NSF Workshop on Barycentric Coordinates in Geometry Processing and Finite/Boundary Element Methods

DISCRETE DAMAGE ZONE MODEL FOR FRACTURE INITIATION AND PROPAGATION

XIA LIU, RAVINDRA DUDDU, HAIM WAISMAN
DEPARTMENT OF CIVIL ENGINEERING AND ENGINEERING MECHANICS, COLUMBIA UNIVERSITY, NEW YORK, NY 10027

INTRODUCTION

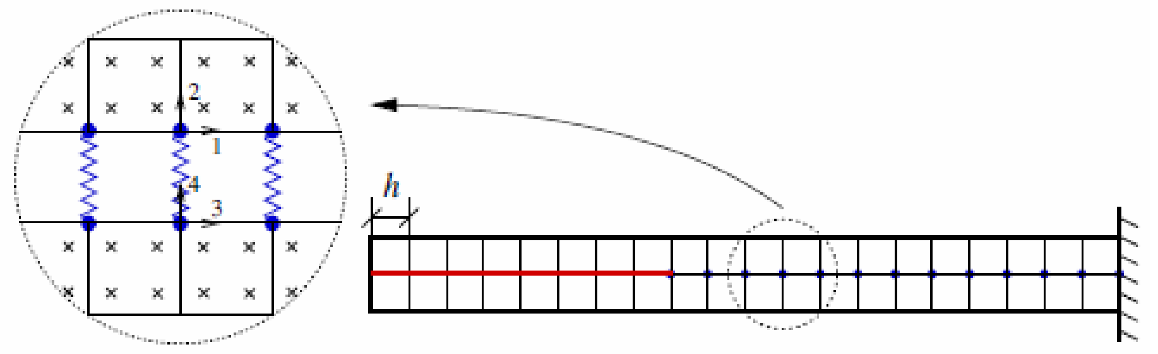
In this poster, we present a discrete temperature dependent damage zone model (DDZM) for static and fatigue delamination in composites.

In this approach, nonlinear spring elements are placed at finite element nodes of the laminate interface and damage laws are used to derive the interface element constitutive law. Herein, the interface element softening is described by a combination of static and fatigue damage growth laws so as to model delamination under high-cycle fatigue. The irreversibility of damage naturally accounts for the permanent reduction of material stiffness once the material is loaded beyond the elastic limit. The dependence of fatigue delamination on the ambient temperature is incorporated by introducing an Arrhenius type relation in to the damage evolution law.

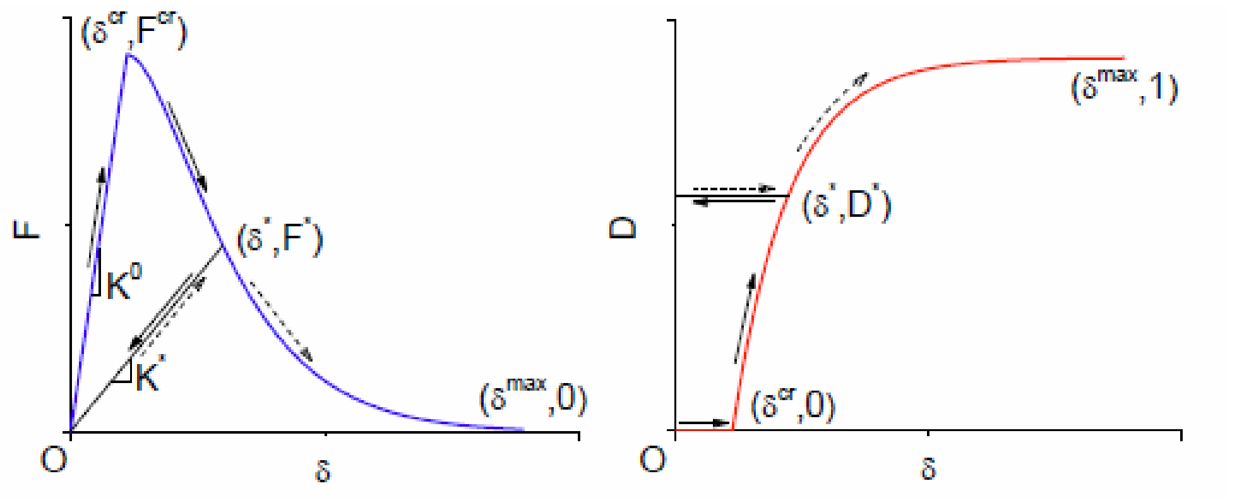
This model is implemented in the commercial Abaqus via a user defined element subroutine (UEL). Numerical results for mixed mode static and fatigue delamination growth are presented. The suitability of the method for studying fracture in fiber-matrix composites involving fiber debonding and matrix cracking is demonstrated. The model parameters for fatigue simulations are calibrated from previously published experimental data and the results are validated under varying mode mix conditions demonstrating the viability of the approach.

BACKGROUND

The proposed DDZM is developed entirely from the perspective of continuum damage mechanics, wherein delamination is interpreted as a process of damage evolution at the laminate interface resulting in the degradation of the interface element stiffness. The discrete interface element is a two dimensional spring like element that connects the interface nodes, shown in the following figure,



The force-separation relationship for the discrete spring element is based on the continuum damage evolution law governing the material behavior. Herein, we derive a force-separation law for the spring element for exponential softening under monotonic loading.



(a) Force vs. separation (b) Damage vs. separation

The relationship between the force in the spring and the critical force is,

$$F^* = K^*\delta^* = (1-D^*)\,K^0\delta^{cr}\frac{\delta^*}{\delta^{cr}} = (1-D^*)\,F^{cr}\frac{\delta^*}{\delta^{cr}},$$

where K^0 is initial or undamaged stiffness of the spring and $F^{cr}=K^0\delta^{cr}$. Let us consider the continuum damage model proposed by Mazars for brittle material,

$$D_s' = 1-(1-A)\frac{\epsilon^{cr}}{\epsilon} - \frac{A}{\exp\left(B(\epsilon-\epsilon^{cr})\right)},$$

where A and B are material parameters and ε is the uniaxial tensile strain. We may assume the parameter A=1. Now, let us write a discrete damage law for the springs in terms of the separations based on Mazars damage law as,

$$D_s = \begin{cases} 0, & \text{if } \delta < \delta^{cr}, \\ 1-\dfrac{1}{\exp\left(B(\delta-\delta^{cr})\right)}, & \text{if } \delta \geq \delta^{cr}. \end{cases} \xrightarrow{\text{we get}} F = \begin{cases} K^0\delta = F^{cr}\dfrac{\delta}{\delta^{cr}}, \\ \dfrac{K^0\delta}{\exp\left(B(\delta-\delta^{cr})\right)} = F^{cr}\dfrac{\delta}{\delta^{cr}\exp\left(B(\delta-\delta^{cr})\right)}, \end{cases}$$

Note that the solid and dashed arrows in the above plots represent a cyclic process of loading-unloading-reloading-unloading, which shows the irreversibility of damage model takes account the stiffness degradation automatically.

METHOD

The model considers both static and fatigue damage. Generally, an additive decomposition of the damage rate is assumed as,

$$\frac{\partial D}{\partial t} = \dot{D} = \dot{D}_s + \dot{D}_f$$

where D represents the total damage in the discrete spring elements, D_f is the fatigue damage component and D_s the static damage rate component is given by,

$$\dot{D}_s = \exp(-B(\delta-\delta^{cr}))B\dot{\delta}$$

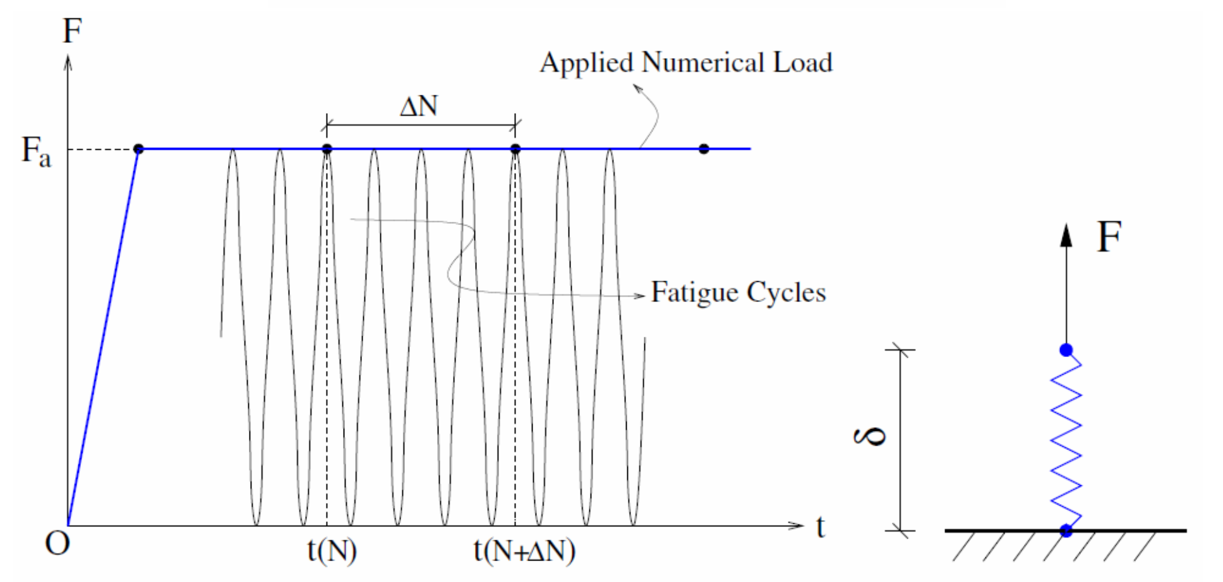
The fatigue damage law is based on a continuum model proposed by Peerlings etal., and the discrete form is written as,

$$\dot{D}_f = C\exp(\lambda D)\left(\frac{\delta}{\delta^f}\right)^{\beta}\frac{\dot{\delta}}{\delta^f}$$

Where C, β and λ are parameters. δ^f is an interface separation measure introduced solely for dimensions reasons.

For the temperature dependence of damage, we propose a relation for the fatigue damage rate as.

$$\dot{D}_f(T) = \dot{D}_f(T_{rm})\exp\left(-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{rm}}\right)\right)$$



(a) Fatigue loading history (b) Test configuration

The relation between the force in the spring and the interfacial separation is given by,

$$\begin{aligned} F(t(N+\Delta N)) &= K(t(N+\Delta N))\;\delta(t(N+\Delta N)) \\ &= (1-D(t(N+\Delta N)))\,K^0\;\delta(t(N+\Delta N)), \end{aligned}$$

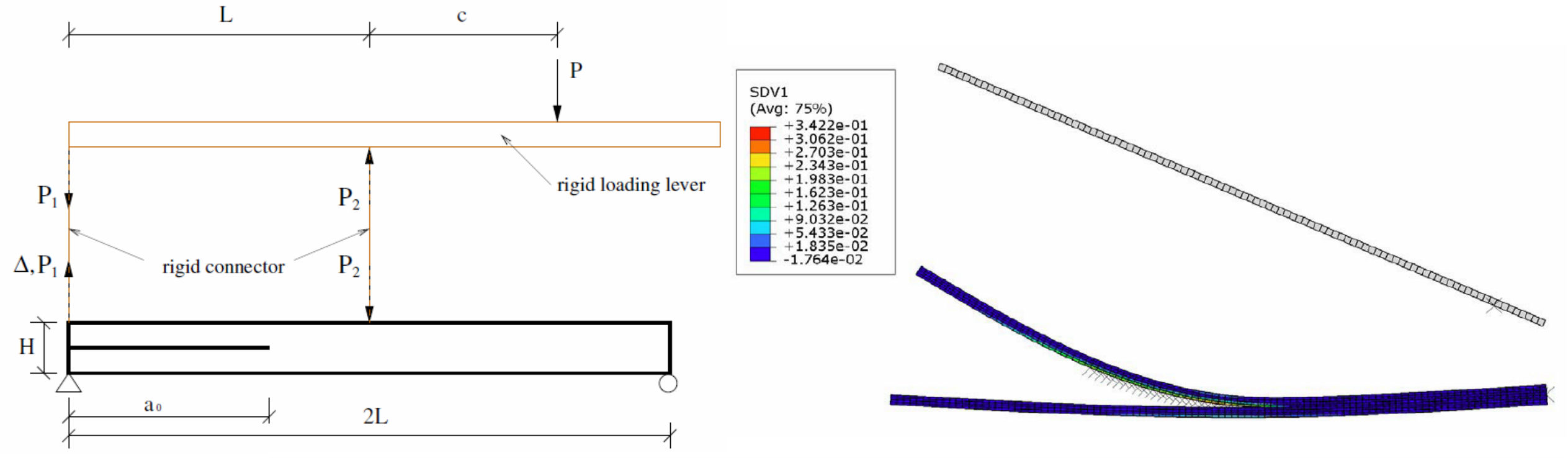
Where damage is given as,

$$D(t(N+\Delta N)) = D(t(N)) + \int_{t(N)}^{t(N+\Delta N)}(\dot{D}_s+\dot{D}_f)dt.$$

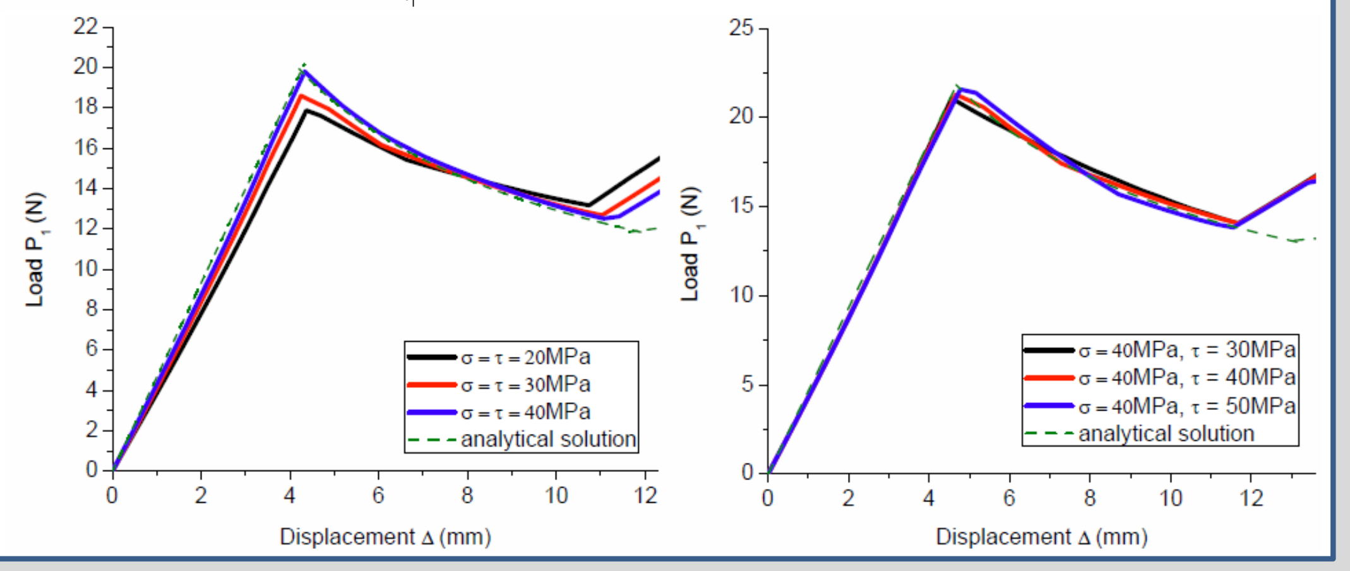
RESULTS

For static delamination simulations, we present results of mixed mode bending test and the fiber-matrix debonding.

MIXED MODE (MMB):

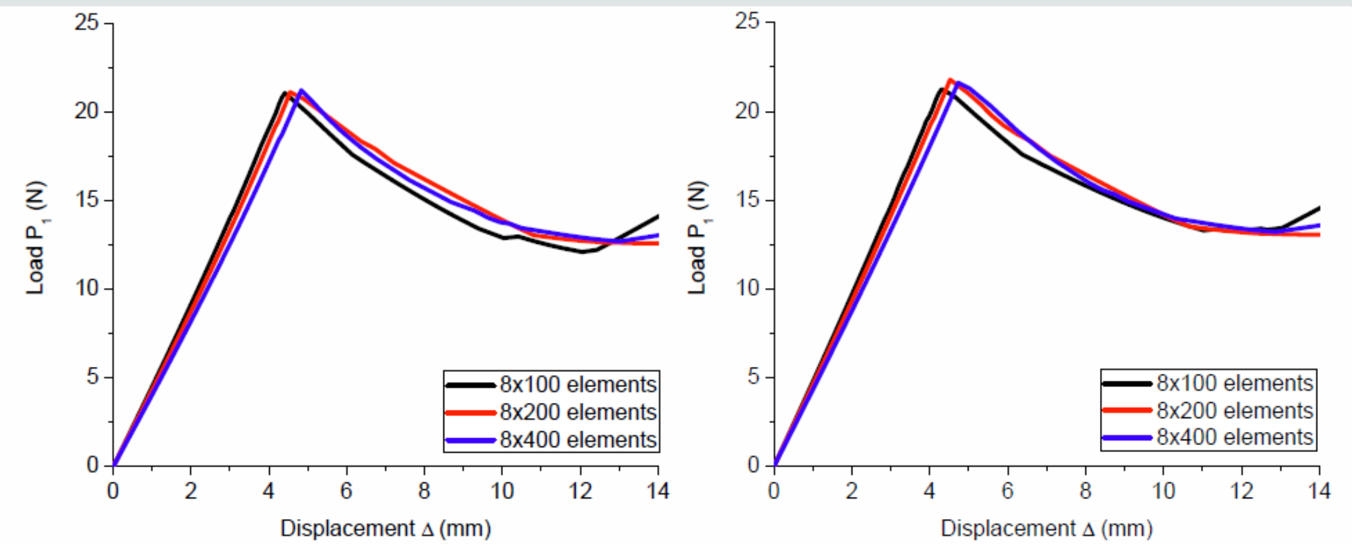


Convergence test:

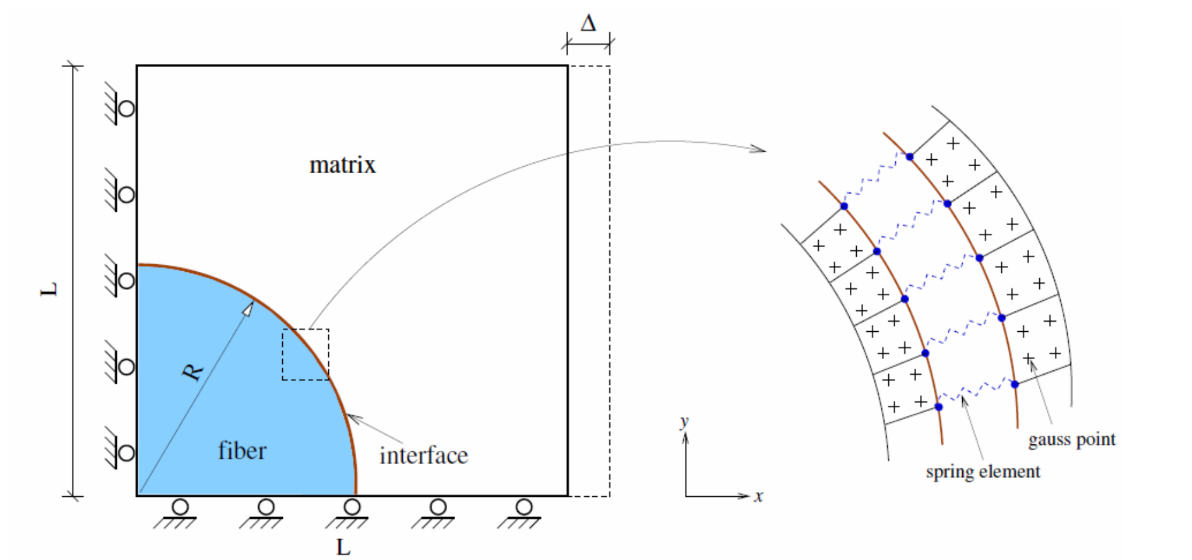


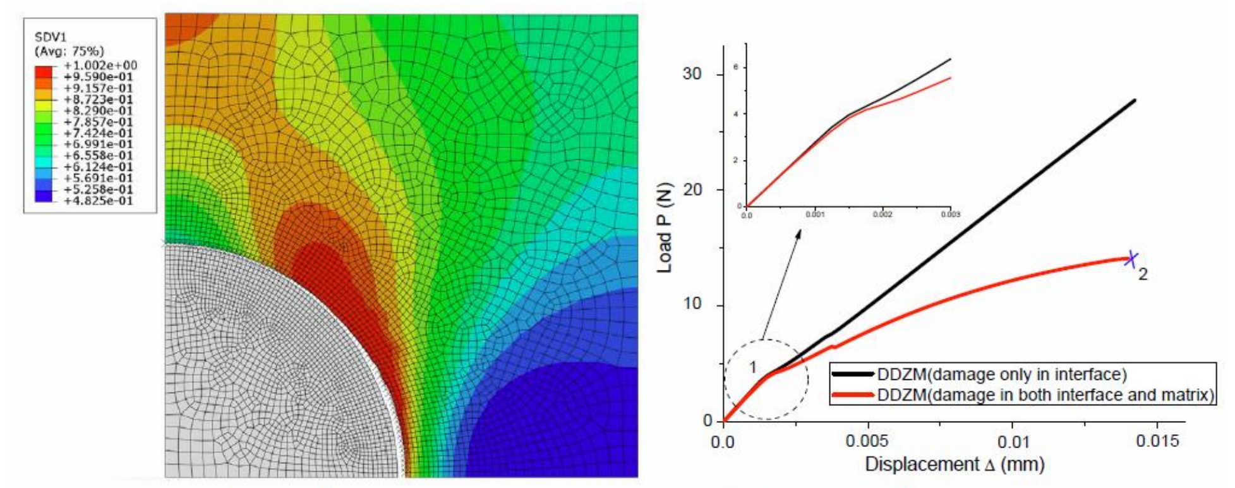
RESULTS(CONTINUED)

Mesh Sensitivity:



FAILURE OF FIBER-MATRIX COMPOSITES

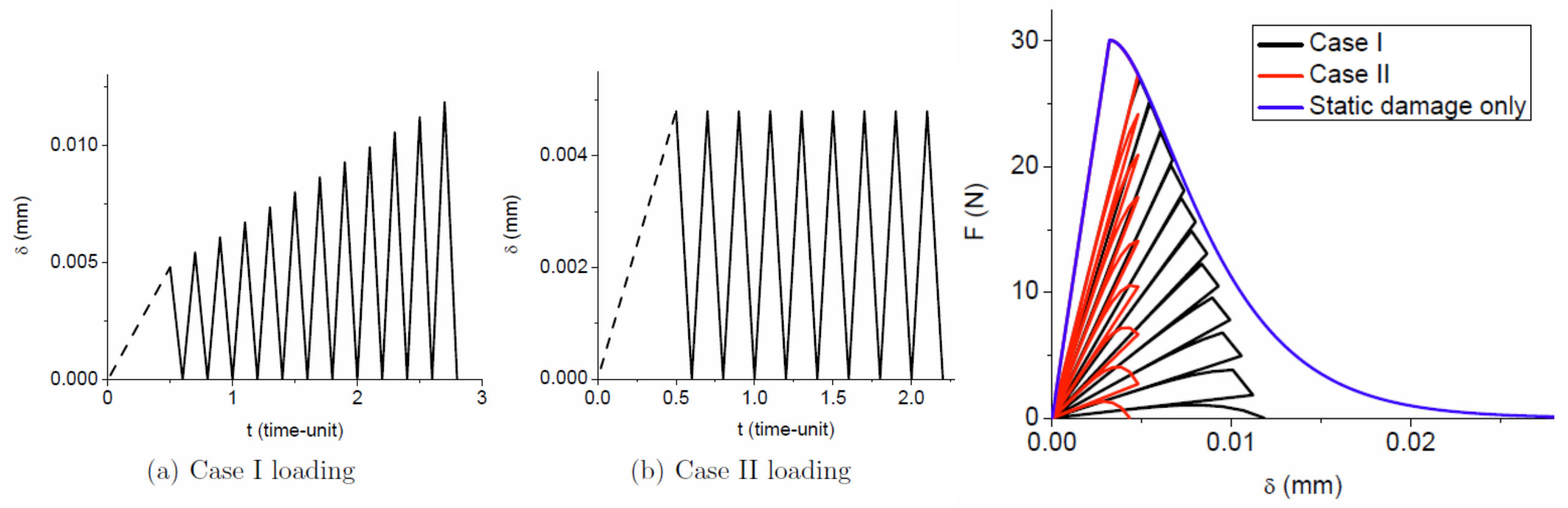




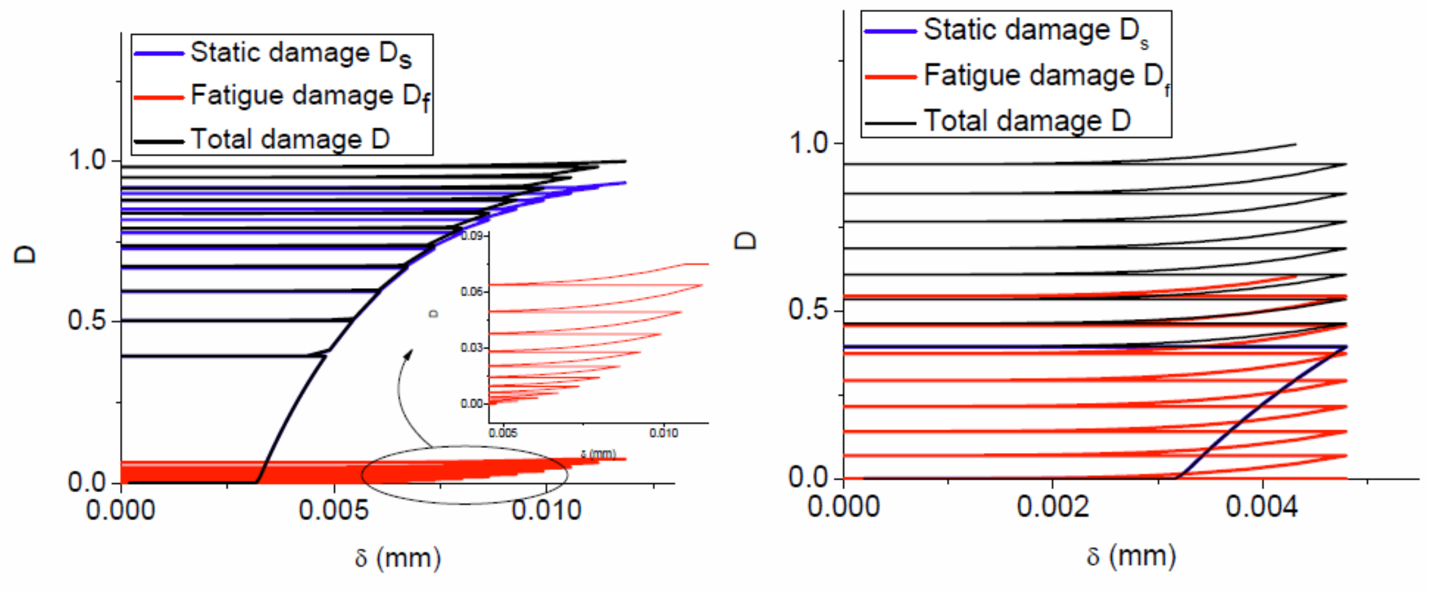
(a) Contour plot of the continuum damage just before failure (b) Load vs. displacement curve.

THE PERFORMANCE OF A DISCRETE SPRING ELEMENT UNDER CYCLE BY CYCLE LOADING

In this section, we present a simple one element test to demonstrate the applicability of the DDZM for low cycle fatigue. The set up of one element test is shown to the left. We consider two cases of loading histories shown below.



(a) Case I loading (b) Case II loading (a) Force vs. separation

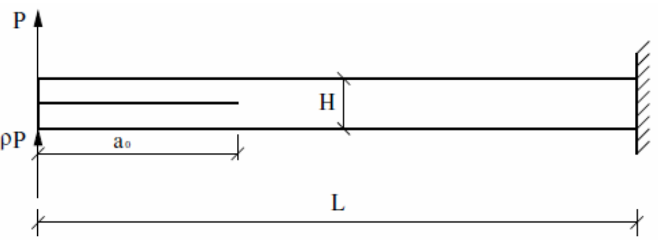


(b) Case I: damage vs. separation (c) Case II: damage vs. separation

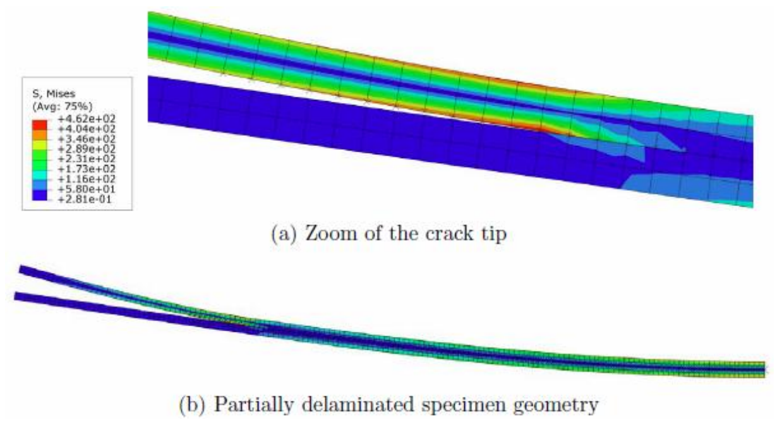
RESULTS(CONTINUED)

DELAMINATION AT ELEVATED TEMPERATURE:

We calibrate the temperature dependence of fatigue delamination from the experimental data. We plot the data available at two different temperatures for mixed mode. A single value for the damage activation energy Q=25KJ/mol can fit the experimental data well.

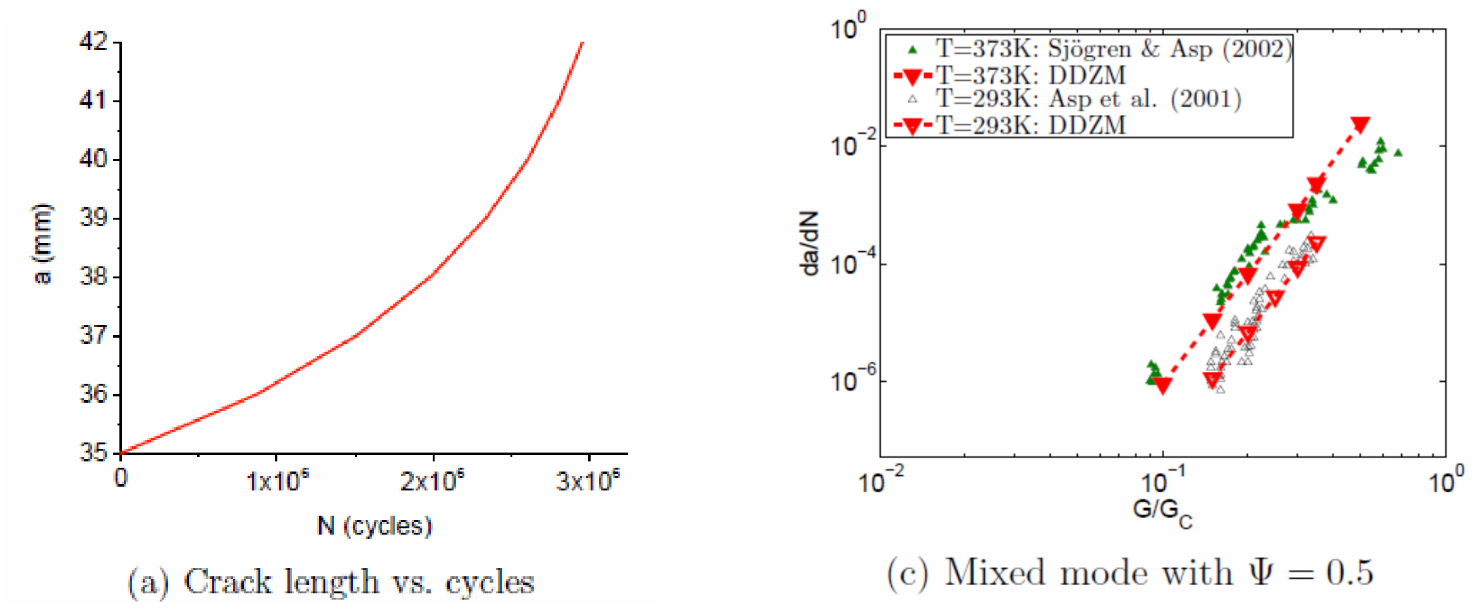


$$\rho = \frac{1-\dfrac{\sqrt{3}}{2}(\Psi^{-1}-1)^{1/2}}{1+\dfrac{\sqrt{3}}{2}(\Psi^{-1}-1)^{1/2}}. \qquad \Psi = \frac{G_{II}}{G_I+G_{II}}.$$



(a) Zoom of the crack tip

(b) Partially delaminated specimen geometry



(a) Crack length vs. cycles (c) Mixed mode with $\Psi = 0.5$

CONCLUSIONS

A discrete damage zone model (DDZM) for studying mixed mode fatigue delamination in composite laminates has been developed, wherein the fracture process zone is interpreted as a damage zone. This model has the following improvements,

(1) The interface element is discrete spring placed at the finite elment nodes;
(2) The constitutive law of the discrete element is derived entirely from damage laws by combining Mazars law for static damage growthn and Peerlings law for fatigue damage growth;
(3) A quadratic criterion describes the fatigue delamination for varying mode mixe ratios;
(4) An Arrhenius type relation captures the temperature dependence of fatigue damage.

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