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Design-experimental analysis of strength of composite flange with a delamination defect

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Abstract. This paper presents the results of a computational and experimental study of the strength and rigidity of a composite flange with a defect in form of delamination. The locations of interlayer cracks at different loading levels are determined. It is shown that the L-shaped structurally similar element is destroyed by the delamination in the corner zone, without breaking the fibers of the layers with partial preservation of the bearing capacity. Based on the results of numerical simulation, stress and strain fields were obtained in and the strength of the structure was evaluated by the criterion of maximum stresses in layers. Analysis of stress fields showed that when testing flange samples, the most dangerous, determining the fracture initiation of the structure, are regular tensile interlayer stresses. The verification of the developed numerical model is carried out.

1. Introduction

Successful realization of the potential capabilities of polymer composite materials (PCM) in the creation of composite parts largely depends on the design and selection of the reinforcement scheme. The scheme of reinforcement and material laying of composite parts is chosen on the basis of strength calculations in accordance with the standards of strength and rigidity taking into account the features of the manufacturing technology. To calculate parameters of the composite flange units of aircraft engine parts, mathematical models should be used taking into account the inhomogeneity of the part, the anisotropy of the materials in layers and the presence of technological defects. It should be noted that a complex stress state arises in the nodes of the flange joints, high strength characteristics of the composite material in the reinforcement direction are not fully realized, the destruction of the composite flanges begins by delamination with loss of stiffness and bending of the structure [1, 2].

At the same time, the values obtained by the calculation require experimental confirmation. Carrying out experimental studies for such structures is individual and rather difficult task. So, if there are generally accepted standards for testing materials (GOST, ASTM, etc.), then for designs it is necessary to find techniques that must take into account all the features of the mechanical behavior of the object under study and ensure the possibility to use them in the experiment. In addition, it is also necessary to confirm physic-mechanical properties of the composite material used in the part [3, 4]. It should be noted that the composite material and the part are created in one technological process, while the properties of the material on standard samples may differ from the properties in the part, in addition, technological defects, including delamination, may arise during manufacturing [5, 6]. Therefore, the development of a methodology for computational and experimental research of stress-strain state and evaluation of the strength of a flange with a delamination defect is an actual task.

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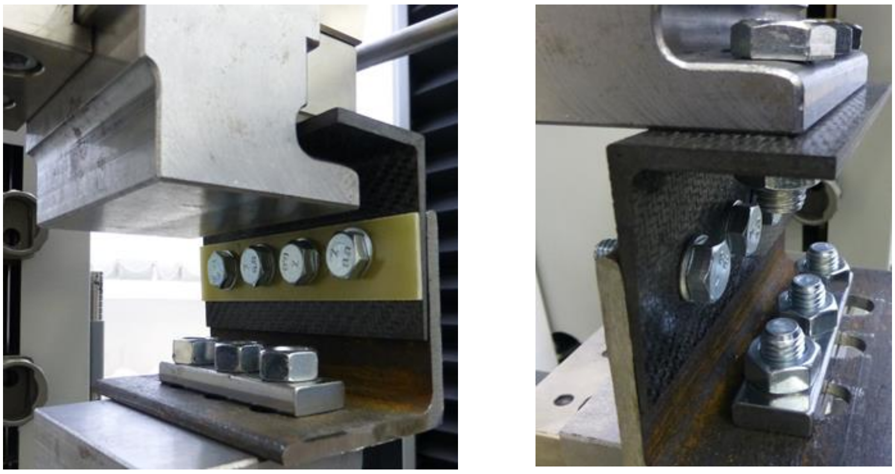
The object of this study is the carbon-fiber segment of the flange of the casing of an aircraft engine with a delamination defect. In this paper, the results of a design-experimental analysis of strength of a composite flange with a delamination defect are presented.

2. Mechanical tests

At the first stage of the study, the technique of mechanical testing of flange segments with a delamination defect and without it was tested. For that purpose, various dimensions of the object under study, different fixing methods were examined and specialized equipment was developed. The method for fixing the samples with the equipment on the testing machine is shown in figure 1 (a, b).



a b

Figure 1. Methods for fixing samples on the testing machine: a - rigid fixing of the lower part of the segment and application of a vertical tensile load to the upper shelf; b - rigid fixing of the lower part of the segment and application of a vertical tensile load to the upper rigidly fixed shelf.

Among the two options for fixing, the option was chosen with rigid fastening of the bottom of the segment and the upper shelf (Figure 1 b), because when using the first method of fixing (Figure 1 a), the upper cross head slipped along the inner surface of the frame shelf.

All mechanical tests of the samples were carried out at room temperature + 22°C and with a constant loading rate of 5 mm/min. During the tests, the loading force and movement of the grippers of the testing machine were recorded. In total, 5 samples without defects and 5 with a delamination defect were tested. For all samples, deformation diagrams were obtained in the "force-displacement" axle.

During the loading, after reaching a load of ~ 16 kN, acoustic signals were received - "clicks", after which there was a decrease in load. This indicates the appearance of interlayer cracks in the part. The appearance of the interlayer crack at the end surface of the sample was detected visually. Just as for a non-defective specimen, cracks are found in the upper corner zone of the inner surface segment near the layer #6. When the load increases, further cracking of the sample occurs. The tearing up of layers and fiber rupture does not occur, only the rigidity and bearing capacity of the damaged structure decreased. The sample breaks down, at a load of ~ 19 kN.

The tests of the flange segments made it possible to evaluate their strength and stiffness an indirect evaluation of the mechanical properties of the composite material was made in the presence of a delamination defect.

In all tested samples, a mechanism of loss of the load-carrying capacity has been determined, locations and indicative sizes of interlayer cracks occurring at different load levels have been identified. In all samples, cracks were found in the upper corner zone of the inner surface segment in the 5th-7th layer region. Analysis of the results obtained from the samples with a defect revealed that they are destroyed by delamination in the corner zone, without breaking the fibers of the layers while maintaining 86.11% of the load-carrying capacity, for samples without defects this value was about 65%.

3. Numerical simulation

To calculate the stress-strain state of the flange, a three-dimensional model was constructed using the Siemens NX and Fiber SIM CAD systems. In terms of design, in the segment of the flange, a long base can be found, with four holes for the bolted connection and a shelf, which also has three holes equidistant from each other. According to the testing scheme, the lower base is fixed to the steel equipment with four bolts, the shelf is attached to the upper steel traverse of the testing machine. The delamination defect was set in the central part of the bend between layers 10 and 11, in the form of a circle with a radius of 5 mm and a thickness of 0.02 mm.

The mathematical formulation of the problem corresponded to the theory of elasticity of an anisotropic body. In the variational formulation this problem consists of finding the minimum of the Lagrange functional with additional conditions in the form of geometric Cauchy relations [7].

The boundary conditions for the computational model include the prohibition of axial displacements along X and Y for the bolt joint holes of the upper flange and a 6kN tensile load applied to the inner surfaces of the holes. For the holes for the bolted connection of the equipment and the long base of the flange, a restriction of movements in all directions is specified. For the outer surface of the tooling, the movable joint defines a boundary conditions. The contact between the layers of the flange was considered ideal. The considered boundary conditions correspond to the conditions for laboratory mechanical tests of the segment of the flange.

Evaluation of the strength of the flange segment from PCM was carried out by the criterion of maximum stresses. The strength of the orthotropic material corresponds to the satisfaction of the system of inequalities at each point of the part:

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

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

The safety factor of carbon fiber reinforced plastic (CFRP) on different components of the stress state was estimated from the equation:

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

where k is the coefficient of reduction of the static strength of the material due to the influence of various environmental factors.

Discretization of the model was carried out using the spatial tetrahedral ten nodal finite elements SOLID187 with nonlinear approximation of the displacement function The total number of analyzed elements was 5 million.

Based on the results of numerical simulation of mechanical tests of the flange, stress and strain fields were obtained. Analysis of the axial displacement fields of the flange showed that the central part of the flange along the Z axis has maximum deviation from its original condition. The maximum displacement along the Y axis was 0.51 mm. The obtained values of the maximum deflection in the center of the flange shelf are in good agreement with the results obtained during laboratory tests.

Analysis of the distribution of stress fields in layers' reinforcement directions along the base and weft in the local coordinate system shows that they reach maximum value in the vicinity of the zone of layers' bend. The zones of concentration of these stresses are near the bends of the layers, in the central part of the flange. In this case, the maximum values of these stresses arise on the surface of the first and fifth layers. The maximum normal tensile stresses along the base are σ_{11} = 248.86 MPa, along the weft σ_{22} = 217.17 MPa, and the maximum compressive stresses are σ_{11} = -248.08 MPa, σ_{22} = -251.04 MPa (Figure 2 a, b).

The fields of normal interlayer stresses and tangent stresses in the plane σ_{33} and τ_{12} are shown in figure 3 (a, b). The maximum values of the normal interlayer stresses σ_{33} are observed between the first

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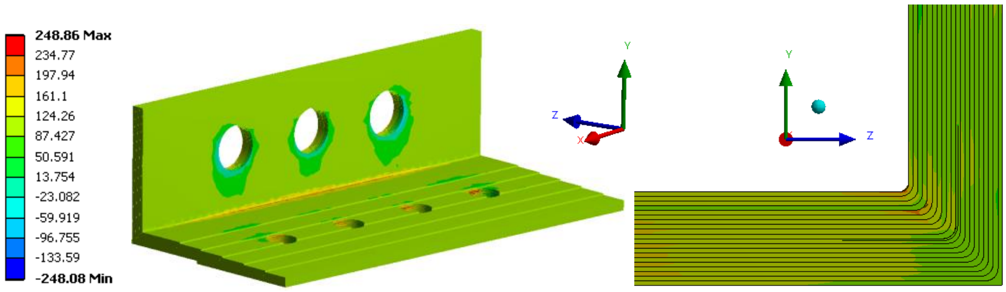
and second layers of the central part of the bend of the CFRP layers, as well as between the 5th and 6th layers. The maximum value of the tensile interlayer stresses σ_{33} was 17.40 MPa. The compressive stresses reach an absolute value of -14.05 MPa.



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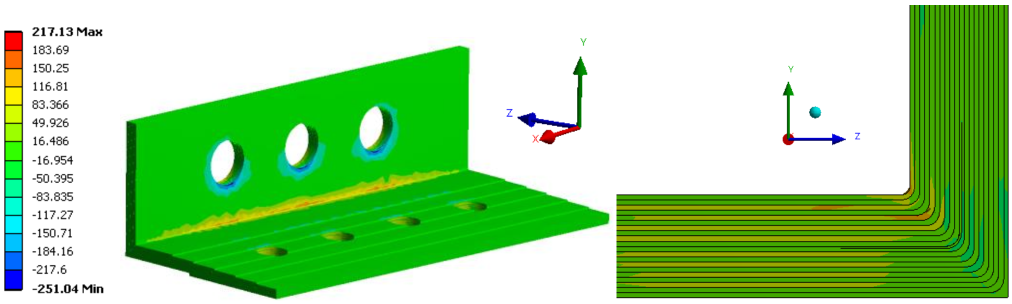
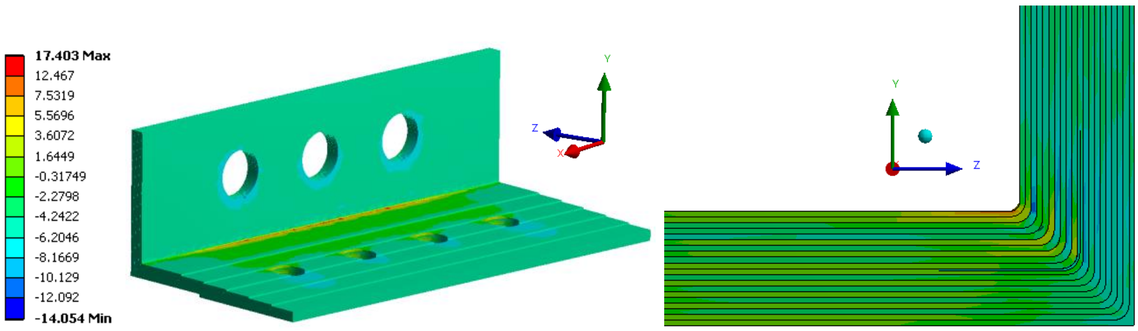
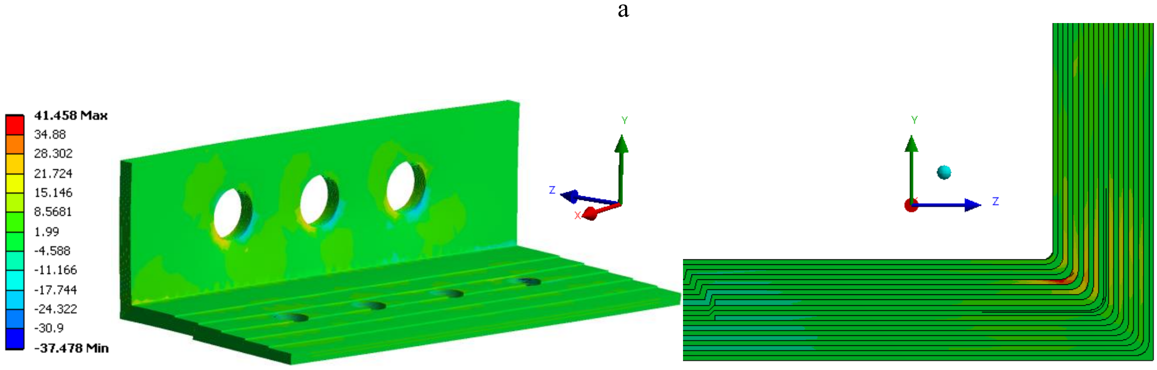


b

Figure 2. Distribution of stress fields along the base σ_{11} (a) and along the weft σ_{22} (b) in the isometry and in longitudinal plane of flange symmetry [MPa].



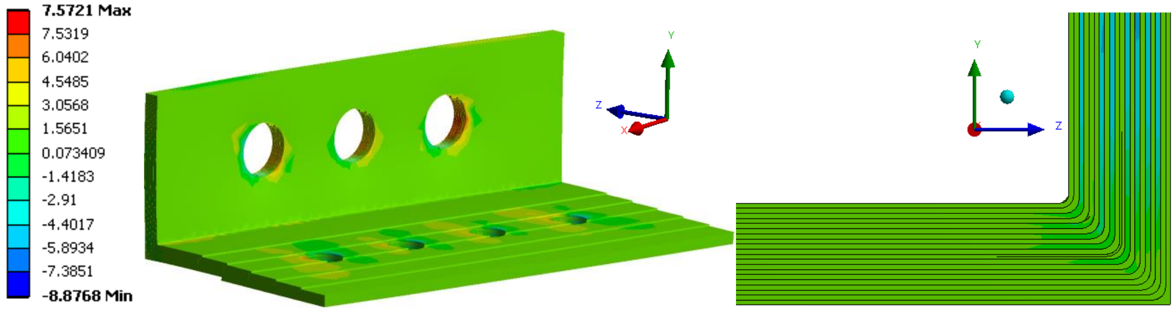
a



b

Figure 3. The distribution of interlayer normal σ_{33} (a) and tangent τ_{12} (b) stresses in isometric view and longitudinal plane of flange symmetry [MPa].

For tangent stresses τ_{13} and τ_{23}, concentrations are observed in the central layers near the bolt holes for flange fixing. The maximum value of the interlayer tangent tensile stresses τ_{13} and τ_{23} is 7.57 and 13.73 MPa, respectively. The maximum value of the interlayer compressive stresses τ_{13} and τ_{23} is 7.57 and 13.73 MPa, respectively (Figure 4 a, b).



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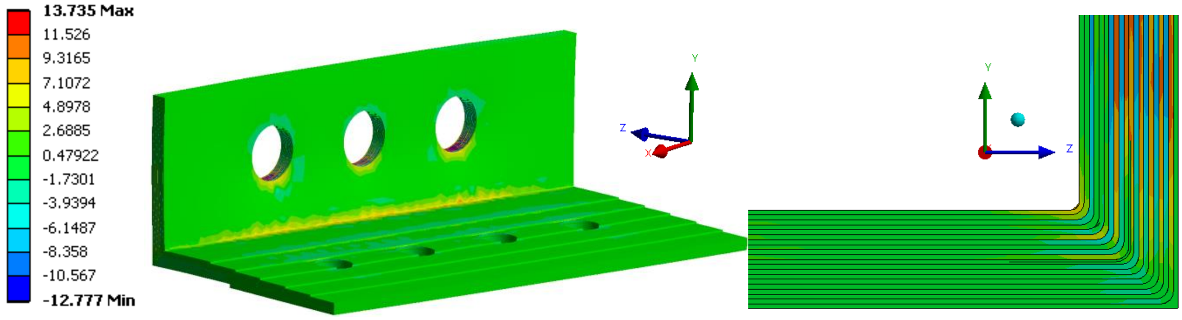

b

Figure 4. Distribution of interlayer tangent stresses τ_{13} (a) and τ_{23} (b) stresses in isometry and in the longitudinal symmetry plane of the flange [MPa].

The static strength of the flange segment was evaluated using the maximum stress criterion (1). The values of the static strength of CFRP are shown in Table 1. The presented data was obtained experimentally, with the exception of the strength characteristics crosswise of the S_{33} layer, the values of which were taken from [8]. The coefficient k in equation (2) taking into account the decrease in the static strength of the material due to the influence of various environmental factors, was taken to be 1.2, which corresponds to the requirements imposed on structures of this type.

Table 1. 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 evaluation of the strength of a composite flange with a defect under calculated loads (Table 2) revealed that the most dangerous in the design of the flange from PCM are normal interlayer stresses. The margin of the static strength of the carbon-fiber flange is defined by these stresses and equal to 2.59. It can be expected that the destruction of the structure will begin by the delamination in the regions of the bending in the central layers of the structure in the region where the defect is located. It can be predicted that the damage of the structure will occur at a load of 15.54 kN.

Table 2. Coefficients of static strength of CFRP flange design.

Material	n_{11}	n_{22}	n_{33}	n_{12}	n_{13}	n_{23}
CFRP	3.72	3.26	2.59	3.61	10	5.72

4. Conclusion

Thus, in this work, samples of flanges from PCM without defects, as well as with delamination defects were tested. In total, 10 samples were tested. The locations of interlayer cracks at different loading levels are determined. It is shown that the structurally similar element of the L-shaped profile is damaged by the delamination in the corner zone, without breaking the fibers of the layers with partial preservation of the bearing capacity. For samples with defects in laboratory tests, characteristic features of mechanical behavior were revealed: a low difference between the delamination load and fracture load was found (13.89%), while for samples without defects, the difference was 35%.

Based on the results of numerical simulation of mechanical tests of the flange samples, stress and strain fields in the layers were obtained and the strength of the structure was evaluated by the criterion of maximum stresses in the layers. Analysis of stress fields showed that when testing flange samples, the most dangerous, determining the beginning of the destruction of the structure, are normal tensile interlayer stresses. Calculations on the developed model showed that the destruction of the structure will occur at a load of 15.54 kN. A comparison with the results of the tests showed that the calculated value of the critical load of the beginning of the delamination is 10.41% larger than the observed value in the experiment.

Thus, mathematical modeling using the structural phenomenological model allowed to determine the rigidity of the structure, the critical load and the region of the appearance of the delamination recorded during the laboratory tests. The difference in the calculated and experimental data can be caused both by the indicative value of the strength of the laminate composite for the layer peeling-off used for estimating the strength of the structure, and by the scatter of the characteristics of materials observed in laboratory tests.

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