" and "J" stiffeners shape in order to minimize weight of the airplane. An important problem in the design of fuselage stiffeners is also the effect of sound attenuation. The paper [11] dealt with this problem by analysis of 4 types of different cross sections.

Summarizing the above considerations, it is clear that the study of fuselage structures mechanical response is a very complex problem. The crucial role in the analysis plays:

- the type of used profile,
- the method of connection to the skin,
- choice of strength test.

3. Description and construction of the FEM models.

The aim of the present numerical study is comparison of two models of fuselage segment one with “L” stiffener and the other with“C” stiffener. Detailed dimensions are shown in Fig. 2. All boundary conditions and the used materials are the same for both models. The only difference is the use of a different profile, wherein it should be noted, that the cross-sectional areas are identical.

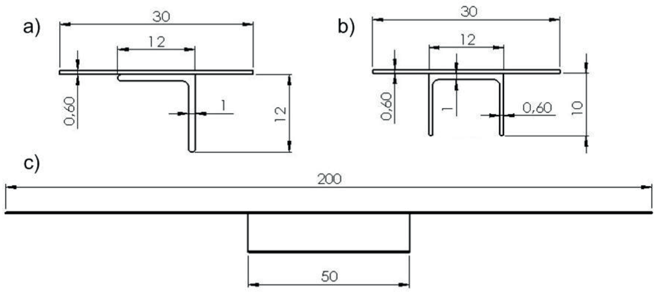

Fig. 2. Shapes and dimensions of the analyzed stiffening models, a) angle bar with stiffener, b) channel bar c) longitudinal view .

A method of stiffening profile joining to fuselage skin consisted of application both adhesive bonding and spot welding. The adhesive layer with thickness 0,1mm was modeled by using cohesive elements. Stress values at which damage in adhesive layer occurred were: 18MPa for tension and 25MPa for shear. Skin aluminum sheets were modeled as an elastic – plastic material with damage. The following characteristic material parameters for aluminum were assumed: E=73,1GPa, ν=0,3, σ_y=324MPa, σ_u=469MPa, A_5=20%. The description of aluminum material in Abaqus code includes also description of the damage process using “Ductile damage” model e.g. [65-71]. Table 1 summarizes the amount of finite elements used to build numerical models. For the skin sheet and the spot weld C3D8R elements were used, whereas the adhesive layer was modeled by COH3D8 cohesive elements.

TABLE 1

The quantity of finite elements.

skin sheet	„C” profile	„L” profile	spot weld	adhesive layer
19882	13150	11120	634	2724

4. Results of the numerical simulations

Figure 3 presents the sample with the stiffener for numerical simulation with fully clamped boundary edges. The specimen is subjected to imposed displacement vector $\bar{u}$ in the symmetry plane (x, y). In order to perform skew bending of the specimen the displacement vector was inclined to the axis x under angle α.

In the formulated numerical models, the damage was included both in the adhesive layer as well as in spot welds.

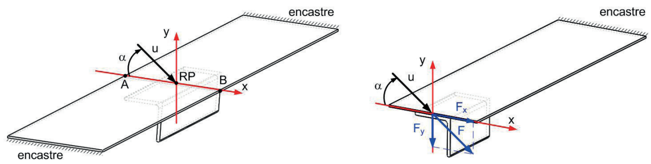

Fig. 3. Scheme of model load.

In the carried out simulations, we observed deformation process controlled by displacement vector $\bar{u}$. The length of the $|\bar{u}|$ grew linearly from 0 to 10 mm during the whole simulation. We calculated also in the symmetry plane the component R_x and R_y of the resultant force R.

Figure 4 presents correlation between the resultant force $|\bar{R}|$ and the displacement $|\bar{u}|$ in the reference point RP. The numerical results collect the mechanical response of the joints in different skew symmetric displacements for different angles of inclination a from 10° to 90° with increment of 10°.

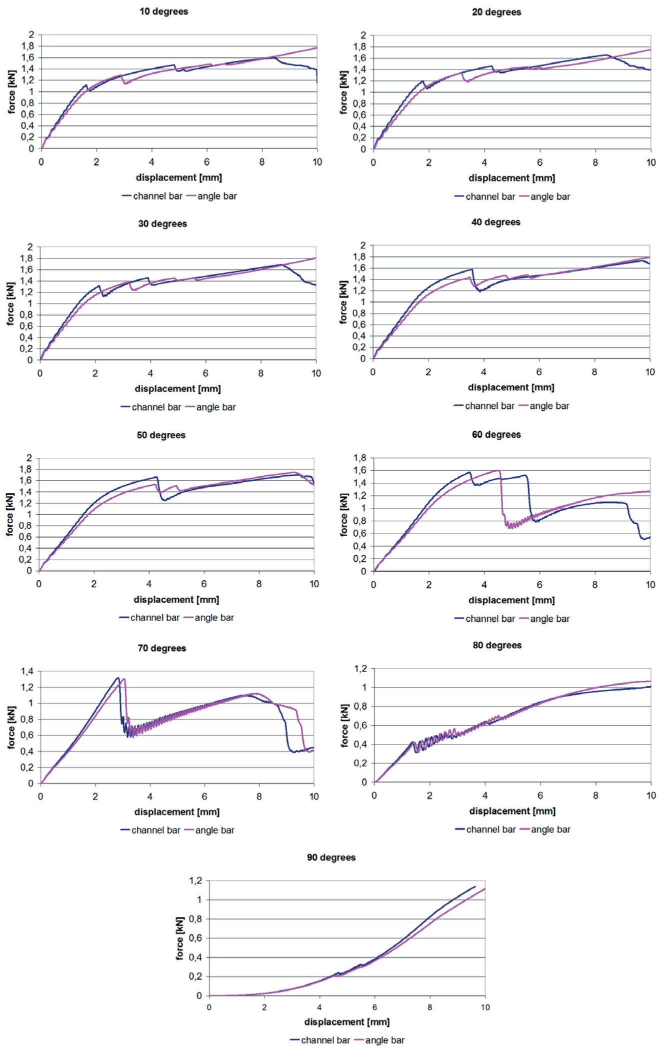

Fig. 4. Force – displacement curves.

One can conclude, that the initial stiffness of the joint with application of the channel bar is noticeable higher about 7 – 12% in dependence to angle of inclination displacement vector $\overline{u}$. The damage process associated to the current value of the displacement $\overline{u}$ is very complex and 3 dimensional, as 2 damage mechanisms were included in the model: in the adhesive layer and in the plastic adherents. Therefore the degradation of the joints takes place in two stages, first comes to destruction of the adhesive layer. The second stage starts after total destruction of adhesive layer and then the load is carried out by spot welds. One can observe the force increase again.Therefore, hybrid joints are much safer than traditional adhesive or mechanical joints.

Detailed analysis of Fig. 4 indicates, that damage of the adhesive layer may occur in several steps. It is particularly visible for angle of displacement $\overline{u}$ inclination α=60° and channel bar stiffener.

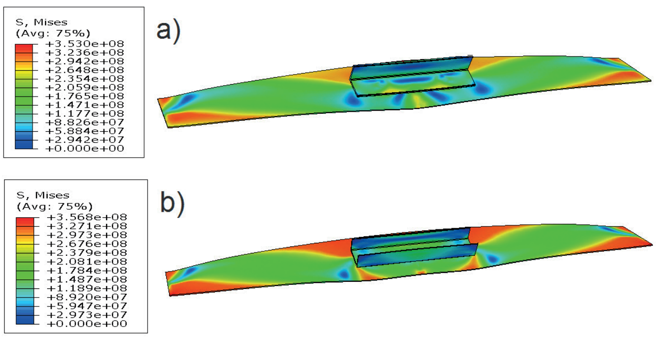

Fig. 5. Deformations for displacement of 3,73mm and angle a=400 (a – model with angle bar, b – model channel bar)

Figure 5 shows the von Mises stress fields for displacement $\overline{u}$=3,75 *mm* and angle α=40° for models with angle bar (a) and channel bar (b). One can observe in case (b) that wider area of the analysed structural element is subjected to higher level of the von Mises stress above the yield stress σ_y=324MPa. The corresponding damage state of adhesive layer, for the same displacement conditions, can be observed in Fig. 6. Application of the angle bar makes the hybrid joint more sensitive to damage growth. The degradation of the adhesive layer in the sample subjected to tensile takes place in different manner [34, 56]. The damage of the adhesive layer progresses in the direction from axis of symmetry to edges and it stops on the line of mechanical joints occurrence.

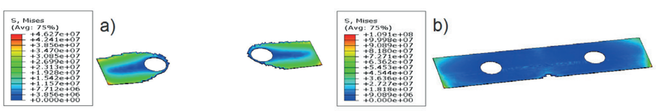

Fig. 6. Degradation of adhesive layer for displacement of 3,73mm and angle α=40° (a – model with angle bar, b – model with channel bar)

In order to underline the differences between the mechanical response of the analyzed models, Fig. 7 collects maximum forces recorded just before damage initiation of the adhesive layers for $\alpha \in (10^0, 90^0)$. Therefore we can distinguish three zones of the mechanical response:

- zone I – the forces $\overline{F}$ are higher for the models with the angle bar,
- zone II – the forces $\overline{F}$ are higher for the models with the channel bar,
- zone III – the force $\overline{F}$ values recorded before damage of adhesive layer are comparable for both models.

Figure 8 summarizes the amount of energy needed to failure initiation in the adhesive layer. Likewise to Fig. 7, we can also observe division into three specific zones. Within the interval from 10° to 30°, initiation of damage in the adhesive layer requires almost 2 times more energy as for the model with the angle bar. In the range from 40° to 50° models with channel profile are more advantageous, but this advantage is in the range of several percents. The most dangerous is the interval from 80° - 90°. Then the load is nearly vertical in relation to the fuselage skin and a small amount of energy is required to initiate damage in the adhesive layer.

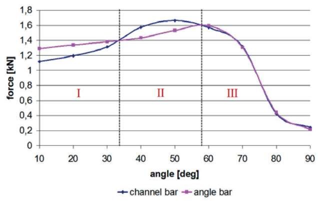

Fig. 7. Forces $\overline{F}$ required to damage initiation in the adhesive layer

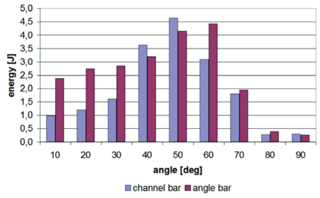

Fig. 8. The energy required to damage initiation in the adhesive layer

5. Conclusions

The paper presents the literature review concerning description of different methods of stiffeners fastening to fuselage skin of aircraft structures and the types of applied stiffener profiles. The numerical studies were performed for complex states of loads of the fuselage segments which are currently used in PZL - Mielec. In particular, the analysis of replacement of the currently used angle bar by the channel bar with the same cross section area was performed. The study shows the following results:

1. The stiffness of connections with channel bar is about 10% greater than in the case of angle bar.
2. The damage in the adhesive layer occurs earlier in the case of the model with the channel bar for the exciting displacement vector $\overline{u}$ inclination equal to α=10°-30°
3. When the exciting displacement angle α belongs to the interval 40°-50° the channel bar stiffener is more effective because of increase of the currying force $\overline{F}$ about 10% at the moment when the damage starts in adhesive layer.
4. The mechanical response of the analyzed models with the angle bar and the channel bar are almost the same for $\alpha \in (60^0, 90^0)$, i.e. we obtain a similar force level at the moment when damage starts in adhesive layer.

From the above listed conclusions it cannot be clearly determined which of the models is more advantageous. Therefore, further research on complex state of stress eg. bending with torsion is necessary, including cracks propagation models e.g. [72-79].

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