

Transverse Propagation Dynamics of Crack Fronts in Brittle Fracture

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Abstract

Crack propagation in brittle materials is characterised by intermittent, discontinuous dynamics rather than smooth advancement. This behaviour, known as crackling dynamics (Bonamy 2009), results from the competition between material heterogeneity, which pins the crack front, and increasing elastic energy release rates, which drive it forward. When the driving force exceeds a critical threshold, the crack transitions from a stable pinned phase into a moving phase. This transition gives rise to the stick-break phenomena that we examine. Recent experiments and simulations have shown that extended fractures propagate through a material via localised nucleation, inducing a forward jump of the crack front followed by rapid transverse expansion (Cochard 2024). The transverse velocity of the fracture depends on the amplitude of the forward jump at a nucleation site and can reach the Rayleigh-wave speed for sufficiently large jumps. However, for smaller jumps, much lower transverse speeds can occur; the drop in speed is inconsistent with predictions from current theoretical frameworks, thus further investigation is warranted to uncover the underlying dependencies. It has been demonstrated that the amplitude and width of localized crack-front perturbations diminish and ultimately vanish as the crack front velocity approaches the Rayleigh-wave speed. While the velocity of these perturbations has been examined through a Lorentz transformation co-moving with the crack tip, the underlying reason why smaller perturbation velocities are associated with smaller spatial lags remains

unaddressed. Since linear elastic fracture mechanics (LEFM) solutions do not yet exist to describe these dynamic crack front distortions in space and time, we employ numerical modelling. The simulations are run under the assumption of linear-elastic material response, with fracture modelled via a linear cohesive law that regularises the crack-tip singularity by introducing a finite cohesive-zone (representing the material failure region). We investigate the crack front nucleation and propagation dynamics as a function of the crack-jump amplitude. We validate the previous analysis presented in (Cochard 2024) and further extend the parameter study to examine the relationship between jump amplitude, crack length, and cohesive zone length scales. A normalisation of the transverse crack front motion in space and time is proposed, with the aim of deriving an equation of motion for the three-dimensional fracture front. The two-dimensional equation of motion for a crack is known to derive from dynamic crack-tip energy balance (Freund 1990); accordingly, we examine how Griffith length scaling (Griffith 1921) relates to the stick-break regime and assess its relevance in three dimensions. The normalisation, and subsequent scaling analysis, allow us to elucidate the influence of our scaling parameters on crack-front dynamics, and to verify that the transverse propagation mechanism is scale-independent and applicable across fracture sizes ranging from the microscopic to geological and industrial scales.

Keywords:

Fracture Mechanics Computational Modelling Brittle Fracture