THE STUDY OF THE MECHANICAL BEHAVIOR OF COMPOSITE BULKHEAD FOR DEVELOPMENT OF A METHODOLOGY OF EFFICIENT DEFECTS IDENTIFY USING MICROFOCUS X-RADIOGRAPHY

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Abstract
In this paper, we consider the method of mechanical impact on a composite structural-like frame with the purpose of opening closed interlayer cracks to a minimum size that will allow to detect this defect by the X-ray diffraction method of nondestructive testing, provided that loading does not lead to the formation of new defects and further growth of existing defects.

1. Introduction

At present, polymer composite materials are widely used in the construction of modern aviation equipment. When creating responsible structures, it is necessary to take into account a number of key features, such as low interlayer strength, the possibility of various defects at the stage of their manufacture, and their development during subsequent operation. To detect emerging defects, one of the promising means of nondestructive testing is the X-ray method.

X-ray inspection of parts made of composite materials in comparison with their metal counterparts is a more complicated process. This is due to the low density of the material, significant structural heterogeneity, and a small difference in defect density with the matrix and filler of the starting material. In addition, closed interlayer cracks or bundles that have a planar character of defects are observed in a number of designs. To detect this type of defect by X-ray diffraction, it is necessary to apply a load that will open the existing crack to the required value. At the same time, laboratory loading should not lead to the formation of new defects and further growth of existing defects.

The object of the study in this work is the "U" - shaped segment of the composite frame made of CFRP using the technology of impregnation with resin under pressure (RTM) of dry layers of carbon fabric laid out in a special form-building tooling. In previous experiments it was shown that such a part under the impact of operational loads is destroyed by delamination in the corner zone, without breaking the fibers [1]. After removal of the load, the interlayer cracks are closed, which prevents their identification by the X-ray method. As an example, Figures 1, 2 show the frame segment after carrying out mechanical tests in a pre-loaded and unloaded condition.

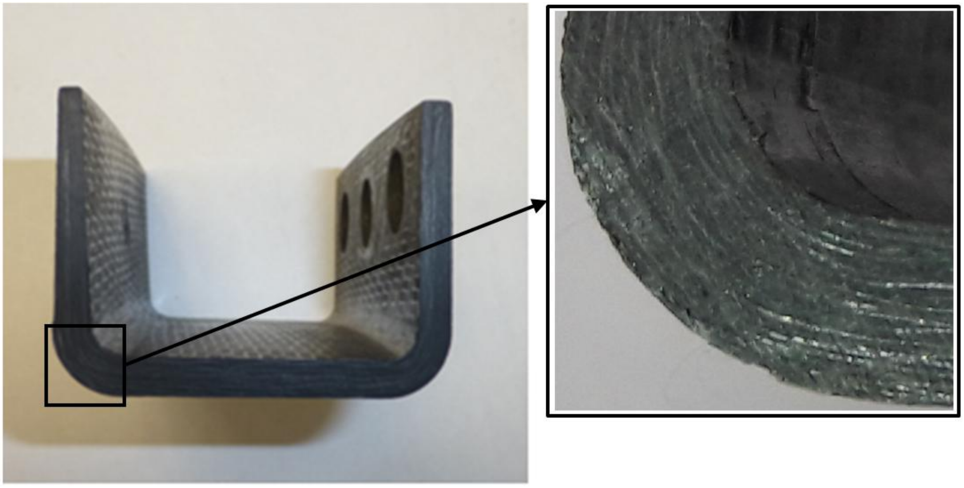


Figure 1. Composite frame segment after mechanical testing in unloaded state.

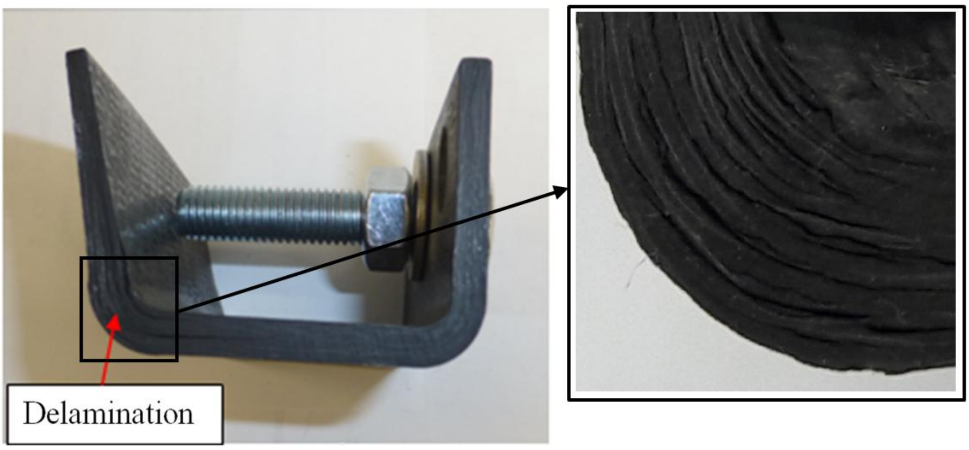


Figure 2. Composite frame segment after mechanical tests in the forced-loaded state.

In the process of X-ray studies aimed at determining the minimum crack opening sizes in the frame samples, it was shown that in an unloaded state all cracks are closed, which does not allow their identification. When the structure is being loaded, cracks are opened, so that they can be recognized and parameterized. As an example, Figures 3 and 4 show X-ray images of the frame segment in an unloaded and forced-loaded state.

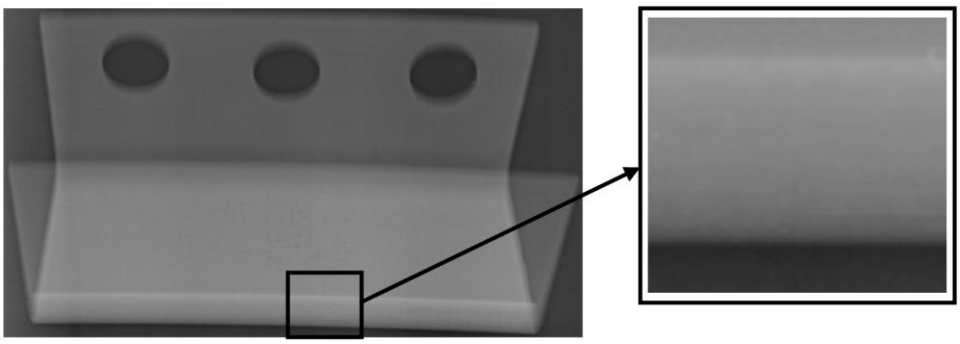


Figure 3. X-ray image of the frame segment in an unloaded state.

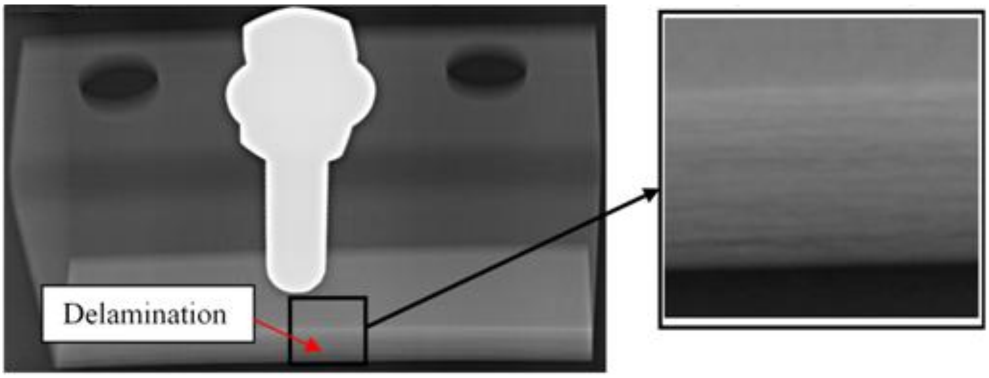


Figure 4. X-ray image of the frame segment in the forced-loaded state.

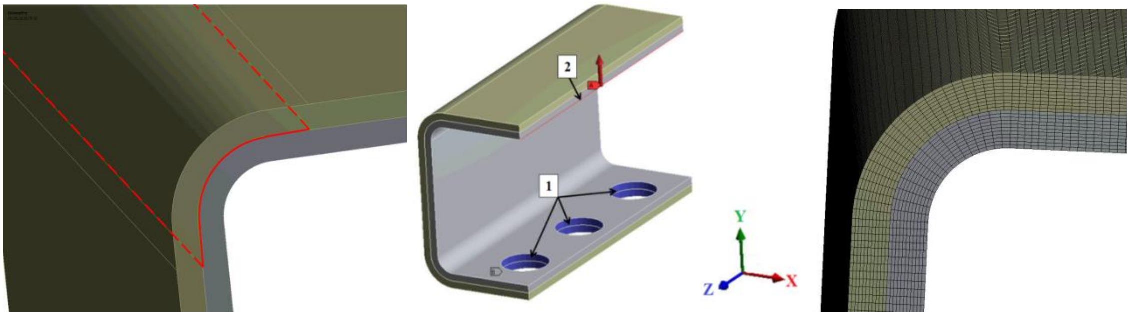
It was found experimentally that the minimum size of crack opening necessary for reliable detection of defects by the method of microfocus radiography is about 0.1 mm.

At the same time, there arises the need to calculate the stress-strain state and estimate the strength of the frame under laboratory loading, which provides the indicated crack opening.

2. Statement of the problem of calculating the stress-strain state of a composite frame segment

A segment of a composite frame with a length of 100 mm and a thickness of XX mm was calculated, made of carbon fiber reinforced plastic based on an equally strong woven filler and an epoxy binder using RTM technology. For the numerical calculation of the segment, its three-dimensional computer model was developed with an explicit description of 21 layers of the frame. Such a model makes it possible to estimate the interlayer normal and shear stresses that determine the appearance and development of delamination in the investigated segment. In the developed model of the frame segment, a defect was made, which describes the interlayer delamination. In the entire volume of the construction, contact between the layers of the composite material was considered ideal, contact conditions without friction were set in the defect zone between the layers. The defect was set in the zone of inflection of the layers between the 10 and 11 layers in the upper part of the segment along its entire length, the width of the defect b_0 was assumed to be 10 mm, 15 mm and 20 mm (Fig. 5, a). Such a defect can appear when the technological process of fabrication of the frame is violated or because of prolonged operation, similarly, the destruction of frame occurs in laboratory tests [1].

The task was to calculate the stress-strain state and evaluate the strength of the frame segment under mechanical stress, which causes the closed delamination to open. This makes it possible to determine the parameters of mechanical loading on the frame in the process of non-destructive testing to ensure the correct detection of a defect without its further spread and formation of new defects. In this case, the loading parameters should ensure a maximum opening of the delamination by a value of approximately 0,1 mm. As a mechanical load in the present calculations, a uniformly distributed force along the lower edge of the upper shelf of the frame segment was considered. At the same time, on the lower shelf in the places of the bolted connection of the lower shelf of the frame segment, there was no movement (Fig. 5, b).



a) b) c)

Figure 5. The design diagram of the frame segment
a – defect location area; b – border conditions: the fixing surfaces (1) and the boundary of the distributed force application (2); c – finite element mesh.

Table 1. Elastic properties of composite material.

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}
Equal-strength carbon fiber reinforced plastic	63,9	63,9	5,0	19,5	2,7	2,7	0,04	0,3	0,3

Note: E_{11} - modulus of elasticity along the base; E_{22} - modulus of elasticity across the base (along the weft); E_{33} - module across the plane of the layer; G_{12}, G_{13}, G_{23} - shear moduli; ν_{21}, ν_{13}, ν_{32} – the Poisson ratios.

Table 2. Strenght properties of composite material.

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
Equal-strength carbon fiber reinforced plastic	809	804	809	804	44	128	150	77	77

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

The nonlinear contact three-dimensional problem of mechanics of inhomogeneous media was solved by finite element method (FEM) using the ANSYS Workbench package. Deformation of the layers of carbon fiber in the structure was considered elastic, the elastic and strength properties of CFRP are given in Table 1, 2 [2-5]. The loading was carried out in steps, the initial value of the total load was assumed to be 100 N, with its subsequent increase to 2500 N with a step of 100 N. At each loading step, the stress-strain state of the frame segment was analyzed, the maximum opening of the specified delamination was determined, and the static strength segment by the criterion of maximum stresses. The calculation was carried out using solid-state three-dimensional 8-node elements Solid185. In this case, the dependence of the FEM solution on the grid density was investigated. The maximum value of the normal stresses at the boundary layer was estimated, the maximum size of the element in this neighborhood was chosen in such a way that the change in these stresses did not exceed 5% with a subsequent reduction in the size of the element (Fig. 5, c). The total number of finite elements used for segment sampling was of the order of 10^6, the minimal characteristic dimension of the element in the area of the delamination was of the order of the layer thickness.

3. Analysis of the results of the calculation of the composite frame segment

A general analysis of the stress-strain state of the frame segment at a given loading showed that the stresses in the structure are uniform and small, except for the region of the delamination. The safety factor for normal and shear stresses in the plane of the layers, as well as tangential interlaminar stresses, is more than 4 times in the entire loading range from 100 N to 2500 N.

The most dangerous are interlayer tear-off stresses σ_{33}, the maximum values of which are observed in the area of bending of the layers at the boundary of the delamination (Fig. 6). As the load increases, these stresses increase, in two calculated variants for the delamination width b_o=10 mm and 15 mm stresses σ_{33} exceed the limit values S_{33}^+=44 MPa (table 3) at a load of more than 1,2 kN and 1,5 kN respectively. In this case, the maximum opening of a given delamination for b_o=15 mm is h=0,095 mm, and for b_o=10 mm h=0,062 mm (table 3). Opening of the delamination h=0,1 mm, required for detection by means of X-ray inspection, width b_o=10 mm and 15 mm is possible to achieve only at a load exceeding the critical value.

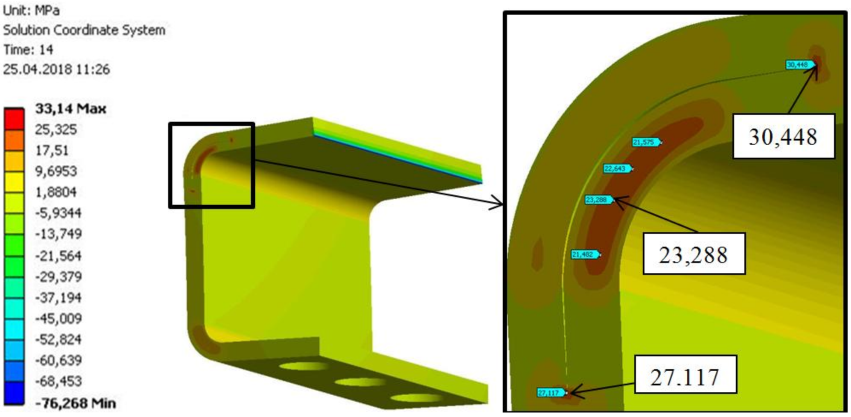


Figure 6. Distribution of interlayer normal stress σ_{33} (MPa) in the defect location area at a load of 1.3 kN.

Table 3. Results of numerical analysis.

Given defect width b_o, mm	Current maximum defect opening h, mm	Applied load, kN	Maximum interlayer stresses σ_{33}, MPa
10	0,1	2	75,07
	0,059	1,1	42,2
15	0,1	1,6	48,7
	0,09	1,4	42,6
20	0,1	1,3	30,4
	0,13	1,7	42,98

For a calculated variant of a frame segment with a defect width b_o =20 mm required opening of the delamination h=0,1 mm is achieved at the load of 1,3 kN. In this case, the maximum interlayer normal stresses σ_{33} on the boundary of the delamination reach the value of 30,4 MPa, that is less than the strength limit S_{33}^{+}=44 MPa in 1,4 times (Fig. 6). The critical load value for the considered variant is 1,7 kN, while the maximum opening of the delamination reaches a value of h = 0,13 mm. Thus, the chosen method of loading the frame segment allows a safe crack opening up to the required minimum value for its detection by X-ray inspection.

4. Conclusion

The conducted researches have shown the possibility of safe opening of delaminations with a width of more than 20 mm in the segment of the composite frame for detection by X-ray inspection. To identify delaminations of less than 20 mm, additional studies are needed. At the same time, it is of interest to improve the software and hardware and methods of nondestructive testing, which allow detecting delaminations with a maximum opening amount of no more than 0,05 mm.

Acknowledgments

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