

# The Influence of Hole Shape on the Elastic-Plastic Properties of Fiber Composites

ASKHAD POLATOV, AKHMAT IKRAMOV, UCHQUNBEK ADAMBAEV,  
SUKHBATULLA PULATOV

Department of Software Engineering and Artificial Intelligence,  
National University of Uzbekistan,  
4 University Street, Tashkent, 1000124,  
UZBEKISTAN

**Abstract:** - Understanding the influence of hole geometry on the elastoplastic behavior of fiber-reinforced composites is critical for designing lightweight, high-performance structural components. This study introduces an efficient framework that combines a simplified theory of small elastoplastic deformations for transversely isotropic media with the finite element method, enabling accurate prediction of stress and strain localization in perforated composites. The material is modeled as an elastoplastic continuum composed of stiff reinforcing fibers embedded in a softer matrix, capturing key anisotropic effects while avoiding costly multiscale simulations. A systematic parametric study of circular, elliptical, and crack-like holes reveals that hole geometry dramatically alters stress concentration patterns. In particular, when the ratio of the semi-axes of an elliptical hole falls below 0.2, maximum shear stresses localize near the lateral surfaces, creating a high risk for matrix–fiber separation and damage initiation. The findings provide quantitative design guidelines for optimizing hole shapes in reinforced composites and demonstrate a practical method to bridge the gap between idealized elastic models and computationally intensive full-scale elastoplastic simulations. This approach offers direct relevance for aerospace, automotive, and energy applications, where stress concentrators critically impact structural reliability.

**Key-Words:** - fiber, matrix, composite, deformation, effective mechanical parameters, hole, stress.

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## 1 Introduction

Recent advancements in science and technology enable the creation of numerical models that accurately reflect stress distribution in spatial structures. Special attention is given to studying how the structural characteristics of the material and the geometry of stress concentrators affect the deformation of structural elements. Stress concentration around holes in fiber-reinforced composite structures remains a critical issue due to its strong influence on stiffness degradation, plastic strain localization, and failure initiation. Recent studies increasingly emphasize the role of anisotropy, fiber architecture, and elastoplastic behavior in accurately predicting the mechanical response of perforated composite components.

In [1] investigated variable-stiffness laminates with different open-hole geometries and demonstrated that tailored fiber paths significantly reduce stress concentration factors. Their results highlight the importance of coupling hole geometry with directional stiffness, although plastic deformation effects were not considered.

Experimental and numerical analyses of open-hole carbon fiber reinforced polymer laminates [2] confirmed that hole-induced stress redistribution strongly depends on laminate configuration and anisotropy, but the analysis was mainly restricted to elastic behavior and ultimate failure.

The influence of matrix plasticity on failure mechanisms near holes was addressed in [3], who showed that local plastic deformation delays crack initiation in open-hole laminates. These findings emphasize the necessity of elastoplastic formulations when analyzing stress concentrators in composite structures.

Advanced constitutive models have recently been proposed to describe anisotropic elastoplastic behavior. In [4] developed a finite-strain fiber-angle plasticity model based on isogeometric shell elements, capable of capturing fiber reorientation effects. Multiscale elastoplastic behavior was investigated in [5] using a direct finite element squared approach, providing high-fidelity predictions at the expense of high computational cost. Data-driven and direct numerical simulation–

based anisotropic elastoplastic models were introduced in [6], demonstrating improved prediction of plastic strain localization under complex loading.

Coupled elastoplastic–damage formulations have further enhanced predictive capabilities. References [7] and [8] showed that regions of maximum shear stress near holes govern damage initiation and stiffness degradation in fiber-reinforced laminates. Failure prediction in high-performance composites was also examined in [9], who highlighted the dominant role of matrix-driven plasticity near stress concentrators. The article [10] demonstrated that equivalent homogeneous anisotropic models can adequately reproduce elastoplastic stress redistribution when effective material properties are properly identified.

Despite these advances, many existing approaches rely on either purely elastic assumptions or computationally intensive multiscale formulations. In contrast, the present study employs a simplified elastoplastic theory for transversely isotropic media, which is particularly suitable for composites with a high stiffness contrast between fibers and matrix. This framework enables an efficient and systematic investigation of the influence of hole shape (circular, elliptical, and crack-like geometries) on stress concentration and elastic–plastic response, providing a practical alternative for engineering-scale analyses.

The development of mathematical models and the exploration of deformation in transversely isotropic bodies with stress concentrators have been widely examined, as reviewed in reference [11]. The study presented in reference [12] outlines fundamental principles of continuum mechanics. In addition to traditional models, new approaches are considered, which include composites and models that account for the interaction between fibers and the matrix [13], [14], [15], [16]. References [17] and [18] analyze stress concentration and distribution in isotropic, orthotropic, and multilayer composite plates featuring a central circular hole, providing stress concentration factor values in the region around the hole.

To determine the effective mechanical properties of fibrous materials, reference [19] employs relationships derived from asymptotic methods. These methods allow for radial interactions between components, taking into account the differences in Poisson's ratios of the matrix and the fiber.

The article [20] developed a finite element model that takes into account the anisotropic structure of the material and the orientation of the

fibers, which makes it possible to identify zones of stress concentration and evaluate the effect of reinforcement on the strength of structures. Reference [21] combines elements of strength of materials, elasticity theory, plasticity theory, creep theory, and fracture mechanics. The presentation emphasizes the relationship between physical and mechanical theories.

Monograph [22] develops the foundations of modern plasticity theory based on the principles of continuum mechanics, invariance, and tensor analysis. Particular attention is given to the kinematics of deformation and constitutive relations for elastic-plastic materials.

In [23], a computational algorithm was developed, and the problem of physically nonlinear deformation of fibrous composite materials with a stress concentrator was solved, and the influence of a circular cavity on the stress state of its vicinity was investigated.

References [24], [25] focus on automating the construction of numerical models and visualizing the results of computational experiments.

The above studies have extensively examined the mechanisms of stress concentration and failure mechanisms in fiber-reinforced composites containing open holes of various geometries. However, most existing works rely on purely elastic or damage-based formulations, while the role of matrix plasticity is often neglected. At the same time, advanced elastoplastic models are typically developed without considering geometrical stress concentrators such as non-circular holes. Therefore, the combined influence of hole shape and elastoplastic material behavior in fiber-reinforced composites remains insufficiently explored. The present study aims to fill this gap by systematically investigating the effect of hole geometry on the elastoplastic response of fibrous composites using a consistent finite-element framework.

## 2 Problem Statement and Solution Method

An elastoplastic medium consists of a non-homogeneous continuous material made up of two components: fibers and a matrix (or binder) that facilitates the combined action of the reinforcing elements. To address the issue of fiber composite deformation, we apply the theory of small elastic deformations for a transversely isotropic medium, as proposed in reference [26]. In reinforced composites, when the stiffness of the reinforcing elements is significantly greater than that of the

matrix, a simplified deformation theory can often be used to solve many practical problems [27], [28].

This notation is appropriate for implementing the iterative process of A.A. Ilyushin's method of elastic solutions. According to it, the solution to the problem in the theory of small elastoplastic deformations under active loading is reduced in each approximation to the successive solution of the problem in the linear theory of elasticity.

The general formulation of elastic problems for anisotropic bodies is represented by the following equations:

$$\sigma_{ij,j} + X_i = 0, \quad x_i \in V \quad \text{-- equilibrium equation;} \quad (1)$$

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \quad \text{-- generalized physical law;} \quad (2)$$

$$\varepsilon_{kl} = \frac{1}{2} \left( \frac{\partial u_k}{\partial x_l} + \frac{\partial u_l}{\partial x_k} \right) \quad \text{-- Cauchy relation;} \quad (3)$$

and the given boundary conditions

$$u_i|_{\Sigma_1} = u_i^o, \quad x_i \in \Sigma_1, \quad (4)$$

$$\sum_{j=1}^3 \sigma_{ij} n_j|_{\Sigma_2} = P_i^o, \quad x_i \in \Sigma_2, \quad (5)$$

where

$u_i$  – denote the components of the displacement vector;

$X_i$  and  $S_i$  – represent the volumetric and surface force, respectively;

$\Sigma_1, \Sigma_2$  – components of surface  $\Sigma$  and volume  $V$ ;

$n_j$  – the outward normal to  $\Sigma_2$  and volume  $V$ ;

$C_{ijkl}$  – elastic constant tensor.

In transversely isotropic elastoplastic materials, the physical law of the relationship between stresses and strains is described by a generalized version of Hooke's law, which accounts for the isotropy of the material relative to the axis of symmetry and in the plane perpendicular to this axis.

For a simplified deformation theory of transversely elastoplastic media, the physical law (3) is represented as a decomposition of the stress tensor into spherical ( $\tilde{\sigma}, \sigma_{33}$ ) and deviatoric ( $P_u, Q_u$ ) parts:

$$\tilde{\sigma} = (\lambda_2 + \lambda_4) \tilde{\theta} + \lambda_3 \varepsilon_{33}, \quad \sigma_{33} = \lambda_3 \tilde{\theta} + \lambda_1 \varepsilon_{33}, \quad (6)$$

where

$\lambda_i$  – are the elastic constants of transversely isotropic materials:

$$\lambda_1 = E'(1-\nu)/l; \quad \lambda_2 = E(\nu + k\nu'^2)/[(1+\nu)/l]; \quad \lambda_3 = E\nu'/l; \\ \lambda_4 = G = E/[2(1+\nu)]; \quad \lambda_5 = G'; l = 1 - \nu - 2\nu'^2 k; k = E/E'.$$

Here,  $\nu$  and  $\nu'$  – are the effective Poisson's ratios,  $E, G$  and  $E', G'$  – are the effective elastic moduli, respectively, in the plane and along the isotropy axis of the transversely isotropic material;

$(P_u, p_u)$  and  $(Q_u, q_u)$  are the intensities of the stress and strain tensors, respectively, in the plane and along the isotropy axis:

$$P_u = \frac{\sqrt{2}}{2} \sqrt{(\sigma_{11} - \sigma_{22})^2 + 4\sigma_{12}^2}, \quad Q_u = \sqrt{\sigma_{13}^2 + \sigma_{23}^2},$$

$$p_u = \frac{\sqrt{2}}{2} \sqrt{(\varepsilon_{11} - \varepsilon_{22})^2 + 4\varepsilon_{12}^2}, \quad q_u = \sqrt{\varepsilon_{13}^2 + \varepsilon_{23}^2}$$

The given differential formulation of problem (1-5) is equivalent to a variational formulation in the form of the Lagrange principle of minimum potential energy :

$$\iiint_V \delta(\varepsilon)'(\sigma) dV - \iint_S \delta(U)'(P) dS = 0. \quad (7)$$

By substituting geometrically possible displacements, stress tensor components, and surface loads, various systems of resolving equations can be obtained.

Equation (7) is solved using the finite-element method in displacements and method of small elastic deformations for a transversely isotropic medium.

### 3 Validation and Applicability of the Equivalent Homogeneous Anisotropic Model

#### 3.1 Validation of the Equivalent Homogeneous Anisotropic Model

In [29], the effect of fibrous architecture on stress concentration around a circular hole in a boron–aluminum composite is investigated using composite mechanics approaches. The material consists of an aluminum matrix reinforced with boron fibers. It is shown that the presence of fibers significantly alters the stress distribution compared to a homogeneous isotropic medium. To account for this effect, the composite is modeled as an equivalent homogeneous material with effective anisotropic properties [30]. A continuum formulation accounting for fiber-induced anisotropy is adopted, and the applicability of a discrete–continuum reinforcement model is justified. Fibers

are assumed to possess a single plane of isotropy, enabling a more accurate representation of their mechanical response than transversely isotropic models. The proposed approach allows reliable analysis of highly anisotropic composites and demonstrates good agreement with experimental data.

The elastoplastic response is computed using Ilyushin's elastic solution method, implemented within an iterative computational scheme. An elastic trial state is first evaluated and subsequently corrected to satisfy the yield condition. The resulting nonlinear equations are solved using a Newton-type iterative method. For associative plasticity models with convex yield surfaces, the algorithm exhibits local quadratic convergence when a consistent tangent operator is employed [31]. Global convergence is ensured under standard assumptions on the constitutive operator, including coercivity and monotonicity [32].

To validate the homogeneous model, a test elastic problem of uniaxial tension of a plate with a central circular hole was solved. The plate is stretched vertically under a uniformly distributed load of  $P_{zz}=10$  MPa. The material under investigation is a fiber-reinforced composite, with D-16 duralumin as the matrix and boron fibers (volume fraction 60%) aligned along the fiber direction as reinforcement.

For D16 duralumin, the material properties are: Young's modulus  $E=70\times10^3$ MPa, tensile strength  $\sigma_s=400$  MPa, and Poisson's ratio  $\mu=0.32$ . For boron fibers:  $E'=390\times10^3$ MPa,  $\sigma_s'=3.5\times10^3$ MPa, and  $\mu'=0.21$ . The effective elastic properties of the boron–aluminum composite are:  $E=160\times10^3$ MPa,  $E'=260\times10^3$ MPa, and  $G'=51\times10^3$ MPa.

Table 1. Comparison of parameter values

| Structure    | $\sigma_{xx}$ [MPa] | $\tau_{zx}$ [MPa] | $\tau_{zy}$ [MPa] |
|--------------|---------------------|-------------------|-------------------|
| Fibrous [29] | 5.91                | -9.12             | 1.81              |
| Homogeneous  | 5.65                | -9.83             | 1.64              |

Source: created by the authors.

Table 1 presents a comparison of the results obtained using the fibrous and homogeneous models at characteristic points of the structure. The close agreement between the solutions of the fibrous and homogeneous models indicates that the homogeneous model is valid.

### 3.2 Limitations of the Model

The composite material is modeled as an equivalent homogeneous transversely isotropic elastoplastic medium. This macroscopic representation neglects microscale effects such as discrete fiber distribution,

fiber–matrix debonding, and local damage mechanisms, and is valid under the assumption of a clear separation of scales.

The formulation is based on the simplified theory of small elastoplastic deformations and assumes a high stiffness contrast between fibers and matrix. The analysis is restricted to small strains and quasi-static loading; geometric nonlinearities, dynamic effects, and time-dependent behavior are not considered.

Plastic deformation is described using an effective macroscopic yield criterion without accounting for anisotropic plastic flow, damage evolution, thermal effects, or stiffness degradation. Hole geometries are assumed to be ideal with smooth boundaries, while manufacturing imperfections are neglected.

Within these assumptions, the model provides an efficient framework for evaluating the influence of hole shape on stress concentration and elastic–plastic response in fiber-reinforced composites.

## 4 The Effect of Hole Shape on Stress Concentration

The results of the elastic test problem of stretching a square plate with a central circular hole are close to the solutions obtained using the fiber model, confirming the correctness of the proposed homogeneous model.

To study the effect of an isolated hole on the strain state of a unidirectional composite, a three-dimensional elastic problem of uniaxial tension ( $P=100$  MPa) in the direction of fibers of a rectangular plate 10 mm high, 5 mm wide, and 1 mm thick is considered. The matrix material is aluminum alloy D16 (duralumin) with the following parameters:  $E=7.1\times10^4$  MPa,  $\mu=0.32$ , and  $\sigma_s=2.13\times10^2$  (elastic limit). For boron fiber, they are:  $E'=39.7\times10^4$  MPa,  $\mu'=0.21$ , and tensile strength is  $\sigma_s'=2.5\times10^3$  MPa. The fibers of the material are located parallel to the OZ-axis. The volumetric fiber content in the composite is  $v=60\%$ . The corresponding effective mechanical parameters have the following values:

$$E=1.3992\times10^5 \text{ MPa}, E'=2.6682\times10^5 \text{ MPa},$$

$$G=0.6551\times10^5 \text{ MPa}, G'=0.5396\times10^5 \text{ MPa},$$

$\mu=0.0682$ ,  $\mu'=0.2480$  and the elastic deformation limit of duralumin is  $p_u=0.003$ . We determine the

locations of points A and B; for an ellipse: point A is located at the intersection of the horizontal diametrical cross-section with the hole contour,

while point B corresponds to the intersection of the vertical diametrical cross-section with the hole contour. In the case of a crack,  $A$  denotes the crack tips, and  $B$  denotes the crack midpoint.

The influence of the hole shape on the distribution of the strain and stress fields is studied through a computational experiment. The dimensions of an elliptical concentrator with radius  $r_1$  and  $r_2$  are varied. To logically complete the process, an elastic problem is solved for stretching a fibrous structure with a horizontal rectilinear crack at the center. The length of the crack is equal to the diameter of the hole. Table 2 and Table 3 show the values of the stress-strain state components at characteristic points in the vicinity of the hole, located in stress concentration zones.

Table 2. Effect of the  $r_2 / r_1$  ratio (at point B,  $\tau_{xy} = 0$ )

| $r_2 / r_1$ | $\sigma_{xx}$<br>[MPa] | $\sigma_{yy}$<br>[MPa] | $p_u \times 10^4$ | $P_u$<br>[MPa] |
|-------------|------------------------|------------------------|-------------------|----------------|
| 4           | -46.10                 | -12.59                 | 1.81              | 23.71          |
| 2           | -69.29                 | -13.31                 | 3.02              | 39.59          |
| 4/3         | -78.65                 | -10.79                 | 3.66              | 47.00          |
| 1           | -83.02                 | -7.941                 | 4.05              | 53.10          |
| 3/4         | -81.18                 | -7.413                 | 3.98              | 52.17          |
| 1/2         | -80.71                 | -7.006                 | 3.97              | 52.13          |
| 1/4         | -85.33                 | -7.628                 | 4.19              | 54.96          |
| 0           | -77.20                 | -4.476                 | 3.93              | 51.44          |

Source: created by the authors.

Table 3. Effect of the  $r_2 / r_1$  ratio (at point A)

| $r_2 / r_1$ | $\sigma_{xx}$<br>[MPa] | $\sigma_{yy}$<br>[MPa] | $\tau_{xy}$<br>[MPa] | $P_u$<br>[MPa] |
|-------------|------------------------|------------------------|----------------------|----------------|
| 4           | 4.21                   | 5.56                   | -0.609               | 1.97           |
| 2           | 8.68                   | 11.42                  | -1.025               | 3.49           |
| 4/3         | 14.25                  | 18.05                  | -1.315               | 4.59           |
| 1           | 20.40                  | 25.21                  | -1.537               | 5.52           |
| 3/4         | 32.74                  | 37.87                  | -1.008               | 4.61           |
| 1/2         | 53.18                  | 59.04                  | -0.115               | 4.16           |
| 1/4         | 85.80                  | 94.23                  | 0.961                | 6.55           |
| 0           | 74.88                  | 30.86                  | 2.288                | 32.0           |

Source: created by the authors.

Figure 1 shows the dependency of displacements  $w$  (at point B) and  $u$  (at point A) on the radius ratio  $r_2 / r_1$ .

The displacement  $w$  increases as  $r_2 / r_1$  grows, reaching a maximum at  $r_2 / r_1 = 1.2$ . After this point, a gradual decrease is observed, suggesting that the sensitivity of this point to further changes in the concentrator geometry is reduced. Displacement  $u$  at

point A takes negative values at small  $r_2 / r_1$ , reaching its minimum around  $r_2 / r_1 = 1$ . As the radius ratio increases, the displacement rises monotonically, crossing the zero level and becoming positive for  $r_2 / r_1 > 3$ . This shift indicates a change in the local deformation pattern from compressive to tensile at point A.

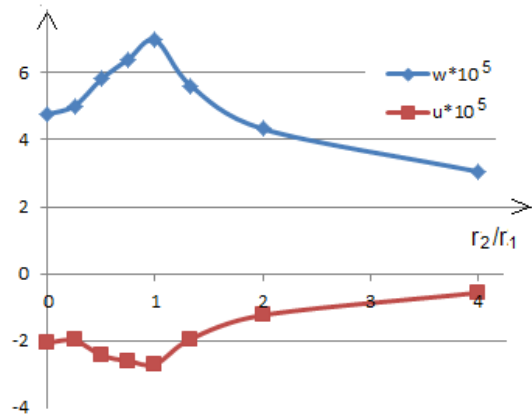


Fig. 1: Graph of the change in displacements  $w$  at point B and  $u$  at point A.

Source: created by the authors.

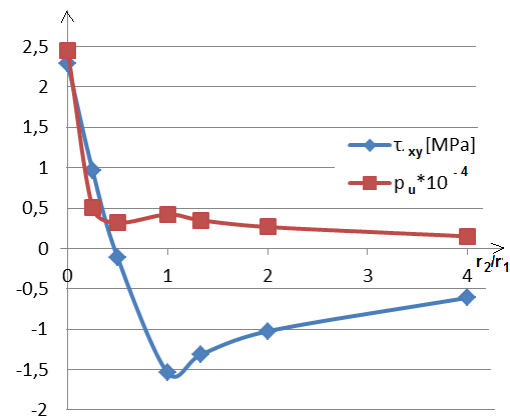


Fig. 2: Graph of the change in values  $\tau_{xy}$  and  $p_u$  at point A.

Source: created by the authors.

Figure 2 presents the dependencies of shear stress  $\tau_{xy}$  and the intensity of strain  $p_u \times 10^{-4}$  on the radius ratio  $r_2 / r_1$ . At small values of  $r_2 / r_1$ , shear stress reaches its maximum, after which a sharp decrease is observed, followed by a transition into the negative region. The minimum stress value occurs at  $r_2 / r_1 \approx 1$ , indicating significant redistribution of the stress field around the concentrators. As  $r_2 / r_1$  continues to increase, the stress gradually becomes less negative, trending toward zero. In contrast, the intensity of strain  $p_u$  shows a smooth variation. After a slight initial

decline, the curve stabilizes into an almost horizontal regime, where the values of  $p_u$  remain nearly constant within the range  $0.5 \leq r_2 / r_1 \leq 3$ . This indicates that displacements are less sensitive to changes in the geometric parameter compared to shear stresses. Only at  $r_2 / r_1 = 4$  is a minor further reduction in displacement noted.

Figure 3 shows the distribution of the stress tensor intensity  $p_u$  (along the isotropy surface  $XOY$ ) in the vicinity of a stress concentrator, for  $r_2 / r_1$  ratios ranging from 1 to  $1/8$ , with the constant value of  $r_1 = 0.05$ . The maximum values are concentrated near the upper and lower sides of the hole [33]. However, as the hole height decreases, a zone of high values of  $p_u$ , is formed near the lateral parts of the hole, which is associated with an increase in the curvature coefficient of the hole. It should be noted that in the vicinity of point A, located directly on the edge of the lateral part of the hole, the stress intensity is insignificant. This zone is clearly visible in the case of an isolated rectilinear crack (Figure 3e).

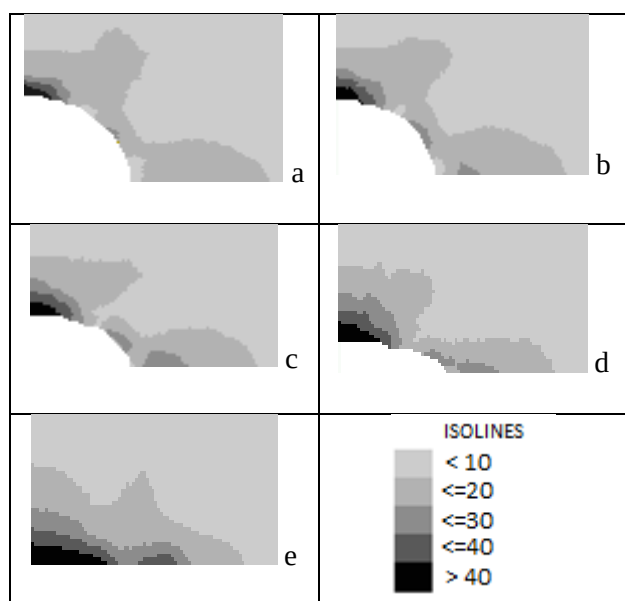


Fig. 3: Distribution of stress intensity  $p_u$  in the vicinity of a stress concentrator (1/4 part)

Source: created by the authors.

When a plate with a horizontal rectilinear crack in the center is stretched, its surfaces shift in directions perpendicular to the crack faces. The maximum values of the strain intensity  $p_u$  in the material are concentrated in a small vicinity of the crack tip, due to the small radius of curvature. The effect of the hole on the deformation of the structural matrix in the vicinity of A is an order of

magnitude smaller than in the upper part (the values of  $p_u$  and  $p_v$ ). However, when the  $r_2 / r_1$  ratio reaches zero (i.e., toward the crack), their values increase sharply (Table 3).

Figure 4 shows a graph of the change in the tangential stress component  $\tau_{xy}$  and strain intensity  $p_u$  along the isotropy plane  $XOY$  as a function of the  $r_2 / r_1$  ratio. Analysis of the calculation results shows that for  $r_2 / r_1$  ratio values close to zero, i.e., at  $r_2 / r_1 = 0$  (crack) and  $1/8$  (horizontally oblate ellipse), the shear stresses are positive. As the  $r_2 / r_1$  ratio increases, starting from  $1/4$  and onward, the shear stresses become negative, reaching a maximum at  $r_2 / r_1 = 1$  (circle). Since shear stresses usually lead to a change in shape, the change in sign with decreasing height of the elliptical hole indicates that at  $r_2 / r_1 < 0.2$ , higher tensile stresses occur near point A.

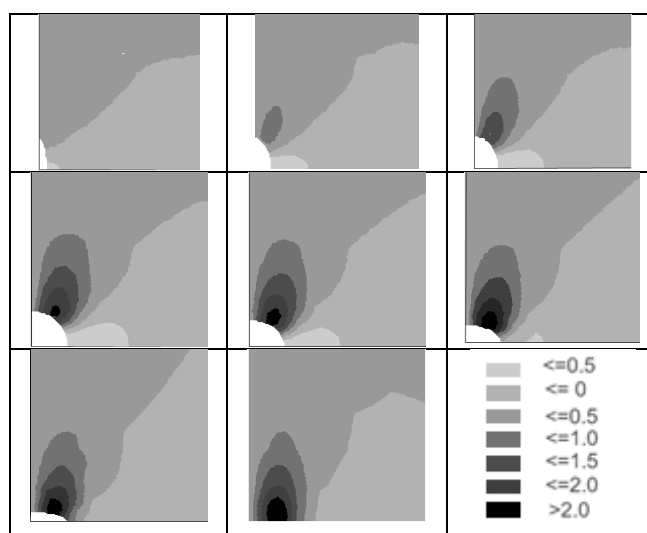


Fig. 4: Displacements of the zone of maximum stresses (tangential stress component  $\tau_{xy}$  and strain intensity  $p_u$ ) (1/4 part)

Source: created by the authors.

Unidirectional materials have poor shear resistance, which leads to the formation of cracks in places where the shear stress reaches its maximum. These cracks propagate along the fibers across the entire length of the sample, leading to its destruction. In this regard, a computational experiment was conducted to determine the region where the maximum shear stresses  $\tau_{xy}$  are concentrated for various hole shapes, ranging from a vertically elongated ellipse to horizontally compressed ones (the values of the  $r_2 / r_1$  ratio are

given in Table 2). The results of the experiment are presented in Figure 4. It was found that for the values of ratio  $r_2 / r_1 = 1$  (circle) and less (ellipse), a stable zone with maximum  $\tau_{xy}$  values is formed in the region around the hole. As the height  $r_2$  of an elliptical hole decreases (at the constant value of  $r_2 / r_1 = 0.05$ ), the zone of maximum stress encompasses the contour of the hole, while in crack-related problems, the region with maximum stresses is formed near the vertices (Figure 4). These areas are the most vulnerable in fiber structures with holes, and it is here that separation of the matrix from the high-strength fibers occurs.

Thus, the computational experiment enabled us to examine how the shape of holes in fiber composite structures affects their performance. Specifically, we aimed to identify the areas with the highest shear stresses that can lead to matrix separation from the fibers.

## 5 Conclusion

A computational experiment was conducted to investigate the influence of a hole shape on the stress-strain state of structures with holes, made of fibrous materials. Our investigation revealed that, when the radius ratio of an elliptical hole is less than 0.2, maximum shear stress occurs near the side surface of the hole. This condition can result in the separation of the matrix from the high-strength fibers.

### Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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### **Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)**

- A.M. Polatov formulated the research goal and objectives, supervised and managed the implementation of research activities.
- A.M. Ikramov applied computational research methods and developed software for solving problem, was responsible for data visualization.
- Adambaev and S.I. Pulatov implemented computer software code and tested programs.

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### **Conflict of Interest**

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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