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14. ABSTRACT

The integrity of engineering structures is often limited by the fracture resistance at connections. This is particularly the case when materials having large differences in mechanical properties are joined. Research directed at the direct calculation of fracture at interfaces and connections under dynamic loading conditions was carried out. The accomplishments under this grant include: 1. showing that the ductile-brittle transition temperature for welds as measured in the Charpy impact test is a structural not a material property; 2. predicting intersonic crack growth along an interface in excellent agreement with experiment; 3. developing a partition of unity based methodology applicable when crack growth is discontinuous; 4. finding a 3-dimensional effect that leads to brittle cleavage failure under impact loading earlier than predicted by a two dimensional plane strain analysis; and 5. analyses and experiments that reveal the rich phenomenology that occurs under dynamic frictional sliding including a variety of pulse-like modes and the supersonic propagation of trailing pulses with much of the predicted phenomenology also seen in experiments.

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The Mechanics of Failure at Connections: Size Effects and Scaling

Summary

The integrity of engineering structures is often limited by the fracture resistance at connections. This is particularly the case when materials having large differences in mechanical properties are joined. These differences can be an outcome of the joining process as, for example, the property differences in the heat affected zone of a weld. Under load, the difference in mechanical impedance leads to a stress and/or deformation concentration in the vicinity of the interface, In addition, the joining process may result in a degradation of properties there. In any case, the interface and its vicinity are more prone to failure than the surrounding bulk material. Research directed at the direct calculation of fracture at interfaces and connections under dynamic loading conditions was carried out. The accomplishments under this grant include: (i) showing that the ductile-brittle transition temperature for welds as measured in the Charpy impact test is a structural not a material property; (ii) predicting intersonic crack growth along an interface in excellent agreement with experiment; (iii) developing a partition of unity based methodology applicable when crack growth is discontinuous; (iv) finding a three dimensional effect that leads to brittle cleavage failure under impact loading earlier than predicted by a two dimensional plane strain analysis which was generally regarded as conservative in this respect; and (iv) analyses and experiments that reveal the rich phenomenology that occurs under dynamic frictional sliding including a variety of pulse-like modes and the supersonic propagation of trailing pulses with much of the predicted phenomenology also seen in experiments.

Research Accomplishments

In this Section, some of the key findings obtained under this grant are noted. Subsequently, a full listing of publications is given.

In [1], dynamic crack growth was analyzed numerically using the nonlocal constitutive formulation for a porous ductile material. Finite element computations were carried out for edge cracked specimens subject to tensile impact loading. When the size and spacing of the larger voids is directly specified, it was found in previous work that crack growth predictions show practically no mesh sensitivity. By way of contrast, for a homogeneous porous plastic material with no material length scale specified, the predicted crack growth behavior is mesh sensitive in that a finer mesh gives earlier onset of crack growth and somewhat higher crack speed, with no convergence as the mesh is refined. The results obtained from the nonlocal material model show that the incorporated material length gives a delay in the onset of crack growth and a reduced average crack speed. For one value of the material characteristic length, convergence was obtained with increasing mesh refinement, but for a larger value of the material characteristic length, surprisingly, convergence was not found. The difference between these two situations is that in the first fracture precedes localization while in the second, mesh dependent case, localization occurred before fracture and affected the crack growth pattern. The mesh resolutions used, relative to the material characteristic length, are usually found to give adequate refinement for resolving shear localization in more homogeneous fields. The requirements for resolving localization at a crack tip are evidently more stringent. It is expected that a fine enough mesh will provide a converged solution. In any case, the results indicate that a very fine mesh, relative to material the characteristic length is needed to resolve localization in the near crack tip region.

When equations for damage evolution are incorporated into the constitutive characterization of the material, the resulting constitutive equations are highly nonlinear and contain parameters that need to be determined either experimentally or from detailed micromechanical analyses. In either case, much effort is needed to quantitatively characterize the material properties. In order to focus the experiments and micromechanical analyses, the key constitutive parameters for failure prediction need to be determined. At present, there is no systematic procedure for doing this. Identifying parameters that have the greatest influence on response is of particular importance for welds because of the large number of characterizing parameters needed. An analysis of the sensitivity of failure predictions to parameters entering a micromechanically based ductile fracture material model was presented in [2]. The equations of motion emanating from a finite element semi-discretization were integrated using an explicit central difference scheme. First- and second-order sensitivity coefficients of the response quantities (derivatives with respect to various material parameters) were evaluated using a direct differentiation approach in conjunction with an automatic differentiation software facility. Numerical results were presented for tensile specimens subjected to impact loading. The first- and second-order sensitivity coefficients were generated by evaluating the derivatives of the response quantities with respect to various macroscopic and microscopic material parameters. Time histories of the response and sensitivity coefficients, and their spatial distributions at selected times were calculated. The first- and second-order sensitivity coefficients can be used to generate Taylor series approximations for the dynamic response of specimens with slightly different material parameters.

A micromechanics based analysis of weld failure was carried out in [5]. The predictions are based on a material model which accounts for ductile failure by the nucleation and growth of voids to coalescence as well as cleavage failure. Good confidence in this material model has been obtained through previous ductile-brittle transition studies as discussed in [4]. Plane strain conditions were assumed in the analyses, with the weld running in the direction transverse to the plane of deformation. The interaction between different material regions at the weld was studied by assuming various combinations of material parameters in the base material, the weld material, and in the heat affected zone (HAZ) where higher flow strength often tends to give more brittle behavior. In a reference case, with the weld material 20% undermatched relative to the base material and the initial flow strength of the HAZ 20% above that of the base material, the values of the strain hardening exponents in these three material regions were chosen such that the material with the highest initial flow strength has the lowest hardening rate, and the material with the lowest initial flow strength has the highest hardening rate, as is common for structural steels. Subsequently, to get a parametric understanding of the fracture behavior, the values of the initial flow strengths in the three regions were varied, but here the values of the strain hardening exponents kept fixed at the values first chosen for the reference case. In the computations the initial flow strength of the base material was kept fixed, while various levels of initial flow strength in the weld and the HAZ, respectively, were considered. For all three regions the void nucleation parameters as well as the critical stress for cleavage were kept fixed.

Due to the temperature dependence of the flow strength, the stress levels during plastic yielding are generally higher at low temperatures than at high temperatures, and therefore the low temperature cases reached the cleavage stress at an early stage, resulting in brittle fracture initiation, which spreads rapidly. Thus, the weld computations in [5] represent the transition from brittle failure at low temperatures to ductile failure at higher temperatures, with a much larger work to fracture at ductile failure. It was found by comparison of the 20% undermatched reference case with a case where the initial flow strength equals that of the base material, both in the weld and the HAZ, that the transition temperature was not affected by these differences. This is somewhat surprising, as both brittle failure and ductile failure were found to initiate at the base of the weld where the HAZ meets the free surface, and therefore a higher initial flow strength in the HAZ could be expected to promote a lower transition temperature. Also when the 20% undermatched reference case was compared to a 20% overmatched case, i.e. a case where the initial flow strength in the weld matches that of the HAZ, the transition temperature was essentially unaffected by the differences between the two cases. The main difference found was that the undermatched case, with a lower flow strength in the weld, showed a significantly higher work to fracture in the ductile regime.

The effect of a much higher initial flow strength in the HAZ was also studied, i.e. a flow strength 80% above that of the base material rather than 20% above, and it was found that this gave significant differences. This resulted in an increased transition temperature, so that brittle failure plays a more important role. The calculations in [5] illustrate that the amount of increase of the flow strength in the HAZ can have a very strong effect on the ductile-brittle transition in the fracture of a welded component.

A welded "T-joint" under dynamic loading conditions was analyzed using the present micromechanics approach. For 20% undermatched or overmatched welds, it was found that the ductile-brittle transition temperature was not greatly different from that of the base material. On the other hand, 80% overmatched and undermatched welds gave rise to a noticeable difference between the predicted transition temperatures for these two cases. Calculations have also shown that the amount of increase of the flow strength in the HAZ has a very strong effect on the predicted ductile-brittle transition. In addition, the stress triaxiality is predicted to have a strong influence on the ductile-brittle transition temperature. Hence, this transition temperature is predicted to be a structural and not a material property.

Work on size effects in the Charpy V-notch test was carried out in [6,8,11,12]. In addition to two dimensional plane strain analyses, the computational capability was extended to be fully three dimensional. An inherently 3D effect was found that leads to cleavage failure occurring earlier than predicted by a two dimensional plane strain analysis. Consistent with our previous findings, our analyses show that the ductile-brittle transition temperature in structural steels as obtained from the Charpy impact test is a structural property and not a material, property. The extent to which the ductile-brittle transition temperature varies with the size of the specimen depends on the material properties. As a consequence, the ductile-brittle transition temperature from laboratory size Charpy specimens cannot be directly used for large scale structures.

Dynamic fracture along interfaces was studied in [9] both experimentally and computationally. The predictions of the theory were found to be in excellent agreement with the observations. In the calculations and experiments the circumstances investigated are when the mismatch in elastic properties is large. Crack propagation along interface only occurs in discrete ranges of crack speeds. The near-tip stress fields in the various ranges differ significantly. This, in turn, plays a major role in determining the apparent fracture toughness of the interface. Our work in [9] presents the first conclusive experimental evidence of interfacial crack speeds faster than any characteristic elastic wave speed of the more compliant material. The occurrence of this crack speed was predicted in our numerical calculations and these calculations were used to design the experiments. In addition, in [9] we presented the first experimental observation of a mother-daughter crack mechanism allowing a subsonic crack to evolve into an intersonic crack is documented. The calculations exhibit all the crack growth regimes seen in the experiments and, in addition, predict a regime with a pulse-like traction distribution along the bond line that remains to verified experimentally. In the work in [9] a cohesive surface constitutive relation along the bond line describes the separation process.

In [10], we developed a partition of unity based cohesive finite element method based that is applicable when crack growth is discontinuous. The crack is not regarded as a single entity. Instead, it is modeled as a collection of overlapping cohesive segments, which are represented as displacement jumps by using the partition-of-unity property of finite element shape functions. A combination of overlapping crack segments can behave as a continuous crack. In addition, crack segments can be added at arbitrary positions and with arbitrary orientations, so that (at least in principle) the method allows for complex crack patterns to emerge.

In [13], frictional sliding along an interface between two identical isotropic elastic plates under impact shear loading was investigated experimentally and numerically. The plates are held together by a compressive stress and one plate is subject to edge impact near the interface. The experiments exhibit both a crack-like and a pulse-like mode of sliding. Plane stress finite element calculations modeling the experimental configuration were carried out, with the interface characterized by a rate and state dependent frictional law. For low values of the initial compressive stress and impact velocity, sliding occurs in a crack-like mode. For higher values of the initial compressive stress and/or impact velocity, sliding takes place in a pulse-like mode. A variety of sliding modes were obtained in the calculations depending on the impact velocity, the initial compressive stress and the values of interface variables. One pulse-like mode involves well-separated pulses with the pulse amplitude increasing with propagation distance. Another pulse-like mode involves a pulse train of essentially constant amplitude. The propagation speed of the leading pulse (or of the tip of the crack-like sliding region) is near the longitudinal wave speed and never less than the square root of two times the shear wave speed. Supersonic trailing pulses were seen both experimentally and computationally.

In the experiments, the speed of the leading pulse or the leading edge of the crack-like sliding region ranges from somewhat above the square root of two times the shear wave speed to the longitudinal wave speed. This propagation speed increases with increasing impact velocity and decreasing compressive stress. A speed exceeding the longitudinal wave speed was seen for a trailing pulse.

A variety of frictional sliding modes were obtained in the calculations, depending on the initial compressive stress, the impact velocity and the interface characterization: a crack-like mode; a pulse-like mode with well-separated pulses that increase in amplitude; and a train of pulses that propagate with an essentially constant amplitude. In addition, combinations of these modes occurred as well as transitions between modes. This variety of sliding modes emerges even though there is no elastic mismatch across the interface. The slip resulting from the pulse-train mode and that resulting from the crack-like mode are hard to distinguish. In all calculations the speed of the leading pulse or the leading edge of the crack-like sliding region exceeds the square root of two times the shear wave speed and is close to (or slightly exceeds) the longitudinal wave speed. As in the experiments, trailing pulses with a speed exceeding the longitudinal wave speed were found. The elasticity of the interface was found to play a significant role in setting the mode of sliding. The range of sliding modes obtained in the calculations appear to be generic, arising in a wide variety of configurations and applications, and at a wide variety of size scales.

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