EFFECT OF INTERFACIAL PROPERTIES ON LOCAL STRESS CONCENTRATION FACTORS IN UNIDIRECTIONAL FIBRE-REINFORCED COMPOSITES: A NUMERICAL ANALYSIS

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ABSTRACT

Enhancing the prediction of tensile strength in fibre-reinforced polymer composites (FRPCs) is an active and critical research field. However, discrepancies between predicted and experimental values persist due to complex factors affecting FRPC behaviour. Current models rely on simplifying assumptions, such as the strain-independent stress concentration factor (SCF) and cross-sectional average stress evaluation, which may not accurately represent material behaviour under different loading conditions. Surface defects, void diameters, and crystallite orientations play significant roles in determining the mechanical properties of PAN-based carbon fibres. If carbon fibres do not have a homogeneous structure, then using average cross-sectional stress to evaluate SCF is questionable. While evaluating different interfacial properties, this study exemplifies the difference between the non-averaged local stress concentration factor (LSCF) and cross-sectional average stress concentration factor (ASCF). Revealing significant differences and emphasising the importance of changing LSCF on strength and damage progression. The results highlight the influence of interfacial strength on stress concentration factors, with notable variations as a function of strain. The maximum LSCF remains unaffected by interfacial properties and reaches approximately 40%. Friction impacts the location of the maximum stress concentration factor along the fibre length but has a smaller effect than interfacial strength. Incorporating these factors into current models can lead to improved predictions and designs, advancing materials science and the development of high-performance materials.

1 INTRODUCTION

One of the primary objectives of fibre-reinforced polymer composite (FRC) research is to enhance the accuracy of predicting tensile strength. This is because tensile strength is a critical mechanical property that influences the performance and durability of FRPC materials. However, achieving accurate predictions of tensile strength is a complex task, and there is often a discrepancy between the predicted values and the actual experimental data. There are a variety of factors that can influence their behaviour, from constituent mechanical properties to microstructure. One of the main assumptions used in current models for strength and damage progression is the strain-independent stress concentration factor (SCF) [1]. Another assumption is the use of cross-sectional average stress to evaluate SCFs. While these assumptions simplify aspects of the model implementation, they may not represent the behaviour of the material under different loading conditions, resulting in a discrepancy between experimental and numerical results. While investigating SCFs, some modelling studies have noticed changes in the SCF with applied strain. The work of van den Heuvel *et al.* [2] with a 2D fibre arrangement was one of the first to notice the variation in the SCF throughout loading, and more recent studies have confirmed this using dynamic simulations [3], [4]. However, interpreting or describing this behaviour is challenging, and more research is needed to understand its implications fully.

For PAN-based carbon fibres, damage caused by tension starts near or at the surface of the fibre, as shown in Fig. **1**. Tanaka *et al.* [5] infer that this is mainly due to the effect of surface defects. Given that surface defects are in the order of 100 times larger than voids in the fibres. Correspondingly, in places where surface defects are not pronounced, Lee *et al.* [6] reasoned that void diameter and crystallite orientations are the next significant contributors to determining the mechanical properties of T700S carbon fibres. In the same work, they also described the difference in these structural factors between the surface and the core, having the smallest voids and better orientation in the surface rather than the core. Considering these facts, the question arises: why do we use average cross-sectional stress to evaluate the stress concentration factor? Furthermore, Yamamoto *et al.* [7] presented an alternative approach to this dilemma, by splitting a fibre into segments and assigning them a fitted SCF. The SCF fitting was done to match double, triple and quadruple in-plane fibre fragmentation tests. This method, although an improvement, still discretises the SCF over a large section of the fibre surface.

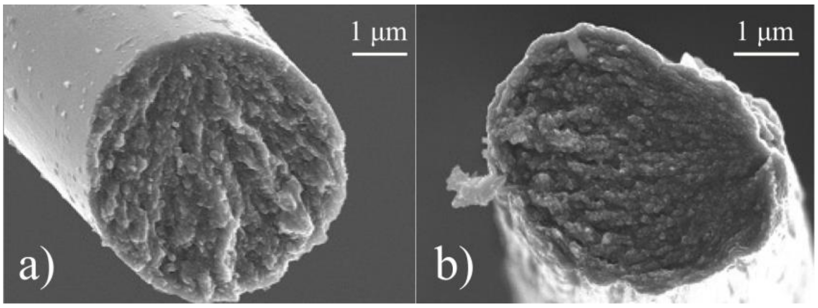

Fig. 1 Scanning electron microscope micrographs of tensile fracture surfaces for a) T1000GB and b) M60JB, adapted from [8].

To address the aforementioned issues in SCF usage, we will first describe how we define the non-averaged local stress concentration factor (LSCF). Second, the characteristics of our finite element model. And lastly, the results of evaluating different interfacial properties on both average cross-sectional stress concentration factor (ASCF) and LSCF. We will show the magnitude of the difference when looking at non-averaged local stress concentration factors and how the changing LSCF can also affect strength and damage prediction. Likewise, by incorporating these factors into current strength models, we could more accurately predict the behaviour of these materials under different loading conditions, which can lead to improved designs and has the potential to advance the fundamental understanding of materials science and contribute to the development of new materials with enhanced mechanical properties.

2 MODELING METHODOLOGY

It is common practice in modelling longitudinal tensile failure of unidirectional composites to use the average cross-sectional stress to evaluate the stress concentration factor [1]. This assumption can be traced to two main benefits: first, it fits the weakest link theory that is used for fitting single fibre strength models. Second, it reduces the number of variables that need to be tracked when performing simulations. Given that we already established the carbon fibre heterogeneity, then let us approach the SCF as a local matter rather than an averaged one. The LSCF is calculated (see eq. 1) in discretized volumes (V_n). Each V_n lies in a path that follows the centre of the fibre. For each volume segment, there is a maximum local stress $\sigma_{(n,max)}$. And the remote volumetric average stress $\sigma_{(r,avg)}$ is shared among all discretised volumes, see Fig. **2**.

$$LSCF = \frac{\sigma_{n,\mathrm{max}} - \sigma_{\mathrm{r,avg}}}{\sigma_{\mathrm{r,avg}}} \times 100 \quad (1)$$

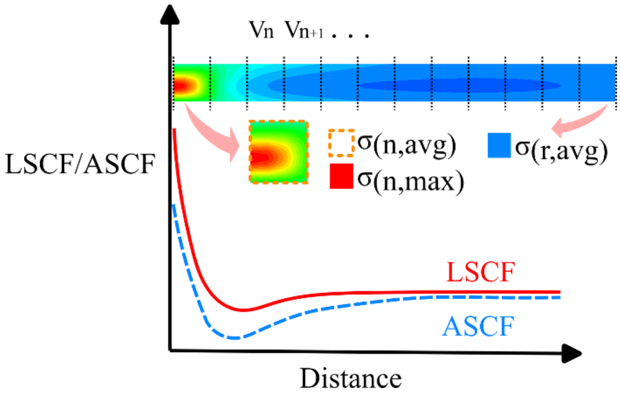

Fig. 2 Schematic comparison of LSCF and ASCF over the length of a fibre.

The finite element method (FEM) is a numerical technique used to solve complex engineering problems by dividing a structure into smaller and simpler elements. In this study, we used FEM to model a hexagonal fibre packing with a 50% fibre volume fraction, consisting of the epoxy matrix Sicomin SR8500/KTA313 reinforced with T700S carbon fibres. The goal was to analyse the effect of the interfacial properties on the ASCF and LSCF behaviour of the nearest neighbour of the broken fibre.

To represent the matrix's behaviour, we used an elastic-plastic model. This model is simplified by using a few key data points, such as the yield point and linear hardening up to the maximum plastic stress, as shown in Fig. 1. This approach enables us to simulate the nonlinear behaviour of the matrix material while helping with the stability issues associated with material softening. The carbon fibres were modelled using transversely isotropic elastic properties.

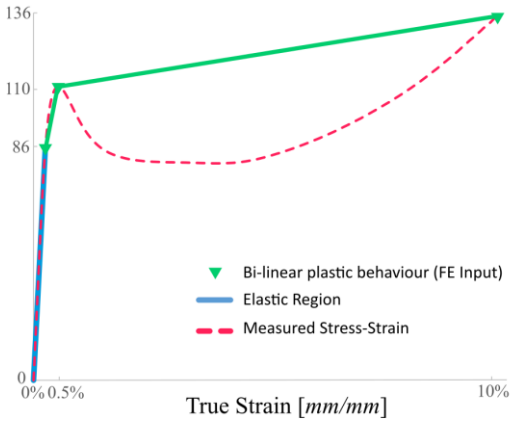

Fig. 3 Matrix characterization with elastic-plastic input for the FEM, adapted from [9].

To introduce residual thermal stresses, we applied a temperature difference of ΔT=-100 °C and used the coefficient of thermal expansion (CTE) values of α_m=62.5, α_{f1}=-0.38, and α_{f2}=10 [10^{-6}/°C] for the matrix, fibre longitudinal, and transverse directions, respectively. These values were used to calculate the thermal expansion or contraction of each material component, leading to thermal stresses in the composite material. The mechanical properties of the matrix are listed in Table **1** and the carbon fibres in Table **2**. The behaviour of the fibre-matrix interface was modelled using the cohesive zone model coupled with contact friction. The cohesive zone model is a technique used to represent the debonding and shearing behaviour of the interface between two materials. The critical shear strength and critical energy release rate were modified together with friction, to evaluate their effect on the stress concentration factors and to correctly model the cohesive behaviour.

Sicomin SR8500/KTA313	Value
Tensile modulus [MPa]	3687
Shear modulus [MPa]	1073
Poisson's ratio [-]	0.4
Yield stress [MPa]]	86
Maximum plastic stress	110
α_m *[10-6/°C]*	62.5

Table 1. Properties for Sicomin SR8500/KTA313 [10], [11]

To analyse the effect of friction, we kept the interfacial strength parameters constant, using τ_c=40 MPa and G_c=50 J/m^2. At the same time, to analyse the effect of the interfacial strength parameters, we kept a constant friction coefficient of (μ=0.3). The model's geometry was a cylindrical wedge with an angle of 60° and a radius of 42 µm. Symmetry boundary conditions were applied to the internal surfaces of this wedge. Additionally, a longitudinal displacement of 2% was applied. Please refer to Fig. **4**. for visualisation.

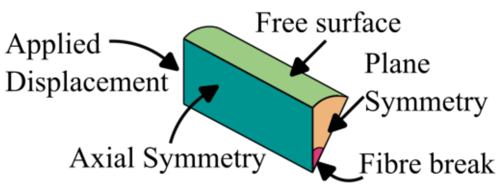

Fig. 4 Model boundary conditions

T700S Carbon fibre	Value
Fibre diameter [µm]	7
E_{11} *[GPa]*	230
E_{22} *[GPa]*	15
G_{12} *[GPa]*	13.7
v_{12} *[-]*	0.25
v_{23} *[-]*	0.25
α_{f1} [10^{-6}/°C]	-0.38
α_{f2} [10^{-6}/°C]	10

Table 2. Properties for T700S carbon fibre [9]

3 RESULTS AND DISCUSSION

We conducted a study using six different models to analyse the impact of the interface on the ASCF and LSCF. First, for the fibre-matrix interface, we used: perfect bonding, a strong interface (τ_c=56MPa, G_c=100 J/m^2), and a weak interface (τ_c=18MPa, G_c=10 J/m^2). Second, we studied the effect of friction by varying μ=[0.2, 0.4, 0.5] while keeping a constant interfacial strength. In the interfacial strength analysis, both LSCF and ASCF exhibit an early spike caused by overcoming residual thermal stresses, see **Fig. 5**. It is important to note that neglecting the initial peak, which is primarily attributed to these residual thermal stresses, has a negligible effect on the strength models. This is because the strain at which the peak occurs is relatively small compared to the final failure strain. Consequently, when the initial thermal peak is not considered, both ASCF and LSCF exhibit a similar trend. The maximum LSCF reaches approximately 40%, while the maximum ASCF is limited to around 9%. The LSCF is 4 times larger, and it could have great implications for the single fibre probability of failure when in combined with the fibre Weibull strength distribution. Furthermore, there is also an approximate 4 times drop in the LSCF when going from 0.2% to 2% applied strain. After all not only does localization matters but also the loading stage of the composite. As with higher applied strains, there is a bigger plastic zone in the matrix, helping reduce the localization of the stresses.

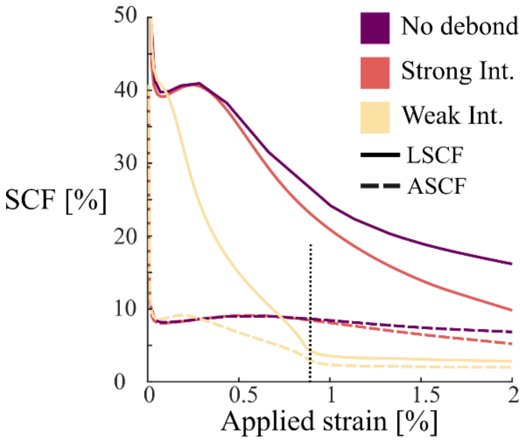

Fig. 5 Effect of the fibre-matrix interface in the maximum (A/L)SCF over the length of the fibre as a function of applied strain.

When examining the impact of friction on the maximum stress concentration factors (SCFs) along the length of the fibre, we observe that it does not cause a significant change compared to the interfacial strength (refer to Fig. 6.**a**). However, there is a minor effect observed in the last 0.2% of applied strain, where lower friction coefficients lead to faster convergence of both LSCF and ASCF to similar values. On the other hand, friction clearly influences the location of the maximum SCF, as shown in Fig. 6.**b**. Lower friction coefficients allow for a longer stress recovery distance. Nevertheless, there is a strong correlation between the recovery distance, LSCF, and its location. Furthermore, the location of the maximum (L/A)SCF changes through loading. The position change can be identified in Fig. 6.**a** as a step-like drop. If we see the case for μ=0.2, it drops at 1.7% applied strain. While for μ=0.4 it starts at 1.85% applied strain. When comparing Fig. 6.**a** and **Fig. 5**, the interfacial strength properties have again a higher impact on the stabilization of the LSCF (marked by the dashed line in the figures).

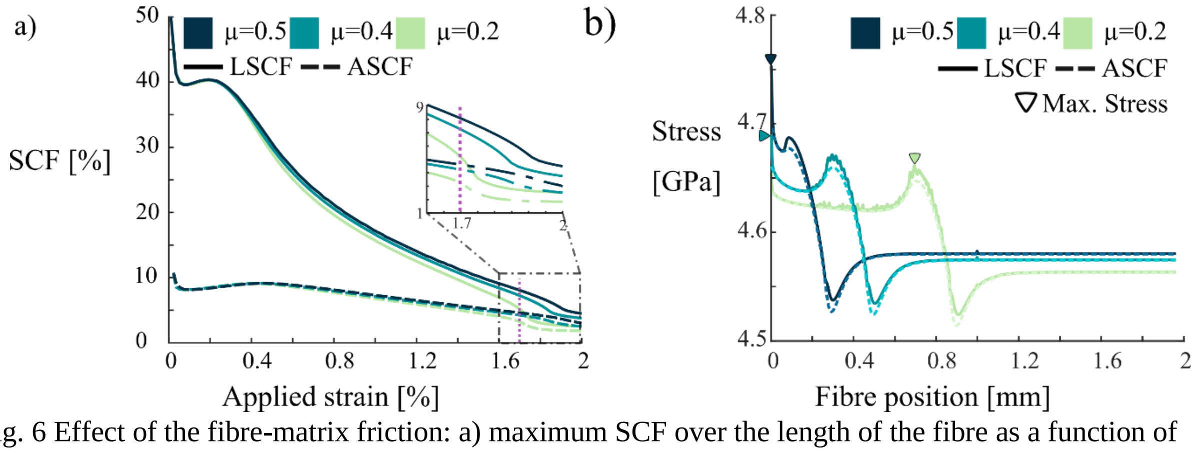

Fig. 6 Effect of the fibre-matrix friction: a) maximum SCF over the length of the fibre as a function of applied strain, and b) maximum stress along the length of the fibre at a 2% applied strain.

4 CONCLUSIONS

In conclusion, the FEM modelling technique allowed us to simulate the effect of the interfacial properties on the SCFs. We found that the strength of the fibre-matrix interface has a more significant impact on the stress concentration factors (ASCF and LSCF) compared to the effect of friction. Different interface strengths result in notable variations in the maximum stress concentration factors over the applied strain. Notably, the maximum LSCF reaches approximately 40% and was not affected by interfacial strength or friction. The initial peak observed in both LSCF and SCF, caused by overcoming residual thermal stresses during the initial loading phase, has minimal effect on the strength models. Neglecting this initial peak does not significantly impact the overall trend because it occurs at a small strain compared to the final failure strain. Friction influences the location of the maximum stress concentration factor along the fibre. Lower friction coefficients allow for a longer stress recovery distance, and there is a clear connection between it, the recovery distance and the maximum LSCF location. LSCF provides more detailed information, allowing the tracking of the movement of the maximum LSCF. However, the overall impact of friction on the maximum stress concentration factors along the length of the fibre is not as significant as the interfacial strength.

With the proposed localised analysis of stress concentration factors, we expect the next steps of our research to improve the capabilities of the longitudinal tensile strength models for unidirectional composites. Another future step will be to explore the effect of the full elastoplastic matrix behaviour on the ASCF and LSCF.

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