A NEW RATE-DEPENDENT COHESIVE MODEL FOR SIMULATING DYNAMIC COMPOSITE DELAMINATION

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Abstract

A new eight-node adaptive rate-dependent cohesive element is proposed in this paper. In this model, a pre-softening zone is proposed ahead of the existing softening zone. In this pre-softening zone, the initial stiffness and the interface strength are gradually decreased. The onset displacement corresponding to the onset damage is not changed in the proposed model. In addition, the critical energy release rate of the materials is kept constant. Moreover, the constitutive equation of the new cohesive model is developed to be depended on the opening velocity of the displacement jump.

The traction based model includes a cohesive zone viscosity parameter (η) to vary the degree of rate dependence and to adjust the maximum traction. The new cohesive element is implemented in LS-DYNA as a user defined material subroutine (UMAT) designed for solid elements. The numerical simulation results of DCB in Mode-I is presented to illustrate the validity of the new model. It is shown that the proposed model brings stable simulations and can be widely used in quasi-static, dynamic and impact problems.

1 Introduction

Delamination is one of the predominant forms of failure in laminated composites when subjected to transverse dynamic loads and due to the lack of reinforcement in the thickness direction. Delamination can cause a significant reduction in the compressive load-carrying capacity of a structure.

Cohesive elements are widely used at the interface between solid finite elements to predict and to understand the damage behavior in the interfaces of different layers in composite laminates [1-7]. Many models have been introduced including: extrinsic, intrinsic, perfectly plastic, linear softening, progressive softening, and regressive softening [8]. Several rate-dependent models have also been introduced [9-14]. A rate-dependent cohesive zone model was first introduced by Glennie [9], where the traction in the cohesive zone is a function of the crack opening displacement time derivative. Xu et al. [10] extended this model by adding a linearly decaying damage law. In each model the viscosity parameter (η) is used to vary the degree of rate dependence. Kubair et al. [14] thoroughly summarized the evolution of these rate-dependant models and provided the solution to the mode III steady-state crack growth problem as well as spontaneous propagation conditions.

However, generally, numerical instabilities frequently occur when using the cohesive interface model to simulate the interface damages. To stabilize the finite element simulations of delamination propagation in composite laminates under dynamic loads and to over come these numerical instabilities, a new 8-node cohesive element model is proposed in this paper. In this model, a pre-softening zone is proposed ahead of the existing softening zone. In this pre-softening zone, the initial stiffness and the interface strength are gradually decreased. The onset displacement corresponding to the onset damage is not changed in the proposed model. In addition, the critical energy release rate of the materials is kept constant. Moreover, the constitutive equation of the new cohesive model is developed to be depended on the opening velocity of the displacement jump.

Finite element simulation is a powerful tool and can be used in the initial design stage without going through multiple-cycles of prototype testing and iterative design changes. Among the various commercial finite element codes, LS-DYNA [15] excels in large deformation transient dynamic problems and impact simulations due to the explicit time integration algorithms within the code. LS-DYNA has a large library of material options which have been widely used in the automobile and aerospace industries. However, continuous cohesive elements are not available within the code.

In this study, the new cohesive element is formulated and implemented in LS-DYNA as a user defined material subroutine (UMAT) designed for solid elements. The formulation of this model is fully three dimensional and can simulate mixed-mode delamination. However, the objective of this study is to develop new adaptive cohesive elements able to capture delamination onset and growth under Mode-I loading condition.

2 Constitutive Equations of Adaptive Cohesive Elements

The cohesive element is used to model the interface between sublaminates. The elements consists of a zero-thickness volumetric element in which the interpolation shape functions for the top and bottom faces are compatible with the kinematics of the elements that are being connected to it [16].

Cohesive elements are typically formulated in terms of traction vs. relative displacement relationship. In order to predict the initiation and growth of delamination, an 8-node cohesive element shown in Fig. 1 is developed and modified to overcome the numerical instabilities.

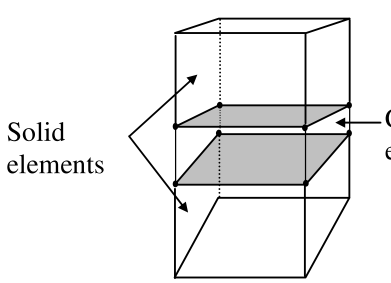

Fig. 1. Eight-node cohesive element

The need for an appropriate constitutive equation in the formulation of the interface element is fundamental for an accurate simulation of the interlaminar cracking process. A constitutive equation is used to relate the traction to the relative displacement at the interface. The bilinear model, as shown in Fig. 2, is the simplest model to be used among many strain softening models. Moreover, it has been successfully used by several authors in implicit analyses [17].

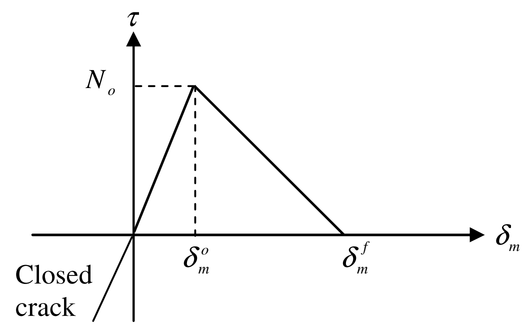

Fig.2. Normal (Bilinear) constitutive model

However, using the bilinear model leads to numerical instabilities in an explicit implementation. To overcome this numerical instability, a new adaptive model is proposed and presented in this paper.

In this model, as shown in Fig .3, a pre-softening zone is proposed ahead of the existing softening zone. In this pre-softening zone, the initial stiffness and the interface strength are gradually decreased. The onset displacement corresponding to the onset damage is not changed in the proposed model. Moreover, the critical energy release rate of the materials is kept constant. Also, the traction based model includes a cohesive zone viscosity parameter (η) to vary the degree of rate dependence and to adjust the peak or maximum traction.

The adaptive interfacial constitutive response shown in Fig. 3 is implemented as follows:

1. $\delta_m^{\max} < \delta_m^o$, the constitutive equation is given by

$$\tau = (\tau_m + \eta \dot{\delta}_m)\frac{\delta_m}{\delta_m^o} \qquad (1)$$

and

$$\tau_m = K\delta_m^o \qquad (2)$$

where τ is the traction, K is the penalty stiffness and can be written as

$$K = \begin{cases} K_o & \delta_m \le 0 \\ K_i & \delta_m^{\max} < \delta_m^o \\ K_n & \delta_m^o \le \delta_m^{\max} < \delta_m^f \end{cases} \qquad (3)$$

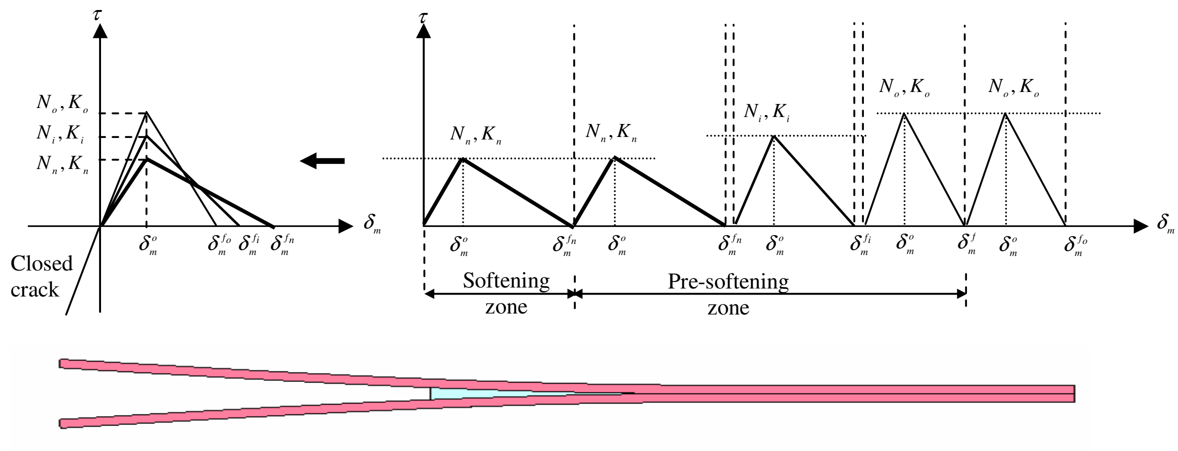

Fig. 3. Adaptive constitutive model for Mode-I

δ_m is the relative displacement in the interface between the top and bottom surfaces (in this study, it equals the normal relative displacement for Mode-I), δ_m^o is the onset displacement and it is remained constant in the simulation and can be determined as follows:

$$\delta_m^o = \frac{N_o}{K_o} = \frac{N_i}{K_i} = \frac{N_{\min}}{K_{\min}} \qquad (4)$$

Were N_o is the initial interface strength, N_i is the updated interface strength in the pre-softening zone, $N_{\min}$ is the minimum limit of the interface strength, K_o is the initial stiffness, K_i is the updated stiffness in the pre-softening zone, and $K_{\min}$ is the minimum value of the stiffness. The $\delta_m^{\max}$ is the max relative displacement of the cohesive element occurs in the deformation history and can be defined as

$$\delta_m^{\max} = \max\left\{\delta_m^{\max}, \delta_m\right\} \qquad (5)$$

Using the max value of the relative displacement $\delta_m^{\max}$ rather than the current value δ_m prevents healing of the interface. The updated stiffness and interface strength are determined in the following forms:

$$N_i = \frac{\delta_m^{\max}}{\delta_m^o}(N_{\min} - N_o) + N_o\,,\ N_o > N_{\min} \qquad (6)$$

$$K_i = \frac{\delta_m^{\max}}{\delta_m^o}(K_{\min} - K_o) + K_o\ ,\ K_o > K_{\min} \qquad (7)$$

The energy release rate for Mode-I G_{IC} is also remained constant. Therefore, the final displacements associated to the complete decohesion $\delta_m^{f_i}$ are adjusted as shown in Fig. 3 as

$$\delta_m^{f_i} = \frac{2G_{IC}}{N_i} \qquad (8)$$

Once the displacement of the interface reaches the softening process, the current strength N_n and stiffness K_n which are almost equal to $N_{\min}$ and $K_{\min}$, respectively, will be used in the softening zone.

2. $\delta_m^o \le \delta_m^{\max} < \delta_m^f$, the constitutive equation is given by

$$\tau = (1-d)(\tau_m + \eta\dot{\delta}_m)\frac{\delta_m}{\delta_m^o} \qquad (9)$$

Where d is the damage variable and can be defined as

$$d = \frac{\delta_m^f(\delta_m^{\max} - \delta_m^o)}{\delta_m^{\max}(\delta_m^f - \delta_m^o)},\ \ d \in [0, 1] \qquad (10)$$

3 Implementation of Adaptive Cohesive Elements

The proposed cohesive element is implemented in LS-DYNA finite element code as a user defined material subroutine (UMAT) using the standard library 8-node solid brick element. This approach for the implementation requires modeling the resin rich layer as a non-zero thickness medium. In fact, this layer has a finite thickness and the volume associated with the cohesive element can in fact set to be very small by using a very small thickness (e.g. 0.01 mm). To verify these procedures, the crack growth along the interface of a double cantilever beam (DCB) is studied. The two arms are modeled using standard LS-DYNA 8-node solid brick elements and the interface elements are developed in FORTRAN subroutine using the algorithm shown in Fig. 5.

The LS-DYNA code calculates the strain increments for a time step and passes them to the UMAT subroutine at the beginning of each time step. The material constants, such as the stiffness and strength, are read from the LS-DYNA input file by the subroutine. The current and maximum relative displacements are saved as history variables which can be read in by the subroutine. Using the history variables, material constants, and strain increments, the subroutine is able to calculate the stresses at the end of the time step by using the form of constitutive equations.

The subroutine then updates and saves the history variables for use in the next time step, and outputs the calculated stresses. Note that the *DATABASE_EXTENT_BINARY command is requires to specify the storage of history variables in the output file.

4 Numerical Simulations

The DCB specimen, as shown in Fig. 4, is made of a unidirectional fiber-reinforced laminate containing a thin insert at the mid-plan near the loaded end. A 25 cm long specimen (L), 2.5 cm wide (w) and composed of two 1.50 mm thick plies of unidirectional material ($2h$) shown in Fig. 4 was analyzed by Moshier [18]. The initial crack length (l_c) is 3.4 cm. A displacement rate of 650 mm/sec is applied to the appropriate points of the model. The properties of Epoxy/Carbon-fiber composites and the interface are given as following:

(1) Epoxy/Carbon-fiber composites properties:

E =115 GPa, ρ =1566 Kg/m3, and υ =0.27

where E , ρ and υ are the Young's modulus, density and Poisson's ration, respectively.

(2) DCB specimen interface:

G_{IC} = 0.7 kJ/m^2, K_o = 1x10^5 N/mm^3, $K_{\min}$ = 0.333x10^5 N/mm^3, N_o = 50 MPa, and $N_{\min}$ = 16.67 MPa

where G_{IC} , K_o , $K_{\min}$, N_o and $N_{\min}$ are defined as energy release rate for Mode-I, initial stiffness, minimum stiffness, initial interface strength and minimum limit of the interface strength, respectively.

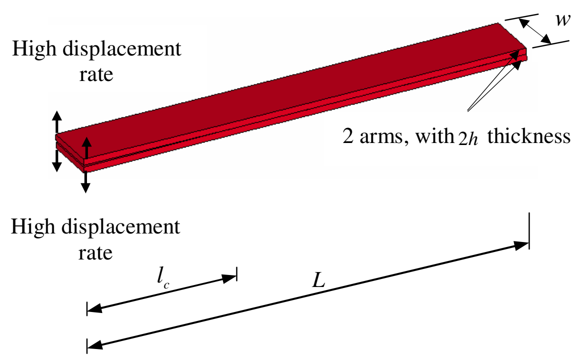

Fig. 4. Model of DCB specimen

The LS-DYNA finite element model consists of two layers of fully integrated S/R 8-noded solid elements. Each arm of the specimen is modeled using fully integrated S/R 8-noded solid elements, with 3 elements across the thickness.

5 Results and Discussions

The adaptive rate-dependent cohesive zone model is implemented using a user defined cohesive material model in LS-DYNA. Two different values of viscosity parameter are used in the simulations; η = 0.01 and 1.0 N.s/mm^3, respectively. In addition, two sets of simulations are performed. The first set involves simulations of normal (Bilinear) cohesive model. The second set involves simulations of the new adaptive rate-dependent model.

A plot of a reaction force as a function of the applied end displacement of the DCB specimen

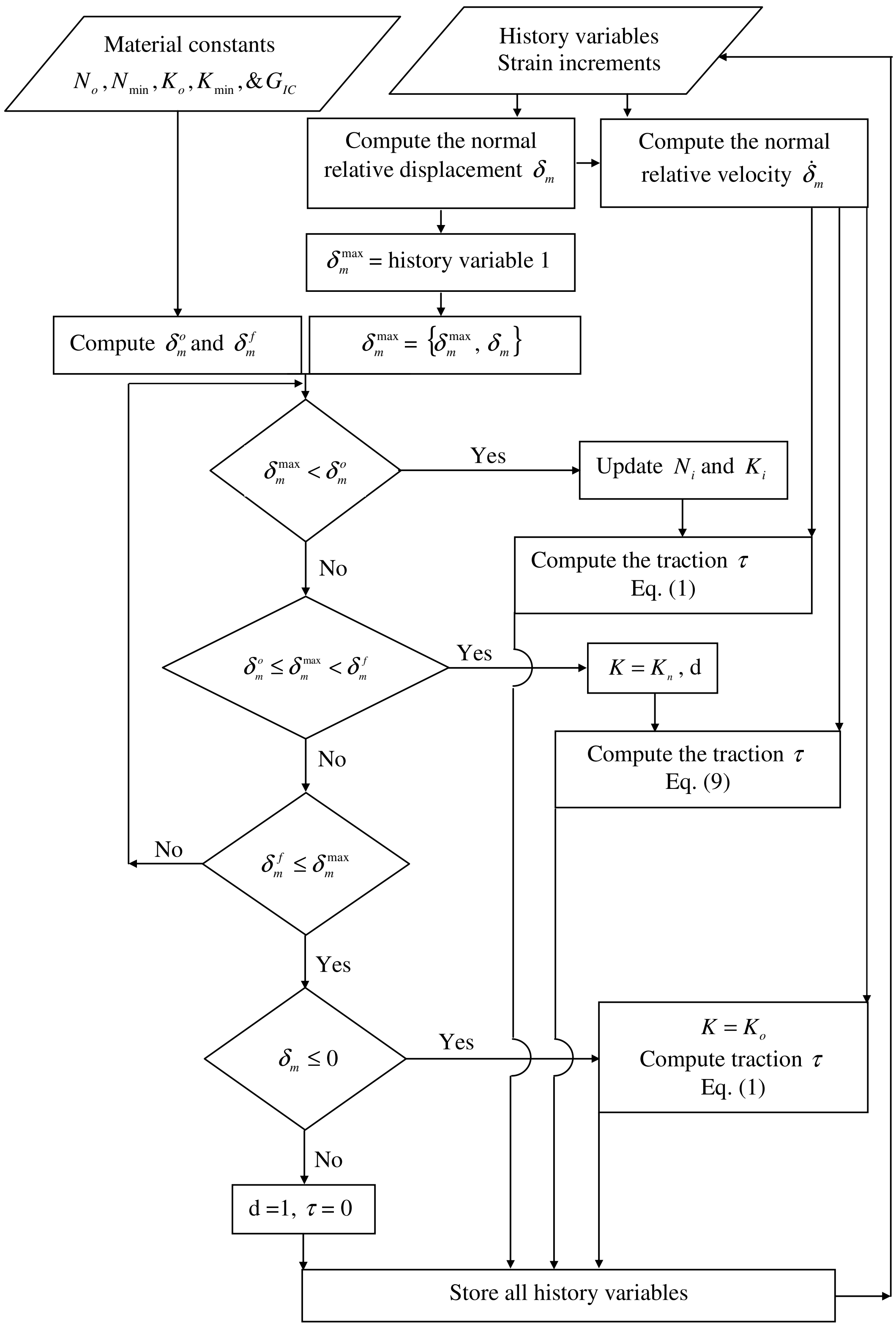

Fig. 5. Flow chart for traction computation in Mode-I

using cohesive elements with viscosity value of 0.01 N.s/mm^3 is shown in Fig. 6.

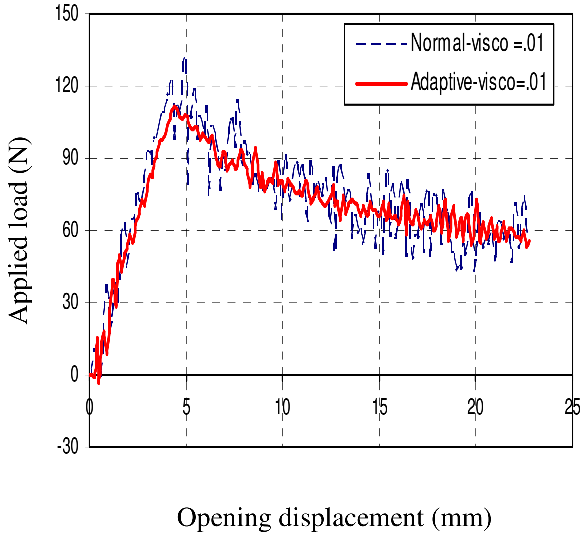

Fig. 6. Load-displacement curves obtained using both normal and adaptive formulations (η =0.01)

It is clearly shown from Fig. 6 that the bilinear formulation results in a severe instability once the crack starts propagating. However, the adaptive constitutive law is able to model the smooth, progressive crack propagation. It is worth mentioning that the bilinear formulation might bring smooth results by decreasing the element size. In the case of very fine mesh, it was noticed by Elmarakbi et al. [19] that both bilinear and adaptive formulations are found to be stable under quasi-static load. This indicates that the higher accuracy using bilinear formulation requires the smallest element size in the softening zone and this leads to large computational costs.

The load-displacement curves obtained from the numerical simulation of both bilinear and adaptive cohesive model using viscosity parameter of 1.0 N.s/mm^3 is presented in Fig. 7. It can be seen that, again, the adaptive constitutive law is able to model the smooth, progressive crack propagation while the bilinear formulation results in a severe instability once the crack starts propagating.

The average maximum load obtained using the adaptive rate dependent model is 110 N, whereas the average maximum load predicted form the bilinear model is 120 N.

Figure 8 shows the load-displacement curves of the numerical simulations obtained using the bilinear formulation with two different viscosity parameters, 0.01 and 1.0 N.s/mm^3, respectively.

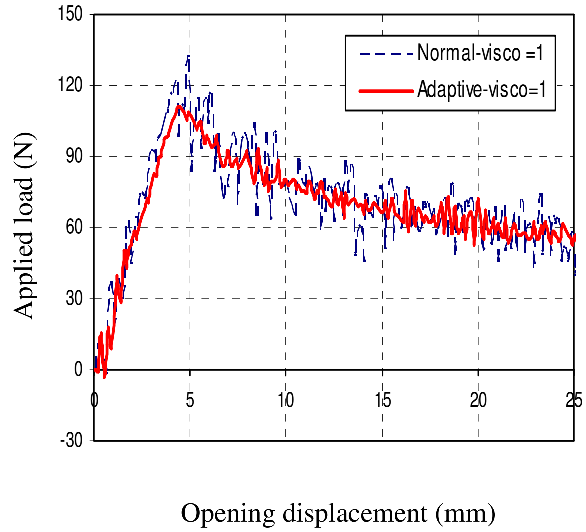

Fig. 7. Load-displacement curves obtained using both normal and adaptive formulations (η =1)

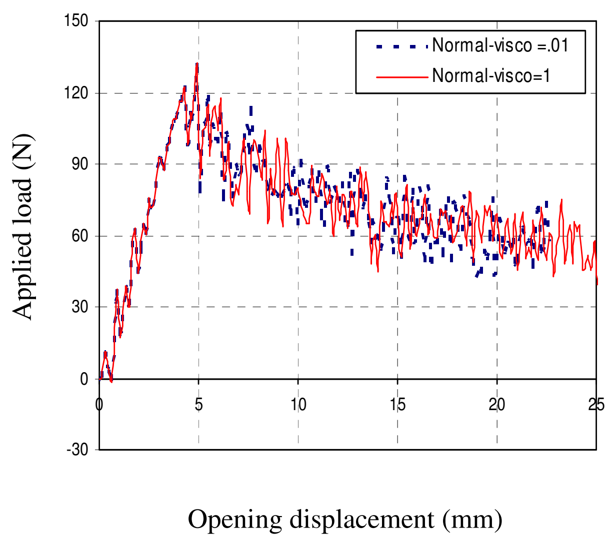

Fig. 8. Load-displacement curves obtained using normal formulations (η =0.01,1)

It is noticed from Fig.8 that, in both cases, the bilinear formulation results in severe instabilities once the crack starts propagation. It is also shown that the higher viscosity parameter the more stability of the results. There is a slight improvement to model the smooth, progressive crack propagation using bilinear formulations with a high viscosity parameter. On the other hand, the load-displacement curves of the numerical simulations obtained using the new adaptive formulation with two different viscosity parameters, 0.01 and 1.0 N.s/mm^3, respectively, is depicted in Fig. 9.

It is worth noting that the viscosity parameter almost has no effects on the results using the adaptive models. It is clear from Fig. 9 that the adaptive formulation able to model the smooth, progressive crack propagation irrespective the value of the viscosity parameter. More parametric studies will be performed in the ongoing research to accurately predict the effect of very high value of viscosity parameter on the results using both bilinear and adaptive cohesive element formulations.

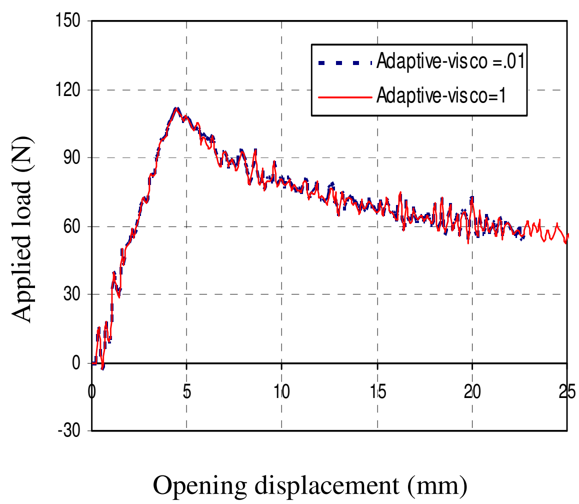

Fig. 9. Load-displacement curves obtained using adaptive formulations (η =0.01,1)

6 Conclusions

A method for simulation of progressive delamination based on cohesive elements is presented. A new adaptive rate-dependent cohesive element is developed and implemented in LS-DYNA to overcome the numerical insataibility occurred using the bilinear cohesive model. The formulation is fully three dimensional, and can be simulating mixed-mode delmaination, however, in this study, only DCB test in Mode-I is used as a reference to validate the numerical simulations. The numerical simulation shows that the new model is able to model the smooth, progressive crack propagation.

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