Stress redistribution around fiber breaks in unidirectional steel fiber composites considering the nonlinear material behavior

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Abstract

The use of steel fibers as reinforcement in polymer composites is recently increasing thanks to their ductility, high stiffness and wide range of diameters. Unlike carbon and glass fibers, steel fibers often end up with a non-circular cross-section due to their manufacturing technology. This may influence the stress redistribution around fiber breaks, which is important in longitudinal tensile failure of unidirectional composites. A parametric study was performed by using 3D finite element models with randomly distributed and oriented hexagonal fibers. Rather than the fiber shape, the distance between fibers was shown to have an influence on stress concentrations in terms of both average and peak stress concentrations. The plastic behavior of steel fibers resulted in smaller stress concentrations and faster stress recovery whereas the opposite was observed for the plastic behavior of epoxy. For different strain levels, results were shown to depend on the relative stiffness of steel and epoxy in the plastic region.

Keywords: steel-fiber composites; stress concentrations; large deformation; finite element analysis

1. Introduction

The use of fiber-reinforced composite materials has significantly increased thanks to their high stiffness-to-weight and strength-to-weight ratio, design flexibility and excellent fatigue resistance. Because of their widespread use, a fundamental understanding of failure of composite materials is vital. Virtual testing is an important avenue to better understand the failure process in a cost-effective manner [1].

In fiber-reinforced composites, failure often occurs suddenly without any visible warning sign of damage. Predicting such damage is not an easy task, especially in multidirectional composites. However, even in multidirectional composites, the failure is usually still governed by failure of the 0° plies or bundles. A solid understanding of the longitudinal failure of unidirectional composites is hence crucial. A broken fiber locally loses its capability to carry load and therefore sheds its load to other surrounding fibers [2-5]. This increases the stresses in the nearby intact fibers. This relative stress increase is called the stress concentration factor (SCF) [6,7]. The SCFs increase the failure probability of nearby fibers, causing a tendency for clusters of fiber breaks to develop [8]. Eventually, a critical cluster becomes unstable and leads to catastrophic, complete failure.

Predicting SCFs is a crucial step in any model for longitudinal strength of unidirectional composites. Shear lag models were developed to calculate stress concentration factors. In the

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first shear lag models, it was assumed that normal loads are carried only by fibers and shear loads are carried only by matrix. Hedgepeth [9] used a 1D packing of shear lag model, which is a single-layer arrangement of parallel fibers on a straight line. As a result, an SCF of 33% was predicted. In Hedgepeth et al. [10], this model was improved to 2D square and hexagonal packings of parallel fibers, which lowered the SCFs to 14.6% and 10.4%, respectively. These initial models still had some disadvantages, such as not including matrix plasticity, assuming perfect fiber-matrix bonding and assuming an ordered packing. Landis et al. [11], Zeng et al. [12] and Beyerlein et al. [13] all developed improved versions of the shear lag model addressing some of these drawbacks. Since the nineties, researchers also started using 3D finite element models (FEM) to calculate stress redistributions around a single fiber break. Nedele et al. [14] used a hexagonally packed 3D finite element model, leading to an SCF of 5.8%. Van Den Heuvel et al. [15] used 3D FEM, consisting of a planar array of five carbon fibers positioned in the center of an epoxy tensile bar. Their FEM results were validated by experimental results using micro-Raman spectroscopy, confirming the accuracy of 3D FEM.

In the aforementioned studies, fiber packings were always regular, whereas real composites always feature random packings. Swolfs et al. [7] however developed 3D finite element models based on random fiber packings generated using an adapted version of the algorithm of Melro et al. [16]. Their results showed that random distribution of fibers in the model and fiber volume fractions have a significant effect on stress concentration factors. In Swolfs et al. [17], the stress redistribution around a single carbon fiber break in unidirectional carbon/glass hybrid fiber-reinforced composites was investigated using 3D FEM. It was shown that having the same fiber radii for both fiber types leads to significant errors in the results and the stiffness of the hybridisation fiber has a significant effect on the SCF of hybridisation fiber.

Stress concentrations around fiber breaks are nearly always averaged over the cross-section. However, a review paper pointed out that the local stress concentrations can lead to stresses close to the theoretical strength of carbon fibers [8]. The same feature was recently explored in more detail by Yamamoto et al. [18], showing that this stress averaging caused an overestimation of the predicted strength values. The effect of local stress concentrations is much more severe for random than for regular fiber packings [8].

Generally, carbon, glass and aramid fiber-reinforced composites are more commonly used. However, steel fibers are increasingly seen as a fiber with significant potential thanks to their ductility, high stiffness and wide range of production diameters. However, due to the manufacturing technology, the final cross-sectional shapes of steel fibers often end up being irregular hexagons or pentagons (see Figure 1). Steel fibers have similar stiffness value to traditional carbon fibers in longitudinal direction. However, due to the isotropic nature of steel fibers, their transverse stiffness is much higher than that of carbon fibers. Sabuncuoglu et al. [19] therefore analyzed the effects of non-circular fiber cross-section and high stiffness contrast between fiber and polymer on stress concentrations in a composite under transverse loading. They showed that there is no significant effect of the high stiffness contrast on stress concentrations in composites under transverse loading. However, due to the sharp corners, polygonal cross-sections led to significant stress concentrations at the corners. Also, Sabuncuoglu et al. [19] showed that results of randomly packed models differ from that of the regularly packed models. Therefore, to get more realistic results, it is crucial to use randomly packed models while analyzing the mechanical behavior of unidirectional composites under transverse loading. As can be seen in Figure 1, the corners of steel fibers are not sharp at all. There is slight radius present on the corners of polygons. In a different study, Sabuncuoglu [20] analyzed similar effects on stress concentrations, but this time fillets at fiber corners to extinguish sharp corners and stiffness variation between fiber and matrix were introduced to the models. The results show that fillets at corners significantly decrease the stress

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concentrations compared to sharp corners. The stiffness variation introduced to fiber-matrix interface did not have a significant effect on stress concentrations.

Figure 1. Scanning electron microscope (SEM) images of composites reinforced with different types of fibers (a) carbon; (b) glass; (c) steel (reprinted from [19], with permission from Sage)

In the present study, the stress redistribution around a fiber break in unidirectional steel fiber-reinforced composites will be examined under longitudinal loading by using 3D FEM. Unlike carbon and glass fibers, the steel fibers can have irregular, polygonal cross-sections, a high failure strain and non-linear tensile behavior [19]. Therefore, the focus will be on the effects of cross-sectional fiber shape and applied strain levels.

The study starts with the introduction of the finite element model for a broken fiber in an impregnated fiber bundle in section 2. Section 3 presents the results with respect to different parameters. Finally, what has been done and the obtained results are concluded in section 4.

2. Model Setup

2.1. Parametric Model Development

The models were generated with finite element analysis software Abaqus 2016 with the aid of the programming language Python for parametric modelling. The models involve randomly distributed, parallel fibers with surrounding matrix and a broken fiber in the middle, similar to the ones generated in [7,21]. The difference here is the cross-sectional shape of fibers. As steel fibers are generally produced having a cross-sectional shape of a polygon, they were modelled with hexagonal cross-sectional shapes similar to the models in Sabuncuoglu et. al. [19]. Therefore, the Python script developed in Swolfs et. al. [21] was combined with the one used in Sabuncuoglu et. al. [19] to obtain the finite element models for the broken steel fibers with hexagonal shape.

The center coordinates of the fibers with the broken fiber in the center were determined via an algorithm developed by Melro et. al. [16] which performs this with a high level of randomness according to the desired fiber volume fraction (V_f) up to 70%. In the original algorithm, the minimal distance between two fiber centers was set to two times the fiber radius (R). The dimensions of hexagonal fibers were generated according to their circular counterparts having the same cross-sectional area to be able to compare the results as presented in [19]. However, this approach would cause fiber overlaps. To prevent this, the minimal distance was calculated according to the distance between the center of the hexagon and one of its corners (R_h) instead

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of a circle radius. This modification completely prevented the possibility of overlapping hexagons but does limit the maximum V_f to around 60% instead of around 70% for circular cross-sections. The distance was defined as a random number between $2R_h$ and $2.1R_h$ to make the packing more representative of real microstructures [22].

The Python script started with the generation of cylindrical representative volume element (RVE) with a diameter of $24R$ and a length of $120R$, which is similar to the RVEs in [21]. These dimensions were large enough for stresses around the fiber break to be unaffected by the model size [7,17]. Then, the fibers were generated according to their pre-determined center coordinates and fiber radius (R), which was taken as $15\ \mu\text{m}$ [19]. Before the generation of fibers, their orientations were randomly arranged to maintain the high level of randomness and generate a more realistic model. The counterpart models with circular fibers were also generated to compare the results with 60% V_f . The models with both hexagonal and circular fibers are presented in Figure 2a and b, respectively.

Figure 2. 3D finite element models: Fibers with (a) hexagonal and (b) circular cross-section, and (c) close-up of hexagonal broken fiber.

Considering the large deformation in the subsequent analyses, elastic and elastoplastic material behavior were used to define the mechanical behavior of fibers and matrix. Elastic properties of steel fibers and epoxy matrix are given in Table 1 [7,23]. Elastoplastic property data of steel and epoxy (see Figure 3) were taken from Callens et. al. [23] and Okabe et. al. [24], respectively.

Table 1. Elastic properties of steel and epoxy.

Material	Stiffness, E [GPa]	Poisson's Ratio, ν
Epoxy	3	0.4
Steel	193	0.3

Figure 3. Elastoplastic stress-strain diagram of steel fibers and epoxy up to around 8% strain.

The boundary conditions are presented in Figure 4. A displacement (δ) was applied to the entire top plane in longitudinal direction according to the applied strain (ε) and the length of the model (L) while symmetric boundary conditions were applied to the entire bottom plane except the middle fiber, which represents the broken fiber. Symmetric boundary conditions were applied starting from the matrix element nodes nearest to the nodes at the perimeter of the broken fiber. These conditions were suggested to be a more realistic representation of a broken fiber [21].

Figure 4. Boundary conditions of the FE model: (a) top plane, (b) bottom plane, and (c) close-up of the broken fiber on bottom plane.

Models contain 101 fibers in total including partial fibers at the edge of the model and they comprise of over 150000 elements with 75-90% second-order brick elements and 10-25% second-order wedge elements.

2.2. Calculation of stress concentration factors and ineffective length

The ineffective length and SCFs were calculated by extracting average fiber stresses over the cross-sections for each group of fiber elements having the same axial coordinate. The cross-sectional average SCF on a certain plane, z^* , was defined as the relative increase in average fiber stress with respect to stress value on a plane far away from the break plane. Its formulation was given in [7]. In addition to the average SCFs, the peak SCFs were also calculated similarly by using equation (1).

$$SCF_{peak}(z = z^*) = \frac{\sigma_{z,peak}(z = z^*) - \sigma_{z,avg}(z = L)}{\sigma_{z,avg}(z = L)} * 100\% \quad (1)$$

The ineffective length was defined according to the definition in [7]: ‘twice the fiber length over which 90% of strain recovery occurs’.

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2.3. Mesh optimization

As mentioned in [7], sufficiently refined meshes are needed to obtain accurate results in the high stress concentration sites, especially at the edges of broken fiber. For this purpose, two models with different element sizes were prepared (see Figure 5). Note that mesh sizes are different only in lateral direction, but not in longitudinal direction.

Figure 5. Mesh distribution perpendicular to the fiber direction and in the vicinity of broken fiber: (a) fine mesh, and (b) extra fine mesh.

The extra fine mesh model contains approximately two times more elements than the fine mesh model. The results of maximum cross-sectional average SCFs and ineffective lengths were compared (see Table 2). The maximum relative difference was determined to be 0.44% between these two models. As using the model with extra fine element sizes would cost more computational time and memory without significantly altering the accuracy, the model with fine mesh was used for the rest of the analyses.

Table 2. Maximum cross sectional average SCFs and ineffective lengths for both mesh types.

Mesh type	SCF [%]	Ineffective length
Fine mesh	11.44	$24.78 \cdot r_f$
Extra fine mesh	11.49	$24.85 \cdot r_f$

A total of 3 different models were prepared (see

Table 3) and using these models, several analyses were performed with different applied strain levels. The first two models, named “Hex” and “Circ”, were used to examine the effects of cross-sectional fiber shape. To compare the models with elastic material properties, a strain of 0.1% was applied which does not cause plastic deformation. Then, the same two models were loaded with a displacement corresponding to 2% strain to observe whether plastic deformation and fiber shape together create a difference in results. The third model, named “Hex-EF” (hexagonal and elastic fiber), was compared with model Hex to analyze the effects of steel fiber plasticity.

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Table 3. Properties of finite element models.

Model Name	Hex	Circ	Hex-EF
Fiber cross-section	Hexagonal	Circular	Hexagonal
Matrix material behavior	Elasto-plastic	Elasto-plastic	Elasto-plastic
Fiber material behavior	Elasto-plastic	Elasto-plastic	Elastic

3. Results and Discussion

3.1. Effect of the cross-sectional shape of fibers

Figure 6a shows that the stress recovery results are nearly the same for both cross-sections. The surface area of the hexagonal fibers is 5% higher than for circular fibers. However, this caused the ineffective length of the hexagonal fibers for 0.1% and 2% applied strains to be just 2.8% and 1.9% smaller than for circular fibers, respectively. This contradicts with traditional shear lag theory based on the Kelly-Tyson model, which would predict a 5% shorter ineffective length for the hexagonal fibers. There are two reasons why this is not observed in the present modelling results. Firstly, the most common shear lag models are based on perfect plasticity for the matrix and linear elasticity of the fibers, both of which are not the case here. Secondly, nearly all shear lag models ignore the shear stress recovery in the intact fibers, and this has been shown to be important for random fiber packings [7].

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Figure 6. Stress redistribution around a broken steel fiber: (a) stress recovery profiles of the broken fiber, and (b) maximum cross-sectional average SCF results of intact fibers.

Figure 6b presents the maximum cross-sectional average SCF results of intact fibers for 0.1% and 2% applied strains. Comparing the results of the closest fiber, the hexagonal fibers resulted in a slightly higher SCF than for circular fibers, whereas the opposite is true for the second closest fibers. These inconsistent differences can be also seen in the SCF results of the other intact fibers. An investigation of these fibers revealed that this was due to the orientations of the hexagonal fibers. These fibers are closer to each other compared to their circular counterparts in the same locations if their corners are faced to each other (see Figure 7). The matrix in between the broken and intact fiber as well as the corner of the intact fiber close to the broken fiber are loaded more [7]. Therefore, whether the SCF is higher or lower depends on the orientations of the neighboring fibers. However, these differences are very small and therefore, it was shown that the cross-sectional shape of the fibers barely affects the cross-sectional average SCF. Similar results were obtained with the application of higher strain and the contribution of elastoplastic material behavior.

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Figure 7. Different orientations of hexagonal fibers presented with circular fibers: (a) hexagon corners are faced to each other, (b) hexagon sides are faced to each other.

In Figure 6b, the SCFs were averaged at the cross-sections having the same axial coordinate along the length. So, there were regions inside a single cross-section where stresses were significantly above the average stress in that cross-section. As mentioned in [7], these high stresses are found in the regions closest to the broken fiber, and they can be so high that they approach the theoretical fiber strength. In this study, the corners of the hexagonal fibers can further magnify these stresses. Figure 8 presents the SCF results of models Hex and Circ for 0.1% applied strain in terms of peak stresses. For a more detailed examination, results of the first five closest fibers to the broken fiber are given in Table 4.

Considering the results in Figure 8 and Table 4, the maximum peak stress in the model with hexagonal fibers, which is observed in the closest fiber to the broken one, is significantly higher than the one with the circular fibers. This indicates that the corners of the hexagonal cross-section are responsible for this higher peak SCF. However, for the second closest fiber, the higher peak stresses are observed for the circular fibers rather than for the hexagonal ones. A careful investigation attributed this to the same reason as described in Figure 7: the orientations of the hexagons. The d/R values in Table 4 were calculated with respect to the distances between circular fibers. Figure 9 shows the five intact fibers closest to the broken fiber with their hexagonal and circular cross-sections. Due to the corners of hexagons, depending on their orientations, the actual distance (d_h) between the hexagonal fibers can be significantly different than their circular counterparts (d_c). These corrected distances are given in Table 4 together with the ones for circular fibers.

Figure 8. Maximum SCF results of intact fibers in models Hex and Circ for 0.1% applied strain in terms of peak stresses.

Table 4. The first five maximum peak SCF results of models Hex and Circ for 0.1% applied strain and actual d/R values for hexagonal fibers compared to the circular ones.

d/R	Hexagonal peak SCF [%]	Circular peak SCF [%]	Difference in SCF [%]	Hexagonal, d_h/R	Circular, d_c/R
0.203	89.5	69.9	19.6	0.149	0.203
0.246	40.1	42.6	-2.6	0.294	0.246
0.326	40.1	34.1	5.9	0.307	0.326
0.623	15.2	15.0	0.2	0.575	0.623
0.736	12.7	11.5	1.2	0.753	0.736

Figure 9. The closest intact fibers to the broken fiber with hexagonal and circular shapes.

As can be seen in Table 4, the closest points of the first, third and fourth closest hexagons are 36%, 6% and 8% closer to the broken fiber compared to their circular counterparts, respectively, while the closest points of the second and fifth hexagons are 16% and 2% farther from the broken fiber, respectively. Therefore, to understand whether the shape or distance affects the SCFs in terms of peak stresses, another finite element model with circular fibers was created. In this model, the closest five fibers were moved to their new positions so that the minimum distances between those five fibers and broken fiber are the same for both models with hexagonal and circular cross-sections. The results are given in Figure 10 and Table 5. The modified distances brought the results for both fiber shapes significantly closer together. This demonstrates that the surface-to-surface distance is the most important parameter for the peak SCFs rather than the fiber shape.

Figure 10. Maximum SCF results of intact fibers in terms of peak stresses for the same minimum distances.

Table 5. The first five maximum peak SCF results for hexagonal, circular and modified circular fibers.

d/R	Hexagonal peak SCF [%]	Circular peak SCF [%]	Modified circular peak SCF [%]	Difference between hexagonal and modified circular results [%]	d/R change of circular model fibers
0.149	89.5	69.9	85.5	4.0	0.054
0.294	40.1	42.6	37.8	2.3	-0.048
0.307	40.1	34.1	34.7	5.4	0.019
0.575	15.2	15.0	16.6	-1.4	0.048
0.753	12.7	11.5	11.1	1.6	-0.022

3.2.Effect of steel fiber plasticity

Steel fibers have the advantage of high failure strain compared to conventional glass and carbon fibers. For applied strains above the yield point, the behavior of steel fiber composites is different from the conventional glass and carbon fiber composites due to steel fibers' plastic nature [23,25]. To analyze this effect on SCF and ineffective length, a Hex-EF model was prepared with the same location of fibers, but without the implementation of elastoplastic material behavior of steel fibers (see

Table 3). Results are presented in terms of cross-sectional average stresses. A strain of 2% was applied to the Hex-EF model to compare the results with model Hex in section 3.1. In another run of the Hex model, a 7% strain was applied, which corresponds to the failure strain of the unidirectional steel fiber/epoxy composites reported in [23].

Figure 11 presents the stress recovery profiles and maximum cross-sectional average SCFs for the Hex and Hex-EF models. Figure 11a proves that stress recovery in the Hex model with 0.1% applied strain occurred more rapidly than in the Hex-EF model. This is due to the shear stress build-up on the surrounding matrix. For the Hex model, the ratio of broken fiber stress to be

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recovered over the matrix shear stress is constant if applied strain does not cause plastic deformation on both fiber and matrix materials, which is the case for 0.1% applied strain. For the Hex-EF model, however, this ratio increases in case of 2% applied strain as the matrix shear stress development decelerates in the plastic region. Due to this relatively lower shear stress development on the surrounding matrix, the stress recovery in the Hex-EF model occurs more slowly than in the Hex model. A similar reason applies to the differences between the Hex-EF and Hex models with 2% applied strain. In the Hex model, a 2% applied strain causes plastic deformation for both materials. In this case, the stress to be recovered in the broken fiber is lower than in the Hex-EF model, in which fibers were defined with elastic behavior. Therefore, the stress recovery in the Hex model with 2% applied strain occurred more rapidly. Similar stress recovery profiles were obtained for both 2% and 7% strain levels in the Hex model. This can be explained by the fact that the ratio of broken fiber stress to be recovered over the matrix shear stress for both strain levels are close to each other. The ineffective length results for each model are presented in Table 6.

Table 6. Comparison of ineffective lengths for different fiber volume fractions.

Model Name	Ineffective length
Model Hex (0.1 strain)	25R
Model Hex (2% strain)	6.5R
Model Hex-EF (2% strain)	49R
Model Hex (7% strain)	6.5R

Figure 11. For Hex and Hex-EF models: (a) stress recovery profiles of broken fibers, and (b) maximum cross-sectional average SCF results of intact fibers.

In Figure 11b, it is apparent that the SCFs of the Hex-EF model were mostly greater than the SCFs in the Hex model with 0.1% applied strain. The reason is the stiffness-dependency of SCFs. In the Hex-EF model, the 2% applied strain pushed the matrix in its plastic regime, resulting in a lower matrix secant stiffness than in the Hex model with 0.1% applied strain. The epoxy in the Hex-EF model was therefore less effective in transferring stresses and the intact fibers carried a higher SCF compared to the fibers in the Hex model with 0.1% applied strain. The same effect can be seen when the elasto-plastic material behavior of steel was implemented. Due to the elastic behavior of steel in the Hex-EF model, the steel fibers have their maximum stiffness value in that model. However, the stiffness of steel in the Hex model with 2% applied strain was lower as the tangential modulus is decreased in the plastic region. In this model, due to stiffnesses of epoxy and steel becoming closer, the matrix carried more load than the matrix in the Hex-EF model. This caused smaller stress concentrations in the Hex model with 2% applied strain in which both materials were plastically deformed. 2% and 7% strain levels for Hex model did show significant differences in the maximum cross-sectional average SCF results, where the results of the 7% strain level were slightly higher than the 2% one. This can

be explained by examining the stress-strain plots of steel fiber and epoxy in Figure 3. The slopes of the curves and thus the tangential modulus values decrease with increasing strain. This decrease rate is higher in epoxy compared to steel fibers. Therefore, the stiffness ratio of steel and epoxy increases for higher strains. Due to the increase in the stiffness ratio, the intact fibers in the model with 7% applied strain carried more load compared to those in the models with 2% applied strain causing higher stress concentrations. So, the effect of higher strain in the plastic region depends on the relative mechanical behavior of fibers and epoxy in the plastic region. From these results, it can be concluded that in steel fiber composites under high strain, the plastic behavior of the steel fibers reduces the stress concentrations and speeds up the stress recovery while the plastic behavior of the matrix increases the stress concentrations and slows down the stress recovery.

This section revealed that plastic behavior of steel fibers reduces the SCFs and speeds up the stress recovery while the opposite is true for the plastic behavior of the matrix in case the elastic limit is exceeded. Even within the plastic region, the applied strain level still changes the stress redistributions. As mentioned in [8], accurate longitudinal strength predictions for unidirectional composites require calculating SCFs at the relevant strain levels. Since the failure strain of steel fiber composites was reported as 7% in [23], which is in the plastic region for both steel and epoxy, this is the most relevant strain level to analyze. To maximize accuracy however, strength models should take into account the strain dependency of the SCFs.

4. Conclusion

Stress concentrations and ineffective lengths were investigated for unidirectional steel fiber-reinforced composites under longitudinal tensile loading. By comparing models with randomly distributed and oriented hexagonal and circular fibers, the fiber shape was shown to have a small effect on the SCFs and ineffective length in terms of cross-sectional average fiber stresses. Those small differences were due to the orientations of the hexagons. In terms of peak stresses, due to the corners of the hexagons, the differences in SCFs were proven to depend more on the distance to the broken fiber than on the cross-sectional fiber shape.

Plastic behavior of steel fibers was shown to decrease the SCFs and speed up the stress recovery. However, the opposite is valid for plastic behavior of epoxy. Finally, depending on the relative stiffness of fiber and matrix in the plastic region, differences in SCFs for different strain levels can be expected. This is clear evidence that the correct material behavior needs to be considered in predicting the stress redistribution around fiber breaks. Future work will implement these stress redistributions into a fiber break model [21,26-28], so that the effects on the longitudinal tensile strength can be predicted.

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Data Availability

The raw/processed data required to reproduce these findings can be obtained from the corresponding author upon request.

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