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Numerical study of composite bulkhead partition strength with in-situ X-ray monitoring

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Abstract. The aim of this work is the stress-strain analysis of bulkhead partition made of carbon fiber reinforced plastic (CFRP) at mechanical testing. The problem was solved in a general 3-D statement for an anisotropic elastic body. The strength prediction of the construction was done by stress analysis in each ply of composite laminate. The numerical simulation was obtained with ANSYS Workbench software. The detailed ply-by-ply stress analysis with special attention to areas of plies curvature was done. The results of numerical simulation were compared with the test data for verification of the proposed numerical algorithm.

1. Introduction

Nowadays composite materials are increasingly being used for design of high-loaded parts and components of aircraft machinery and space-rocket industry. Generally, implementation is done as a replacement of the metallic component with its composite analog. Such implementation involves structure interchangeability in attaching points, moreover the structure must be unified and standardized, but not lose its strength.

For this it is necessary to design accurate numerical models of a composite part, allowing detailed research of stress strain in the most loaded areas with complex reinforcement geometry. As a rule, these areas include joints, technological junctions and various surface attachments in complex geometry parts. These areas can be considered *a priori* a weak link in the structure, as they are mostly prone to interlayer fracture due to low contact and interlayer resistance of polymer composite materials. Moreover, the probability of process defects is increased in these areas.

The object of current study is the composite bulkhead partition (Figure 1) of aircraft construction consisting of several plies of composite material. When in service, the bulkhead is exposed to compound structural loading, which may cause interlayer cracks and stiffness decline.

Figure 1. A view of bulkhead partition.

In the context of this work the boundary value problem for a laminate composite with different spatial orientation of layers and contact conditions is set up. A detailed structure ply-by-ply stress-strain analysis with the use of refined finite element mesh was done and the strength of bulkhead section was evaluated.

2. Calculation of bulkhead partition stress-strain

Geometrical model of the bulkhead and mechanical testing scheme is presented in Figure 2. The bottom part of the bulkhead is attached to the base by bolting, the top shelf is in contact with the test rig; the width of the contact area is 6 mm.

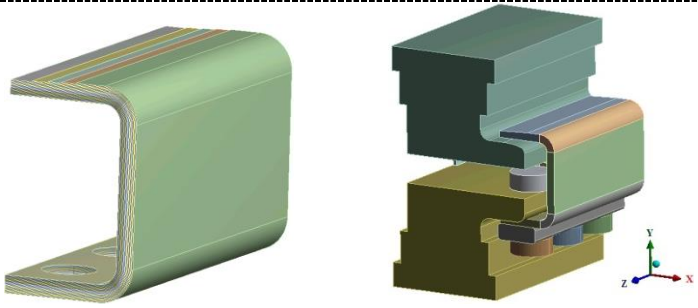

Figure 2. Geometrical model of the bulkhead (a); test rig with the bulkhead (b).

The mathematical formulation of the problem corresponded to the theory of anisotropic elasticity. The variational formulation of this statement is to find minimizer of the Lagrange functional with additional terms in the form of geometric Cauchy relations [1].

Strength evaluation of the bulkhead partition made of CFRP carried out by the criteria of ultimate stress. Strength of orthotropic material corresponds to satisfy the inequality system in each point of the structure:

$$S_{11}^- \le \sigma_{11} \le S_{11}^+,\ S_{22}^- \le \sigma_{22} \le S_{22}^+,\ S_{33}^- \le \sigma_{33} \le S_{33}^+,\ S_{12} \le \sigma_{12},\ S_{13} \le \sigma_{13},\ S_{23} \le \sigma_{23}, \quad (1)$$

where S_{ii}^+, S_{ii}^-, S_{ij} – the static strength of the material in tension, compression and shear, respectively, in the local coordinate system of the layer.

CFRP factor of safety for various components of stress state was estimated by the equation:

$$n_{ij} = \min_{\mathbf{r}\in V^{(1)}} \left(\frac{S_{ij}}{\sigma_{ij}(\mathbf{r})k} \right), \quad (2)$$

where k– coefficient of static strength reduction due to the various environmental factors.

Numerical simulation of mechanical testing carried out by finite element system with the use of ANSYS Workbench software. The bulkhead partition under consideration consists of 24 anisotropic plies of epoxy carbon fiber on the basis of Porcher 3692 fabric.

Technical elastic constants of the carbon fiber used in the numerical simulation was adopted both as the results of standard sample (for E11, E22, G12) testing, and on estimates of the research works [2, 3] (Table 1).

Table 1. Elastic properties of the material used in the calculation

Material	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{21}	ν_{13}	ν_{32}
CFRP	63.9	63.9	20.0	19.5	2.7	2.7	0.04	0.3	0.3

The multilayer bulkhead model completely illustrated all 24 structure layers. The constant load of 1.5kN was set at the low surface of the upper bulkhead rim. Surface area of loading corresponds to the contact area of bulkhead and the beam in laboratory tests at the appropriate load. The kinematic boundary conditions were set as restrain of displacement in all directions in the bolting of low bulkhead rim.

Contact between the bulkhead layers was considered to be ideal. Figure 3 illustrates the scheme of the boundary conditions.

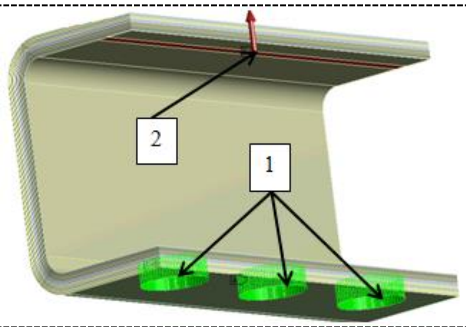

Figure 3. The scheme of boundary conditions: 1-bolting; 2 – load 1.5kH at the attachment of bulkhead and beam.

The computational mesh with prismatic type cells was generated to ensure better convergence of the solution and reduce errors in results. Within the construction and local mesh refinement sharp differences in geometric dimensions of the neighboring elements more than two times were not allowed. The maximum size of the element for each ply was 1mm, the minimum - 0.1mm. The total number of finite elements was about two million. Figure 4 shows a view of the finite element mesh.

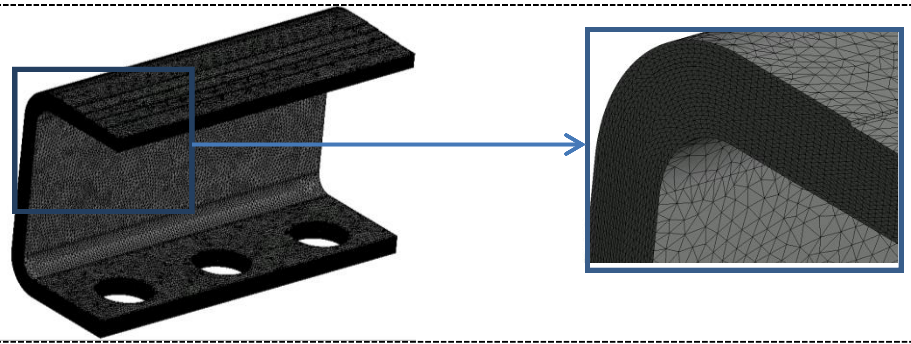

Figure 4. View of finite element mesh.

Stress distribution analysis in the warp and weft directions indicates that they reach the highest value around the inflexion zone. The maximum stress values arise on the surface of the upper layer. The maximum normal tensile stress along the warp is σ11 = 168.69 MPa, along the woof is σ22 = 42.55 MPa, and the maximum compressive stress is σ11 = -116.28 MPa, σ22 = -33.171 MPa. According to the loading nature the normal stress σ33 is the most dangerous and destructive for the given structure.

Normal stresses fields σ33 are shown in Figure 5. The maximum values of normal stress σ33 are observed in the central plies of the bulkhead in the upper and lower bending areas. Compressive stress σ33 = -22.72 MPa and tensile stress σ33 = 28.917 MPa.

Figure 5. Interlayer normal stresses in the regions: a- lower bending, b- upper bending.

Maximum values of shear stresses τ_{12} occur between the first and second layer at the upper inflexion point. The maximum value of the interlayer shear stresses τ_{13i} τ_{23} amounted 12.8MPa and 3.38 MPa, respectively. The maximum value τ_{12} of shear stresses in the reinforcement plane reached 22.9 MPa.

Evaluation of the static strength of bulkhead partition conducted by the maximum stresses criteria (1). Table 2 demonstrates the static strength of the carbon fiber values. The presented data have been obtained experimentally, except of strength properties across S33 layer, which estimates have been taken from research paper [4].

The coefficient *k* in the equation (2), considering the material static strength reduction due to the various environmental factors, was assumed to be 1.2, that corresponds to the requirements imposed at similar structures.

Table 2. CFRP static strength properties

Material	S^{+}_{11}, MPa	S^{-}_{11}, MPa	S^{+}_{22}, MPa	S^{-}_{22}, MPa	S^{+}_{33}, MPa	S^{-}_{33}, MPa	S_{12}, MPa	S_{13}, MPa	S_{23}, MPa
CFRP	809	804	809	804	56.4	128	150	77	77

The conducted evaluation gives the safety factor of carbon fiber plastic static strength in the bulkhead partition for stresses in the layers as follows:

- the factor of safety n_{11} is 4.8 with tensile stresses alongside fiber warp;
- the factor of safety n_{22} is 19.0 with tensile stresses alongside fiber woof;
- the factor of safety n_{33} is 1.6 on interlaminar normal tensile stresses ;
- the factor of safety n_{13} and n_{23} is 6 and 22.8 respectively on interlaminar shearing;
-the factor of safety n_{12} for shear stresses in reinforcement plane is 6.6.

Thus, the normal interlaminar stresses are the most dangerous in the structure of bulkhead from composite materials. These stresses determine the static strength of carbon fiber plastic bulkhead which factor of safety is 1.62. Structure failure is expected to be delamination type in the central plies of the structure, mainly in the region of bend.

Taking into account that the limit of static strength S_{33}^{+} for considered carbon fiber plastic is 56.4 MPa [4], the structure failure delamination type is expected to take place with a load of 2.93 kN.

3. Comparison of numerical modeling results and mechanical testing data

Stress-strain diagram analysis (Figure 6) obtained during the mechanical testing indicated that load, corresponding to the load bearing capacity of the structure makes up 3 kN. Further loading leads to partial delamination in the laminated bulkhead structure reducing stiffness and bearing capacity. After multiple delamination further laminate deformation of the bulkhead takes place at a relatively constant load.

X-Ray testing was conducted at three strain levels, characterizing the main stages of damage development (Figure 6). Monitoring was performed with one projection. The source and the X-ray receiver located that way to detect interlaminar cracks reliably [5]. Herewith, the exposure time was fifty seconds at an anode voltage of 40 kV and anode current of 40 mA. In order to fix the crack opening, the applied load at the time of measuring remained constant. X-ray images were obtained and processed within monitoring.

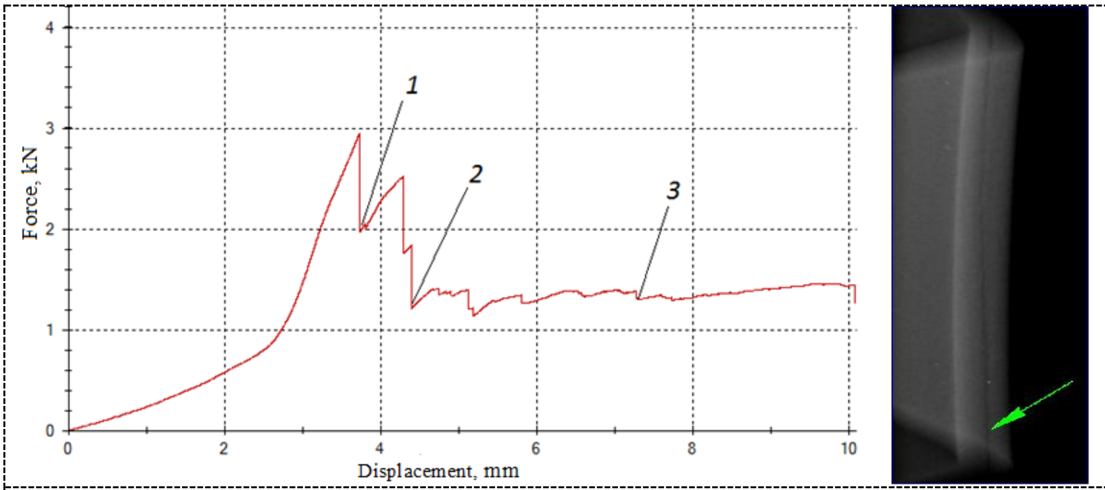

Figure 6. Tensile test diagram and X-Ray image of bulkhead (deformation 3.8 mm, load 3 kN).

Comparison of mathematical simulation and mechanical testing data revealed the difference between calculated and experimental values of the ultimate load limit in about 1%. High stresses regions in the central bend segments of layers coincide with areas of crack formation identified by radiography testing.

4. Conclusion

Within the conducted research the technique of stress-strain analysis and strength prediction for composite bulkhead partition was developed. The study was done in a general 3-D statement for anisotropic elastic body. Stress analysis in the layers of bulkhead revealed that interlaminar normal stresses are the most dangerous for structural strength. The structural failure is expected to start with delamination in bend regions in the central laminar of the structure.

Approbation of mechanical testing technique including microfocus x-ray is presented. This technique allows the precise determining of intelaminar cracking under different loads of structure.

Numerical results compared to experimental data obtained from mechanical testing of bulkhead section show that the difference between estimated and experimental values of the ultimate load is not more than 1%.

Acknowledgement

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