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Y.W. Kwon (NPGS) and C.T. Liu, "Damage Study in Notched Particulate Composite Specimens Under Nonuniform Strain Loading"

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DAMAGE STUDY IN NOTCHED PARTICULATE COMPOSITE SPECIMENS UNDER NON-UNIFORM STRAIN LOADING

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ABSTRACT

This paper studied crack initiation in a hard particle reinforced composite with a soft rubber-like matrix material using a numerical technique. The numerical specimen considered had a semi-circular notch with a linearly varying length. The initial crack size occurring at the notch tip was modeled and predicted using a micro/macro-approach along with a damage model. A criterion to predict the initial crack size was proposed based on the size of a localized unstable material zone. Different notch sizes were compared to their initial crack sizes.

INTRODUCTION

There are many kinds of composite materials. They can be classified depending on reinforcing materials, matrix materials, and/or their shapes. One of commonly used composites is a particle reinforced composite. Particle reinforced composite (or particulate composite) is easy to produce. Thus, many researchers have devoted their studies to particulate composites in order to understand and predict their mechanical characteristics [Farris 1971, Gent and Park 1984, Schapery 1973, Weng 1984]. One of the important mechanical characteristics is strength and toughness. In particular, crack initiation and growth in such composite materials is an important issue for safety.

A ~~One of~~ particulate composites ~~has~~ may have very hard/stiff particles embedded in a soft/weak matrix. For example, particles may ~~are~~ be metallic while the binding matrix is a rubber-like polymer material. The present study considers crack initiation in such composite materials. Progressive damage at the notch tip and its vicinity in a rectangular specimen with a center hole was studied in the past [Kwon and Baron 1998, Kwon and Liu 1997, 1998]. In the present study, a specimen whose geometry is shown in Fig. 1 was considered. Crack initiation at the notch tip was simulated using a numerical technique. Especially, the study focused on the prediction of initial crack size occurring at the crack tip.

For the numerical study, a micro/macro-approach was used along with damage mechanics at the micro-level. The approach is described below and the criterion to determine the initial crack length at the crack tip is also discussed.

ANALYSIS

As an analysis tool, a micro/macro-approach was utilized to model and simulate progressive damages in particulate composite specimens. The approach consists of two levels of analyses: micro-level and macro-level analyses. The macro-level analysis is the structural level analysis while the micro-level analysis is the constituent material level analysis like particle and matrix materials. Each level of analysis has its own merits and the two levels are closely coupled together.

Complex composite structures under diverse loading conditions can be modeled in the macro-level analysis using the finite element method. That is, plate/shell or three-dimensional solid structures can be analyzed at the macro-level. However, damage modes at the macro-level are quite complex. These complex damage modes can be described in a much simpler way at the micro-level like matrix cracking, particle cracking, and interface debonding. Further, the material behavior at the micro-level is simpler than that at the macro-level. Even if the

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macro-level properties are anisotropic, the micro-level properties are mostly isotropic or orthotropic. Thus, simpler constitutive laws for damage description can be used at the micro-level than the macro-level.

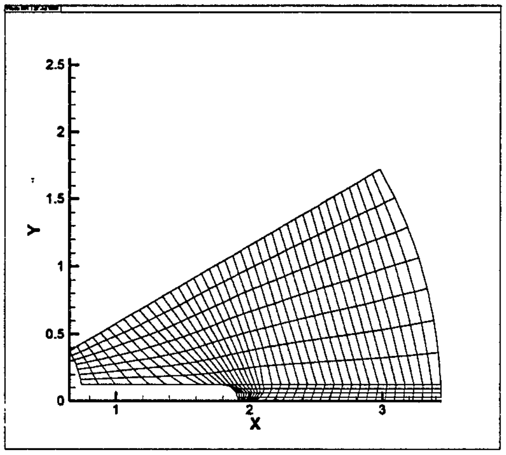

Figure 1. Finite Element Mesh of a Specimen

A main part of the micro/macro-approach is how to couple the two different levels of dimensions. The macro-level structures have much larger dimensions than the micro-level fibers. In order to relate the two different levels, the micro-level analysis represents collective behaviors of local particle and matrix materials rather than a single particle and the surrounding matrix. Then, the collective behavior is applied to the macro-level analysis. The interaction between the micro-level and macro-level analyses is schematically shown in Fig. 2 and explained below:

The macro-level finite element analysis requires smeared composite material properties to compute element stiffness matrices. The smeared properties are required at the Gauss integration points of every isoparametric finite element. Thus, smeared composite properties of collective particle and matrix materials at local areas (i.e.,area around each Gauss integration point) are computed at the micro-level and provided to the macro-level analysis.

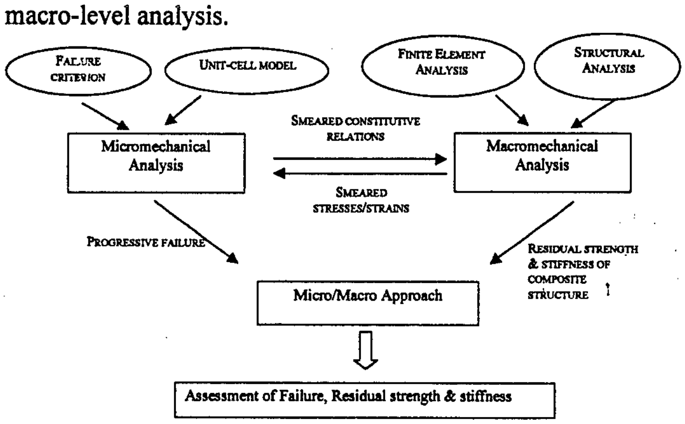

Figure 2. Interaction between Micro- and Macro-Level

The macro-level analysis computes global (i.e., macro-level) stresses, strains, and deformation for a given incremental load. These macro-level stresses and strains are passed to the micro-level analysis at which the micro-level stresses and strains (i.e.,stresses and strains in the particles and matrices) are computed from the macro-level stresses and strains. The micro-level stresses and strains represent those of collective particles and matrices instead of any single particle and the surrounding matrix.

Damage mechanics is applied to the collective entities of particles and matrices using the micro-level stresses and strains. Based on the damage states in the particles, matrices, and interfaces, their respective degraded material properties are computed from the damage mechanics. These degraded properties are again used in the microlevel analysis to calculate the smeared degraded material properties of the composite and they are applied to the next macro-level analysis. Thus, the micro-level and macro-level analyses are conducted in tandem and the cyclic analyses repeat with incremental loads to determine the progressive damages.

As stated above, the micro-level analysis must be used repeatedly for each finite element as damage progresses. In order to make the whole approach computationally efficient, the micro-level analysis must be computationally efficient. Therefore, the micro-level study uses an analytical model of the constituent materials, so-called simplified three-dimensional unit-cell model. The model is shown in Fig. 3. The unit-cell model consists of eight subcells for general applications. It can be applied to fibrous, particulate, and aligned short fiber composites. However, for the present study, particulate composites are considered here. For a particulate composite, subcell 1 denotes the particle and the rest are the matrix material. Here, the particle does not mean a single particle but the averaged particle of collective particles. The same thing applies to the matrix material.

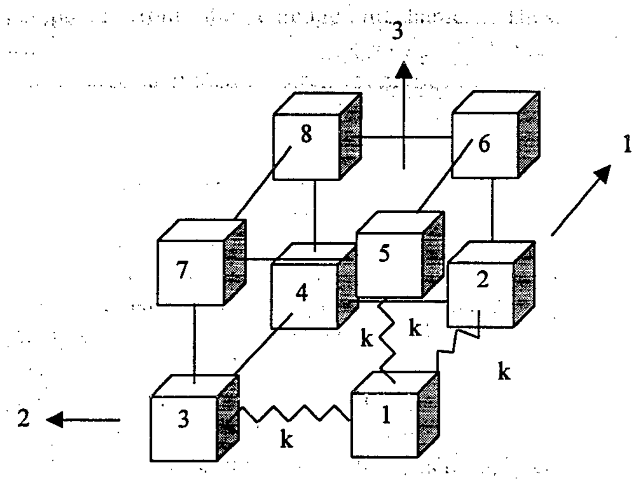

Figure 3. Unit-Cell Micro-model

The micro-level analysis has two functions in the micro/macro-approach. The first function is to compute smeared composite material properties based on the particle and matrix materials with or without damages. The second function is to decompose the macro-level stresses and strains into micro-level stresses and strains.

Once the stresses and strains are computed at the micro-level, these are used to determine the initiation and growth of damages at the particles, matrices, and their interfaces. Because there are three distinctive damage modes at the micro-level like the matrix damage, particle cracking, and interface debonding, these damages must be incorporated in the micro-model. The detailed works are described below:

Matrix Damage

In most cases, the initial damage is the matrix damage because matrix materials are much weaker than particle materials. In order to implement the matrix damage (i.e., initiation, growth, and nucleation of micro-voids in the matrix materials) into the micro-model, two kinds of approaches can be used.

The first approach is the continuum damage mechanics. Since the matrix is mostly an isotropic material, the isotropic continuum damage mechanics [Kwon and Liu 1997] will be utilized to describe the matrix damage. The isotropic continuum damage mechanics has a scalar quantity to denote the damage state. This is called the damage parameter that is assumed as a function of a strain energy measure in the matrix material of the micro-model. The damage parameter is zero before the damage and increases along with the damage. When the damage saturates, the parameter approaches to unity. It will be assumed that a macro-scale matrix crack forms when the damage in the matrix saturates across neighboring finite elements. In this way, macro-scale crack growth can be modeled. The reduced moduli are also computed based on the parameter. The damage parameter will be computed based on the micro-level strains at the matrix material of the micro-model. As a result, initiation and growth of matrix damage and macro-scale matrix crack formation will be modeled using the continuum damage mechanics.

The second approach is the use of Gurson's void model [Gurson 1997]. Gurson's constitutive equation has been successfully applied to model micro-void growth and nucleation in metallic materials. Gurson's model was developed for ductile materials and it can be properly modified for the polymer matrix materials. This model is applied to the matrix material so that damage growth and the resultant matrix material properties can be computed from Gurson's constitutive equation.

Particle Cracking

Because most reinforced particles are brittle, particle cracking can be modeled as brittle failure. Thus, the maximum normal stress/strain criterion is suitable for this. However, because the composite material under study has much stronger particles than the matrix, particle cracking did not occur. Hence it was not considered in this study.

Interface Debonding

Interface debonding is modeled with linear springs between the particle and matrix interface of the micro-model as shown in Fig. 3. If the spring constant is large enough, there is no interface crack. As the interface crack progresses, the spring constant will be reduced. The combined normal and shear stresses at the micro-level will be used to determine the interface debonding.

Once the damage models at the micro-level are completed, the micro/macro-approach will be used to investigate damage initiation, growth, saturation, and interaction in particulate composite specimens with notches.

The finite element models will be used for the macro-scale structures with incremental static loading. Three-dimensional solid elements were used to model the structures as necessary. The mathematical derivation for the 3-D unit cell model was given in Refs [Kwon and Liu 1997, 1998] and was omitted here.

CRITERION FOR INITIAL CRACK

It is proposed that the size of a crack initiating from a notch tip of the composite specimen is the same as the length of an unstable material zone at the immediate front of the notch tip at the onset of crack initiation at the notch tip. The unstable material zone is caused by accumulated damage in the zone. The onset of crack initiation is considered to be damage saturation at the notch tip so that it cannot sustain the load any more.

The previous statements are explained further below. As the applied load increases to a composite specimen, localized damage initiates and grows at the immediate neighbor around the notch tip. Before damage initiation, there is a stress/strain concentration at the notch tip. Therefore, stress/strain at the notch tip is much greater than that at any other location. The greater stress/strain causes damage and the damage material loses load-carrying capability. As the damage grows, the load-carrying capability decreases further. Then, the stress at the notch tip becomes lower than that at its immediate neighbor that takes extra load. This process continues so that the load-transfer moves from the notch tip to away from it. Eventually, the stress distribution in front of the notch tip is shown as in Fig. 4 with damage saturation at the notch tip.

The figure shows a localized unstable material zone at the immediate front of the notch tip. The reason it is called a unstable material is explained below. If the induced stress is plotted against the applied strain at a location in the unstable zone, the curve shows material softening (instability) as shown in Fig. 5. Thus, it is proposed that when crack initiates at the notch tip, it will continue to propagate through the unstable material zone.

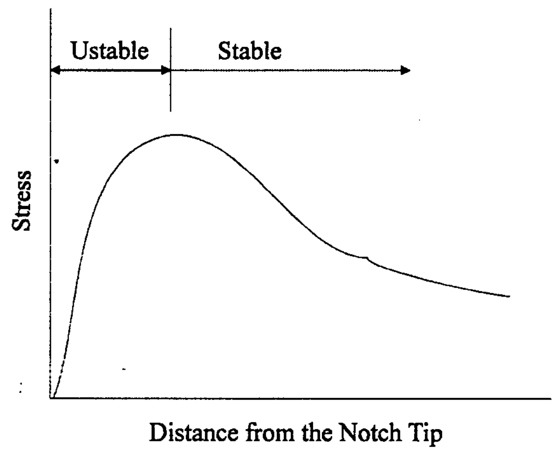

Figure 4. Localized Unstable Material Zone

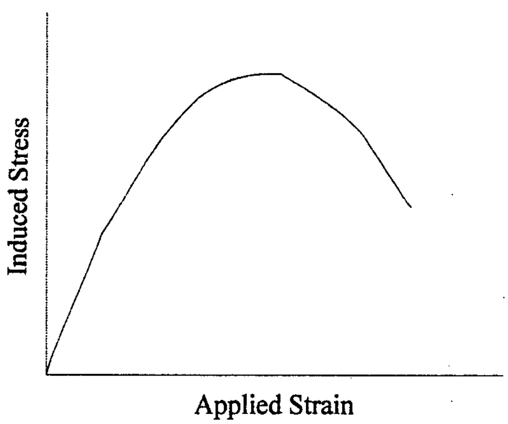

Figure 5. Stress-Strain Curve of an Unstable Material

RESULTS AND DISCUSSION

The geometry of the specimen along with its finite element mesh is shown in Fig. 1. A uniform displacement is applied to the top boundary of the specimen. Radii of the inside and the outside are 19.05mm and 87.38mm, respectively. The angle is 30 degrees. The notch tip radius varied from 3.18mm to 6.35mm.

As the uniform displacement is applied to the specimen, its initial crack size was determined from the analysis. For the specimen with the notch radius of 3.18mm, the initial crack size was 1.8mm while the larger notch radius of 6.35mm resulted in the crack of 2.1 mm. The larger notch radius resulted in the longer initial crack length.

The comparison between two different notch radii is given in Figs. 6 and 7. Figure 6 plots the major strain component along the axis from the notch tip. The major strain is that along the loading direction. In the figure, 'large' and 'small' indicate the larger radius (6.35mm) and the smaller radius (3.18mm) of the notch, respectively. The smaller radius of notch results in a more localized strain distribution at the notch tip. As a result, damage is also more concentrated at the immediate zone of the tip for the smaller radius as seen in Fig. 7

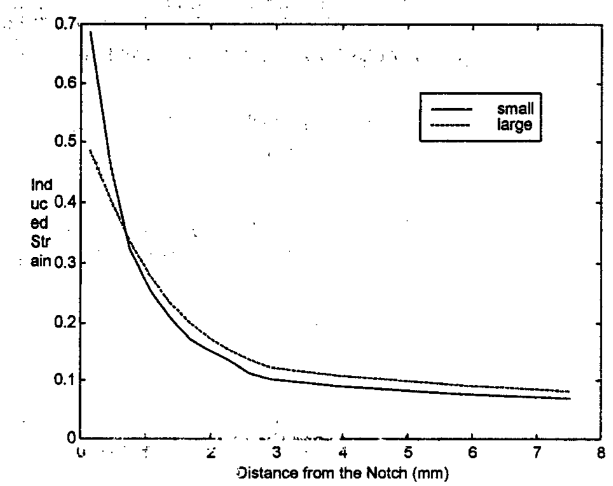

Figure 6. Comparison of Strain Distribution between Two Different Notch Radii

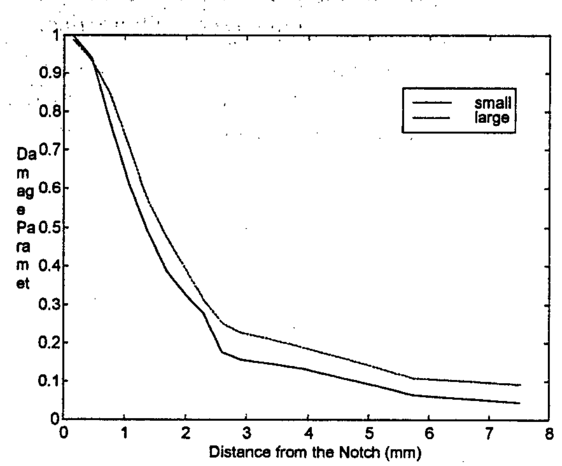

Figure 7. Comparison of Damage Distribution between Two Different Notch Radii

CONCLUSIONS

Particulate composite specimens as shown in Fig. 1 were examined for their crack initiation at notch tips for two different notch radii. The numerical modeling and simulation were conducted using a micro/macro-approach, damage mechanics at the micro-level, and a proposed criterion for the initial crack length. The study showed that a smaller notch radius resulted in a more localized damage at the crack tip and a smaller initial crack length. Those results need to be further confirmed by an experimental study.

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