

Constitutive Laws for Engineering Materials Theory and Applications

Volume I

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STRAIN-SOFTENING CONTINUOUS DAMAGE : LOCALIZATION AND SIZE EFFECT *

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ABSTRACT

The paper reviews recent work by the authors in the modeling of strain-softening arising from damage, such as cracking, in heterogeneous brittle materials. Attention is focused on the concept of localization instabilities - mathematical methods which ensure that strain-softening does not spread locally into a region of zero volume. Localization instabilities make it possible to achieve proper convergence with mesh refinement, with a finite energy dissipation in the limit of vanishing element size. Certain recently obtained exact solutions for strain-softening wave propagation problems are reviewed and the convergence of a finite element model to these solutions is discussed. As an essential consequence of the localization instabilities properties of heterogeneous materials, the size effect observed in the failure of geometrically similar specimens or structures of different sizes is analyzed, and certain size effects of the previously identified approach are also presented. Consequences of the size effect for the validity of finite element programs for strain-softening or continuous damage mechanics are reviewed and the application of the size effect for identifying the localization instabilities properties of the material, and especially its fracture energy, are analyzed. The conclusions are supported by test results. Finally, recent work on simulation of heterogeneous strain-softening materials by discrete elements with a random arrangement is discussed, and the localization instabilities properties are emphasized.

INTRODUCTION

The topic of strain-softening has recently attracted considerable attention because efforts to model the damage of materials and analyze the failure of structures are inevitably linked with stress-strain curves which have negative slopes. Some mechanisms, such as Hopper and Bead (1984), have attributed negative slopes entirely to decrease in the area over which the stress acts, and have consequently argued that strain-softening does not exist. While a decrease in the effective area which results from damage may be observed in structures subjected to cracking in brittle materials, this is not the only class of materials in which strain-softening is observed.

For example, in certain types of projectile penetration, the generation of heat associated with adiabatic plasticity results in a decrease in the yield stress and hence in a stress-strain curve which exhibits strain-softening. Similarly, in two-phase materials and even granular media, the pressure-volume curve exhibits a local strain softening domain. Furthermore, the argument that microstructural considerations may allow one to bypass the difficulties associated with strain-softening do not appear to be sound since regardless of whether the stress-strain behavior is based on microstructural considerations or on phenomenological grounds, it leads to the same type of mathematical behavior in the governing equations of the problem.

*This contribution represents a combination of two invited papers.

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1. The strain at the point in which strain-softening first is initiated depends on finite, and, the displacement at that point becomes discontinuous.
2. Strain-softening in this type of material is limited to a single point so that the displacement associated with this damage mechanism vanishes.
3. The fact that strain-softening is limited to a point overcomes the objection of Haddad about the applicability of the equations to the strain-softening domain through at this point is always a set of measure zero.

In view of the character of the closed form solution, the mesh dependence which was reported by Sandler and Wright is not surprising. As the size of the element in which strain-softening is initiated is reduced, the strain at that element becomes larger and larger in its attempt to reach the closed form solution, where the strain is infinite. The major drawback of the local strain-softening model is not its lack of mesh dependence, but the fact that the energy dissipation associated with the damage process in the strain-softening model tends to zero as the mesh is refined. This characteristic was identified by Bazant, Belytschko and Chang (1985) who also proposed a nonlocal type of formulation to overcome this pathology; this will be discussed subsequently.

Further studies of the properties of finite element solutions with strain-softening by Belytschko et al. (1986, 1988) showed that the remedy of damping as proposed by Sandler and Wright is not sufficient to alter the pathological behavior in finite element solutions. This was exhibited in a spherically converging wave in a sphere. The character of a strain-softening solution in this geometry is especially complex when the load is a ramp function in time. In this case, a portion of the stress wave always passes a surface before strain-softening is initiated. This portion of the wave does grow because of the geometrically converging and again triggers strain-softening. Then, it is surmised that strain-softening in this case actually occurs on an infinite number of surfaces, although closed form solution could not be constructed for this case. Finite element solutions for these problems are shown in Fig. 4. As the mesh is refined, very large strains are generated at more and more points inside the domain; the location of these high strains in the finite element solution does not seem to be completely chaotic and there is no trend with mesh refinement. Furthermore, this pathological behavior is not alleviated by adding damping to the material.

Recently Belytschko et al. (1986) have presented closed form solutions for materials of the stress-strain law shown in Fig. 5. The first is similar to the stress-strain law considered by Bazant and Belytschko (1985) except that the stress takes on a nonzero value σ_0 at the strain becomes infinite. In the second material law, the negative portion of the stress-strain law is limited to the point between the strains ϵ_1 and ϵ_2 and for

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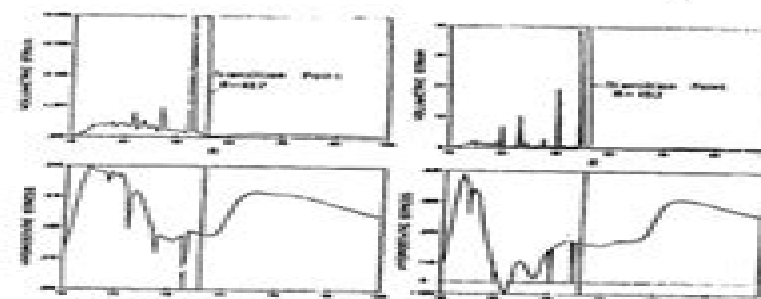
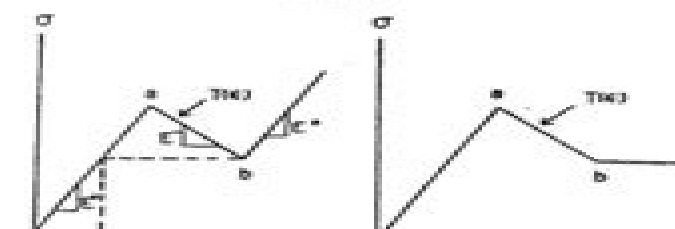


FIG. 4. Deflections for spherical converging wave with different finite element meshes.



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