PROGRESSIVE DAMAGE MODELLING FOR DYNAMIC LOADING OF COMPOSITE STRUCTURES

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Abstract

A three parameter constitutive model was developed for representing progressive damage of the nonlinear large-deformation rate-dependent behavior of polymer-based composite materials, which was characterized using off-axis composite specimens. A strain based failure criterion was proposed that reduces data for different loading directions and strain rates to a single representation. A method of combining the nonlinear constitutive theory and the failure strain methodology for different strain rates is suggested. The strength of the material was successfully represented with a single material constant, for all strain rates and loading directions.

1 Introduction

Many structure applications of composite materials involved dynamic loading, while there are many structural codes that can analyze dynamic structure response, design of such structures using composites materials requires that the nonlinear response of those materials be properly represented as a function of strain rat, and that some criteria for failure be established. Many such structures are designed on the basis of limit stresses for damage initiation. However, this results in inefficient use of materials and provides no realistic results for remaining stiffness of strength after loading events such as blast loading.

The present investigation attempts to represent progressive damage in composite laminates, up to strain of 18 percent, in terms of constitutive equations that are elastic-plastic, with coefficients that are rate dependent. In this paper, a plain-weave vinyl ester material was selected and a number of different strain rate tensile tests of off-axis coupon specimens were conducted. A three-parameter constitutive model was proposed to model the large deformation stress-strain relationship. Comparison of model predictions with experimental data indicated that one single master curve could be used for modeling the progressive damage development response, and to predict the failure point. A strain to failure criterion based on a Monkman-Grant concept was developed to represent the failure model of different loading directions at different strain rates. Applications to structures by incorporating the resulting methodology into commercial discrete element codes such as ABAUS to enable structural analysis in the presence of large strain progressive damage under dynamic loading were enabled.

2 Experiments and Results

The present work was conducted on woven glass reinforced vinyl ester composites specimens, by cutting out the specimens at different angles to the principal directions of the reinforcement of a ten-ply laminated plate configured as [0º, 90º, 0º, 90º, 0º, 90º, 0º, 90º, 0º, 90º]$_s$.

Tensile tests were performed at various strain rates from low (0.0001/s) to moderate (0.01/s) on an Instron™ servo hydraulic testing machine with a maximum loading capacity of 20,000 lb.; tests were controlled with a digital control loop using Instron™ Fast-Track 8800 software.

Fig 1 shows typical results of such testing at 0.0001/s strain rate. It can be seen that large deformation occurred on off-axis specimens, such as 45º orientation's specimen has a strain to break up to 18% and material shows high nonlinear characteristics. Fig 2 shows a different strain rate behavior of one same orientation specimen. Fig 3 shows the failure specimen of the tests.

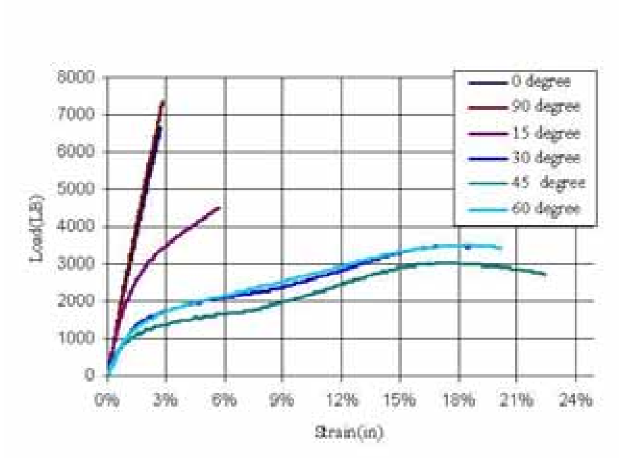

Fig 1. Load-strain behavior of woven glass reinforced vinyl ester specimens at 0.0001/s.

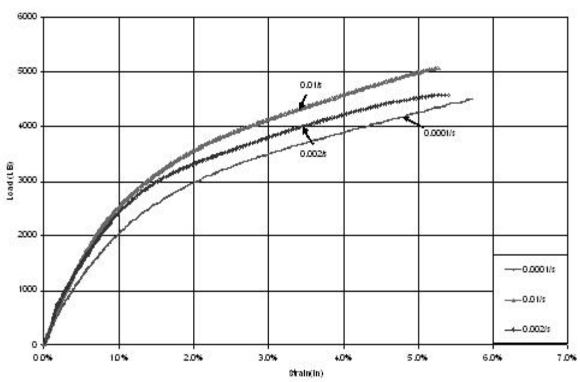

Fig 2. Load-strain behavior of 15° specimen at different train rates.

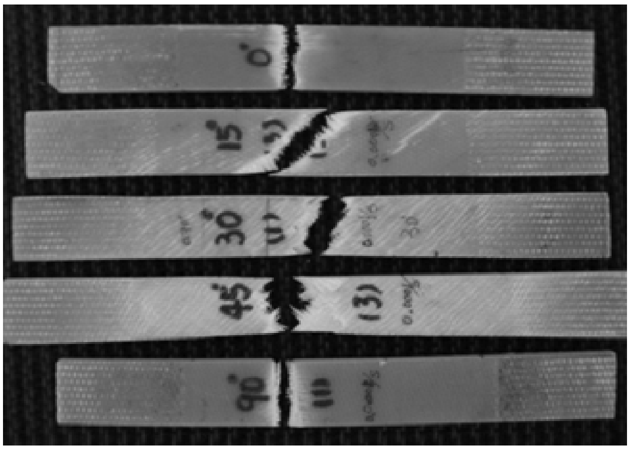

Fig 3. Failure modes of specimen of different orientations to the principal fiber.

3 Nonlinear Constitutive Modeling

Although the strain to break is small for uniaxial loading in the directions of the fiber reinforcement, for loading in the off axis directions the strains are large, up to 18% for this material. The material behavior can be represented by constricting constitutive models based on the nonlinear response of anisotropic composites under dynamic loading, i.e. loading at different strain rates.

If we consider two-dimensional stress states in an orthotropic material, we require the engineering constants, $E_1, E_2, G_{12}, \frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$. Then the elastic potential may be written as

$$w = \frac{1}{2}\left(\frac{\sigma_{11}^2}{E_1} - \frac{2\nu_{12}}{E_1}\sigma_{11}\sigma_{22} + \frac{\sigma_{22}^2}{E_2} + \frac{\sigma_{11}^2}{G_{12}} \right) \qquad (1)$$

If loading is applied by stress σ_θ at angle θ to the axis of symmetry, the potential w becomes

$$w = \frac{1}{2}\sigma_\theta^2 \left[\left(\frac{1}{E_1}\cos^4\theta + \left(\frac{1}{G_{12}} - \frac{2\nu_{12}}{E_1} \right)\sin^2\theta\cos^2\theta + \frac{1}{E_2}\sin^4\theta \right] \qquad (2)$$

The linear strain ε_θ is expressed as:

$$\varepsilon_\theta^l = \frac{\partial w}{\partial \sigma_\theta} = \frac{\sigma_\theta}{E_1} h_l^2(\theta) \qquad (3)$$

For the nonlinear deformation, Ogihara and Reifsnider have introduced a three-parameter generalization of the 2-D single plasticity model to construct a constitutive representation of the nonlinear quasi-static behavior of angle-ply laminates. A quadratic yield function is assumed for the 3-D composite in the form

$$2f(\sigma_{ij}) = a_{11}\sigma_{11}^2 + a_{22}\sigma_{22}^2 + a_{33}\sigma_{33}^2 + 2a_{12}\sigma_{11}\sigma_{22} + 2a_{13}\sigma_{11}\sigma_{33} + 2a_{23}\sigma_{22}\sigma_{33}$$
$$+ 2a_{12}\sigma_{11}\sigma_{22} + 2a_{44}\sigma_{23}^2 + 2a_{55}\sigma_{13}^2 + 2a_{64}\sigma_{12}^2 = k$$

Where k is a state variable and the stresses are referred to the principal material directions. The yield function is taken as the plastic potential function from which the incremental plastic strain can be derived in the usual way. Introducing an effective stress, $\sigma^* = \sqrt{3f}$, one can write

$$dW^p = \sigma_{ij} d\varepsilon_{ij}^p = 2f d\lambda = \sigma^* d\varepsilon^{*p} \Rightarrow d\varepsilon^{*p} = \frac{2}{3}\sigma^* d\lambda$$

and $d\lambda = \frac{3}{2}\left(\frac{d\varepsilon^{*p}}{d\sigma^*} \right)\left(\frac{d\sigma^*}{\sigma^*} \right)$ (4)

Where ε^{*p} is the effective plastic strain and W^p is the plastic work per unit volume. For plane stress equation (3) reduces to four terms.

For unidirectional loading, σ_x, in a direction that forms a positive angle θ with the fiber direction, x_1, the stress components in the material system are

$$\sigma_{11} = \sigma_x \cos^2(\theta) \qquad \sigma_{22} = \sigma_x \sin^2(\theta)$$

$$\sigma_{12} = -\sigma_x \sin(\theta)\cos(\theta) \tag{5}$$

Where, $\sigma^* = \sigma_x h(\theta)$ and

$$h(\theta) = \sqrt{\frac{3}{2}\left(a_{11}\cos^4\theta + a_{22}\sin^4\theta + 2(a_{12}+a_{66})\sin^2\theta\cos^2\theta\right)} \tag{6}$$

For woven composites, Ogihara introduced that a_{11}=1, resulting in the most general three parameter plasticity model for planar problems and uniaxial loading. Then the plastic potential function reduces to

$$2f = \sigma_x^2 h^2(\theta) \tag{7}$$

Where

$$h(\theta) = \sqrt{\frac{3}{2}\left(\cos^4\theta + a_{22}\sin^4\theta + 2(a_{12}+a_{66})\sin^2\theta\cos^2\theta\right)}$$

Since the effective stress-strain relation should be a material property under monotonic loading, the material parameters in (7) must be chosen so that the $\sigma^*\left(\varepsilon^{*p}\right)$ relations are independent of loading angle. If (7) is cast in the following form, it is possible to determine c_1 and c_2 in the following manner.

$$h(\theta) = \sqrt{\frac{3}{2}\cos^4\theta + c_1\sin^4\theta + 2c_2\sin^2\theta\cos^2\theta} \tag{8}$$

We can determine the parameters of the plastic potential function so that the effective-stress, $\sigma \cdot h(\theta)$ Vs effective-strain $\varepsilon^n / h(\theta)$, forms a single master curve. It is seen that for $\theta = 90^0, h(90^0)$ depends only on the potential function parameter c_1. Hence, we can determine the numerical value of c_1 from the test data of 0º and 90º orientation specimens.

From our test data, as shown in Figure 3 and Figure 4, we obtained c_1=0.98, c_2=20 for all strain rates considered. Fig 4 shows the results at a strain rate of 0.002/s.

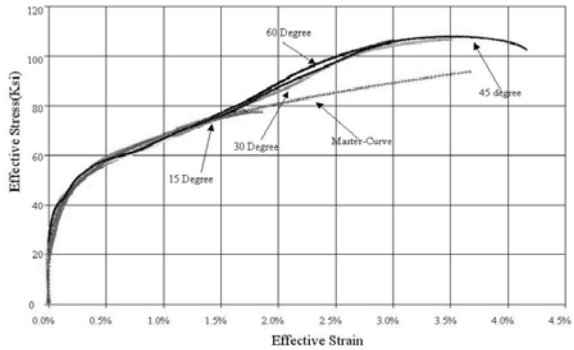

Fig 4 Effective stress-effective strain for 0.002/s off-axis tension test with c_1=0.98, c_2=20.

Let the master effective stress-effective strain curve be fitted by a power law as

$$\bar{\varepsilon}^p = A(\bar{\sigma})^n \tag{9}$$

In which, amplitude A is a function of strain rate as:

$$A = \chi\left(\dot{\bar{\varepsilon}}^p\right)^m \tag{10}$$

where χ and m are constant.

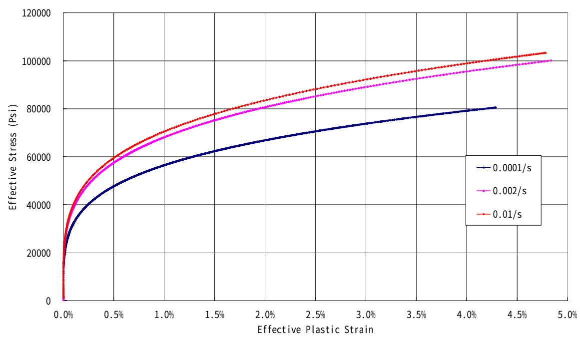

Fig 5 Different master curves for different strain rates with n=4.1

The A values show a strong strain rate dependence. Having a set of different values of A, we can calculate χ and m values based on logarithmic transformations; then we can use linear extrapolation to get different A values at different strain rates.

By now we treat the material as a nonlinear behavior material only for off-axis orientation, and we assume 0/90 orientation to principal fiber direction behavior is linear elastic. In this case, 0/90 test data were not considered in the nonlinear material behavior modeling. However, if we consider the damage effect in the material, there were nonlinear behavior even for 0/90 orientation also, i.e., the well knee effect for fiber principal direction as shown in Fig 6 below.

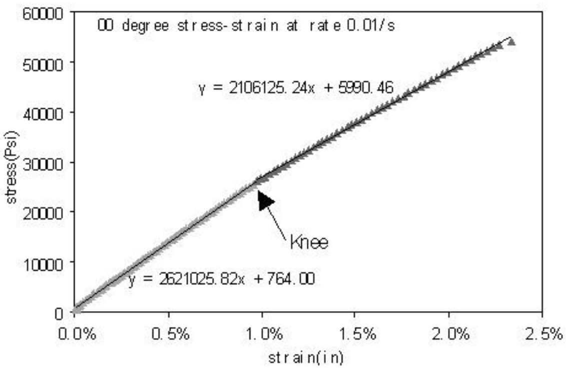

Fig 6 Nonlinear behavior of 0 degree orientation specimen after damage occurs.

It would be more accurate if we take this damage lead knee effect into account in our model developing process. That leads to a bilinear treatment of the 0/90 behavior. And we found that the model will more accurate especially in the elastics range. It is because the initial elastic stiffness was underestimated by overall averaging the whole deformation range that include the after matrix damage behavior of the composites.

By considering the bilinear behavior of 0/90 orientation specimens, the master curve parameters can be determined to include all of material direction's nonlinear characteristics. Fig 7 shows the modified master curve and its parameters.

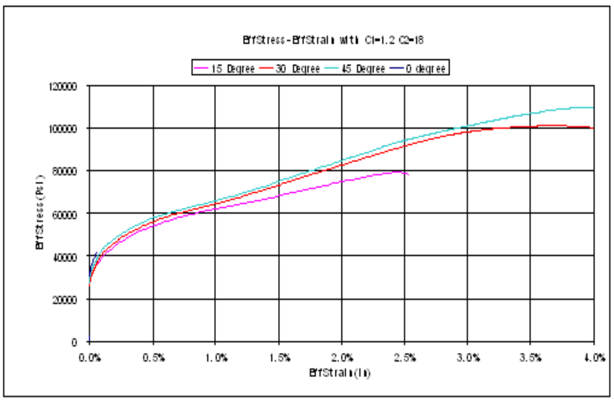

Fig 7 Modified master curve for 0.002/s off-axis tension test with c_1=1.2, c_2=18.

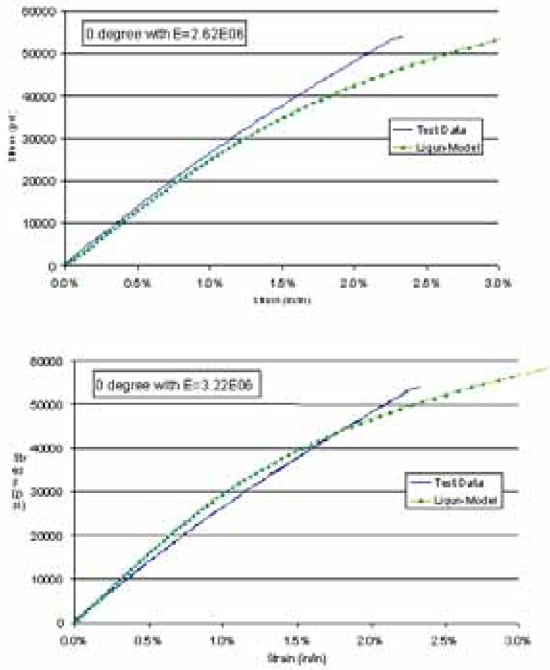

Fig 8 Comparison of different approach of 0º/90º orientation model prediction.

Fig 8 shows the comparison between different approaches for the 0/90 orientation behavior.

Fig 9 shows the model prediction for different orientation behaviors.

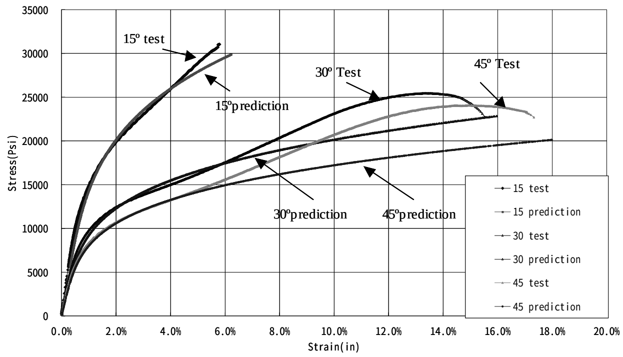

Fig 9 Predictions of off-axis stress/strain curves for 0.01/s

4. Failure Criterion under Dynamic Loading

For engineering application, especially for structure analysis, the mechanistic approach of failure criterion for composites are not appealing due to composite properties, which are governed by local material response such as strength and interfacial phenomena. And more in-depth knowledge of the physics will be involved when dealing with local rather than global material responses. On the other hand, the phenomenological failure criterion approach is suitable for engineering characterization of the material properties governed by either the averaged globe or the local material responses. The well-known Tsai-Hill and Tsai-Wu failure criterion for composites are belong to the phenomenological approach. However, there are no existing failure criteria that can be used to include the strain rate effect for the composite materials in the literature.

In the structure level analysis, failure criterion needs to be addressed in a light computation loading way such that it can be implemented in numerical analysis codes and given more efficient analysis. There, we introduced a Monkman-Grant concept to be a generalized failure criterion for dynamic loading conditions.

Monkman-Grant equation suggests that

$$t_b \cdot \left(\dot{\varepsilon} \right)^m = C_1 \qquad (11)$$

Where t_b is the failure time and m is a constant effect, C_1 is a material constant. It inherently includes the strain rate effect and has been successfully used in metal materials. However, it cannot be used directly for anisotropic materials like composites. For different angles relative to the fiber principle direction θ, there would be different constant C1 and n for each strain rate. We may record different failure times t_b (θ) and $\dot{\varepsilon}(\theta)$ for different orientation and strain rate, and then converge different angle and strain rate constants into a material constant C_θ by generating a suitable $f(h(\theta))$ function.

Having the strain to failure under different orientation and strain rate, we then can generate the strain to failure surface as $g(\varepsilon_{ij}, G) = 0$ in order to have a general material failure criterion that can include the strain rate effect.

Some examples of predicted and observed strains to break using this approach are shown in Table 1 below, for three different strain rates.

Strain rate	Failure stress (Psi)	15^0	30^0	45^0	60^0
0.0001/s	σ_b (experiment)	29849	25261	24160	25109
	σ_b^* (model fit)	29107	23102	22894	23102
	$\Delta\%$	2.49%	8.55%	5.24%	7.99%
0.002/s	σ_b (experiment)	34366	27138	25815	27806
	σ_b^* (model fit)	33216	26169	23636	26169
	$\Delta\%$	3.35%	3.57%	8.44%	5.89%
0.01/s	σ_b (experiment)	36489	28515	28144	29069
	σ_b^* (model fit)	35225	27431	25896	27431
	$\Delta\%$	3.46%	3.81%	7.99%	5.7%

Table 1 Comparison between experimental strength data and predicted values

5. Conclusion

Tensile tests were conducted on off-axis woven glass reinforced vinyl ester composite laminate specimens with different strain rates. A three-parameter plastic potential function was employed to construct a nonlinear constitutive model for describing the nonlinear stress/strain relations of the composite.

Based on a Monkman_Grant concept, a new (single) material constant that can be used to represent the failure strain of different angles and at different strain rate was postulated. A new strength concept based on failure strain was developed to characterize composite laminates and to construct a robust stress, strain, strength model that can be used for structural analysis.

Continuing efforts focus on micromechanical failure analysis, and modeling the structural response of composites and laminates subjected to general dynamic loading conditions.

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