FINITE ELEMENT MODELING OF SOME FRACTURE MECHANISMS

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ABSTRACT

The damage can occur by slow growth of microcracks, the sudden growth of cleavage cracks, or the development of shear bands. The response of the material is a loss of strength that may lead to the failure of a structure. One approach to simulating the response of structures is to explicitly model the mechanisms of damage and failure in the material. This paper highlights three failures, namely penetration of high strength woven fabrics, fracture of steel weldments and cleavage fracture in tank car steel.

Keywords: vibration, trajectory path, computer aided dynamic analysis

1. INTRODUCTION

Structural failures usually occur as a result of localized yielding and fracture, sometimes in combination with global or local buckling. In general, predicting the initiation of failure is not as difficult as predicting the process and final resolution of the failure. For example, constitutive models that can accurately describe nonlinear material behavior in standard cases of elastic-plastic response are commonly found in finite element codes. However, predicting the progression of failure after initiation is made difficult by strongly nonlinear processes such as dramatic changes in material properties and structural geometry, or by redistribution of the loads resulting from damage.

Often the mechanisms of material failure are related to microstructural processes that occur in the materials as a result of the loading conditions. For example damage can occur by slow growth of microcracks, the sudden growth of cleavage cracks, or the development of shear bands. The response of the material is a loss of strength that may lead to the failure of a structure. It is important to realize in cases of damage that measured force-displacement curves including the softening response after the peak load are a structural response to the damage, and should not be considered as stress-strain curves for the material.

One approach to simulating the response of structures is to explicitly model the mechanisms of damage and failure in the material. The objective of this paper is to describe three methods for modeling material damage using finite element methods.

2. METHODS

Methods are described for modeling damage using finite element methods for two different failure processes: (1) penetration of high strength woven fabrics, (2) fracture of steel weldments and (3) cleavage fracture in tank car steel. In each case equations are given that describe the evolution of damage in the material. These damage equations were then implemented into finite element codes and used to simulate structural response. To perform these computations, LS-DYNA was used [1].

3. RESULTS

3.1 High Strength Fabrics

The high strength fabrics are produced by weaving high strength yarns (Zylon). One important characteristic response of the high strength yarn is that under tension it has very little stiffness until the fibers align and straighten out. To implement a continuum treatment of this response an orthotropic constitutive model was used with a low shear modulus in planes oriented along the axial direction of the yarn [2].

A procedure for damage and failure was also implemented into this material model. The Zylon yarns are comprised of about 250 fibers. The damage model assumes that the fibers are elastic until they break at which point they lose all strength. Thus, the stress in the yarn is a function of the strain and the number of broken yarns,

$$\sigma_y = E(1-D)\varepsilon_y \qquad \ldots(1)$$

where σ_y is axial stress in the yarn, ε_y is the axial strain in the yarn and D is the fraction of broken fibers. It is assumed that the fibers break at a uniform rate between a minimum and maximum value of strain (e.g., 0.024 and 0.052]. Thus the stress rate equation is given by,

$$\sigma_y = E(1-D)\dot{\varepsilon}_y - E\varepsilon_y \frac{\partial D}{\partial \varepsilon_y}\dot{\varepsilon}_y \qquad \ldots(2)$$

Equation (2) demonstrates an important feature of the yarn response. The first term on the right is the increase in load due to stretching the unbroken fibers. The second term is the loss in load due to breaking new fibers. A drop in stress for a positive strain rate will occur the loss in stress due to fiber breakage is greater than the increase in elastic strain of the unbroken fibers.

The computational response of this model was tested by performing simulations of single uncrimped and crimped yarn pulled axially. Fig.1 shows the finite element mesh for a short section of an uncrimped yarn. The mesh is constructed of solid elements, with eight elements in the cross section. The geometry is modeled to match photographs taken of a yarn cross section. The amount of crimp is representative of that found in yarns in a 30 x 30 pitch fabric weave.

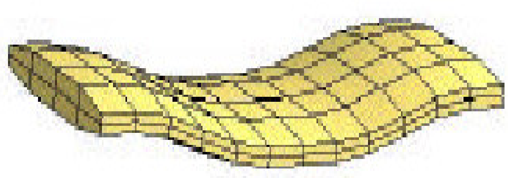

Fig.1 Finite element mesh of a yarn segment

Fig.2 shows the stress developed in an uncrimped yarn as it is pulled, compared to a tested yarn. At a nominal strain of about 0.025 the stress levels out at 4.3 GPa and the yarn breaks at a nominal strain value of 0.032 (local strain values are higher).

To investigate the response of woven fabrics the impact of a small fragment against a patch of fabric was simulated as shown in Fig.3. Finite element simulations of the impact resistance of woven Zylon fabric were used to investigate the effect of boundary conditions and the effect of the size of the patch on ballistic performance.

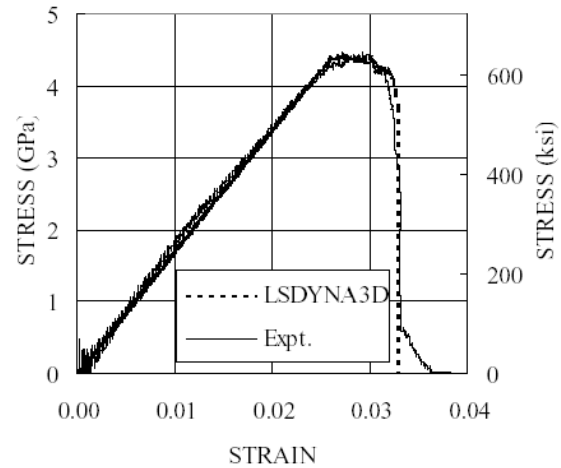

Fig.2 Calculated response of an uncrimped yarn

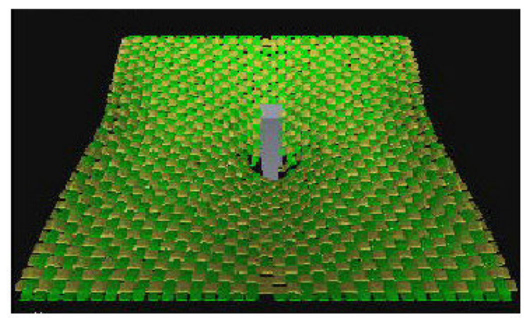

Fig.3 Simulation of fragment impact on Zylon fabric

3.2 Fracture in T - Weldments

In this example, a local fracture criterion is used to predict the fracture behavior of steel T- weldments [3]. The purpose of the analysis was to understand the effects of weld process and experimental scale on fracture behavior. Developing the fracture model in LS-DYNA required implementing a local damage model in the constitutive model and a fracture algorithm which allows discrete separation of the elements along an arbitrary fracture path within a region of the mesh. This approach allowed calculation of not only fracture initiation but also the path of fracture propagation through the structure.

T-shaped weldments were produced by welding two stiffeners normal to a slotted base plate. Each stiffener was bolted to a steel anchor, and the specimen plate was bolted to a steel die. The center of the specimen plate was loaded with strips of sheet over an area bounded by the two slots but not extending all the way to each stiffener. With this test arrangement, only the center portion of the specimen plate is significantly deformed during the experiments, while the portion supported by the die acts as a reaction frame, inducing membrane stresses in the plate. The specimens were prepared from high-strength steel. The welding process produces a heat-affected zone (HAZ) of approximately constant width, independent of the absolute weldment size. The experiment induces fractures that initiate in the plate HAZ of the weldments and then extend either through the base plate or through the stiffener.

The weldment fracture model used in this example is based on three components: (1) a material damage model formulated in terms of plastic deformations weighted by a stress state function; (2) a geometric and strength model of the weldment, based on metallographic observations and hardness measurements; and (3) a finite element algorithm permitting independent degrees of freedom for nodes on either side of the calculated fracture path. As implemented, the fracture model is a basic form of a ductile fracture criterion [4]. It assumes that failure at a material location occurs when the damage within a surrounding characteristic volume (V_{mic}) exceeds a critical value.

The damage failure criterion can be written in the form

$$D = \int \frac{d\varepsilon_{eq}^{p}}{\varepsilon_c(\sigma_{mean}/\sigma_{eq})} = 1 \quad \text{over} \quad V_{mic}$$

…(3)

where D is the normalized damage parameter; $d\varepsilon_{eq}^{p}$ is an increment in equivalent plastic strain; and $\varepsilon_c(\sigma_{mea}/\sigma_{eq})$ is the critical failure strain as a function of the stress triaxiality, defined as the ratio of the mean stress to the equivalent stress. This critical strain function can be determined by a series of notched tensile tests with specimens of varying notch radii. V_{mic} is a characteristic volume of the microstructural process zone.

Fig.4 shows the results of a simulation of a specimen with velocity sufficient to cause complete fracture. The crack path across the plate was faithfully reproduced in the simulation. Furthermore, the calculated deflection history was in good agreement with the experimental measurement and by lowering the initial velocity, we were able to simulate the arrest of the crack in the base plate. The good agreement between simulations and experiments partially validates the use of the fracture model for performing analyses of the weldment fracture.

3.3 Cleavage Fracture in Steel

A model for cleavage failure in steel was implemented in LS-DYNA. Laboratory fracture experiments were performed to measure the behavior of plates containing damage in the form of simulated gouges and dents. To ensure that cleavage fracture occurred, tests were performed on smooth, macroscopically unflawed TC-128B specimens at -150°C.

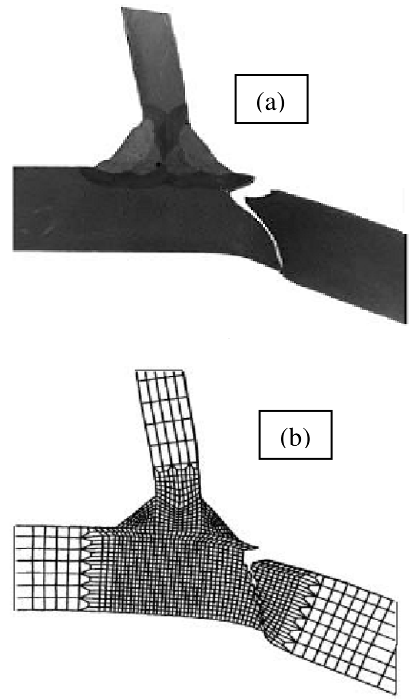

Fig.4 Weld fracture (a) experiment and (b) FEA

The model used is the local cleavage criterion developed by Beremin [5]. Damage is calculated locally within the material based on the stress and strain histories and micro-mechanical model for the fracture processes. The prediction of cleavage fracture is different than for most ductile damage processes because there is typically large scatter in the measured cleavage fracture stress for identical tests on a single batch of material. Thus a cleavage failure criterion will ideally predict a statistical probability of fracture for a given material, geometry, and stress level, rather than a deterministic failure stress.

The microstructural processes leading to a cleavage fracture are that the material has a distribution of preexisting microcracks, typically initiated in the material from the inhomogeneities. For example, in mild steels, microcracks are produced by fracture of sulfide inclusions or grain boundary carbides. The catastrophic propagation of these cracks results in a cleavage fracture, which occurs when the stress normal to the microcrack planes reaches a critical value. This critical stress can be approximated as

$$\sigma_c = \left[\frac{2E\gamma}{2(1-\nu)l_0}\right]^{0.5} \qquad \ldots(4)$$

where E is Young's modulus, γ is the fracture surface energy, ν is Poisson's ratio, and l_0 is the microcrack length.

The statistical nature of the cleavage criterion is introduced by the distribution of microcrack sizes within the material. Within a given microstructural characteristic volume V_0, the probability of finding a crack of length between l_0 and $(l+dl_0)$ is taken as

$$P(l_0)dl_0 = \frac{\alpha}{l_0^{\beta}} dl_0 \qquad \ldots(5)$$

Upon integration the above microcrack distribution function over the range of crack lengths greater than or equal the critical crack length at a given stress level, the probability of failure can be obtained as

$$P(\sigma) = \left[\frac{\sigma}{\sigma_u}\right]^m \qquad \ldots(6)$$

where $m = 2\beta - 2$ and the cleavage stress, σ_u, is a material constant.

The cumulative rupture probability of the structure, combining the probabilities in each of the small representative volumes, can be approximated as,

$$P_r = 1 - \exp\left[\sum_j \frac{-V_j}{V_0}\left(\frac{\sigma_j}{\sigma_u}\right)^m\right] \qquad \ldots(7)$$

Coupon tests were used to calibrate the cleavage model. First, from smooth round bar tests the true stress versus plastic strain curve for the material was obtained. This curve was then used to analyze notched round bar specimens and determine the cleavage stress. For a given value of the cleavage stress, a probability of rupture can then be determined at any load level using equation (7). The statistical nature of cleavage fracture can be seen by normalizing all the notched round bar failure stresses by the predicted 50% probability load level. These normalized failure stresses can then be plotted against a normalized rupture probability curve as shown in Fig.5 for the A515-70 steel. This fit is good over the full range of tests performed.

The model was then used to predict the cleavage response of three point bend specimens as shown in Fig.6. The local fracture model calibrated using round bar tests predicts the stress-strain and cleavage failure response of the bend specimens reasonably well. The prediction is better for more acute features such as the 1/8-inch radius gouges than for blunt features such as the 1/2-inch radius gouges and the bend specimens, but errs on the conservative side, predicting that cleavage occurs at lower stresses and strains than actually occurs in tests. Thus, the model can be applied with confidence to a wide range of tank car damage situations.

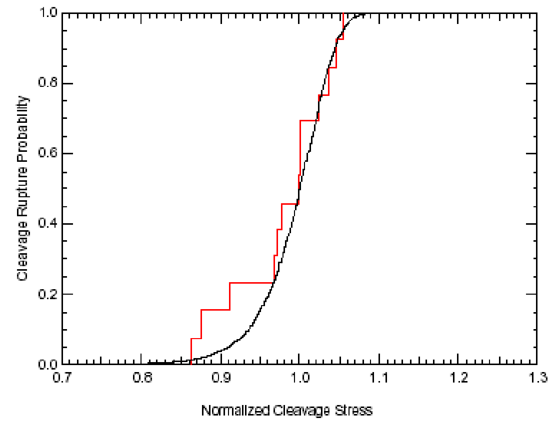

Fig.5 Normalized cleavage rupture probability

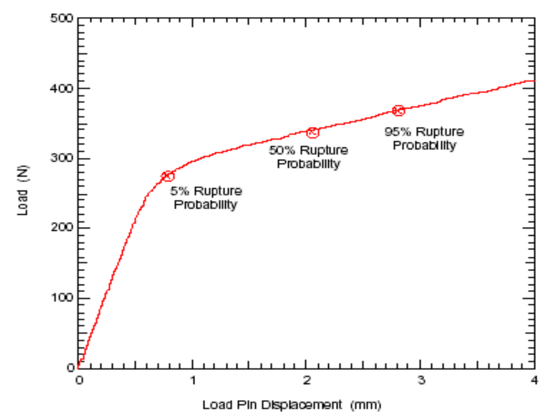

Fig.6 Probability of rupture for three-point bend tests

4. CONCLUSIONS

Methods were described for modeling damage in finite element methods for three different failure processes: (1) penetration of high strength woven fabrics, (2) fracture of steel weldments, and (3) cleavage fracture in tank car steel. The example simulations showed that by modeling the mechanisms of failure, useful computational models could be implemented in finite element codes that are applicable under a wide range of loading conditions.

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