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Modelling of High Velocity Impact on Carbon Fibre Composite Materials

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This paper investigates modelling of shock wave propagation, damage evolution and failure in an orthotropic material undergoing extreme loading conditions. More specifically, the material of the interest is Carbon Fibre Reinforced Plastic (CFRP) laminate of the type commonly used in aerospace engineering. A constitutive model is developed in a framework of thermodynamics for small deformation problems. Shock wave propagation is predicted well owing to the accurate decomposition of the material volumetric compression effects and the equation of state (EOS) [2]. A modified Tuler-Bucher criterion [4] is proposed for modelling damage in the framework of irreversible thermodynamics. The model is implemented into the LLNL DYNA3D nonlinear hydrocode and coupled with the rest of the constitutive model. The results obtained with the proposed model are compared with the experimental data generated at Cranfield University [8, 11].

Key words: **composite materials, orthotropic materials, laminates, carbon fibre, dynamic loading, stress loading, process modeling, process decomposition, structure damage.**

Introduction

COMPOSITE materials are of significant importance in many applications, including aerospace and automotive industry, due to their high strength to weight ratio. A key to a wider utilisation of materials is a proper understanding of their behaviour, especially when they undergo extreme dynamic loading. The complexity of the problem arises from the properties such as pronounced anisotropy, high level of heterogeneity, different response to different loading rates, stress transfer factors, etc. Equally, a high velocity impact, as one of the most dangerous threats in the space environment, is accompanied with the shock wave generation and propagation through the material, damage initiation and failure. Due to these uncertainties, modern simulation tools are limited in their capability to predict the material degradation, its progression and failure for composites. Hence, the following areas in the modelling of the dynamic behaviour of composite structures are still to be addressed:

- shock wave formation and propagation in anisotropic material
- damage and failure, including damage induced by shock wave propagation out of the zone of impact and
- damaged and failed material areas for the purpose of residual strength assessment and for structural health monitoring

The objective of this paper is the modelling of shock wave propagation and damage in a particular type of composite materials. The material of interest is woven Carbon Fibre Reinforced Plastic (CFRP) laminate that is commonly used in aerospace engineering. It is modelled as a quasi orthotropic material with equivalent properties. The paper describes the physical background of the equation of state, a model for damage evolution and failure in composites under high-rate loading, the implementation of the proposed model and the coupling with the rest of the constitutive model. The results obtained with the proposed model are compared with the available experimental results.

Constitutive model

Decomposition of the stress tensor

For modelling a high velocity impact and accompanied shock wave propagation through the material, it is crucial to decompose the material response to the volumetric and deviatoric deformation. Hence, two parts of the constitutive model can be identified: the equation of state (EOS) which determines the material response under unified compression and the shear part, responsible for shear deformation. This decomposition is relatively simple for isotropic materials, since the spherical part of the stress tensor and the strain tensor are collinear and both orthogonal to the deviatoric plane. However, in the case of anisotropic materials this orthogonality does not hold because the spherical component of stress induces a change in shape i.e. deviatoric strain. The first attempt to address the problem was by Anderson [1], but the proposal failed to predict the material response accurately. Thus an alternative decomposition of stress was proposed in [2]. The principal equations governing the decomposition are given below, whilst all the details and the comprehensive derivation can be found in [2].

Constitutive relations can be mathematically represented using either stiffness or a compliance form. For orthotropic

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materials, stiffness and compliance tensors are symmetric tensors of the fourth order, determined by nine material parameters. A constitutive equation of the stiffness form in the current configuration can be expressed in the index notation as:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \tag{1}$$

where: σ_{ij} is the Cauchy stress, C_{ijkl} is the stiffness tensor and ε_{kl} is the total strain tensor. The proposed decomposition is based on a definition of a generalized pressure as a state of stress induced by the volumetric part of strain only. Physically, the pressure is defined as a vector in the stress space which is not orthogonal to the deviatoric plane i.e. it is not collinear with the hydrostat. Thus, one can write the equations:

$$-\hat{P}\psi_{ij} = C_{ijkl}\delta_{kl}\varepsilon_{ss}/3 = C_{ijkk}\varepsilon_{v} \tag{2}$$

where the direction of the pressure $\hat{P}$ in the stress space is defined by the tensor ψ_{ij}, whilst the volumetric strain is given as $\varepsilon_v = \varepsilon_{ss}/3$. ψ_{ij} is a diagonal tensor, so there is no summation for the repeated indices. With the use of definition (2), a Cauchy stress can be decomposed as:

$$\sigma_{ij} = -\hat{P}\psi_{ij} + \hat{S}_{ij} \tag{3}$$

where the components $\hat{P}\psi_{ij}$ and $\hat{S}_{ij}$ are not mutually orthogonal. However, one can introduce a couple $\tilde{P}\psi_{ij}$ and $\tilde{S}_{ij}$, where the orthogonality holds, i.e. $\tilde{P}\psi_{ij}\tilde{S}_{ij} = 0$. The governing equations of the decomposition are summarized below:

$$\sigma_{ij}\psi_{ij} = -\hat{P}\psi_{ij}\psi_{ij} + \hat{S}_{ij}\psi_{ij} = -\tilde{P}\psi_{ij}\psi_{ij} + \tilde{S}_{ij}\psi_{ij} \tag{4}$$

$$\tilde{P} = \hat{P} - \frac{\hat{S}_{ij}\psi_{ij}}{\psi_{kl}\psi_{kl}} = \hat{P} - \hat{S} = -\frac{\sigma_{ij}\psi_{ij}}{\psi_{kl}\psi_{kl}} \tag{5}$$

$$\tilde{S}_{ij} = \hat{S}_{ij} - \frac{\hat{S}_{kl}\psi_{kl}}{\psi_{sr}\psi_{sr}}\psi_{ij} = \hat{S}_{ij} - \hat{S}\psi_{ij}\,, \tag{6}$$

$$\tilde{S}_{ij} = \sigma_{ij} - \frac{\sigma_{kl}\psi_{kl}}{\psi_{sr}\psi_{sr}}\psi_{ij} = \sigma_{ij} + \tilde{P}\psi_{ij} \tag{7}$$

This decomposition was implemented into the Lawrence Livermore National Laboratory (LLNL) code DYNA3D [3] and coupled with an orthotropic elastic constitutive model and Mie-Gruneisen EOS.

Damage model

A proposed constitutive model is developed in the framework of thermodynamics with internal variables [4], following the principal laws of thermodynamics. Internal energy is defined from the conservation of energy (the first law of thermodynamics), whilst damage is assumed to be an irreversible process, consistent with the second law of thermodynamics. The energy dissipated during the damage process thus converts to heat and the rate of this dissipation is always positive. Mathematically, the first law of thermodynamics is expressed in terms of internal energy equation (8), while the second law of thermodynamics is given in the form of Clausius-Duhem inequality in (9):

$$\dot{u} = \frac{1}{\rho}\sigma_{ij} : \dot{\varepsilon}_{ij} + r - \frac{1}{\rho}\nabla\cdot \mathrm{q} \tag{8}$$

$$\dot{s} \geq \frac{r}{\theta} - \frac{1}{\rho}\nabla\frac{\mathrm{q}}{\theta} \tag{9}$$

where: s is entropy, r is the strength of the internal heat source, θ is temperature, ρ is density and q is heat flux. A dot above a symbol denotes a material time derivative. By using the Legendre transformations between the thermodynamics potentials, i.e. the internal energy and the Helmholtz free energy given in (10), the Clausius-Duhem inequality (9) can be written as:

$$\psi = u - \theta s \tag{10}$$

$$\dot{u} - \dot{\psi} - \dot{\theta}s - r + \frac{1}{\rho}\nabla\frac{\mathrm{q}}{\theta} - \frac{\mathrm{q}}{\rho\theta}\nabla\cdot\theta \geq 0 \tag{11}$$

With the first law of thermodynamics, the inequality becomes:

$$\frac{1}{\rho}\sigma_{ij}\dot{\varepsilon}_{ij} - \dot{\psi} - \dot{\theta}s - \frac{\mathrm{q}}{\rho\theta}\cdot\nabla\theta \geq 0 \tag{12}$$

Thermodynamics with internal variables assumes the Helmholtz-free energy to be a function of the elastic strain, temperature and a set of internal variables which represent the irreversible processes. In general, the number of internal variables which constitute the free energy function is determined by the type of irreversible processes and the level of details the model is capable of representing. The current development accounts only for damage as an irreversible process, which is defined by a damage parameter ω. Therefore, the time derivative of the free energy function is defined as:

$$\dot{\psi} = \frac{\partial\psi}{\partial\varepsilon_{ij}^{e}}\dot{\varepsilon}_{ij}^{e} + \frac{\partial\psi}{\partial\theta}\dot{\theta} + \frac{\partial\psi}{\partial\omega}\dot{\omega} \tag{13}$$

The elastic part of the strain tensor in the equation above can be obtained from an additive decomposition of the strain tensor:

$$\varepsilon_{ij} = \varepsilon_{ij}^{e} + \varepsilon_{ij}^{p} \tag{14}$$

Substituting the last two equations into inequality (12), the rate of dissipation of the irreversible process is determined as:

$$\delta = \left(\frac{1}{\rho}\sigma_{ij} - \frac{\partial\psi}{\partial\varepsilon_{ij}^{e}}\right) : \dot{\varepsilon}_{ij}^{e} + \frac{1}{\rho}\sigma_{ij} : \dot{\varepsilon}_{ij}^{p} - \frac{\partial\psi}{\partial\omega}\dot{\omega} - \frac{1}{\rho}\frac{q\cdot\nabla\theta}{\theta} \geq 0 \tag{15}$$

The first term in the inequality represents the reversible part of the model, whilst the other three terms represent three mechanisms of energy dissipation: the rate of plastic dissipation; the rate of damage-induced dissipation and the dissipation due to heat flow, respectively. It is assumed that dissipative rates are decoupled and positive.

This investigation is focused on the dissipation due to damage and its influence on the material response to dynamic loading; hence the plastic dissipation term is excluded from the further consideration. Given the high strain rates, the energy dissipates adiabatically as heat, meaning that the heat flow term in inequality (15) is equal to zero. The damage-induced dissipation is a function of the rate of change of the damage parameter, $\dot{\omega}$, and its conjugate force i.e. the functional dependence of free energy in regard to the damage parameter, i.e.:

$$\delta_{dam} = -\frac{\partial \psi}{\partial \omega}\dot{\omega} \geq 0 \tag{16}$$

Dissipation due to damage, i.e. the evolution of the damage parameter is obtained using a modified Tuler-Bucher criterion [6]. Originally, Tuler Bucher proposed a criterion for failure:

$$\phi = \int_0^{t_{cr}} f\left(\sigma(t)\right) dt \tag{17}$$

Where: f can be any convenient function of stress, usually $\left(\sigma - \sigma_0\right)^{\lambda}$; σ_0 is a threshold stress below which no failure occurs and t_{cr} is the time to failure. The method was originally proposed for unidirectional loading; in order the criterion to be applied to the orthotropic material and three dimensional loading conditions, an effective value for the stress is used. Delamination is modelled by an in-plane criterion based on the out of plane (through thickness) normal stress component. The function $f\left(\sigma(t)\right)$ is normalized with the corresponding member of the material stiffness matrix. The evolution of the damage parameters is defined as:

$$\dot{\omega} = \dot{\omega}(\omega,\sigma) = \Omega_{\omega}\left(\frac{\sigma}{C_m(1-\omega)} - \frac{\sigma_{CR}}{C_m}\right) H\left(\frac{\sigma}{C_m(1-\omega)} - \frac{\sigma_{CR}}{C_m}\right) \tag{18}$$

$$\dot{\omega}_{del} = \dot{\omega}_{del}(\omega,\sigma) = \Omega_{del}\left(\frac{\sigma_{33}}{C_{33}(1-\omega_3)} - \frac{\sigma_{CRdel}}{C_{33}}\right) H\left(\frac{\sigma_{33}}{C_{33}(1-\omega_3)} - \frac{\sigma_{CRdel}}{C_{33}}\right) \tag{19}$$

where: Ω_{ω}, Ω_{del} are the material parameters determined by time to failure, σ and σ_{33} are the effective stress and the out-of-plane stress respectively, σ_{CR} and σ_{CRdel} are the critical effective stress and the critical out-of-plane stress, C_m and C_{33} are the maximum in-plane stiffness member and through the thickness coefficient respectively and H is the Heaviside function. The integration of equations (18) and (19) provides damage parameters for material directions, ω_1, ω_2 and ω_3 which are further used to degrade the members in the stiffness matrix. The first two parameters correspond to the fibre directions, whilst the third is a damage parameter for the out-of-plane direction.

Damage is incorporated in the constitutive model with the concept of effective stress, originally introduced by Kachanov [5]. The effective stress for the orthotropic material model is given in a tensor form as:

$$\tilde{\sigma} = \mathbf{M}(\omega) : \sigma \tag{20}$$

where $\mathbf{M}(\omega)$ is the damage effect tensor of the forth order. The stiffness matrix of the damaged material is calculated using the energy equivalence principle [7]:

$$\tilde{\mathbf{C}} = \mathbf{M}(\omega)^{-1} : \mathbf{C} : \mathbf{M}(\omega)^{-T} \tag{21}$$

where $\tilde{\mathbf{C}}$ is the stiffness tensor of the damaged material and $\mathbf{C}$ is the stiffness tensor of the virgin material. The damage effect tensor and the members in the stiffness tensor are given as:

$$\mathbf{M}(\omega)^{-1} = diag \left[1-\omega_1 \quad 1-\omega_2 \quad 1-\omega_3 \quad \sqrt{(1-\omega_1)(1-\omega_3)} \quad \sqrt{(1-\omega_3)(1-\omega_1)} \quad \sqrt{(1-\omega_1)(1-\omega_2)}\right] \tag{22}$$

$$\tilde{\mathbf{C}} = \begin{bmatrix} \mathbf{C}_{11}(1-\omega_1)^2 & \mathbf{C}_{12}(1-\omega_1)(1-\omega_2) & \mathbf{C}_{31}(1-\omega_3)(1-\omega_1) & 0 & 0 & 0 \\ & \mathbf{C}_{22}(1-\omega_2)^2 & \mathbf{C}_{23}(1-\omega_2)(1-\omega_3) & 0 & 0 & 0 \\ & & \mathbf{C}_{33}(1-\omega_3)^2 & 0 & 0 & 0 \\ & & & \mathbf{C}_{44}(1-\omega_2)(1-\omega_3) & 0 & 0 \\ symm & & & & \mathbf{C}_{55}(1-\omega_1)(1-\omega_3) & 0 \\ & & & & & \mathbf{C}_{12}(1-\omega_1)(1-\omega_2) \end{bmatrix} \tag{23}$$

If criteria (18) and (19) are satisfied, the damaged stiffness matrix is calculated and the true stress is updated to account for damage effects. The proposed damage model has been implemented into the Lawrence Livermore National Laboratory (LLNL) code DYNA3D [3] and coupled with an orthotropic elastic constitutive model explained in the previous section.

Experimental validation

The results from two experiments were used for the model validation: a plate impact test [8]-[10] and a steel sphere penetration of a CFRP laminate [11]-[12]. In both experiments, the material of the target plates was a woven CFRP laminate which is widely used in aerospace engineering. The composite laminate was modelled as a quasi-orthotropic material with equivalent material properties given in Table 1 [2]. The parameters for the Mie-Grüneisen EOS had the following values: $c = 5240$ m/s, $S_1 = 1.4$, $\gamma_0 = 1.97$, $a = 0.48$.

Table 1. Mechanical properties of Carbon Fibre/Epoxy Composite

Density	1500 kg/m^3
Elastic modulus in longitudinal direction E_a	68.457 GPa
Elastic modulus in longitudinal direction E_b	66.527 GPa
Elastic modulus in longitudinal direction E_c	10.0 GPa
Poisson's ratio υ_{ba}	0.039
Poisson's ratio υ_{ca}	0.0044
Poisson's ratio υ_{bc}	0.045
Shear modulus G_{ab}	4.57 GPa
Shear modulus G_{bc}	3.57 GPa
Shear modulus G_{ca}	3.57 GPa

Plate impact test

The plate impact test is usually employed at Cranfield University to obtain data for EOS [8]. It was modelled as a uniaxial strain state, with the assumption that the process was adiabatic. An impact at 504 m/s generated shock wave propagation through the thickness of the composite plate. The thickness of the plate was 3.8 mm with the layup $[0/90, \pm45]_4$. A schematic representation of the finite element model is given in Fig.1.

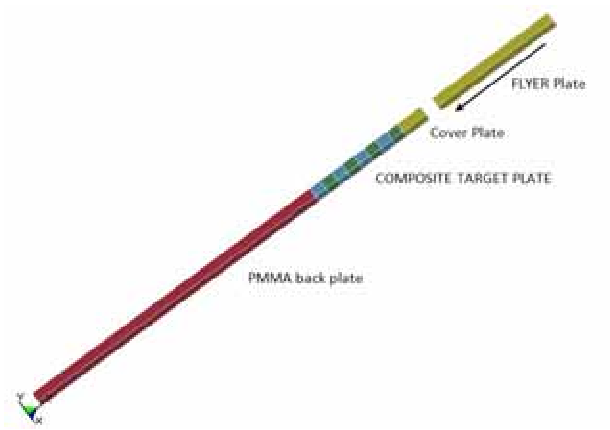

Figure 1. Finite Element model of plate impact on the composite target plate; impact at 504 m/s through the thickness direction

The comparison of the experimental and numerical results obtained for the two impact cases is shown in Fig.2. The magnitude of the stress in the impact direction (Z direction) and the pulse length for both numerical models agreed well with the experimental findings. However, the two numerical signals are different at the end of the pulse. The results obtained for the impact case 1 captured the time of unloading well but the rate of unloading the (slope of the stress curve) is higher compared to the experimentally observed curve. The impact case 2 was run for different EOS data, in order to achieve better agreement. However, the experimentally obtained curves were overestimated.

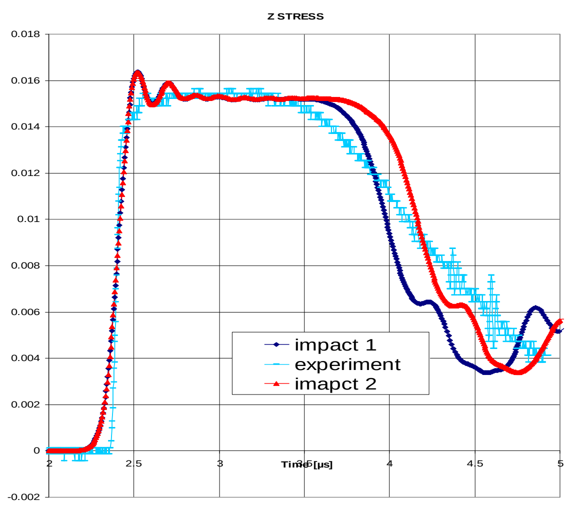

Figure 2. Stress history - numerical and experimental results

Sphere impact test

The second test case is the impact of a steel sphere on a woven CFRP laminate. The target plate is 6 mm thick, consisting of 16 plies with an asymmetric layup [11]. As before, the target was modelled as a quasi orthotropic material, with the properties given in Table 1. The impact at 1199 m/s was normal to the target and the fibre plane. The sphere was fully annealed stainless steel with a diameter of 12 mm. The steel is assumed to be isotropic. The high velocity impact response is dominated by local effects, so the dimensions of the model of the plate are not representing the dimensions of the real specimen; they are chosen just to avoid the boundary effects. Thanks to the symmetry of the problem, only a quarter of the finite element model was analysed, as shown in Fig.3. The layers with the same orientation are presented in the same colour: 0/90 layers are coloured blue whilst ±45 are pink in Fig.3.

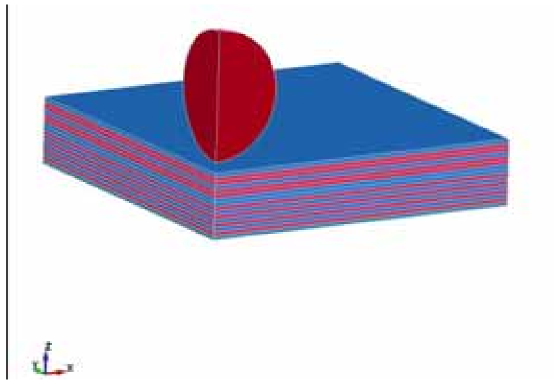

Figure 3. Finite element model of the sphere impact test at 1.2 km/s; quarter of the model

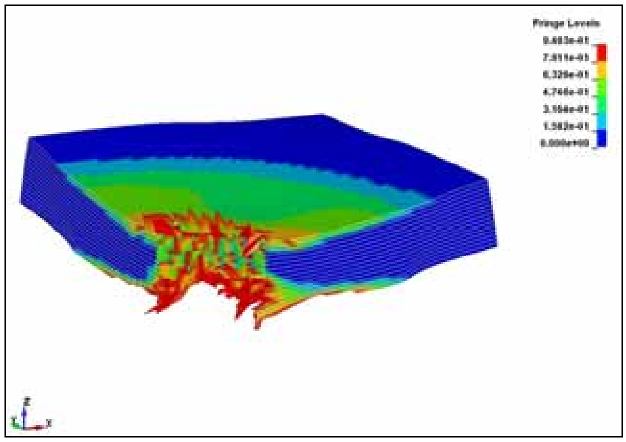

Figure 4. Damage distribution in the composite plate after the impact at 1.2 km/s, 20μs after the impact

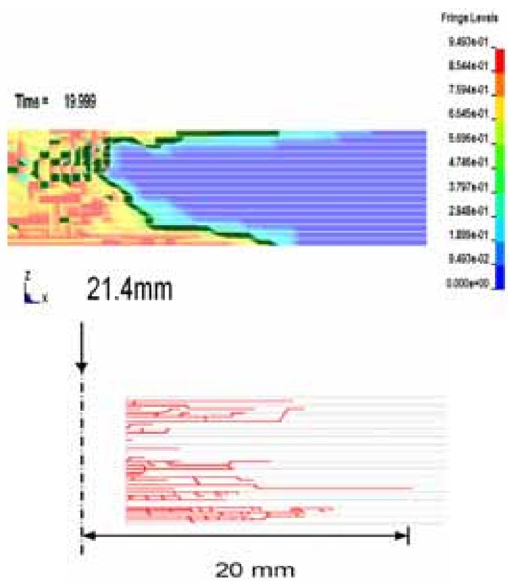

Figure 5. Damage distribution in the composite plate after the impact at 1.2 km/s; numerical and experimental results [11]

The calculated damage distribution in the CFRP composite target is shown in Fig.4 and compared to the experimental results observed through C scans [12], Fig.5. The numerical results compare well with the experimental observation:

- calculated average diameter of the hole differs below 8%,
- the hourglass shape of delaminated zone is captured within the simulation,
- a bigger delamination zone at the back of the target plate compared to the front and the middle plies,
- the radius of the numerical delamination zone at the back of the target differed by less than 5% from the experimental result.

Summary

Modelling of damage in composite materials is a challenging task and modern simulation tools are limited in their capability to predict it. This paper proposes a modified Tuler-Bucher criterion to model the process of damage and failure in composite materials undergoing extreme dynamic loading. The proposed damage model was incorporated within a constitutive model and implemented in an explicit finite element code. The results of two numerical analyses are shown: plate impact test and sphere impact penetration. The prediction of the model with damage agreed well with experimental observations, particularly in the simulation of the sphere penetration. There was a slight discrepancy between the results for plate impact which will be studied further.

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Modeliranje brzog udara na ugljenične kompozitne materijale

U ovom radu analizirano je modeliranje propagacije šoka, evolucija oštećenja i lom kod ortotropnih materijala koji su izloženi intenzivnom dinamičkom opterećenju. Predmet istraživanja su kompozitni laminati sa karbonskim vlaknima koji su veoma zastupljeni u aero inženjeringu. Konstitutivni model je razvijen u okviru termodinamike malih pomeranja. Pouzdano modeliranje propagacije šok-talasa/diskontinuiteta napona kroz materijal omogućeno je tačnom dekompozicijom odziva materijala na kompresibiline efekte, koji ulaze u jednačinu stanja i devijatorske efekte, [2]. Za modeliranje propagacija ostecenja u okviru nepovratnih termodinamickih procesa, razvijen je model koji je jedna verzija Tuler-Bucher kriterijuma, [6]. Model je implementiran u nelinearni kod DYNA3D. Dobijeni numerički rezultati veoma se dobro slažu sa eksperimentalnim rezultatima, koji su urađeni na Univerzitetu Cranfield [8, 11].

Ključne reči: **kompozitni materijali, ortotropni materijali, lamirani materijali, ugljenično vlakno, dinamičko opterećenje, udarno opterećenje, modeliranje procesa, dekompozicija procesa, oštećenje konstrukcije**

Моделирование скоростного удара на углеродистые композитные материалы

В настоящей работе анализировано моделирование распространения удара, эволюция повреждения и излом у орфотропных материалов, подвергнутых чрезвичайной динамической нагрузке. Предметом исследования здесь являются композитные материалы с углеродистыми волокнами, которые широко распространены в авиационно-космической промышленности. Учредительная модель развита в рамках термодинамики небольших деформаций. Предсказуемое моделирование распространения удара-волн / отсутствия

непрерывности напряжения сквозь материал обеспечено точным разложением реакции материала на сжимающиеся эффекты, которые входят в уравнение состояния и отклоняющихся от норм эффектов [2]. Для моделирования распространения повреждения в рамках нереверсивных термодинамических процессов развита модель, которая представляет одну версию критерия Тулер-Бушер (Tuler-Bucher) [6]. Модель осуществена в нелинейном коде DYNA3D. Полученые цифровые результаты совсем совпадают с экспериментальными результатами, получеными в Университете Кренфилд [8, 11].

Ключевые слова: **композитные материалы, орфотропные материалы, ламинированные материалы, углеродистое волокно, динамическая нагрузка, ударная нагрузка, моделирование процесса, разложение процесса, повреждение конструкции.**

La modélisation de l'impact rapide sur les matériaux composites de carbone

Dans ce papier on a analysé la modélisation de la propagation du choc, l'évolution de l'endommagement et la défaillance chez les matériaux orthotropes qui sont exposés à l'intense charge dynamique. L'objet de cette recherche sont les laminés composites aux fibres de carbone qui sont souvent employés dans l'ingénierie aérienne. Le modèle constitutif a été développé dans le cadre de la dynamique de petites déformations. La modélisation fiable de la propagation de l'onde de choc/discontinuité de la tension à travers le matériel est permis par la décomposition précise de la réponse des matériaux aux effets de compression qui font partie de l'équation de l'état et les effets de déviation [2]. Pour la modélisation des propagations des endommagements, dans le cadre des processus thermodynamiques irréversibles, on a développé un modèle qui est une version du critère Tuler – Bucher [6]. Le modèle est mis à effet dans le code non linéaire DYNA3D. Il y a bon accord entre les résultats numériques obtenus et les résultats expérimentaux réalisés à l'Université de Cranfield [8, 11].

Mots clés: **matériaux composites, matériaux orthotropes, matériaux laminés, fibre de carbone, charge dynamique, charge d'impact, modélisation du processus, décomposition du processus, endommagement de la construction**