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IMPLEMENTATION OF AN ANISOTROPIC DAMAGE MATERIAL MODEL FOR NON-PROPORTIONAL LOADING.

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Summary. Anisotropic damage for non-proportional loading is incorporated in an implicit finite element code under the framework of continuum damage models, using two different methodologies. Simple simulations are carried out to check the performance of the models. The advantages and drawbacks of both methodologies are discussed briefly.

1 INTRODUCTION

Damage is a pre-fracture phenomena, caused by the nucleation, growth and coalescence of voids at the micro-scale. The consequence of damage is that the material starts to soften and ultimately looses its load carrying capacity. Damage not only governs the failure but also effects the mechanical response of the material under deformation and the properties of the final product. Isotropic damage models are relatively simple and easy to implement, but they do not accurately represent the actual damage phenomena in most of the engineering materials and industrial applications. More accurate failure models require an anisotropic definition of damage.

The anisotropy in damage can be classified into two categories; Material Induced Anisotropy in Damage (MIAD) and Load Induced Anisotropy in Damage (LIAD). MIAD is related to the anisotropy in distribution and shape of second phase particles. Nucleation of voids governs MIAD. It can be seen from Figure 1a that initially the mechanical response of the material is the same in rolling and transverse directions but starts to deviate after some amount of straining. LIAD is related to the stress state and is governed by void growth. The schematic in Figure 1b shows how the stress state induces anisotropy in void growth.

Two methodologies were adopted to incorporate anisotropic damage in FEA simulations. In the first method, the parameters in Hill-48 yield criteria were made a function of strain to induce softening in the material. The second method is a coupled elasto-plastic damage continuum model, using a second order damage tensor as an internal state variable.

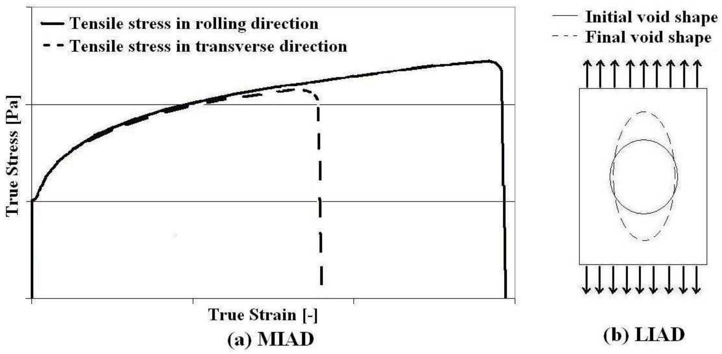

Figure 1: Two types of induced damage anisotropy. (a) Material induced (Courtesy TNO) (b) Load induced

2 SCHEME-I

The first scheme was motivated by the work of Huétink[1]. Softening was introduced in the material by varying the parameters for a plane stress Hill-48 yield function. Using the elastic degradation data and work done by Tang[2] for Al-2024T3, Hill parameters are made a function of elastic properties. The elastic properties are a function of strain. Consequently, the Hill parameters become a function of strain.

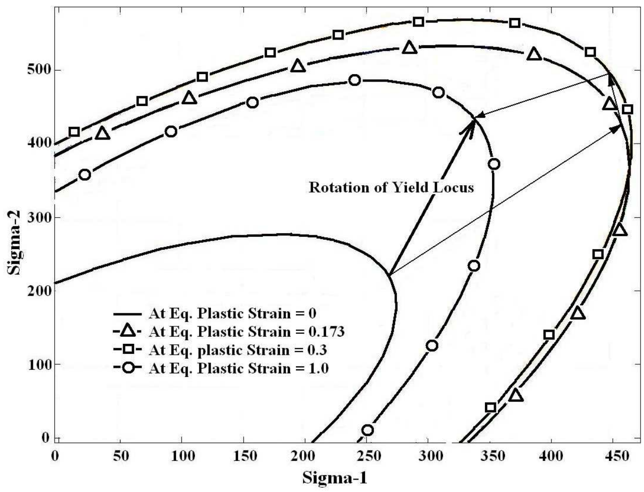

Figure 2: Hill yield locus for Al-2024-T3, plotted as a function of equivalent plastic strain

The Hill yield locus was plotted for different values of plastic strain, see Figure 2. Isotropic hardening was assumed. It was observed that the hardening and softening behavior was different in principal direction-1 and principal direction-2. Another prominent effect was the rotation of the yield locus as soon as softening dominates hardening.

Simulations were carried out using the in-house FEA code DiekA. Although the model was capable to simulate the effect of MIAD, a couple of limitations restricts the useability of this approach. First, no damage variable is defined in this implementation, therefore defining the critical damage (element failure) point is not possible. Secondly, it is not possible to simulate the effect of LIAD.

3 SCHEME-II

The second scheme was implemented based on the fully coupled elasto-plastic continuum damage model of Lemaitre[3]. A second order damage tensor is defined as an internal state variable. An effective stress is defined using the hypothesis of strain equivalence. The key feature of this model is the capability to have different effects of damage under hydrostatic and deviatoric stress state.

$$\tilde{\boldsymbol{\sigma}} = (\mathbf{H}\boldsymbol{\sigma}^D\mathbf{H})^D + \frac{\sigma^H}{1-\eta D^H}\mathbf{1} \qquad \text{and} \qquad \mathbf{H} = (\mathbf{1}-\mathbf{D})^{-\frac{1}{2}} \tag{1}$$

Where $\tilde{\boldsymbol{\sigma}}$ is the effective stress tensor, $\mathbf{D}$ is the second order damage tensor, $\mathbf{H}$ is the second order damage effect tensor, $\boldsymbol{\sigma}^D$ is deviatoric stress tensor, σ^H is the hydrostatic stress, D^H is the hydrostatic damage and η is the hydrostatic sensitivity parameter.

In Lemaitre's model, the damage evolution is defined in the principal damage direction

$$\dot{D}_{ij} = \left(\frac{\bar{Y}}{S}\right)^s \left|\dot{\lambda}\frac{\partial f}{\partial \sigma}\right|_{ij} \qquad \text{for} \qquad (\epsilon^p_{eq} \geq \epsilon^p_{th} \quad \text{upto} \quad max(D_{ij}) \leq D_c) \tag{2}$$

The material parameters used in this model are S, s, ϵ^p_{th} (threshold for damage) and D_c (critical damage). These parameters are determined from a uniaxial test and a low cycle fatigue test. All the material data is taken from Lemaitre[3]. $\bar{Y}$ is the effective elastic energy density, f is the plastic dissipation potential, and λ is the plastic multiplier.

Lemaitre's model is a well known model for damage, but it has its restrictions. The model defines evolution of damage in principal damage direction and with the assumption that the principal damage and principal stress directions coincide, it enables to rotate to the principal damage direction using the stress tensor. This assumption is not valid for non-proportionality but it is mandatory to use the damage tensor to rotate to the principal damage direction. According to Equation (2), components of damage neither can be negative nor can decrease (no healing effects). Therefore the damage tensor can not distinguish between a biaxial and a pure shear condition. Another problem is that the number of non zero components of damage tensor and plastic strain tensor are not compatible in the principal damage direction.

This problem was solved by defining the damage evolution in material direction rather than the principal damage direction. This requires evolution of all the components of damage tensor thus increasing the number of equations to be solved but at the same time reducing the computation time required for rotations of variables.

The modified model was implemented in the in-house FEA code DiekA. Some simple simulations were carried out to check the performance of the anisotropic damage model under load path changes. Figure 3 shows one simulation in which the load is changed from tensile to shear. Initially the model is loaded in z-direction. The evolution of the damage components in the lateral (x and y) directions are exactly half of that in the loading (z) direction. Then a simple shear load is applied in the x-z direction. The stress in z direction drops to zero and shear stress in x-z direction builds up and straight away starts to soften. The x-z damage components starts to evolve whereas, as expected, all the normal components remain unchanged.

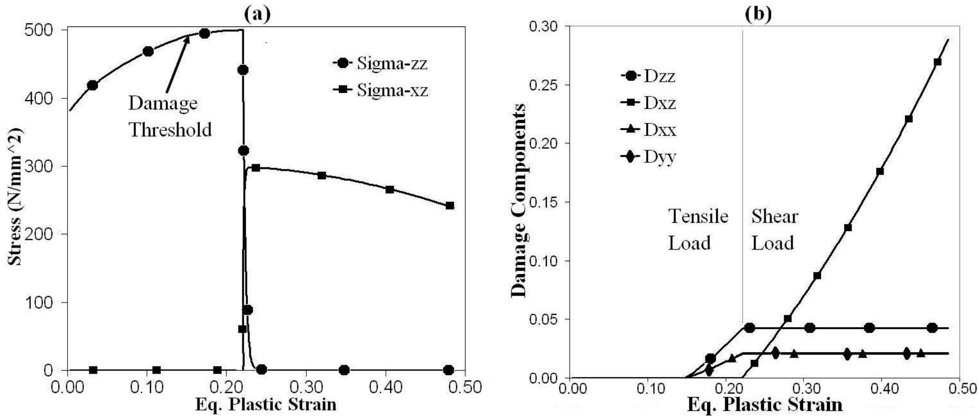

Figure 3: Single hex element simulation for tensile load to shear load (a) stresses vs. eq. plastic strain (b) damage evolution

Although this approach looks promising, there are some limitations with the currently implemented anisotropic damage model. First, this model has the same damage evolution behavior under tensile and compressive loadings. Secondly, the effect of MIAD is not included in this model yet. A numerical limitation is that this model converges only for very small steps (known for models based on strain equivalence[3]).

4 CONCLUSIONS

The continuum anisotropic damage model is successfully implemented in the FEA code DiekA for non-proportional loads. However the model need some improvements towards the physical behavior of damage such as stress state dependency and MIAD. To make it applicable for industrial applications the CPU time must also be decreased.

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