Crack Formation and Crack Path in CFRP Machining

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ABSTRACT. *During milling of carbon fiber reinforced plastics (CFRP) material a very distinct material removal process has been identified. Instead of forming continuous chips of a certain size, the material is removed in a powder-like fashion shooting out of the tool / workpiece contact area. The brittle, powder-like chip formation in cutting CFRP suggests crack formation as main material removal process. Analyzing the material removal for different fiber orientations characteristic matrix (epoxy) and fiber failure behavior can be identified. Some orientations show a frequent crack formation reaching deeper into the structure, while for others the matrix and fiber removal takes place only at the very surface. The crack path in the epoxy matrix and in the fibers depends on the fiber orientation relative to the trajectory of the cutting edge, respectively tool. Matrix removal and fiber fracture is minimum and limited to the surface itself when the cutting takes place parallel to the fiber orientation or the tool is running on fibers which gradually ascending to the surface. The most complex crack formation is observed when the tool runs head-on on the fiber ends at the surface. Here the crack path starts with a matrix / fiber interface failure which causes deeper cracks running from the surface into CFRP followed by fiber cracking below the cut surface.*

INTRODUCTION

Carbon fiber reinforced plastics (CFRP) with high-modulus fibers are increasingly used in aerospace applications, because of their high-modulus/weight ratio, but also in automotive and general engineering, because of their new opportunities for product design [1]. Although CFRP components can generally be produced by near-net-shape manufacturing methods, a majority of these parts requires post mould machining such as drilling of boreholes for rivets and screws, as well as trimming of openings or edges according to specific sizes and geometrical tolerances [1, 2]. However, the material behavior of CFRP composites is inhomogeneous due to the matrix properties, fiber orientation, and relative volume fraction of matrix. Furthermore, it possesses low inter-laminate bonding strength and very high tensile strength. CFRP when machined with conventional technique often results in high surface roughness, fiber damage, interlaminate failure, delamination at surfaces, high tool wear rate and high operating cost [3]. This study focuses on the load related fiber, matrix and interface failure as well as on the resulting crack path due to milling of unidirectional CFRP with an epoxy resin matrix. For the identification of the load conditions and the underlying failure mechanisms, additional finite element analyses (FEA) were carried out.

EXPERIMENTAL SETUP

The milling experiments have been carried out using a discmilling cutter with a diameter of 160mm (cf. Fig.1). The discmill was equipped with solid carbide inserts with a rake angle of -12°, a clearance angle of 7° and a cutting edge radius of about 35 µm. An up-cut milling process was applied under dry conditions to machine a slot into the CFRP specimens.

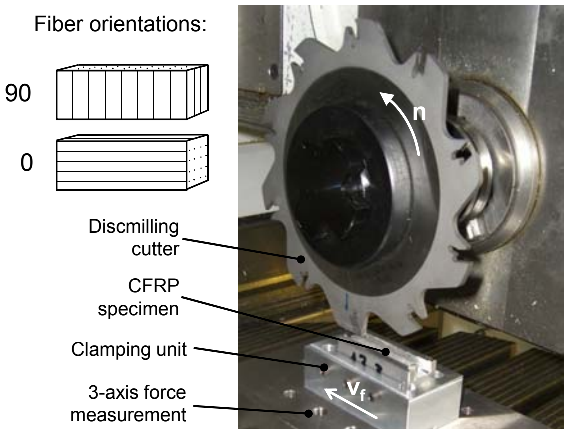

Figure 1. Experimental setup for slot milling in unidirectional CFRP with fiber orientation 0°, 45°, -45°and 90°

The specimens with a dimension of 10 x 10 x 50 mm^3 were separated from a unidirectional laminated CFRP plate made of high tensile carbon fibers and a thermoset epoxy resin matrix. The plate was manufactured in a mould vacuum injection process resulting in a fiber volume content of about 50%. To minimize the influence of vibrations and to ensure an adequate clamping of the CFRP specimens they were embedded into aluminium shells which were clamped on a multidirectional force measurement platform. The test setup is shown in Figure 1. The cutting speed was set to 100 m/min and the fiber orientation within the cutting plane from 0° to +/- 45° and 90°. The feed per tooth f_z as well as depth of cut a_e have been kept constant with a value of 0.1 mm and 0.6 mm respectively. The resultant maximum of chip thickness was 12.5 µm. Additional experimental results going beyond the scope of this article have been published elsewhere [4, 5].

EXPERIMENTAL OBSERVATIONS

The experimental results were analyzed on basis of micrographs of the sub-surface region at the bottom of the machined slotes. Four types of CFRP specimens with different fiber orientations were machined at identical milling conditions as described before. Figure 2 shows the fiber structure of these specimens at the surface along the arc of contact with the discmilling cutter.

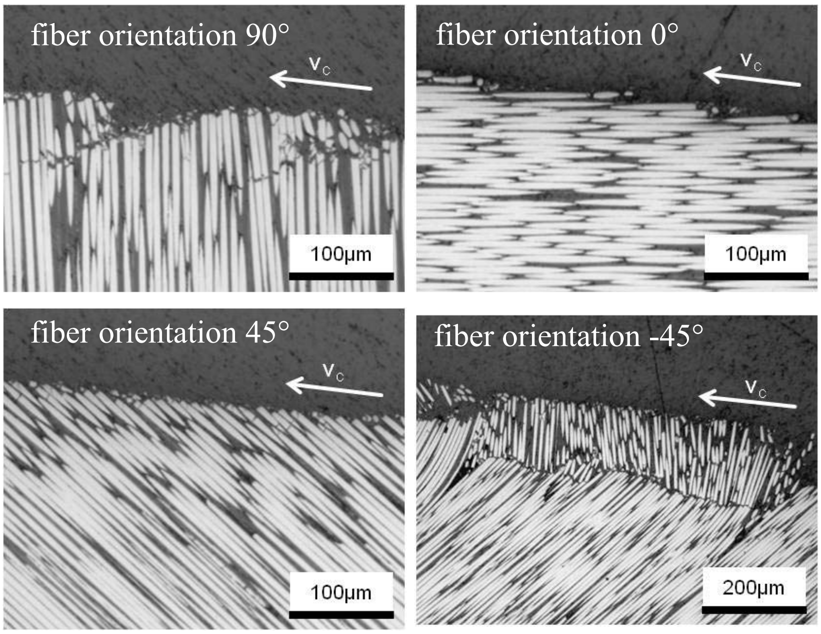

Figure 2. Micrographs of specimens with different fiber orientations

Visible damages can be found at specimens with a fiber orientation of 90° (Fig.2, upper left) and -45° (lower right) while the surfaces for 0° (upper right) and +45° fiber orientation (lower left) appear to be very consistent and nearly free of cracks or larger damages. Specimens with 90° fiber orientation are showing cracks extending frequently from the milled surface at an angle of about 18° into the material at intervals of 200 µm. The worst results were found for a fiber orientation of -45°. The micrographs (Fig.2, lower right) show larger cracks parallel to the surface as well as recurring cracks with a length of about 300 µm extending from the surface into the material in direction of the fibers. This behaviour is well reported in the literature [6].

In Figure 3 the surface and crack tip regions are presented in more detail. If the fibers are cut perpendicular, i.e. at 90° (cf. Fig.3a), a moderated form of crack formation is observed. In this case the characteristic 18° crack path proceeds across the fibers which fracture in a brittle manner. At the resulting surface relatively short fiber particles were found, which appear to be broken as well in a brittle mode, but due to a bending load. In case of 0° fiber orientation (cf. Fig.3b) only the upper layer of fibers is crushed, which is limited to about 10 to 15 µm (1 to 2 times the fiber diameter). In case of the +45° orientation (cf. Fig.3c) also only the tips of the fibers at the cut surface are damaged in a comparably large region. Similarly to the brittle fiber removal mode at the surface for the 90° fiber orientation (cf. Fig.3a) also here cracks extending from the impact side of the cutting edge (from left to right) perpendicular across the fiber cross-section. In case of the -45° fiber orientation not only crack formation is observed, but also matrix / fiber interface failure (cf. Fig.3d). The interface failure generates cracks of up to 250 µm in length parallel to the fibers. Additionally cracks of about 150 µm below the cut surface are generated, which extend from these interface failures (cf. Fig.2, lower right). Further

Figure 2 (lower right) and Figure 3d) show clearly a different fiber orientation in the region with the broken fibers and a rather strong bending of the fibers at both ends where interface failures occurred.

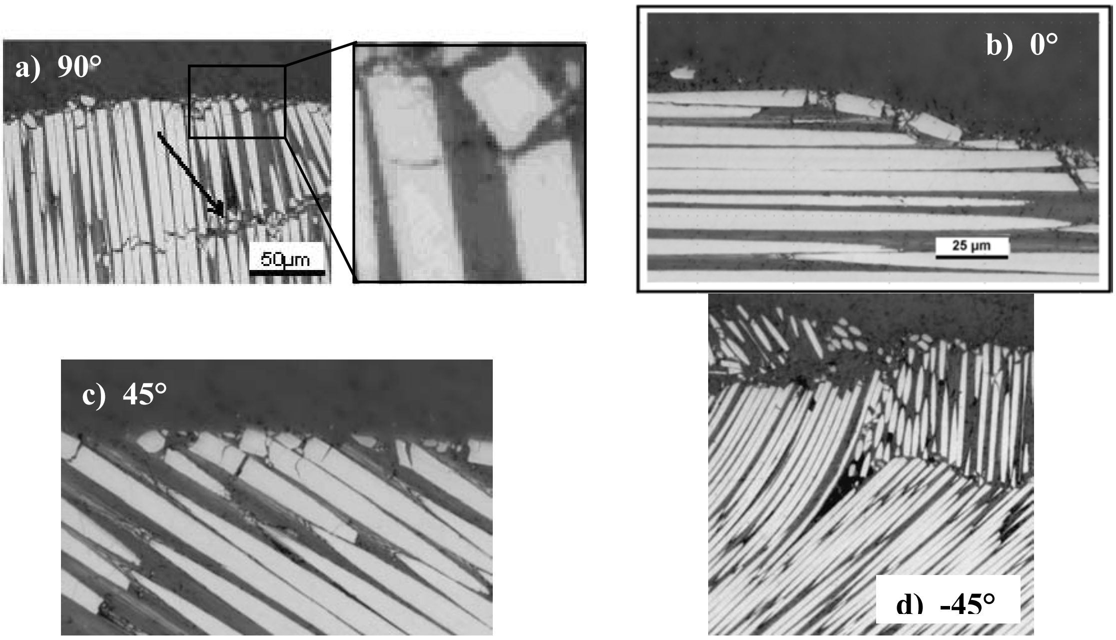

Figure 3. CFRP fiber / matrix microstructures at bottom of milled slots in specimens with different fiber orientation (cutting from right to left)

NUMERICAL ANALYSIS

For the cutting process simulation of CFRP material two different FEM approaches were developed: a macroscopic model, which is based on continuous but anisotropic material properties with implicitly defined fiber orientation, and a microscopic model with explicit fiber / matrix representation (cf. figure 4).

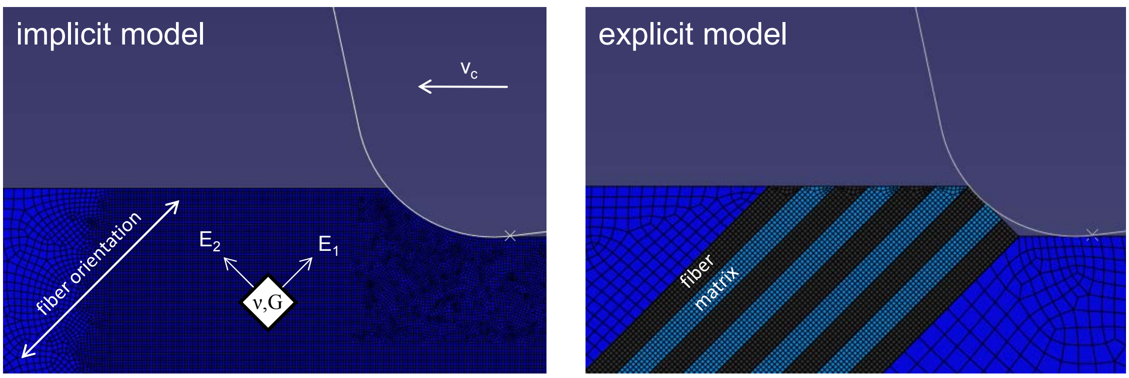

Figure 4. Setups of an implicit macroscopic and an explicit microscopic FEM model for the CFRP cutting simulation

The models were designed two dimensional in a so-called orthogonal cutting setup considering a rigid cutting edge (contour lines in figure 4) with a cutting edge radius of 35 µm engaging with the CFRP specimens. All values were chosen according to experimental setup, additionally the friction coefficient was set to 0.3. The cutting conditions result in a maximum chip thickness of 12.5 µm, which was used as engagement depth in the models. The employed software is the FEM program ABAQUS using element type CPS4R for implicit macroscopic model. For the cutting process simulation the progressive damage model by Hashin [7] was considered (for further details about the modeling refer to [4]). The microscopic model contains only a few explicit fibers (diameter about 6 µm) because of the numerical expense and the rapid model degradation soon after damage initiation due to the tool impact. Here fiber and matrix were modeled with element type CPS4R and the interface between them with element type COH2D4.

For the 0° fiber orientation the microscopic model provides the most interesting result (cf. Fig. 5). Due to fiber bending at the comparably large cutting edge radius, the model predicts a break up of the upper most fiber into pieces like it is found in experiment.

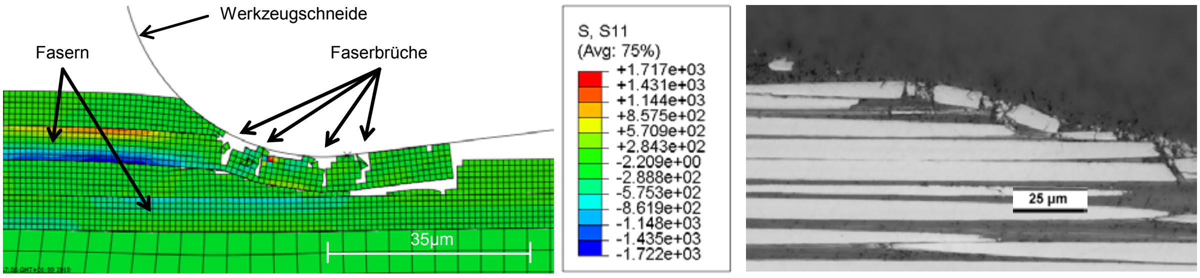

Figure 5. Horizontal stress and damage for 0° fiber orientation (microscopic model)

In case of the crack formation in CFRP with a 90° fiber orientation, the macroscopic model with the implicit fiber property representation revealed an excessive matrix tension as significant failure loading mode (cf. Fig. 6). Also the angle of the failure path in the FEM model agrees very well with the crack path observed in experiment. The shows that the crack is initiated behind tool / workpiece contact.

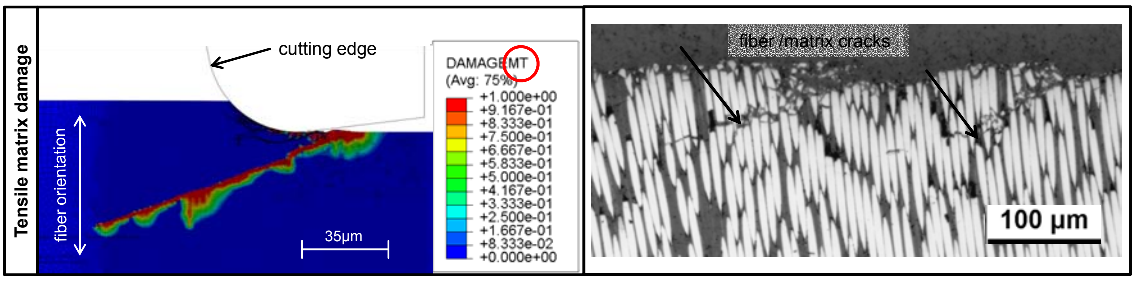

Figure 6. Main CFRP damage for 90° fiber orientation by matrix tensile failure (left, macroscopic model) and its respective experimental observation (right)

Because of material compression in front of the cutting edge (in Fig. 6 cutting from right to left), tensile stresses are generated relative to the non-compressed regions (in CFRP mainly in fiber direction). The matrix tensile damage mode (cf. DAMAGEMT in scale of Fig.6) reveals the transition region between these two differently loaded areas. The frequently occurring cracks hint at a cyclic occurring effect during cutting possibly due to friction related slip-stick in the tool / workpiece contact.

Like for the 0° fiber orientation, the microscopic model provides the related stress mode for the localized material removal at the surface of the CFRP with +45° fiber orientation. Again due to bending of the fibers, cracks are initiated on the side of the tensile load and, as simulation and micrograph show (cf. Fig.7), cracks run across the fiber cross-section close to the surface. Fiber crack initiation takes place within a region of about 15 to 20 µm from the generated surface.

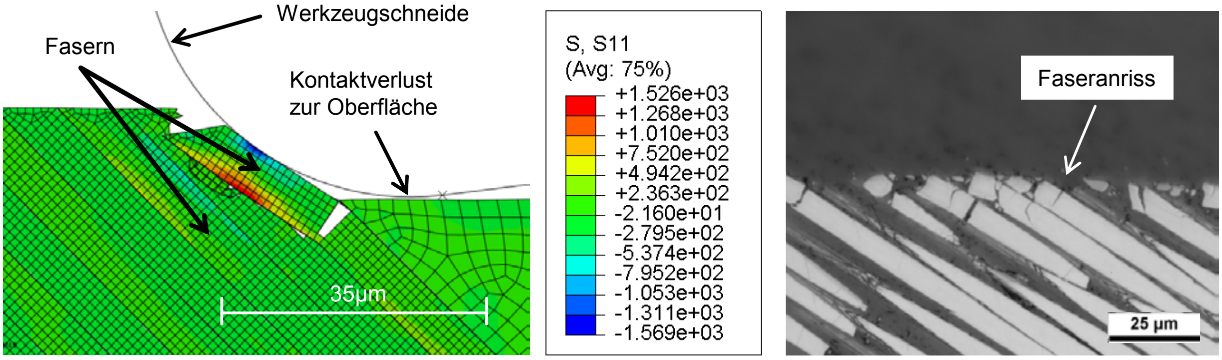

Figure 7. Longitudal fiber stress and damage for +45° fiber orientation (microscopic model) and its respective experimental observation (right)

At the specimens with -45° fiber orientation the crack formation and crack path is more complex. The macroscopic model in Fig.8 shows a matrix tensile damage mode, like for the 90° fiber orientation, with rather deep running damages along the fibers as seen in the experiments as well. The related microscopic model reveals the underlying process

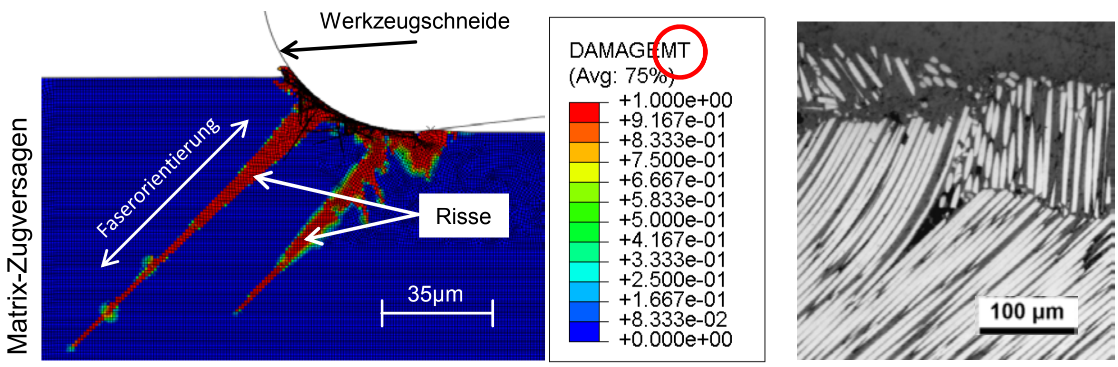

Figure 8. Main CFRP damage for -45° fiber orientation by matrix tensile failure (left, macroscopic model) and its respective experimental observation (right)

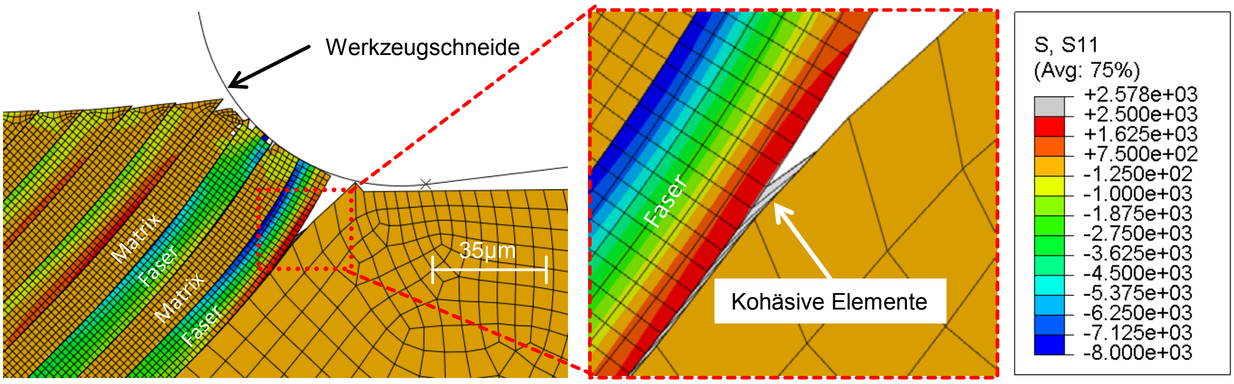

Figure 9. Longitudal fiber stress just before fiber failure and fiber/matrix interface failure for -45° fiber orientation (microscopic model)

respectively mechanism in more detail (cf. Fig.9). At -45° fiber orientation the rather round cutting edge runs head on the top ends of the fibers and compresses the first to some degree. However the initial failure occurs as interface fracture due to bending. The bending leads to a failure of the so-called cohesive elements, which lead to the formation of a crack along fiber direction. Because of the 45° fiber orientation the interface cracks can run rather deep into the CFRP and allow for an intensive bending of the fiber also reaching deeper into material. Because of the intensive fiber bending, fiber fracture is also taking place at larger depth than for the other fiber orientations. Once fibers start to fracture under the bending load, the fracture mode changes its mode and path from an interface fracture along fiber direction to a trans-fiber crack mode parallel to the surface.

DISCUSSION

For the 0° and +45°fiber orientation the matrix / fiber structure at the generated surface is damaged by the cutting edge only in a small range of about 15 µm (1 to 2 times the fiber diameter of about 6 µm). The developed microscopic FEM model with explicit fiber / matrix representation shows for these conditions brittle crack formation in the fibers close to the surface due to fiber bending. For these two orientations the deeper lying fibers and fiber parts are well supported so that no deep reaching cracks were observed in the micrographs and neither the microscopic nor the macroscopic model showed deep running stress concentrations or failure modes.

During cutting of CFRP with 90° to -45° fiber orientation, the crack formation was 10 to 15 times larger than for 0° and +45° fiber orientation. Although in both cases fiber bending and interface failure into deeper regions play a role, the crack path for the 90° fiber orientation is quite different to that of the -45° orientation. For -45° fiber orientation the cracks seem to be somewhat deeper, but in case of the 90° orientation a frequent crack formation occurs with a characteristic crack path across the fibers, reaching into the material in cutting direction at an angle of about 18°. The cracks are initiated behind the cutting edge at the clearance face, where the material experiences a tensile load as opposed to the compressive load a head of the cutting edge, i.e. in cutting direction. The matrix tensile failure mode of the implicit macroscopic fiber/matrix model resembles this characteristic failure behavior very closely. For the -45° fiber orientation the crack formation is initiated by an intensive fiber bending upon which first a matrix / fiber interface failure occurs that causes deep cracks of up to 250 μm running along the fibers. Upon exceeding the fiber tensile strength during further fiber bending, fibers start to break at a depth of about 150 μm below the cut surface. The interface crack transforms into a trans-fiber crack and the crack path changes direction from -45° to about 0° (parallel to the surface). Perpendicular to the fiber length direction the tensile strenght of the fibers is much lower than in fiber direction, for the unidirectional CFRP accordingly (see [4]).

CONCLUSION

The material removal process at CFRP is governed by brittle crack formation in the reinforcing fibers. The crack path and depth is strongly dependened on the fiber orientation relative to the trajectory of the cutting edge. Fiber fracture is limited to a region smaller than 15 μm for fiber orientations between 0° and +45°. For fiber orientations between 90° and -45° a matrix/fiber interface failure due to fiber bending causes the formation of cracks that run 10 to 15 times deeper into the material.

Localized damage is analyzed best by the explicit microscopic fiber/matrix model and large scale failure analysis is represented better by the implicit macroscopic model.

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