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FINITE ELEMENT ANALYSIS OF DELAMINATION IN A NEW WOVEN COMPOSITE

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The objective of this work is to develop a delamination model that can be used to predict delamination growth in a new hybrid composite for orthopaedic use. The composite is obtained by incorporating a natural organic load (granulates of date cores) into a laminated woven composite makes it a hybrid. The matrix of the composite is based on methyl methacrylate, the reinforcement contains glass fiber and a perlon fabric, which plays an absorbing role. The walk cycle has been used to determine the working conditions of tibiae prosthesis. Hence, the bending tests were discussed with orthopedists and they approved it. A 3ENF tests were carried out on the composite to detect delamination phenomenon. In modeling, assumptions of a bi-linear softening behaviour of the interlaminate surface and a special interfacial bonding were made. A scalar damage was introduced and the degradation of the interface stiffness was found. A damage surface which combines stress-based and damage-mechanics-based failure criteria was set up to derive the damage evolution law. The damage model is implemented into a commercial finite element ANSYS program to simulate the delamination of mode II. Numerical results obtained for a (90, 45_2, 0) laminate occur to be in good agreement with experimental observations.

Keywords: fibre reinforced polymers, hybrids, delamination, modeling, orthopaedic applications.

КОНЕЧНО-ЭЛЕМЕНТНЫЙ АНАЛИЗ РАССЛОЕНИЯ В НОВОМ КОМПОЗИТЕ С ТКАНЕВЫМ АРМИРОВАНИЕМ

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Цель работы состоит в том, чтобы построить модель расслоения, позволяющую рассчитывать межслоевое расслоение в новом гибридном композите, используемом в ортопедии. К обычному армированию матрицы на основе метил-метакрилата стекловолокном добавлены перлоновая ткань и частицы, полученные дроблением косточек финика. Цикл шага человека использован для опредения условий нагружения большеберцового протеза. Испытания на изгиб были согласованы с экспертами-ортопедистами. Компютерные экперименты проводились по схеме 3ENF. При моделировании расслоения граница раздела между слоями наделена билинейным «размягчением». Модель повреждения основана на квадратичном критерии накопления повреждения, используется при этом стандартная программа в пакете ANSYS. Показано, что численные расчёты хорошо согласуются с экспериментом.

Ключевые слова: армированные пластики, гибриды, расслоение, моделирование, ортопедические приложения.

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 are complex. It is widely recognised that the major contribution to delamination fracture resistance is done by the damage developing in matrix-rich interlaminar layer. Delamination is created by an accumulation of cracks in the matrix. Consequently, the delamination occurs, generally, after some laminate damage has been accumulated. Transverse matrix cracking can reach the interface between two layers of different fibre orientation. The interface between two neighbouring layers can debond under inerlaminar stresses. As a result, free surfaces occur between the two layers.

In the present paper, a simple continuum damage model is proposed. A non-dimensional damage parameter is introduced to describe the distributed micro-defects macroscopically at a local point on the interface in the context of continuum damage mechanics. By adapting a procedure proposed in Ref. [1] and 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. Such an approach allows reaching the main objective of this paper, which is a developing of a model to simulate delamination growth in new woven laminated composite doped by particles of cores to be used in orthopedic applications. The walk cycle has been used to determine the operating conditions of tibiae prosthesis. The bending 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 bi-linear 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.

Interface damage fundamentals

The laminated composite structures are normally composed of layers with different fibers orientation. The phenomenon of delamination occurs between two adjacent layers. Laminated structures can be considered as a homogeneous stacking of orthotropic layers. An interface between two adjacent layers can be introduced into the zone where possible delamination can occur. The interface behaves as a surface entity [2] with zero thickness. Delamination takes place in these layer. 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_{13} are the relative displacement components across the interface and k_{i3}^{0} are penalty stiffnesses of the interface. We define a local co-ordinate system where subscript 33 indicate the direction normal to the thickness, and directions 23, 13 are two other orthogonal directions in the plan of the interface where a potential delamination can occur.

The stiffness of the interface must be both sufficiently large to ensure reasonable a connection and small to avoid problems in numerical calculations [3]. A reasonable choice of the interface stiffnesses was suggested in Ref. [4]:

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

where $\hat{S}^{i3}$ $(i = 1,2,3)$ are the interlaminar tensile and shear strengths and $k_{i3} = k = 10^{5} \sim 10^{7}\ \mathrm{mm}^{-1}$.

As the load increases, the delamination damage occurs and starts to grow. From a micromechanical point of view, there are often zones containing micro-defects such as the microcracks and the microvoids, which are potential sources of damage. Macrocracks are formed as a result of the growth and coalescence of the microdefects.

Considering these micro-defects in terms of continuum damage mechanics, a damage parameter is necessary to introduce to describe macroscopic effects caused by these microdefects. Effective properties of the material can be expressed by using the damage parameters. Delamination in a process zone can be characterized by the surface of micro-delaminations. Dimensionless parameter w, which is actually a fraction of micro-delaminations in a representative volume of the interface [5]. The interlaminar stresses can be then written as

$$S^{i3} = k^0_{i3}(1-\omega_{i3})u_{i3} \quad (i=1,2,3). \tag{2}$$

Equation (2) is the constitutive law of an interface undergone to damage. The effective stiffness of the interface, $k^0_{i3}(1-\omega_{i3})$, decreases gradually with the delamination damage increases. Damage parameter $\omega_{i3} = 0$ represents the undamaged state and $\omega_{i3} = 1$ correspons to a completely damaged state.

The free energy potential has the following form

$$\psi(u_{i3}, \omega_{i3}) = \frac{1}{2}\sum_{i=1}^{3}(1-\omega_{i3})k^0_{i3}[u_{i3}]^2.$$

The tractions at the interface are

$$t_{i3} = \frac{\partial \psi}{\partial u_{i3}} = (1-\omega_{i3})k^0_{i3}[u_{i3}].$$

The thermodynamic conjugate forces associated to the three delamination modes are

$$Y_{i3} = -\frac{\partial \psi}{\partial \omega_{i3}} = \frac{1}{2}k^0_{i3}[u_{i3}]^2. \tag{3}$$

The mechanical dissipation inequality for isothermal conditions

$$\sum_{i=1}^{3} Y_{i3}\dot{\omega}_{i3} \geq 0.$$

A model

For an intact interface, the delamination initiates when an interlaminar stress or a combination of stress components reaches a limit. The Hashin quadratic failure criterion [6], is taken as a criterion of the delamination initiation that is

$$\left(\frac{S^{33}}{\hat{S}^{t33}}\right)^2 + \left(\frac{S^{23}}{\hat{S}^{23}}\right)^2 + \left(\frac{S^{13}}{\hat{S}^{13}}\right)^2 = 1. \tag{4}$$

Equation (4) can be rewritten in the following form

$$f_s(S^{i3}) - 1 = 0,$$

where

$$f_s\left(S^{i3}\right)=\begin{cases}\left(\dfrac{S^{33}}{\hat{S}^{t33}}\right)^2+\left(\dfrac{S^{23}}{\hat{S}^{23}}\right)^2+\left(\dfrac{S^{13}}{\hat{S}^{13}}\right)^2 & \text{if} \quad S^{33}>0; \\ \left(\dfrac{S^{23}}{\hat{S}^{23}}\right)^2+\left(\dfrac{S^{13}}{\hat{S}^{13}}\right)^2 & \text{if} \quad S^{33}<0. \end{cases}$$

For the delamination, a damage mechanics approach has been proved as successful desribe its propagation. Considering the thermodynamic forces as being the energy release rates, the criterion the propagation of delamination can be expressed by the following equation [7, 8]:

$$\left[\left(\frac{Y_{33}}{G_{CI}}\right)^{\alpha}+\left(\frac{Y_{23}}{G_{CII}}\right)^{\alpha}+\left(\frac{Y_{13}}{G_{CIII}}\right)^{\alpha}\right]^{1/\alpha}=1, \tag{5}$$

which can be rewritten in the form

$$f_g\left(Y_{i3}\right)-1=0,$$

where $f_g\left(Y_{i3}\right)$ is the left side of Equation (5) and G_{ic} $(i = I; II; III)$ are the corresponding critical energy release rates. Normally $\alpha = 2$ is taken, which corresponds to the quadratic failure criterion. It allows finding a traditional form of the surface of rupture propagation [2].

In continuum damage mechanics, two damage stage are usually considered, the initiation and growth of damage. A damage surface is then introduced [9] as

$$F\left(S^{i3}, Y_{i3}\right)= f_s\left(S^{i3}\right)-\left[1-f_g\left(Y_{i3}\right)\right]=0.$$

At $F<0$, no damage occurs at the interface, thus $\Delta\omega=\mathbf{0}$. Damage initiates if $F>0$.

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

$$dF=\sum_{i=1}^{3}\left(\frac{\partial F}{\partial S^{i3}}dS^{i3}+\frac{\partial F}{\partial Y_{i3}}dY_{i3}\right)=0. \tag{6}$$

Damage evolution law

Making use of Equations (2), (3) and (6), the incremental interfacial constitutive law and damage evolution law can be obtained in terms of incremental relative displacements as [3]:

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

and

$$\dot{\omega}=\sum_{i=1}^{3}A_{i3}du_{i3},$$

respectively, where

$$A_{i3}=\left[\frac{\partial F}{\partial S^{i3}}k_{i3}^{0}\left(1-\omega_{i3}\right)+\frac{\partial F}{\partial Y_{i3}}k_{i3}^{0}u_{i3}\right]\Bigg/\sum_{j=1}^{3}\frac{\partial F}{\partial S^{i3}}k_{i3}^{0}u_{i3},\left(i=1,2,3\right).$$

When no delamination geowth occurs

$$\dot{\omega}=0$$

and the incremental constitutive law becomes

$$S^{i3}=k_{i3}^{0}\left(1-\omega_{i3}\right)u_{i3}\ \left(i=1,2\right);\ S^{33}=k_{33}^{0}u_{33}.$$

Numerical simulation of failure of new woven composite

To implement the above method into a finite element scheme, the delamination has been modeled by the interface element, COMBIN14, available from ANSYS element library [10]. This is a 1D element with the capability of taking generalized non-linear 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 the interfacial nodes, three of these spring elements will be associated acting in mutually perpendicular directions corresponding to three fracture modes. The element is defined by two initially coincident nodes. Penalty stiffness k, which appears in Equation (1) has to be expressed in spring stiffness form to be used in the finite element analysis (FEA). Each pair of interfacial nodes (those belonged 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. 1. These “spring” elements, used for the elastic interface, have no thickness. This satisfies the condition of very thin interfacial zone comparatively to

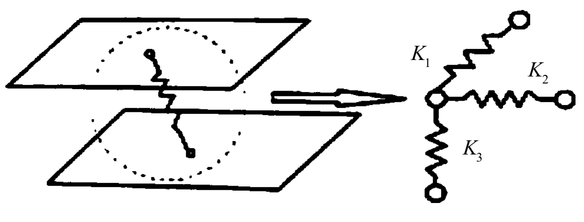

Fig. 1. Schematic of the interfacial bond based on an assembladge of three springs
Схематическое трёхпружинное представление о взаимодействии берегов расслоения

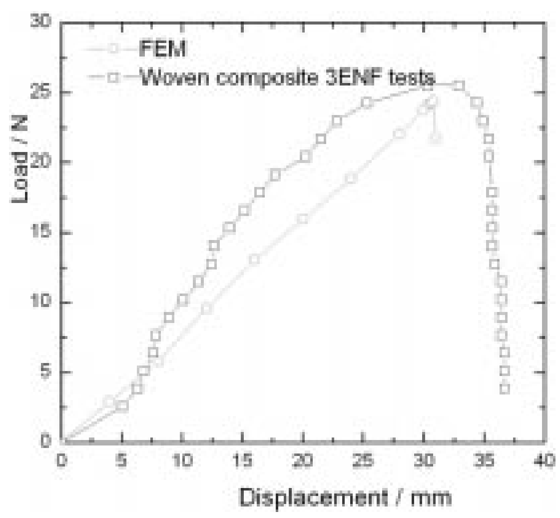

Fig. 2. Experimental and calculated curves of laminated composite specimens in 3ENF tests
Экспериментальная и расчётная кривые композитных образцов с надрезом, испытанных на изгиб с перерезывающей силой

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 language, a subroutine was developed and implemented into the main code to model delamination growth. All parts of the structure are meshed with 4-noded linear elements. 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 prevents negative mode I relative displacement across the interface. A negative relative displacement would indeed mean a physically impossible interpenetration of two free surfaces. No friction between surfaces of the crack is assumed, which means perfect sliding [11]. As for the numerical modelling of the elastic interface, it is represented by a spring layer which resists normal extension and shear deformation (Fig. 1). 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 an initial interface crack, the damage is calculated and compared with the critical value, w = 1. When the damage increases the crack grows by one step at the evaluated position. This is realised by disabling the spring element at this location.

As was mentioned earlier, the objective of present work is to develop a delamination model that can predict delamination growth in a new woven laminated composite for orthopaedic use. This composite contains a methyl methacrylate matrix incorporated with a natural organic load (granulates of date cores) and woven reinforcement including glass fiber and perlon fabric having an absorbing role/ The laminate (90, 45_2, 0) stacking ply.

Numerical simulations were carried out in end-notched flexure (3ENF) tests to detect initiation and growth of delamination in the composite. The length of aspecimen 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 the specimen thickness. The material properties as follows: E_{11} = 1.1 GPa, $E_{22} = E_{33}$, $n_{12} = n_{13}$, $G_{12} = G_{13}$, G_{IIC} = 0.0382 N/mm, $\sigma_{12m} = \sigma_{23m} =$ = 4.0 MPa, k = 248 N/MPa. Figure 2 shows the numerical predictions and experimental data for the 3ENF tests of the woven laminated composite. The results show that the difference between the calculated and experimental results for a maximum loads does not exceed 6%.

Conclusions

A method based on a damage mechanics approach is developed by introducing softening relationships between tractions and separations on the interfaces of lamina. The method is now used for simulation of delamination including both the initiation and growth of the interlamina cracks. A delamination behaviour of a new woven laminated composite for orthopaedic use was analysed by both experimental and computer simulation ways. Resulta of these studies are nearly the same, which proves a reliability of the model.

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