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Dynamic failure mechanics

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Abstract

Advances in computing as well as measurement instrumentation have recently allowed for the investigation of a wider spectrum of physical phenomena in dynamic failure than previously possible. The current status and potential topics for research in dynamic failure mechanics are described in this article. These include basic research in dynamic crack initiation and growth in brittle materials, elastic–plastic solids, heterogeneous solids, such as layered materials and composites, and adiabatic shear banding in ductile materials. Research that would benefit and advance practical applications such as aircraft hardening, micrometeorite impact shielding and high speed machining is also outlined. For each of the topics, research needs in terms of theory, numerical simulation and validation as well as experimentation are described.

Keywords: Dynamic failure; Crack initiation; Crack growth; Adiabatic shear banding; Elastic–plastic fracture; Layered materials; Composites; Applications

1. Introduction

Dynamic Failure Mechanics is the study of failure phenomena in the presence of high local strain rates. Such phenomena can be divided into two major categories. These are, Dynamic Fracture and Dynamic Shear Localization or Adiabatic Shear Banding. A common characteristic of these failure phenomena is the rapid loss of stress carrying capability in time scales such that inertial and or material rate sensitivity effects are important or in time scales short compared to the characteristic wave transit times in a structure.

Dynamic Fracture deals with conditions leading to the rapid creation of displacement discontinuities (opening and/or shear) resulting in the creation of new surfaces. Dynamic Shear Localization deals with conditions leading to the rapid creation of velocity (displacement gradient/strain rate) discontinuities across narrow rapidly expanding regions accompanied by rapid loss of stress carrying capability and

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intense heating due to the dissipation of plastic work. Shear bands often serve as sites of initiation and growth for subsequent dynamic fracture.

Dynamic fracture problems can be classified into two major problem types:

1. Dynamically (stress wave) loaded stationary cracks resulting in fracture initiation at times t^*, short compared to the time associated with the transit time of a Rayleigh wave (wave speed, c_R) along the crack length, l ($c_R\ t^*/l < 1$).
2. Dynamically growing cracks featuring crack tip speeds higher than 20% of the material Rayleigh wave speed. Such growing cracks can be generated by either static or wave dominated loading. They can be classified as 'steady state' dynamic (high but constant speeds) and 'transient dynamic' (high speed and acceleration [10^5–10^8 g]).

Dynamic Shear Localization is intimately related to three different aspects of material constitutive behaviour as follows:

1. Material Strain Hardening
2. Strain Rate Hardening (Rate Sensitivity)
3. Thermal Softening

Dynamic localization is a result of the highly coupled competition between thermal softening and the strain and strain rate hardening mechanisms. Dynamic shear bands typically feature 'large' shear strains (typically in excess of 1). High strain rates (10^4–$10^7\ \mathrm{s}^{-1}$) and very high temperatures (80–100% of the material melting point) all happening within narrow regions (1–100 μm). The speeds of propagation of dynamic shear bands are often comparable to those observed during dynamic fracture phenomena in the same solid.

A number of important but isolated contributions to dynamic failure mechanics have been made as early as the decade of the fifties. However, this sub-discipline of failure mechanics has emerged as a well-defined scientific field only in the last three decades. The early development of the discipline was motivated by a number of real world problems related to defense, mining, and structural reliability. Such applications included armor/anti-armor problems, fragmentation, catastrophic failure of weldments in ships, pipelines, nuclear pressure vessels, and other structures. This work was funded by a variety of Federal agencies which include ONR, ARO, DOE, NSF, NRC, and USGS.

In the early years (40's and 50's), a few isolated experimental observations of the dynamic fracture of brittle materials and some qualitative observations of dynamic shear localization motivated the development of strong analytical foundations. This was followed by critical experiments which strived to verify the theories and to identify key phenomena. However, despite some initial success in the 70's and 80's, rapid progress was impaired by a number of factors. These included the high complexity of analytical models of failure, the absence of computational methodologies capable of modeling dynamic decohesion and localization and the lack of the technology and tools necessary for performing high speed deformation and temperature measurements with requisite accuracy.

In the last few years several new exciting developments have taken place and have opened up the possibility of major breakthroughs in this area. In particular, we have recently witnessed major developments in computational mechanics tools capable of simulating dynamic failure processes in practically reasonable computational times and high accuracy. These include cohesive element methodologies, adaptive mesh refinement techniques, meshless methods, and large-scale atomistic simulations all of which are now being implemented in three dimensions. Concurrently, new Charge Coupled Device (CCD) technology and data acquisition devices have enabled the development of ultra high speed diagnostics (framing rates up to 100 million frames per second) capable of performing high fidelity, full field measurements of transient deformation and temperature fields in real time (both visible and infrared wavelengths).

These concurrent computational and experimental developments are indeed serendipitous. On the one hand, the availability of experimental tools capable of performing accurate measurements have provided *new observations* of previously unknown dynamic physical phenomena and have generated new insights regarding failure criteria. They have also opened up the possibility for providing much needed calibration and validation of the newly proposed elaborate computational methodologies by insuring that the correct physical mechanisms of dynamic failure are incorporated into the numerical codes. This has created a multiplicity of new exciting avenues for research of an interdisciplinary nature. On the other hand, these dual developments have opened up wide ranging possibilities of realistic and cost effective analysis and simulation of *full scale structures* undergoing dynamic deformation with the goal of assessing and predicting possible failure modes. Indeed, this is the first time in the history of computational mechanics that codes have attained the possibility of incorporating the phenomena of dynamic fracture and localization and not merely performing elaborate dynamic stress analysis.

The above computational/experimental framework is motivated by new, emerging applications, which are not primarily driven by defense needs. These applications include high speed machining (e.g. cutting, drilling), aircraft hardening (blast induced fuselage failure), spacecraft shielding against micometeorite impact, fragmentation, failure of composite and sandwich structures and on a very different length scale, fault rupture leading to earthquakes. As will be discussed in the end of the following section, this latter area has recently been associated with a series of new and existing theoretical developments on the subject.

In this article we outline our views on future basic research needs in Dynamic Failure Mechanics. We also discuss, through examples, strategies of transferring basic knowledge of dynamic failure into acceptable engineering design practice. We first subdivide our discussion along the lines of dynamic failure phenomena characteristic of different classes of materials such as Brittle, Ductile, and Inhomogeneous Solids. We also discuss separately the issues pertinent to simulation verification and validation as well as engineering applications.

2. Brittle solids

The field of dynamic fracture mechanics was initiated with nominally brittle materials in mind. Indeed, both early experimentation and theory was based on materials that were assumed to remain linear elastic up to failure, an assumption that enabled the analytical treatment of dynamic fracture problems. From the analytical point of view, emphasis was placed on formulating and solving well posed initial/boundary value problems in linear elastodynamics involving either stationary or propagating cracks subjected to static or stress wave loading (Early examples include: Yoffe, 1951; Broberg, 1960; Atkinson and Eshelby, 1968; Achenbach, 1970a,b; Kostrov and Nikitin, 1970; Freund, 1972a,b,c; Achenbach, 1974; Willis, 1975). The major reference on these subjects is the extensive monograph by L.B. Freund (Freund, 1990). Such analyses typically provided the time history of the dynamic *stress* intensity factor $K_I^d(t)$ as a function of loading condition, geometry, and crack tip speed. A key result of such analyses relates the dynamic stress intensity factor $K_I^d(P(t),a(t),(t))$ for a running crack with an instantaneous speed $\dot{a}(t)$ and generalized load $P(t)$ to the value of the stress intensity factor of an equivalent stationary ($\dot{a}(t)=0$) crack at the same instantaneous crack length $a(t)$ and load $P(t)$ as follows (Freund, 1972b, 1990).

$$K_I^d(P(t),a(t),\dot{a}(t)) = k(\dot{a})K_I^d(P(t),a(t),0) \tag{1}$$

where $k(\dot{a})$ was found to be a universal function of crack tip speed which decreases from 1 to 0 as the crack tip speed increases from 0 to c_R (Rayleigh wave speed).

This remarkable result (Freund, 1972b), allows for the evaluation of stress intensity factors for propagating cracks in terms of known solutions for equivalent stationary cracks subjected to arbitrary dynamic loading. An equivalent form of Eq. (1) is also available for dynamic energy release rates. (See discussion by Freund, 1990)

Continuum mechanics analyses are, however, incapable of providing crack initiation conditions and velocity histories in the absence of *additional* crack initiation and growth criteria. Such criteria have customarily been based on two approaches. The first is related to the assumptions that there always exists a region (albeit small) near the crack tip (stationary or growing) where the dynamic stress intensity factor characterizes the amplitude of the local stresses and thus controls the failure process (condition of K-dominance) (Freund and Rosakis, 1992). Once this assumption is made, the notion of a material property called the *dynamic fracture toughness* emerges. For crack initiation under different loading rates the *critical* dynamic stress intensity factor K_{IC}^{d} corresponding to crack initiation at time $t=t^*$ is called the *dynamic initiation fracture toughness*. It has been recognized that this property should be a function of an appropriate measure of the loading rate experienced near the crack tip. Consistent with the initial assumption of K-dominant conditions, this can only be related to the rate of change of the common amplitude of the stresses there (e.g. $\dot{K}_{I}^{d}(t^*)$ or K_{IC}^{d}/t^*). As a consequence of the above, a dynamic crack initiation criterion can be formulated as follows:

$$K_{I}^{d}(t) = K_{IC}^{d}(\dot{K}_{I}^{d}(t)) \text{ at } t = t^* \tag{2}$$

The right hand side of Eq. (2), symbolically representing the dependence of the dynamic initiation fracture toughness, K_{IC}^{d}, on loading rate, $\dot{K}_{I}^{d}(t)$, can only be obtained experimentally (Ravi-Chandar and Knauss, 1984a; Dally and Barker, 1988; Suresh et al., 1990; Owen et al., 1998). This quantity is crucial in the prediction of dynamic crack initiation time and critical loading conditions and should be used as input to the new generation of fracture based, numerical codes.

When a mode-I crack initiates dynamically, after Eq. (2) is satisfied, it grows with a crack tip speed history, $\dot{a}(t)$, not predictable by continuum mechanics alone. Here again we require the notion of a *dynamic crack growth toughness* which would similarly be a material dependent function of a near tip measure of deformation rate. For growing mode-I cracks, the dominant contribution to the strain rate near the propagating crack tip is proportional to the instantaneous crack tip speed. As a result, the dynamic crack growth toughness is expected to also be some material dependent function of the crack tip speed, (i.e. $K_{ID}(\dot{a})$). For this case a dynamic crack growth criterion could be formulated as follows:

$$K_{I}^{d}(P(t),a(t),\dot{a}(t)) = K_{ID}(\dot{a}(t)) \quad \text{for} \quad t > t^* \tag{3}$$

In the above relation, the right hand side can only be determined by experiment (Bradley and Kobayashi, 1970; Dally, 1979; Dally and Shukla, 1980; Ravi-Chandar and Knauss, 1984a,b; Dally et al., 1985). Eq. (3) is a nonlinear first order differential equation for $a(t)$ and is called the *equation of motion* for the crack tip (Freund, 1990). The left-hand side can either be obtained analytically, for simple cases, or through numerical computation, for complex loading histories and geometries of practical interest. For high strength metals and polymers, $K_{ID}(\dot{a})$ is typically found to be an increasing function of crack tip speed (e.g. Kobayashi et al., 1976; Kobayashi and Dally, 1979; Rosakis and Zehnder, 1985; Shukla et al., 1988). The drastic increase of the crack growth toughness at a speed approximately equal to 30% of the Rayleigh wave speed, c_{R}, has been explained for metals on the basis of a mechanism of interaction between crack tip plasticity and material inertia present due to the dynamic growth of the crack (Freund and Douglas, 1982; Lam and Freund, 1985; Freund and Hutchinson, 1985). This toughness increase accounts for the existence of a mode-I terminal crack tip speed of approximately 30% c_{R}. For more brittle solids such as ceramics or glasses the mechanism of dynamic toughness increase is still under investigation as is the detailed nature of $K_{ID}(\dot{a})$ Here again single, mode-I, dynamic cracks are not sustainable above 40–45% c_R. When this speed is approached, the cracks go in to a mode of attempted branching that greatly enhances the energy required for crack growth. Eventually they choose to branch (Kobayashi et al., 1974; Ramulu and Kobayashi, 1983; Ramulu et al., 1983; Ravi-Chandar and Knauss, 1984c; Gao, 1993, 1996, 1997; Suzuki et al., 1998) thus eventually minimizing the requisite energy for damage evolution. Most recently a series of investigators from the Physics community revisited this phenomenon and have provided alternative interesting viewpoints to its explanation (Langer, 1992; Abraham et al., 1994, 1998; Boudet et al., 1995; Marder and Gross, 1995; Sharon et al., 1995, 1996; Sharon and Fineberg, 1998). The introduction of a weak crack path in the form of a bond between identical plates (Washabaugh and Knauss, 1994) can suppress branching and thus allow a mode-I crack to reach c_R. It should be noted at this point that c_R is the upper theoretical speed limit for Mode-I cracks as established by energetic arguments described by Broberg, 1985 and Broberg, 1989 and extensively discussed by Freund, 1990 (for dynamic mode-II shear cracks propagating along weak planes the situation is entirely different. For discussion, see section on Inhomogeneous solids).

The forgoing discussion, although formally complete, has been based on the assumption of dynamic K-dominance, a condition that may break down under severe transient loading. Under such circumstances, two points may be relevant. First, the experimental measurements leading to the evaluation of the dynamic initiation and growth toughness are particularly difficult and should be performed by properly accounting for the higher order structure of the near tip deformation fields at finite (even small) distances from the tip where the measurement is performed. Second, at short times following initiation at highly transient instances (e.g. wave arrivals or arrest events) the assumptions leading to toughness being a simple function of a crack tip speed, may be questionable since for highly transient situations the crack tip speed may not be the only dominant measure of near tip rate. Indeed, this observation leads us to a totally unexplored area of dynamic fracture in nominally brittle solids that of highly transient crack growth (Freund and Rosakis, 1992).

In addition to the two-dimensional issues discussed above, in the past five years we have witnessed a revival of the interest in three-dimensional analytical crack growth studies, primarily driven by problems in Geomechanics (Dmowska and Rice, 1986). Here some of the questions of interest include the non-uniform (planar or out of plane) growth of three-dimensional, mixed-mode, crack fronts which propagate unstably through a locally heterogeneous material of spatially varying fracture toughness. Pioneering contributions to various aspects of this highly challenging problem has been made by Rice et al. (1994), Perrin and Rice (1994), Willis and Movchan (1995), and more recently by Morrissey and Rice (1998), Woolfries and Willis (1999), Willis and Movchan (1999), and Morrissey and Rice (1999). One of the exciting new predictions associated with this series of investigations is the identification and study of persistent elastic waves generated due to a localized perturbation of the growing crack front. These waves either propagate along the moving crack front or propagate outwards as body and surface waves which may later intersect distant segments of the same crack front (Morrissey and Rice, 1996, 1999).

2.1. Research needs

1. Analyze the basic local micromechanisms of failure, responsible for the rate dependence of dynamic toughness (for both initiation and growth). Explain the differences in the rate dependence of toughness observed between nominally brittle structural solids, such as high strength steels, and highly brittle materials such as structural ceramics, glasses, and geomaterials.
2. Identify the appropriate macroscopic measures of dynamic crack initiation toughness as well as measures of loading rate for dynamically loaded cracks under mixed mode conditions.
3. Extend the steady state dynamic crack growth concept to highly transient conditions and far field

mixed-mode loading. Examine the conditions leading to dynamic crack growth along curved paths and non-planar crack fronts.
4. Establish engineering criteria for crack tip kinking and branching (predict branch angles, toughness, speeds, and examine post-branching behavior).
5. Develop fracture mechanics based theories of fragmentation and investigate the relation of these phenomena to basic branching and toughness mechanisms.
6. Perform critical experiments involving high accuracy, high speed optical diagnostics to verify the newly developed, three-dimensional, non uniform crack front growth theories
7. Use dynamic fracture mechanics models and benchmark experiments to investigate the phenomenon of spall.
8. Develop micromechanical, mixed mode, dynamic fracture models to study macroscopic failure modes occurring during compression failure of brittle solids such as axial splitting and comminution.

3. Ductile solids

3.1. Dynamic fracture

The dynamic fracture of ductile materials is a subject that remains virtually unexplored. This situation is a result of the lack of advanced analytical numerical and experimental tools for the study of such a complex phenomenon. The typical approach encountered in the literature is to attempt to extrapolate the behaviour encountered during quasistatic failure of such solids into the regime of 'intermediate' loading rates.

For growing tensile cracks in highly idealized plastic solids there have been only a few, two-dimensional, asymptotic analytical solutions as well as some preliminary numerical investigations (e.g., Achenbach and Dunayevsky, 1981; Achenbach et al., 1981; Freund and Douglas, 1982; Lam and Freund, 1985; Deng and Rosakis, 1991; Deng and Rosakis, 1994). However, these solutions, despite their fundamental importance, have failed to provide appropriate engineering measures of dynamic crack growth toughness and to thus establish detailed crack growth criteria. Furthermore, these solutions have not been conclusively corroborated by detailed experiments.

The few successful experiments which have been performed in such solids are limited to, a) strictly small scale yielding (SSY) conditions in which $K_{IC}^{d}(\dot{K}_{I}^{d})$ was still used as a measure of *initiation* toughness (Costin and Duffy, 1979; Nakamura et al., 1985; Owen et al., 1998) b) large scale yielding (LSY) conditions, where a critical value of the generalized J integral, $J_{c}^{d}(\dot{J}^{d})$ was used as a measure of dynamic crack initiation toughness (e.g., Nakamura et al., 1988; Guduru et al., 1998). Proposed measures have included other forms of concervation integrals e.g., T^{*} (Nishioka and Atluri, 1983) and crack growth opening displacement δ.

In both of the above cases, experimental difficulties included the determination of the time of crack initiation, the actual measurement of the toughness parameter and were hindered by the limited range of loading rates that could be generated easily in the laboratory.

Typically, mode-I fracture of plate geometries of ductile solids involves two distinct modes of failure both contributing to the apparent structural toughness. In addition to the well-defined tunnel region in the plate's interior (mainly plane strain) there always exist extensive regions of out of plane localization and ductile shear failure (shear lips) which contribute heavily to the mechanism of energy dissipation. The relative extent of tunneling versus shear lip formation and its dependence on loading rate has remained elusive. Another important aspect of the ductile fracture process which is only present during dynamic (virtually adiabatic) failure, is the effect of the conversion of plastic work into heat near the initiating or growing crack tip region and at the vicinity of the resulting shear lips (Zehnder and Rosakis, 1991). This phenomenon which may be in competition with rate hardening mechanisms could lead to the phenomenon of 'rate induced' *brittle to ductile transition* at elevated loading rates. Finally, recent theories of the effect of crack tip constraint (e.g. J–Q theory) on quasistatic toughness (O'Dowd and Shih, 1992) have not as yet received any attention in dynamics.

3.2. Research needs

1. Identify the appropriate measures of dynamic toughness and strain rate at crack initiation (e.g. J, T^*, δ) for mode-I and Mixed mode loading. For mixed mode loading identify appropriate measures of mode mixity.
2. Evaluate the effect of the time varying constraint, $Q(t)$, on the proposed dynamic crack initiation criterion. Extend the concepts of crack tip constraint to dynamic fracture.
3. Assess the roles of the competing mechanisms of strain hardening, strain rate hardening and local thermal softening on the loading rate dependence of dynamic toughness.
4. Develop high-speed diagnostics for the full field measurements of large near tip deformations and temperatures for reliable determination of initiation time and toughness.
5. Investigate the range of achievable crack growth speeds under plane strain conditions and at different crack tip constraints.
6. Investigate dynamic fracture/failure of thin plates mainly involving failure by shear lip formation across the thickness.
7. Study the physical mechanisms of failure. In particular investigate the effect of loading rate on the choice of either shear versus tensile modes of failure.
8. Investigate the mechanics of the micromechanisms of failure (void generation, growth coalescence in the presence of interial, rate, and adiabatic heating).
9. Investigate dynamic failure phenomena in the vicinity of joints or welds.

3.3. Dynamic shear banding

Dynamic shear band initiation and growth involves the generation and subsequent growth of narrow regions of highly deformed material, across which, high gradients of strain, strain rate and temperature are encountered. These entities, often referred to as adiabatic shear bands, posses a distinct edge or tip which propagates dynamically with speed as high as 30–50% of the shear wave speed (Zhou et al., 1996a) and may even branch. This phenomenon is ultimately related to the constitutive nature of the solid and in particular to the competition between strain and strain rate hardening and deformation induced thermal softening. In ductile solids dynamic shear bands are a mechanism, alternative to dynamic tensile fracture but can also serve as precursors and preferred sites for subsequent dynamic crack initiation and growth.

Most of the existing analysis and experimentation in this area has been confined to situations that are essentially one dimensional (e.g., Clifton, 1980; Bai, 1982; Molinari and Clifton, 1987; Wright and Walter, 1987; Shawki, 1992; Leroy and Molinari, 1992; Bai and Dodd, 1992; Wright and Ravichandran, 1997; Marchand and Duffy, 1988). and have been primarily concerned with the investigation of critical conditions leading to shear band initiation. Only recently, the two dimensional nature of shear bands has been recognized and studied experimentally (Kalthoff and Wrinkler, 1987; Mason et al., 1994; Ravi-Chandar, 1995; Zhou et al., 1996a; Rittel and Levin, 1998) theoretically and numerically (Needleman and Tvergaard, 1995; Gioia and Ortiz, 1996; Zhou et al., 1996a,b; Batra and Nechitailo, 1997; Mercier and Molinari, 1998).

The relation between dynamic shear bands and dynamic cracks, although strong, remains elusive. It is indeed attractive to attempt to introduce the notion of *shear band initiation and growth toughness* (Grady, 1992; Zhou et al., 1996b) equivalent to that of dynamic cracks. However, it should be recognized that the essential lack of a driving singularity at a shear band tip necessitates modifications of the fracture mechanics based toughness notion in order to apply to this phenomenon. Only extensive and high-speed thermographic and optical experimentation can identify the details of the basic physics involved in this process to be included into meaningful analytical and numerical models.

The connection of dynamic shear band formation to dynamic fracture is even made stronger by the phenomenon of failure mode transition. As has been observed experimentally, dynamic shear loading of precracked plates may either induce dynamic tensile cracking or dynamic shear banding as a direct result of the competition between material ductility, rate, and fracture toughness. (Lee and Freund, 1990; Needleman and Tvergaard, 1995; Ravi-Chandar, 1995; Zhou et al., 1996b). Critical conditions leading to such a transition of failure modes, which may not be present in all materials, are poorly understood.

3.4. Research needs

1. Examine the conditions leading to the formation of two-dimensional shear bands (develop a shear band initiation criterion).
2. Perform detailed real time experimental examinations of the two-dimensional deformation and temperature fields near initiating and propagating shear band tips and within the evolving shear bands.
3. Study the constitutive behaviour of material within the shear band. This material typically experiences very high strain rates, large strains, and high temperatures.
4. Establish the physical phenomena and processes leading to the selection of failure modes (cracking vs. shear banding) in solids.
5. Identify appropriate measures of shear band initiation and growth toughness and thus establish an equation of motion for the shear band. Investigate the relation of shear band toughness to dynamic fracture toughness and classify solids according to their resistance or propensity to shear banding.
6. Investigate the role of superposed hydrostatic pressure on shear band characteristics (width, temperature, etc.).
7. Examine the phenomenon of dynamic shear band branching.

4. Inhomogeneous solids

With increasing demand for specialized lightweight, high strength structures, failure of inhomogeneous solids has been receiving increased attention. Such inhomogeneous solids include structural composites such as bonded and sandwich structures, layered and composite materials, as well as functionally graded solids. Many of such solids are composed of brittle constituents possessing substantial mismatch in wave speeds, and are bonded together with weak interfaces, which may serve as sites for catastrophic failure. Indeed, many of such solids are designed for applications involving either anticipated or accidental impact loading. On a very different length scale, the layered structure of the earth's crust, containing weak interfaces in the form of earthquake faults, presents another example where dynamic failure

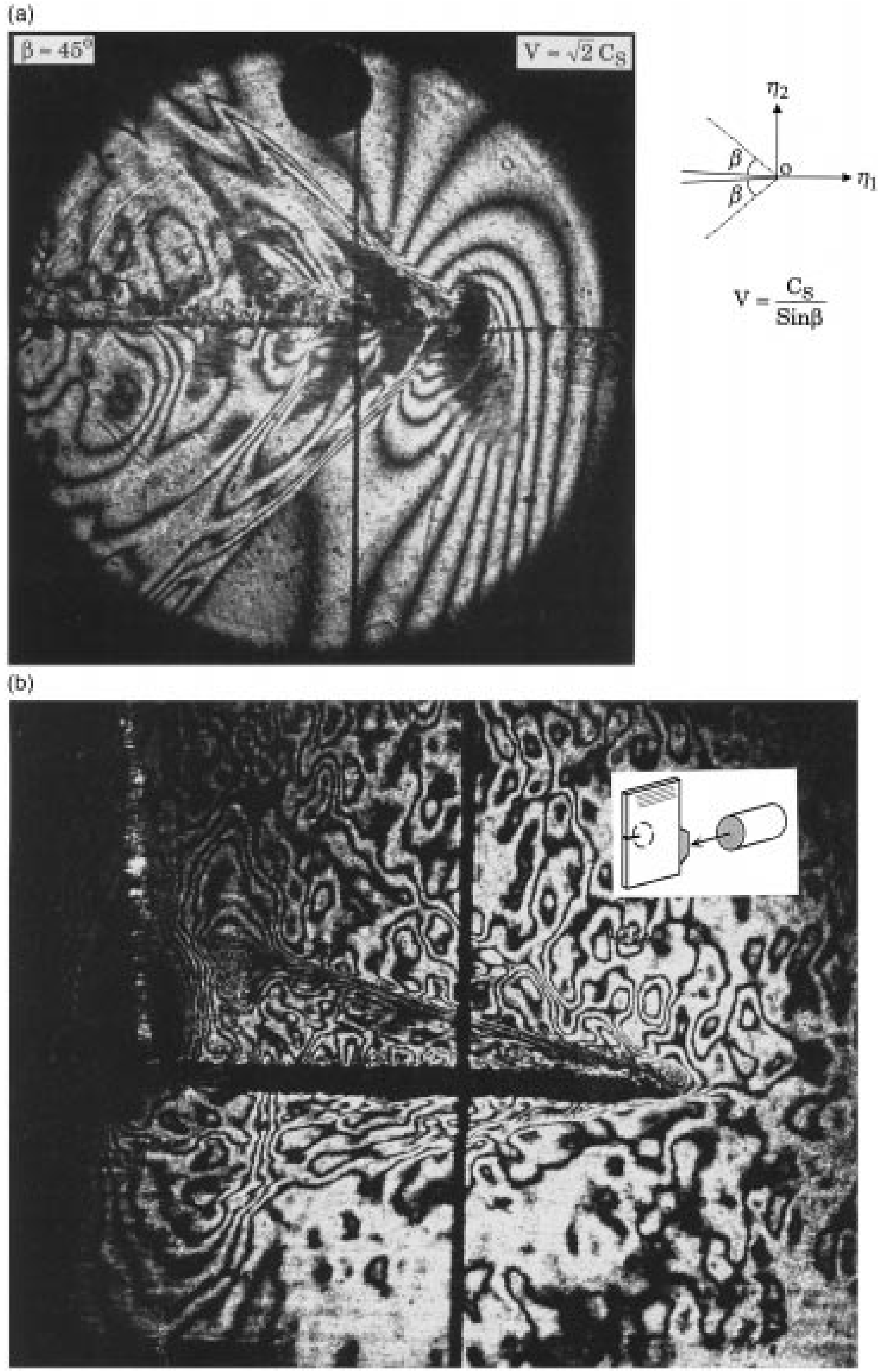

Fig. 1. (a) A photoelastic image of a shear crack moving intersonically along the bond between two identical Homalite-100 plates. (Crack tip motion is from left to right. Shear shock waves are visible). (b) A CGS interferogram (reflection) of a shear crack moving intersonically along the fibers of a unidirectional graphite-fiber, epoxy-matrix composite plate (crack tip motion is from left to right, shear shock waves are visible).

through rupture is important (Andrews, 1976, 1985; Burridge et al., 1979; Heaton, 1990; Zheng and Rice, 1998).

It should be noted that many of the above mentioned systems are lacking the traditional ductile dissipation mechanisms present in common structural solids (e.g. metals). This makes them prone to failure by dynamic fracture even in the presence of initially quasistatic loading conditions. Despite its importance in practice, dynamic failure of inhomogeneous systems has received scant experimental attention at best. From the theoretical point of view, early important contributions on the subject include those of Atkinson and Head, 1966; Atkinson, 1974; Atkinson, 1977; Willis, 1971; Achenbach, 1975; Achenbach and Bazant, 1975; Brock and Achenbach, 1973. Recently, several new, counter intuitive, dynamic failure phenomena of layered and composite materials have been identified in the laboratory. Such new phenomena include the observation of shear dominated *intersonic* crack propagation in bimaterial systems (Lambros and Rosakis, 1995b; Singh et al., 1997; Rosakis et al., 1998a) and composite materials (Coker and Rosakis, 1998), as well as in assemblies of homogeneous isotropic solids bonded along weak bonds (Rosakis et al., 1999). These shear dominated intersonic cracks often exhibit large-scale frictional contact even in the absence of superposed pressure. They also feature the formation of distinct *shear shock waves* emanating from the crack tip and the end points of the propagating contact regions. It has also been observed that *subsonic* dynamic cracks propagating along interfaces in either bimaterial or layered composites or even in weakly bonded isotropic solids, do so with toughness decreasing with increasing crack tip speed (Lambros and Rosakis, 1995a). This behaviour is a precursor to the intersonic crack growth regime since it produces highly unstable crack growth histories with accelerations as high as 10^8 g. For identical pieces of weakly bonded isotropic materials, intersonic shear crack tip speeds are found to be as high as 95% of the longitudinal wave speed of the solid (maximum crack tip speed $\sim$2.2 km/s) while for carbon/epoxy unidirectional composites, the maximum observed crack tip speeds are almost equal to 90% of the longitudinal wave speed along the fibers (maximum shear crack tip speed $\sim$9 km/s). In both cases the crack tips greatly exceed the Rayleigh wave speed of the respective solids violating conventional wisdom regarding limiting crack tip speeds (see section on Brittle Solids).

Fig. 1(a) shows a photoelastic image of a shear crack propagating intersonically in the interface between two identical plates of Homalite-100 bonded by a weak polymeric bond (see Rosakis et al., 1998b, 1999). Fig. 1(b) corresponds to a high speed Coherent Gradient Sensing (CGS) interferogram obtained by reflection from the surface of a thick unidirectional carbon fiber/epoxy matrix composite plate (see Coker and Rosakis, 1998). In both cases, asymmetric impact was used to generate the intersonic shear cracks. Both images clearly show the existence of *shear shock waves* characteristic of the propagation of intersonically moving disturbances.

The accessibility of such crack tip speed regimes, for both Mode-I and Mode-II growing cracks, has been a matter of theoretical debate in the past (Broberg, 1985, 1989; Freund, 1979, 1990; Burridge et al., 1979) while the complete lack of laboratory evidence has hindered progress on the subject. However, the recent laboratory evidence has re-invigorated analytical (Liu et al., 1995; Yu and Yang, 1995; Huang et al., 1998, 1999) and numerical (Lo et al., 1994; Xu and Needleman, 1996; Needleman and Rosakis, 1999; Breitenfeld and Geubelle, 1997) research in this area where a complete explanation of the observation still awaits discovery. An additional source of interest arises from the indirect evidence of intersonic crustal earthquake rupture speeds occurring along fault lines of interest to Geophysics (Archuleta, 1982; Broberg, 1985, 1989; Freund, 1979, 1990; Zheng and Rice, 1998).

Other important dynamic failure modes that are also present in fiber reinforced composites include ply and matrix/fiber delaminations, kink band formation and axial splitting. Such phenomena have been studied extensively in the quasi-static regime, however, their dynamic equivalents are poorly understood. The role of confining pressure and rate on the selection and competition between the above modes should be a focus point of research in this area.

4.1. Research needs

1. Investigate the effect of loading rate and bond strength on the dynamic initiation and dynamic crack growth (subsonic regime) toughness of bonded structures.
2. Study the choice (and mode) of initial dynamic crack path selection in bonded structures as a function of rate, far field, load mixity, and relative dynamic toughness of bond and constituent solids.
3. Investigate the critical conditions leading to highly unstable, intersonic, and even supersonic, crack growth along bonds as a function of bond strength, loading rate, and constituent solid anisotropy (for bimaterial, multimaterial and single material bonded structures).
4. Analyze and measure dissipation mechanisms resulting from large-scale contact and crack face friction during intersonic crack growth (investigate the effects of velocity dependent friction).
5. Establish fracture criteria for intersonic crack growth by identifying appropriate, measurable, fracture parameters. Investigate the formation of shear shocks during failure of inhomogeneous solids and strengthen the connection between laboratory observations, geological field data, and geological models of fault rupture.
6. Examine the effect of strain rate and hydrostatic pressure on the selection of failure modes in fiber reinforced composites (dynamic kinking, splitting, delamination).
7. Experimentally study and formulate criteria for dynamic delamination and/or failure of layered and graded structures.

5. Numerical simulation, validation and verification

The majority of computational advances to date have primarily been concerned with the development of codes limited to performing elaborate linear or nonlinear stress analysis. Within this framework, the simulation of both quasi-static and dynamic failure processes has traditionally proceeded through either the use of continuum damage accumulation constitutive models, resulting in eventual loss of stress carrying capability, or through the artificial release of nodal forces, to simulate crack initiation and growth, based on some experimentally established fracture criterion. Typical difficulties characteristic of these approaches are inherent mesh sensitivity, in the absence of a material length scale (damage models), and the lack of a physical basis for the details of the assumed nodal release mechanisms (introducing artificial history dependence). Among the shortcoming of these traditional methods for simulating dynamic fracture and shear banding are their inability to track the formation, propagation, and branching of multiple dynamic cracks (e.g. fragmentation, multisite spall) and to experimentally predict observed propagation histories of dynamically growing shear bands.

Recent spectacular computational advances have made it possible for the first time to incorporate key fracture concepts into the numerical formulation in the form of randomly distributed cohesive interfaces (Needleman, 1990; Xu and Needleman, 1994 and 1996; Camacho and Ortiz, 1996; Pandolfi et al., 1999). Indeed, in addition to the traditional constitutive behaviour of the bulk material, the new cohesive methodology attempts to incorporate the physics of material separation through a separate decohesion law whose parameters can be calibrated from fracture experiments. Remaining research issues include the question of validation and verification of such approaches through comparison with model experiments and existing analytical solutions, respectively (Ortiz, 1998; Rosakis et al., 1998b).

Other developments have also contributed to the advances in the simulation of both quasistatic and dynamic fracture events. These include recent impressive advances in meshless methods (Belytschko et al., 1996; Belytschko and Tabbara, 1996) recent work on Atomistic simulations of fracture (Abraham et al., 1994, 1998; Gao, 1996, 1997; Gumbsch et al., 1997 Cramer et al., 1997), and the availability of massively parallel computation necessary for complex dynamic failure problems. It should be noted that the above new methods have already shown promise for modelling dynamic fracture in brittle solids, however, their applicability to the study of failure mechanisms in ductile materials has yet to be established. For the case of Atomistic simulations, it should be noted that the issue of the connection with larger length scales is very important and is still under investigation (Kohlhoff et al., 1991; Miller et al., 1998).

5.1. Research needs

1. Establish consistent procedures for calibration, verification and validation of the newly proposed methods against existing analytical solutions and key benchmark dynamic fracture experiments (e.g. prediction of crack tip speed histories, and the dependence of dynamic fracture toughness on loading rate and crack tip speed).
2. Perform realistic simulations of dynamic crack kinking, branching, and fragmentation, validated against detailed real time experiments (see section on brittle solids).
3. Clarify and separate the individual roles of bulk plasticity/rate sensitivity, inertia, and cohesive law properties on the evolution of dynamic fracture toughness.
4. Expand the notion of cohesive separation to include the physical mechanisms of ductile failure by void growth and coalescence, introduce different length scales.
5. Extend all new numerical methodologies to the simulation of three-dimensional mixed-mode dynamic failure events compare to newly developed analytical solutions of non uniform (planar or out of plane) crack front growth (see end of section on Brittle Solids). To include the prediction of failure by flat fracture, (tunneling) shear lip formation, and their dependence on rate, temperature, and constraint (see section on ductile solids).
6. Perform three-dimensional realistic simulations of dynamic shear band initiation and growth including the accurate prediction of shear band speeds, mechanical, and transient temperature fields. Identify the relative importance of strain hardening, strain rate hardening, and thermal softening (see Section 3 on Ductile Solids).
7. Apply of the new computational methodologies to the accurate prediction of new highly dynamic and intersonic fracture phenomena characterizing bonded and layered structures (see Section 4 on Inhomogeneous Solids).
8. Model failure modes and their transition for layered, sandwich and composite structures at a variety of dynamic loading conditions. Predict favored dynamic failure mechanisms including kinking, axial splitting, and delamination (see Section 4 on Inhomogeneous Solids).
9. Expand the magnitude of Atomistic simulations to the point that meaningful comparisons with dynamic fracture experiments can be made. To be achieved by multiscale simulations.

6. Applications

The use of dynamic fracture mechanics principles has historically been confined to the analysis of certain limited applications which include rupture and catastrophic failure of pressurized pipelines (Kanninen et al., 1976; Freund and Parks, 1980; Kobayashi et al., 1988) and other conventional pressure vessels (Kanninen and Popelar, 1985; Kanninen and O'Donoghue, 1995). In recent years, substantial advances in the understanding of the basic principles governing dynamic fracture, coupled with the development of new, relatively easy to use verifiable computational methodologies have made it possible to utilize the concepts of dynamic fracture to a much wider spectrum of very diverse applications some examples of which are outlined below.

It is commonly perceived that dynamic failure is mainly relevant to military applications including armor/anti-armor problems and to situations involving explosive loading. However, it has been recently recognized that dynamic fracture plays a pivotal role in a number of non-military applications relevant to our rapidly developing technological world, such as accident prevention, manufacturing processes, and reliability in design. Examples include *aircraft hardening* (prevention or containment of catastrophic explosive failure of fuselage or cargo holds of aging aircraft), *spacecraft/satellite shielding* (prevention of failure due to hypervelocity impact of micrometeorites, space debris particles on critical components such as fuel tanks), and high speed machining (understanding the physics of high speed cutting, drilling, etc.).

6.1. Research needs

6.1.1. Aircraft hardening

Determine the interplay between aircraft structure (global dynamic loading due to internal explosion) and the response of individual fatigue cracked panels (e.g. pre-existing multisite damage in aging aircraft). Use proven dynamic fracture principles to predict/control crack initiation, growth arrest and to obtain simple engineering criteria for the residual strength of the damaged structure. Perform experimental verification of these concepts. Also investigate the related phenomena of petalling (mode-III fracture) along abrupt changes in thickness. Equivalent approaches can be used for the analysis of any pressurized containers subjected to explosive loading.

6.1.2. Spacecraft/satellite shielding

Perform controlled experiments to obtain basic phenomena of hypervelocity impact to elucidate the underlying mechanisms (e.g. phase changes involved, tensile and shear dynamic failure mechanisms). Design effective shielding based on structural and failure response of shielded component (optimization of shield configurations). Develop verifiable computational methodologies to simulate the phenomena in the experimentally available velocity range (10 km/s). Perform extrapolation of the numerical simulations to higher velocity ranges of interest (10–35 km/s).

6.1.3. High speed machining

Perform controlled experiments to identify the failure modes and the resulting chip morphology as a function of dynamic material properties, dynamic fracture toughness, and shear band formation resistance (dynamic shear band toughness). Perform three-dimensional simulations of the high speed machining process using a fully coupled thermomechanical framework and automatic remeshing. Incorporate a dynamic failure criterion based on fracture mechanics concepts.

6.1.4. Armor penetration

Incorporate the mechanics of dynamic shear band initiation and growth to investigate and model penetration mechanisms. Investigate possible failure modes during penetration based on the selection of dynamic failure mechanisms (plugging, petalling, fracture, fragmentation, spall).

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