

FROM FAILURE TO FRACTURE: FIELD MEASUREMENTS OF STRENGTH AND FRACTURE TOUGHNESS OF BURIED SURFACE HOAR UNDER MIXED-MODE LOADING

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ABSTRACT: Dry-snow slab avalanche release involves failure initiation in a weak layer followed by crack propagation. Weak layer strength describes resistance to failure initiation, whereas fracture toughness describes resistance to crack propagation. Because avalanche release occurs on inclined terrain, both processes generally involve mixed-mode compression and shear loading. Weak layers are known to be weaker in shear than in compression, while recent mixed-mode fracture measurements suggest that fracture toughness may show the opposite trend. Here, we combine two field methods to characterize multiaxial strength and mixed-mode fracture toughness for the same buried surface hoar weak layer. A mobile shear–compression unit (MSCU) was used for strength measurements, and a portable mixed-mode fracture test (MMFT) was used to characterize fracture toughness. For the weak layer investigated here, strength was higher in compression than in shear, whereas fracture toughness was higher in shear loading (mode II) than in compression-dominated loading (closing mode I). These contrasting responses highlight the importance of considering failure initiation and crack propagation separately when characterizing weak layer mechanical behaviour.

KEYWORDS: Weak layers, mixed-mode fracture toughness, multiaxial strength, field experiments, snow mechanics

1. INTRODUCTION

Dry-snow slab avalanche release involves failure initiation in a weak layer followed by crack propagation through the snowpack (Schweizer et al. 2008). These two processes involve different aspects of weak layer mechanical behaviour. Strength describes the stress required to initiate failure, whereas fracture toughness describes the resistance to crack propagation. Because avalanche release generally occurs on inclined terrain, the weak layer is subjected to a combination of compression and shear (Heierli et al. 2008; Gaume et al. 2015; Rosendahl and Weißgraeber 2020). Both strength and fracture toughness therefore need to be characterized under mixed-mode loading conditions.

Weak layer strength is known to depend strongly on loading mode. Early field measurements focused mostly on shear strength (Perla et al. 1982; Jamieson and Johnston 1999; Jamieson and Schweizer 2000), while more recent laboratory experiments and numerical studies have characterized weak layer strength under multiaxial load-

ing (Reiweger and Schweizer 2010; Reiweger et al. 2015; Chandel et al. 2015; Schöttner et al. 2026a). These studies show that weak snow layers are generally weaker in shear than in compression. Field measurements of multiaxial strength, however, remain scarce.

Much less is known about the dependence of fracture toughness on loading mode. Fracture toughness is commonly inferred from propagation saw tests (PSTs) (Sigrist and Schweizer 2007; van Herwijnen et al. 2016). As most PSTs are performed on level terrain, the mode II contribution remains small. To investigate mixed-mode fracture, Adam et al. (2024) developed the mixed-mode fracture test (MMFT), in which a PST is tilted and loaded to increase the mode II contribution. Their measurements on buried surface hoar showed that fracture toughness was higher under shear-dominated than under compression-dominated loading. Interestingly, this trend is opposite to that observed for weak layer strength.

However, mixed-mode strength and fracture toughness have so far been measured in separate experiments and on different weak layers. It therefore remains unclear whether their contrasting dependence on loading mode reflects differences between weak layers or a more general difference between resistance to failure initiation

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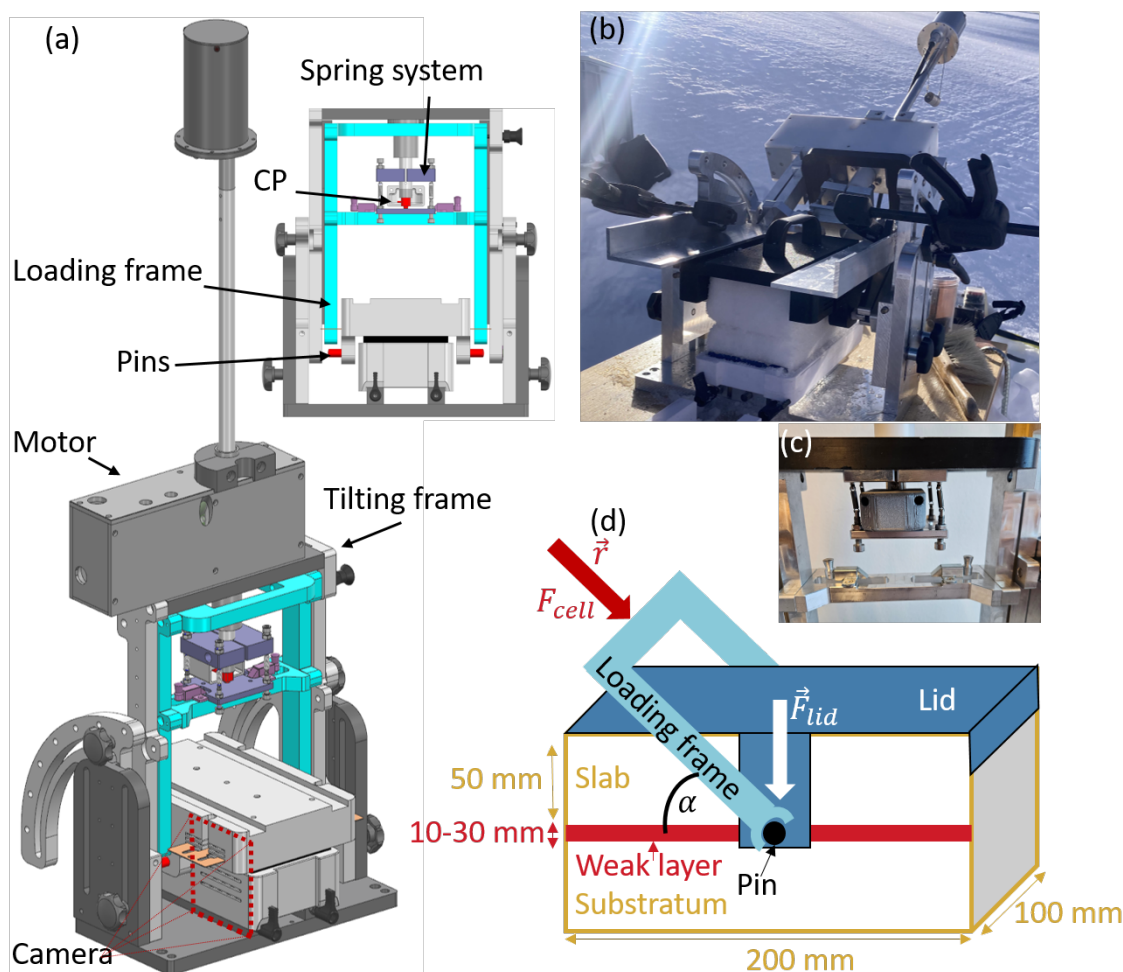


Figure 1: (a) Schematic overview of the MSCU, with the spring system highlighted in purple. The red point inside the spring system is the contact point (CP) of the motor unit to the lower plate of the spring system, which is part of the loading frame (in turquoise). The pins of the lid, on which the loading frame applies force, are also highlighted in red. The camera view is presented by the dotted red square. (b) Picture of the MSCU in use in the field, with additional stabilizers and clamps used for loading angles $\alpha \leq 30^\circ$. (c) Close-up of the spring system, which is mounted around the rod of the motor unit. Here, the loading frame is not yet connected to the spring system. (d) Schematic overview of the sample with the lid and the tilting frame. The load cell moves down on the tilting frame, which pushes around the pins under various loading configurations from $\alpha = 0^\circ$ (shear) to $\alpha = 90^\circ$ (compression). The lid creates an additional vertical force F_{lid} on the sample.

and resistance to crack propagation.

Here, we combine two field methods to measure both properties for the same buried surface hoar weak layer. We use a custom mobile shear-compression unit (MSCU) to characterize weak layer strength from shear- to compression-dominated loading and an improved portable MMFT to characterize fracture toughness over a range of mode mixities. By comparing the relative dependence of strength and fracture toughness on loading mode, we investigate whether resistance to failure initiation and crack propagation follow the same trend under mixed-mode loading.

2. FIELD EXPERIMENTS

2.1. Multiaxial strength measurements (MSCU)

We conducted multiaxial failure tests in the field using a custom-designed mobile shear-compression unit (MSCU; Figure 1) that loads snow samples at an adjustable angle α between 0° (shear-dominated, parallel to the weak layer) and 90° (compression-dominated, perpendicular to the weak layer). The MSCU uses a linear actuator adapted from the SnowMicroPen (SMP5) (SLF 2025) with a calibrated piezoelectric load cell (Kistler 9313AA1, series 643364).

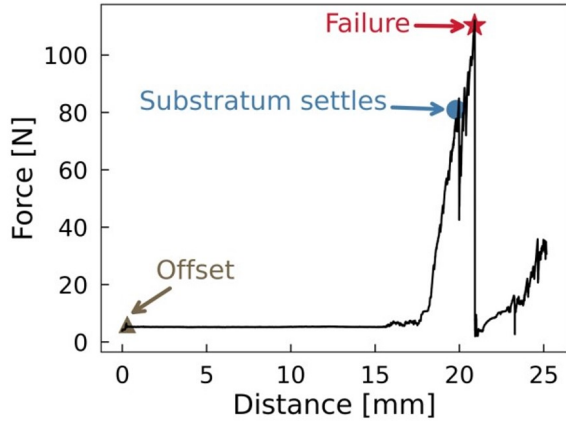


Figure 2: Exemplary force signal versus the distance covered by the loading frame, as measured during the strength tests. Indicated are the offset (brown triangle) caused by the first contact between the loading frame and the sample, substrate settling (blue circle) and weak layer failure (red star).

Snow samples ($10 \times 20 \times 8$ – 10 cm) were cut from the pit wall with the weak layer centered between a ~ 5 cm cohesive slab and a supporting substratum (Figure 1d). Samples were kept in the shade and tested within 5 min of extraction. The load was applied in displacement control and transmitted through a rigid loading frame via pins at the height of the weak layer. Force and displacement were recorded throughout each experiment. Samples were sprayed with black ink and filmed to identify outlier experiments and derive effective strain rates in the weak layer during loading.

From the strength experiments, we used the peak of the force-displacement signal (Figure 2), corresponding to weak layer failure, and decomposed it into shear and compressive components acting on the weak layer:

$$\begin{aligned} \tau &= \frac{(F_{\text{cell}} - F_{\text{offset}}) \cos(\alpha)}{A}, \\ \sigma &= \frac{(F_{\text{cell}} - F_{\text{offset}}) \sin(\alpha) + F_{\text{lid}}^v}{A}, \end{aligned} \quad (1)$$

where α is the loading angle, F_{cell} denotes the force measured by the load cell, and F_{offset} is a constant force offset present prior to loading of the snow sample. The parameter A is the area of the sample ($A = 0.02 \text{ m}^2$). F_{lid}^v is the additional normal force resulting from the dead weight of the lid. We then fitted an empirical power law to the strength values in τ – σ space to obtain the failure envelope and the corresponding shear and compressive strength values.

2.2. Mixed-mode fracture measurements (MMFT)

Mixed-mode fracture tests (MMFTs) were performed as described by Adam et al. (2024). The MMFT is a propagation saw test (PST) tilted to steep angles and loaded with dead weights to increase the mode II energy release rate contribution (Figure 3).

Snow samples ($100 \times 30 \times 15$ – 10 cm) were cut from the snowpack, loaded onto a sledge and placed on the tilting device. Samples were tilted between 0 and 65 degrees (Figure 3b). The slab height was reduced, and weights were added on top (Figure 3c). We cut either from above (downslope) or from below (upslope) in the weak layer until reaching the critical cut length, at which the crack started to self-propagate, and the slab slid down (Figure 3e,f). Samples were sprayed with black ink and filmed to verify the critical cut length, identify outliers, and enable digital image correlation.

We used the critical cut lengths, slab densities and experiment-dependent values (tilt angle, slab length, slab height and dead weights) as input for the analytical layered first-order shear deformation theory beam model WEAC (Weißgraeber and Rosendahl 2023) to compute the critical energy release rates in mode I ($\mathcal{G}_I$) and mode II ($\mathcal{G}_{II}$). Effective elastic properties of the slab and weak layer are also required. We used a weak layer modulus of 0.3 MPa and $\gamma = 4.5$ as density parametrisation exponent for slab elasticities following Gerling et al. (2017). We then fitted an empirical power law in $\mathcal{G}_{II}$ – $\mathcal{G}_I$ space to obtain the fracture envelope and the corresponding fracture toughness values $\mathcal{G}_{Ic}$ and $\mathcal{G}_{IIc}$.

3. RESULTS AND DISCUSSION

3.1. Field site and weak layer

We performed the experiments on a 10 mm thick layer of buried surface hoar at Steintälli, above Davos (2443 m a.s.l.). The weak layer was buried approximately 40 cm below the snow surface beneath a predominantly faceted slab. Snowpack properties were characterized using snow profiles following Fierz et al. (2009), and slab densities were measured with a cylindrical density cutter (diameter 3 cm). To limit the influence of spatial variability, the multiaxial strength and mixed-mode fracture experiments were performed close to each other and within a short time period.

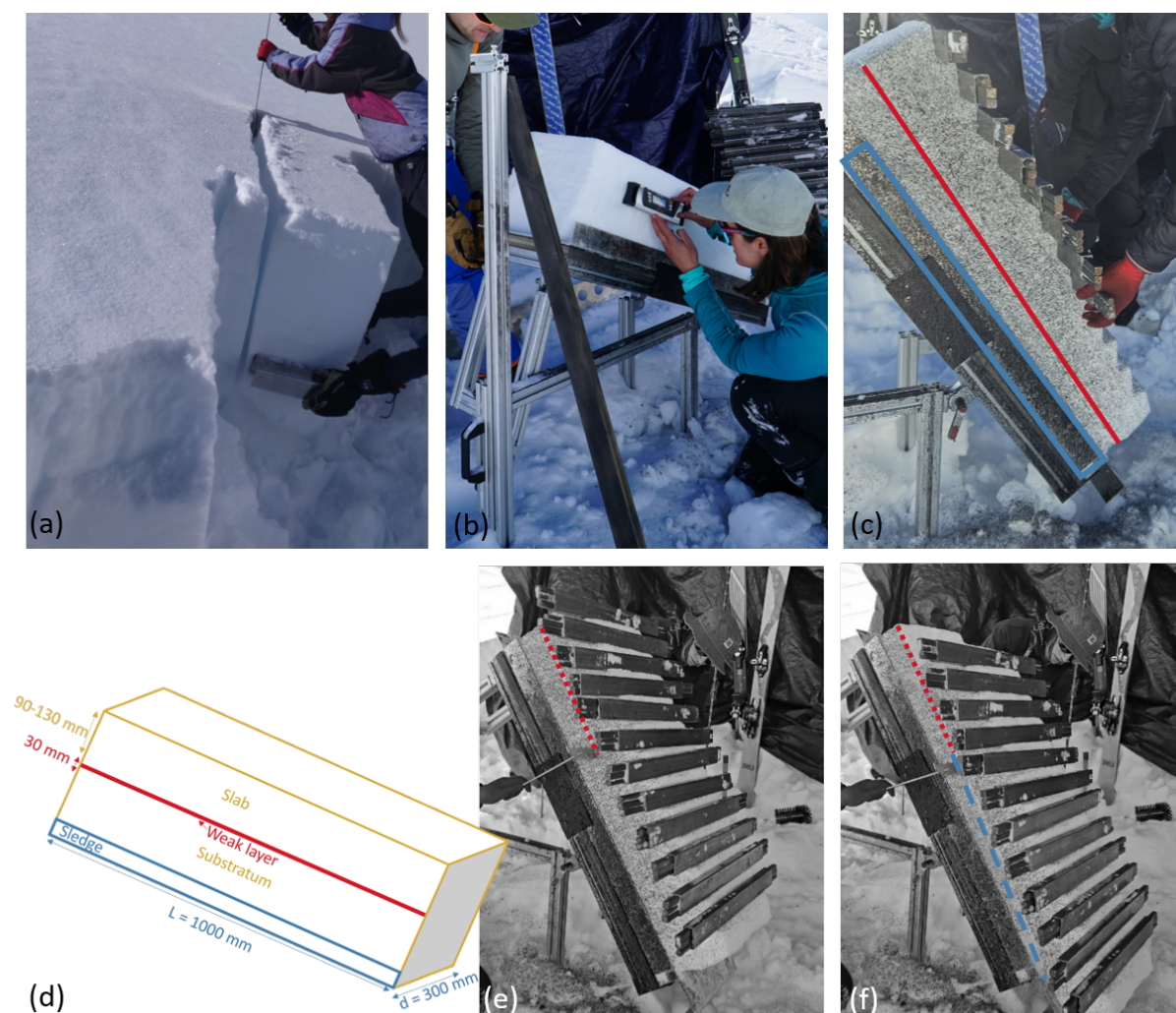


Figure 3: (a) A sample for the MMFT is extracted using a sledge and a saw, and (b) tilted to the desired tilt angle before (c) we spray the sample and add dead weights. Here, the weak layer is highlighted in red and the sledge in blue. (d) shows a schematic overview of the sample dimensions. We cut into the weak layer until we reach a critical cut length (red dotted line in (e)), after which the crack propagates (blue line in (g)).

3.2. *Multiaxial strength measurements*

We performed 88 multiaxial strength tests over six days, of which 75 were retained for analysis. Tests covered loading angles from shear- to compression-dominated conditions. The MSCU generally performed well under field conditions and allowed controlled loading over the full range of loading angles. Experiments were discarded when the sample fractured before weak layer failure or when the force signal did not show a clear peak associated with weak layer failure.

Measured strength generally increased with loading angle from shear- to compression-dominated loading (Figure 4). The measurements also showed substantial scatter, as expected for field measurements on a natural weak layer.

The fitted apparent strength was higher in compression than in shear ($\Sigma = 5.0 \pm 0.3 \text{ kPa}$ versus $3.5 \pm 0.2 \text{ kPa}$), corresponding to a shear-to-compression ratio of 0.7.

Compared with laboratory measurements by Schöttner et al. (2026a) on buried surface hoar from another location ($\sigma = 7.8 \text{ kPa}$, $\tau = 2.2 \text{ kPa}$, shear-to-compression ratio 0.28), our compressive strength was smaller and our shear strength larger. This variation may reflect differences in weak layer microstructure as well as differences between field and laboratory testing conditions.

An important limitation of the MSCU is compliance of the loading system. Video recordings showed that the weak layer was not loaded in perfect displacement control because the slab and substra-

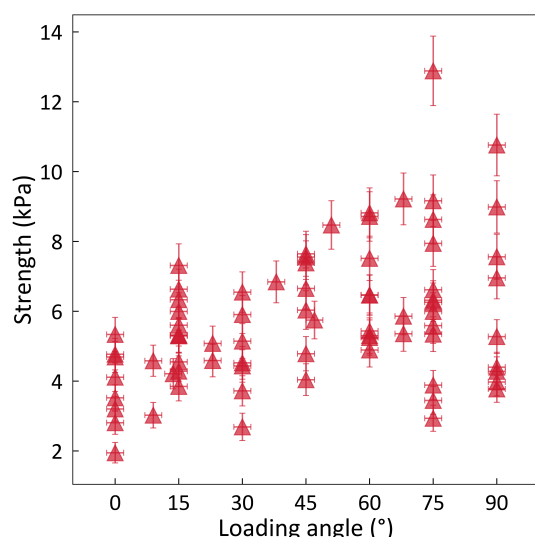


Figure 4: Measured weak layer strength as a function of MSCU loading angle. Small loading angles correspond to shear-dominated loading and large loading angles to compression-dominated loading.

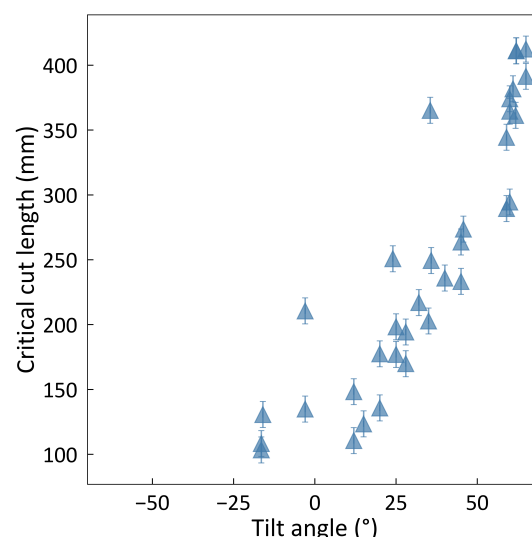


Figure 5: Measured critical cut length, verified with video recordings, as a function of tilt angle in the MMFT. Positive angles are downslope cuts, negative angles are upslope cuts.

tum surrounding the weak layer also deform. The measured values should therefore be interpreted as apparent strengths rather than absolute material values.

3.3. Mixed-mode fracture measurements

We performed 45 mixed-mode fracture tests over five days, of which 34 were retained for analysis. The portable MMFT generally performed well in the field and remained mechanically stable even at steep tilt angles. Experiments were discarded when cutting was not performed cleanly or when the critical cut length could not be determined reliably.

The measured critical cut length increased with increasing tilt angle, in line with Adam et al. (2024) (Figure 5). Critical cut length is closely related to fracture toughness but should not itself be interpreted as a material property; it is a system response that depends on experimental geometry, including cutting direction and slab layering.

Using the measured critical cut lengths together with the experimental geometry and elastic parameterization in WEAC resulted in a fitted fracture toughness of $0.412 \pm 0.042 \text{ J m}^{-2}$ in mode I and $0.551 \pm 0.069 \text{ J m}^{-2}$ in mode II, corresponding to a mode II/mode I ratio of 1.3.

Adam et al. (2024) reported $0.56 \pm 0.02 \text{ J m}^{-2}$ in mode I and $0.79 \pm 0.04 \text{ J m}^{-2}$ in mode II for another buried surface hoar layer. Their ratio of 1.4 is

similar to ours, although our absolute values are about 25 to 30% smaller.

The derived fracture toughness depends on the assumed elastic properties of the slab and weak layer. Different elastic parameterizations therefore change the absolute toughness values.

3.4. Comparison of failure and fracture envelopes

Despite being measured on the same weak layer, strength and fracture toughness showed opposite responses to loading mode. Weak layer strength decreased from compression- to shear-dominated loading, whereas fracture toughness increased from mode I to mode II loading.

Normalized by their respective compression-dominated values, the fitted envelopes show opposite trends: the shear strength was approximately 70% of the compressive strength, whereas the mode II fracture toughness was approximately 130% of the mode I toughness. For the buried surface hoar investigated here, shear-dominated loading thus facilitated failure initiation but increased resistance to crack propagation.

4. CONCLUSIONS AND OUTLOOK

We combined two field methods to characterize the mixed-mode strength and fracture toughness of the same buried surface hoar weak layer. The two properties showed contrasting depen-

dence on loading mode: strength decreased from compression- to shear-dominated loading, whereas fracture toughness increased from mode I to mode II. Thus, for the weak layer investigated here, shear-dominated loading facilitated failure initiation but increased resistance to crack propagation.

These results highlight the importance of considering failure initiation and crack propagation separately when characterizing weak layer mechanical behaviour. Measurements on additional weak layers are needed to determine whether this contrasting mode dependence is systematic and how it relates to weak layer microstructure, similar to the laboratory work by Schöttner et al. (2026b). The paired measurements can also provide consistent mechanical constraints for process-based avalanche release models.

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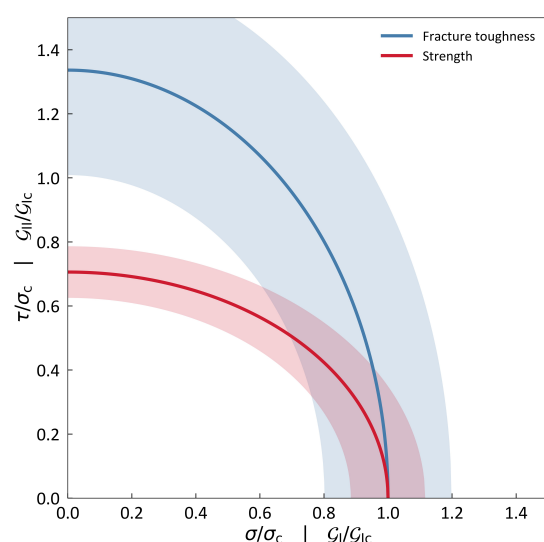


Figure 6: Normalized fitted weak layer strength and fracture toughness envelopes as a function of loading mode. Strength is normalized by the compression-dominated strength and fracture toughness by the mode I⁻ toughness. The bands represent the 95% confidence intervals.

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