PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Introduction

Check for updates

Cite this article: Uenishi K. 2021 Fracture dynamics of solid materials: from particles to the globe. *Phil. Trans. R. Soc. A* **379**: 20200122.
https://doi.org/10.1098/rsta.2020.0122

Accepted: 21 January 2021

One contribution of 13 to a theme issue 'Fracture dynamics of solid materials: from particles to the globe'.

Subject Areas:
geophysics, civil engineering, mechanical engineering

Keywords:
dynamic fracture, fracture energy, friction, dynamic coupling, phase transition, earthquake physics

Author for correspondence:
Koji Uenishi
e-mail: uenishi@dyn.t.u-tokyo.ac.jp

Fracture dynamics of solid materials: from particles to the globe

Koji Uenishi[1,2]

[1]Department of Advanced Energy and [2]Department of Aeronautics and Astronautics, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561 Japan

KU, 0000-0002-6835-816X

Solid materials have been used extensively for various kinds of structural components in our surroundings. Stability of such solid structures, including not only machinery, architectural and civil structures but also our solid earth, is largely governed by fracture development in the solids. Especially, dynamic fracture, once occurring—quite often unexpectedly—evolves very rapidly and can lead to catastrophic structural failures and disasters like earthquakes. However, contrary to slowly enlarging fractures that can be recognized spatio-temporally in detail, it is extremely difficult to trace dynamically growing fractures even in controlled laboratory experimental conditions, and its physics still remains unexplored. This theme issue introduces and summarizes recent advancements in our understanding of the widespread topics of dynamic fracture of solids from well-assorted perspectives, involving laboratory experiments, simulations and analytical methods as well as field observations, with the common background of mechanics of fracture. Multi-scale subjects range from fracture of metals at atom or particle levels to disastrous rock bursts in deep gold mines and detection of unique signals before devastating fracture such as large, global-scale earthquakes.

This article is part of the theme issue 'Fracture dynamics of solid materials: from particles to the globe'.

1. Introduction

As old as the design of stone tools for breaking solid materials in Neolithic times, understanding and using fracture development in solids has historically

THE ROYAL SOCIETY PUBLISHING

played a crucial and familiar role in our daily life. However, if fracture, here defined as displacement gaps (slips) in solid materials, occurs in an uncontrolled way, it may cause truly catastrophic events. The importance of comprehending the mechanics behind such devastating fracture phenomena has been increasingly recognized particularly since the Industrial Revolution when structures made of steels became common. Thus, research into the mechanics of fracture, or investigation into finding some order in apparently disordered phenomena of fracture, has been conducted by prominent scientists like A. A. Griffith [1]. In contrast with the scientific and engineering work on the static or quasi-static fracture behaviour of solid materials where remarkable progress has been made, dynamic fracture phenomena, typically represented by seismic disasters and rapid collapse of natural and artificial structures, normally progress at high speeds that cannot be observed by the naked eye. The mechanisms of fracture nucleation and dynamic evolution have not yet been fully clarified, and still there exist unexpected and unrestrained failures of solids that may threaten our living environments. In order to evaluate the behaviour of fracturing solids more quantitatively with higher accuracies and prevent possible dreadful failures, the advancement of fracture investigation based on dynamics that incorporates more rigorous physics is strongly desired.

This theme issue integrates, both in review and original research formats, the latest attractive establishments and findings in the investigation of fracture dynamics in solids. The readers will notice a wide variety of physical phenomena where fracture dynamics is involved and how sophisticatedly diverse disciplines of science and engineering are combined to understand the complex and seemingly disordered phenomena of dynamic fracture at drastically different spatio-temporal scales. Indeed, the examination of dynamics of fracture can be undertaken with different methodologies developed, e.g. in applied mathematics and mechanics, physics, geophysics and engineering science, which can include both deterministic and stochastic approaches. Of course, combined techniques of analytical, numerical methods as well as laboratory experiments and field observations are required for a deeper comprehension of fracture dynamics. The theme issue consists mainly of two parts where the above disciplines, methods and techniques are lined up in a balanced way. The former part [2–7] handles the fundamental mechanisms related to physical processes of dynamic fracture, basically at the laboratory scale. By knowing the essentials, the readers proceed to the latter part [8–12] where more practical and geophysical issues at larger scales are discussed. Finally, unsolved problems of dynamic fracture are introduced for further consideration [13].

2. Summary of the theme issue

With the main keyword ‘fracture dynamics’, this theme issue covers diverse subjects, extending from theoretical yet significantly important model analyses, such as J. D. Eshelby-based [14] collective treatment of damage evolution in brittle materials [3], to practical safety and environmental problems associated with mining or rock excavation engineering, including the fundamental study on the brand-new contactless rock drilling technique using thermal shock [4]. As stated earlier, the scale treated is also diverse, ranging from a fracture at the atomic or microscopic level [2] to largely macroscopic rock/strain bursts or sudden collapse of stopes in deep underground gold mines [9], field observation-based reliable physical estimation of earthquake source parameters [8] or even to megathrust rupture (fracture) near tectonic boundaries of the earth [11]. The theme issue also handles front-line topics like fracture asperity development during the change between stick-slip and stable sliding [5], fracture-induced gravitational perturbations that propagate at the speed of light [12] and seismic events induced by human activity like a fluid injection that can become concerns of the residents nearby [6]. Methodologically, not only classical methods based on mechanics of continua but also a modern technique incorporating nonlinear material behaviour with phase transition between solid and liquid phases [10], as well as a statistical and discrete approach [7], are employed.

More specifically, in the first part, Yashiro [2] describes the dynamic behaviour of cracks that develop along with bi-metal interfaces at an atomistic scale based on an ambitious molecular dynamics study. By taking into account his own concept of 'atomic elastic stiffness' and surface energy, he shows that, depending on the combination of metals, the crack under consideration does not propagate along the bi-metal interface but moves rather in the adjacent phase of smaller surface energy. In their mathematical study [3], Gomez & Ionescu address the collective behaviour of micro-scale cracks that dynamically evolve due to waves in a damaging solid material and indicate semi-analytically and numerically the relation between wave propagation and damage evolution in brittle materials. Then, Saksala *et al.* [4] shed light on challenging coupled thermo-mechanical problems of thermal spallation to examine more environmentally-friendly, non-mechanical contactless thermal jet drilling of rocks in extracting deep geothermal energy. By numerically applying their model of viscoplastic damaging materials, they illustrate that thermal drilling using heating-forced cooling cycles is viable when boring hot rock mass. Mei & Wu [5] perform a series of direct-shear experiments scrutinizing the evolution of fracture asperities during the transition between stick-slip and stable sliding, which has rarely been addressed in the literature but is important for understanding the fracture behaviour of solid materials. They indicate that the transition stage occurs during the progressive reduction in normal stress on the smooth and rough fractures, and both fractures show the alternate occurrence of small and large shear stress drops with the ensuing deterministic chaos in the transition stage. Further, Garagash [6] studies a general equation of motion for crack propagation, owing to the injection of fluids, on geological fault surfaces with so-called rate- and state-dependent friction, and derives an expression for the fracture energy as a function of crack propagation velocity. This opens a window to modelling dynamics on intricate rate-and-state faults as singular cracks with approximately steady-state frictional resistance. Debski & Klejment [7] summarize and numerically investigate the discrete and statistical aspects of fracture dynamics related to seismic sources. By evaluating the energy accumulation and transformation during fragmentation processes of solids under tension, they highlight the usefulness of employing a discrete approach in addition to the continuum one.

In the latter part, Abercrombie [8] comprehensively summarizes and points out the difficulties in estimating the fracture properties of seismic sources from seismological datasets, in particular, those of small and moderate-sized earthquakes (magnitude less than about 5 or 6) that are not well resolved and may contain significant random and potentially systematic uncertainties. She also discusses the recent progress made towards more reliable estimates of seismic source parameters. For the enhancement of the safety of everyday operations in seismically active deep mines where operating levels are now reaching as deep as 4000 m, Linzer *et al.* [9] investigate the physics of mining-induced seismicity numerically from a fracture dynamics point of view and discuss the influence of the mining environment on seismic sources. Gabriel *et al.* [10] review cutting-edge approaches in fracture mechanics including the varifold-based description of crack nucleation and apply the emerging phase-field approach to the dynamic fracture problems met in geophysics, bearing in mind earthquake rupture propagation in geometrically and rheologically complex fault zones. The numerical examples they treat range from the co-seismic generation of secondary off-fault shear cracks to the natural convection in molten rock-like solid. By taking into account a sophisticated rate- and state-dependent friction law with the parameters constrained by geodetic fault locking, Li & Liu [11] develop a three-dimensional megathrust earthquake cycle model for the Cascadia subduction zone that may cause a seismic event with a magnitude over 9. They present a numerical simulation of earthquake sequences and evaluate potential seismic risks. Then, Kame [12] reviews the latest progress in the brand-new research subject of fracture of the solid earth, namely, the transient gravity perturbations that are induced by rock mass redistribution due to a large-scale earthquake and can propagate even quicker than the fastest elastic waves, longitudinal (P) waves. Such pre-P gravity signals have drawn more and more attention both in modelling and observations owing to their potential use for earthquake early warning. In the last article, Uenishi [13] introduces fracture development experimentally found in typical brittle solids and emphasizes the challenge in understanding the physical process of real three-dimensional dynamic fracture. Although the final fracture patterns recognized in the experiments are astonishingly simple, it seems hard to elucidate the associated physics with traditional analytical and numerical methods.

The word 'fracture' may present a terrifying image to ordinary people, and fracture in solid materials, especially those that are dynamically evolving, has been regarded as something to be avoided. However, once the dynamics behind is rightly comprehended, the acquired knowledge can in turn be useful in analysing previously unpredictable events or in safely and effectively protecting our environments in a controlled manner, for instance, in dismantling structural components in a very short period of time of operation. At this precise moment, there seems to be a paradigm shift in the research of fracture from 'how to prevent fracture' to 'how to precisely use and manoeuvre it for efficient structural disintegration and disaster mitigation'. This theme issue collects important and breakthrough articles that will lead an effort to this paradigm shift. The problems handled involve important social issues directly connected to energy saving and environmental protection, and solving them will have a high impact on our everyday life and contribute greatly, e.g. to disaster prevention and Goal 11 'Sustainable Cities and Communities' of the Sustainable Development Goals of the United Nations.

Data accessibility. This article has no additional data.

Competing interests. The author(s) declare that they have no competing interests.

Funding. I received no funding for this study.

Acknowledgements. We are grateful to all authors who have contributed their work to this theme issue, the reviewers having provided valuable comments, and to the Commissioning Editor, Alice Power and her team at Philosophical Transactions A for their help and support, as well as for having offered the opportunity to guest edit this issue in early 2019.

References

1. Griffith AA. 1920 The phenomena of rupture and flow in solids. *Phil. Trans. R. Soc. A* **221**, 163–198. (doi:10.1098/rsta.1921.0006)
2. Yashiro K. 2021 Molecular dynamics study on atomic elastic stiffness at mode I crack along bi-metal interface. *Phil. Trans. R. Soc. A* **379**, 20200124. (doi:10.1098/rsta.2020.0124)
3. Gomez Q, Ionescu IR. 2021 Micro-mechanical fracture dynamics and damage modelling in brittle materials. *Phil. Trans. R. Soc. A* **379**, 20200125. (doi:10.1098/rsta.2020.0125)
4. Saksala T, Kouhia R, Mardoukhi A, Hokka M. 2021 Thermal jet drilling of granite rock: a numerical 3D finite-element study. *Phil. Trans. R. Soc. A* **379**, 20200128. (doi:10.1098/rsta.2020.0128)
5. Mei C, Wu W. 2021 Fracture asperity evolution during the transition from stick slip to stable sliding. *Phil. Trans. R. Soc. A* **379**, 20200133. (doi:10.1098/rsta.2020.0133)
6. Garagash DI. 2021 Fracture mechanics of rate-and-state faults and fluid injection induced slip. *Phil. Trans. R. Soc. A* **379**, 20200129. (doi:10.1098/rsta.2020.0129)
7. Dębski W, Klejment P. 2021 Earthquake physics beyond the linear fracture mechanics: a discrete approach. *Phil. Trans. R. Soc. A* **379**, 20200132. (doi:10.1098/rsta.2020.0132)
8. Abercrombie RE. 2021 Resolution and uncertainties in estimates of earthquake stress drop and energy release. *Phil. Trans. R. Soc. A* **379**, 20200131. (doi:10.1098/rsta.2020.0131)
9. Linzer LM, Hildyard MW, Wesseloo J. 2021 Complexities of underground seismic sources. *Phil. Trans. R. Soc. A* **379**, 20200134. (doi:10.1098/rsta.2020.0134)
10. Gabriel A-A, Li D, Chiocchetti S, Tavelli M, Peshkov I, Romenski E, Dumbser M. 2021 A unified first-order hyperbolic model for nonlinear dynamic rupture processes in diffuse fracture zones. *Phil. Trans. R. Soc. A* **379**, 20200130. (doi:10.1098/rsta.2020.0130)
11. Li D, Liu Y. 2021 Cascadia megathrust earthquake rupture model constrained by geodetic fault locking. *Phil. Trans. R. Soc. A* **379**, 20200135. (doi:10.1098/rsta.2020.0135)
12. Kame N. 2021 Pre-P gravity signals from dynamic earthquake rupture: modelling and observations. *Phil. Trans. R. Soc. A* **379**, 20200136. (doi:10.1098/rsta.2020.0136)
13. Uenishi K. 2021 Unexpected, mystifying but simple three-dimensional dynamic fracture phenomena. *Phil. Trans. R. Soc. A* **379**, 20200123. (doi:10.1098/rsta.2020.0123)
14. Eshelby JD. 1957 The determination of the elastic field of an ellipsoidal inclusion, and related problems. *Proc. R. Soc. A* **241**, 376–396. (doi:10.1098/rspa.1957.0133)