EFFECT OF NON-POLLUTING AND RENEWABLE LOAD ON DELAMINATION OF A COMPOSITE BIOMECHANICAL MATERIAL

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ABSTRACT

The objective of this paper is to develop a delamination model that can predict delamination growth in a new woven composite for orthopedic use. This composite material is obtained from a laminated composite woven by incorporating a natural organic load (granulates of date cores) which becomes hybrid composite. The 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. Three end-notched flexure (3ENF) tests were carried out on the new woven composite to detect delamination phenomenon. The formulation is based on damage mechanics and uses only two constants for delamination damage. We assume that the interface has a bi-linear softening behaviour and regarded as being a whole of several interfacial bonds. The model has been implemented into the commercial (FE) code. Numerical simulations were carried out in end-notched flexure (3ENF) tests to detect initiation and growth of delamination in the new woven composite.

KEYWORDS*: Woven composite; natural organic load; delamination; numerical simulation*

1.0 INTRODUCTION

Laminated composites can fail in a variety of failure modes, typically matrix cracking, compression failure, fibre fracture, fibre kinking, and delamination between adjacent plies. The main inherent weakness of laminated composites is the extremely low through thickness strength, which is an obvious weakness within the composite meso-structure. This weakness can lead to interior delaminations when subjected to external

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loadings that generate high peeling stresses, namely the two through thickness shears and the normal stress perpendicular to the laminae (Iannucci, 2006). Delamination is one of the predominant forms of damage in laminated. The mechanisms of delamination are complex. 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 (Benzerga et al., 2007). A simple but appropriate continuum damage representation 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 the procedure established in Zou et al. (2004), the damage evolution law is established. 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 (Katherine et al., 2013). 3ENF tests were carried out on the new woven composite to detect delamination. We assume that the interface is 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.

2.0 DAMAGE INTERFACE RELATIONSHIP

The laminated composite structures are often made up of layers with different fibers orientation. 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 (Gorne, 2000) 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_{i3} are the relative displacement components across the interface and k^{0}_{i3} are penalty stiffnesses of the interface. One defines a local co-ordinate 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 (Zou et al., 2003). A reasonable choice of the interface stiffnesses was suggested by (Zou et al., 2002)

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

$$\text{and} \quad k_{i3} = k = 10^{5} \sim 10^{7}\ mm^{-1}$$

where $\hat{S}^{i3} \quad (i = 1,2,3)$, 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 often zones containing micro-defects such as the microscopic cracks and the micro-voids which are potential sources of damage. Macroscopic cracks of delamination are formed after the growth and the coalescence of the micro-defects. Considering these micro-defects in the context of continuum damage mechanics, a parameter of damage is necessary for the description of the macroscopic effects of these micro-defects. An adimensional parameter d can be introduced representing the fraction of micro-delaminations into representative volume of the interface (Chaboche, 1988). The interlaminar stresses over the volume element can be written as

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

The Equation (3) represents the constitutive law of an elastic and damageable interface. The effective stiffness of the interface $k^{0}_{i3}(1-d_{i3})$ decreases gradually when the delamination damage increases (Abisset et al., 2011) . 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

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

The tractions at the interface are

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

The thermodynamic conjugate forces associated to the three delamination modes are:

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

The mechanical dissipation inequality for isothermal conditions,

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

It is assumed that the mechanical behaviour of the interface ($\sigma_{i3} - u_{i3}$) follows the law described in Figure 1 (Dongmin et al., 2011) where $u_{i3',0}$ and $u_{i3',m}$ (i = 1,2,3) correspond to the displacements obtained for the maximum stress σi3,m at the initial and final rupture of the interface.

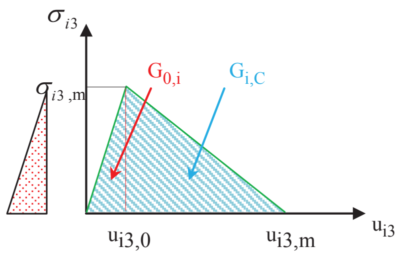

Figure 1. Relation stress-relative displacement $\sigma_{i3} - ui_3$ of the interface

The proposed damage model is able to describe three possible modes of delamination and is based on an indirect use of rupture mechanics (De Moura & Gonçalves, 2004). The model is completed by evolution equations for the interface damage parameters, which may be derived using the CDM framework described in (Allix et al., 1995). Damage evolution is sometimes made a function of the damage energy release rate divided by a critical value (Allixet al., 1998). The relative displacement and the damage energy release rate are related in a trivial mode. Hence in the present formulation, damage evolution is made a function of the relative displacement within a unit volume of material. The evolution of damage follows a simple bilinear relationship given by (Valoroso & Champaney, 2005).

$$d_{i3} = \frac{u_{i3,m}}{\left(u_{i3,m} - u_{i3,0}\right)}\left[1 - \frac{u_{i3,0}}{u_{i3}}\right] \tag{8}$$

$$\text{with } u_{i3,0} = \sigma_{i3,m} / k^{0}_{i3}\text{, and } u_{i3,m} = 2G_{i,C} / \sigma_{i3,m} \tag{9a,b}$$

where *i* can be used to represent mode *I, II or III*, and $u_{i3,m}$ is the strain at zero stress or damage = 1 (propagation), and $u_{i3,0}$ is the relative crack opening displacement at maximum stress or damage = 0 (initiation). The critical energies of rupture G_{IC}, G_{IIC} and G_{IIIC} can be calculated as:

$$G_{IC} = \int_0^{u_{33,m}} \sigma_{33} du_{33}\,,\; G_{IIC} = \int_0^{u_{13,m}} \sigma_{13} du_{13}\,,\;\; G_{IIIC} = \int_0^{u_{23,m}} \sigma_{23} du_{23} \tag{10}$$

It can be shown that the area under the curve in Figure 1 is equal to the fracture energy $G_{i,C}(i = I, I\ , III)$.

In general, a three-dimensional stress state exists: the three modes of rupture coexist at the same time and an analysis in mixed mode of delamination is necessary simultaneously to include the three damage modes. To begin with, consider the stored energy function (Truesdell & Noll, 1965):

$$2\zeta_d = (1 - d_{13})k^0_{13}[u_{13}]^2 + (1 - d_{23})k^0_{23}[u_{23}]^2 + (1 - d_{13})k^0_{33}[u_{33}] \tag{11}$$

Considering an isotropic damage $d = d_{ß} = d_{3} = d_{3}$ (the interface is a medium of very small thickness), Equation (11) becomes

$$2\zeta_d = (1 - d)\left[k^0_{13}[u_{13}]^2 + k^0_{23}[u_{23}]^2 + k^0_{33}[u_{33}]^2\right] \tag{12}$$

where $d \in [0;1]$ is the scalar damage variable.

The work-conjugate of the damage variable follows from the classical thermodynamic argument as (Alfano et al., 2004):

$$Y = -\frac{\partial \zeta_d}{\partial d} = \frac{1}{2}\left[k^0_{13}[u_{13}]^2 + k^0_{23}[u_{23}]^2 + k^0_{33}[u_{33}]^2\right] = Y_{13} + Y_{23} + Y_{33} \tag{13}$$

Using the same penalty stiffness in mode *II* and *III* ($k^0_{13} = k^0_{23} = k^0_{II}$), and assuming the delamination mechanisms in mode *II* and mode *III* to be same. Therefore, mode *III* can be combined with mode *II* by using a total tangential displacement u_{II} defined as the norm of the two orthogonal tangential relative displacements u_{13} and u_{23} as

$$u_{II} = \sqrt{\left(u_{13}^{\ 2} + u_{23}^{\ 2}\right)} \tag{14}$$

Based on Equation (13), the mixed-mode energy release rate Y can be expressed as:

$$Y = \frac{1}{2} k_{33}^{0} \left[U_{33}^{\ 2} + \gamma^{2} U_{II}^{\ 2} \right]$$
$$\text{with } \gamma = \left(\frac{k_{II}^{0}}{k_{33}^{0}} \right)^{1/2} \tag{15}$$

A mode mixity parameter β_1 can thus be defined as:

$$\beta_1 = \gamma \tan(\psi) \tag{16}$$

ψ being the loading angle:

$$\psi = \arctan\left(\frac{U_{II}}{U_{33}} \right) \in \left[0, \pi/2 \right] \tag{17}$$

Where by the expressions of the pure-mode contributions to Equation (13) follow as:

$$Y_{33} = \frac{1}{1+\beta_1^{\ 2}} Y \ ; \ \ Y_{II} = \frac{\beta^{2}}{1+\beta_1^{\ 2}} Y \tag{18}$$

In particular, assuming that initiation of damage can be predicted using a Hashin-type criterion (Alfano et al., 2004), i.e.

$$\left(\frac{Y_{33}}{G_{0I}} \right)^{\alpha_1} + \left(\frac{Y_{II}}{G_{0II}} \right)^{\alpha_1} = 1 \tag{19}$$

where G_{0I} and G_{0II} are the initial damage thresholds for a given loading angle as shown in Equation (17) while α_1 is positive model parameter. The initial mixed-mode threshold Y0 is computed from Equation (19) as:

$$Y_0 = \frac{\left(1+\beta_1^{\,2}\right)G_{0I}G_{0II}}{\left[\left(G_{0II}\right)^{\alpha_1} + \left(\beta_1^{\,2}G_{0I}\right)^{\alpha_1}\right]^{1/\alpha_1}} \tag{20}$$

where the pure-mode threshold energies G_{0I} and G_{0II} (Figure 1) are recovered in the limit as: $\psi \rightarrow 0$ and $\psi \rightarrow \pi/2$ respectively. The criteria used to predict delamination propagation under mixed-mode loading conditions are generally established is terms of the energy release rates and fracture toughness. We use the criterion, recently developed by Benzeggagh and Kenane (Camanho et al., 2001)

$$G_T = G_{IC} + \left(G_{IIC} - G_{IC}\right)\left(\frac{G_{II}}{G_T}\right)^{\eta} \tag{22}$$

with $G_T = G_I + G_I$ and η a parameter.

The energies releases at failure are computed from (Figure 1):

$$G_{X,C} = \int_0^{u_{i3,\max}} \sigma_{i3}\,du_{i3} \quad avec\ X = I, II, III\ et\ i = 1,2,3 \tag{23}$$

The propagation of decohesion takes place for:

$$Y_f = G_{IC} + (G_{IIC} - G_{IC})\left(\frac{\beta_1^{\,2}}{1+\beta_1^{\,2}}\right)^{\eta} \tag{24}$$

In order to account for irreversibility, the maximum over time value of the mixed-mode energy release rate Y (t) is defined as, at time

$$Y_{max}(t) = \max_{t \le \tau}\{Y\} \tag{25}$$

The constitutive law (5) could be expressed as

$$\sigma_{i3} = (1-d)\,k\,u_{i3} \tag{26}$$

In order to avoid interpenetration for compression situations, simple contact logic already available in most FE codes could be used. Instead, the following condition is added to Equation (5):

$$\sigma_{33} = k_{33} u_{33} \Leftarrow u_{33} < 0 \tag{27}$$

where only one damage variable is used, and computed as

$$D = \frac{\sqrt{Y_f}}{\sqrt{Y_f} - \sqrt{Y_0}} \left(1 - \frac{\sqrt{Y_0}}{\sqrt{Y_{\max}}} \right) (\text{si } D < 1; \; D = 1 \text{ otherwise}) \tag{28}$$

3.0 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 (ANSYS, 2001). 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 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. 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 delamination growth simulation. All parts of the structure are meshed with 4-noded linear elements. We assume that there is no friction between the lips of the crack (perfect sliding case) (Benabou, 2002). 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 realised by disabling the spring element at this location.

As was mentioned earlier in this paper, the objective of 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 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 1/100 of specimen thickness. The material properties are shown in table 1. Figure 2 shows the numerical predictions and experimental data for the 3ENF tests of the woven laminated composite.

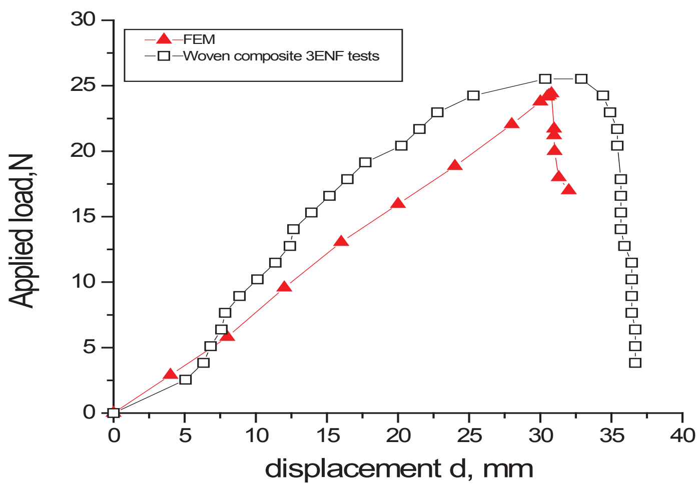

Figure 2. Experimental and predicted curves of the woven laminated composite 3ENF tests

Table 1. The properties of the woven laminated composite

E_{11}	$\upsilon_{12}=\upsilon_{13}$	
1.1 GPa	*0.25*	
G_{IIC}	$\sigma_{13m} = \sigma_{23m}$	k
0.0382 N/mm	4.0 MPa	248 N/mm

4.0 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 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.

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