6. Fracture mechanics

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6.0 ABSTRACT

Fracture mechanics is an active research field that is currently advancing on many fronts. This appraisal of research trends and opportunities notes the promising developments of nonlinear fracture mechanics in recent years and cites some of the challenges in dealing with topics such as ductile-brittle transitions, failure under substantial plasticity or creep, crack tip processes under fatigue loading, and the need for new methodologies for effective fracture analysis of composite materials. Continued focus on microscale fracture processes by work at the interface of solid mechanics and materials science holds promise for understanding the atomistics of brittle vs ductile response and the mechanisms of microvoid nucleation and growth in various materials. Critical experiments to characterize crack tip processes and separation mechanisms are a pervasive need. Fracture phenomena in the contexts of geotechnology and earthquake fault dynamics also provide important research challenges.

6.1 INTRODUCTION

Fracture mechanics began as a means of understanding the tensile failure of brittle materials; it has grown into a field of great breadth and applicability. The subject is concerned with failure by cracking or cavitation of materials (structural, geological, biological, etc.) under a wide variety of loadings and environments. Applications range from the microscale of materials where cavity sizes may be a fraction of a micron to engineering structures with cracks in the millimeter to centimeter scale to earthquake rupture where faults are many kilometers in extent. Fracture mechanics is now being developed and applied around the world. Hardly a week goes by without some fracture-related problem reaching the nation's newspapers. Such problems have involved, for example, cracking in artificial heart valves, reactor piping, welding affected zones of bridges and offshore structures, aircraft landing gear, tail and engine attachments, ship structures, undercarriages of transit buses, turbine discs and blades, gas transmission pipelines, and train rails and railwheels.

The stage was set for the modern development of fracture mechanics in all its aspects by Irwin and Orowan, who in the 1950s and early 1960s reinterpreted and extended Griffith's classical work of the 1920s on brittle materials. Irwin's approach in particular brought progress in theoretical solid mechanics, especially on elastic stress analysis of cracked bodies, to bear on the practical problems of crack growth testing and structural integrity. The field has continued in this synergistic mode. It is characterized by remarkably close contact between advanced theoretical mechanics focused on nonlinear and often time-dependent material response, the examination and characterization of materials on the microscale, laboratory study of crack growth and fracture phenomena, and applications to structural integrity assurance that themselves drive new advances in materials testing and stress analysis methodology.

Irwin's approach to fracture, sometimes called linear elastic fracture mechanics, permitted engineers to analyze cracking in the more brittle structural materials such as high strength metal alloys. A precise measure of fracture toughness (i.e., the critical stress intensity fractor or energy release rate) was one of the early successes of the new approach. The growing fracture mechanics community quickly extended the new approach to deal with fatigue cracking, a problem which had then begun to plague the aircraft industry and which still today presents many challenges, especially in circumstances of hostile environments and elevated temperatures.

6.2 NONLINEAR FRACTURE MECHANICS

6.2.1 Ductile structural metals

The early methods and concepts of fracture mechanics, being based on the theory of linear elasticity, were limited to applications in which plastic (nonlinear) deformations were confined to the immediate neighborhood of the crack tip itself. The theory could not be applied to a number of important cracking problems involving some of the tougher, more ductile structural materials, such as many steels for example, which often experience fracture only after extensive plastic deformation. Indeed, for many of these materials the linear approach did not even permit a practical means of assessing fracture toughness for overload failure. This posed a severe limitation on the applicability of fracture mechanics in such areas as nuclear reactor technology, sea and ground transport systems, pipelines, storage tanks, bridge safety, and the like. Crude ways for extending the linear theory were devised, but these have now been supplanted by nonlinear fracture mechanics developed by theoretical and experimental mechanics researchers over the last 15 years.

The new methods were based on parameters such as the crack tip opening displacement and J integral that characterize the intensity of near tip elastic-plastic deformation fields. In their range of validity, these are geometrically invariant parameters, the same for laboratory test specimen and cracked structural components. The parameters suffice for describing the onset of crack growth and limited stable growth when the fracture process zone is sufficiently localized to the crack tip and when there is adequate constraint to maintain high stress triaxiality at the tip. These conditions are met closely enough in many applications that the resulting methodology has been adopted widely in recent years. It is being used, for example, as a basis for fracture control of nuclear reactor coolant piping and of vessels under thermal shock. Significant problems remain in effectively performing the stress analysis necessary to relate the elastic-plastic crack tip parameters to remote loading conditions. This is expecially the case for cracks in complex structural geometries such as nozzle intersections, or in areas of mechanical heterogeneity such as welds where, also, large residual stresses may be present.

In addition, there are significant and fundamental research challenges in dealing with fracture in circumstances that involve transition from initially ductile failure to brittle low-energy cleavage and also with cases for which substantial initially stable crack growth occurs on the route to overload fracture. The analysis of such stable ductile crack growth requires contention with the full nonlinear strain path dependence of plastic response and poses difficult problems for mechanics analysis. Further, there is a critical need for improved experimental techniques to more directly characterize crack tip processes and separation mechanisms in the ductile regime. These should guide the use of advanced computational mechanics techniques for elastic-plastic response to predict crack growth.

Fracture with substantial plasticity is important for all aspects of metal forming. Significant progress has been made on evaluation of limits to sheet metal forming processes based on plastic flow concentrations into thin necking zones. The satisfactory explanation of forming ductility in common circumstances, e.g., punching, for which there are positive extensions in all directions in the plane of the sheet, is a recent development in this area. At present, ductile fracture mechanics is relatively well developed for cases dominated by a crack that is long compared to its fracture process zone, and for cases of plastic instability that are uninfluenced by macroscopic cracks. Very little progress has yet been made on understanding fracture nucleation, e.g., from a localized shear zone, and growth as a crack in a region undergoing substantial plastic flow.

6.2.2 Creep fracture

A rapidly developing area involves high temperature cracking problems where nonlinear creep deformation must be taken into account. Such is important for components operating in the vicinity of half or more of the material melting temperature, as in gas turbine engines. There are then significant transients in the crack tip stress field associated even with the application of a simple step loading. Although the zone of significant nonlinear creep strain after loading is initially confined to the vicinity of the crack tip, like the plastic zone confined by essentially elastic surroundings in classical brittle fracture mechanics, ultimately the entire cracked component undergoes substantial creep and responds as a nonlinear purely viscous body. Transitions of this type occur not only from nominally elastic to steady (secondary) creep but also involve primary creep and short-time plasticity effects. In these circumstances the problems are considerable in understanding how laboratory crack growth data at elevated temperature can be interpreted in terms of crack tip fields and used for rational prediction of growth rates in components in service. Such components typically experience complicated temperature and stress histories, as in turbine engine operating cycles. Fortunately, major steps have been made in recent years towards identifying the types of time-dependent singular crack tip stress/deformation fields that can exist and the transition times between them for step or other variable loading. Results have the strong dependence on load level and temperature expected for response in the creep regime, and the resulting basis for rationalizing creep crack growth data is impressive. Many challenges remain in dealing with general load histories, as in creep fatigue, and in properly accounting for oxidizing or corrosive environmental effects in high temperature crack growth.

As in lower temperature ductile failure, there are some cases where fracture is best modeled by the growth of a single dominant crack, autocatalytic in concentrating deformation at its tip, whereas in other cases creep flow and gradual material degradation by microcavitation occurs over a relatively extensive zone of a component. Older continuum damage theories have long been applied to describe such degradation, and it seems important to bring those approaches into better correspondence with the microscopic mechanisms of failure and to understand the conditions leading to macroscale cracking vs. distributed damage.

6.2.3 Distributed microcracking

Significant nonlinearities are encountered in fracture analysis of many brittle solids, including structural concrete, some rocks, and some fiber-strengthened composites, which show extensive zones of microcracking ahead of the main tensile fracture. Such microcracking zones may be regarded as the approximate equivalent of plastic or creep zones in ductile solids. The applicability of fracture mechanics methods to concrete structures has been greatly enhanced by accounting for general microcracking, modeled most simply as a planar zone of material degradation on the prolongation of the crack plane. Coordinated experimental developments for concrete have enabled the measurement of tensile strength as a decreasing function of the separation across the macroscale tensile rupture; the gradual strength degradation is due to the bridging effects of aggregate particles and, when present, fiber reinforcements.

The fracture of brittle solids under compressive principal stresses typically involves complex nonlinear overall deformation governed by the profuse nucleation, growth, and interaction of cracks. Important progress has been made in describing some aspects of those compressive failures, such as the local stable growth, parallel to the principal compression direction, of tensile cracks nucleated at the edges of sliding shear fissures. However, the description of multicrack behavior and the ultimate localization of deformation into a shear failure or delamination zone remains a challenging research problem.

6.2.4 Composites

Significant nonlinearities are encountered in fracture analysis of both unidirectional and laminated fibrous composite materials. Large zones of microcracking are often found ahead of the main fracture in composites with brittle thermoset matrices; equally extensive zones of plastic deformation exist at crack tips in metal matrix composites. In general, these zones vary in size, shape, and damage intensity according to ply orientation. Ply delaminations at free crack edges, and at free edges in general, further complicate crack geometry.

Although generalizations of traditional fracture mechanics to composites can be routinely made using crack stress analysis in anisotropic solids, the failure processes in composites are often too complex and extensive to be described by such models. Incompletely pulled-out fibers may bridge parts of the surface of a macroscale crack and the crack advance itself may involve fiber debonding, ply delamination, and fiber failure in a relatively large volume of distributed damage and/or plastic deformation. The crack tip is often replaced by a long separation zone, indeed the size of the crack tends to be more important than its shape: Strength of laminated composite plates usually depends on the length of a defect, e.g., hole diameter, notch or crack length, and not on its shape. Here the challenge is to develop a fracture mechanics theory which applies existing concepts to understanding elements of damage accumulation at the microlevel, and to develop macroscopic descriptions which can be used for reliable life assessment in design with composites.

The problems of interest involve diverse classes of materials, e.g., most commonly matrices are polymeric, but metal matrix composites have been developed for higher temperature applications, and composites with ceramic fibers in a ceramic matrix are under development also.

6.2.5 Polymers

Polymeric materials are used as matrices of composites, as materials of adhesive joints, and increasingly as load-bearing structural components. Typically the failure process is time-dependent, reflecting at least in part the viscoelastic nature of polymer mechanical response, and can be accompanied at high stress by permanent deformation, crazing, voidage, and shear flow localization. Progress has been made on elucidating the structure of craze zones, i.e., zones of parallel molecular elongation often forming at the tips of cracks, and in relating time-dependent crack growth to parameters from viscoelastic analysis of response outside the crack and craze zones. Also, developments analogous to crack tip opening displacement and J integral methods of ductile fracture mechanics have been adapted usefully for a class of inelastic response. Nevertheless, in relatively ductile polymers such as polyethelene, the extent of the zone of material undergoing very large strains ahead of the propagating fracture is often not small compared to crack length. Also, the craze zone forming just behind this large strain region is made up of finitely deformed fibrils. Those factors suggest the need for new analysis procedures that directly incorporate large strain phenomena. As applications of polymeric solids continue to proliferate, it becomes increasingly important to achieve a better understanding of fracture in these materials and of environmental effects, e.g., moisture and solvents, on crack growth and failure processes.

6.3 FATIGUE; LIFETIME PREDICTION

Advances in nonlinear and time-dependent fracture mechanics of the type described set the stage for attaining a sounder basis for lifetime prediction in engineering systems. Typical failure routes involve crack nucleation and growth towards critically under variable loads, i.e., fatigue. At present the basis for using representative test data for fatigue crack growth under cyclic loading in prediction for more general variable load histories is largely empirical and little influenced by basec mechanics modeling. The fatigue process is often strongly affected by the chemical environment which, if sufficiently aggressive, may cause crack growth referred to as stress corrosion cracking even under fixed load. Further, depending on material and application, time-dependent inelastic response such as elevated temperature creep may interact with the fatigue crack growth process and cause additional effects of load hold time, frequency and the like under variable loading.

For a more fundamental understanding of fatigue crack growth, it would seem to be necessary to more fully identify how successive crack tip opening and closing relates to the load history and material constitutive response properties, how the process is affected by the inevitable mechanical contact between protruding features on the crack surfaces (i.e., crack closure), and how local environmental effects control the geometry and relative kinematic reversibility of opening and closing processes at the tip. The nonlinear solid mechanics analysis problems implied are formidable, but possibly they are within range of what can be attacked with modern numerical methods implemented on supercomputers. Concomitant advances in observational techniques and in instrumentation to detect crack closure and to determine how crack advance occurs within a loading cycle are also needed.

A major problem which has emerged in fatigue analysis involves the treatment of very short cracks, e.g., with lengths on the order of one to a few grain diameters or with lengths on the scale of local plasticity. Here the classical approach based on prediction from (usually) long crack laboratory data based on the stress intensity factor seems to be inadequate. Difficulties may arise from unusual surface closure, large scale nonlinearity, local environmental effects, or other as yet unidentified sources. This is an important topic because large fractions of structural lifetime often involve crack sizes in this range. Further, it is essential to deal with the small crack range to develop rational life prediction methodologies inclusive of both fatigue crack nucleation and growth, which are classically treated separately.

Modeling of fatigue in composites, both fibrous and particulate, is still in its infancy. Experimental results point to possibly large stiffness reductions and to strength degradation caused by distributed cracking prior to failure. Analysis of distributed cracking phenomena, as well as of fatigue-assisted growth of large cracks, poses many challenging problems of practical importance in both material and structural design.

Continuing advances in nondestructive evaluation so as to detect and size defects are essential in making advances in life prediction methodology useful in engineering practice. Also, it is important to develop a sounder probabilistic basis for lifetime prediction in design based on uncertainties of the inspection process, on flaw size statistics, and stochastic aspects of flaw growth. Such a development should have significant impact on understanding system reliability, setting inspection intervals and managing availability of replacement parts for critical engineering systems.

6.4 DYNAMIC FRACTURE MECHANICS

Dynamic fracture problems have received a surge of recent attention, and the area has some exciting new results. Potential applications include structural design for crack arrest and earthquake faulting analysis. The analysis and observation of dynamic crack propagation has substantially advanced the understanding of unstable crack growth and how it is influenced by material behavior. Major advances have followed from elastodynamic stress field solutions for unsteady crack growth and from extensions of nonlinear fracture mechanics so as to determine the often substantial influences of material inertia on near tip distributions of stress and plastic deformation. Understanding of dynamic fracture has profited from a close link between advances in theory and in experimental techniques. Those techniques include the generation of controlled dynamic loadings and measurement of unsteady crack motion and intensities of crack tip deformation, e.g., by optical methods, including reflected light caustics, and high speed photography.

An area which is still poorly understood is the viscoplastic-dynamic crack tip response with very high rate plastic flow and this may be essential for understanding such phenomena as fracture mode transitions from, say, ductile voidage to cleavage with low energy adsorption in constructional steels. Also, rapidly moving cracks tend to bifurcate or branch from straight paths and develop often complicated morphologies. At an extreme of such behavior, fragmentation of solids such as resource-containing rocks by multiple cracking under explosive loading is a challenging area in need of basic understanding, as is the related problem of penetration or perforation in high speed impact.

6.5 MATERIALS SCIENCE OF FRACTURE PHENOMENA

Cooperation between researchers in mechanics and materials science has long been a hallmark of fracture research. Such collaboration is now more apparent, and even more essential, in several areas on the forefront of research. The tailoring of materials with improved fracture properties, while still maintaining desired strength, requires a more fundamental understanding of the mechanics of crack initiation and growth as it is influenced by material deformation and failure mechanisms at the microscopic level. In different circumstances consideration of microscopic response at the level of atoms, long chain polymer molecules, dislocations, interfaces, grains, or other elements of structure may be appropriate.

The methods of both mechanics and materials science are needed to make progress on the challenging problem of characterizing macroscopic fracture properties in terms of material microstructure. Understanding the atomic structure at a crack tip is an important problem for brittle solids failing by cleavage. A critical question is that of what atomic arrangements, material properties and local chemical species, available environmentally or as solutes, enable certain crystal lattices or grain interfaces to undergo atomically brittle separation of bonds, whereas others fail by processes that involve substantial local ductility and plastic shear. For the more ductile structural metals it is essential to understand how stress and plastic flow by dislocation motion lead to microvoid nucleation, by cavitation of interphase boundaries or by inclusion or precipitate cracking, and how the subsequent plastic growth of cavities occurs leading to their coalescence with one another or with a larger crack tip in macroscopic failure. The tendence of plastic flow to localize into shear bands is often an important part of the failure process in such metals. Localization severely limits crack tip fracture toughness in ductile alloys by allowing microvoids to be coalesced unstably at crack tip openings considerably smaller than those expected on the basis of quasistable growth to coalescence. This critical behavior is poorly understood, although very encouraging progress has been made recently in understanding flow localization and related phenomena, such as patchy slip in metals, as instabilities in solutions to the equations of continuum plasticity of ductile crystals.

At elevated temperatures cavities grow in metals and ceramics by diffusive processes, sometimes in combination with plastic flow. The elucidation of the mechanics of such processes applied on the microscale to cavity nucleation and growth on grain boundaries has opened an active area of research on fracture in the creep range. Other research which cuts across the boundaries of mechanics and materials science has made noticeable progress in understanding crazing and associated fracture phenomena in polymers. The design of ceramics with enhanced fracture toughness by exploiting the mechanics of processes such as phase transformation, crack branching and deflection, and stable microcracking has led to toughness levels undreamed of a decade ago and opened new potential structural applications of ceramics. Much remains to be achieved. Even for metal systems the connections between macroscopic features, such as fracture toughness and the ductile-brittle transition, and microstructural features are only qualitatively established at present.

In studies of metals and ceramics there has been a healthy obliteration of the traditional boundaries between applied mechanics and materials science, and leading workers (and their students) have mastered and usefully applied advanced techniques from both disciplines. Thus studies in the micromechanics of fracture draw upon modern instrumentation techniques of electron microscopy, surface analysis, and the like, and both profit from and contribute to fundamental understanding in areas of alloy design and materials processing. Similar interdisciplinary approaches need to be fostered for polymers and composites. The increasing involvement of fracture mechanicians in experiments that measure details of microscale events should enhance significantly the fundamental understanding of fracture.

6.6 FRACTURE MECHANICS IN EARTHQUAKE GEOPHYSICS AND GEOTECHNOLOGY

The solid mechanics techniques developed for fracture studies have found wide recent application in geotechnology and geophysics, especially in earthquake seismology. For example, the compressive failure of brittle rock occurs by microcracking, and progress has been made there on understanding both the growth of cracks in regions of local tensile stress concentration and, although more limited, the interactions between microcrack arrays in final failure by fault formation. Hydraulic cracking of rock formations for hydrocarbon extraction or geothermal power is an active area of fracture mechanics, and similar techniques have enabled measurement of tectonic stress in the Earth's crust at depths accessible by drilling. Crack modeling of a related kind has helped in understanding magma transport to the surface in volcanic regions.

For earthquake processes, methods developed originally for understanding opening or tensile cracks have been adapted to crustal faults treated on the macroscale as shear-slipping cracks. Here there has been exciting progress in understanding both by rock mechanics experiment and fault modeling the processes which may lead to slip instabilities in the form of earthquakes in relation to slip rate and history dependence of fault frictional resistance. Interest in such studies resides in their potential for identifying possible precursors, in distributions of minor seismicity and ground deformation, to forthcoming large earthquake ruptures and also in understanding the dynamics of rupture propagation. Significant problems arise, however, in reconciling laboratory based estimates of such parameters as critical shear fracture energy or slip weakening displacement on a fault with similar parameters inferred seismologically. The seismological estimates are based on earthquake nucleation or arrest conditions and are generally much larger. This poses the important problems of scaling to field conditions and of the assessment of fault zone geometric complexity effects on macroscale shear fracture response. The elastodynamics of seismic radiation from nonuniformly propagating faults, as affected by "asperities" or "barriers" identified from geological examination and the past seismic record, is an area of intense interest for understanding earthquake ground motions in evaluation of seismic risk and structural response. Here too, as with materials science, an interdisciplinary community of researchers has grown with roots in previously distinct areas of classical seismology and technologically oriented fracture mechanics.

6.7 SUMMARY OF RESEARCH NEEDS

Modern fracture mechanics is a broad discipline that is advancing on many fronts. A partial summary of research needs is as follows:

- *Critical experiments:* Needed for all classes of materials and loading modes to better characterize crack tip processes and separation mechanisms.
- *Fundamental mechanics analysis:* Incorporate realistic inelastic constitutive response, large deformations, and inertial effects as appropriate to provide accurate continuum mechanics characterization of crack tip fields.
- *Fatigue:* Understand how crack growth occurs in a loading cycle, including effects of environment, temperature, crack closure, and hold time.
- *Very short cracks:* Resolve the differences with long crack fatigue response; unify crack nucleation and growth stages in fatigue lifetime prediction.
- *Ductile to brittle cleavage transition in steels:* Address in terms of fracture micromechanisms and viscoplastic dynamics of rapid crack tip stressing processes.
- *Ductile crack growth:* Develop methodologies for predicting initially stable crack growth and final instability conditions, especially beyond regime of validity of J and CTOD approaches.
- *Elevated temperature creep rupture:* Characterize crack tip stress fields for variable load/temperature histories in creeping solids, include distributed damage by cavity nucleation and growth and develop predictive methods for time-dependent fracture development.
- *Fiber-reinforced composites and laminates:* Develop fatigue and fracture methodologies accounting for large zones of microcracking, fiber pullout, debonding, and ply delamination.
- *Structural analysis:* Improve stress analysis to implement fracture mechanics procedures for flaws in structures in service, taking account of residual stresses at welds, complexities of stress state at adhesive joints, etc.
- *Atomistics of fracture:* Address atomic structure of brittle crack tip and factors determining brittle vs. ductile response to loading.
- *Void nucleation and growth:* Model mechanisms of microvoid nucleation and plastic and/or diffusive processes of growth to coalescence as they occur in various classes of materials, both as macrocrack tip processes and distributed damage mechanisms.
- *Shear localization:* Understand factors leading to shear localization as a precursor to or accelerator of ductile voidage failure mechanisms.
- *Microstructure design:* Address design of materials microstructures in heterogeneous alloys and composites to promote crack branching and deflection, favorable phase transformations, and other features leading to resistance to crack growth.
- *Brittle failure in compression:* Model crack nucleation in compression, interaction of crack arrays, and ultimate formation of throughgoing fault.
- *Earthquake fault dynamics:* Relate conditions leading to earthquake instability and shear rupture propagation to laboratory response of fault zone materials; address geometric complexity of natural faults and scaling.

6.8 BIBLIOGRAPHY

Contributions on fracture phenomena can be found throughout the engineering solid and structural mechanics literature and in much of that on materials science and some on solid earth geophysics. Thus it is difficult to cite inclusive sources. However, two journals specializing in fracture phenomena are *Engineering Fracture Mechanics* (Pergamon) and *International Journal of Fracture* (Noordhoff). Many of the seminal theoretical mechanics contributions to the field have appeared in *Journal of the Mechanics and Physics of Solids* (Pergamon) and *Journal of Applied Mechanics* (ASME Transactions); frequent contributions are also to be found in other ASME Transaction Journals, e.g., *Pressure Vessel Technology* and *Engineering Materials and Technology*. A major journal for materials science oriented contributions fracture in recent years is *Acta Metallurgica* (Pergamon).

An overall perspective on fracture research is provided by proceedings of the International Conferences on Fracture (ICF), held approximately every four years since 1965. Citations for the two most recent are:

Francois, D (Ed) (1981). *Advances in fracture research,* Proc 5th ICF, Cannes, Pergamon, New York.

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Bradt, R C, Evans, A G, Hasselman, D P H, and Lange E F (Eds) (1983). *Fracture mechanics of ceramics,* Proc 3rd Int Symp, Plenum, New York, vols 5 and 6.

Latanision, R M, Pickens, J R (Eds) (1983). *Atomistics of fracture,* Plenum, New York.

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Also, many ASTM special technical publications are devoted to fracture topics, including proceedings of the annual ASTM National Symposia on Fracture Mechanics.

Many good textbooks on fracture now exist, emphasizing different combinations of basic solid mechanics, materials aspects, and structural applications. A comprehensive and up-to-date coverage of advanced developments in crack mechanics, especially those of interest for structural applications, is given by

Kanninen, M F, and Popelar, C H (1985). *Advanced fracture mechanics,* Oxford Univ Press/Clarendon Press, Oxford.

Also, an earlier and somewhat more elementary treatment, focused on materials aspects for brittle solids, is given by

Lawn, B R, and Wilshaw, T R (1975). *Fracture of brittle solids,* Cambridge Univ Press, Cambridge.