MODELLING COMPRESSION DAMAGE IN CFRP: COMBINING FRICTION WITH DAMAGE

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1 Introduction

Modelling damage growth under compressive loading is of great interest in many composite applications such as bolted joints, crash structures or even during impact loading. Damage models currently available (cohesive elements or ply damage models) make it possible to account for the energy dissipated by fracture. However, the frictional energy spent on fractured surfaces is often not included.

In the literature [1,2], models combining friction and damage have been developed to model the cohesive fracture of interfaces in composites or masonry work. Friction is added either after damage is fully developed or from the initial state, i.e. even during the elastic behaviour. These approaches correspond to two limit behaviour. Physically, friction builds up as new crack surfaces are created. The combination of damage and friction is therefore a continuous process. Ragueneau et al. [3] proposed a model for concrete where a frictional shear force grows linearly with a damage variable, characterising the state of damage.

The present contribution introduces a traction separation law which combines the effect of both damage and friction. The model is developed in a general 3D framework which makes it applicable to ply failure (fibre and matrix dominated failure modes) and to interlaminar failure.

To validate a simple experimental investigation on the crushing of a wedge specimen is designed. Typical crushing experiments are performed on multi-directional tubes [4] or corrugated specimens [5,6]. These designs, which are aimed at studying practical stacking sequences and to prevent buckling during crushing, are however difficult to use for model validation. The sequence of event during failure is intricate with damage in plies with different orientation interacting. The circular or corrugated shapes are an added difficulty which may shadow over some of the material model features. The experiments presented here are an attempt to trigger crushing on a simplified geometry and layup, by using short unidirectional specimen with a wedge as initiator.

2 Model description

2.1 Framework

The present model looks at damage propagating in a given fracture plane, either well defined between two plies or at any orientation within a ply. In a general sense, two components of the traction vector (normal and shear) can be defined on that plane, as seen in Fig.1.

Fig. 1. Normal and shear tractions acting on an arbitrarily oriented plane

For fibre reinforced plastics, fracture in compression, either along or transverse to the fibre direction, is often shear dominated. Therefore the present model assumes that only the shear tractions
acting on the fracture plane are affected by damage and friction.

2.2 Model development

2.2.1. Elastic

The traction separation law has an initial elastic behaviour. The components of the traction vector are calculated by rotating the stresses in potential fracture planes. For the case of matrix failure, focus of this contribution, the planes are those rotated around the 1-axis in Fig. 1.

2.2.2. Initiation

From the elastic calculations, a failure index is calculated using Eq. 1

\[
\frac{\left(\frac{\tau_T}{S_T}\right)^2 + \left(\frac{\tau_L}{S_L}\right)^2 \gamma}{\gamma_0} \gamma_0 \left(\gamma_f - \gamma\right)
\]

with \(S_T\) and \(S_L\) being the transverse and longitudinal shear strengths. The model is here developed only for compressive damage, i.e. \(\sigma_N < 0\). If \(\sigma_N > 0\) the behaviour is assumed to remain elastic. The angle of the fracture plane for which Eq. 1 is satisfied is stored in memory and remains fixed during damage growth.

2.2.3. Propagation

During damage growth, the shear component, \(\tau\), is assumed to have two components, similar to the assumption taken in [3]: (i) a component associated with damage growth and (ii) a frictional shear component. The damage variable \(d\) reduces the nominal traction \(\tau\) according to Eq. 2. Note again that only the shear tractions are affected.

\[
\tau^{\text{damage}} = (1 - d) \tau
\]

The evolution of the damage variable follows previous model [7] and corresponds to a linear softening of the \(\tau^{\text{damage}}\).

\[
d = 1 - \frac{\gamma_0}{\gamma} \left(\frac{\gamma_f - \gamma}{\gamma_f - \gamma_0}\right)
\]

where \(\gamma_0\) is the strain at damage initiation and \(\gamma_f\) is the final separation strain, which is function of the fracture toughness \(G_c\) as

\[
\gamma_f = 2 \frac{G_c}{I_c \tau_0}
\]

with \(\tau_0\) the shear stress at damage initiation. \(I_c\) is a length (typically dimension of a finite element) introduced to convert a traction separation law into stress strain relationship see [7] for details.

A frictional shear stress following a Coulomb law is defined in Eq. 5.

\[
\tau^{\text{friction}} = \mu (\sigma_N - p_0)
\]

The vector \(p_0\) is introduced to account for compressive residual stresses built up around the fibres during curing. The identification of this parameter is detailed later on.

To ensure a correct unloading and reloading behaviour, the evolution of friction is governed by a flow rule and standard Khun-Tucker conditions. The resultant nominal stress is then given by Eq. 6

\[
\tau = \tau^{\text{damage}} + d \tau^{\text{friction}}
\]

2.2.4. Pressure

Fig. 2 shows the shear responses for different levels of compressive normal stresses and with a friction coefficient of 0.3. In this example, the shear strength is set to 100 MPa and it can be seen that for the three pressure levels the maximum shear stress allowable increases with pressure. The fracture toughness, controlling the evolution of damage, is kept constant for the three curves. Therefore, the changes in the softening part of the curves are a consequence of friction alone. Once the damage variable reaches one, only friction remains, which corresponds to the constant part of the curves.
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2.2.5. Mixed mode

The model is formulated to account for different behaviour in shear in the longitudinal and transverse direction. Fig. 3 shows the shear responses for pure longitudinal, pure transverse and mixed mode loading. In this figure, the standard linear softening response is shown for a case where the coefficient of friction \( \mu \) is set to 0.

The evolution of the damage variable in the L-T plane is assumed to be isotropic. Similarly, specific and different values can be attributed to the components of the vectors \( \mu \) and \( p_0 \) in the transverse and longitudinal directions. It has been shown in [8] that the coefficient of friction are not equal in these two directions, however they are taken equal for simplicity.

4 Model Identification

Besides elastic properties, the parameters required for the model can be subdivided in three categories: (i) strength properties, (ii) damage properties and (iii) friction properties. In the experimental and numerical studies presented below, a carbon epoxy system MTM57/T700 has been used and the properties for this material are summarized in Table 1.

Table 1. Material properties for MTM57/T700

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic Properties</td>
<td></td>
</tr>
<tr>
<td>( E_{11} ) (GPa)</td>
<td>128</td>
</tr>
<tr>
<td>( E_{22} ) (GPa)</td>
<td>7.9</td>
</tr>
<tr>
<td>( G_{12} ) (GPa)</td>
<td>3</td>
</tr>
<tr>
<td>( \nu_{12} ) ()</td>
<td>0.3</td>
</tr>
<tr>
<td>( \nu_{23} ) ()</td>
<td>0.4</td>
</tr>
<tr>
<td>Strength Properties</td>
<td></td>
</tr>
<tr>
<td>( S_L ) (MPa)</td>
<td>50</td>
</tr>
<tr>
<td>( S_T ) (MPa)</td>
<td>50</td>
</tr>
<tr>
<td>Damage Properties</td>
<td></td>
</tr>
<tr>
<td>( G_{Ic} ) (kJ/m²)</td>
<td>1.2</td>
</tr>
<tr>
<td>Friction Properties</td>
<td></td>
</tr>
<tr>
<td>( p_0 ) (MPa)</td>
<td>75</td>
</tr>
<tr>
<td>( \mu ) ()</td>
<td>0.3</td>
</tr>
<tr>
<td>( k ) (GPa)</td>
<td>3</td>
</tr>
</tbody>
</table>

The elastic and strength properties are given from the manufacturer. The remaining properties are calculated from a cyclic shear response test. Fig. 4 shows the identification of the shear response with experimental longitudinal shear tests from [9] (Note...
that in [9] the cyclic tests are performed on an MTM57/E-glass system, but it is also shown there that this system and MTM57/T700 have the same behaviour for strain under 10%). The schematic in Fig. 4b described the different stages during a cyclic loading.

After damage initiation, the nonlinear response is the result of the decreasing elastic traction due to damage growth and an increasing frictional shear component – stage 1 – which magnitude is a function of the instantaneous damage variable \( d \) and of the frictional force, i.e. the product \( \mu p_0 \). Unloading after damage initiation is first through stick behaviour with a contact stiffness \( k \) – stage 2 – then through elastic slip with a stiffness \( dG \) – stage 3.

By matching the stiffness during stage 2, the contact stiffness \( k \) is identified. The evolution of the damage variable \( d \) as a function of strain is calculated from the stiffness in stage 3 at several unloading cycles. Once the damage variable is defined, the product \( \mu p_0 \) is identified from stage 1.

As mentioned in the introduction, the purpose of the tests performed is to validate the material model. Therefore, care has been taken to develop a specimen as simple as possible so that any uncertainty regarding the loading conditions or geometrical features can be removed. Furthermore, a unidirectional layup is chosen to isolate the damage mechanisms at a single ply level. The setup and a schematic representation are given in Fig. 5a and b, respectively. The specimens are made of a MTM57/T700 carbon epoxy system, manufactured in an autoclave according to the manufacturer recommendations, with a 90˚ layup. The specimens are then cut to dimensions using a band saw and one end is chamfered at an angle of 10˚.

The specimens are then clamped between two metal plates over a length of 12 mm, leaving 4 mm for crushing. Support and specimens are then placed during to loading plate, and crushing takes place at a quasi-static rate of 0.1 mm/s.
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Fig. 5. (a) Experimental setup; (b) schematic of the setup with dimensions in mm.

Fig. 6a and b show the specimen sidewise during loading. Because of the sharp wedge damage initiates early in the test. Besides the rather short gauge length, the specimens show some bending as the chamfer is being consumed. Eventually, a matrix crack forms across the specimen at an angle of approximately 40° to the loading direction (joining the low side of the wedge to the opposite side of the specimen close to the support).

Fig. 6. (a) Experimental setup; (b) schematic of the setup with dimensions in mm.

Loading proceeds until the 4 mm available are fully crushed and the final fracture morphology is shown in Fig. 7a. Note that the specimen is unloaded in this figure. The first main matrix crack shown in Fig. 6a is clearly visible in this figure. The central top of the specimen, which initially corresponded to low end of the specimen, shows extensive crushing, with a large accumulation of microcrack. Material from this area might have been removed in the form of debris. The initial wedge corresponds to the top left part of the specimen in Fig. 7a, and it can be seen that it is fractured in two pieces by a matrix crack. The bottom part of the specimen (above the support) is characterised by a double sided wedge formed by the initial matrix crack from Fig. 6a and a complementary crack. The region within the wedge appears to be rather undamaged.

Only two specimens have been tested, but the fracture topologies and global responses are consistent. Applied strain versus stress curves are shown in Fig. 8. One test was interrupted at the maximum load and the second when a 50% load drop occurred. The response appears to be linear initially, before reaching a constant load level and eventually a sharp load drop.

Even though the response appears initially linear, the wedge is being crushed and the material behaves
highly nonlinearly. The constant stress level is reached when the wedge is fully consumed, i.e. when the loading plate reaches the low end of the wedge and the drop in load occurs when the matrix crack crossing the specimen is formed.

![Image](image1.png)

Fig. 7. (a) Experimental setup; (b) schematic of the setup with dimensions in mm.

6 FE modelling

A 3D finite element (FE) model of the experimental setup has been developed. The specimen is modelled using quad elements with reduced integration (C3D8R in Abaqus). The mesh size is arbitrarily chosen to 0.1 mm to capture the geometrical features (including the wedge) with high fidelity. The support is not physically represented and instead clamped boundary conditions are applied to the lower part of the model. The loading plate is represented as a rigid body and the contact between the specimen and plate is accounted for with a general contact including friction. A study on the coefficient of friction between plate and specimen showed that it had only a small effect on the global response. A value of 0.15 is therefore chosen.

The material model developed in Section 2 is implemented in a Fortran user subroutine for the commercial finite element package Abaqus/Explicit. A baseline model using the material data given in Table 1 is first studied. The damage variable during crushing is given in Fig. 6c and d, corresponding to the experimental pictures in Fig. 6a and b. As in the experiments, the model predicts first the crushing of the specimen and a slight bending. Once the loading reaches the low end of the wedge, the model predicts that top left side of the specimen (Fig. 6d) is damaged with a boarder lying at 40° to the loading direction. Compression is applied further on the model and the state of damage is shown in Fig. 7b. On the contrary to the experiments, the FE model is shown loaded. The same features as in the experiments are predicted by the model, with a top part severely damaged and a bottom part forming a double sided wedge being undamaged.

In terms of global response, the prediction by the FE model is shown in Fig. 8 with the label \( G_{IIc} = 1.2 \text{ kJ/m}^2 \). The slope up to the maximum is well predicted. It is reminded that this slope is mainly dependent on damage growth. The model predicts also well the level of the plateau, considering the experimental scatter.

![Image](image2.png)

Fig. 8. Crushing of wedge specimen.
The main feature of the model being the coupling between damage friction, a parameter study is performed on the fracture toughness, governing the evolution of damage, and the coefficient of friction, controlling the magnitude of the friction force. The results are shown in Fig. 8 and Fig. 9.

Three values of fracture toughness are investigated. It is shown that increasing the fracture toughness results in both an increase in load level at the plateau, but also an increase in the initial slope. A similar effect is observed when the coefficient of friction is changed. However, the coefficient of friction has a more pronounced effect on the slope than on the plateau load level, while the fracture toughness affects more the load level than the slope.

7 Numerical difficulties

Modelling crushing is difficult using traditional FE tools as the processes involved are highly nonlinear and the material is subject to large deformation. In the case of composites, the damage process means that elements loose stiffness in a given direction and are therefore prone to excessive distortion. Most FE software have in-built functions which are meant to prevent these large distortion and to ensure that the Jacobian of the element will remain positive. These schemes are in particular useful when reduced integration elements are used, to prevent hourglassing phenomena.

The drawback of these methods is that when large deformations are actually occurring, as in crushing, the numerical method introduces a spurious energy which, amongst others, affects the global response.

Fig. 9 shows the ratio between numerical (spurious) energy and strain energy. For an analysis to be valid this ratio should be as close as possible to zero and not more than 5%. It can be seen for the two cases (baseline and no friction) the ratio is well above 5%. However, the case with friction remains well below the case with no friction. This effect is a result of the frictional force which adds stiffness to the element when damage grows.

Other schemes, such as adaptative remeshing, or element technologies, full integration, are available, but at a clear added cost of computational time.

8 Conclusions

A physically based 3D model combining damage and friction has been developed. The model allows for an anisotropic shear response and frictional behaviour on the fracture plane to be defined. The model can be used for matrix and fibre ply damage growth under compression. It enables large deformation, which makes it well suited for impact, bearing failure and crash analyses. Further work will look at damage growth in the fibre direction (fibre kinking) as well as alternative solution schemes allowing for large element distortions.
References


