Efectos dinámicos de la fractura de fibras en materiales compuestos unidireccionales

La redistribución de la tensión alrededor de una fibra rota es una cuestión importante en el análisis de la resistencia longitudinal de compuestos unidireccionales (UD). La mayoría de los modelos investigados se basan en empaquetamientos de fibra regulares y en la teoría clásica del shear lag (falla estática) donde se consideran las fibras pre-rotas y se omiten los aspectos dinámicos de la fractura frágil de la fibra. En el presente trabajo, se han modelizado Elementos de Volumen Representativo (RVE) con empaquetamientos de fibra aleatorios mediante análisis de elementos finitos 3D y se simularon considerando el evento dinámico de fractura de fibra. Se observaron efectos significativos sobre el factor de concentración de tensiones (SCF) y la longitud de carga inefectiva, los cuales están relacionados con la longitud de decohesión de la fibra y con el volumen de las zonas de plasticidad-dano de matriz. Por lo tanto, se puede concluir que una representación precisa de la redistribución de la tensión después de un evento de rotura de fibra requiere la consideración de efectos dinámicos.

Palabras clave:
Factor de concentración de estrés
Método de elementos finitos
Longitud ineficaz
Longitud de desunión de la interfaz
Matriz dañada de plasticidad

Effects of dynamic fibre failure in unidirectional composites

The stress redistribution around a broken fibre is a substantial issue in longitudinal strength analysis of unidirectional (UD) composites. Most investigated models are based on a regular fibre packings and classical shear lag theory (static failure) that considers pre-broken fibers, where the dynamic aspects of brittle fiber failure are not considered. In the present work, Representative Volume Elements with random fibre packings were modeled by means of 3D finite element analysis, and simulated considering the event of dynamic fibre failure. Significant effects were observed on the stress concentration factor (SCF) and ineffective load length which are related to the fibre debonding length and the volume of matrix damage-plasticity zones. Hence, it can be concluded that an accurate representation of the stress redistribution after a fibre breakage event requires consideration of dynamic effects.
1 Introduction

Unidirectional (UD) fibre reinforced polymers (FRP) are widely used in the most transportation sectors, especially in lightweight aerospace structures, mainly thanks to their high specific mechanical properties such as stiffness and strength. However, their low fracture toughness translates in brittle behaviour that often leads to catastrophic failure without prior damage symptoms. The development of reliable failure models for UD-FRP is rather challenging due to the complexity of the stress redistribution and damage phenomena. Nowadays, Computational Micromechanics has stood out as a powerful tool to predict these failure mechanisms.

It has been shown that induced stress concentrations from a fibre break drives the longitudinal tensile failure event [1,2]. So a deep understanding of the stress distribution mechanism after a fibre break is essential to improve the fibre FRP composites overall performance. When a fibre breaks, it loses its load transfer capability and the stress in the neighboring fibres increases. This increase in stress is quantified using the stress concentration factor (SCF), which is the relative increase in stress in the neighboring fibres due to induced stress from the adjacent broken fibre. Depending on the magnitude of the SCF and the stress recovery length, the initial breaks could cause additional fiber breaks, leading to formation of clusters of fiber breaks and the catastrophic failure. This failure propagation scheme shows the importance of the stress distribution after a fibre break.

There are two main approaches to calculate the SCF. Shear lag models (SLM) which are an analytical method and has some disadvantages such as: the matrix nonlinearity (plasticity) is not included, it assumes perfect bonding between fibre and matrix and it is suitable just for regular packings with anisotropic properties. An alternative approach to calculate the stress concentration factor is to use finite element models (FEM). Xia and Okabe [3] compared SLM versus finite element model and have shown FEM can be a more accurate tool.

Swolfs et al. [4-6] carried out a wide range of studies about the SCF for the hybrid and non-hybrid unidirectional composites using the FEM random fibre packings. These studies investigate the effects of several parameters such as: the fibre packing, volume fraction, matrix cracks and stiffness ratio on the SCF. They concluded that the fibre volume fraction has an important influence on the SCF and ineffective length, that the influence of the fibre/matrix stiffness ratio is small for the SCF but important for the ineffective length and that the presence of matrix cracks has little influence on the SCFs and ineffective length. Their models have some limitations in some aspects such as: lack of interface debonding, dynamics effect, matrix damaged-plasticity and thermal stress.

Most investigations in the SCF area are done based on classical shear lag theory (static failure) that considers pre-broken fibers, where the dynamic aspects of brittle fiber failure are not considered [7-10]. Hence, this model cannot model the real behavior of the failure process.

The present paper explores the uses of computational micromechanics modelling by means of RVE’s with random fibre distributions to investigate the effects of dynamic fibre failure, on the stress concentration factor and damage mechanisms around a broken fibre. Finally, the influence of fibre volume fraction will also be studied. In this study a novel 3D periodic boundary condition (PBC) [11] will be used instead of the symmetry BC, as used in [4-6] which leads to a more realistic analysis and reduces the computational domain.

2 Micromechanics modelling

A random 2D fibre packing composite microstructure model of size $W \times H$ is generated using the in-house software VIPER which can generate the representative volume elements (RVE) based on three input parameters: the fibre radius, the fibre volume fraction and the size of the RVE. The fibre volume fraction was set to 60%, as the reference case. This 2D microstructure representation is extruded along fibre direction for a distance $L$ (see Figure 1). Two slightly different models are generated to simulate static and dynamic events, respectively one with a pre-broken central fiber at the plane $z = L/2$ and another one wherein that same fibre is initially intact but has the possibility of failure by means of a cohesive fracture plane at $z = L/2$.

The RVE’s were discretized using 8-node fully integrated brick isoparametric elements (C3D8) and 6-node fully integrated wedge isoparametric elements (C3D6) in Abaqus [12]. To minimize the influence of the boundary conditions on the mechanical response of the model, periodic boundary conditions (PBC) were imposed between opposite faces of the RVE to ensure the displacement continuity with the neighboring RVEs as a jigsaw puzzle [11]. The generated RVE and applied boundary conditions are shown in Figure 1. Loads were applied by means of controlled displacement on the entire front plane $(z=0)$. More details about the model can be found in Table 1.

![Figure 1](image)

**Figure 1.** Description of the model: a) 3D view of the model and boundary conditions. b) RVE with a random fibre packing and $V_f = 60\%$. The broken fibre, indicated in black, is located at the center of the RVE. Intact neighboring fibres have been numbered based on distance from broken fibre.
The carbon/fibre material AS4/8552 was chosen for the purpose of demonstration of the methodology. The AS4 carbon fibers are modelled as linear elastic and transversely isotropic solid representative of a typical carbon fiber used in unidirectional reinforcements. The 8552 epoxy matrix is represented using the isotropic damaged-plasticity model [13] included in Abaqus/Standard [12]. This model requires not only the definition of the uniaxial tensile and compressive mechanical response, but also the evolution of the yield surface (plasticity) and material degradation (damage). The fiber-matrix interface was taken into account using the cohesive zone method implemented in Abaqus through cohesive surfaces. A mixed-mode bilinear traction-separation law is used to define the constitutive behavior of the interface. Damage initiation was modelled using a mixed-mode quadratic criterion and post-damage softening using a power law. The penalty stiffness of the cohesive surfaces was chosen to be a sufficiently high value in order to maintain continuity of displacements across the cohesive surface until initiation of the fracture process. The parameters and the properties employed in the simulations were taken from [14,15] and are reported in Table 2. In the dynamic model, the fracture plane of the central fibre was modelled using a cohesive surface with a bilinear traction-separation behavior which breaks at a break strength 2.7 GPa. The critical strain energy release rate in the AS4 carbon fiber, $G_{\text{IC}}$, was set to 52 J/m$^2$ [16].

### Table 1. Parameters of the finite element model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre radius</td>
<td>3.59 $\mu$m</td>
</tr>
<tr>
<td>Width $L$ of RVE</td>
<td>84 x $R$</td>
</tr>
<tr>
<td>Length $W$ of RVE</td>
<td>12 x $R$</td>
</tr>
<tr>
<td>Height $H$ of RVE</td>
<td>12 x $R$</td>
</tr>
<tr>
<td>Number of elements</td>
<td>$&gt; 195,000$</td>
</tr>
</tbody>
</table>

The simulations were carried out using the implicit static and dynamic solvers in Abaqus/Standard [12].

### 3 Results and discussion

#### 3.1 The effect of dynamic fibre failure on the SCF

The growth of the SCF (the slope of the SCF versus the applied strain and time) for the nearest neighbor fibre (fibre 1) of the broken fibers is plotted in Figures 2. Figure 2 shows, fiber 1 in static model is under stress concentration from the beginning and increases gradually up to 15% at applied strain of $\varepsilon = 0.3\%$ and then decreasing gradually. But the condition is different for dynamic model, as the dynamic SCF is equal to zero since the beginning and varied suddenly from 0 to 12.7% at applied strain of $\varepsilon = 1.2\%$ and time of $t = 1.4$ ms. This dynamic effect continues until the applied strain $1.3\%$ and $t = 1.5$ ms. This region can be called as dynamic region (indicated with green box). By passing through this region, the dynamic effect fades away and dynamic SCF curve approaches to static SCF and shows a similar behavior. This decline can be due to the size of RVE as stress wave reaches to the RVE’s boundaries and reflect back several times. This process can be called as dynamic reflection and its order of quantity can be estimated by finding the critical time taken by a wave to go and reflect back. This critical time can be calculated using the Newton–Laplace equation;

$$c = \sqrt{\frac{E}{\rho}}$$

where $c$ is speed of stress wave, $E$ Young’s modulus and $\rho$ is density. Then the critical time ($t_c$) is needed by the stress wave to propagate through the RVE is $t_c = W/c = 4.25$ ns. As a result, the number of dynamic reflections (NDR) through the RVE during the dynamic response phase in the order $10^4$.

![Figure 2. The SCF-strain curves for the nearest neighbor fibre (fibre 1).](image)

#### 3.2 The effect of dynamic fibre failure on stress transfer and damage micromechanisms

By using random fibre distribution, the SCF results can be expressed as a function of the distance between the intact fibres.
and broken fibres. Figure 3 shows the results for the calculated SCF as a function of the distance to the broken fibre. The maximum static SCF occurs at the applied strain of 0.3%, while the maximum dynamic SCF occurs at applied strain of 1.2%, right after the failure of the central fibre. The static model results in a higher SCF at \( d/R < 0.45 \) but gradually this relation changes at \( d/R > 0.45 \) in which the dynamic model results in a higher SCF. The trend line in static model is up to +15% higher and -100% lower than the dynamic model for the nearest fibre and for the farthest one considered, respectively. Distance \( d/R = 0.45 \) can be considered as inflection point where the static and dynamic SCFs are equal.

These differences can be caused by: (1) the influence of interface debonding and (2) the effect of matrix damaged-plasticity. First, interface debonding length (IDL) and ineffective interface debonding and (2) the effect of matrix damaged-plasticity. In the next step, matrix damage-plasticity is captured for both cases at the maximum SCF and plotted in Figure 6. The matrix damaged-plasticity area in the dynamic model is much higher than in the static model. In the static model the damage occurs in a very small area between the broken fibre and the nearest adjacent fibre (fiber 1) but in the dynamic case the damage occurs in a larger area around the broken fibre and surrounding a significant surface of the nearby fibres (fibres 1, 2, 3 and 4). Each fibre which interferes with the matrix damage area has a lower SCF compared to its counterpart in the static model.

In Figure 6, the cohesive interface damage for static and dynamic models at maximum SCF. The applied strain is equal to 0.3% and 1.2% for the static and dynamic models, respectively.

Figure 5. The cohesive interface damage for static and dynamic models at maximum SCF. The applied strain is equal to 0.3% and 1.2% for the static and dynamic models, respectively.

Figure 6. The matrix damaged-plasticity for the static and dynamic models. a) static model at \( \varepsilon = 0.3\% \), b) dynamic model at \( \varepsilon = 1.2\% \).

To have a better comparison, the growth of the debonding length versus the applied strain of the broken fibre is plotted in Figure 7. It shows that the debonding length in the static model increases almost linearly with the increase in applied strain. In the dynamic model, the debonding length is zero up to applied strain of 1.2% and then the fibre failure causes a big jump in the interface debonding length. Interestingly, above the strain of \( \varepsilon = 1.3\% \) the dynamic model shows an identical trend as the static model and increases linearly.

![Figure 3. The predicted SCFs for the static and dynamic models.](image1.png)

![Figure 4. Ineffective lengths-strain for the static and dynamic models.](image2.png)

![Figure 5. The cohesive interface damage for static and dynamic models at maximum SCF. The applied strain is equal to 0.3% and 1.2% for the static and dynamic models, respectively.](image3.png)

![Figure 6. The matrix damaged-plasticity for the static and dynamic models. a) static model at \( \varepsilon = 0.3\% \), b) dynamic model at \( \varepsilon = 1.2\% \).](image4.png)

![Figure 7. The growth of the debonding length versus the applied strain of the broken fibres.](image5.png)
The results were quite the opposite in previous publications [17-19] which concluded that the SCF increases with fibre volume fraction. All previous publications used regular distribution RVE. In this case, fibres have the same distance to the broken fibre, so the fibre volume fraction is coupled with the distance between the considered fibre and the broken fibre. In random distribution RVE, as each fibre has a different distance, these two parameters are decoupled. It can be seen in Figure 8: in a higher fibre volume fraction there are more fibres at smaller distances and thus with higher SCFs. However, when comparing SCFs at the same distance from the broken fibre, the higher fibre volume fraction results in a lower SCF.

Figure 10 shows the ineffective and interface debonding lengths. A high fibre volume fraction results in a low ineffective length. Interestingly, the interface debonding length shows the opposite trend as the ineffective length. A higher fibre volume fraction results in a higher debonding length. Figure 10 presents the results for the matrix damaged-plasticity. The matrix damaged-plasticity also follows the same trend to the debonding length. With regards to the higher shielding effect in a high volume fraction, matrix around the broken fibre should transfer a lower load so the matrix damage decreases. However, Figure 10 shows the opposite tendency: the matrix damaged-plasticity increases with the increase in the volume fraction. The reason could be that the increase in fibre volume fraction led to a decrease in the epoxy layer thickness between the fibres. The thinner layer undergoes higher strains and deformation and can intensify the debonding length and matrix damage.
4 Conclusions

The stress redistribution after a single fibre breakage in various cases was analysed and the effects of the dynamic failure and volume fraction on the stress concentration factor were studied by means of 3D computational micromechanics. The AS4/8552 carbon epoxy composite, which widely used in structural applications, was used in all studies.

The dynamic failure and fibre volume fraction were shown to have an important effect on the SCF, matrix damaged-plasticity, ineffective and debonding length. The dynamic effect is even more impressive for the debonding length (up to 500%) and matrix damaged-plasticity (up to 80%) in comparison to static model. The results show that the dynamic fibre failure can reproduce more realistically the behaviour of the failure process in a real fibre and give more accurate stress distribution. The increase in volume fraction has subtractive effect on the SCF and ineffective length whereas has an incremental effect on the debonding length and matrix damaged-plasticity.

The dynamic fibre failure phase needs to be explored deeper in future research. Towards that end, the use of a proper characteristic time increment is critical to capture the essentials of dynamic fiber failure mechanisms. The use of the duration of the stress-wave propagation through a single fibre or even across the RVE would render the analyses unnecessarily time consuming. Instead, practical results can be achieved by using the single fibre failure event, which has been determined to occur within a few micro-seconds, as determinant of the characteristic analysis time increment.

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Referencias