Published in final edited form as:

J Mech Behav Biomed Mater. 2016 April ; 57: 260–268. doi:10.1016/j.jmbbm.2015.12.004.

A comparison of stress in cracked fibrous tissue specimens with varied crack location, loading, and orientation using finite element analysis

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Abstract

Cracks in fibrous soft tissue, such as the intervertebral disc annulus fibrosus and knee meniscus, cause pain and compromise joint mechanics. A crack concentrates stress at its tip, making further failure and crack extension (fracture) more likely. Ex vivo mechanical testing is an important tool for studying the loading conditions required for crack extension, but prior work has shown that it is difficult to reproduce crack extension. Most prior work used edge crack specimens in uniaxial tension, with the crack 90° to the edge of the specimen. This configuration does not necessarily represent the loading conditions that cause in vivo crack extension. To find a potentially better choice for experiments aiming to reproduce crack extension, we used finite element analysis to compare, in factorial combination, (1) center crack vs. edge crack location, (2) biaxial vs. uniaxial loading, and (3) crack-fiber angles ranging from 0° to 90°. The simulated material was annulus fibrosus fibrocartilage with a single fiber family. We hypothesized that one of the simulated test cases would produce a stronger stress concentration than the commonly used uniaxially loaded 90° crack-fiber angle edge crack case. Stress concentrations were compared between cases in terms of fiber-parallel stress (representing risk of fiber rupture), fiber-perpendicular stress (representing risk of matrix rupture), and fiber shear stress (representing risk of fiber sliding). Fiber-perpendicular stress and fiber shear stress concentrations were greatest in edge crack specimens (of any crack-fiber angle) and center crack specimens with a 90° crack-fiber angle. However, unless the crack is parallel to the fiber direction, these stress components alone are insufficient to cause crack opening and extension. Fiber-parallel stress concentrations were greatest in center crack specimens with a 45° crack-fiber angle, either biaxially or uniaxially loaded. We therefore recommend that the 45° center crack case be tried in future experiments intended to study crack extension by fiber rupture.

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Preprint submitted to Elsevier

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Keywords

Fibrocartilage; crack propagation; finite element analysis; tensile testing

1. Introduction

Cracks in fibrocartilage are a common affliction with potentially severe consequences. In the intervertebral disc annulus fibrosus, cracks (i.e., tears) occur as the disc degenerates, causing pain or mechanical disruption (Osti et al., 1992; Vernon-Roberts et al., 2007; Haughton et al., 2000; Lee et al., 2004; Peng et al., 2005; Videman and Nurminen, 2004). Overload of the knee meniscus, such as in sport-related injuries, can also create cracks (Isaac et al., 2010; Drosos and Pozo, 2004; Fox et al., 2015; Snoeker et al., 2013). Meniscus cracks cause pain, compromise knee motion and, most importantly, promote osteoarthritis (Englund et al., 2012; Bedi et al., 2010; Mononen et al., 2013; Maffulli et al., 2010; Berthiaume et al., 2005; Lento and Akuthota, 2000; Lohmander et al., 2007). Furthermore, cracks in avascular fibrocartilage have poor healing potential (Arnoczky and Warren, 1983).

Cracks can grow quickly, so the future risk posed by a given crack is not necessarily obvious. A crack creates a stress concentration at its tip that facilitates local failure and thus crack extension (fracture) (Anderson, 2004). Even a small, asymptomatic crack may consequently be cause for concern. However, the mechanisms and mechanical loading conditions required for crack extension in fibrocartilage (and other fibrous soft tissues) are still largely unknown.

It has proven very difficult to produce crack extension in ex vivo mechanical testing. Only a few publications report fracture toughness for fibrous soft tissue (Purslow, 1985; Stok and Oloyede, 2007; Chin-Purcell and Lewis, 1996; Oyen-Tiesma and Cook, 2001; Koombua et al., 2006; Beatty et al., 2008; Wu et al., 2006). Taylor's review of these studies indicated that most did not actually produce fracture (Taylor et al., 2012). Von Forell et al. noted a lack of crack extension in their fracture tests of Achilles tendon and anterior longitudinal spine ligament (Von Forell et al., 2014). Although fracture is not necessarily a relevant failure mode for all fibrous tissues (Taylor et al., 2012), cracks in fibrocartilage clearly do grow in vivo. Fracture cannot be studied directly in controlled conditions without an experimental protocol that actually produces crack extension. Identifying good loading conditions for crack extension is consequently quite important.

The absence of crack extension in most experiments may be caused by loading conditions that do not sufficiently represent in vivo conditions. The fracture tests cited above were all done using edge-cracked specimens in uniaxial tension, with the crack perpendicular to the edge of the specimen. In contrast, in vivo cracks (1) are often situated in the middle of the tissue, (2) are loaded multiaxially, and (3) come in a variety of orientations (Shieh et al., 2013; Swenson and Harner, 1995; Osti et al., 1992; Kawamura et al., 2003; McNally and Adams, 1992; Yoder et al., 2014).

The objective of this study was to identify new test configurations that are more likely to produce crack extension than uniaxially loaded edge crack specimens. Finite element

analysis (FEA) was used for this search because the search space is very large. FEA also allows the application of previously validated models for tissue mechanics to estimate fracture risk. This approach cannot show that a specimen will definitely fracture, but it does identify the configurations most likely to produce fracture based on our current understanding of tissue elasticity. These configurations can then be specifically targeted in future work with physical specimens.

In this study, we compare specimens with varying (1) crack location (center vs. edge), (2) loading (uniaxial vs. biaxial), and (3) crack-fiber angle. The likelihood of fracture was compared using the magnitude of the crack-induced stress concentration. Greater stress was interpreted as greater fracture risk. Since fibrous tissue has multiple failure mechanisms, including fiber rupture, matrix rupture, and fiber sliding, fracture risk was evaluated separately for fiber-parallel, fiber-perpendicular, and fiber shear stress.

We hypothesized that at least one of the test configurations would have a greater stress concentration (a greater risk of fracture) than uniaxially loaded edge crack specimens. Our results partially supported this hypothesis. Center crack specimens with oblique crack-fiber angles produced more fiber-parallel stress, and thus a greater likelihood of fiber rupture, than edge crack specimens. Still, edge crack specimens produced large amounts of fiber-perpendicular stress (matrix rupture) and fiber shear stress (fiber sliding).

2. Materials and methods

2.1. Specimen geometry and loading

The specimen geometry was a 1 mm thick plate, which was meant to represent typical tensile test specimens. Through-thickness slit cracks were created either in the center or edge of the plate. The center crack meshes were $20 \text{ mm} \times 20 \text{ mm} \times 1 \text{ mm}$, with a 2 mm long crack, and the edge crack meshes were $10 \text{ mm} \times 20 \text{ mm} \times 1 \text{ mm}$, with a 1 mm long crack (Figure 1). All cracks thus had a characteristic crack length of 1 mm (Janssen et al., 2002).

Uniaxial or biaxial tensile stretch was applied by displacing the edge nodes. Biaxial stretch was chosen because it is a standard test procedure for multi-axially loaded tissue (Sacks and Sun, 2003; Bass et al., 2004; O'Connell et al., 2012). Thus, three combinations of crack location and loading were examined: center crack biaxial (CCB), center crack uniaxial (CCU), and uniaxially loaded single edge notch (SENT) (Figure 1).

In all cases, the stretch ratio in the fiber direction was set to 1.14. The CCB case was stretched equibiaxially in the xy plane. The uniaxially loaded cases were stretched parallel to the fiber axis, and the fiber-perpendicular axis was free to contract. This stretch ratio was chosen to fully load the simulated fibers, such that the resulting stress ($\sim 70 \text{ MPa}$) would be the same order of magnitude as fibrous tissue strength (LaCroix et al., 2013; Green et al., 1993; Skaggs et al., 1994; Holzapfel et al., 2005; Ebara et al., 1996; Tissakht and Ahmed, 1995).

2.2. Crack-fiber angle

For each configuration, the crack angle was varied relative to the fibers from 0° (parallel to the fiber axis) to 90° (perpendicular to the fiber axis). This variation was done in 15° increments. There is one exception: the SENT specimen has no 0° SENT case, as in that case the crack line and specimen edge would coincide.

2.3. Mesh construction

Meshes were created using 8-node trilinear brick elements. A primary goal of the meshing procedure was to ensure that differences in outcome between cases were not caused by differences in mesh geometry. Consequently, we explicitly defined the size and position of each element relative to the crack such that where large deformation gradients existed (i.e., near the crack tip) elements were sized and positioned the same for every load case. The mesh contained five layers of elements in the out-of-plane direction. Since the strain gradients were expected to be greatest at the crack tip, the element size was log-biased, with the smallest elements at the crack tip (Figure 1). The crack tip element size was parameterized, and all other element sizes were relative to this minimum element size. All elements touching the crack face were set to the minimum element size. In some of the center crack cases, regions containing large stress gradients extended further from the crack than in the SENT cases; consequently, for the center crack cases all elements within 1 mm of the crack were set to the minimum element size.

The ability of the mesh to simulate stress fields in cracked specimens was checked by comparing the FEA solution for a linear isotropic material to the Westergaard solution (Janssen et al., 2002), which showed an average error of ~1% and a peak error on the same order of magnitude as the far-field stress. Since this study deals with differences >10 times the far-field stress, this was considered good performance. Comparison against a known stress field solution for fibrous soft tissue would be preferable, but no such data are available. Comparison against linear elastic fracture mechanics establishes that mesh is basically suitable for simulating cracked specimens.

The effect of element size on the near-crack tip stresses was investigated by varying the minimum element size (the size of the elements near the crack tip). Three sizes were examined: 50 µm, 100 µm, and 200 µm. For all analysis other than the convergence study, the 50 µm mesh was used.

2.4. Constitutive model and material properties

Fibrous tissue mechanics were represented by a mixture model with matrix and fiber terms. The matrix was represented by the Holmes-Mow strain energy function (Holmes and Mow, 1990; Jacobs et al., 2014, 2013)

$$\Psi_m(I_1, I_2, J) = \frac{1}{2} \frac{\lambda + 2\mu}{2\beta} \left\{ e^{\frac{\beta}{\lambda + 2\mu} ((2\mu - \lambda)(I_1 - 3) + \lambda(I_2 - 3) - (\lambda + 2\mu)\ln J^2)} - 1 \right\}. \quad (1)$$

The fibers were represented by the exponential-power strain energy function

$$\Psi_f = \frac{\xi}{c_1 c_2} (\exp [c_1 (I_n - 1)^{c_2}] - 1). \quad (2)$$

The total strain energy is the sum of Ψ_m and Ψ_f . The λ μ parameters are calculated from E and ν using $\lambda = \frac{E}{(1+\nu)(1-2\nu)}$ and $\mu = \frac{E}{2(1+\nu)}$. The material parameters were $E = 75.8$ kPa, $\nu = 0.2205$, $\beta = 0.9438$, $c_1 = 65$, $c_2 = 2$, and $\xi = 296$ kPa. These parameters were previously obtained and validated for annulus fibrosus in uniaxial and biaxial testing, and have been validated in whole-disc FEA as successfully predicting whole-disc mechanics, including internal strain distributions (Jacobs et al., 2013, 2014; Showalter et al., in review).

2.5. Stress components

Due to the composite structure of fibrous soft tissue, crack extension can occur by multiple mechanisms: fiber rupture (fiber-parallel stress), matrix rupture (fiber-perpendicular stress), and fiber sliding (fiber shear stress). Therefore, Cauchy stress (σ) tensors were expressed in a fiber-aligned coordinate system, defined as follows: axis 1 is parallel to the fibers, axis 2 is perpendicular to the fibers (in the specimen plane), and axis 3 is normal to the specimen plane. Fiber rupture risk was assessed using fiber-parallel stress (σ_{11}), matrix rupture risk was assessed using fiber-perpendicular stress (σ_{22}), and fiber shear risk was assessed using fiber shear stress (σ_{12}). Fracture risk was ranked separately for each failure mechanism.

2.6. Fracture risk analysis

Fracture risk was compared between cases (CCB, CCU, and SENT, each with varied crack-fiber angles) using the peak stress, which indicates the severity of the stress concentration (Sano et al., 2006). Greater stress was considered to indicate greater risk of fracture. The peak stress was calculated using two methods: (1) fitting a stress profile to obtain the crack tip stress and (2) calculating the stress at each element centroid and taking the maximum.

The stress profile fit was used because an FEA solution does not directly specify crack tip stress. To obtain the stress profile, stress was sampled at evenly spaced points on a line (in the reference configuration) extending from the crack tip, in the mid-z plane, in the same direction as the crack (Figure 2a). Interpolation within an element was done using a sub-element formed by its Gauss points. To obtain the stress at the crack tip, the near-tip part of this stress profile was fit with an exponential function (Figure 2b). This stress profile method was used for the fiber-parallel stress component.

For the fiber-perpendicular stress and fiber shear stress profiles, the stress profiles tended to be near-constant (e.g. Figure S1) or oscillatory (e.g. Figure S2). The fiber-perpendicular and fiber shear stress concentrations did not follow a conventional crack tip centered pattern (see results section 3.1), so in these cases the profile line did not sample the most relevant regions. The maximum element-wise stress was used as a workaround for these cases.

3. Results

3.1. Stress fields

Each stress component (fiber-parallel stress, fiber-perpendicular stress, and fiber shear stress) had a different spatial distribution. Fiber-parallel stress concentrations in all three test configurations were centered on the crack tip (Figure 3). The fiber-parallel stress concentrations extended far in the fiber direction, but hardly at all perpendicular to the fibers. Acutely oriented center cracks (Figure 3a,b) created more intense fiber-parallel stress bands than the other cases. Center cracks 90° to the fibers (Figure 3d,e) produced stress fields similar to SENT cracks of any orientation (Figure 3c,f).

Fiber-perpendicular stress concentrations were also centered on the crack tip (Figure 4). Acutely oriented center cracks produced fiber-perpendicular stress concentrations that extended for a short distance perpendicular to the crack, gradually curving to follow the fibers (Figure 4a,b). Regions of great tensile or compressive stress were also evident along the crack faces. In contrast, the fiber-perpendicular stress concentrations produced by 90° center cracks, or any of the SENT cracks, were very local to the crack tip (Figure 4c–f).

Fiber shear stress concentrations for acutely angled center cracks were distributed in fiber-aligned bands above and below the crack faces (Figure 5a,b). The crack tip stress did not always dominate the fiber shear stress field; stresses similar in magnitude to the crack tip stress occurred ~ 1 mm away from the crack tip (asterisks in Figure 5a,b). However, 90° center cracks produced more conventional fiber shear stress concentrations that were tightly centered on the crack tip and elongated along the fiber axis (Figure 5d,e). The fiber shear stress in the 90° center crack case, like the other stress components, was similar to the SENT cases (Figure 5c–f).

3.2. Relative stress concentration severity

The fiber stress at the crack tip, as quantified by stress profile fitting (section 2.6), was greatest for center-crack cases with oblique cracks (Figure 6). The CCB and CCU configurations were essentially identical. In contrast, the crack tip fiber stress for obliquely oriented SENT cracks were much less severe. Cracks oriented 90° to the fibers exhibited the same crack tip fiber stress for all three configurations. Cracks oriented 0° to the fibers did not increase the fiber stress relative to the crack-free condition.

Since the matrix stress and fiber shear stress at the crack tip could not be obtained by fitting stress profiles (see section 2.6), they were instead quantified by the maximum element-wise stress (Figure 7). Fiber-perpendicular stress was equal between 90° CCB, CCU, and SENT cases, but was greatly lessened for the center crack cases with crack-fiber angles $< 90^\circ$ (Figure 7b). Fiber-perpendicular stress for SENT specimens remained essentially constant regardless of crack-fiber angle. Similarly, fiber shear stress was equal for 90° CCB, CCU, and SENT cases, and decreased greatly for center crack cases with crack-fiber angles $< 90^\circ$ (Figure 7c). However, fiber shear stress for SENT specimens increased slightly as crack-fiber angle decreased.

As a consistency check, the maximum element-wise stress was also computed for the fiber-parallel stress. Trends in fiber-parallel stress measured by the maximum stress method are essentially the same as measured by the stress profile fits (compare Figure 7a to Figure 6).

3.3. Element size sensitivity

The crack tip fiber stress obtained from the stress profile fits was sensitive to the mesh size (Figure 8). Stress approximately doubled for each halving of the element size, with no apparent limit.

4. Discussion

4.1. Implications for physical crack extension testing

This study's primary purpose was to identify load configurations that are likely to cause crack extension and are thus good candidates for physical fracture testing. This was successful. Fiber rupture is most likely in center crack specimens with oblique crack-fiber angles, regardless of uniaxial or biaxial loading (Figure 6). Matrix rupture (perpendicular to the fibers) and fiber shear, however, are most likely in edge crack specimens or 90° center crack specimens (Figure 7b,c). Based on these results, the commonly used SENT configuration is a reasonable choice for tests of matrix rupture and fiber shear. Center-crack specimens with oblique crack-fiber angles should be more effective for producing fiber rupture.

When choosing a test configuration, the crack extension path must also be considered. Although the simulated SENT specimens did produce a relatively severe fiber-perpendicular stress and fiber shear stress concentrations, these stress components promote failure along the inter-fiber boundary. For any crack not parallel to the fibers, extension (in the original direction of the crack) requires fiber rupture, which is promoted by fiber-parallel stress. Since the SENT configuration produces relatively weak fiber-parallel stress concentrations, it makes sense that crack extension has not been observed in experiments using this configuration. The strong fiber-perpendicular and fiber shear stress concentrations in the SENT configuration instead increase the likelihood of crack deflection or the creation of secondary cracks between fibers. Secondary cracks of this type, extending perpendicular to the main crack, are visible in Purslow et al.'s Figure 5 (Purslow, 1985). In future work, it may be useful to systematically report secondary crack formation.

Crack extension by matrix rupture can be specifically studied using specimens with the loading axis perpendicular to both the fiber axis and the crack axis. This test configuration was not included in the present work because it leaves the fibers unloaded, but it has been previously applied to spine ligament, tissue engineered cartilage, deep zone articular cartilage, and temporomandibular joint disc (Von Forell et al., 2014; Koombua et al., 2006; Von Forell et al., 2014; Oyen-Tiesma and Cook, 2001). Cracks did not extend in spine ligament (Von Forell et al., 2014), did extend in tissue engineered cartilage (Oyen-Tiesma and Cook, 2001), and also extended in a subset of articular cartilage specimens (Chin-Purcell and Lewis, 1996; Taylor et al., 2012). It was ambiguous whether the temporomandibular joint disc failed by fracture (Koombua et al., 2006; Taylor et al., 2012).

This test configuration thus has a fair chance of producing crack extension, depending on the tissue.

Lastly, similar fiber stress between the CCB and CCU specimens (Figures 3a,b,d,e and 6) indicates that CCU specimens may be useful as a proxy for CCB specimens. Fiber-perpendicular stress and fiber shear stress are also similar, albeit to a lesser degree (Figures 7b,c, 4a,b,d,e, and 5a,b,d,e). Matrix stress coupling between the fiber-parallel and fiber-perpendicular directions may contribute to the greater fiber-parallel stress of the CCB case compared to the CCU case. However, the differences in stress between the CCB and CCU cases are less than the sensitivity threshold of this study, and they can be considered similar—the location of the crack is more important. Uniaxial fracture testing for fibrous soft tissue is much easier than biaxial fracture testing, so the ability to substitute one for the other would be convenient.

4.2. Crack blunting and plastic deformation

The cracks changed shape dramatically during the simulation due to the high degree of material anisotropy and the large deformation. Cracks in the 0° and 90° center crack cases and all the edge crack cases opened extremely widely. Large elastic crack opening such as this blunts the crack and reduces the crack tip opening stress (Hui et al., 2003). In comparison, the oblique ($15\text{--}75^\circ$) center crack cases twisted into a tilde-like shape that maintained the sharpness of the crack tip and better concentrated the crack tip opening stress (Figure 3).

In a real material, plastic deformation will further contribute to crack blunting. Wide opening and blunting of edge cracks, with no crack extension, has been previously observed in physical testing of tissue and scaffolds (Stok and Oloyede, 2003; Koh et al., 2013; Von Forell et al., 2014). Plastic inter-fibril sliding occurs in tendon (Szczesny and Elliott, 2014). SENT tests of ligament with fibers 45° to the loading axis showed blunting that was slanted along the fiber axis, consistent with fiber shear (Von Forell et al., 2014). The severity and kind of plastic blunting in the cases examined herein are not yet known.

4.3. Calculation of crack tip stresses and mesh sensitivity

We calculated crack tip stress by a fitting procedure (Figure 2) in an attempt to improve upon the use of maximum element-wise stresses. In elements with extreme stress gradients, such as those near the crack tip, small changes in sampling location cause large changes in the sampled stress value. Computation of maximum element-wise stresses uses the element centroids as sampling locations; thus, the sampling position is determined solely by the mesh geometry. This can be an unwanted source of variability. Additionally, the maximum is not a robust statistic; it only takes a single misbehaving element to distort the result. The crack tip stress obtained by fitting the stress profile corrects these disadvantages by using a specific sampling point and incorporating data from multiple elements. However, it is limited in that the stress profile must be sufficiently regular to suggest a fit. Thus, the stress profile method cannot supersede the maximum stress measure in all cases.

Note that the stress profile method is still sensitive to the element size in the mesh (Figure 8). This is because the underlying FEA solution is an approximation using a piecewise

discontinuous linear strain field. Making the elements smaller improves the approximation; however, the true crack tip stress for a sharp crack is singular. Refinement of the solution therefore cannot cause the crack tip stress to converge to a finite value.

Comparison of the crack tip stress in the present study is really a comparison of the strength of the stress concentration, and the values only have meaning in terms of their relative rank. Extreme caution should be used when comparing stress values between studies, as the meshes are unlikely to have been prepared in the same way. Development of a metric for stress concentration severity that is mesh-independent, and so can be compared between independent studies or used for prediction of in vivo failure, is a high priority for future work in biomechanics.

4.4. Limitations

This study has several limitations that should be considered when interpreting the results. The use of elastic models in this study means that damage and plastic deformation are not represented. Plasticity and damage may greatly affect the stress field in real specimens, most likely by reducing the stress concentration magnitude and spreading it over a larger region. Nonetheless, specimens with greater elastic stress concentrations should surpass the threshold for damage and plastic deformation before those with lesser elastic stress concentrations, so the elastic stress based ranking, albeit imperfect, is still useful.

Second, stress profiles could not be fit to the fiber-perpendicular and fiber shear stress fields, requiring that the fracture risk associated with these components be assessed using maximum element-wise stress. This measure is less robust than the crack tip stress fit used for the fiber-parallel stress. This lesser robustness is of greater concern when combined with severely deformed elements. Consequently, accurate maximum values for fiber-perpendicular stress and fiber shear stress could not be obtained for the 15° CCB and CCU cases (Figure 7b,c). Despite this, the crack tip stress obtained by stress profile fitting and the maximum element-wise stress had consistent trends for the fiber-parallel stress component (Figures 6 and 7a). This consistency increases our confidence in the use of maximum element-wise stress to compare the fiber-perpendicular and fiber shear stress concentrations.

Due to these limitations, we considered only the relative risk of failure modes between test configurations. Furthermore, since small differences are more likely to be artifactual or irrelevant, we interpreted only large (> 0.5 orders of magnitude) differences as meaningful.

5. Conclusion

The goal of this work was to identify test configurations that are more likely to produce crack extension in fibrocartilage than the commonly used SENT configuration. Center-cracked specimens with the crack 30° to 60° relative to the fibers were predicted to stress the fibers much more than SENT specimens, and are therefore most likely to produce crack extension by fiber rupture. However, SENT specimens produce equal or greater fiber-perpendicular and fiber shear stress compared to center crack specimens. Consequently, SENT specimens are a good choice for investigating failure by matrix rupture and fiber sliding, although care must be taken to choose a test setup in which these kinds of failure

can produce crack extension. This information will assist in choosing the most relevant loading configurations for future experimental testing of cracked fibrous soft tissues.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank Dr. Michael H. Santare for advice regarding how to quantify the FEA results.

Research reported in this publication was supported by NIAMS of the National Institutes of Health under award number R01AR050052 and NIBIB of the National Institutes of Health under award number R01EB002425. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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Figure 1.

Test configurations. Three configurations were compared: center crack biaxial (CCB), center crack uniaxial (CCU), and single edge notch (SENT). Each is illustrated here for a crack perpendicular to the fibers. The crack angle was varied in each case.

Figure 2.

Quantification of crack tip stress. (a) Stress was sampled along a line (in the reference configuration) extending from the crack tip to the edge of the mesh. (b) To find the stress at the crack tip, the stress profile was fit with an exponential function and extrapolated to 0 mm distance. This example shows the fit for the 45° CCB case with 50 μm elements.

Figure 3. Fiber-parallel stress fields. (a) 45° CCB, (b) 45° CCU, (c) 45° SENT, (d) 90° CCB, (e) 90° CCU, and (f) 90° SENT. Each panel shows a 3.2 mm tall subset of the specimen.

Figure 4.

Fiber-perpendicular stress fields. (a) 45° CCB, (b) 45° CCU, (c) 45° SENT, (d) 90° CCB, (e) 90° CCU, and (f) 90° SENT. Each panel shows a 3.2 mm tall subset of the specimen.

Figure 5.

Fiber shear stress fields. (a) 45° CCB, (b) 45° CCU, (c) 45° SENT, (d) 90° CCB, (e) 90° CCU, and (f) 90° SENT. In panels a and b, asterisks mark locations with stress magnitudes similar to the crack tip stress, yet distant from the crack tip. Each panel shows a 3.2 mm tall subset of the specimen.

Figure 6.

Fiber-parallel stress calculated by the stress profile fitting method. Center-cracked specimens with acutely angled cracks have greater fiber stress compared to edge-cracked specimens. 0° = crack parallel to fiber axis; 90° = crack perpendicular to fiber axis.

Figure 7.

Maximum element-wise stress for (a) fiber-parallel stress, (b) fiber-perpendicular stress, and (c) fiber shear stress components. For fiber stress, Figure 6 uses a more robust metric. The 15° CCB and CCU cases are excluded from panels b and c because these cases nearly inverted some elements near the crack tip (shown in Figure S3), producing spurious values for fiber-perpendicular stress and fiber shear stress. The 0° CCU case has approximately zero fiber-perpendicular stress and fiber shear stress, so it is not shown in panels b or c. 0° = crack parallel to fiber axis; 90° = crack perpendicular to fiber axis.

Figure 8.

Effect of mesh element size on crack tip fiber stress. Each panel plots data from specimens with the indicated crack-fiber angle. For all acutely oriented cracks, smaller elements caused increases in stress. Specimens with a crack-fiber angle of 90° are much less sensitive to mesh size. Since specimens with cracks 0° to the fibers have no fiber stress concentration, they are insensitive to mesh size. 0° = crack parallel to fiber axis; 90° = crack perpendicular to fiber axis.