UDK 539.42:519.6
Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 39(3)77(2005)

NUMERICAL SIMULATION OF THE PROGRESSIVE DAMAGE TO FRC PANELS DUE TO SHOCK LOADING

NUMERIČNI MODEL NARAŠČAJOČE POŠKODBE FRC-PANELOV PRI UDARNI OBREMENITVI

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Prejem rokopisa – received: 2004-09-17; sprejem za objavo – accepted for publication: 2005-04-11

This work focuses on the numerical simulation of failure of composite structures. In the previous study we have developed a computational model for the prediction of the critical state of a structure made of fiber-reinforced composite (FRC) panels and capable of quasi-static simulation of the subsequent process of local material damage also known as progressive failure analysis (PFA). In this paper, we have extended this model so that the simulation is now a fully dynamic process and therefore the phenomenon of stress wave propagation occurs in the structure. Also, the static Puck's failure criterion used previously has been modified to achieve so-called temporal criterion. The performance of the proposed model is demonstrated on examples of tensile tests of unidirectional single-ply FRC panel with circular hole.

Keywords: FEA, FRC, damage, shock, PFA

Numerična simulacija preloma kompozitne strukture. Že razvit računski model za napovedovanje kritičnega stanja strukture iz panelov iz kompozita, ojačenega z vlakni (FRC) uporaben za kvazi statično simulacijo lokalnih poškodb materiala, ki sledijo, je znan kot progresivna analiza poškodbe (PFA). V tem članku je model razširjen tako, da je simulacija dinamičen proces propagacije napetostnega vala skozi strukturo. Že uporabljen statičen Puckov kriterij poškodbe je spremenjen tako, da je upoštevano tudi časovno merilo. Uporabnost predloženega modela je prikazana z nateznimi preizkusi enosmernih monoplastnih FRC-panelov z okroglo izvrtino.

Ključne besede: FEA, FRC, poškodbe, udarna obremenitev PFA

1 INTRODUCTION

Regarding the safety regulations, many applications require the structure to be failure free. In such cases, the most important thing in fracture analysis is the "first-failure state", in other word, the prediction of when the first instability occurs. There are cases, however, when the process of subsequent fracture (failure) of the structure can be crucial for the function of for instance neighboring components. In other cases, reaching the "conservative" first-failure state of the structure may not necessarily mean the ultimate failure, thus the knowledge of the following processes could mean significant reduction in overall structure weight and cost.

The prediction of instability (crack initiation) and the process of subsequent failure (by crack growth) of composite materials have been investigated by many researchers. A numerous approaches have been proposed usually incorporating the finite element analysis (FEA). Some of the methods are known as node releasing (Rousselier [9]) or splitting (Bakuckas et al. [1]) where the nodes are released from boundary or 'split' to create new crack surface, hence the crack propagates along element boundaries. Extended FEA (XFEA) pioneered by Belytschko and others can model arbitrary discontinuity (crack) within an element by the use of modified or enriched approximation function [5].

The most common technique is the simulation of material damage (or degradation) within the volume of an element. Such numerical procedure is known as progressive failure analysis (PFA). A recent approach by Knight et al. in their STAGS program (quasi-static) is one example [4]. Knight uses several interacting as well as non-interacting criteria for local failure assessment together with heuristically determined knockdown factor for the reduction of the stiffness of an element upon failure.

In our previous study, the PFA was designed and implemented at first into non-linear quasi-static finite element model so as to simulate local damage in individual layers of composite materials consisting of fiber-reinforced plies (orthotropic) by degrading the stiffness matrix of a damaged element. In this work, our model has been extended to simulate transient processes. This was achieved by taking into account the material inertia effects and by modifying the static failure criterion.

2 COMPUTATIONAL MODEL AND ALGORITHMS

The computational model uses finite element analysis (FEA). The location of the critical state is found with the Puck's criteria [7,8] which allow for the prediction of both

Table 1: Puck's fiber and inter-fiber criterion failure conditions [8]
Tabela 1: Puckov kriterij za pogoje vlaknaste in medvlaknaste poškodbe [8]

a)	$\frac{1}{\epsilon_{1T}}\left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right) = 1$	$(\ldots) \geq 0$
b)	$\frac{1}{\epsilon_{1C}}\left|\left(\varepsilon_1 + \frac{\nu_{f12}}{E_{f1}} m_{\sigma f}\sigma_2\right)\right| = 1$	$(\ldots) < 0$
c)	$\sqrt{\frac{\tau_{21}}{F_6}^2 + \left(1 - p_{\perp\parallel}^{(+)}\frac{F_{2T}}{F_6}\right)^2\left(\frac{\sigma_2}{F_{2T}}\right)^2} + p_{\perp\parallel}^{(+)}\frac{\sigma_2}{F_6} = 1$	$\sigma_2 \geq 0$
d)	$\frac{1}{F_6}\left(\sqrt{\tau_{21}^2 + \left(p_{\perp\parallel}^{(-)}\sigma_2\right)^2} + p_{\perp\parallel}^{(-)}\sigma_2\right) = 1$	$\sigma_2 < 0 \leq \left|\frac{\sigma_2}{\tau_{21}}\right| \leq \frac{R_{\perp\perp}^A}{\lvert\tau_{21c}\rvert}$
e)	$\left[\left(\frac{\tau_{21}}{2(1+p_{\perp\perp}^{(-)}F_6}\right)^2 + \left(\frac{\sigma_2}{F_{2C}}\right)^2\right]\frac{F_{2C}}{-\sigma_2} = 1$	$\sigma_2 < 0 \leq \left|\frac{\tau_{21}}{\sigma_2}\right| \leq \frac{\lvert\tau_{21c}\rvert}{R_{\perp\perp}^A}$

the inter-fiber (matrix) and fiber failure. The criterion can be written in terms of five conditions (failure types), each as a function of current stress, hence "$f_i(\sigma) = 1$", $i = 1\ldots5$ (see **Table 1**). The first two conditions correspond to fiber tensile and compressive failure and the latter three conditions correspond to matrix (or inter-fiber) failure designated as Mode A (tensile), B (shear) and C (compressive), respectively (see [8] for detailed explanation of all terms).

This well-known static criterion was modified in this work to achieve so-called temporal criterion [6]:

$$\int_{t-T}^{t} f_i\sigma(t')\mathrm{d}t' = T_i,\; i = 1, \ldots, 5 \qquad (1)$$

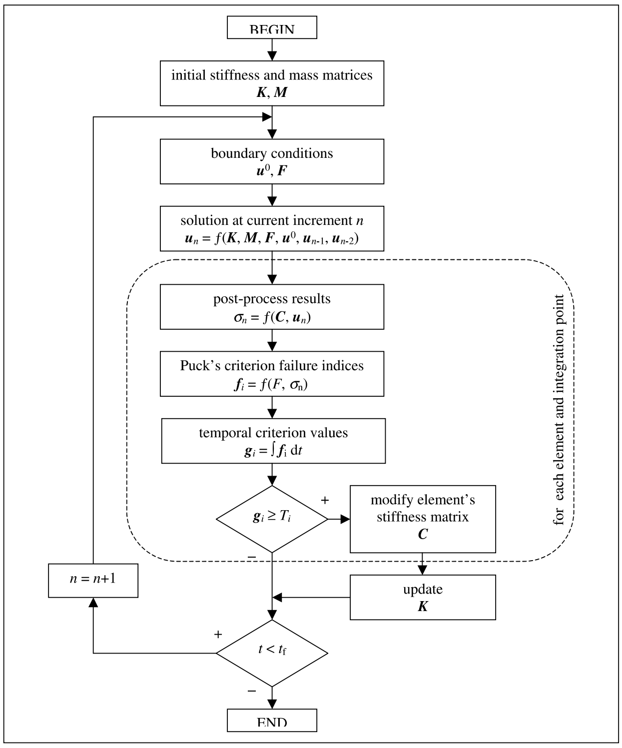

Figure 1: Flow chart showing the numerical model with PFA
Slika 1: Pretočni diagram za numerični model PFA

Where t is time and T_i are assumed to be additional material parameters.

The material behavior at each location is fully linear until local damage occurs. Should damage occur, the material stiffness matrix in the corresponding element is modified (degraded) accordingly to the failure type found [11]. This approach is called progressive failure analysis (PFA). The flow chart of the embedded PFA in the FEA code for transient problems is shown in **Figure 1**.

The finite-difference method is used in the time domain. The capability of the model to describe the phenomenon of stress wave propagation in FRC panel correctly was verified experimentally on a similar specimen without damage simulation [10,12]. The equations of motion for plane-stress case and orthotropic material are

$$\begin{aligned} C_{11}\frac{\partial^2 u}{\partial x^2} + C_{12}\frac{\partial^2 v}{\partial x\partial y} + C_{66}\left(\frac{\partial^2 v}{\partial x\partial y} + \frac{\partial^2 u}{\partial y^2}\right) &= \rho\frac{\partial^2 u}{\partial t^2} \\ C_{12}\frac{\partial^2 u}{\partial x\partial y} + C_{22}\frac{\partial^2 v}{\partial y^2} + C_{66}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 u}{\partial x\partial y}\right) &= \rho\frac{\partial^2 v}{\partial t^2} \end{aligned} \qquad (2)$$

An important information necessary for correct setting of the parameters of the computational model is the solution of (2) in terms of so-called velocity surfaces, i.e., the distance from the center is a distance traveled by a plane wave moving along the direction θ in unit time (one second). These are plotted in graphs in **Figure 2** for common steel (isotropic) and Kevlar/epoxy (orthotropic), respectively. In each graph, there are two velocity surfaces – one for quasi-longitudinal (QL) and the latter for quasi-transverse (QT) waves. The short intersecting lines (for selected angles) are displacement vectors and they show the motion direction of a particle laying on the wave front corresponding to the direction of propagation θ [3].

The Matlab environment is used for this model for easy and user-friendly modification of the model various parameters.

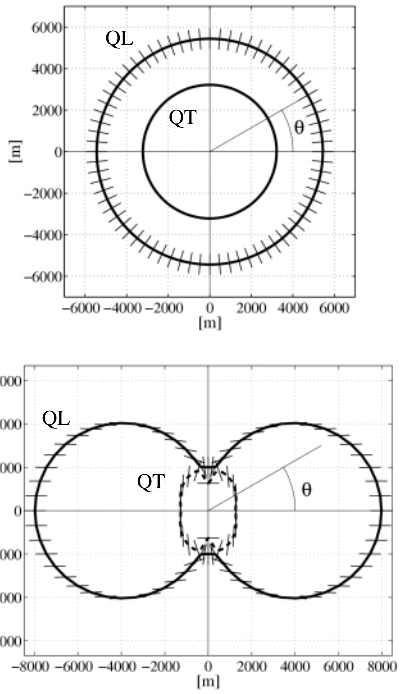

Figure 2: Velocity surfaces for steel (upper) and Kevlar/epoxy (lower) for plane-stress. Corresponding displacement vectors are shown by short lines.
Slika 2: Hitrostne površine za jeklo (zgoraj) in kevlar/epoksi (spodaj) za ravninsko napetost. Ustrezni vektorji premikov so prikazani s kratkimi črtami

3 EXAMPLES

The performance of the proposed model is demonstrated on two kinds of examples – tensile tests of a specimen with jaws either at rest or moving after preload. The specimen is a rectangular FRC panel of dimensions 20 mm × 60 mm × 1 mm having a circular hole of diameter 10 mm in the center and it is clamped at the jaws of the tensile testing device. The panel is made of Kevlar/epoxy unidirectional ply with material properties shown in **Table 2**.

Table 2: Material properties of Kevlar/epoxy [2]
Tabela 2: Materialne lastnosti kompozita kevlar/epoksi smola [2]

Elasticity constants		Main material strengths, F/MPa	
E_1	87 GPa	F_{1T}	1280
E_2	5.5 GPa	F_{2C}	335
υ_{12}	0.34	F_{1T}	30
G_{12}	2.2 GPa	F_{2C}	158
ρ	1380 kg·m^{-3}	F_6	49

In the first case (A), the specimen is pre-loaded statically (by moving the jaws) to the moment when the first location of the panel is to undergo failure (i.e. the failure condition is satisfied). Hence, at least one of the maximum fiber (f_{Pf}) or matrix (f_{Pm}) failure indices equals one. This could be considered the "crack initiation". The rest of the simulation is transient and thus the crack can propagate or new cracks can emerge while keeping the jaws at rest.

The time interval investigated was 100 increments, each increment Δt = 0.05 μs (i.e. final time t_{f} = 0.05 μs). Analyzed is mainly the level of damage, i.e., the location and shape of the region with damaged matrix and/or fibers. The results are compared for various orientations of the fibers (denoted by the angle θ) in the specimen ranging between 0 and 90 degrees. The unknown constants are assumed to be T_i = 0.25 μs (5 increments) in these tests.

In the second test (case B), the specimen (only [90] fiber orientation) is also statically preloaded (jaws shift is u = 160 μm). The maximum fiber and matrix failure index values are f_{Pf} = 0.76 and f_{Pm} = 0.87, respectively.

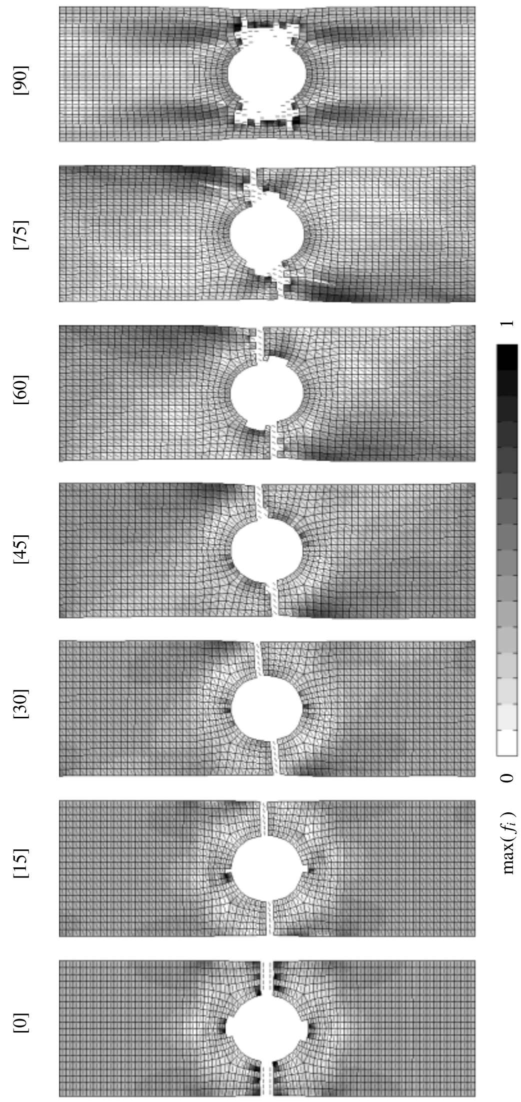

Figure 3: Damage patterns in all specimens at t = 5 μs after first-crack initiation (case A)
Slika 3: Oblika poškodbe pri vseh preizkušancih pri t = 5 μs po iniciaciji razpoke (primer A)

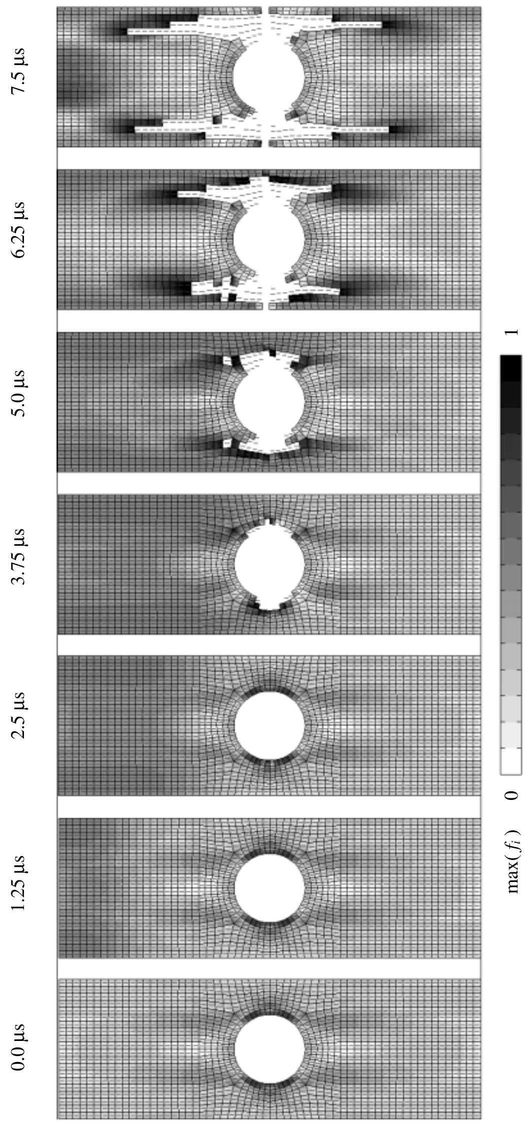

Figure 4: Damage patterns in shock-loaded specimen ([90]) at 1.25 µs intervals (case B)
Slika 4: Oblika poškodbe v sunkovito obremenjenem preizkušancu ([90]) v 1,25 µs intervalih (primer B)

The specimen is then loaded by a rapid shift of the jaws (constant speed v = 34 ms^{-1}). The time interval investigated was 200 increments with the same parameters Δt and T_i as in the previous case.

4 RESULTS

The resulting damage patterns of the first example (case A) are shown in **Figure 3**. The colors within failure-free elements correspond to the maximum of the 5 failure indices values, ranging from 0 (white) to 1 (black), however, the maximum values may not be present in individual cases. Failure-free elements also have a fiber symbol drawn inside (also showing the corresponding orientation). Edges and faces of elements

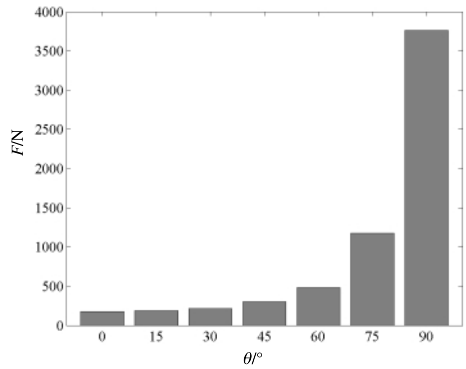

Figure 5: Tensile-force values reached during static preload for each specimen
Slika 5: Natezna sila pri statični preobremenitvi vsakega preizkušanca

where matrix damage occurred are not plotted and, similarly, the fiber symbol is not drawn where fiber failure occurred.

The situation corresponds to the final time t = 5 µs. It is obvious that until this moment all but the last specimen ([90]) have partially failed – matrix failure occurred over the whole cross-section perpendicular to the axis of loading. The values of the tensile force at the jaws during the static preload are plotted in **Figure 5** for all specimens.

The results for case B in terms of sequential snapshots are shown in **Figure 4**. The snapshots are taken at 25 increment intervals. It can be seen how the damage level increases with time. The specimen failed at t = 6.3 µs in this test (between the last two snapshots).

5 CONCLUSIONS

A numerical model capable of the simulation of wave propagation and material damage in orthotropic composite materials (FRC) is introduced here. The reliability of the code in terms of transient wave propagation was verified previously by a comparison with experimental measurements. The damage model uses a modified Puck's criterion for the detection of local fiber or matrix failure. The criterion was modified to resemble the temporal criterion. The performance is tested on two kinds of tensile testing examples. These are statically preloaded single-ply FRC specimens with circular hole having various fiber orientations and undergoing transient response due to shock loading caused by either crack initiation or rapidly shifted jaws.

Acknowledgement

This paper was financially supported by the project KONTAKT No. 09-2004-05 and project MSM 4977751303.

6 REFERENCES

[1] Bakuckas Jr. J. G., Lau A. C. W., Tan T. M., Awerbuch J.: Computational methodology to predict damage growth in unidirectional composites – I. Theoretical formulation and implementation. Engineering fracture mechanics 52 (**1995**) 5, 937–951

[2] Daniel I. M., Ishai O.: Engineering mechanics of composite materials. Oxford University Press, New York, 1994

[3] Hearmon R. F. S.: Introduction to elasticity of anisotropic materials (in Czech). SNTL, Praha, 1965

[4] Knight N. F. Jr., Rankin C. C., Brogan F. A.: STAGS computational procedure for progressive failure analysis of laminated composite structures, International Journal of Non-Linear Mechanics, 37 (**2002**), 833–849

[5] Moes N., Dolbow J., Belytschko T.: A finite element method for crack growth without remeshing. Int. J. Numer. Methods Engrg. 46 (**1999**) 1, 131–150

[6] Morozov N., Petrov Y.: Dynamics of fracture. Foundations of Engineering Mechanics, Springer, Berlin, 2000

[7] Puck A., Kopp J., Knops M.: Guidelines for the determination of the parameters in Puck's action plane strength criterion. Composite Science and Technology 62 (**2002**), 371–378

[8] Puck A., Schürmann H.: Failure analysis of FRP laminates by means of physically based phenomological models, Composites Science and Technology, 58 (**1998**), 1045–1067

[9] Rousselier D.: Numerical treatment of crack growth problems. Larsson, L. H. (Ed.), Advances in Elasto-plastic Fracture Mechanics, (**1979**), 165–189

[10] Zemčík R., Červ J., Laš V.: Numerical and experimental investigation of stress wave propagation in orthotropic strip. In: Computational Mechanics 2003, Nečtiny, 2003

[11] Zemčík R., Laš V.: Numerical simulation of progressive damage and ultimate failure during tensile testing of composite panels. In: Youth Symposium on Experimental Solid Mechanics 2003, Milano Marittima, 2003

[12] Zemčík R., Laš V.: Numerical simulation of stress wave propagation in orthotropic panel and comparison with experiment. In: Experimental Stress Analysis 2003, Milovy, 2003