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On the elastic-wave imaging & interfacial characterization of heterogeneous fractures

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Abstract

An experimental investigation is pursued to: i) verify a recently proposed inverse approach [3] for **simultaneous** reconstruction of fracture geometry and characterization of its interfacial condition at low and high frequency regimes, and ii) better understand the nature of the contact condition in pre-existing, and evolving, fractures in quasi-brittle materials. To this end, slab-like laboratory specimens of granite, Fig.1, are: a) induced with fractures, b) subjected to suitable static stress, and c) excited by 20 kHz ultrasonic waves, while monitoring the induced (in-plane) particle velocity over a high density of scanning grid via a Scanning Laser Doppler Vibrometer (**SLDV**). The SLDV data are then used to reconstruct the full displacement, and thus, stress fields over the measurement surface. Accordingly, one can compute i) the fracture opening displacement, **FOD**, and ii) tractions applied to the fracture surface, enabling point-wise computation of their correlation, and its **evolution in time**, which can be translated in terms of **heterogeneous** normal k_n and tangential k_s interfacial stiffnesses.

Motivation

Identification of the spatial distribution and temporal variation of k_s and k_n has recently come under the spotlight [2] owing to: i) its potential role as an **early indicator** of interfacial instability and failure, and ii) its relevance to deciphering the mechanism of **shallow earthquakes**. In hydraulic fracturing, imaging k_s/k_n in the fracking process is the subject of mounting attention [1,4] due to its potential application in: i) imaging the **proppant injection process**, ii) discriminating between newly created, old, and proppant-filled fractures, and iii) monitoring the **evolution of hydraulic conductivity** of an induced fracture network and thus assessing the success of stimulation strategies.

Methodology & Recent developments

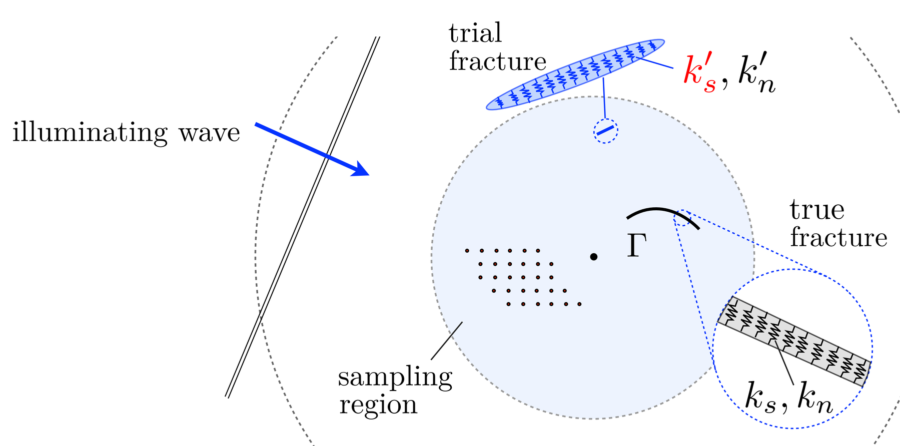

Fig.1 : Sensing configuration.

The concept of **topological sensitivity** (TS) is extended [3] to enable **simultaneous** 3D reconstruction and interfacial characterization of fractures by way of elastic waves. Interactions between the fracture faces, due to e.g. asperities, fluid, or proppant, are described via the Schoenberg's linear slip model with the contact parameters k_s and k_n, Fig.1. The proposed TS sensing platform entails point-wise interrogation of the subsurface volume by infinitesimal fissures endowed with interfacial stiffness k_s' and k_n'. Simulations demonstrate, Fig.2, 3 and 4, that **irrespective of the true contact condition** at a hidden fracture surface, the TS is capable of **non-iterative** reconstruction of its geometry. Given such geometrical information, it is further shown via asymptotic analysis that by certain choices of k_s' and k_n', the ratio k_s/k_n along the surface of a nearly-planar (finite) fracture can be qualitatively identified at virtually no surcharge.

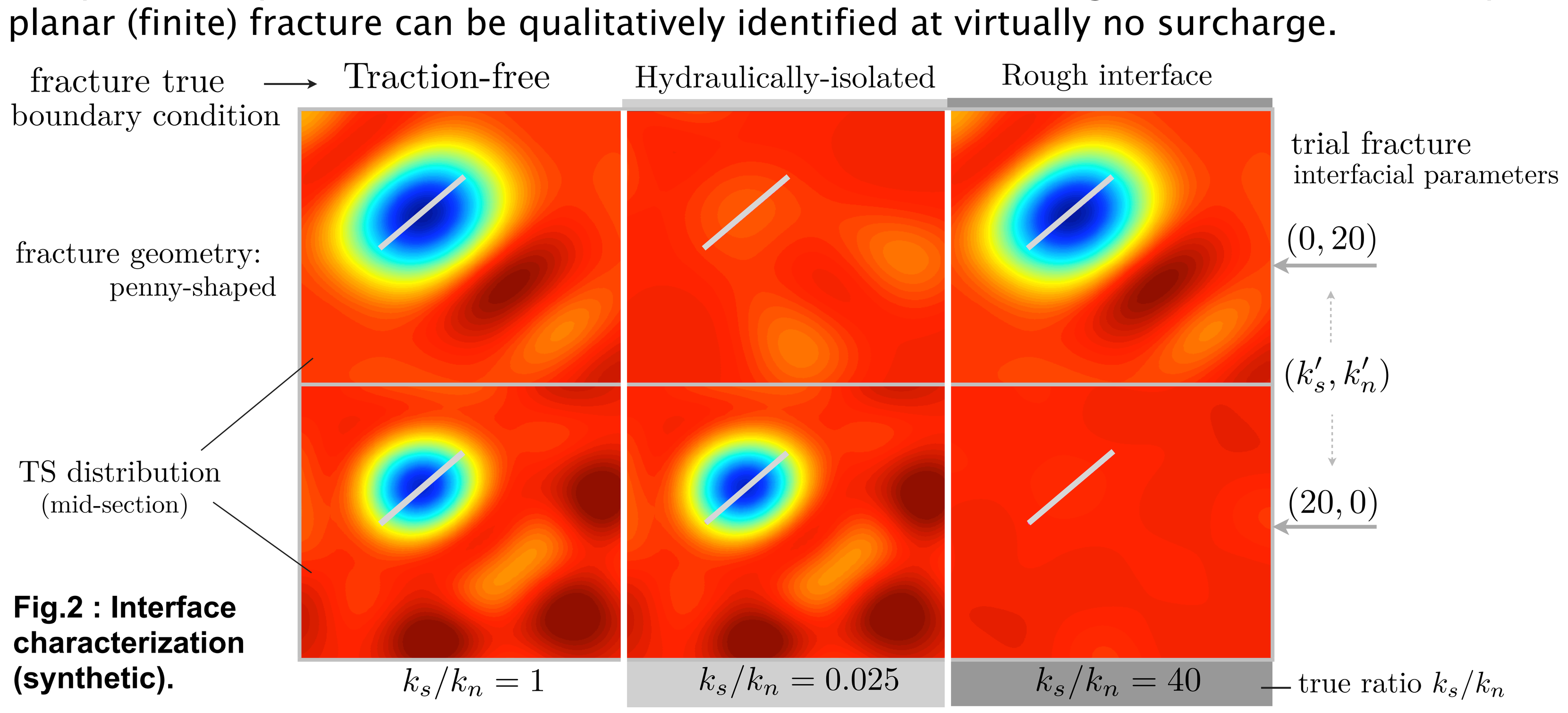

Fig.2 : Interface characterization (synthetic).

Synthetic results

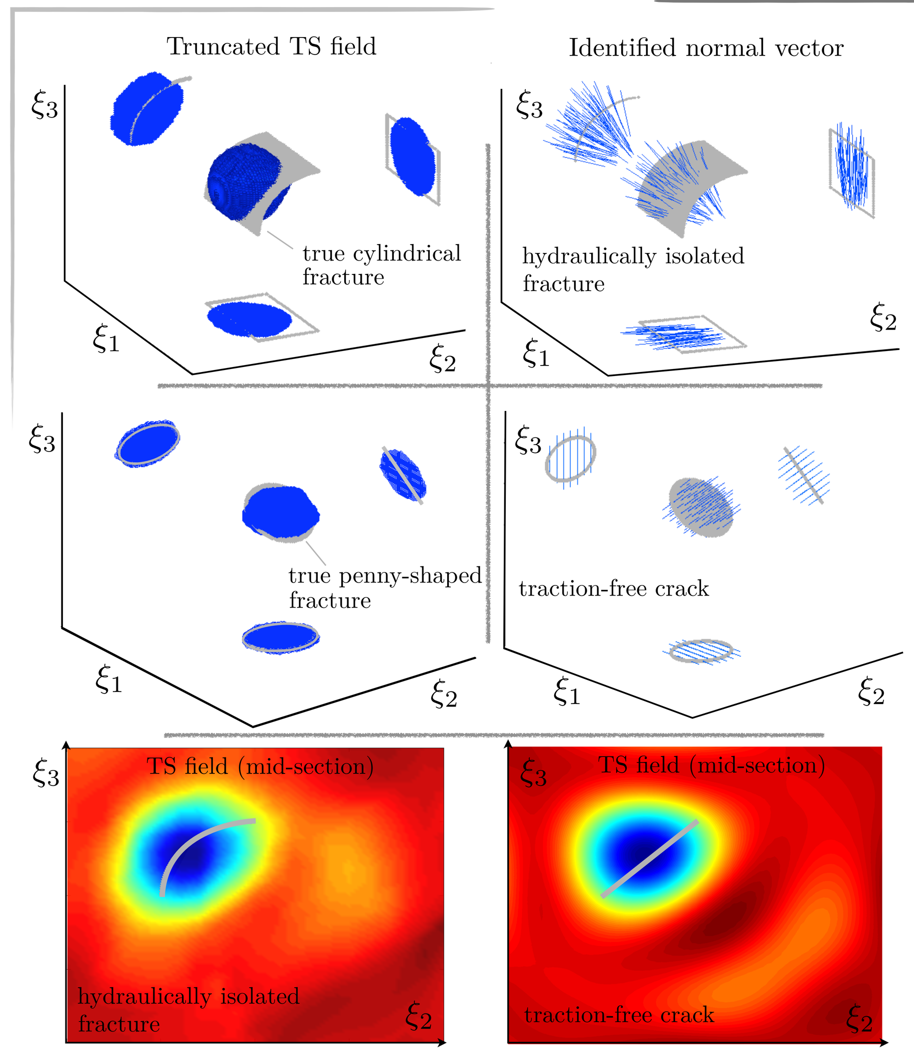

Fig.3 : 3D TS reconstruction at low frequencies

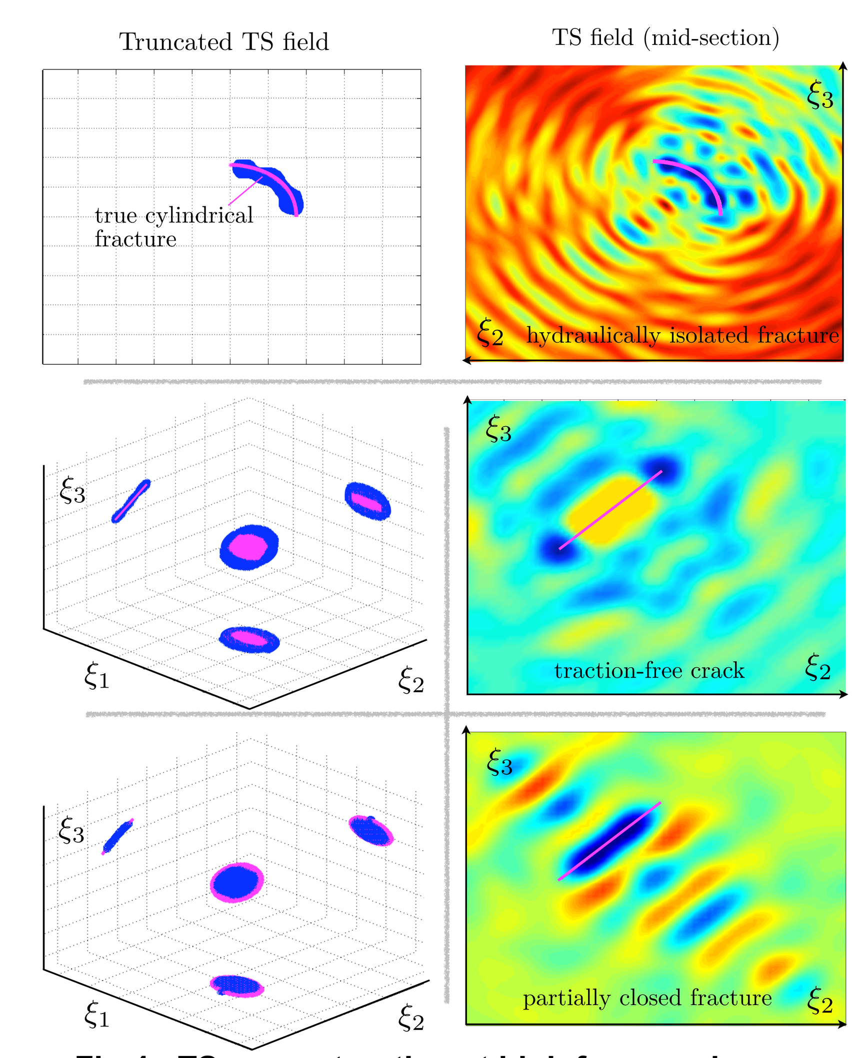

Fig.4 : TS reconstruction at high frequencies

Experimental Platform

Two sensing configurations, shown in Fig.5, are designed as the following; 1) a **through-fracture** is induced in a granite slab via three-point bending (3PB) in an MTS load frame; the pieces are then reconnected by applying a normal force to the opposite sides of a specimen – top left panel of Fig.5. The 3PB fracturing of specimens is done with the aid of an asymmetric notch to create a **non-planar fracture**, and thus induce a spatial variation of interfacial stiffness under uniaxial compression due to **uneven normal stress** on the fracture. The prepared sample is then used as a testbed, elastic waves are generated externally by an ultrasonic transducer, while scanning the induced surface motion via SLDV – bottom left panel of Fig.5; 2) an effort is made to reconstruct and characterize **evolving fractures** in rock – top right panel of Fig.5. This is accomplished by fracturing the specimen in a 3PB setup and sensing the fracture surface periodically during the loading process. The 3PB testing with an eccentric notch gives rise to **mixed-mode loading** and the creation of an advancing fracture behind a cohesive zone. In the approach, the crack initiation and propagation is controlled by a closed-loop, servo-hydraulic system with crack mouth opening displacement (CMOD) as the feedback signal. The granite samples (in both set-ups) have the target dimensions of 0.9 m × 0.3 m × 0.03 m. The tests are performed in the 1000kN MTS load frame which has 1m clearance between columns, providing an unimpeded SLDV vantage of the entire specimen. The target SLDV scan is performed at approximately 70% of the maximum stress (in post-peak) while the CMOD is held constant.

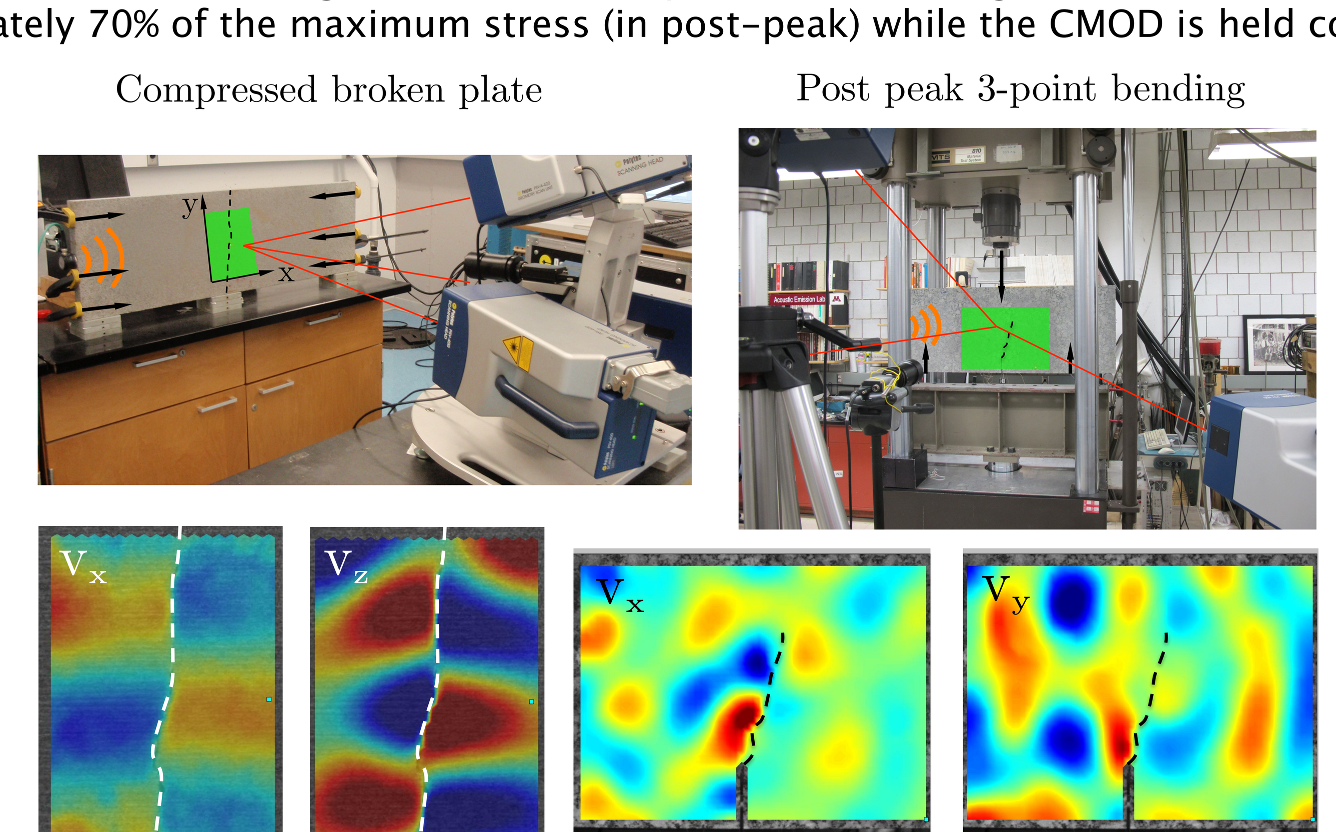

Fig.5 : Experimental set-ups for imaging stationary and evolving fractures.

Preliminary experimental results

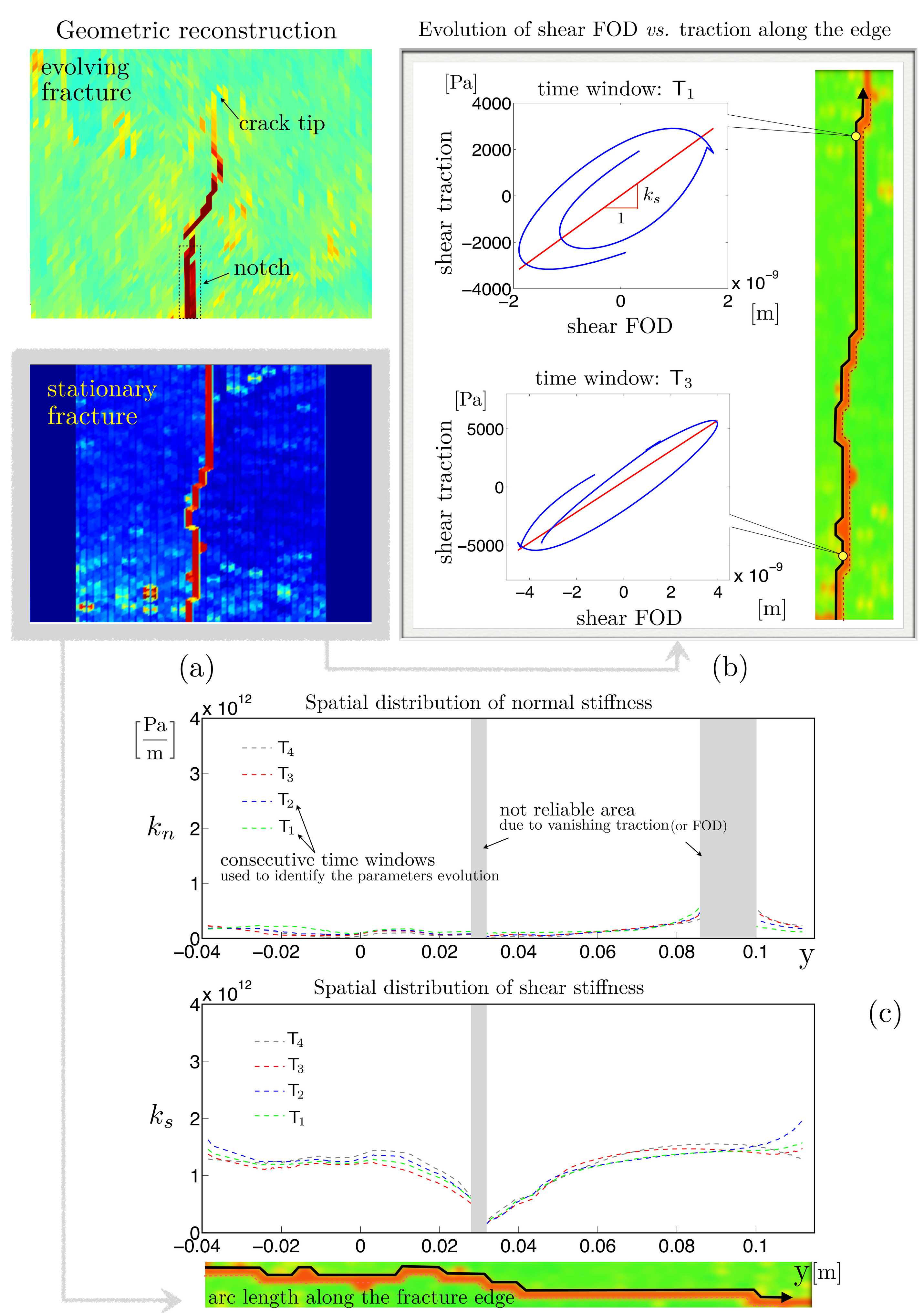

Fig.6 : Fracture characterization via SLDV measurements; a) geometric reconstruction of evolving (top panel) and stationary (bottom panel) fractures; b) hysteresis loops along the fracture edge; c) identification of heterogeneous contact parameters.

References

[1] A. F. Baird, J.-M. Kendall, J. P. Verdon, A. Wuestefeld, T. E. Noble, Y. Li, M. Dutko, and Q. J. Fisher. "**Monitoring increases in fracture connectivity during hydraulic stimulations from temporal variations in shear wave splitting polarization**", Geophys J. Int, 2013.

[2] A. Hedayat, L. J. Pyrak-Nolte, and A. Bobet. "**Precursors to the shear failure of rock discontinuities**", Geophys Res Lett, 41:5467-5475, 2014.

[3] F. Pourahmadian and B. Guzina. "**On the elastic-wave imaging and characterization of fractures with specific stiffness**", under review by Int. J. Solids Struc., arXiv preprint, arXiv:1501.03525, 2015.

[4] J. P. Verdon and A. Wustefeld. "**Measurement of the normal/tangential fracture compliance ratio (zN/zT) during hydraulic fracture stimulation using s-wave splitting data**", Geophys Prospec, 61:461-475, 2013.