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MECHANICS OF OFF-FAULT TENSILE CRACKING GENERATED BY DYNAMIC SHEAR RUPTURES

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Off-fault tensile cracking has been observed for many exhumed earthquake faults and in laboratory experiments. A series of breakthrough experiments clarifying features of the off-fault cracking process was recently conducted on brittle photoelastic materials combined with high-speed digital photography (Griffith et al., 2009). The use of modern technology made visible important nuances of the stress field variation associated with off-fault cracking around the dynamically propagating shear rupture. At the same time even this modern technology did not allow identifying the shear rupture mechanism itself operated within the narrow rupture interface. This paper demonstrates that all features associated with the off-fault cracking process observed in the photoelastic experiments are caused by a shear rupture mechanism recently identified for hard rocks at highly confined compression (Tarasov, 2010, 2014).

In the new mechanism, shear rupture propagation associated with consecutive creation of small tensile cracks and inter-crack blocks (known as ‘domino-blocks’) in the rupture tip is driven by a fan-shaped domino structure representing the rupture head. The fan-head can be formed in primary (continuous) ruptures and in segmented faults. Domino-blocks operating as hinges within the fan-head decrease dramatically friction between the fault faces. The fan-head combines such unique features as: extremely low shear resistance, self-sustaining stress intensification, and self-unbalancing conditions. Due to this the failure process caused by the fan-mechanism is inevitably very dynamic and violent. It is shown that the fan-head intensifies off-fault tensile stresses causing the off-fault cracking. The fan-head shear rupture mechanism provides all intriguing features of the off-fault crack development observed in the photoelastic experiments:

- Bilaterally propagating shear rupture tips created off-fault tensile cracks in the opposite interfaces.
- Off-fault tensile cracks generated parallel to each other, steeply inclined to the fault path ($\theta \approx 80°$) and some curved slightly as they propagated into the specimen body.
- Off-fault cracks nucleated at some distance behind the shear rupture tip.
- Off-fault cracks grew as the shear rupture tip propagated a certain distance after which the cracks were left in the wake of the propagating rupture.

Figure 1 illustrates features of the photoelastic experiments and explains the off-fault cracking generated by the fan-head. To mimic the earthquake rupture processes in laboratory each tested specimen was made from two plates of a brittle resin Homalite hold together by bonding (see schema in Figure 1a). The bond represented a layer of brittle solid between two stronger interfaces. In the pre-compressed specimen the bilateral rupture was nucleated at the center of the simulated fault by producing a local pressure pulse in a small area of the interface. A photograph of the row of off-fault cracks generated in the interface is shown in Figure 1b (from Griffith et al., 2009).

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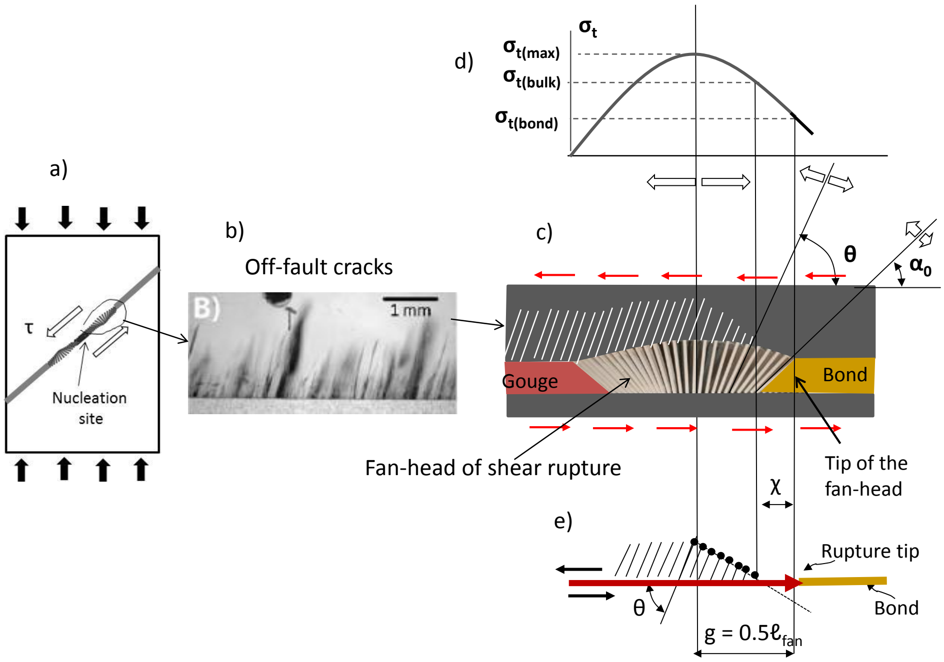

Figure 1. Explanation of features of the off-fault cracking process observed in the photoelastic experiments

Figure 1c shows symbolically a fan-head propagating along the bond line from left to right. The driving shear stress is applied to the fan-structure from the face material. The graph in Figure 1d shows the variation of tensile stress σ_t generated in the interface by the fan-head (details will be presented in the article). At the rupture tip the level of tensile stress corresponds to the tensile strength of the bond material $\sigma_{t(bond)}$ which is subjected to splitting with the formation of domino-blocks. Behind the tip the level of tensile stress increases with distance from the tip.

The maximum principal tensile stress acts in a direction perpendicular to the plane of a domino-block, which is variable along the head. Open arrows in the model illustrate this. This fact determines the orientation of generated tensile cracks. At the rupture tip the crack angle is α_0. At distance χ from the tip, the level of tensile stress reaches the strength of the bulk material $\sigma_{t(bulk)}$ nucleating a secondary tensile crack oriented along the domino-block at angle θ. This crack grows with propagation of the fan-head until the zone of maximum tensile stress $\sigma_{t(max)}$ created by the head has reached this point. Due to rotation of the stress field generated by the rotating domino-blocks the growing crack slightly alters its orientation approaching the vertical direction as observed in the Homalite experiments. After the point of the fan-head characterized by $\sigma_{t(max)}$ has passed the growing crack, the crack growth stops due to the decrease in tensile stresses in the second half of the fan-structure. The schema observed in the photoelastic experiments which illustrates features of the off-fault cracking is shown in Figure 1d.

Along with off-fault cracking the fan-mechanism provides shear rupture development at very low shear stresses which can be below the frictional strength as observed in the photoelastic experiments and many earthquakes. This question is also discussed in the paper.

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