DYNAMIC EFFECTS IN CRACK BRIDGING

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ABSTRACT

Problems in the mechanics of fiber bridging under dynamic conditions are solved theoretically using shear lag approximations and FEM. Various aspects are investigated further using experiments on model material systems. Special attention is paid to the problem of dynamic fiber pullout and push-in, which has been central to understanding fracture in aligned fiber composites under static conditions. Highlights for the dynamic problem are that: 1) inertia complicates the fiber pullout problem considerably; 2) disturbances propagate along frictionally coupled fibers at less than the bar wave speed; and 3) unstable regimes appear in interfacial friction.

1 INTRODUCTION

Figure 1 shows a typical problem of current interest in the dynamic performance of structures. A projectile impacts upon a laminated armored structure, which absorbs energy and limits damage by a series of mechanisms, including comminution of ceramic tiles, viscous flow of the comminuted ceramic, spreading of the load transferred to structural elements, multiple delamination of a structural skin, and detachment of structural stiffeners. Performance characteristics of interest include the maximum dynamic deflection and the residual strength of the skin/stiffener assembly. Such structures are currently designed by intuition and analyzed by fabricating and testing hardware. Predictions of the ballistic performance, which might greatly reduce the cost of design and optimization, are unavailable because the physics and mechanics of the various mechanisms involved are not well known. Here we review recent efforts to understand some aspects of the problem of Fig. 1, especially relating to efforts to suppress delamination damage by incorporating through-thickness reinforcement, which are also relevant to diverse other dynamic damage problems.

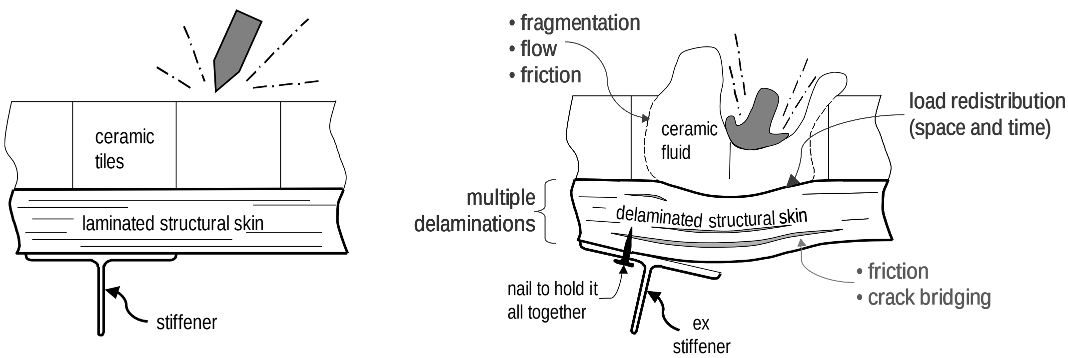

Figure 1. A typical complex problem in dynamic damage evolution.

2 DYNAMIC FIBER PULLOUT AND PUSH-IN

Through-thickness reinforcement, such as pins, stitches, or woven yarns, greatly enhances delamination resistance under both static and dynamic loading. A central problem in this phenomenon is the mechanics of pullout or push-in of a fiber (or pin, stitch, or yarn) embedded in a matrix that is a half-space. For static loading, this problem can be accurately described in mode I conditions using simple shear lag models, which incorporate the debond energy and interfacial friction as scalar parameters. Quite simple models of reasonable accuracy are also now available for mode II and mixed mode conditions [2]. In contrast, little attention has been paid to the dynamic case.

Figure 2 compares experimental and theoretical stress fields (σ_1 - σ_2, where x_1 and x_2 are the in-plane coordinates) in a model planar fiber coupled by friction alone (the interface was

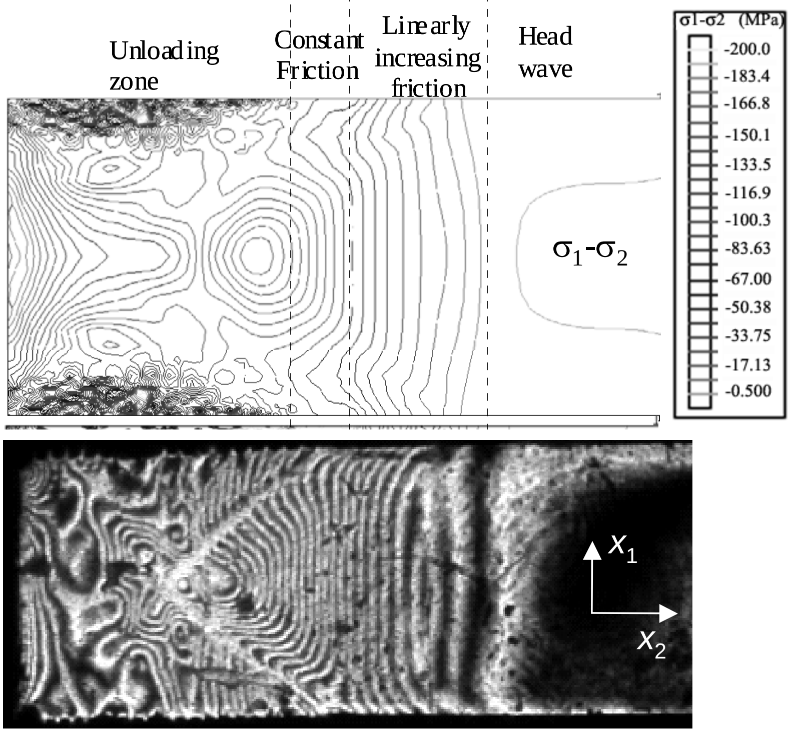

Figure 2. Snap-shot of stress fields: dynamic fiber push-in.

initially not bonded) to a matrix (not shown) and subjected to a dynamic pulse load at the left end. The experimental data were acquired with dynamic photoelasticity methods. The calculations were per-formed with finite element methods, assuming a constant friction stress, apart from a linear variation with shear displacement rate for small rates, which is necessary because the numerical procedures do not converge if the friction changes sign as a step function. The stress contours show regions, during loading and where the friction stress is saturated (constant), where they are not far from vertical, consistent with the simplified Lamé-like fields of a shear lag model. More complex behaviour is found approaching and during unloading (zones labeled “constant friction" and "unloading zone" in Fig. 2), where both experiment and model suggest, among other characteristics, instability or chaotic behaviour at the interface. The instability is presumably related to that predicted for Coulomb friction laws [3, 4], but here the distinction arises that the friction is not related to the normal stress. These results suggest that a fundamental difference exists between problems of uniform far-field loading, the case assumed in prior studies of instability at frictional interfaces, and time-varying loads; and that loading and unloading show distinct interfacial physics.

Other finite element calculations confirm that many of the characteristics of pullout/push-in problems are well approximated by Lamé-like solutions, at least in the case that friction is assumed to be of uniform magnitude [1]. Such analytical solutions have led to some interesting results that are not easily seen in numerical work, where the strong nonlinearity whenever friction changes sign causes difficulty. Behaviour is much richer than in the corresponding static loading

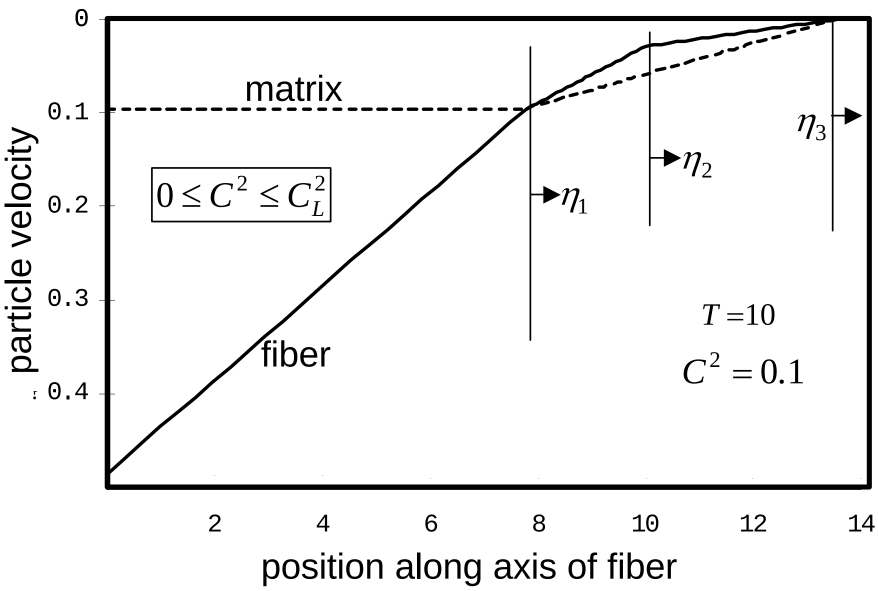

Figure 3. Particle velocity variations in a pullout case: slip and reverse slip zones under linearly increasing end load [1].

case [1, 5]. Under linearly increasing end loads, zones of interfacial slip, slip-stick, and reverse slip are all possible, depending on the loading rate and the properties of the fiber and matrix. Figure 3 illustrates the interfacial particle velocity jump for a case that includes reverse slip.

Another characteristic of interest is the stiffness of the response of the end-point displacement to dynamic loading. For linearly increasing loading, inertial effects increase the effective stiffness; but if loading stops increasing and is held constant, the momentum of the fiber continues to displace the fiber end and the final displacement is larger than for static loading. Estimates show that such inertial effects could significantly modify crack bridging laws and therefore the dynamic propagation of cracks bridged by fibers [6].

3 CONCLUSIONS

Certain problems in dynamic damage evolution can be well aproximated by beam and shear models. Great challenges remain in understanding large scale friction, mixed mode fracture, and multiple delamination effects.

Acknowledgments

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