Seismic imaging & characterization of heterogeneous fractures in rock

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Abstract

The focus of this research is a comprehensive analytical, computational, and experimental framework for **(a)** 3D seismic imaging of arbitrary-shaped fractures and fracture networks in rock, e.g. geothermal fractures (Fig. 1), and **(b)** reconstruction of their heterogeneous contact condition [3]. The analytical part is accomplished via a novel 3-step approach (Fig. 2) that takes advantage of recent advancements in waveform tomography [1,2] and Boundary Integral Equations (BIE). To cater for efficient numerical simulations, a computational platform is developed based on a regularized BIE for elastic-wave scattering by heterogeneous fractures [1], providing a fertile ground for validating the effectiveness of the 3-step inverse solution. The experimental component makes use of the **3D Scanning Laser Doppler Vibrometer** (SLDV) capable of remotely monitoring the triaxial motion waveforms (up to 1MHz) on the surface of rock specimens with 0.1mm spatial resolution and O(nm) displacement accuracy. In this setting, a set of laboratory experiments is performed for monitoring the full-field interaction of ultrasonic waves with stationary and advancing fractures in rock. The measured data are then used to: (1) non-parametrically expose the true contact law and its spatiotemporal variations along the surface of fractures in rock, and (2) extract the linearized contact properties in terms of the distribution of shear and normal specific stiffness along the fracture [3].

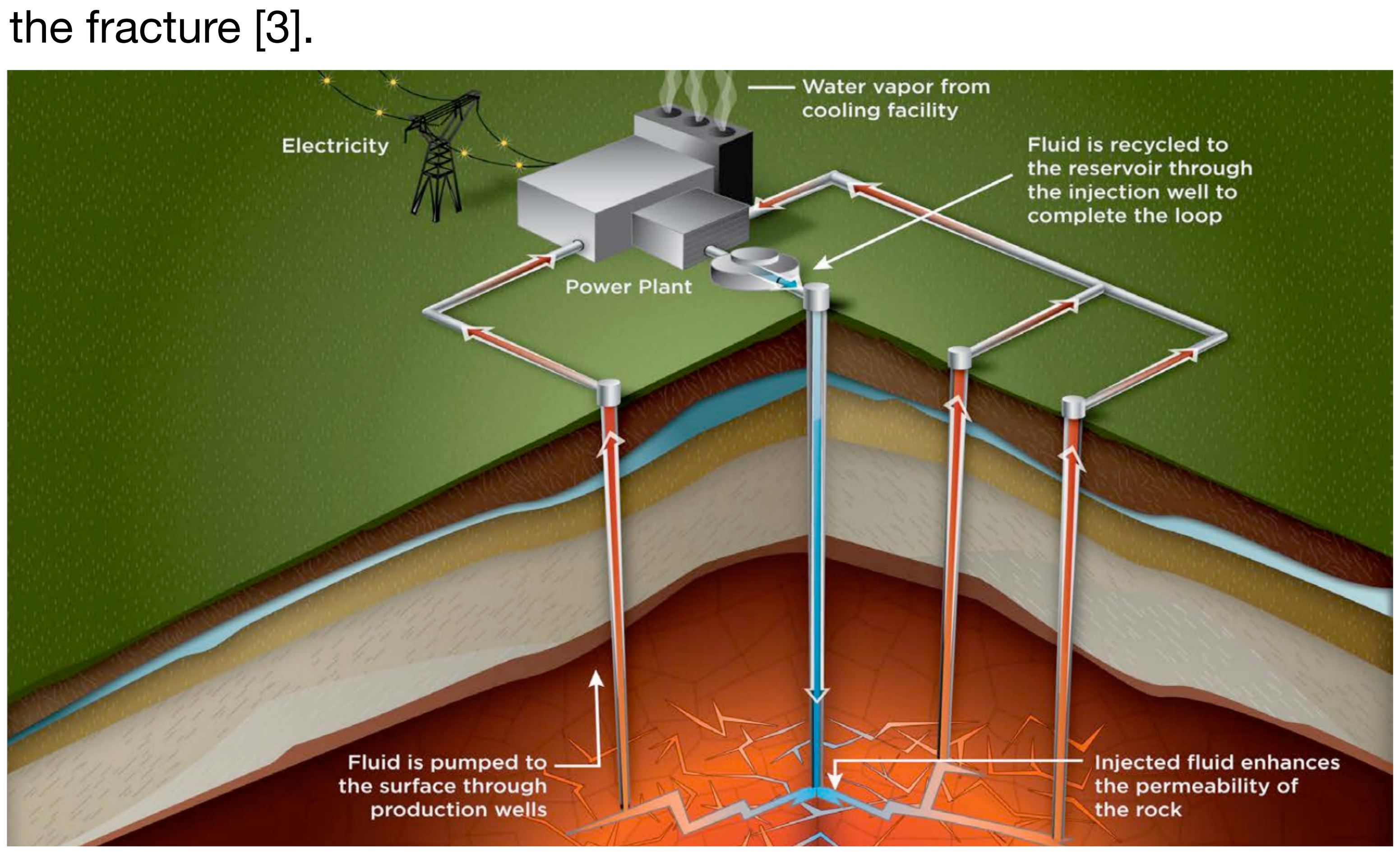

Fig.1 :Heterogeneous (geothermal) fractures in rock (eere.energy.gov)

Inverse Solution

Existing approaches to the seismic characterization of fractures with heterogeneous contact condition are, by and large, limited to sensing configurations where the fracture is planar, while the seismic sources and receivers are placed on the opposite sides of a discontinuity. The proposed sensing paradigm [3] is unique in that it allows for the imaging and characterization of arbitrary-shaped fractures, and caters for significant flexibility in terms of the sensing arrangement (location of sources and receivers). With reference to Fig. 2, this is realized by a novel **3-step inverse solution** where:

1. The fracture geometry is reconstructed in 3D irrespective of its contact condition via the Topological Sensitivity approach [1], given the availability of high-frequency seismic data, or by the Generalized Linear Sampling paradigm [2], in a more general setting with no limitations on the excitation frequency;

2. The fracture's opening displacement profile (FOD) is computed using thus obtained fracture reconstruction (denoted by $\breve{\Gamma}$) via a boundary integral representation of the seismic field scattered by the fracture, and

3. The distribution of specific stiffness, given by its normal and shear components $\breve{k}_n(\boldsymbol{x})$ and $\breve{k}_s(\boldsymbol{x})$ is computed from the knowledge of FOD, making use of the (elastodynamic) traction boundary integral equation written over $\breve{\Gamma}$.

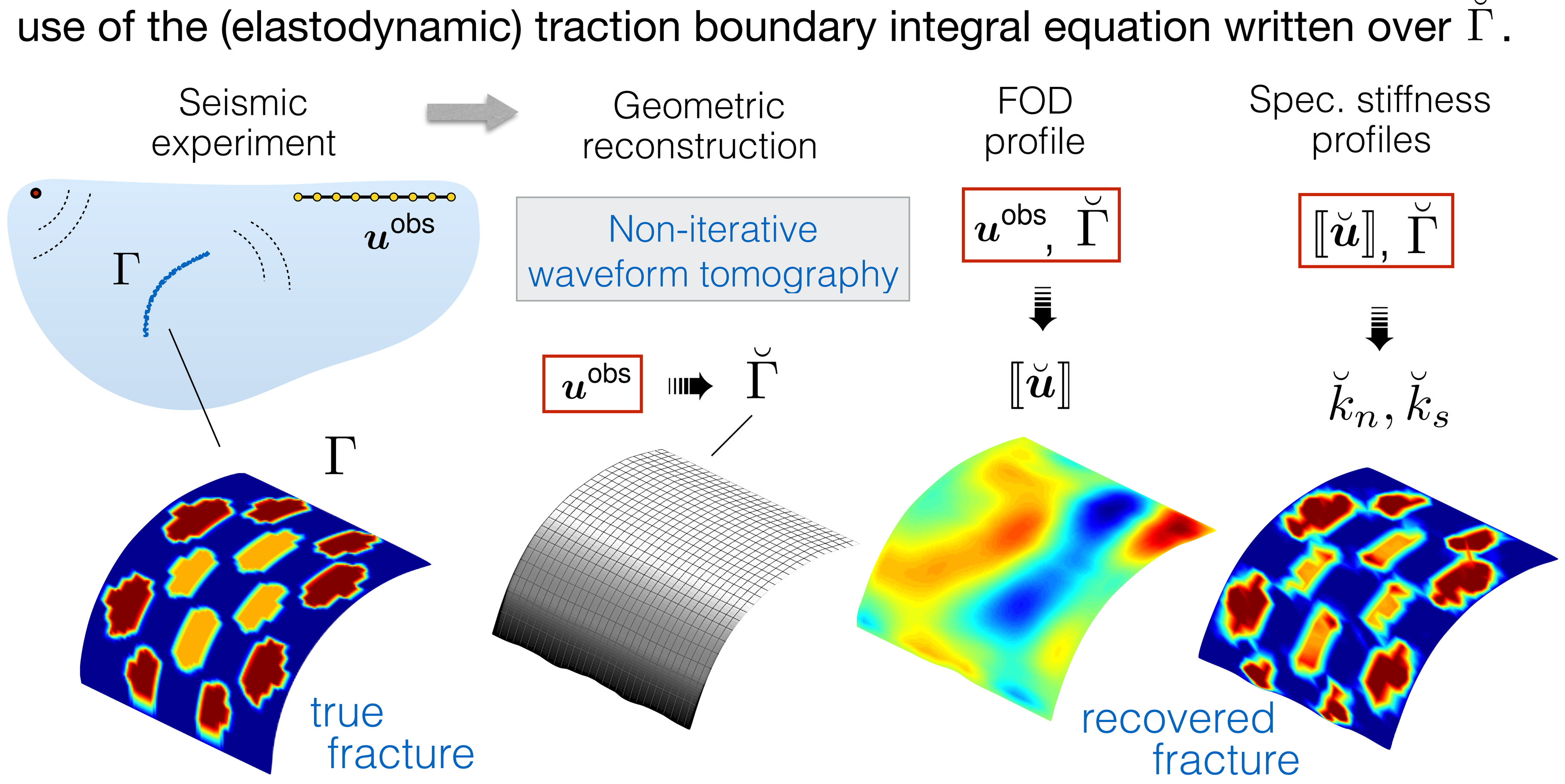

Fig. 2 Three-step approach to holistic seismic sensing of heterogeneous fractures

Experimental Platform

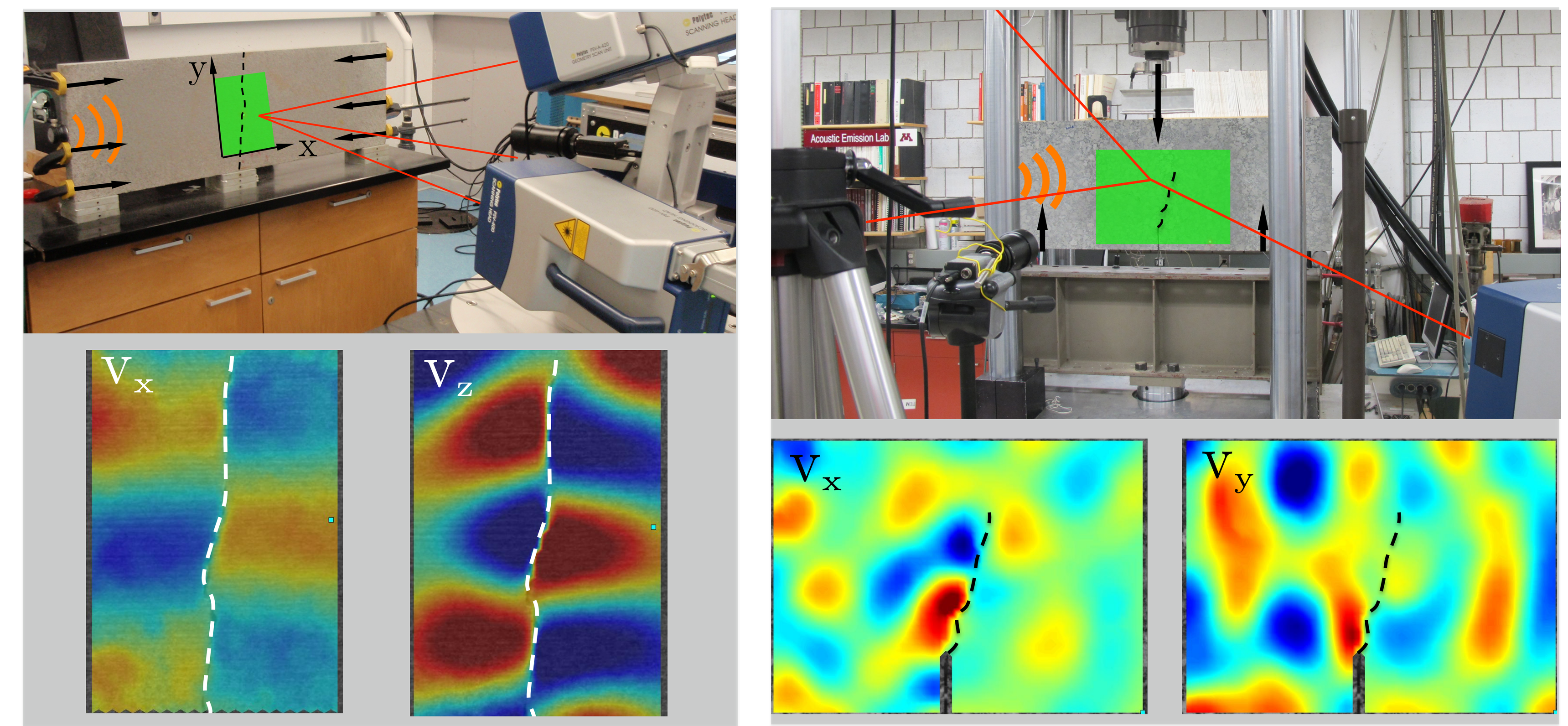

Fig.3 : SLDV setup for full-field ultrasonic sensing of stationary and evolving fractures in rock

The two ultrasonic sensing configurations shown in Fig.3 are realized as follows. **1. Left panels.** A *through-fracture* is induced in a granite slab; the pieces are then reconnected by applying a normal force to the opposite sides of a specimen. The sample is excited by an ultrasonic transducer, while scanning the induced *wave motion across the fracture* via SLDV. **2. Right panels.** An *advancing fracture* is introduced in a granite specimen via the 1000kN MTS load frame (3 point-bending mode), while periodically monitoring the fracture evolution by ultrasonic waves and SLDV. The granite samples (in both set-ups) have the target dimensions of 0.9m x 0.3m x 0.03m. The roadmap for the **full-field fracture characterization** is shown in Fig. 4(a), where **(I)** the fracture geometry is exposed, see Fig. 4(b), by computing the jump in the SLDV-observed particle velocity distribution; **(II)** the FOD along the fracture edge is obtained by integrating the measured waveforms in time; **(III)** the strain/stress distributions in the scanning area are computed from the observed displacement fields using nominal elastic properties — thus allowing the computation of tractions on the fracture, and **(IV)** the contact law at the fracture's interface and its spatiotemporal behavior is exposed via traction vs. FOD plots, Fig. 4(c), at every point along the fracture edge. A linear approximation of the latter exposes the *heterogeneous distribution of specific stiffness in normal and shear directions, see Fig. 4 (d).*

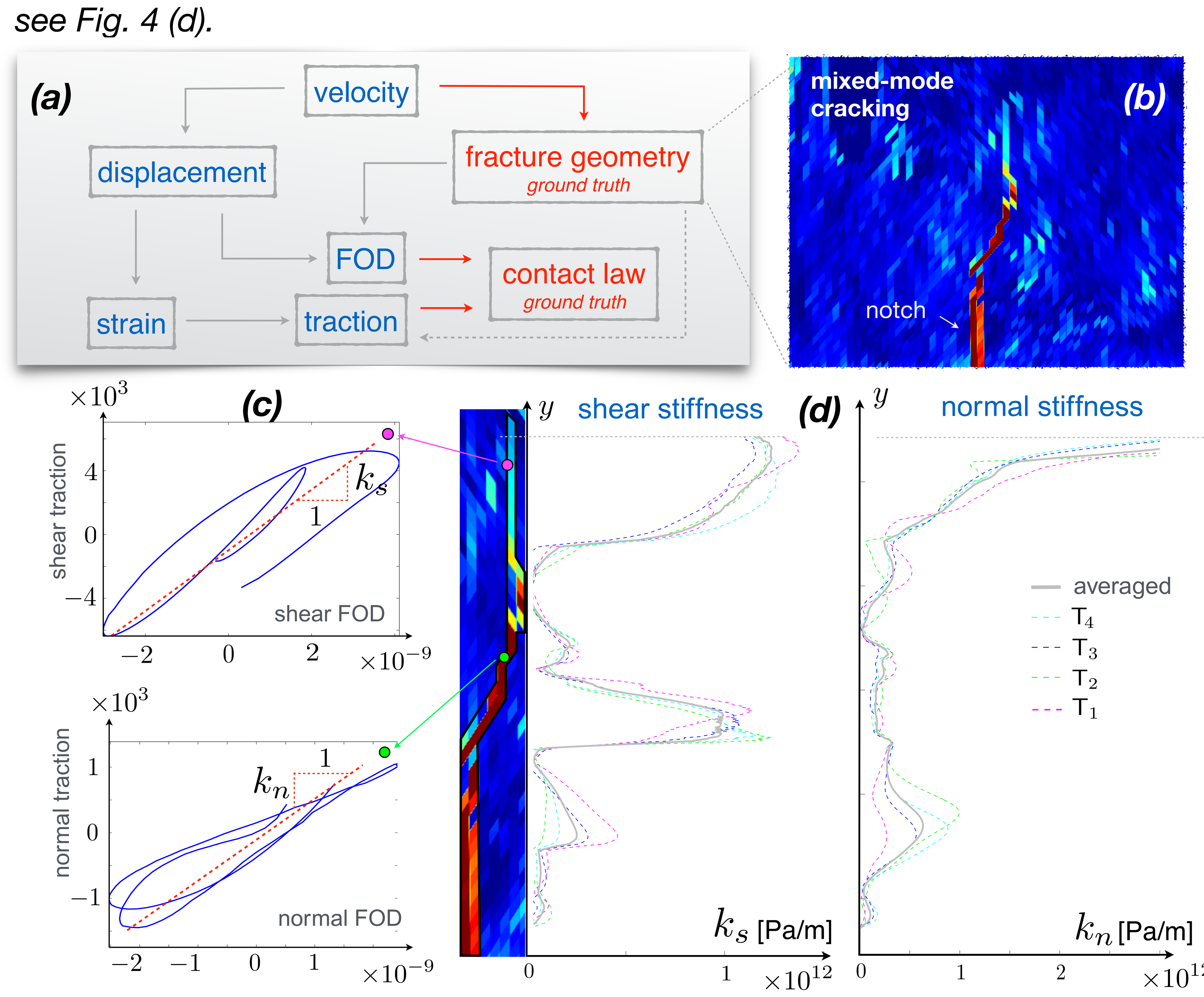

Fig.4 : Full-field characterization of the fracture geometry and heterogeneous interfacial condition: (a) roadmap, (b) reconstructed geometry, (c) contact law, (d) heterogeneous distribution of the specific stiffness in shear and normal directions

References

[1] F. Pourahmadian and B. Guzina. ``On the elastic-wave imaging and characterization of fractures with specific stiffness", *Int. J. Solids Struc., 71:126–140,2015*.

[2] F. Pourahmadian, B. Guzina and H. Haddar. ``Generalized linear sampling method for elastic-wave sensing of heterogeneous fractures", under review by *Inverse Problems, arXiv preprint arXiv:1605.08743, 2016*.

[3] F. Pourahmadian. ``A holistic approach to seismic waveform tomography of subsurface fractures: from geometric reconstruction to interfacial characterization", PhD thesis, *University of Minnesota*, 2016.