Influence of a Delamination Defect Location on the Operating Life of a Multi-Layered Composite Sample

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Abstract. In the framework of this research, the authors proposed an algorithm for predicting the residual life of structures made of polymer composite materials (PCM) using the structural-phenomenological model. To assess the residual life of PCM structures under cyclic loading, it was proposed to use the approach of explicit description of the adhesive layers destruction process. In accordance with the developed algorithm, in the process of cyclic loading in the adhesive layers, the level of damage was recorded; upon reaching a critical damage level, the adhesive layers destruction was simulated. The algorithm was tested on sample structures with a defect in the form of delamination and without defects. A numerical study of the delamination defect location influence at the onset of fatigue failure of model structures was carried out.

1. Introduction
Composite materials are widely used in the construction of aircraft structures. The use of composites can reduce weight, improve manufacturability and, in some cases, reduce costs. During operation, parts and components of the aircraft are subjected to various kinds of dynamic loads. As a result of prolonged exposure to dynamic loads in composite structures, damage accumulates, which, in the future, can lead to fatigue failure [1]. Therefore, an important point in the design and development of PCM aircraft structures is forecasting of structure operating life, which should be based on new mathematical models of the mechanics of composite materials.

A review of publications on the problem of modeling the fibrous composite materials fatigue strength [2-5] made it possible to obtain an extensive list of developed models - about 60. These models can be divided into three main groups: a) models based on the Palmgren-Miner hypothesis, b) phenomenological models that include two subclasses: residual strength models and residual stiffness models, c) - successive damage models, including models based on fatigue life, damage increase models and damage accumulation models.

Models based on the Palmgren-Miner hypothesis introduce a damage parameter without physical interpretation using the effects of fatigue damage accumulation. Most of these models were originally used for metallic materials. The nonlinear dependence of the long-term strength on such parameters as the load sequence and the level of fatigue stresses is taken into account. They include models such as the Macro and Starkey model [6] (modified linear law of static damage summation, 1954), Owen and Howe (based on observations of the cracks development in fiberglass, 1972), Hashin and Rotem (1978,) and others. Models based on the linear Miner rule still play a very important role in the study of composite materials fatigue strength under the action of a variable amplitude load.
Of particular interest are phenomenological models that relate the process of material fatigue damage to physically measurable quantities such as residual stiffness or strength. For most phenomenological models, the material parameters should be experimentally determined for each configuration of the layers package (laminate). The aim of the residual strength models is to assess the drop in static strength after a certain number of load cycles [7–9]. Residual stiffness models were developed on the basis of non-destructive residual stiffness measurements during long-term loading, which is the main advantage over residual strength models.

In the framework of this work, a mathematical formulation of the problem and an algorithm for the sample resource numerical prediction using the structural-phenomenological model were proposed. A numerical study of the delamination type defect location influence on the values of the model structures minimum operating time to failure was carried out.

2. Numerical model
The object of this study was a multilayer composite sample (Figure 1) made by autoclave molding. The sample consisted of 33 carbon fiber reinforcing layers with a reinforcement scheme $[0^\circ/45^\circ]$. Lay up of the layers was carried out to the central layer with a reinforcement scheme 0. Thus, all even layers had an angle of $[45^\circ]$, uneven layers - $[0^\circ]$. The number of layers in the sample corresponds to the number of layers in the composite flange joints used in aircraft products. The geometric dimensions of the sample are as follows: length 170 mm, width 35 mm, height 6.5 mm.

![Figure 1. Appearance of a multilayer composite sample.](image)

To predict the operating life of a multilayer PCM sample, the algorithm presented in [10, 11] was used. The algorithm is based on the finite element method using kinetic equations with a scalar damage function.

In accordance with the developed algorithm, the level of damage in the adhesive layers during cyclic loading was recorded. Upon reaching a critical level of damage, the destruction of adhesive layers was modeled. In the destroyed elements of the adhesive layers, the elastic constants were assumed to be approximately equal to zero (multiplied by $10^{-6}$), which corresponds to the interlayer destruction of the layered package. To describe the damage accumulated in an elementary volume in the vicinity of a certain material point in the structure, we used the scalar function of time $\psi(t)$. It is believed that the $\psi(t)$ function takes values on the interval $[0,1]$. Moreover, the $\psi=0$ value corresponds to the case when there are no damages, the $\psi=1$ value corresponds to the level of damage at which the destruction of the elementary volume occurs. It was assumed that at the initial time $t=0$ for all points of the construction under consideration the value was $\psi=0$. The $\psi=1$ state corresponds to such a moment of time or the number of loading cycles $N$ when a certain strength criterion is violated, depending on the stress state at a given point $\sigma_{ij}$ and the material constants $S_{ij}(N)$.

We write the kinetic equation for damage accumulation, which determines the $\psi(N, \sigma_{mn})$ value, in accordance with the linear rule for summing damage:

$$\psi(N, \sigma_{mn}) = \sum_{k=1}^{N} \frac{1}{N_b(I_{k})},$$

where $N_b$ is the function of the number of cycles to failure, $I_{k}$ is the stress intensity in the $k$-th finite element.

The loading is assumed to be cyclic, symmetrical with an amplitude corresponding modulo the maximum static load. The influence of dynamic effects were neglected, the stress and strain fields in
the structure at amplitude loads were considered equal to the corresponding fields under static loads. The strength of the adhesive layer under cyclic loads was taken according to [6]. Based on the given experimental data, a two-link fatigue strength curve was constructed, approximated by the equations:

\[
\begin{align*}
\log[N_b(\sigma_i)] &= -0.0684 \cdot \sigma_i + 9.18, & \sigma_i < 42 \text{ MPa}, \\
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\end{align*}
\]

For each layer in each finite element, we obtain a nonlinear equation for \( N_{bj} \). After the solution the number of cycles before the destruction of each element \( N_{bj} \) was determined. The minimum value \( N_{b\Sigma} \) for all finite elements is the number of cycles until the first act of fatigue failure in the structure \( N_{b\Sigma} \). After this, it was assumed that the corresponding element was destroyed and the elastic moduli were reduced in it.

The remaining elements received damage, which was calculated by the formula corresponding to the kinetic equation (1)

\[
\psi_j^1 = \frac{N_{b\Sigma}^1}{N_{b\Sigma}^1}.
\]

For the previous amplitude external load, a new stress-strain state of the structure with one damaged element \( q \) was calculated. Next, we determined the number of cycles before the destruction of each \( N_{b\Sigma}^2 \) element at the current stresses \( \sigma_{ij} \). Failure in this case will occur in the element where the damage, taking into account the value already accumulated in the previous step (\( \psi_j^\Sigma \)), will be equal to unity:

\[
\psi_j^\Sigma + \psi_j^2 = 1.
\]

Damage at the current (second) step was determined by the formula:

\[
\psi_j^2 = \frac{N_{b\Sigma}^{2\text{add}}}{N_{b\Sigma}^2},
\]

where \( N_{b\Sigma}^{2\text{add}} \) - the additional number of operating cycles in the second step. Substituting (3) into (4), we calculate \( N_{b\Sigma}^{2\text{add}} \) for each element, the minimum value of which is an additional operating time of the structure before the second act of destruction in the corresponding element. The total number of structure life cycles was calculated by the formula

\[
N_{\Sigma}^2 = \min_j (N_{b\Sigma}^{2\text{add}}) + N_{\Sigma}^1.
\]

The tensor of elastic modules for the destroyed element was reduced, and for the remaining unresolved elements, the accumulated damage was calculated

\[
\psi_j^\Sigma = \psi_j^1 + \frac{\min_j(N_{b\Sigma}^{2\text{add}})}{N_{b\Sigma}^2}.
\]

The next step begins with the calculation of the stress strain state for the structure with two damaged elements.

The calculation of a structure fatigue life using this algorithm can be carried out until the structure exhausts its bearing capacity for amplitude load, determined by the static tensile strength, or by a critical decrease in the structure rigidity, or by the formation of a given critical value damage zone. The final \( N_{\Sigma} \) value is the adjusted value of the structure fatigue life compared to the estimate obtained by the weakest link criterion.

One of the common types of defects in the manufacture of layered composite materials is delamination. In this work, we researched the influence of the location of the defect in the form of delamination on the life of a multilayer composite sample. The defect was located in the adhesive
layer, between the reinforcing layers. Numerical forecasting of the operating life in the ANSYS Mechanical software package was considered using the software developed by the authors on APDL.

The problem was solved in an elastic three-dimensional formulation. The analogy of cantilever fixing was used. From one end at a distance of 35 mm, nodes were identified that were limited by the displacements in the direction of the X, Y, Z axes: \( U_x = 0, U_y = 0, U_z = 0 \). The amplitude alternating load \( U_z = U_{z0} \) was set to the edge of the opposite end. The boundary conditions are shown in Figure 2.

![Figure 2. Scheme of boundary conditions.](image)

The “delamination” defect was modeled as a region with a length of 10 mm, a width of 15 mm, and a height equal to the adhesive layer thickness, with reduced elastic properties (close to zero) [12]. Figure 3 shows the finite element model and the location of the defect in the adhesive layer.

![Figure 3. The location of the defect in the finite element model of a multilayer composite sample.](image)

The parameters of the research were the distance of the defect location from the edge of the sample (l) and the adhesive layer number (t). The l parameter took the following values: 25, 35, 45, 55, 65, 75, 85 (mm). The numbers of adhesive layers (t) considered were: 1, 4, 7, 10, 13, 16, 17, 20, 23, 26, 29, 32.

### 3. Numerical simulation results

At the first stage, a research was made of the defect location influence at the onset of fatigue failure and stress strain state. As a result of the numerical calculations, the values of the maximum stress intensities \( \sigma_i^{\text{max}} \) (Table 1) and the minimum number of run-in to failure \( N_b^{\text{min}} \) at the first loading step (Table 2) were obtained for the examined adhesive layers and defect locations, where t is the number of the adhesive layer, \( i \) is the distance from the defect fixing.

| Distance of the defect location from the edge of the sample (l) | 25  | 35  | 45  | 55  | 65  | 75  | 85  |
|---------------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| 1                                                             | 25.8| 26.24| 25.8| 25.8| 25.8| 25.8| 25.8|
| 4                                                             | 25.8| 26.51| 25.79| 25.8| 25.8| 25.8| 25.8|
| 7                                                             | 25.8| 30.85| 31.22| 29.17| 28.19| 27.6| 27.16|
| 10                                                            | 25.8| 34.53| 36.45| 34.53| 33.65| 33.25| 33.01|
| 13                                                            | 25.8| 36.84| 39.99| 38.25| 37.4| 37.09| 36.95|
| 16                                                            | 25.8| 37.68| 41.37| 39.74| 38.9| 38.63| 38.53|
| 17                                                            | 25.8| 37.68| 41.37| 39.74| 38.9| 38.63| 38.53|
| 20                                                            | 25.8| 36.84| 39.99| 38.25| 37.4| 37.09| 36.95|
| 23                                                            | 25.8| 34.53| 36.45| 34.53| 33.65| 33.25| 33.01|
| 26                                                            | 25.8| 30.85| 31.22| 29.17| 28.19| 27.6| 27.16|
| 29                                                            | 25.8| 26.51| 25.79| 25.8| 25.8| 25.8| 25.8|
| 32                                                            | 25.8| 26.24| 25.8| 25.8| 25.8| 25.8| 25.8|

Table 1. Values of maximum stress intensities \( \sigma_i^{\text{max}}, \text{MPa} \) in the adhesive layers.
Table 2. The minimum values of run-in \((N_b^{\text{min}} \cdot 10^6)\) at the first loading step.

| Adhesive layer number \((t)\) | Distance of the defect location from the edge of the sample \((l)\) | 25 | 35 | 45 | 55 | 65 | 75 | 85 |
|-------------------------------|-------------------------------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| 1                             | 25.986                                                      | 24.265 | 25.995 | 25.991 | 25.989 | 25.989 | 25.989 |
| 4                             | 25.986                                                      | 23.245 | 26.029 | 26.005 | 25.996 | 25.993 | 25.988 |
| 7                             | 25.986                                                      | 11.750 | 11.072 | 15.294 | 17.852 | 19.576 | 21.005 |
| 10                            | 25.986                                                      | 6.578  | 4.861  | 6.578  | 7.56  | 8.045  | 8.351 |
| 13                            | 25.986                                                      | 4.574  | 2.785  | 3.662  | 4.184 | 4.393  | 4.492 |
| 16                            | 25.986                                                      | 4.005  | 2.238  | 2.896  | 3.301 | 3.448  | 3.504 |
| 17                            | 25.986                                                      | 4.005  | 2.238  | 2.896  | 3.301 | 3.448  | 3.504 |
| 20                            | 25.986                                                      | 4.574  | 2.785  | 3.662  | 4.184 | 4.393  | 4.492 |
| 23                            | 25.986                                                      | 6.579  | 4.861  | 6.578  | 7.56  | 8.045  | 8.351 |
| 26                            | 25.986                                                      | 11.751 | 11.072 | 15.294 | 17.852 | 19.576 | 21.005 |
| 29                            | 25.986                                                      | 23.246 | 26.029 | 26.005 | 25.996 | 25.993 | 25.989 |
| 32                            | 25.986                                                      | 24.266 | 25.995 | 25.991 | 25.989 | 25.989 | 25.989 |

Based on the results of numerical calculations presented in Table 2, the dependences of the minimum operating time to failure at the first loading step on the defect location were constructed (Figure 4, a). According to the results presented in Table 1, the dependences of the maximum stress intensities in the adhesive layers \((\sigma_l^{\text{max}})\) on the delamination defect location \((l)\) in a multilayer composite sample were constructed (Figure 4, b).

![Figure 4](image)

**Figure 4.** The dependence of the minimum operating time to failure at the first loading step on the defect location (a), the dependence of the maximum stress intensities in the adhesive layers on the defect location (b).

An analysis of the obtained dependences revealed that the minimum run-in values until failure \((N_b^{\text{min}} = 2.237854 \cdot 10^6)\) are observed when the delamination defect is located in the central layers \((t = 16, 17)\) of the multilayer sample at a distance \(l = 45\) mm from the sample edge. Since when the defect is located 25 mm from the edge of the sample, the values of the minimum operating time to failure are equal, it can be argued that in the absence of defects in the sample under current loading conditions, \(N_b^{\text{min}} = 25.98616 \cdot 10^6\) cycles. It follows that at \(t = 16, 17\) and \(l = 45\), with a defect size of 10x15 mm, the life of the composite sample will be 11.61 times less than with a defect-free sample.

By analogy with the dependence presented in Figure 4, (a), the maximum stress intensities \((\sigma_l^{\text{max}})\) arise at \(t = 16, 17\) and \(l = 45\) mm \(\sigma_l^{\text{max}}\) at this location is 41.37 MPa, which is 1.6 times more than for a sample without a delamination defect.
4. Conclusion
As the main results obtained in the framework of this work, the following can be distinguished: an algorithm was developed for predicting the residual life of PCM structures using the structural and phenomenological model of composite material. In the framework of the developed algorithm, it was proposed to use the approach of the explicit description of adhesive layers destruction process to evaluate the PCM structures residual life under cyclic loading. In accordance with the developed algorithm, in the process of cyclic loading in the adhesive layers, the level of damage was recorded; upon reaching a critical level of damage, the adhesive layers destruction was modeled. The algorithm was tested on samples with and without defects. A numerical study of the influence of the delamination defect location at the time of the onset of fatigue failure and stress strain state was carried out. According to the results of the numerical study, it was found that for a sample without a defect under specified loading conditions, the values of the minimum operating time to failure amounted to 25.98616*10^6 cycles. The minimum values of run-in until failure amounted to 2.237854*10^6 cycles and were detected when the delamination defect was the central layers. It was revealed that for a multilayer composite structure with cantilever bending, maximum stress intensities arise in the central layers. In this case, the location of maximum stress intensities and minimum run-in until failure is observed in the area of model structures cantilever fixing.

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