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36 separate items are enclosed

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MEMORANDUM FOR PRR (Contractor/In-House Publication)

FROM: PROI (TI) (STINFO)

01 Aug 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-158**
Wei, Y., Chow, C.L. (University of Michigan); Liu, C.T. (AFRL/PRSM), "Damage Analysis for Mixed Mode Crack Initiation"

International Conference on Computational Science (Statement A)
(Anaheim CA, 21-25 Aug 00) (Submission Deadline: 16 Aug 00)

- 1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

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LAWRENCE P. QUINN DATE
Technical Advisor
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20021119 134

Damage Analysis for Mixed-Mode Crack Initiation

? : *hyphenated in conclusions...*

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Distribution A: Approved for Public Release

~~OBJECTIVE~~

Introduction ?

Prediction of mixed mode fracture load and crack initiation angle for Al 2024-T3 and particulate composite material with the theory of damage mechanics

Objectives

- 1) Develop a model to characterize damage in a material element
- 2) Propose a failure criterion with the concept of damage accumulation
- 3) Implement the damage model into ABAQUA through UMAT subroutine
- 4) Apply the model for mixed mode fracture analysis ?

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DAMAGE MODEL

Relationship Between Effective and True Stress

$$\bar{\sigma} = \mathbf{M}(\mathbf{D}) : \sigma$$

The damage effect tensor $\mathbf{M}(\mathbf{D})$ is expressed with two damage variables D and μ as

$$\mathbf{M} = \frac{1}{1-D} \begin{bmatrix} 1 & \mu & \mu & 0 & 0 & 0 \\ \mu & 1 & \mu & 0 & 0 & 0 \\ \mu & \mu & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-\mu & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-\mu & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-\mu \end{bmatrix}$$

DAMAGE COUPLED CONSTITUTIVE EQUATION

The elastic law of damaged material

$$\varepsilon^e = \mathbf{C}^{-1} : \sigma \quad \mathbf{C}^{-1} = \mathbf{M} : \mathbf{C}_0^{-1} : \mathbf{M}$$

\mathbf{C}_0 and \mathbf{C} are elastic tensors respectively for undamaged and damaged materials

The yield surface is postulated with damage consideration as

$$F_p(\sigma, R) = \frac{1-\mu}{1-D} \sigma_{eq} - [R_0 + R(p)] = 0$$

σ_{eq} the Von-Mises equivalent stress

The plastic law of damaged material

$$d\varepsilon^p = \lambda_p \frac{\partial F_p}{\partial \sigma} \quad dp = \lambda_p \frac{\partial F_p}{\partial (-R)} = \lambda_p$$

DAMAGE SURFACE

The plastic damage surface is

$$F_d(Y, B) = Y_d - [B_0 + B(w)] = 0 \quad Y_d = \left\{ \frac{1}{2} (Y_D^2 + \gamma Y_\mu^2) \right\}^{1/2}$$

- Y_D, Y_μ the thermodynamic conjugate forces of the damage variables D and μ
- B_0 the initial damage threshold
- B the damage hardening
- w the equivalent damage
- γ the damage-related material constant

DAMAGE EVOLUTION

$$dD = -\lambda_d \frac{\partial F_d}{\partial Y_D} = -\frac{\lambda_d Y_D}{2Y_d}$$

$$d\mu = -\lambda_d \frac{\partial F_d}{\partial Y_\mu} = -\frac{\lambda_d \gamma Y_\mu}{2Y_d}$$

$$dw = -\lambda_d \frac{\partial F_d}{\partial B} = \lambda_d$$

λ_d the Lagrange multiplier

FINITE ELEMENT FORMULATION

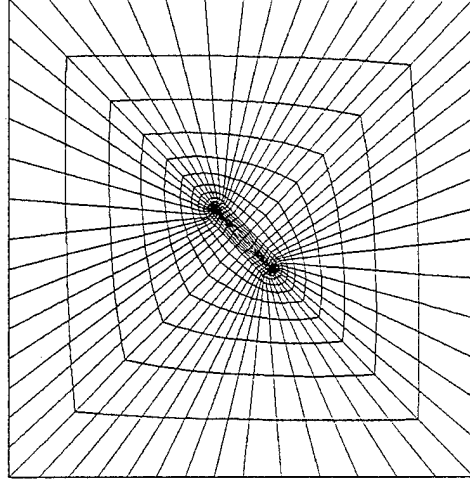
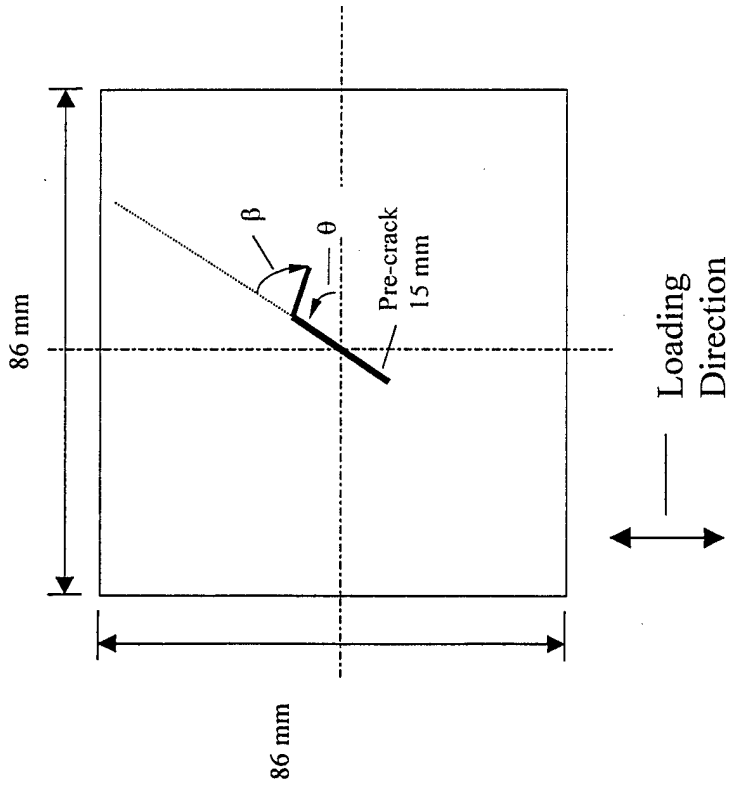
The proposed damage model is discretized and coded in the user subroutine UMAT of a finite element package ABAQUS (version 5.8).

$$d\boldsymbol{\sigma} = \mathbf{C}^{ep} : d\boldsymbol{\varepsilon} \quad \mathbf{C}^{ep} = \mathbf{M}^{T,-1} : \mathbf{U}^{T,-1} : \mathbf{C}_0^{ep} : \mathbf{M}^{T,-1}$$

\mathbf{C}^{ep} the effective instantaneous tangent modulus tensor

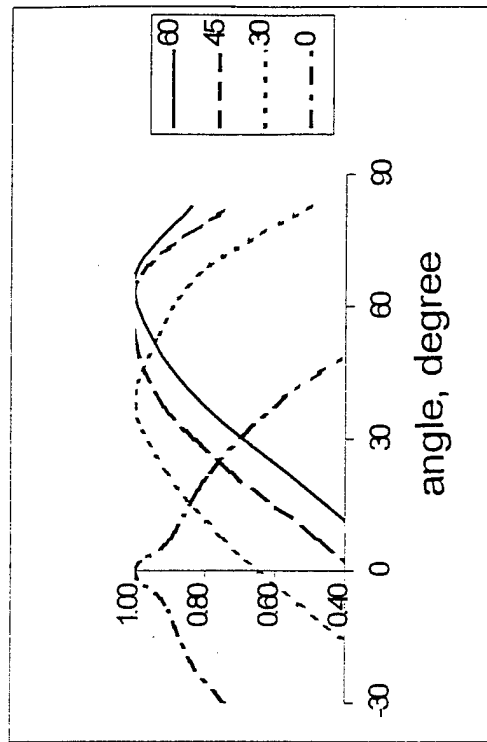
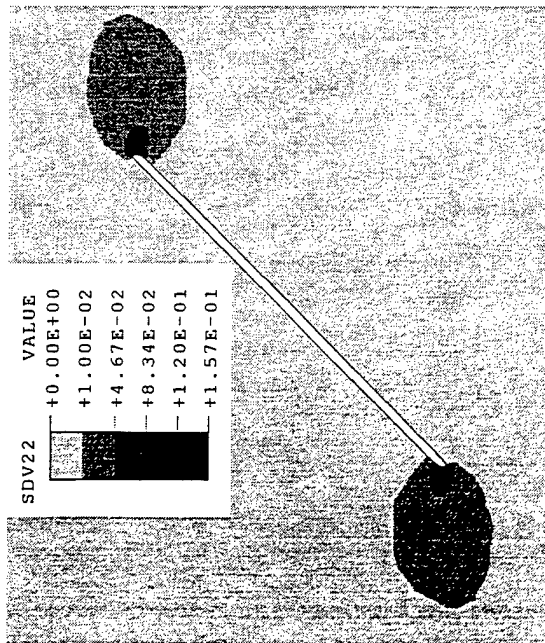
$$\mathbf{U} = \mathbf{I} - \left(\mathbf{U}_0 + \mathbf{C}_0^{ep} : \mathbf{M}^{T,-1} : \mathbf{U}_0 : \mathbf{M}^{T,-1} : \mathbf{C}^{-1} \right) : \boldsymbol{\sigma} : \mathbf{T} : \mathbf{M}^{T,-1}$$
$$\mathbf{U}_0 = \frac{\partial \mathbf{M}}{\partial D} \frac{\partial F_d}{\partial Y_D} + \frac{\partial \mathbf{M}}{\partial \mu} \frac{\partial F_d}{\partial Y_\mu}$$

Crack Initiation Angles for Al 2024-T3 Plates



Typical finite elements
for mixed-mode fracture analysis
?

Crack Initiation Angles for Al 2024-T3 Plates



Damage distribution contours in AL2024-T3 plate for $\theta = 45^\circ$

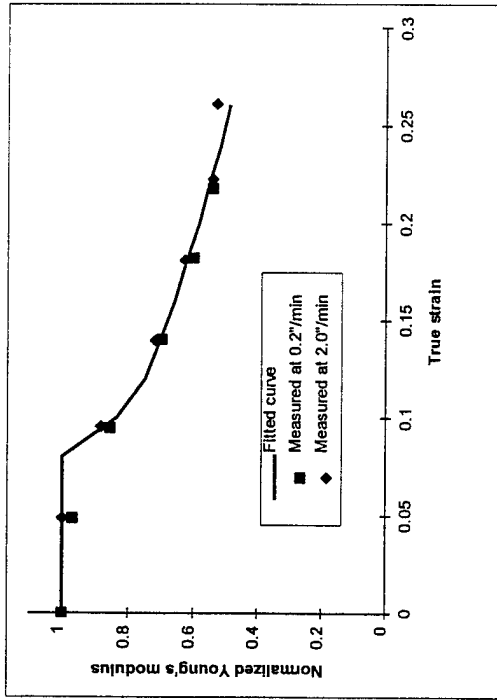
Angular distributions of damage for mixed mode AL2024-T3 specimen

Crack Initiation Angles for Al 2024-T3 Plates

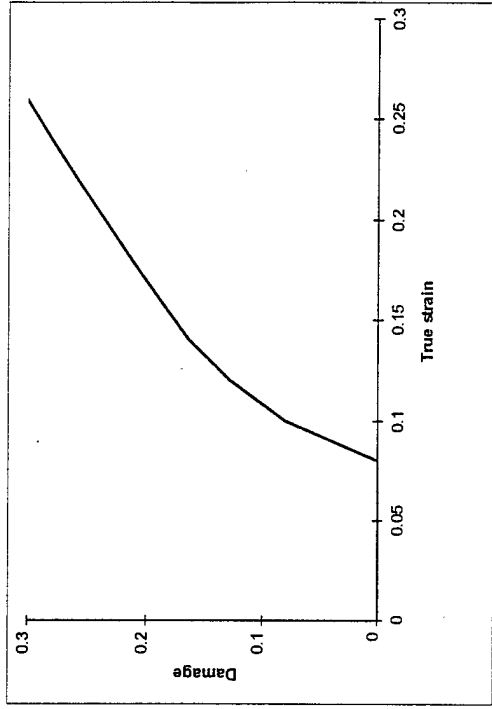
Table 1 Crack Initiation Angle β_i for Al2024-T3

inclined angle θ	test	numerical simulation	
		proposed model	Chow&Wang's model
0	0	0	0
30	35.9	37.5	43
45	53.7	52.5	56
60	71.2	67.5	73

Measurement for Particulate Composite Plates

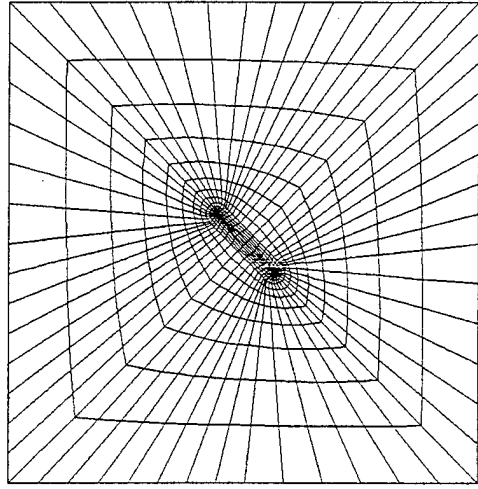
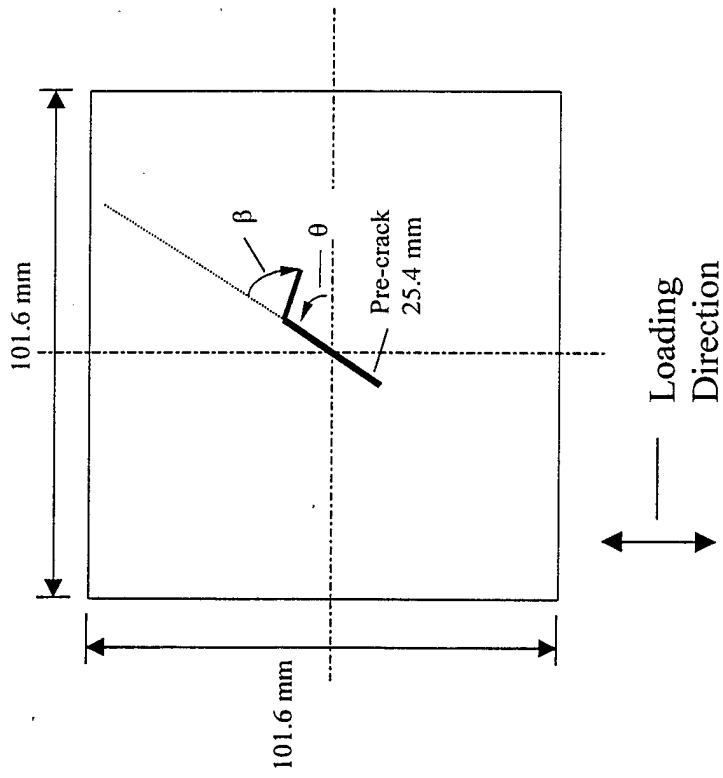


Normalized Young's modulus vs. applied strain for a particulate composite



Damage evolution curve for a particulate composite

Fracture Analysis for Particulate Composite Plates



Typical finite elements
for mixed mode fracture analysis

?

Fracture Analysis for Particulate Composite Plates

Table 2 Crack Initiation Load for Particulate Composite

Pre-crack angle (°)	0	30	60
Load prediction	24.0	27.2	36.9
(lb) test	23.4	27.0	36.2

Table 3 Crack initiation Angle β_i (°) Particulate Composite

Pre-crack angle θ (°)	0	30	60
β_i prediction	0	28	62
(°) test	0	33	68

Conclusions

- (1) Numerical modeling result indicates that damage accumulation is confined around the crack tip region.
- (2) For 2024-T3 Al, both the isotropic and the anisotropic damage models can be used to predict the crack initiation loads and angles under mixed-mode loadings with good accuracy.
- (3) For the particulate composite material, the predicted crack initiation loads and angles, based on the proposed isotropic damage model, agree well with the test results.
- (4) Both the crack initiation loads and angles increase with increasing the initial crack inclined angles.