FATIGUE PROPERTIES OF THE CELL 3D COMPOSITE STRUCTURE BY TENSION AND SHEAR

J. Had[1], M. Růžička[2*]

[1]Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic
[2]Department of Mechanics, Biomechanics and Mechatronics, Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 166 07 Praha 6, Czech Republic
*Milan.Ruzicka@fs.cvut.cz

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Abstract

An experimental investigation of fatigue properties of a novel type of composite structure is described in this paper. The 3D composite structure consists of combination of two materials for which S-N curves were measured. Comparison S-N curves of this basic material itself with final 3D composite structure was done. Fractography analysis was performed above failed samples and failure mechanisms were described.

1 Introduction

A design of composite parts with ultra-high stiffness (for example of machining centre spindle beams) leads to thick-walled reinforcing members characterized by axially oriented fibres in the direction of maximal loading-flows. However, the low shear static and fatigue strengths of these unidirectional thick structures often limit their application, [4]. This is due to the low strength of the composite matrix and the multiaxial stress state. Cracks arise at several points between the fibres (thick-walled pultruded composite flanges), or delaminations occur between the laminates (laminated composite plates). An increase in shear strength is usually produced by various 3D laminate techniques, such as 3D braiding or 3D strengthening (transversal needling). Such technologies can improve or partially eliminate delamination or matrix cracking. However, these techniques lead to a rapid decrease in stiffness in the dominant load direction. Filament fibre winding technology combined with stamping and wrapping with using both high modulus (cell core) and high strength carbon fibers (wrap) was used to manufacture a three-dimensional cell structure (3DC structure). Previous works were focused on the determination of static material properties and elastic stiffness for finite element models of material, [2], [3]. Verification of material parameters of the 3D composite was performed using tensile, compression, three point bending (3PB) quasi-static tests and Iosipescu shear test of various specimens from the Carbon/Epoxy 3D composite [5].
Composite materials are inhomogeneous and anisotropic and their behavior in fatigue is more complicated than isotropic materials. The main reasons that phenomenon is based on the different type of damage. Fatigue of isotropic material is driven by single dominant crack unlike of composites where fatigue properties is driven by different types of failures i.e. matrix cracking, fiber fracture, fiber buckling, interface failure and their interaction. Fatigue failure in composites is therefore extended to larger damage area. Monitoring of stiffness degradation was published in [6], [9]. The goal of this study was to investigate fatigue and

residual strength of 3DC structure, compare them with the classical unidirectional 1D configuration and show some failure mechanisms aspect based on the fractography analysis.

2 Materials and experimental method

2.1 3D cell structure

Filament fibre winding technology with subsequent moulding was used to manufacture a three-dimensional fibre cell structure (see Figure 1). This technology was developed by CompoTech Company Ltd, in research cooperation with the Czech Technical University in Prague [1]. The main application of these 3D structures is for thick-walled or nearly solid beams with maximum bending strength (spars, wing flanges etc.) or with high stiffness (e.g. a spindle beam for the use in a machine tool). Example of such developed spindle beam can be seen in Figure 2.

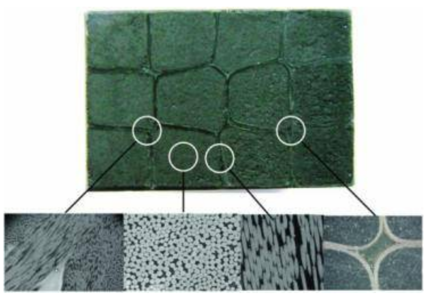

Figure 1. Details of the parts of the 3D composite structure

Figure 2. Cross section of a spindle beam based on the 3D composite structure

This bio-inspired structure in its cross section (in the y-z plane) creates sub-cells, see Figure 1. The sub-cells consist of carbon fiber tows (core) with axial orientation. The diameter of this bundle is usually between 4 and 8 mm. In the next step, another thin layer (winding) is wound around this axially oriented core. A area of core to overall cross-section is up to 75%. The winding is created in the thickness between 0.2 and 1 mm. The thickness can be optimized, as well as the orientation of the winding fibers, which can vary from 0 to 89 degrees. The prefabricated bundles are then put into the form, moulded together and subsequently cured into the final shape.

To compare 3D cell structure with unidirectional composite, both 3D composite structure and pure unidirectional composite samples were made. Two types of 3D composite structure were made for different core material. Unidirectional composite samples were done for 2 types of core's material and one type of winding's material.

The uniaxial fiber tows in core were made from the Nipon Granoc Yarn CN-80 or Mitsubishi Dialed K63712 pitch based ultra-high modulus carbon fibers. Their over-winding layer was made from the Toray T700 high-strength carbon fibers, with the orientation to the longitudinal axis in the range from 85 to 86 degrees. The matrix was the Hybtonite anhydride resin. Basic material properties are in the Table 1.

Material		E_L [GPa]	E_T [GPa]	G_{LT} [GPa]	ν_{LT} [-]
PAN	T700	235	15	50	0.30
PITCH	K63712	640	5	20	0.35
PITCH	CN-80	780	7	20	0.35
Anhydrid resin	Hybtonit	3	3	1.1	0.4

Table 1. Material data

Two types of measurement were done. Bending fatigue properties were tested in four-point bending test configuration. Shear fatigue properties were tested on Iosipescu test configuration. The dimensions of beam sample for bending test were 20 x 30 x 700 mm. Dimension of V-notched samples were according to ASTM D 5379 [7], except of thickness of sample which leads from technology and was 6mm.

2.2 Fatigue testing

Fatigue experiments of bending configuration were carried out using a standalone hydraulic actuator IST-PL40N with the 40 kN loadcell and the displacement range up to 125 mm (see Figure 3). Specimens were loaded using the 4PB loading device. The passive part has the support span of 600 mm and the loading part with the span of 200 mm. The specimens were loaded by force controlled load with the frequency of 5 Hz until the final fracture. The loading level was derived from the preceding quasi-static 4PB test and fatigue properties were measured in range of 65% to 85% of static strength. Four acoustic emission sensors were attached on sample to oobserve increase of damage.

Figure 3. Four-point bending (4PB) test configuration.

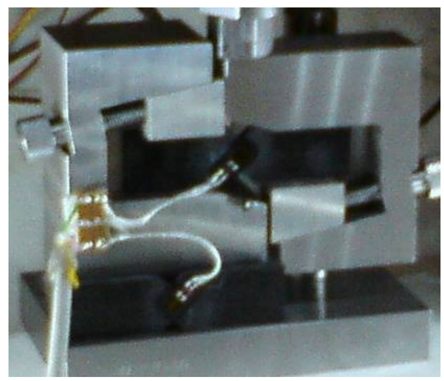

Figure 4. Iosipescu shear test configuration.

Shear test was carried out on hydraulic machine Inova ZUS 200 (displacement range ±50mm), where Iosipescu shear test fixture from Wyoming Test Fixtures Company was installed. Loading level was set in range 50%-75% of static strength. Load controlled test was done with frequency of 1Hz. Measured samples were mounted only with one piece of strain gauge (HBM 1-LY11-6/350) because of limited place option. Interested area of pure shear is concentrated in line between V-notches.

2.2 Residual testing

Residual strength were investigated on the bending specimens having reached more than 10^6 loading cycles (near of the fatigue limit range) without substantive decreasing of stiffness or increasing acoustic emission signal. Stress level of fatigue loading for testing residual strength was set up to 70% of static strength. Residual strength haven't been tested on shear samples yet.

3 Results and discussion

3.1 Mechanical properties

Two basic material combinations of the 3D structures (core CN80/ winding T700 and core K63712/ winding - T700) were compared with the equivalent specimen made without cells structure and containing unidirectional fibre tows only (1D structure). The samples from three material types (T700, K63712 and CN80 were produced.

The flexural yield strength is referred as a static or residual strength actually and it is calculated at certain point of loading path, at which the load does not increase with an increase in deflection according to ASTM D6272, [8].
Comparing static and residual strengths in Figure 5. and 6. it is clearly evident that fatigue degradation has no effect on residual strength of 1D as well as of 3D structure.

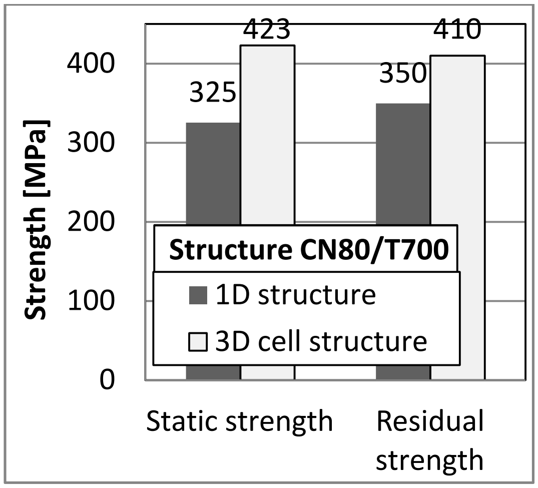

Figure 5. Comparison static and residual strength of 3D structure (CN80/T700) with 1D structure CN80.

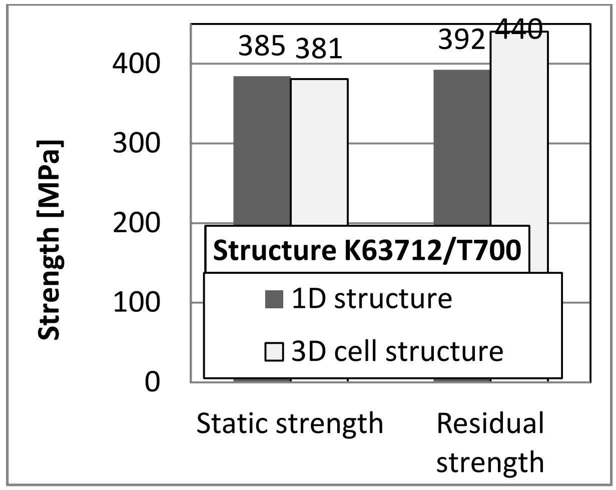

Figure 6. Comparison static and residual strength of 3D structure (K63712/T700) with 1D structure K63712.

The 3D cell structure has higher static strength as the unidirectional 1D configuration, significantly for CN80/T700 cell fibre combination. Similar trends can be observed on fatigue properties on S-N curves, see Figure 7.

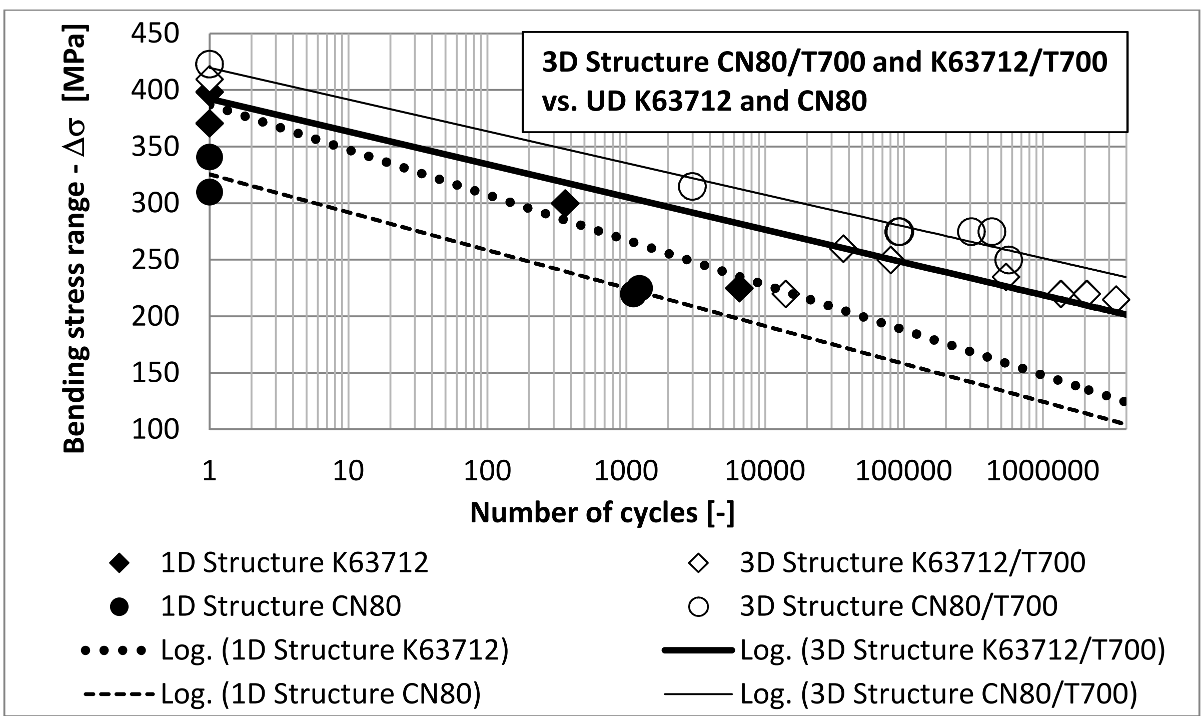

Figure 7. Comparison of the fatigue properties of the hybrid 3D cell structures CN80/T700 and K63712/T700 with equivalent 1D structure CN80 and K63712.

The static shear strength refers in fatigue loading is asses according to ASTM D5379 at point where significant change from linear slope can be indicated. Up to this point no drop of load at any sample didn't observed. ASTM standard provides also description of acceptable and unacceptable failure modes. It has to be noted that unidirectional composite samples failed at acceptable failure mode according to Figure 8. On the other hand 3D cell structure's failure mode has to be treated as unacceptable failure, see Figure 9. Maximum strength calculated in this way is probably lower than real strength because of damage is spread into a larger area.

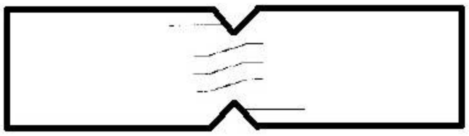

Figure 8. Acceptable failure mode of unidirectional sample.

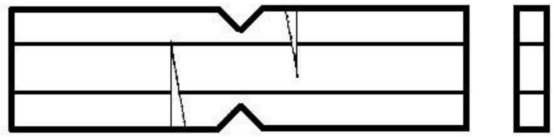

Figure 9. Unacceptable failure mode of 3D structure sample.

Comparison of fatigue life of 3D composite structure with unidirectional (labeled 1D structure) is on Figure 10. There is just a slight difference in fatigue resistance of 3D structure over a unidirectional sample.

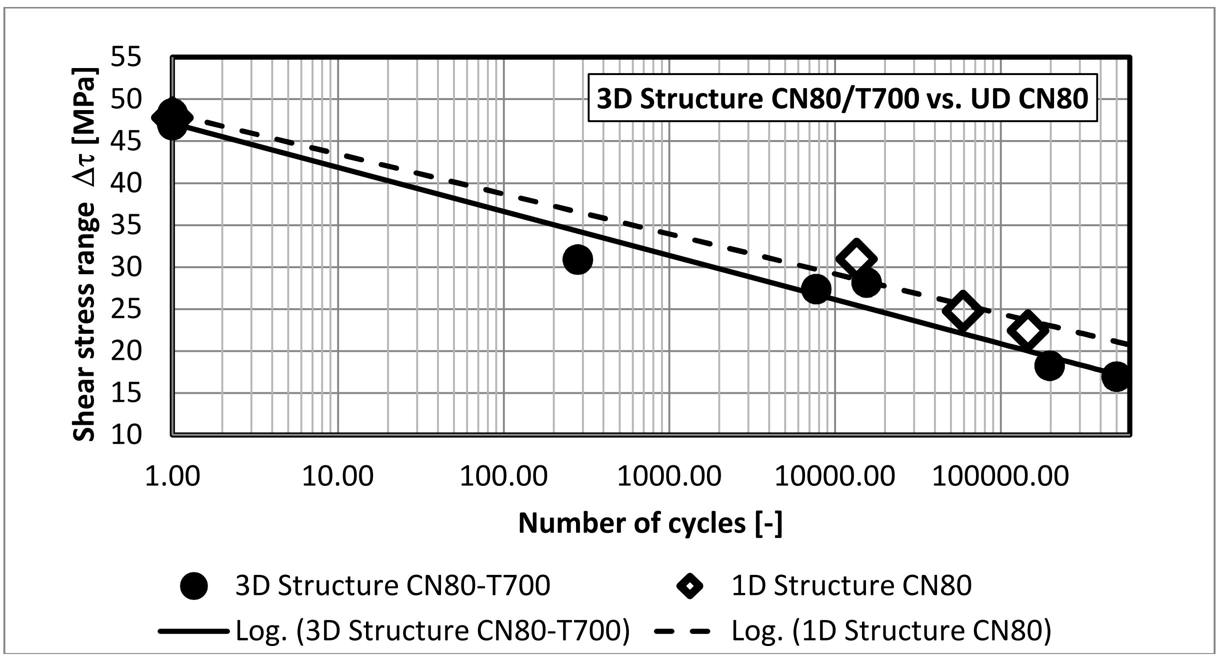

Figure 10. Comparison of the fatigue properties of the hybrid 3D cell structures CN80/T700 and equivalent 1D structure CN80.

3.2 Fractography analysis

The fractography analysis has been done only on specimens tested on bending so far and the aim was to determine causes of final rapture and sources of stiffness degradation.

The four point bending test configuration can be divided in two main domains, area between loading forces and area between force and support. Each area has unique stress condition. According to classical beam theory, there is domain with uniform normal stress (without shear) and combination shear and normal stress for area between force and support.

Failed specimens were cut in each of these two areas and observed on any failure. According to general assumption on composites no dominant crack causing final rapture was revealed in both areas. Based on scanning electron microscope failure mechanisms were observed only in very near place of rapture area.

For the 3D cell structure is typical larger compressive failure area over the tensile fracture area, see Figure 11. More evident this fact can be seen in the case of unidirectional composite, see Figure 12.

Figure 11. Failure area of the sample K63712/T700. Red rectangle pointing out compressive and tensile failure mode

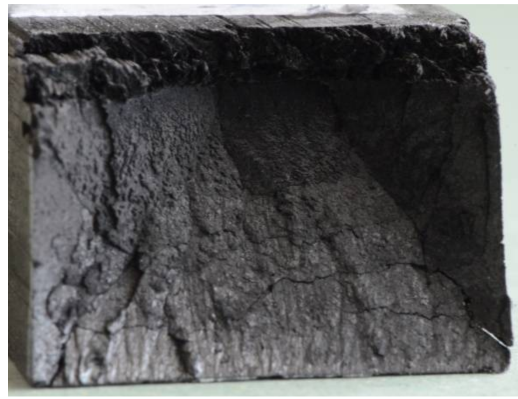

Figure 12. Failure area of the sample from high modulus fiber K63712

Winding layers are splitting whole area into series of smaller domain. In the case of forming crack, the crack is stopped at the domain boundary, which caused important improvement of fatigue properties. This advantage is more evident in transversal tensile loading, see Figure 13.

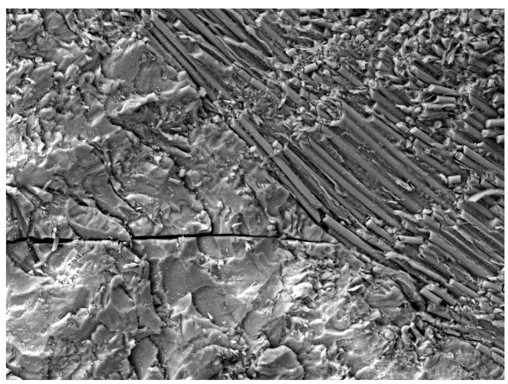

Figure 13. Growing crack inside of core to winding boundary of the sample K63712/T700

Looking at the fatigue, failure mode depends on stress level whether specimen is loaded near to static strength (see Figure 14) or far from that. In the case of in static strength loading fibres are failed along their phase “plane” according to producing technology of PITCH fibres, see Figure 15.

Figure 14. Failure area resulting from measuring of static strength

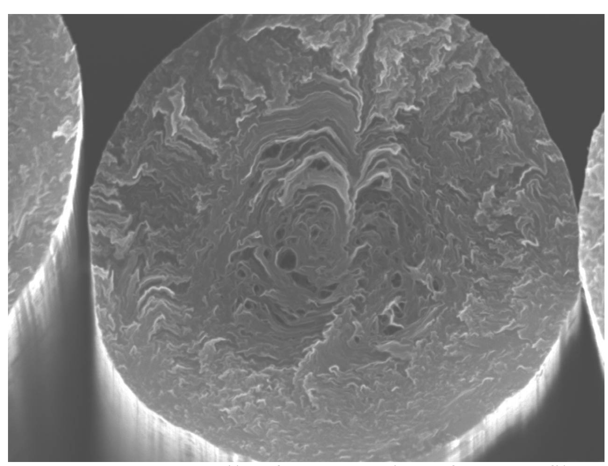

Figure 15. Details of cross-section of PITCH fibre CN-80

Despite static fracture, fatigue area looks differently driven by another mechanism. Decreasing the load level different failure types are arising. In outer compressive section individual fibres are breaking and free failed surface is smoothing each other. Raising this smooth area products very fine fracture area. This behavior is more evident for the sample with very long fatigue life in order 10^5 cycles, see Figure 16.

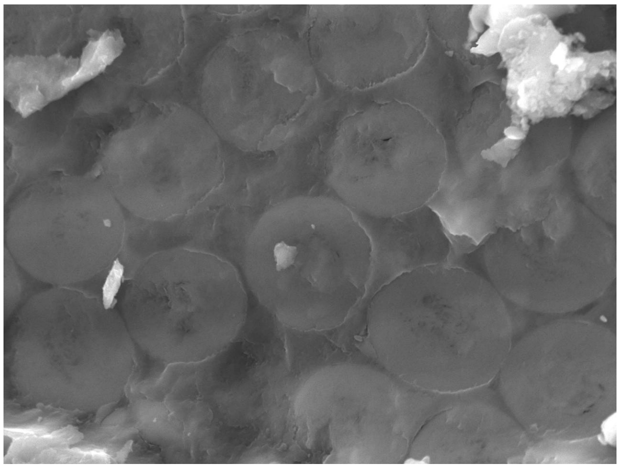

Figure 16. Detail of smoothed fibres. Sample of 3D structure CN-80/T700. Number of cycles N=5*10^5cycles

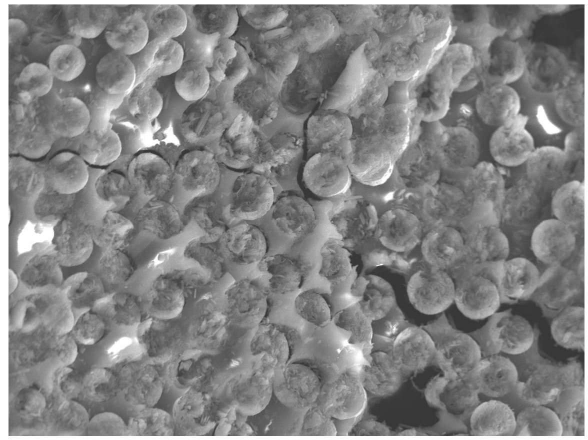

Figure 17. Detail of failed interface fibre-matrix. Sample of 3D structure CN-80/T700. Number of cycles N=2*10^3 cycles

In the area more closer to edge with tensile failure mode transversal failure is more evident and failure of interface between fibre and matrix is going to be the weakest mechanism. Especially in the case of lower fatigue life, single small cracks in interface can be linked into a large crack, see Figure 17.

4 Conclusion

Measured fatigue properties get fundament knowledge about 3D hybrid composite and get basic introduction into microanalysis. Comparing of S-N curves get advantages of 3D composite over unidirectional composite.

Better bending fatigue properties of 3D cell structure over a unidirectional core composite were demonstrated in S-N curves. Comparing both types of 3D structure, CN-80/T700 has a higher fatigue resistance over a K63712/T700 sample. Shear fatigue properties of 3D composite were almost the same. However, because of unacceptable failure mode of 3D composite sample a real higher fatigue strength are expected.

Fatigue loading didn't affect residual strength comparing to static strength on the basis N=10^6 cycles and load level 70% of static strength.

Fractography analysis has shown one of the reasons of better fatigue properties than unidirectional. Dividing cross-section into smaller domain, crack is stopped on the layer boundary. Causes of cracks initiators or stiffness degradation reasons unfortunately wasen't proved satisfactory, however the fracture areas of static and fatigue loading were distinguished. Failure of interface between fibres and matrix can be possible explanation of gradual stiffness degradation. Proving this statement is future work in which series of samples has to be measured, where samples will be prepared for SEM in different state of life. Growing density of crack in fibre-matrix interface will be observed.

Fractography on shear samples is also future work.

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