Numerical Simulation of Damage Accumulation in a Composite Flange with a Delamination Defect

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Numerical Simulation of Damage Accumulation in a Composite Flange with a Delamination Defect

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Abstract. In this work, a numerical model for predicting the residual life of structures made of polymer composite materials using a structural-phenomenological model is proposed. To estimate the residual life of PCM structures under cyclic loading, it is proposed to use the approach of explicit describing the process of adhesive layers' destruction. The model is implemented in the APDL language in ANSYS Mechanical engineering complex. The model and the program testing was carried out on a flange type construction with a defect. A comparison of numerical experiments was made for flanges with and without the defect.

1. Introduction
One of the main issues arising in the process of developing promising composite products for aviation or rocket and space industries is to ensure construction reliability over the long term of operation. This issue is particularly significant when using composites in civil aviation and engine building. Unfortunately, the experience and scope of research on the use of composites in structures subjected to prolonged intense temperature and force impacts is much less than for most steels and alloys [1].

The design of power parts and assemblies made of composite materials should be based on new mathematical models of composite materials mechanics. Mathematical models should take into account the parameters of the structure, including changes in their design due to changes in the geometry or technological features of manufacturing, kinetic processes of damage accumulation during the operation under static and cyclic loads. Mathematical models should allow predicting the physic mechanical properties of the material under static and cyclic loads with different reinforcement options [2].

As part of this work, a model is proposed for predicting the residual life of structures made of polymer composite materials (PCM) with a defect in the form of delamination, using a structural-phenomenological model.

2. Description of the numerical model
In the manufacture of flanges various defects may appear, for example in the area of bending of the layers is the formation of wrinkles, which leads to the appearance of pores or delamination. To study the effect of a defect on the residual life of a PCM flange, two structural-phenomenological models with and without the defect were considered.

In order to build a structural-phenomenological model, a flange with a delamination defect was made according to the results of X-ray scanning. For the fabricated sample, an X-ray photographic survey was made, a reconstructed image was obtained, and a geometric model of the flange was constructed with an explicit description of both the composite material structure and the defect in it (Figure 1).

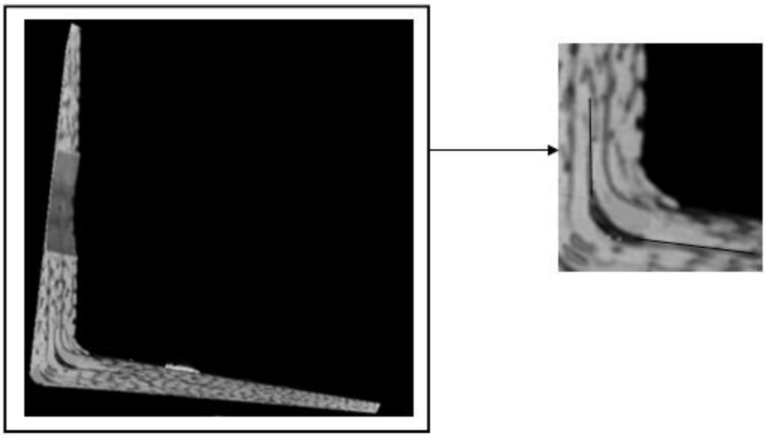
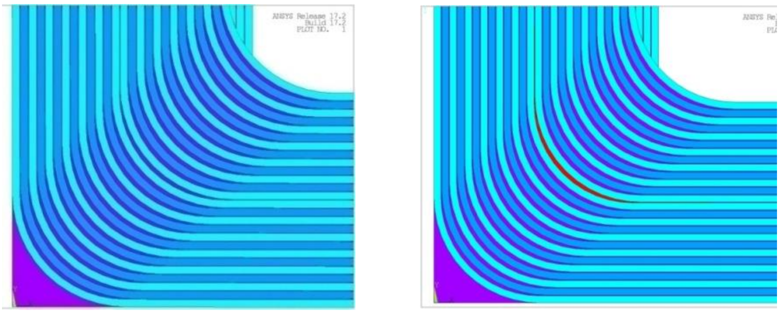


Figure 1. Shear of the reconstructed X-ray image at the location of the defect (delamination-pore)

To simulate the process of damage accumulation under cyclic loading, an approach is proposed to explicitly describe the destruction process for the adhesive layers situated in between the layers of reinforcing material. For numerical simulation of damage accumulations in the flange under a cyclic operational load, a geometric model of a flange with a delamination defect was built (Figure 2b). The model includes a system of reinforcing and adhesive layers. The number of reinforcing carbon fiber layers is 26. The adhesive layers were inserted between each reinforcing layer of the structure and are shown in purple color in Figure 2. The thickness of the adhesive layers was assumed to be 0.02 mm, which corresponds to 10% of the thickness of the structural carbon fiber layer. In the developed structural – phenomenological model with delamination, the defect was placed in the adhesive layer between 13 and 14 layers in the inflection area of the considered structure. The delamination area is shown in Figure 2b in red color.



a b

Figure 2. Areas with adhesive layers in the composite flange model in the inflection area: a - without defects; b - with the defect

The calculations were carried out by the finite element method in ANSYS Mechanical software engineering complex. The finite element model of the flange was developed with an explicit account of its reinforcement scheme and the presence of adhesive layers. For better convergence of the solution and to reduce the amount of the errors of the obtained results, discretization of adhesive and reinforcement layers was carried out to eight-node PLANE182 elements. The maximum element size for the computed model of the composite flange was 0.02 mm, the minimum - 0.002 mm. The total number of finite elements was 500 thousand elements. Also, in the course of the elemental model, the carbon fiber layers' reinforcement scheme was taken into account. Layers with 0^{o} reinforcement are painted in pale blue color, and with 45^{o} reinforcement in dark blue (Figure 1). Technical elastic constants of the reinforcing and adhesive layers are taken from [3-4] and are presented in Table 1, where E_x, E_y, E_z are the Young's modules in the direction of the axes, υ_{xy}, υ_{yz}, υ_{xz} are the Poisson's coefficients, G_{xy}, G_{yz}, G_{xz} are the shear moduli.

Table 1. Elastic properties of materials used in the numerical calculation of the composite flange life

Material	E_x, hPa	E_y, hPa	E_z, hPa	υ_{xy}	υ_{yz}	υ_{xz}	G_{xy}, hPa	G_{yz}, hPa	G_{xz}, hPa
Reinforcement layer	63.9	20	63.9	0.3	0.3	0.04	2.7	2.7	19.5
Adhesive layer		2.9			0.356			1.07	

In the numerical experiments, the development of the "delamination" type damage was simulated, which is a typical and characteristic type of destruction for these structures, occurring both under operational load and during laboratory tests. The strength of an epoxy binder under the action of cyclic loads was taken from the experimental data described in publications. A preliminary assessment of the life of the flanges was carried out according to the weakest link criterion [5].

The calculation of the flange stress strain behavior was carried out in an axisymmetric formulation using a two-dimensional model. The following boundary conditions were used in the calculation (Figure 3): the bolted area was rigidly fixed, a load (F) was applied to the end of the right free part of the flange with a maximum value in the loading cycle of 3000 N for both models, with and without the defect. In the calculations it was assumed that the specified load is periodic, from zero with a sinusoidal loading cycle, and in the process of application of this load in the adhesive layers accumulation of damage occurs followed by the destruction.

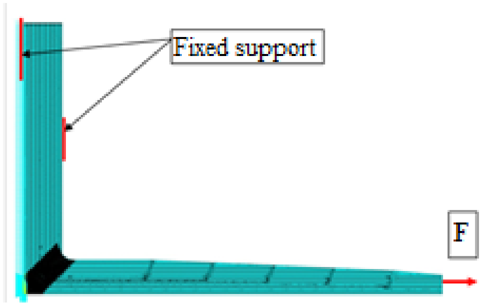


Figure3. Boundary conditions scheme

3. Description of the algorithm for predicting the residual life of a multilayer structure

In accordance with the developed algorithm, during the cyclic loading, the level of damage is fixed in the adhesive layers. When the critical level of damage is reached, the destruction of the adhesive layers is modeled. In the destroyed elements of the adhesive layers, the elastic constants are assumed to be approximately equal to zero (multiplied by 10^{-6}), which corresponds to the interlayer destruction of the laminated package. To describe the damage accumulated in an elementary volume in the area of a certain material point of the structure, a scalar time function $\psi(t)$ is used. It is assumed that the function $\psi(t)$ takes values on the interval [0, 1]. In this case, the value $\psi = 0$ corresponds to the case when there is no damage, the value $\psi = 1$ 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 $\psi = 0$. The state $\psi = 1$ corresponds to such a time or a number of loading cycles N when a certain strength criterion is violated, depending on the stress state at a given point σ_{ij} and material constants $S_{ij}(N)$.

We write a kinetic equation of damage accumulation, which determines the value ψ (N, σ_{mn}), in accordance with the linear rule of summation of damages,

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$$\psi(N,\sigma_{mn})=\sum_{k=1}^{N}\frac{1}{N_b\left(\sigma_i^{(k)}\right)}, \tag{1}$$

where N_b is the function of cycles before failure, $\sigma_i^{(k)}$ is the resultant stress in the k-th finite element.

The loading is assumed to be cyclic, symmetric with the amplitude corresponding to the maximum static load modulo. The influence of dynamic effects is neglected, the stress and strain fields in the structure for amplitude loads are considered equal to the corresponding fields under static loads. The strength of the adhesive coat under the action of cyclic loads is taken from the data reported in [6]. On the basis of these experimental data, two-link fatigue endurance strength was constructed, approximated by the equations

$$\begin{aligned} &\lg\left[N_b(\sigma_i)\right]=-0.0684\sigma_i+9.18 \qquad \sigma_i<42MPa,\\ &\lg\left[N_b(\sigma_i)\right]=-2.1029\sigma_i+94.63 \quad 42MPa<\sigma_i<45MPa. \end{aligned} \tag{2}$$

For each layer in each finite element, we obtain a nonlinear equation for N_b. After the solution, the number of cycles before the destruction of each element N_{bj}^1 is determined. The minimum value of N_{bj}^1 for all the finite elements is the number of cycles before the first act of fatigue failure in the structure $N_{b\Sigma}^1$. It is assumed thereafter that the corresponding element is destroyed and that the elastic moduli are reduced in it.

The rest elements are damaged herewith, the damages being computed by the formula corresponding to kinetic equation (1)

$$\psi_j^1=\frac{N_{b\Sigma}^1}{N_{bj}^1} \tag{3}$$

For the former amplitude of external load, a new stress-strain state of the structure with one damaged element q is calculated. Next, we determine the number of cycles before each element is destroyed N_{bj}^2 at operating stresses σ_{ij}. Destruction in this case will occur in the element where the damage, in view of the value (ψ_j^Σ) accumulated at the previous step will be equal to 1,

$$\psi_j^\Sigma+\psi_j^2=1. \tag{4}$$

The damage at the current (second) step is determined by the formula

$$\psi_j^2=\frac{N_{b\Sigma}^{2add}}{N_{bj}^2}, \tag{5}$$

where N_j^{2add} is the additional number of operating cycles in the second step. Substituting (3) into (4), we calculate N_j^{2add} for each element, the minimum value of which is the additional development of the structure up to the second act of destruction in the corresponding element. The total number of cycles of operating time is calculated by the formula

$$N_\Sigma^2=\min{}_j\left(N_j^{2add}\right)+N_\Sigma^1. \tag{6}$$

The elastic modulus tensor for the destroyed element is reduced and, for the remaining unresolved elements, the accumulated damage is calculated as

$$\psi_j^\Sigma=\psi_j^1+\frac{\min{}_j(N_j^{2add})}{N_{bj}^2}. \tag{7}$$

The next step starts with calculating the design stress-strain state with two damaged items. According to this algorithm, the fatigue life of the structure can be calculated before it exhausts the load-bearing capacity to the amplitude load determined by the static tensile strength, or by a critical reduction in the rigidity of the structure, or by the formation of a zone of damage of a given critical value. The final value N_Σ is the refined value of the fatigue life of the structure in comparison with the estimate obtained by the criterion of the weakest link.

The problem of calculating the stress strain state of the flange for the maximum (amplitude) load in the cycle, taking into account the accumulation of damage and destruction, is solved iteratively in steps. For all the elements of adhesive layers, the current value of damage is determined, which allows us to determine the location and the number of operating cycles prior to the next failure. In the considered variant, the mechanical properties of the adhesive layer material are independent on the level of damage until the critical value 1 is reached. After this value is reached in some finite element, the material was considered failed and the mechanical properties in this element have were reduced to negligible values. The structure with the changed properties in this destroyed final element is calculated thereafter. Thus, at each step of the algorithm, the fatigue damage of the structure, the deformation and stress fields are simulated. The calculations are made in the ANSYS software package with an integrated software module.

4. Analysis of the results

According to the results of the numerical calculation, a description was obtained of the processes of damage accumulation and destruction in the structure of the researched model under cyclic loading; the fields of stress intensity distribution, damage and durability were constructed and analyzed. The number of cycles to failure was estimated for all final elements of the adhesive layers. The minimum values of the operating time before failure were obtained, which for the flange without the defect is $N=2.819\cdot10^8$ loading cycles, and for the flange with the defect - $N=1.108\cdot10^8$ loading cycles. These values are a preliminary estimate of the flanges durability by the criterion of the weakest link, which refers to the first act of destruction in the structure. The maximum values of stresses in the adhesive layers for the defect-free flange are observed in the area of fastening, for the defect flange - on the border of the defect and the adhesive layer.

The estimate of the durability for this flange, obtained at the first simulation step, showed that the destruction begins for the defect-free flange on the $2.819\cdot10^8$ loading cycle in the first adhesive layer in the area of fastening; for the defect flange on the $1.108\cdot10^8$ loading cycle in the central, vertical adhesive layer in the area of the defect. Thus, the preliminary durability of the defect-free flange, evaluated by the weakest link criterion, is approximately 2.54 times more than the durability of the defect flange. The relative area of destruction was determined as the ratio of the area of the destroyed elements to the total area of the elements in the adhesive layers.

Analysis of the destruction kinetics revealed that the destruction of the defect-free flange begins in the area of fixation. At the time of $5.34\cdot10^8$ loading cycles, a through-delamination between the first and second layer in the area of fixation appears in the defect-free flange. The total area of destruction in this case is 1%. Calculations have shown that from the moment of the first fracture occurrence until the occurrence of the through-delamination, the flange can withstand $2.53\cdot10^8$ additional loading cycles.

The destruction of the defect flange begins in the area of the delamination. Once reaching $3.41\cdot10^8$ loading cycles, a through-delamination in the central adhesive layer appears at the defect flange. The total area of destruction was 1.673%. It has been revealed that from the moment of the occurrence of the first destruction until the occurrence of through-delamination, the defect flange withstands additional $2.31\cdot10^8$ cycles.

A comparative analysis of the calculation results of damage accumulation kinetics for both flanges revealed that the appearance of through-delamination in the defect flange occurs 1.5 times faster than in the defect-free one. The difference in additional cycles after the occurrence of the first area of destruction was $0.22\cdot10^8$ cycles.

With the emergence of through-delamination in the flanges, a significant decrease in stiffness is observed. A critical drop in stiffness (approximately more than 15%) for a defect-free flange is observed at the 200th loading step, the value of stiffness falling was about 17.65%, with a total number of operating cycles equaling $534.649\cdot10^6$. For a defect-free flange, a stiffness reduction of 16.32% is observed after the 250th loading step, with a total number of operating cycles equaling $341.798\cdot10^6$. Tables 2, 3 present the values of the maximum displacements and the stiffness reduction of the flanges at different loading steps.

Table 2. Maximum displacements and stiffness drops for a defect-free flange model

Load step	Number of loading cycles, $10^6 N$	Maximum displacement, mm	Stiffness drop, %
1	281.989	0.204	0
100	531.701	0.218	6.86
200	534.649	0.240	17.65
300	534.667	0.271	31.86
400	534.691	0.373	70.1

Table 3. Maximum displacements and stiffness drops for a model of a flange with a defect

Load step	Number of loading cycles, $10^6 N$	Maximum displacement, mm	Stiffness drop, %
1	110.849	0.230	0
100	272.844	0.249	8.26
200	341.230	0.257	11.75
300	342.298	0.339	47.39
400	343.211	0.436	89.57

Thus, the developed model and program make it possible to determine the allowable value of the stiffness reduction for PCM structures in the simulations of damage accumulation and destruction under cyclic loading processes.

5. Conclusion

Thus, in this work, a model and a program for predicting the residual life of PCM structures using a composite material structural-phenomenological model was developed and tested. A preliminary assessment of the fatigue strength of flanges by the weakest link criteria showed that the durability of the defect-free flange is approximately 2.54 times more than the durability of the defect flange. A comparative analysis of the results obtained for both flanges revealed that the occurrence of through-delamination at the defect flange occurs 1.5 times faster than at the defect-free flange. The difference in additional cycles after the occurrence of the first are of destruction was $0.22 \cdot 10^8$ cycles. In addition, it was found that with the appearance of through-delamination, a significant decrease in stiffness is observed for the flanges. It can be concluded that the developed model and program make it possible to determine the acceptable value of the stiffness reduction for PCM structures.

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