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Numerical Simulation of Composite Structure Failure in the Areas of Geometric Discontinuities

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The paper is directed to the failure analysis in layered composite structures with a special view on the impact of geometrical discontinuities on the stress level during which initial failure occurs.

A special attention in the paper has been directed to the strength analysis of layered composite structures in the area of mechanically fastened joints. The emphasis of the paper is on establishing a suitable numerical procedure for the initial failure analysis of mechanically fastened joints of layered composites. To determine stress distribution around the hole, the finite element method (FEM) was used. The failure of a mechanically fastened joint was determined by combining the Chang-Scott-Springer model of the characteristic curve [1] and the Tsai-Wu initial failure criterion. The finite element model, which simulates the contact between the lug and the pin, was used for the analysis. The numerical results were compared to author's own experimental results where good agreement is obtained.

Key words: **composite materials, layered structure, mechanically fastened joint, initial failure, failure analysis, stress analysis, finite element method.**

Introduction

DUE to their good mechanical characteristics, layered composite materials have found broad application in airplane industry, because of their good weight/load ratio. Composite structural elements are connected to other elements by mechanically fastened joints because of low price, simplicity and ease of assembling and disassembling. Drilled holes significantly reduce the load carrying capacity of composites due to the stress concentration in the vicinity of the hole boundary. This load reduction can lead to failure. Due to anisotropic and heterogenic nature of composites, these mechanically fastened joints are much more complicated for analysis than those made of isotropic materials; therefore, many authors studied strength of mechanically fastened composite joints [1-19]. Parameters such as joint geometry and fiber orientation, i.e. layers stacking sequence, have an important role in studying these structures.

Several methods were used in papers done so far to evaluate the strength of mechanically fastened joints [1-17]. One of the most frequently used prediction methods is the Chang's model. In this model the failure of mechanically fastened joint occurs when certain combined stresses have exceeded a prescribed value in any of plies along the characteristic curve. The combined stress limit is evaluated using the Yamada-Sun failure criterion [1-6]. The work methodology in this paper is based on defining the characteristic curve, determining stress conditions and using an appropriate initial failure criterion. Stress distributions in the plate are calculated and then a failure criterion is tested. If there is no failure, the load is increased. In the case of failure, material properties of failure nodes are reduced to appropriate property degradation rules. Stresses are then redistributed at the same load and re-examined for any additional failures. The procedure continues to a point where excessive damage is reached [7–17]. In earlier works, Icten et al. [14] established the behavior of mechanically fastened joints in woven glass-epoxy composites with $[(0/90)3]_s$ and $[(\pm45)3]_s$ material configurations. The failure analysis based on Hashin and Hoffman criteria was performed and compared with experimental results. Okutan and Karakuzu [15] studied on the response of pin loaded laminated E/glass-epoxy composites for two different ply orientations such as $[0/\pm45]_s$ and $[90/\pm45]_s$. The goal of this work is to study numerically the behavior of graphite-epoxy pin loaded joints with particular attention given to the sensitivity of the model to different geometric dimensions. A two-dimensional finite element method was used to obtain stress distribution in the joint. The Tsai-Wu initial failure criterion was used to determine the failure load. The mechanical properties of the composite material are obtained from standard tests [9, 10, 20, 21]. In this analysis, based on the Chang et al. strength prediction model [1], the point stress failure criterion will be used to evaluate the characteristic lengths in tension and compression and a two-dimensional finite element analysis used to evaluate the stress distribution in the vicinity of the joint.

By combining FEM for stress condition analysis and certain failure criteria along the characteristic curve composite structure optimization can be performed in the area of mechanically fastened joints [5, 27].

Compressive and tensile characteristic length determination method

When a laminate is loaded through a fastener, such as pin or bolt, both sides of the fastener hole are subjected to

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high tensile stress due to stress concentration. On the other hand, the front-area of the fastener hole experiences high compressive stress. Furthermore, as applied load increases and laminate deforms the contact surface between the fastener and the laminate changes.

This is why it is considered that the interface stress condition is not standard for determining the strength of mechanically fastened composite joints.

A practical method considered to predict the failure load of composite joints with the least amount of testing is the characteristic length method. This method was proposed by Whitney and Nuismer [24, 25], and has been developed by Chang et al. [3–8]. It is still used for the failure analysis of composite joints [26]. In the characteristic length method, two parameters, i.e. compressive and tensile characteristic length should be determined by the stress analysis associated with the results of bearing and tensile tests on the laminates with and without hole. Once the characteristic lengths are determined, an artificial curve connecting the compressive and tensile characteristic lengths named characteristic curve is assumed [1]. Failure of a joint is evaluated on the characteristic curve, not on the edge of the fastener hole. In this method the joint is taken to have failed when certain combined stresses have exceeded a prescribed value in any of the plies along the characteristic curve.

In order to evaluate the strength of composite pinned joints, Fig. 1, the stress distribution along a characteristic dimension around the hole must be first evaluated. The conditions for failure can then be predicted with the aid of an appropriate failure criterion. The Tsai-Wu failure criterion was used for this analysis. This criterion can be written as:

$$\begin{aligned}(F.I) &= F_1\sigma_1 + F_2\sigma_2 + F_6\sigma_6 + F_{11}\sigma_1^2 + F_{11}\sigma_1^2 \\ &\quad + F_{22}\sigma_{21}^2 + F_{66}\sigma_6^2 F + 2F_{12}\sigma_1\sigma_2\end{aligned}$$

$$\begin{aligned}&F_1 = \frac{1}{X_t} + \frac{1}{X_C} F_2 = \frac{1}{Y_t} + \frac{1}{Y_C} F_6 + 0 \\ &F_{11} = -\frac{1}{X_t X_C} F_{22} = -\frac{1}{Y_t Y_C} F_{66} = \frac{1}{S^2} F_{12} = 0\end{aligned} \tag{1}$$

where $F.I$ is the failure index, σ_i (i=1, 2, 6) are the stress components with respect to the material principal direction, $X_{t,C}$, $Y_{t,C}$ are the longitudinal and transverse tensile/compressive strength of the unidirectional lamina, and S is the ply shear strength. Based on this model, failure is expected to occur when, at any point of the characteristic curve, the failure index is great or equal to unity.

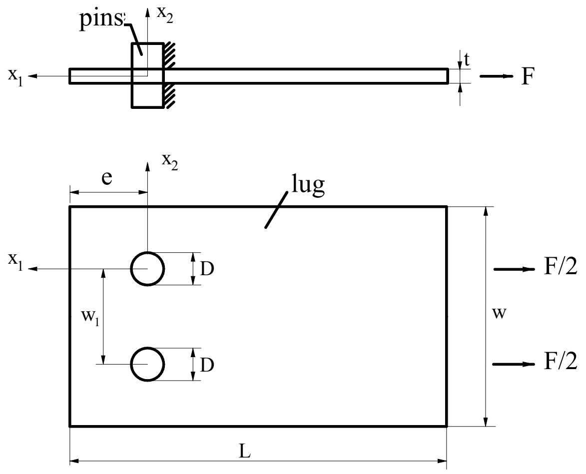


Figure 1. Geometry of the layered composite plate subjected to the pin

In Fig.1, the geometry of the mechanically fastened composite joint discussed in the paper is shown. The figure depicts composite mechanical fastened joints made from CFC laminates utilizing two steel pins.

At a certain distance from both holes, the characteristic curve is defined. The characteristic curve is an artificial curve made of compressive and tensile characteristic lengths. Since the characteristic lengths are determined just for compression and tension, other combined failure modes are evaluated on the characteristic curve.

A popular method to construct the characteristic curve is proposed by Chang and Scott [1]. The characteristic curve is expressed as follows:

$$r_C(\theta) = R + R_t + (R_C - R_t)\cos\theta \tag{2}$$

where R_{0C} and R_{0t} are compressive and tensile characteristic length, respectively. The angle θ is measured counter-clockwise or clockwise from the loaded direction toward the sides of the fastener hole as shown in Fig.2.

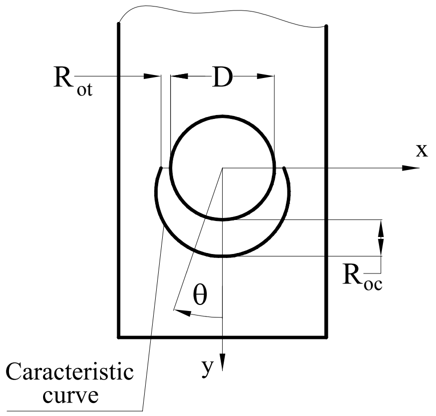


Figure 2. Characteristic curve s*chematic diagram*

The ultimate failure of a joint is generally divided into three modes depending on the failure location, θ_f [1].

$$\begin{aligned}&0^\circ < \theta_f < 15^\circ \text{ Baring mode} \\ &30^\circ < \theta_f < 60^\circ \text{ Shear-out mode} \\ &75^\circ < \theta_f < 90^\circ \text{ Net-tension mode}\end{aligned} \tag{3}$$

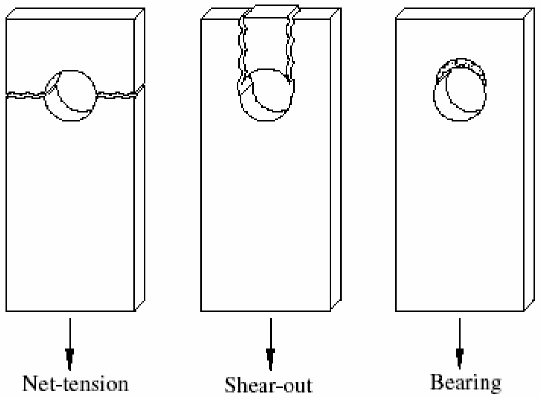


Figure 3. Illustration of three basic failure modes

There are in general three main failure modes: net tension, shear out and bearing as shown in Fig.3. Net tension and shear out modes are catastrophic and result from excessive tensile and shear stresses. Bearing mode is local failure and progressive, and related to compressive failure. Net tension and shear out modes can be avoided by increasing the end distance (e) and width (w) of the structural part for a given thickness but bearing failure cannot be avoided by any modification of the geometry.

Failure of mechanically fastened joints

To determine the failure load of the mechanical fastened joint the procedure is composed of the stress analysis and the failure analysis using adequate initial failure criteria along the characteristic curve.

The strategy for the finite element modeling of the joints is the same as in the finite element model of the laminate for bearing tests shown in Fig.4. The nonlinear finite element analysis for the joints is conducted by MSC/NASTRAN [27]. The interface between fasteners and laminates is modeled by the slide line contact element provided by the software. The slide line element in MSC/NASTRAN was adopted to simulate the contact between the pins and the laminates. The pin and the laminate were modeled using CQUAD4 shell elements.

Force was applied to the pin as uniformly distributed load. The analysis was done with a half of the model, considering the fact that it is symmetrical on the longitudinal axis. A typical finite element model of the mechanically fastened joint is shown in Fig.4.

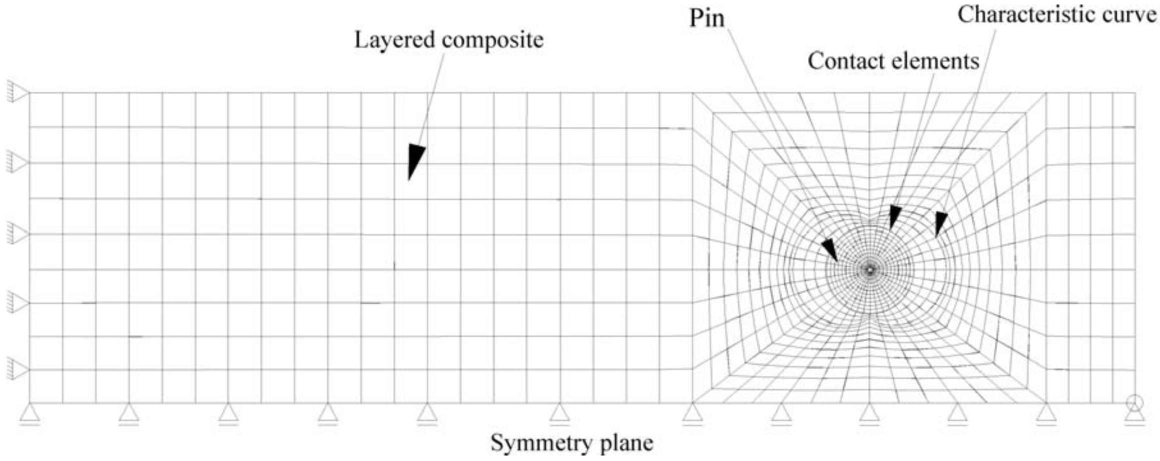


Figure 4. Finite elements model of the mechanically fastened composite joint

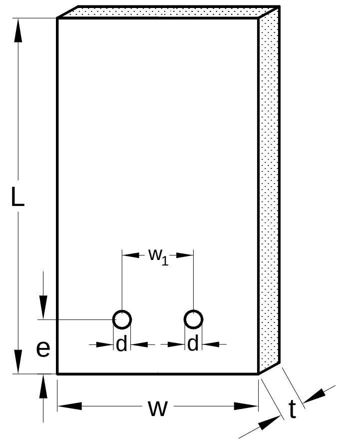
In this paper the problem of mechanically fastened joints of a laminated composite plate with frictional contact conditions is analyzed. The Coulomb friction law is used and the contact constraints are handled by extended interior penalty methods. The perturbed variation principle is adopted to treat the non-differential term due to the coulomb friction. The computed result by our formulations is compared with the experimental result. The experimental result is assumed from Report V9-492-P023 [27].

Numerical verification

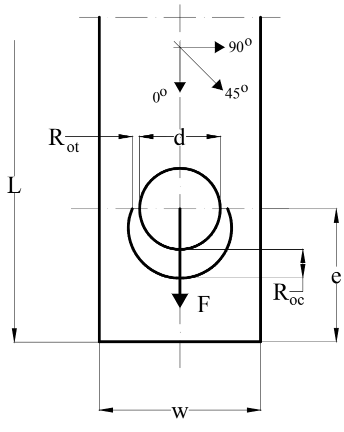
To validate computation procedure of mechanical fastened joints, a numerical example is included. The geometry properties of the mechanical fastened joint at composite structure are shown in Fig.5 and in Table 1. The finite element model of the contact problem of pin-loaded joint is shown in Fig.6. The lug and the pins are made of CFC composite and steel materials, respectively. The mechanical properties of these materials are given in Tables 2 and 3.

Table 1. Geometrical characteristics of the mechanically fastened composite joint

With of the pin	$w = 56\,\mathrm{mm}$
Space between the holes	$w_1 = 24\,\mathrm{mm}$
Hole diameter	$d = 8\,\mathrm{mm}$
Length of the lug	$L = 100\,\mathrm{mm}$
Space from the lug edge to the hole center	$e = 24\,\mathrm{mm}$
Thickness of the lug	$t = 3.9\,\mathrm{mm}$



Composite lug



b) Geometry properties of fastened joint at composite structure

Figure 5. Geometry properties of mechanical fastened joints at composites

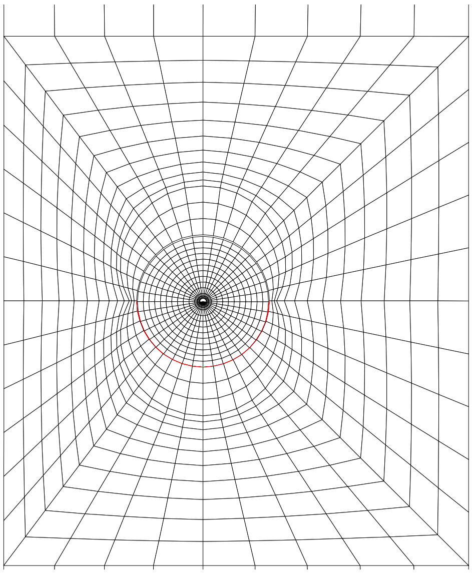


Figure 6. Finite element model of the contact problem of the pin-loaded joint

The geometric factors, clearances and friction play important roles in determining contact stress. With variations of these factors, it can be found that each point takes a different magnitude of pin loading, and extended parametric studies on these factors may be needed for design consideration.

Table 2: Mechanical properties of CFC material:

Longitudinal Young's Modulus	$E_{11} = 14686\,\frac{\text{daN}}{\text{mm}^2}$
Transverse Young's Modulus	$E_{22} = 1172\,\frac{\text{daN}}{\text{mm}^2}$
Shear Modulus	$G_{12} = 618\,\frac{\text{daN}}{\text{mm}^2}$
Poisson's Ratio	$\nu = 0.3$
Longitudinal Tensile Strength	$F_{11}^{T} = 136.2\,\frac{\text{daN}}{\text{mm}^2}$
Longitudinal Compressive Strength	$F_{11}^{C} = 133\,\frac{\text{daN}}{\text{mm}^2}$
Transverse Tensile Strength	$F_{22}^{T} = 4.2\,\frac{\text{daN}}{\text{mm}^2}$
Transverse Compressive Strength	$F_{22}^{C} = 17.2\,\frac{\text{daN}}{\text{mm}^2}$
Rail Shear Strength	$F_{12} = 4.9\,\frac{\text{daN}}{\text{mm}^2}$
One Layer Thickness	$t = 0.13\,\text{mm}$

Table 3. Mechanical properties of pin

Young's Modulus	$E_{12} = 21000\,\frac{\text{daN}}{\text{mm}^2}$
Shear Modulus	$G_{12} = 8140\,\frac{\text{daN}}{\text{mm}^2}$
Poisson's Ratio	$\nu = 0.29$
Ultimate Tensile Strength	$\sigma_{doz} = 125\,\frac{\text{daN}}{\text{mm}^2}$
Ultimate Shear Strength	$\tau_{doz} = 80\,\frac{\text{daN}}{\text{mm}^2}$
Static Friction Coefficient	$\mu = 0.25$

The comparisons of the computation with the experimental results are given in Table 4. The difference between the experimental and the numerical failure force is 1.03%.

Table 4. Comparisons of the computation and the experimental results

Stacking sequence	$\begin{bmatrix} \pm 45°/0°_3/\pm 45°/0°/ \\ 90°/0°_2/\pm 45°/0°_2 \end{bmatrix}_S$
Tensile characteristic length	$R_{ot} = 0.437\,\text{mm}$
Compressive characteristic length	$R_{oc} = 2.949\,\text{mm}$
Experimental failure load	$F^{\exp} = 2296.25\,\text{daN}$
Failure index for experimental load	$F.I.^{\exp} = 0.98$
Numerical failure load	$F^{num} = 2320\,\text{daN}$
Failure index for numerical failure load	$F.I.^{num} = 1$
Difference between $F^{\exp}$ and F^{num}	1.03 %
Failure mode	tension

The failure index distribution for the experimental and the numerical load is shown in figures 7-10.

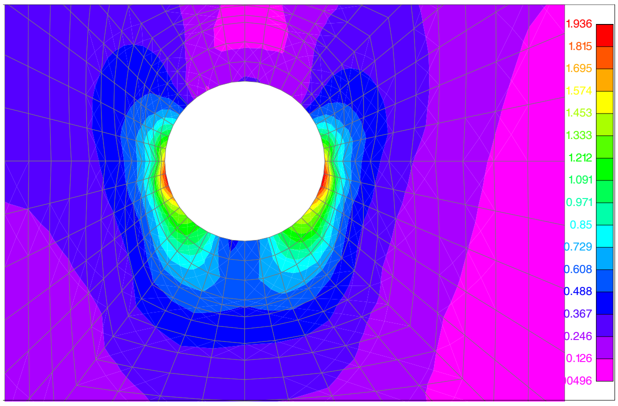


Figure 7. Failure index distribution for the experimental load (F=2295.25 daN)

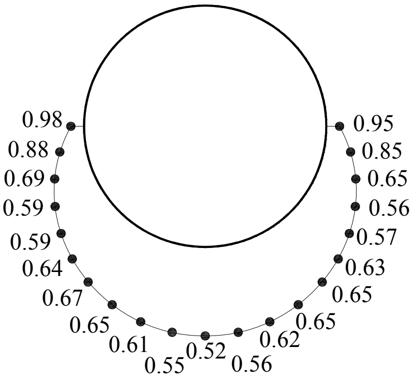


Figure 8. Failure index distribution along the characteristic curve for the experimental load (F=2296.25 daN)

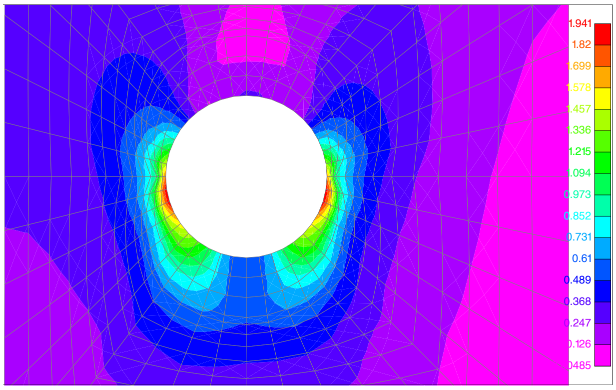


Figure 9. Failure index distribution for the numerical failure load (F=2320 daN)

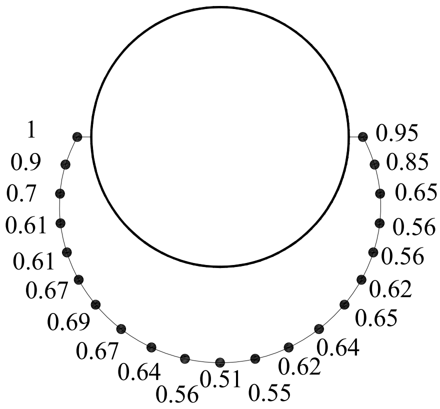


Figure 10. Failure index distribution along the characteristic curve for the numerical failure load (F=2300 daN)

The Coulomb friction law is used and the contact constraints are handled by extended interior penalty methods. The perturbed variation principle is adopted to treat the non-differential term due to the coulomb friction. The computed results by previous formulation are compared with experimental results. Good agreement between the computation and the experimental results is obtained.

Conclusions

In this paper, a numerical and experimental study on the failure load and failure mode of pin loaded composite joints is presented. In the numerical study, the Tsai-Wu failure criterion is used to predict the failure load and failure mode. For the verification of the computation method, the composite laminated joint was examined and compared with the test result. The experimental result concerning the ultimate strength of the joint is obtained and compared with these predictions. To develop the full bearing strength the critical values of in-plane geometric parameters are investigated. The Coulomb friction law is used and the contact constraints are handled by extended interior penalty methods. The perturbed variation principle is adopted to treat the non-differential term due to the coulomb friction. It is seen that the results obtained numerically and experimentally are close to each other. It is shown that the proposed numerical method predicts the strength of composite joints under pin loading with 1% difference from the test results.

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Numerička simulacija otkaza kompozitnih struktura u zonama geometrijskih diskontinuiteta

Rad je usmeren na analizu otkaza kod višeslojnih kompoznih sturktura sa posebnim osvrtom na uticaj geometrijskih diskontinuiteta na nivo opterećenja pri kome se javlja inicijalni lom.
Posebna pažnja u radu je usmerena na analizu čvrstoće višeslojnih kompozitnih struktura u zoni mehaničkih spojeva. Težište rada je stavljeno na uspostavljanje pogodne numeričke procedure za analizu inicijalnog otkaza mehaničkih spojeva višeslojnih kompozita. Za određivanje raspodele napona oko otvora je korišćena metoda konačnih elemenata (MKE). Otkaz mehaničkog spoja je određen kombinujući Chang-Scott-Springer model karakteristične krive [1] i Tsai-Wu kriterijum inicijalnog loma. Za analizu je korišćen model konačnih elemenata koji simulira kontakt između uške i osovinice. Numerički rezultati su poređeni sa eksperimentalnim rezultatima gde je uočeno dobro slaganje.

Ključne reči: **kompozitni materijali, višeslojna struktura, mehanički spoj, inicijalni otkaz, analiza otkaza, analiza napona, metoda konačnih elemenata.**

Цифровая симуляция отказа композитных структур в зонах геометрических дисконтинуитетов

Настоящая работа направлена к анализу отказов у многослоистых структур с особой оглядкой на влияние геометрических дисконтинуитетов на уровень нагрузки, при которой появляется первоначальный излом.
Особое внимание в работе направлено к анализу жёсткости многослоистых композитных структур в зоне механических соединений. Центр тяжести в работе находится на восстановлении подходящего цифрового процесса для анализа первоначального отказа механических соединений многослоистых композитов. Для определения распределения напряжения около отверствия пользован метод конечных элементов (МКЭ). Отказ механического соединения определён комбинированием Цханг-Сцотт-Спрингер модели характерной кривой Ш1Я и Тсаи-Ыу критерия первоначального излома. Для анализа пользована модель конечных элементов, симулирующая контакт между ушком и шпилькой. Цифровые результаты сравниваны с экспериментальными результатами, где обнаружено хорошее взаимное согласие.

Ключевые слова: композитные материалы, многослойная структура, механическое соприкосновение, первоначальный отказ, анализ отказа, анализ напряжения, метод конечных элементов.

Simulation numérique de la défaillance chez les structures composites dans les zones des discontinuités géométriques

L'analyse de la défaillance chez les structures composites par couches et les effets des discontinuités géométriques sur le niveau des charges qui provoquent la fissure initiale font l'objet de cette étude. On a prêté grande attention à l'analyse de la dureté des structures composites par couches dans les zones des jointures mécaniques. La création d'un procédé numérique convenable à l'analyse de la défaillance initiale chez les jointures mécaniques des composites par couches était au centre de cette recherche. Pour déterminer la distribution de la tension autour de l'ouverture on a utilisé la méthode des éléments finis (MKE). La défaillance de la jointure mécanique a été déterminée en combinant le modèle de la courbe caractéristique selon Chang-Scott-Springer avec le critère de la fissure initiale selon Tsai -Wu. Le modèle des éléments finis qui simule le contact entre l'épinglette et le tirant est appliqué au cours de l'analyse. La comparaison a démontré qu'il y avait un bon accord entre les résultats numériques et les résultats expérimentaux.

Mots clés: **matériaux composites, structures composites, jointure mécanique défaillance initiale, analyse de défaillance, analyse de tension, méthode des éléments finis.**