Research of the damage accumulation and destruction processes of perforated composite plates

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Abstract. The main purpose of the research is to comprehensively study the regularities of deformation processes damage accumulation and destruction of modern composite materials in stress concentration zones. The object of research is fiberglass samples with four round holes. As a result of experimental studies loading diagrams were obtained for samples with different length of the working area. The paper presents graphs of the load dependence on the longitudinal deformation. According to the data obtained it can be noted that the longer the length of the working area of the sample the earlier the failure occurs. The deformation was obtained using the optional Vic-3D "virtual extensometer" non-contact optical video system. In the experiments process curves of longitudinal deformations were plotted. From these data it is possible to estimate the maximum longitudinal deformations occurring near the hole. Also in the work numerical modeling of the process of deformation and destruction of perforated plates was carried out in the software engineering complex Ansys. The calculated data obtained confirm the experimental results of the research.

1. Introduction
In industry, in particular in the civil aviation industry the connection of composite elements in the structure is carried out using mechanical fastening. This process requires a large number of drilled holes for location the rivets and bolts. Assembly work is carried out using fasteners. The staggered arrangement of holes for bolted joints is often used both in metal structures and in composite ones, since this allows to increase the strength of structures [1].

With the use of the Vic-3D non-contact optical video system, the mathematical apparatus of which is based on the DIC digital image correlation method, it becomes possible to study the stress-strain state of the material in the area of the concentrator, at the point of crack initiation, and also to characterize the state that precedes fracture [2-5]. Measurements of the total strain field using the digital image correlation method are very important for checking the strain distribution in a loaded specimen where there is a local contact between the bolt and the hole [6, 7]. The processes of structural destruction are reflected in the deformation diagram leading to its nonlinearity, and at the final stage are the cause of softening [8-13]. The fracture resistance at the post critical stage of deformation corresponding to the descending branch of the deformation diagram depends on the rigidity of the loading system. Numerical modeling of the fracture process is performed using various fracture criteria and degradation mechanisms of material properties. The works [14-18] use the fracture criterion based on stress and strain, in [19-20] on the basis of energy.

2. Material, sample and test equipment
This work was carried out in Perm National Research Polytechnic University using Unique Scientific Equipment «Complex of testing and diagnostic equipment to study the properties of structural and
functional materials under complex thermomechanical loading conditions» http://ckp-rf.ru/usu/501309/” at the Center experimental mechanics.

The main purpose of the research is to comprehensively study the regularities of deformation processes damage accumulation and destruction of modern composite materials in stress concentration zones. The experiments were carried out on an Instron 5989 universal electromechanical testing system. Registration of inhomogeneous deformation fields on the sample surface was carried out using a Vic-3D digital optical system based on the DIC digital image correlation method. The experiments were carried out on an Instron 5989 universal electromechanical testing system. Registration of inhomogeneous deformation fields on the sample surface was carried out using a Vic-3D digital optical system based on the DIC digital image correlation method. The speed of the moving gripper was \( u_0 = 2 \text{ mm/min} \). The load was measured with a load cell with an ultimate load of 100 kN. The load measurement accuracy is not less than 0.5% of the measured value. The video system was implemented using two digital monochrome cameras Prosilica GE4900 (lens - 35 mm f / 2.0), the shooting speed was 4 frames per second.

The research program included uniaxial tensile mechanical tests of composite specimens 100 mm wide and 4 mm thick with 4 round holes of equal diameter \( d = 6 \text{ mm} \) and with different length of the working area \( l_{\text{work}} = 150, 200, 240 \text{ mm} \). Different sample lengths were chosen to study the effect of the rigidity of the loading system. A total of two samples of each length were tested. Fiberglass plates were made of GFRP (1.95 mm thick) manufactured in accordance with GOST (National Standard) 12652-74. This material consists of a plain weave fabric (6 layers) and a hot cure phenolic epoxy matrix.

3. Main part

3.1 Results of the experimental study

As a result of experiments, loading diagrams were obtained for perforated specimens with different length of the working part (figure 1). From the data obtained, it can be seen that on the curves for specimens with a minimum working base of 150 mm on the falling branch, in addition to the dynamic section of destruction, there is an equilibrium section. As the length of the working section increases to 200 mm and 240 mm, a gradual dynamic destruction of the sample occurs, while the equilibrium section is practically absent.

Figure 2 shows a graph of the load on the longitudinal deformation dependence, the curves shown are presented with a displacement of 0.02 mm. It should be noted that the deformation was obtained with the help of an additional instrument of the video system «virtual extensometer». With the help of it, it becomes possible to obtain deformations without mechanical impact on the surface of the sample and to apply it in any area of interest. According to the data obtained, it is possible to note the longer the length of the working part of the sample, the earlier the break of the diagram occurs.

During the experiments, plots of longitudinal deformations were obtained along the line get through the holes in the horizontal direction in the images - figure 3 over the entire width of the sample 100 mm at the moment corresponding to the maximum load level. In this case, the Oy axis is directed along the sample (along the tension axis), and the Ox axis is perpendicular to the loading axis in the sample plane.

![Figure 1. Loading diagram of perforated specimens (a), enlarged areas for a specimen with a working section length of 150 mm (b), 200 mm (c), 240 mm (d).](image-url)
Figure 2. Load versus longitudinal strain diagram for perforated specimens.

Figure 3. Plots of longitudinal deformations on the surface of perforated samples in accordance with the inhomogeneous deformation field and a photograph of the destroyed sample.

The presence of the hole leads to a rupture of 6 mm wide, which corresponds to their diameter. From the data presented, it is possible to estimate the maximum longitudinal deformations occurring near the hole. The given field of longitudinal deformations at maximum load clearly demonstrates the location of defects.

According to all the results obtained, it can be noted that in 5 cases out of 6 the destruction of the sample occurred as a result of the development of a zigzag crack along the smallest transverse area.
Taking into account this geometry of the staggered arrangement of the holes, it can be concluded that the two additional holes did not affect the destruction process. As an example, figures 4 show inhomogeneous fields of transverse, shear and longitudinal deformations on the surface of a perforated sample with a working section length of 240 mm at different times. From the presented inhomogeneous fields, it is possible to establish the presence and increase in the concentration of the level of deformations around the hole, which in turn leads to the growth of a crack and subsequent destruction of the sample.

Figure 4. Transverse strain fields (a), fields of shear (b) and longitudinal (c) deformations for a specimen with a working section length of 240 mm.

3.2 Results of numerical calculations
Numerical modeling of deformation and destruction process of a perforated plate with a width of H = 100mm, a length of L = 350mm and four holes with a radius of R = 6mm has been carried out. The mathematical model of the deformation and fracture process is described by a system of equations (1)-(3):

\[
\sigma_{ij}(r) = 0
\]  \hspace{1cm} (1)

\[
\epsilon_{ij}(r) = \frac{(u_{ij}(r) + u_{ji}(r))}{2}
\]  \hspace{1cm} (2)

\[
\sigma_{ij}(r) = [3K(r)(1-k) V_{ijmn} + 2G(1-g) H_{ijmn}] \epsilon_{ij}(r)
\]  \hspace{1cm} (3)

in which the functions \( g \) and \( k \) describe elastic-brittle fracture varying from 0 to 1 in an abrupt manner when the fracture criterion is met:

\[
g(\sigma_{ij})^2 = \begin{cases} 
0, & \sigma_{ij}^2 < \sigma_{ij}^{cr} \\
1, & \sigma_{ij}^2 > \sigma_{ij}^{cr} 
\end{cases}
\]

\[
k(\sigma_{ij})^2 = \begin{cases} 
0, & \sigma_{ij}^2 < \sigma_{ij}^{cr} \\
1, & \sigma_{ij}^2 > \sigma_{ij}^{cr} 
\end{cases}
\]

The system of equations is supplemented by kinematic boundary conditions on the body surface \( S: U_i(r)|_S = U_i^0 \) [10].

In this case, the fracture process is modeled by comparing the largest principal stresses \( \sigma_{ij} \) with the ultimate stress \( \sigma_{ij}^{cr} \), which is the same for all finite elements and with an automatic selection of the loading step. The numerical model is built in the software engineering complex Ansys. The solution of the problem is carried out in a plane-stressed formulation using a four-node finite element Plane 182. The material of the plate is taken to be orthotropic, the properties of which are given in Table 1 [21].
Loading was carried out by applying a displacement along the vertical axis to the upper face of the plate, the lower face was fixed along the loading axis, and the lower left point was fixed rigidly.

**Table 1.** Material properties of the perforated plate.

| $E_{xx}$, Pa | $E_{yy}$, Pa | $\nu_{xy}$ | $G_{xy}$, Pa |
|--------------|--------------|-------------|--------------|
| $28 \cdot 10^9$ | $28 \cdot 10^9$ | 0.18        | $6.2 \cdot 10^9$ |

As a result of the solution, the calculated pictures of the fracture zones were obtained (figure 7), built for various moments of deformation of the plate with concentrators.

![Figures 5](image)

**Figure 5.** Pictures of fracture zones plotted for various moments of deformation of a plate with concentrators.

The crack in all specimens propagates perpendicular to the load application axis. The calculated strain distribution fields, as well as the direction of crack propagation, are in qualitative agreement with the experimental results. The photographs of the type of failure shown in figure 5 are consistent with the calculated and experimental fields, and correspond to the failure of the fibers in the transverse direction in the area of the stress concentrator.

4. **Conclusion**

Based on the results of experimental studies of perforated fiberglass plates with round concentrators, the effect of the loading system on the plate destruction process was estimated. As the length of the test section increased, a gradual dynamic fracture of the sample occurred, and the equilibrium section was practically absent in the loading diagram. Thus, according to the data obtained, it was found that the longer the length of the working area of the sample, the earlier the failure occurs.

In the course of the study, deformation diagrams were obtained on the surface of perforated plates, with the help of which it becomes possible to estimate the maximum longitudinal deformations occurring near the hole.

Taking into account the geometry of the staggered arrangement of the holes presented in the study, we can conclude that the two additional holes did not affect the destruction process. This is confirmed by the similar nature of fracture for all perforated plates and the inhomogeneous fields of transverse, shear and longitudinal deformations on the surface presented in the work. Based on the obtained non-uniform fields, it is possible to establish the presence and increase in the concentration of the level of deformations around the hole, to track the growth of a crack and the subsequent destruction of the sample.
To confirm the experimental results of research and to obtain additional information, a numerical simulation of the process of deformation and destruction of perforated plates was carried out. The calculated data obtained confirm the experimental results of the research.

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