Stevan Maksimović, Ivana Ilić

ANALIZA ČVRSTOĆE MEHANIČKIH SPOJEVA VIJCIMA KOMPOZITNIH PLOČA

STRENGTH ANALYSIS OF MECHANICALLY FASTENED JOINTS ON COMPOSITE PLATES

Originalni naučni rad / Original scientific paper
UDK /UDC: 620.17:621.882
Rad primljen / Paper received: 10.4.2008

Adresa autora / Author's address:
Vojnotehnički institut, Beograd, Ratka Resanovića 1,
s.maksimovic@net.yu

Ključne reči

- kompoziti
- spojevi podešenim vijcima
- analiza otkaza
- metoda konačnih elemenata (MKE)
- kontaktni problem

Izvod

Članak je posvećen analizi loma višeslojnih kompozitnih konstrukcija sa posebnim osvrtom na uticaj geometrijskih diskontinuiteta na nivo napona pri kome dolazi do inicijalnog otkaza. Rad razmatra čvrstoću slojevitih kompozitnih struktura sa otvorima za vijke. Cilj istraživanja je razvoj pouzdane numeričke procedure za određivanje nivoa opterećenja pri kome se javlja inicijalni otkaz u višeslojnoj kompozitnoj konstrukciji na mestu kontakta sa vijkom. Metoda konačnih elemenata (MKE) je korišćena da se odredi raspodela napona oko otvora za vijak. Model karakteristične krive Čang-Skot-Špringer i kriterijum Cai-Vu inicijalnog loma su korišćeni za određivanje otkaza spoja. Posebna pažnja u radu je usmerena na raspodelu opterećenja sa stabla vijka i njen uticaj na nivo opterećenja otkaza i položaj otkaza. Pri tom je analiziran kontaktni model konačnih elemenata vijak-uška. Analiziran je i uticaj sekvence slaganja kompozita sa otvorima za vijak. Saglasnost rezultata proračuna sa sopstvenim i dostupnim eksperimentalnim rezultatima je vrlo dobra.

UVOD

Kompoziti ojačani vlaknima se intenzivno koriste za proizvodnju aviona i letilica zbog njihovog dobrog odnosa težina-opterećenje. Konstrukcijske komponente od kompozita se često spajaju sa drugim komponentama pomoću vijčanih mehaničkih spojeva zbog niske cene, jednostavnosti i lake montaže ili demontaže. Međutim, izbušeni otvori znatno smanjuju nosivost kompozita zbog koncentracije napona u blizini ivice otvora. Ovo smanjenje nosivosti može da dovede do katastrofalnog otkaza. Zbog toga posebna pažnja mora da se posveti projektovanju mehaničkih spojeva tipa kompozitna uška-podešeni vijak.

Zbog anizotropije i heterogene prirode, problemi spojeva konstrukcija od kompozitnih materijala su mnogo složeniji nego kod izotropnih materijala. Kako je problem značajan, mnogi istraživači su proučavali čvrstoću mehaničkih spojeva vijcima u konstrukcijama od kompozitnih materijala, /1–19/.

Keywords

- composites
- pin-loaded joints
- failure analysis
- finite element method (FEM)
- contact problem

Abstract

This paper is devoted to the failure analysis in multi-layered composite structures with special view on impact of geometrical discontinuities on stress level at which initial failure occurs. The paper considers strength of layered components containing pin-loaded holes. The investigation is focused on developing reliable computation procedure to analyze initial failure load for pin-loaded holes at the layered composite structures. Finite element method (FEM) is used to determine stress distribution around the fastener hole. Chang-Scott-Springer characteristic curve model and Tsai-Wu initial failure criterion are used to determine joint failure. Special attention in this work is focused on pin-load distribution from bolt body and its effect on load level and location of failure. Here the contact finite element pin-lug model is analysed. The influence of stacking sequences of layered composites containing pin-loaded holes is investigated too. Very good correlation is obtained by comparison of computational results with own and available experimental results.

INTRODUCTION

Fibre reinforced composites have been used extensively in aircraft and spacecraft constructions because of their high strength-weight ratios. Composite structural components are generally joined with other components by means of bolted joints because of low cost, simplicity and easy to assemble or disassemble. However, drilled holes significantly reduce load carrying capacity of composites due to stress concentration in the vicinity of the hole boundary. This carrying capacity reduction can cause catastrophic failure. Therefore special attention must be paid to the design of mechanically fastened joints as composite lug-bolt.

Due to the anisotropy and heterogeneous nature, joint problems in composite structures are more difficult for analyses than those in isotropic materials. Since this problem is important, many investigators have studied the strength of mechanically fastened joints in composite structures, /1–19/.

Faktori kao što je geometrija spoja i orijentacija vlakana su važni parametri za mehanički spojeve vijcima u kompozitnim pločama.

Za ocenu čvrstoće spojeva vijcima predloženo je nekoliko metoda predviđanja otkaza. Jedna od glavnih metoda za predviđanje otkaza je model Čanga, /1, 3, 4/. U ovom modelu je pretpostavljeno da do otkaza spoja dolazi kada kombinovano stanje napona pređe određenu vrednost u bilo kom sloju kompozita duž karakteristične krive. Kombinovano stanje napona koje dovodi do otkaza definisano je kriterijumom Jamada-San, /1–6/. Druga metoda predviđanja otkaza je model progresivnog oštećenja. U ovom modelu logična metodologija modelovanja problema spoja obuhvata tri važna koraka: analizu napona, kriterijume loma i pravila degradacije karakteristika materijala. Prvo se sračuna stanje napona u ploči, a zatim se ispituje kriterijum otkaza. Ako do otkaza nije došlo povećava se opterećenje. U slučaju otkaza, karakteristike materijala u čvorovima duž karakteristične krive se smanjuju na prikladnu vrednost prema pravilu degradacije. Zatim se preraspoređuje napon za isto opterećenje i analiziraju se mogući otkazi. Postupak se sprovodi sve do tačke dostizanja prevelikog oštećenja, /10, 11/. U ranijim radovima, Ikten i saradnici, /14/, su utvrdili ponašanje mehaničkih spojeva vijcima u tkanom kompozitu staklo-epoksi za oblikovanje materijala, [(0/90)3]s i [(±45)3]s. Analiza otkaza bila je zasnovana na kriterijumu Hašina i Hofmana i upoređena je sa eksperimentalnim rezultatima. Okutan i Karakuzu, /15/, su izučavali ponašanje mehaničkog spoja vijcima kompozita E/staklo-epoksi za dve različite sekvence slaganja slojeva, [0/ ± 45]s i [90/ ± 45]s.

Predmet ovog rada je proučavanje ponašanja mehaničkog spoja tipa grafit-epoksi podešenim vijcima numerički i eksperimentalno, sa posebnom pažnjom posvećenom osetljivosti modela na različite geometrijske dimenzije. Dvodimenzionalna metoda konačnih elemenata (MKE) je korišćena da se dobije raspodela napona u materijalu. Za određivanje opterećenja otkaza i modela predviđanja oštećenja i oblika otkaza korišćen je kriterijum Cai-Vu. Mehaničke osobine kompozitnog materijala su određene standardnim ispitivanja, /9, 10, 20, 21/.

Nelinearna analiza konačnim elementima mehaničkog spoja vijcima je izvedena pomoću MSC/NASTRAN, /27/. Interfejs između stabla vijaka i laminata (kompozitne uške) je modeliran kontaktnim linijama kliznih linija, ugrađenih u softver. Detaljni opis MKE kontaktnog problema može se naći u referencama /2, 21, 23/.

METODA KARAKTERISTIČNE DUŽINE

Kada je laminatna konstrukcija opterećena preko podešenog vijka, sl. 1, obe strane oko otvora za vijak su izložene visokom naponu zatezanja zbog koncentracije napona. Sa druge strane, čeona površina otvora za vijak je izložena visokom naponu pritiska. Sem toga, kako se povećava delujuće opterećenje i laminat deformiše, menja se kontaktna površina između vijka i laminata. Praktična procena nivoa opterećenja otkaza spoja laminata sa najmanje ispitivanja je moguća metodom karakteristične dužine. Ovu su metodu predložili Vitni i Nuismer, /24, 25/, a razvio Čang sa saradnicima, /3–8/. Ona se još uvek koristi za analizu otkaza spojeva kompozita, /26/.

Factors such as joint geometry and fibre orientation are important parameters for mechanically fastened joints in composite plates.

To evaluate the strength of mechanically fastened joints, several prediction methods are proposed. One of the main prediction methods is Chang's model, /1, 3, 4/. In this model the joint is assumed to fail when combined stresses have exceeded a prescribed value in any of the plies along the characteristic curve. The combined stress state producing failure is defined by the Yamada-Sun failure criterion, /1–6/. Another prediction method is the progressive damage model. In this model, the logical methodology for modelling the joint problem is composed of three important steps: stress analysis, failure criteria and rules of material property degradation. Stress state in the plate is calculated first, and then a failure criterion is tested. If there is no failure, the load is increased. In the case of failure, material properties in nodes along the characteristic curve are reduced to an appropriate value according to degradation rules. Stresses are then redistributed at the same load and re-examined for any additional failures. The procedure continues up to a point where excessive damage is reached, /10, 11/. In earlier works, Icten et al., /14/, established the behaviour of mechanically fastened joints in woven glass-epoxy composites with [(0/90)3]s and [(±45)3]s material configurations. The failure analysis based on Hashin and Hoffman criterion 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/ ± 45]s and [90/ ± 45]s.

The objective of this work is to study the behaviour of graphite-epoxy pin-loaded joints numerically and experimentally, with particular attention paid to the sensitivity of the model to different geometry dimensions. The two-dimensional finite element method (FEM) was used to obtain stress distribution in the material. To determine the failure load and prediction model for damage and failure mode, the Tsai-Wu criterion is used. Mechanical properties of the composite material are obtained by standard tests, /9, 10, 20, 21/.

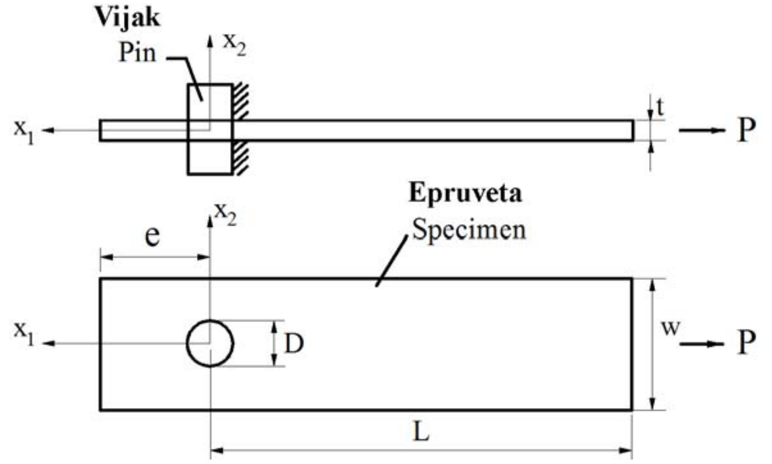
Nonlinear finite element analysis for mechanically fastened joints is conducted by MSC/NASTRAN, /27/. The interface between fasteners and laminates (composite lug) is modelled by the slide line contact element provided by the software. A detailed description of the FEM contact problem can be found in references /2, 21, 23/.

CHARACTERISTIC LENGTH METHOD

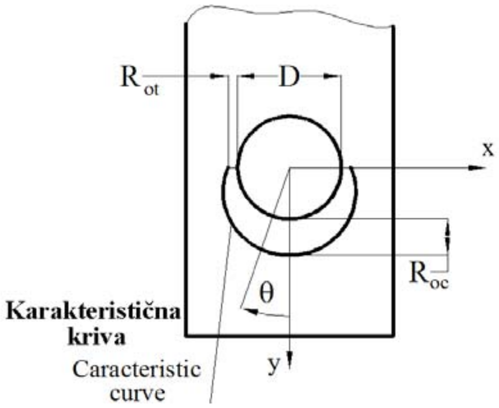
When a laminate structure is loaded through the adjusted bolt, Fig. 1, both sides of the fastener hole are subjected to high tensile stress due to stress concentration. On the other side, the front-area of the fastener hole experiences high compressive stress. In addition, with load increase and laminate deformation, the contact surface between the bolt and the laminate changes. A practical prediction of failure load of composite joints with minimum testing is the characteristic length method. This method was proposed by Whitney and Nuismer /24, 25/, and developed by Chang et al., /3–8/. It is still used for the failure analysis of composite joints, /26/.

U metodi karakteristične dužine, treba odrediti dva parametra, i to karakteristične dužine zatezanja i pritiska, analizom napona dopunjenom rezultatima ispitivanja nosivosti i zatezanja laminata sa i bez otvora. Kada su karakteristične dužine određene, koristi se izvedena kriva koja povezuje karakteristične dužine zatezanja i pritiska, nazvana karakteristična kriva, data na sl. 2, /1/. Otkaz spoja se definiše na karakterističnoj krivoj, a ne na ivici otvora za vijak. U ovoj metodi je usvojeno da je spoj otkazao kada je utvrđena veličina kombinovanih napona prekoračila unapred propisanu vrednost u bilo kom sloju duž karakteristične krive, /2, 3, 5/.

In the characteristic length method, two parameters, i.e. tensile and compressive characteristic lengths should be determined by stress analysis associated with results of carrying capacity and tensile tests of laminates with and without holes. Once the characteristic lengths are determined, a derived curve connecting tensile and compressive characteristic lengths is used, named the characteristic curve, given in Fig. 2, /1/. Joint failure is defined on the characteristic curve, not on the edge of the fastener hole. In this method the joint is considered as failed when certain combined stresses exceed a prescribed value in any ply along the characteristic curve, /2, 3, 5/.



Slika 1. Geometrija kompozitne ploče sa otvorom, spojena vijkom
Figure 1. Geometry of composite plate with circular hole, connected to pin.



Slika 2. Shematski dijagram karakteristične krive
Figure 2. Characteristic curve schematic diagram.

Da bi se ocenila čvrstoća spoja kompozita pomoću vijka, sl. 1, treba prvo poznavati raspodelu napona duž karakteristične dimenzije oko otvora. Uslovi za otkaz se mogu predvideti pomoću odgovarajućeg kriterijuma otkaza. Kriterijum otkaza Cai-Vu je korišćen u ovoj analizi. On može da se napiše u obliku:

In order to evaluate the strength of composite pinned joints, Fig. 1, the stress distribution along a characteristic dimension around the hole has to be known first. The conditions for failure can be predicted with the aid of an appropriate failure criterion. The Tsai-Wu failure criterion is used in this analysis. It can be written in the form:

$$(F.I) = F_1\sigma_1 + F_2\sigma_2 + F_6\sigma_6 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2$$

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c} \quad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c} \quad F_6 = 0$$
$$F_{11} = -\frac{1}{X_t X_c} \quad F_{22} = -\frac{1}{Y_t Y_c} \quad F_{66} = -\frac{1}{S^2} \quad F_{12} = 0 \tag{1}$$

gde su: $(F.I)$–koeficijent inicijalnog otkaza, σ_i (i = 1,2,6)–komponente napona u odnosu na glavne materijalne ose, $X_{t,c}$, $Y_{t,c}$ su zatezna/pritisna čvrstoća u uzdužnom i poprečnom pravcu jednosmerne lamine, dok je S čvrstoća smicanja sloja. U ovom modelu očekuje se da do otkaza dođe kada vrednost $(F.I)$ bude jednaka ili veća od jedinice.

Karakteristična kriva je projektna kriva, izvedena od karakterističnih dužina pritiska i zatezanja. Kako su karakteristične dužine određene upravo za čist pritisak i zatezanje, drugi kombinovani oblici otkaza se određuju na samoj karakterističnoj krivoj.

Opšte prihvaćenu metodu za definisanje karakteristične krive su predložili Čang i Skot, /1/. Karakteristična kriva je izražena na sledeći način:

where: $(F.I)$–failure index, σ_i (i = 1,2,6)–stress components with respect to material principal axes, and $X_{t,c}$, $Y_{t,c}$–longitudinal and transversal tensile/compressive strengths in an unidirectional lamina, and S–ply shear strength. In this model, failure is expected when the value of $(F.I)$ is equal or greater than unity.

The characteristic curve is a design curve, made of compressive and tensile characteristic lengths. Since characteristic lengths are determined just for pure compression and tension, other combined failure modes are determined from the characteristic curve.

A generally accepted method for defining the characteristic curve is proposed by Chang and Scott, /1/. The characteristic curve is expressed as follows:

$$r_c(\theta) = R + R_{ot} + \left(R_{oc} - R_{ot}\right)\cos(\theta) \tag{2}$$

gde su R_{oc} i R_{ot} karakteristične dužine pritiska i zatezanja, respektivno. Ugao θ se meri u smeru suprotno kazaljke na

where R_{oc} and R_{ot} are compressive and tensile characteristic lengths, respectively. The angle θ is measured countersatu ili u smeru kazaljke na satu, od pravca opterećenja prema stranama otvora za vijak, sl. 2.

Konačni otkaz spoja može biti zatezanjem, smicanjem ili gnječenjem, sl. 3, zavisno od položaja otkaza, θ_f, /1/.

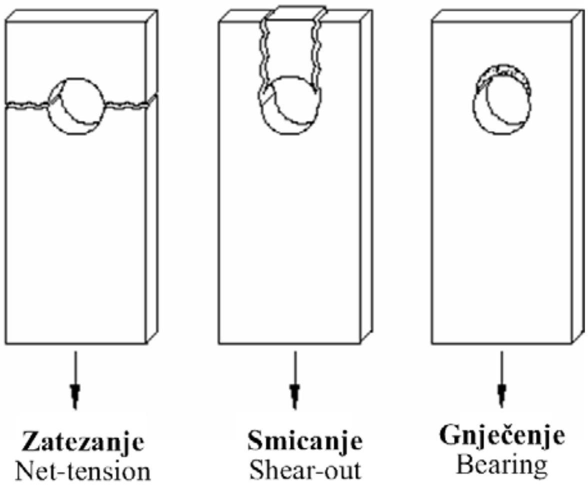
clockwise or clockwise, from the loaded direction toward the sides of the fastener hole, Fig. 2.

Ultimate joint failure can result from net-tension, shear-out or bearing, Fig. 3, depending on failure location, θ_f, /1/.

$$\begin{aligned} 0 \le \theta_f &\le 15^\circ \quad \text{oblik gnječenja (bearing mode)} \\ 30^\circ \le \theta_f &\le 60^\circ \quad \text{oblik smicanja (shear-out mode)} \\ 75^\circ \le \theta_f &\le 90^\circ \quad \text{oblik zatezanja (net-tension mode)} \end{aligned} \qquad (3)$$

Otkazi zatezanjem i smicanjem su katastrofalni i rezultat su prekomernih napona zatezanja ili smicanja. Otkaz gnječenjem je lokalni otkaz i nastupa postepeno, kao otkaz pritiskivanjem. Otkazi zatezanjem i smicanjem se mogu izbeći povećanjem rastojanja do ivice (*e*) i širine (*W*) konstrukcijske komponente pri datoj debljini, ali otkaz gnječenjem ne može da se izbegne bilo kakvom promenom geometrije.

Net-tension and shear-out modes are catastrophic and result from excessive tensile or shear stresses. Bearing mode is a local failure and progressive, 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 component for a given thickness, but bearing failure cannot be avoided by any modification of the geometry.



Slika 3. Prikaz tri osnovna oblika otkaza (zatezanje, smicanje, gnječenje)
Figure 3. Three basic failure modes (net-tension, shear-out, bearing).

OPTEREĆENJE OTKAZA MEHANIČKOG SPOJA

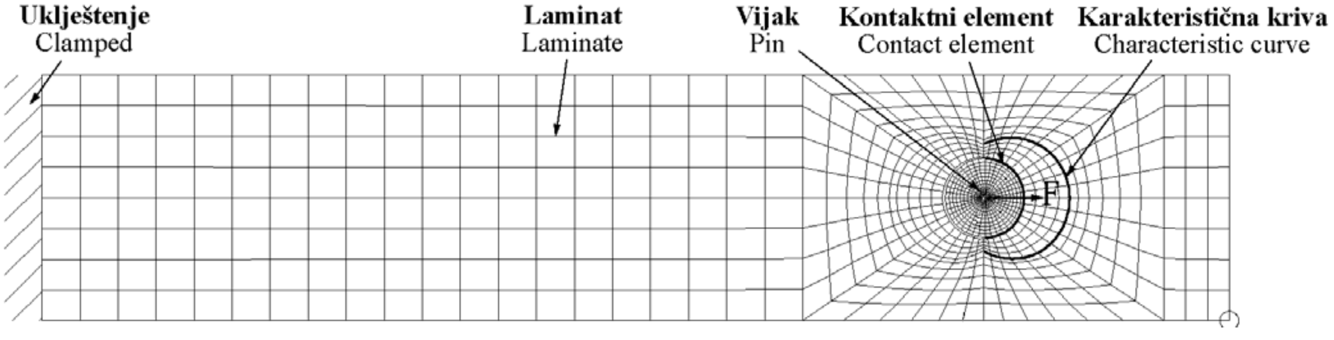
Postupak za određivanje opterećenja otkaza mehaničkog spoja vijkom se sastoji od analize napona i analize otkaza korišćenjem prikladnog inicijalnog kriterijuma loma duž karakteristične krive.

Strategija modelovanja mehaničkog spoja konačnim elementima je ista kao i modelovanja konačnim elementima laminata za test gnječenja. Tipičan model konačnih elemenata mehaničkog spoja vijkom je prikazan na sl. 4.

FAILURE LOAD OF MECHANICALLY FASTENED JOINT

The procedure for determining the failure load of a mechanically fastened joint is composed of stress analysis and failure analysis using adequate initial failure criterion along the characteristic curve.

The strategy for finite element modelling of joints is the same as for finite element modelling of the laminate for bearing tests. A typical finite element model of the mechanically fastened joint is presented in Fig. 4.



Slika 4. Model konačnih elemenata za mehanički spoj vijkom
Figure 4. Finite element model of the mechanical fastened joint.

Nelinearna analiza konačnim elementima za spojeve je izvedena pomoću softvera MSC/NASTRAN, /27/. Interfejs između vijka i laminata je modelovan pomoću kontaktnog elementa linije klizanja, koji je ugrađen u softver. Element linije klizanja u MSC/NASTRAN je prilagođen da simulira kontakt između vijka i laminata. Vijak i laminat su modelovani pomoću CQUAD4 elementa tipa ljuske. Opterećenje na vijku je ravnomerno podeljeno.

U ovom članku je analiziran problem mehaničkih spojeva vijcima kompozitnih laminatnih ploča u uslovima trenja u kontaktu. Primenjen je Kulonov zakon trenja.

Ometanje trenja je razmatrano proširenom metodom unutrašnjih ograničenja. Princip perturbacije promene je prilagođen zbog nediferencijalnog člana Kulonovog trenja. Dobijeni rezultati su provereni numeričkom analizom.

NUMERIČKA VERIFIKACIJA

Da bi se ocenio postupak proračuna mehaničkih spojeva vijkom uključeni su numerički primeri. Geometrijske karakteristike mehaničkog spoja vijkom u kompozitnoj konstrukciji su prikazane na sl. 5. Model konačnih elemenata kontaktnog problema spoja pomoću vijka je prikazan na sl. 6.

Uška je izrađena od CFC kompozita, a vijak je izrađen od čelika. Njihove mehaničke osobine su date u tab. 1. i 2.

Radi poređenja rezultata otkaza mehaničkih spojeva vijcima korišćena je kosinusna raspodela opterećenja.

Rezultati proračuna postupkom prikazanim u ovom članku su upoređeni sa eksperimentalnim rezultatima (tab. 3). Rezultati za slučaj 1 su ilustrovani na sl. 7–10.

Nonlinear finite element analysis for joints is conducted in MSC/NASTRAN software, /27/. The interface between fasteners and laminates is modelled by the slide line contact element provided by the software. The slide line element in MSC/NASTRAN is adopted to simulate contact between pins and laminates. The pin and the laminate were modelled using CQUAD4 shell elements. The loading on the pin is uniformly distributed.

In this article, the problem of mechanically fastened joints of laminated composite plates in conditions of frictional contact is analysed. Coulomb friction law is used.

Contact constraints are handled by extended interior penalty methods. The perturbed variation principle is adopted due to the non-differential term of Coulomb friction. The obtained results are verified by numerical analysis.

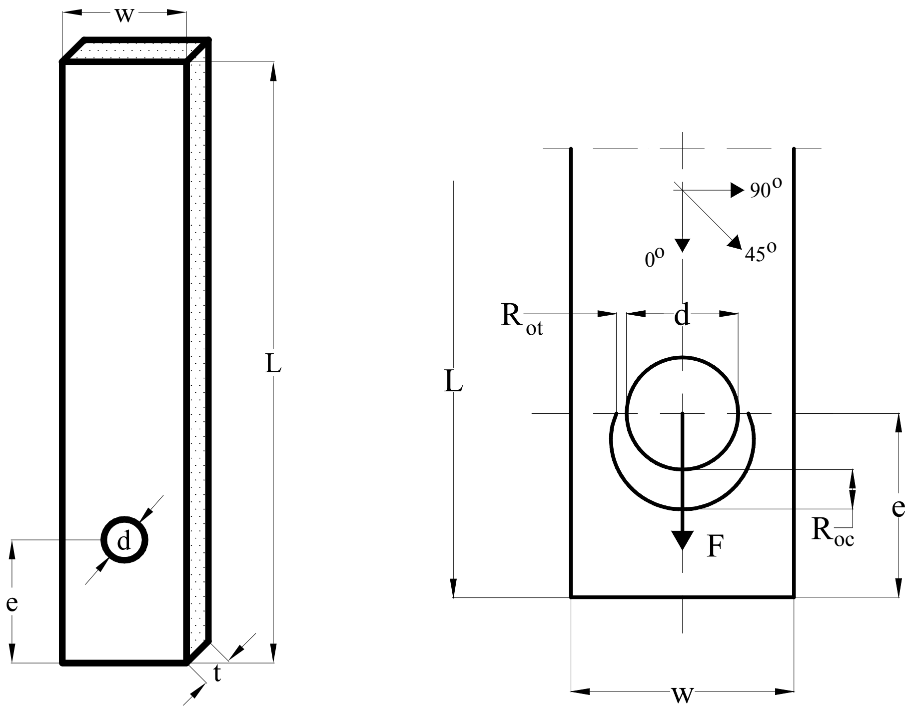
NUMERICAL VERIFICATION

In order to validate the computational procedure of mechanically fastened joints, numerical examples are included. The geometry of the mechanical fastened joint in composite structure are shown in Fig. 5. The finite element model of the contact problem of pin-loaded joint is shown in Fig. 6.

The lug is made of CFC composite, bolt is made of steel. Their mechanical properties are given in Tables 1 and 2.

Comparison of failure results of mechanically fastened joints is enabled by applying a cosine load distribution.

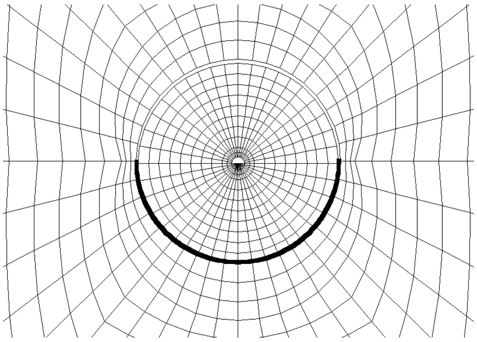
Results computed by procedures presented in this article are compared with experimental results (Table 3). The results for case 1 are illustrated in Figs. 7 to 10.



a) uzorak kompozita
a) composite specimen

b) geometrijski model kontaktnog problema spoja sa vijkom
b) model geometry of contact problem of pin-loaded joint

Slika 5. Geometrijske karakteristike mehaničkog spoja u kompozitu
Figure 5. Geometry of mechanical fastened joint at composites.



Slika 6. Model konačnih elemenata za kontaktni problem spoja preko osovinice
Figure 6. Finite element model of contact problem of pin-loaded joint.

Geometrijski faktori, zazori i trenje imaju važnu ulogu u određivanju kontaktnih napona. Sa promenom tih faktora u svakoj tački se dobija različita veličina opterećenja, pa je dalje parametarsko proučavanje ovih faktora neophodno pri razmatranju konstrukcije.

Tabela 1. Mehaničke osobine CFC materijala

Karakteristika	Oznaka	Veličina	Jedinica
Uzdužni Jungov modul	E_{11}	146 860	MPa
Poprečni Jungov modul	E_{22}	11 720	MPa
Modul klizanja	G_{12}	6180	MPa
Poasonov broj	ν	0,3	–
Uzdužna zatezna čvrstoća	F_{11}^T	1362	MPa
Uzdužna pritisna čvrstoća	F_{11}^C	1330	MPa
Poprečna zatezna čvrstoća	F_{22}^T	42	MPa
Poprečna pritisna čvrstoća	F_{22}^C	172	MPa
Smicajna čvrstoća	F_{12}	49	MPa
Debljina jednog sloja	t	0,139	mm

Tabela 2. Mehaničke osobine čelika vijka

Karakteristika	Oznaka	Veličina	Jedinica
Jungov modul	E_{11}	210 000	MPa
Modul klizanja	G_{12}	81 400	MPa
Poasonov broj	ν	0,29	–
Zatezna čvrstoća	σ_{doz}	1250	MPa
Smicajna čvrstoća	τ_{doz}	800	MPa
Statički koeficijent trenja	μ	0,25	–

Geometry factors, clearance and friction play important roles in determining contact stress. With variation of these factors, a different magnitude of pin loading occurs in each point, and extended parametric studies on these factors may be needed for design considerations.

Table 1. Mechanical properties of CFC material.

Characteristics	Designation	Value	Unit
Longitudinal Young's modulus	E_{11}	146 860	MPa
Transverse Young's modulus	E_{22}	11 720	MPa
Shear modulus	G_{12}	6180	MPa
Poisson's ratio	ν	0.3	–
Longitudinal tensile strength	F_{11}^T	1362	MPa
Longitudinal compressive strength	F_{11}^C	1330	MPa
Transverse tensile strength	F_{22}^T	42	MPa
Transverse compressive strength	F_{22}^C	172	MPa
Real shear strength	F_{12}	49	MPa
One layer thickness	t	0.139	mm

Table 2. Mechanical properties of pin steel.

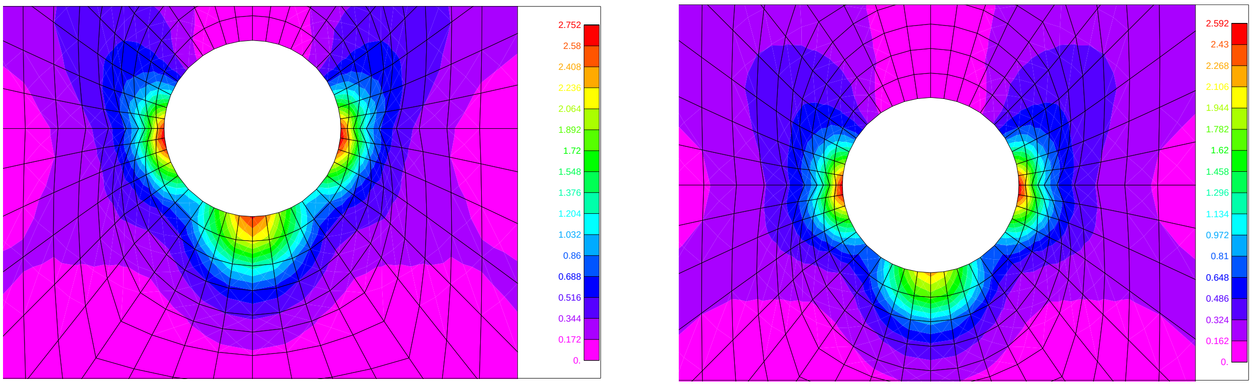
Characteristics	Designation	Value	Unit
Young's modulus	E_{11}	210 000	MPa
Shear modulus	G_{12}	81 400	MPa
Poisson's ratio	ν	0.29	–
Ultimate tensile strength	σ_{doz}	1250	MPa
Ultimate shear strength	τ_{doz}	800	MPa
Static friction coefficient	μ	0.25	–

Tabela 3. Poređenje proračuna i eksperimentalnih rezultata
Table 3. Comparison of computational and experimental results.

Slučaj Case	Slaganje slojeva (Stacking sequence) $[0/(\pm45)_3/90_3]_S$										
	d	e	w	L	R_{ot}	R_{oc}	F^{exp}	$(F.I)^{cont}$	$(F.I)^{cos}$	Tip otkaza	Failure mode
	mm	mm	mm	mm	mm	mm	N	–	–		
1	3,175	9,525	9,525	46	0,457	1,778	56,7	1,03	0,92	Zatezanje	Net-tension
2	6,35	19,05	19,05	93	0,938	2,245	103,4	0,9	0,85	Zatezanje	Net-tension
3	6,35	19,05	31,75	93	1,166	2,395	131,1	0,97	0,87	Gnječenje	Bearing

Tabela 4. Razlike proračuna i eksperimentalnih rezultata
Table 4. Differences of computation and experimental results

Opterećenje otkaza (Failure load) ($F.I = 1$)				Razlika između F^{exp} i F (Difference between F^{exp} and F)	
Kontakt MKE Contact FEM		Kosinusno opterećenje Cosine Load		Kontakt Contact	Kosinusno opterećenje Cosine load
F^{cont}, N	$(F,I)^{cont}$	F^{cos}, N	$(F,I)^{cos}$		
5550	0,99	590	1	–2%	+4%
10 900	1,01	1120	1	+5%	+8%
13 200	0,99	1400	1	+0,7%	+7%

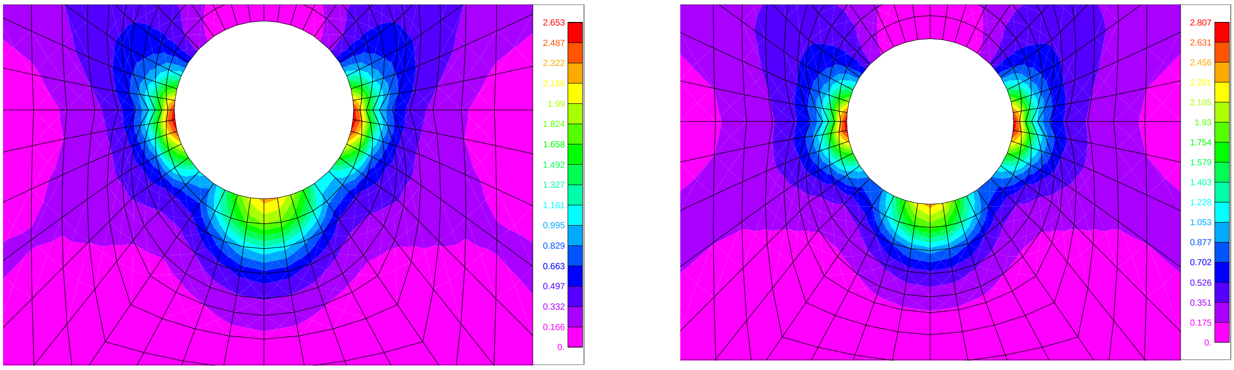


Kontakt problem MKE (Contact problem FEM) (*F* = 5670 N) Kosinusna raspodela (Cosine distribution) (*F* = 5670 N)

Slika 7. Raspodele (*F.I*) u kompozitnoj uški za nivo eksperimentalno dobijenog opterećenja otkaza (slučaj 1)
Figure 7. Distributions of (*F.I*) at composite lug for experimental failure load (Case 1).

Kontakt problem MKE (Contact problem FEM) (*F* = 5670 N) Kosinusna raspodela (Cosine distribution) (*F* = 5670 N)

Slika 8. Raspodela (*F.I*) duž karakteristične krive za nivo eksperimentalno dobijenog opterećenja otkaza (slučaj 1)
Figure 8. Distribution of (*F.I*) along characteristic curve for experimental failure load (Case 1).



Kontakt problem MKE (Contact problem FEM) (*F* = 5550 N) Kosinusna raspodela (Cosine distribution) (*F* = 5900 N)

Slika 9. Raspodela (*F.I*) u kompozitnoj uški za opterećenje otkaza (slučaj 1)
Figure 9. Distributions of (*F.I*) at composite lug for failure load (Case 1).

Kontakt problem MKE (Contact problem FEM) (*F* = 5550 N) Kosinusna raspodela (Cosine distribution) (*F* = 5900 N)

Slika 10. Raspodela (*F.I*) duž karakteristične krive za opterećenje otkaza (slučaj 1)
Figure 10. Distribution of (*F.I*) along the characteristic curve for failure load (Case 1).

ZAKLJUČAK

U ovom članku su prikazane numerička i eksperimentalna analiza nivoa opterećenja pri kome se javlja otkaz kao i oblik otkaza u mehaničkom spoju kompozita pomoću vijka. U numeričkoj analizi je korišćen kriterijum otkaza Cai-Vu za predviđanje opterećenja i oblika loma. Za verifikaciju metode proračuna ispitani su spojevi kompozita sa različitim odnosom širine prema prečniku otvora i odstojanja ivice prema prečniku otvora, i proračun je upoređen sa rezultatima ispitivanja. Analiza otkaza mehaničkog spoja kompozitna uška-podešeni vijak je izvedena primenom modela karakteristične krive Čang-Skot-Špringer, Cai-Vu kriterijuma otkaza i kontaktne MKE analize. Rezultati proračuna dobijeni predloženim postupkom su upoređeni sa eksperimentima i uočena je vrlo dobra saglasnost.

CONCLUSION

In this article, a numerical and an experimental study on the failure load and mode of composite pin loaded mechanically fastened joints is presented. A Tsai-Wu failure criterion is used in the numerical study to predict failure load and failure mode. The verification of the computational method implicated examination of composite laminated joints with various ratios of width-to-hole diameter and edge distance-to-hole diameter and they were compared to test results. An analysis was performed to evaluate failure of pin-loaded composite joints by applying combined Chang-Scott-Springer characteristic curve model, the Tsai-Wu failure criterion, and contact FEM analysis. Computed results obtained by this procedure are compared with experimental results, and very good correlations are achieved.

LITERATURA – REFERENCES

1. Chang, F.K., Scott, R.A., Springer, G.S., *Strength of mechanically fastened composite joints*, J Compos Mater 1982; 16, pp. 470-94.
2. Maksimović, S., Ilić, I., *Failure Analysis of Composite Pin Loaded Joints*, Technical Diagnostics, Vol. 4, No. 3-4, 2005.
3. Chang, F.K., *The effect of pin load distribution on the strength of pin loaded holes in laminated composites*, J Compos Mater, 1986; 20, pp. 401-8.
4. Chang, F.K., Scott, R.A., Springer, G.S., *Failure of composite laminates containing pin loaded holes–method of solution*, J Compos Mater 1984, 18, pp.255-8.
5. Maksimović, S., *Some computational and experimental aspects of the optimal design process of composite structures*, Int. J. of Composite Structures, Vol. 16, pp.237-258, 1990.
6. Maksimović, S., *Postbuckling and failure analysis of axially compressed composite panels using FEM*, Scientific Technical Review, Vol. LVII, No. 3-4, 2007.
7. Dano, M.L, Gendron G., Piccard A., *Stress and failure analysis of mechanically fastened joints in composite laminates*, Compos Struct, 2000, 50, pp.287-96.
8. Lessard, L.B., Shokrieh, M.M., *Two-dimensional modelling of composite pinned-joint failure*, J Compos Mater 1995, 29, pp. 671-97.
9. Aktas, A., Karakuzu, R., *Failure analysis of two-dimensional carbon-epoxy composite plate pinned joint*, Mech Compos Mater Struct, 1999, 6, pp.347-61.
10. Icten, B.M., Karakuzu, R., *Progressive failure analysis of pin-loaded carbon-epoxy woven composite plates*, Composite Science Technology, 2002, 62, pp.1259-71.
11. Camanho, P.P., Matthews, F.L., *A progressive damage model for mechanically fastened joints in composite laminates*, J Compos Mater, 1999, 33, pp.2248-80.
12. Okutan, B., Karakuzu, R., *The failure strength of pin-loaded multidirectional fiber-glass reinforced epoxy laminate*, J Compos Mater, 2002, 36, pp.2695-712.
13. Lin, H.J., Tsai, C.C., *Failure analysis of bolted connections of composites with drilled and moulded-in hole*, Composite Structures, 1995, 30, pp.159-68.
14. Icten, B.M., Okutan, B., Karakuzu, R., *Failure strength of woven glass fiber-epoxy composite pinned joint*, J Compos Mater 2003, 36, pp.1337-51.
15. Okutan, B., Karakuzu, R., *The strength of pinned joints in laminated composite plates*, Compos Sci Technol, 2003, 63, pp. 893-905.
16. Okutan, B., *The effects of geometric parameters on the failure strength for pin-loaded multi-directional fiber-glass reinforced epoxy laminate*, Composite Part B, 2002, 33, pp.567-78.
17. Pierron, F., Cerisier, F., *A numerical and experimental study of woven composite pin-joints*, J Compos Mater, 2000, 34, pp. 1028-54.
18. Maikuma, H., Kobomura, K., *Bearing strength and damage progress for PAN-based and pitch based carbon fiber composites*, J Compos Mater, 1993, 27, pp.1739-61.
19. Okutan, B., Aslan, Z., Karakuzu, R., *A study of the effects of various geometric parameters on the failure strength of pin-loaded woven glass-fiber reinforced epoxy laminate*, Compos Sci Technol, 2001, 61, pp.1491-7.
20. Jones, R.M., Mechanics of composite material, Philadelphia, Taylor & Francis, 1999.
21. Dimitrijević, D., Nikolić, V., Atanasovska, I., *Dynamic analysis of the stress and strain state of the spur gear*, Scientific Technical Review, Vol. LVII, No. 3-4, 2007.
22. Chandrupatla, T.R., Belengundu, A.D., Introduction to finite elements in engineering, Prentice-Hall, 2002.
23. Bathe, K.J., Finite element procedures in engineering analysis, Englewood Cliffs, NJ, Prentice-Hall, 1996.
24. Whitney, J.M., Nuismer R.J., *Stress fracture criteria for laminated composites containing stress concentration*, J Compos Mater 1974, 10, pp.253–65.
25. Nuismer, R.J., Labor, J.D., *Application of the average stress failure criterion: Part II: Compression*, J Compos Mater 1978, 12, pp.49-60.
26. Whitworth, H.A., Othieno, M., Barton, O., *Failure analysis of composite pin loaded joints*, Compos Structures, 2003, 59, pp. 261-6.
27. MSC/NASTRAN, Theoretical Manuals