ISSN 1392 - 1207. MECHANIKA. 2012 Volume 18(5): 503-507

Effect of natural load on delamination behaviour of a new hybrid woven composite

D. Benzerga*, **A. Haddi****, **A. Lavie*****
**Département de Mines et Métallurgie, Faculté de Génie Mécanique, USTO, B.P 1505 Oran 31000, Algérie, E-mail: djeb_benz@yahoo.fr*
***Univ Lille Nord de France, F-59000 Lille, France, Laboratoire Génie Civil et géo-Environnement (LGCgE), EA 4515, Faculté des Sciences Appliquées, Université d'Artois, F-62400 Béthune, France, E-mail: abdelkader.haddi@univ-artois.fr*
****Univ Lille Nord de France, F-59000 Lille, France, Laboratoire Génie Civil et géo-Environnement (LGCgE), EA 4515, Faculté des Sciences Appliquées, Université d'Artois, F-62400 Béthune, France, E-mail: antoine.lavie@univ-artois.fr*

crossref http://dx.doi.org/10.5755/j01.mech.18.5.2692

1. Introduction

Delamination is one of the predominant forms of damage in laminated composite due to the lack of reinforcement through the thickness. The mechanisms of delamination and the evaluation of strength criteria are complex [1]. It is widely recognised that the major contribution to delamination fracture resistance is given by the damage developing in matrix-rich interlaminar layer. Delamination is created by an important accumulation of cracks in the matrix. For this reason the delamination occurs in general later in the history of the laminate damage. Transverse matrix cracking, when it is propagated, can reach the interface between two layers of different fibre orientation. The interface between two adjacent layers can debond under inerlaminar stresses. An interface where delamination could occur is introduced between the constituent layers. A simple but appropriate continuum damage representation is proposed. A nondimensional damage parameter is introduced to describe the distributed microdefects macroscopically at a local point on the interface in the context of continuum damage mechanics. By adapting the procedure established in [2], making use of a constructed damage surface, the damage evolution law is established. The damage surface combines the conventional stress-based and damage-mechanics-based failure criteria unifying the simulation of the initiation and propagation of the delamination.

The objective of this paper is to develop a model to simulate delamination growth in new woven laminated composite reinforced by particles of cores for orthopedic use. The walk cycle has been used to determine the operating conditions of tibiae prosthesis. Hence, the deflection tests were validated by orthopedist experts. Three End-Notched Flexure (3ENF) tests were carried out on the new woven composite to detect the delamination phenomenon. We assume that the interface has a bilinear softening behaviour and regarded as being a whole of several interfacial bonds. Each bond is supposed to be made up of three stiffnesses acting in the three delamination mode directions. The method developed has been used to simulate delamination in mode II. The numerical predictions are compared with experimental results.

2. Damage interface relationship

The laminated composite structures are often made up of the layers with different fibers orientation [3]. The phenomenon of delamination occurs between two adjacent layers. Laminated structures can be regarded as a homogeneous stacking of orthotropic layers. An interface between two adjacent layers can be introduced into the zone where possible delamination may occur. The interface behaves as a surface entity [4] with no thickness. Delamination appears, often, in these layers. The interlaminar stresses of tension and shearing before delamination are written as

$$S^{i3} = k_{i3}^0 u_{i3}, \quad (i = 1,2,3) \tag{1}$$

where u_{ij} are the relative displacement components across the interface and k_{i3}^0 are penalty stiffnesses of the interface. One defines a local coordinate system, such as, subscript 33 indicate the direction through the thickness, and directions 23, 13, are the two other orthogonal directions in the plan of the interface where a potential delamination can occur. The stiffnesses of the interface must be enough large to ensure reasonable connections and small at the same time to avoid numerical problems [5]. A reasonable choice of the interface stiffnesses was suggested by [6]

$$k_{i3}^0 = k_{i3}\hat{S}^{i3} \quad (i = 1,2,3) \tag{2}$$

and

$$k_{i3} = k = 10^5 \sim 10^7\,\mathrm{mm}^{-1}$$

where $\hat{S}^{i3}$ $(i = 1,2,3)$, are the interlaminar tensile and shear strengths. As the level of loading increases, the delamination damage occurs and develops at the interface. From a micromechanical point of view, there are the often zones containing microdefects such as the microscopic cracks and the microvoids which are potential sources of damage. Macroscopic cracks of delamination are formed after the growth and the coalescence of the microdefects. Considering these microdefects in the context of continuum damage mechanics, a parameter of the damage is necessary for the description of the macroscopic effects of these microdefects. The effective properties of material can be expressed according to the parameter of damage to reflect these effects. Delamination in the zone of the process of damage can be characterized by the surface of micro-delaminations. An adimensional parameter d can be introduced representing the fraction of microdelaminations into representative volume of the interface [7]. The interlaminar stresses over the volume element can be written as

$$S^{i3} = k_{i3}^{0}\left(1-d_{i3}\right)u_{i3} \quad \left(i = 1,2,3\right) \tag{3}$$

The Eq. (3) represents the constitutive law of an elastic and damageable interface. The effective stiffness of the interface, $k_{i3}^{0}\left(1-d_{i3}\right)$ decreases gradually when the delamination damage increases. The damage parameter $d_{i3} = 0$ represents the undamaged state and $d_{i3} = 1$, indicates a fully damaged state.

The free energy potential has the following form

$$\psi\left(u_{i3}, d_{i3}\right) = \frac{1}{2}\sum_{i=1}^{3}\left(1-d_{i3}\right)k_{i3}^{0}\left[u_{i3}\right]^{2} \tag{4}$$

The tractions at the interface are

$$t_{i3} = \frac{\partial\psi}{\partial u_{i3}} = \left(1-d_{i3}\right)k_{i3}^{0}\left[u_{i3}\right] \tag{5}$$

The thermodynamic conjugate forces associated to the three delamination modes are

$$Y_{i3} = -\frac{\partial\psi}{\partial d_{i3}} = \frac{1}{2}k_{i3}^{0}\left[u_{i3}\right]^{2} \tag{6}$$

The mechanical dissipation inequality for isothermal conditions

$$\sum_{i=1}^{3} Y_{i3}\dot{d}_{i3} \geq 0\,. \tag{7}$$

3. Description of the model

For an intact interface, delamination initiates when the interlaminar stresses or a combination of them reach a limit. The Hashin quadratic failure criterion [8], allows to predict the initiation of delamination

$$\left(\frac{S^{33}}{\hat{S}^{t33}}\right)^{2} + \left(\frac{S^{23}}{\hat{S}^{23}}\right)^{2} + \left(\frac{S^{13}}{\hat{S}^{13}}\right)^{2} = 1 \tag{8}$$

The Eq. (8) can be written in the following form

$$f_{s}\left(S^{i3}\right) - 1 = 0 \tag{9a}$$

where

$$f_{s}\left(S^{i3}\right) = \begin{cases} \left(\dfrac{S^{33}}{\hat{S}^{t33}}\right)^{2} + \left(\dfrac{S^{23}}{\hat{S}^{23}}\right)^{2} + \left(\dfrac{S^{13}}{\hat{S}^{13}}\right)^{2} & \text{if } S^{33} > 0 \\ \left(\dfrac{S^{23}}{\hat{S}^{23}}\right)^{2} + \left(\dfrac{S^{13}}{\hat{S}^{13}}\right)^{2} & \text{if } S^{33} < 0 \end{cases} \tag{9b}$$

For an existing delamination, a damage mechanics approach has proved successful in dealing with its propagation. Considering the thermodynamic forces as being the energy release rates, the criterion of rupture for propagation of the delamination can be expressed by the following equation [9, 10]

$$\left[\left(\frac{Y_{33}}{G_{IC}}\right)^{\alpha} + \left(\frac{Y_{23}}{G_{IIC}}\right)^{\alpha} + \left(\frac{Y_{13}}{G_{IIIC}}\right)^{\alpha}\right]^{1/\alpha} = 1 \tag{10}$$

That one can write in the form

$$f_{g}\left(Y_{i3}\right) - 1 = 0 \tag{11a}$$

where

$$f_{g}\left(Y_{i3}\right) = \left[\left(\frac{Y_{33}}{G_{IC}}\right)^{\alpha} + \left(\frac{Y_{23}}{G_{IIC}}\right)^{\alpha} + \left(\frac{Y_{13}}{G_{IIIC}}\right)^{\alpha}\right]^{1/\alpha} \tag{11b}$$

where G_{iC} ($i = I; II; III$) are the individual critical energy release rates. $\alpha = 2$ is the most frequently chosen, which correspond to quadratic failure criteria, it allows to find a traditional form of the surface of rupture in propagation [4]. In the context of continuum damage mechanics involves two aspects, the initiation and the growth of the damage. The concept of a damage surface proves to be necessary [11]. A damage surface is therefore constructed as follows

$$F\left(S^{i3}, Y_{i3}\right) = f_{s}\left(S^{i3}\right) - \left[1 - f_{g}\left(Y_{i3}\right)\right] = 0 \tag{12}$$

when $F < 0$, no damage development can occur at the interface, thus the damage variation $\Delta d = 0$. Damage initiates or develops if $F > 0$.

An infinitesimal change of the damage at the interface as a result of a change of tractions requires the satisfaction of the following equation

$$dF = \sum_{i=1}^{3}\left(\frac{\partial F}{\partial S^{i3}}dS^{i3} + \frac{\partial F}{\partial Y_{i3}}dY_{i3}\right) = 0\,. \tag{13}$$

4. Damage evolution law

Making use of Eqs. (3), (6) and (13), the incremental interfacial constitutive law and damage evolution law can be obtained in terms of incremental relative displacements as [5]

$$dS^{i3} = k_{i3}^{0}\left(1-d_{i3}\right)du_{i3} - k_{i3}^{0}\,u_{i3}\sum_{j=1}^{3}A_{j3}du_{j3} \quad \left(i = 1,2,3\right)$$

and

$$\dot{d} = \sum_{i=1}^{3}A_{i3}du_{i3} \tag{15}$$

respectively, where

$$A_{i3} = \left[\frac{\partial F}{\partial S^{i3}}k_{i3}^{0}\left(1-d\right) + \frac{\partial F}{\partial Y_{i3}}k_{i3}^{0}u_{i3}\right] \Bigg/ \sum_{j=1}^{3}\frac{\partial F}{\partial S^{i3}}k_{i3}^{0}\,u_{i3}$$

$$\left(i = 1,2,3\right) \tag{16}$$

When no delamination development occurs

$$\dot{d} = 0 \tag{17}$$

and the incremental constitutive law becomes

$$\left.\begin{array}{l} S^{i3} = k_{i3}^{0}\left(1 - d_{i3}\right)u_{i3} \quad \left(i = 1,2\right) \\ S^{33} = k_{33}^{0}u_{33}. \end{array}\right\} \tag{18}$$

5. New woven laminated composite

As it was mentioned earlier in this paper, the objective of the present work is to develop a delamination model that can predict delamination growth in new woven laminated composite for orthopedic use. The reference composite consists of an organic matrix containing methyl methacrylate and of a woven reinforcement including: a reinforcing glass fiber and fabric perlon having an absorbing role. The textile reinforcement made up of several folds reinforcing laid according to the orientation $[90/45_2/0]$ [12].

Hybrid composite: In addition to the components of the reference composite, a natural load: the date core pellet was built-in thus forming the hybrid composite. The date cores powder incorporation has an increase effect of the mechanical characteristics giving to the hybrid composite a better behaviour and reducing certain types of degradation like delamination. Fig. 1 shows homogenous and

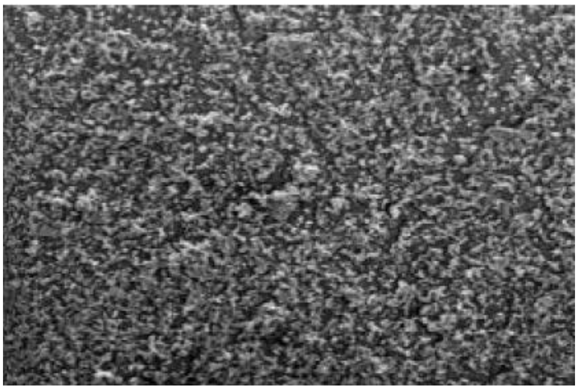

Fig. 1 Micrograph of a polished area of one intermingled with fiber glass twill and granulated of date cores observed to MEB during the development of the hybrid composite [12]

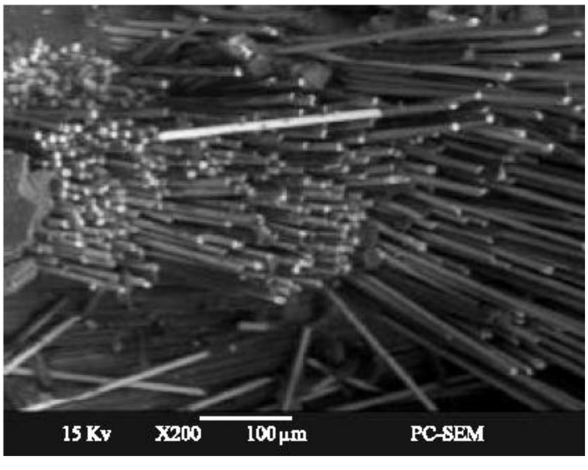

Fig. 2 Micrograph of the fracture surface of prosthetic [12]

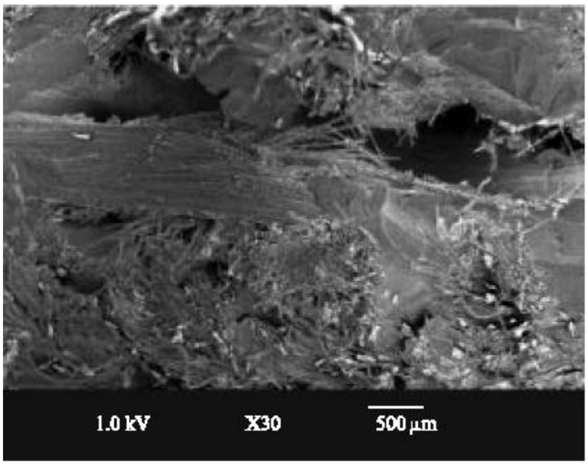

Fig. 3 Fracture topography of hybrid composite [12]

uniform date pellets distribution in the hybrid composite. It is necessary also to notice the phenomenon of date cores granulate intermingling around the fabric wicks (see Fig. 2). On Fig. 2, it appears fibers decoherence of glass fiber and illustrates the fiber rupture. Fig. 3 shows a consolidation due to date cores granulates. The fibers appear well intermingled. This phenomenon gives a better mechanical behaviour to the hybrid composite.

6. Numerical simulation of failure of new woven composite

To implement the above method into an FE model, the delamination has been modeled by the interface element, COMBIN14, available from ANSYS element library [13]. This is a 1D element with the capability of taking generalized nonlinear force-deflection relations. The option provides a uniaxial tension-compression element with up to three degrees of freedom at each node, i.e. translations in the 1, 2, and 3 directions. This element behaves as longitudinal spring (no bending or torsion is considered). Consequently, for each pair of interfacial nodes, three of these spring elements will be associated acting in mutually perpendicular directions corresponding to the three fracture modes. The element is defined by two initially coincident nodes. The penalty stiffness *k* which appears in relation (1) has to be expressed in spring stiffness form (i.e. N/m) to be used in our finite element analysis (FEA). Each pair of interfacial nodes (nodes which belong to the upper and lower plies) is initially coincident on the interface. Hence the interface is replaced by uniform distribution of three springs at each node (Fig. 4). These ‘‘spring’’ elements, used for the elastic interface, have no thickness. This satisfies the condition of very thin interfacial zone comparatively to the dimensions of the constituents. For a spring element the nodal force between two points depends only on the relative displacements of that node-pair. Using the ANSYS programmable language, a subroutine was developed and implemented into the main code to model the delamination growth simulation. All parts of the structure are meshed with 4-noded linear elements [14]. To deal with the contact occurring at some points of the interfacial crack where compression takes place, a contact element available in the ANSYS element library is used. This contact element, based on a penalty type method, does not allow for negative mode I relative displacement across the interface. A negative relative displacement would indeed mean a physically impossible interpenetration of the constituents. We also assume that there is no friction between the lips of the crack (perfect sliding case) [15]. As for the numerical modelling of the elastic interface, it is represented by a spring layer which resists normal extension and shear deformation (Fig. 4). Taking into account all these points the elastic analysis are carried out with the ANSYS finite element program. For each position on the crack front of the initial interface crack, the damage is calculated and compared with the critical value (d = 1). When the damage is bigger the crack grows one step at the evaluated position. This is realized by disabling the spring element at this location.

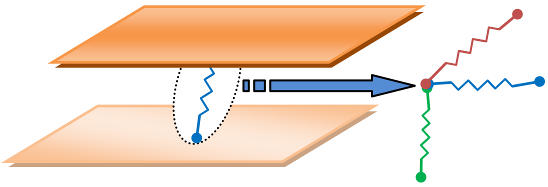

Fig. 4 Rheological representation of the interfacial bond based on the association of three springs

As it was mentioned earlier in this paper, the objective of the present work is to develop a delamination model that can predict delamination growth in new woven laminated composite for orthotropic use. This composite is obtained from a laminated composite woven by incorporating a natural organic load (granulates of date cores) which becomes hybrid composite. The new composite is made of an organic matrix containing methyl methacrylate and of a woven reinforcement including a reinforcing glass fiber and a fabric perlon having an absorbing role and consisting of two plies (90, 45_2, 0). Numerical simulations were carried out in end-notched flexure (3ENF) tests to detect the initiation and growth of delamination in the new woven composite. The length of specimen modelled is 60 mm, its width is 22 mm, and composed of two 1.65 mm thick plies. The thickness of the interface is taken equal to 1/5 of specimen thickness. Fig. 5 shows the numerical predictions and experimental data for the 3ENF tests of the woven laminated composite.

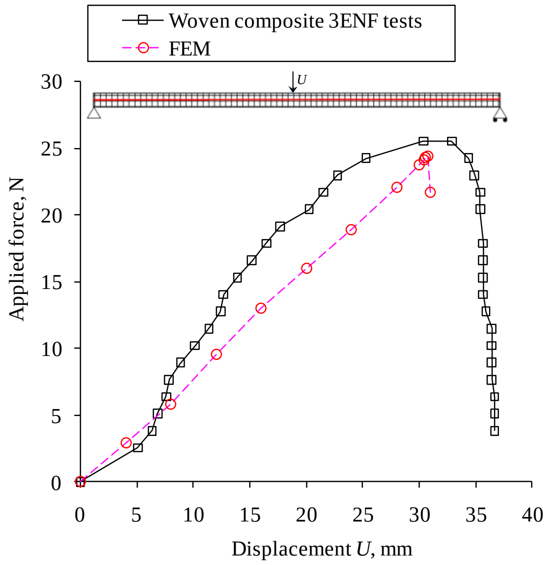

Fig. 5 Experimental and predicted curves of the woven laminated composite 3ENF tests

The results show that the difference between the predicted and experimentally determined maximum loads does not exceed 5%. The material properties are shown in Table.

Table

The proprieties of the woven laminated composite

E_{11}	$E_{22}=E_{33}$	$\nu_{12}=\nu_{13}$	ν_{23}	$G_{12}=G_{13}$	G_{23}
1.1 GPa		0.25			
G_{IC}	G_{IIC}	σ_{33m}	$\sigma_{13m}=\sigma_{23m}$	k	
	0.0382 N/mm		4.0 MPa	248 N/mm	

7. Conclusion

For the prediction of delamination initiation and growth, a method based on a damage mechanics approach by adopting softening relationships between tractions and separations is used to simulate the delamination. An elastic and damageable interface was introduced between the layers. The elastic interface was replaced by a layer of springs covering the whole surface of the interface. The onset of damage and the growth of delamination can be simulated without previous knowledge about the location, the size, and the delamination direction of propagation.

The new woven laminated composite for orthotropic use debond problem was used as a test of the capabilities of the criterion. The example analyzed indicate that the method of interface considered as uniform distribution of springs can predict the strength of composite structures that exhibit progressive delamination.

References

1. **Ziliukas, A.; Malatokiene, A.** 2011. Fracture of laminated rectangular bar after buckling, Mechanika 17(4): 352-357. http://dx.doi.org/10.5755/j01.mech.17.4.560.
2. **Zou, Z.; Fok, S.L.; Oyadiji, S.O.; Marsden, B.J.** 2004. Failure predictions for nuclear graphite using a continuum damage mechanics model, Journal of Nuclear Materials 324: 116-124. http://dx.doi.org/10.1016/j.jnucmat.2003.09.005.
3. **Keršiene, N.; Žiliukas, A.; Keršys, A.** 2010. Influence of ply orientation on mode I interlaminar fracture toughness of woven carbon and glass composites, Mechanika 2(82): 31-36.
4. **Gornet, L.; Lévèque, D.; Perret, L.** 2000. Modélisation, identification et simulations éléments finis des phénomènes de délaminage dans les structures composites stratifiées, Mec. Ind. 1, Ed. Scientifique et médicales, 9p.

5. **Zou, Z; Reid, S.R; Li, S.** 2003. A continuum damage model for delamination in laminated composites, Journal of the Mechanics and Physics of Solids 51: 333-356.
http://dx.doi.org/10.1016/S0022-5096(02)00075-3.
6. **Zou, Z.; Reid, S.R.; Li, S.; Soden, P.D**. 2002. Modelling interlaminar and intralaminar damage in filament wound pipes under quasi-static indentation, J Compos Mater 36(4): 477-499.
http://dx.doi.org/10.1177/002199830203600453 9.
7. **Chaboche, J.L.** 1988. Continuum damage mechanics: Part I–General concepts, Part II–Damage growth,crack initiation and crack growth, Journal of Applied Mechanics 55: 65-72.
http://dx.doi.org/10.1115/1.3173662.
8. **Sprenger, W; Gruttmann, F; Wagner, W.** 2000. Delamination growth analysis in laminated structures with continuum-based 3D-shell elements and viscoplastic softening model, Comput. Meth. Appl. Mech Engrg 185: 123-139.
http://dx.doi.org/10.1016/S0045-7825(99)00255-8.
9. **Alfano, G.; Crisfield, M.A.** 2001. Finite element interface models for the delamination analysis of laminated composites: mechanical and computational issues, Int J Numer Meth Engng 50: 1701-1736.
http://dx.doi.org/10.1002/nme.93.
10. **Willam, K.; Rhee, I.; Shing, B.** 2004. Interface damage model for thermomechanical degradation of heterogeneous materials, Computer Methods in Applied Mechanics and Engineering 193: 3327-3350.
http://dx.doi.org/10.1016/j.cma.2003.09.020.
11. **Zhang, Y.; Zhu**, **P.; Lai, X.** 2006. Finite element analysis of low-velocity impact damage in composite laminated plate, Materiel and Design 27(6): 513-519.
http://dx.doi.org/10.1016/j.matdes.2004.11.014.
12. **Tadjine, K.** 2007. Effet de l'incorporation de poudre de noyaux de dattes dans un composite polymère à usage biomécanique, PhD Thesis, Université d'Annaba.
13. **ANSYS** 2001. Structural and Analysis Guide. SAS IP Inc. Chapter 8: Non-linear structural analysis.
14. **Benzerga, D.; Haddi, A.; Seddak, A.; Lavie, A.** 2008. A mixed-mode damage model for delamination growth applied to a new woven composite, Computational Materials Science 41: 515-521.
http://dx.doi.org/10.1016/j.commatsci.2007.05.022.
15. **Benabou, L; Benseddiq, N; Nait-Abdelaziz, M.** 2002. Comparative analysis of damage at interfaces of composites, Composites Part B 33: 215-224.
http://dx.doi.org/10.1016/S1359-8368(02)00004-5.

D. Benzerga, A. Haddi, A. Lavie

ĮPRASTO APKROVIMO EFEKTAS NAUJO HIBRIDINIO KOMPOZICINIO AUDINIO IŠSISLUOKSNIAVIMO PROCESE

R e z i u m ė

Šio eksperimento tikslas sukurti išsisluoksniavimo modelį, kurį taikant galima būtų numatyti naujo kompozicinio audinio, naudojamo ortopedijoje, išsisluoksniavimą. Naujas kompozitas gautas iš laminuoto kompozicinio audinio įterpiant natūralaus organinio priedo (datulės šerdies granulių). Naujas kompozitas yra pagamintas iš organinės matricos, turinčios metilmetakrilato, audinio armatūros su stiklo pluoštu ir absorbuojančiojo porolono audinio. Vaikščiojimo ciklas bus panaudotas blauzdikaulio protezo darbo sąlygoms nustatyti. Vadinasi, įlinkio bandymai bus patvirtinti ortopedijos ekspertų, bus atliktas naujo kompozicinio audinio 3ENF bandymas išsisluoksniavimo reiškiniams nustatyti. Prognozuojama, kad skyrimosi paviršius bitiesiškai minkštės ir tai laikoma įvairių išsisluoksniavimo ryšių pagrindu. Manoma, kad kiekvienas ryšys yra veikiamas trijų standumo dedamųjų trijose išsisluoksniavimo kryptyse.

Įvesta skaliarinė išsisluoksniavimo dedamoji ir nustatyta tarpsluoksnio standumo degradacija. Pažeidimo paviršiuje pastebėta įtempių ir irimo mechanikos kriterijų įtaka ir nustatytas pažeidimų raidos dėsnis. Pažeidimo modelis yra įdiegtas į komercinę baigtinių elementų sistemą ANSYS, imituojant antrojo tipo išsisluoksniavimą. Skaitiniai rezultatai, gauti naudojant audinį (90, 45_2, 0), gerai sutampa su eksperimento rezultatais.

D. Benzerga, A. Haddi, A. Lavie

EFFECT OF NATURAL LOAD ON DELAMINATION BEHAVIOUR OF A NEW HYBRID WOVEN COMPOSITE

S u m m a r y

The objective of this work is to develop a delamination model that can predict delamination growth in a new woven composite for orthopedic use. This new composite is obtained from a laminated composite woven by incorporating a natural organic load (granulates of date cores) which becomes hybrid composite. The new composite is made of an organic matrix containing methyl methacrylate, a woven reinforcement including a reinforcing glass fiber and a fabric perlon having an absorbing role. The walk cycle has been used to determine the operating conditions of tibiae prosthesis. Hence, the deflection tests were validated by orthopedist experts. 3ENF tests were carried out on the new woven composite to detect delamination phenomenon. We assume that the interface has a bilinear softening behaviour and regarded as being a whole of several interfacial bonds. Each bond is supposed to be made up of three stiffnesses acting in the three delamination mode directions.

A scalar damage variable is introduced and the degradation of the interface stiffness is established. A damage surface which combines stress-based and damage-mechanics-based failure criteria is set up to derive the damage evolution law. The damage model is implemented into a commercial finite element ANSYS to simulate delamination in mode II. Numerical results on (90, 45_2, 0) are in good agreement with experimental observations.

Keywords: effect of natural load, delamination behaviour, hybrid woven composite.

Received March 15, 2011
Accepted September 21, 2012