University of BRISTOL
Bristol Composites Institute

Rate and temperature dependent viscoelastic cohesive zone model for delamination of composites

Ammasai Sengodan Ganapathi,
Giuliano Allegri and Stephen R. Hallett

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Outline

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- Loading rate and temperature dependent traction
- Loading rate and temperature dependent softening
- Model validation for Mode I and Mode II delaminations
- Mixed-Mode viscoelastic CZM
- Summary

Introduction

- Bilinear Cohesive Zone Models capture the interlaminar failure of composites well
- However, they are inadequate for loading rate and temperature-dependent fracture
- Traditionally, empirical expressions are used to include the strain rate effects[1] as

$$T_N(\dot{\varepsilon}_N) = T_{refN} + T_{0N} \ln\left(\frac{\dot{\varepsilon}_N}{\dot{\varepsilon}_{ref}}\right)$$

$$G_{cN}(\dot{\varepsilon}_N) = G_{refN} - G_{0N} \ln\left(\frac{\dot{\varepsilon}_N}{\dot{\varepsilon}_{ref}}\right)$$

Stiffness of the interfaces assumed as rate-independent

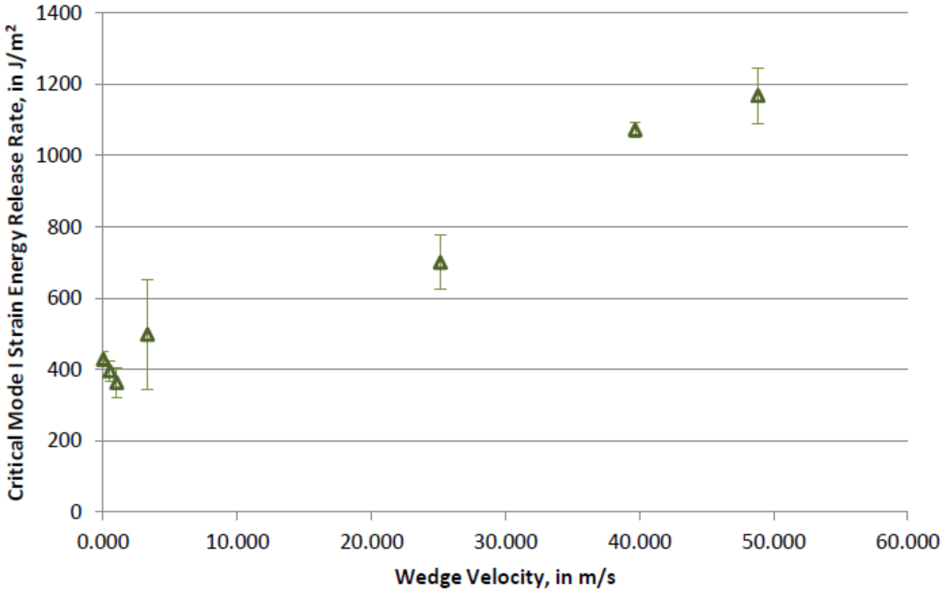


Fig: Typical Mode-I energy release rate for increasing wedge (opening) velocity of IM7/8552 [2]

1. M. Lißner a , et al., Experimental characterisation and numerical modelling of the influence of bond-line thickness, loading rate, and deformation mode on the response of ductile adhesive interfaces , Journal of the Mechanics and Physics of Solids , 2019.
2. Andrew Schlueter, An Experimental Study of Rate Effects on Mode I Delamination of Z-pinned Composite, PhD Thesis, Purdue University , 2012.

Loading rate and temperature dependent traction

A physically-based model that includes

- Strain rate effects at the interfaces due to QS/dynamic loading
- Viscoelastic behaviour of interfaces at extreme temperatures
- Viscoelastic behaviour due to thermoplastic toughening and extreme temperature and moisture

The loading part of the traction-separation curve is modelled by the

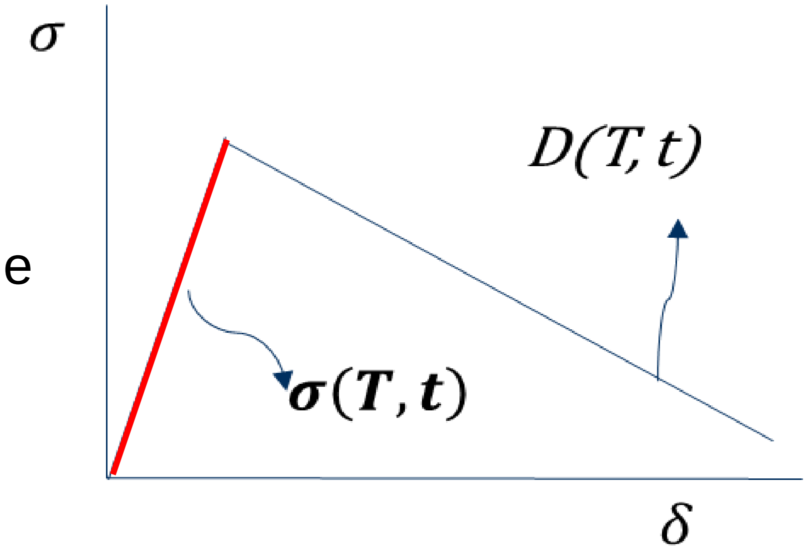
Generalized Maxwell model

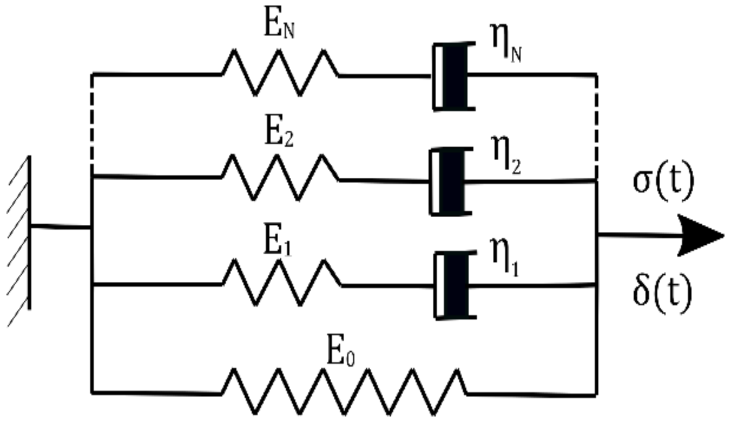
$$\sigma(T,t) = \int_0^t E_0 \dot{\delta}(s)ds + \sum_{i=1}^{N} \int_0^t E_i \exp\left(-\frac{t-s}{\tau_i}\right) \dot{\delta}(s)ds$$

Using FDM forward scheme, we get

$$\boxed{\sigma^{n+1} = \sigma_0^{n+1} + \sum_{i=1}^{N} \exp\left(-\frac{\Delta t}{\tau_i}\right)\sigma_i^n + \frac{E_i \tau_i}{E_0 \Delta t}\left(1 - \exp\left(-\frac{\Delta t}{\tau_i}\right)\right)\left[\sigma_{i0}^{n+1} - \sigma_{0i}^{n}\right]}$$

Traction-Separation curve

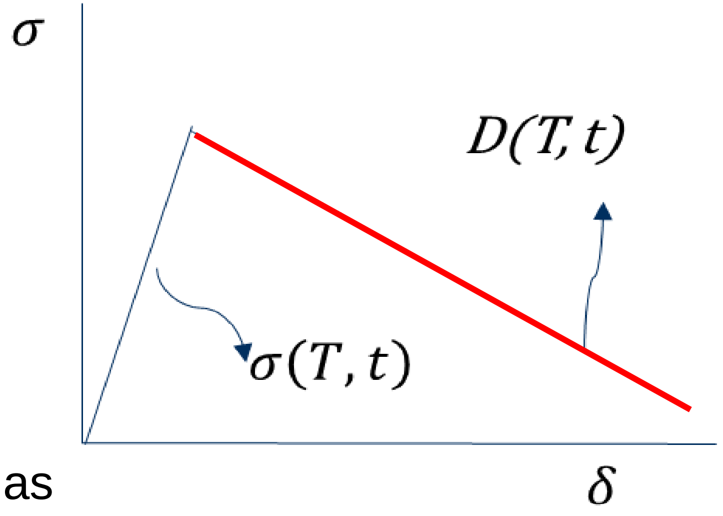




Loading rate and temperature dependent softening

From sub-microcrack formation theory, damage of a material can be represented as

$$D(T,t) = \frac{N(T,t)}{N_r} \; ; \; where \quad \begin{array}{l} D(T,t) = 0 \;\; \rightarrow no\ damage \\ D(T,t) = 1 \;\; \rightarrow macrocrack \end{array}$$



N_r-sub-microcrack concentration at rupture

Assuming a form for rate of damage

$$\frac{dD(T,t)}{dt} = \left(1 - D(T,t)\right)^p A(T,t)$$

where the damage rate constant A is represented by the **Zhurkov's kinetic theory*** as

$$\mathrm{A(T,t)} = \frac{1}{t_0}\exp((-U + \gamma\sigma(t))/(RT))$$

$$\boxed{\frac{dD(T,t)}{dt} = \left(1 - D(T,t)\right)^p \frac{1}{t_0}\exp((-U + \gamma\sigma(T,t))/(RT))}$$

Using FDM forward scheme

$$D^{n+1} = D^n + \Delta t(1 - D^n)^p \frac{1}{t_0}\exp((-U + \gamma\sigma^n)/(RT))$$

Finally, the traction is updates as

$$\sigma(T,t) = \left(1 - D(T,t)\right)^* \sigma(T,t)$$

Implemented as material user subroutine ABAQUS /VUMAT

Model validation against Bilinear CZM – Mode I

Double cantilever Beam

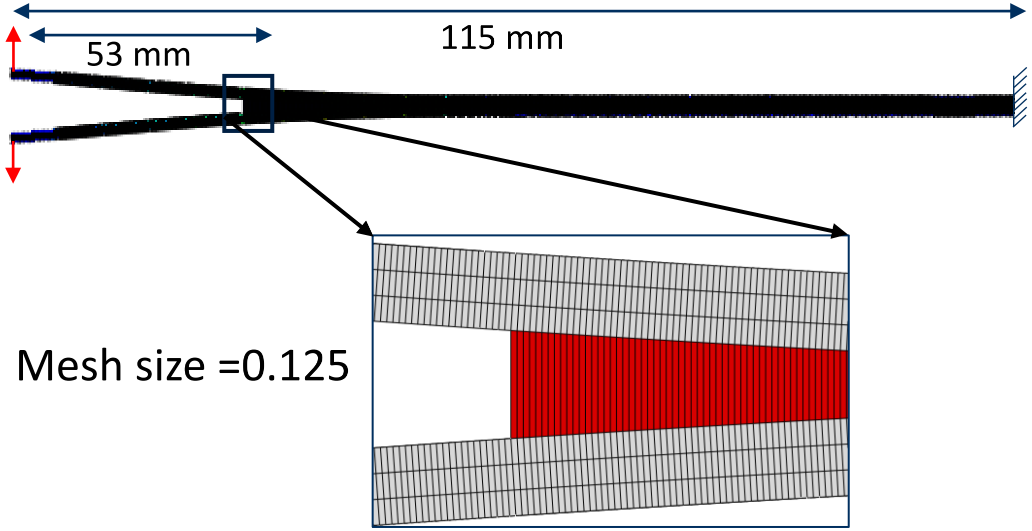
Material - HTA6376/C *

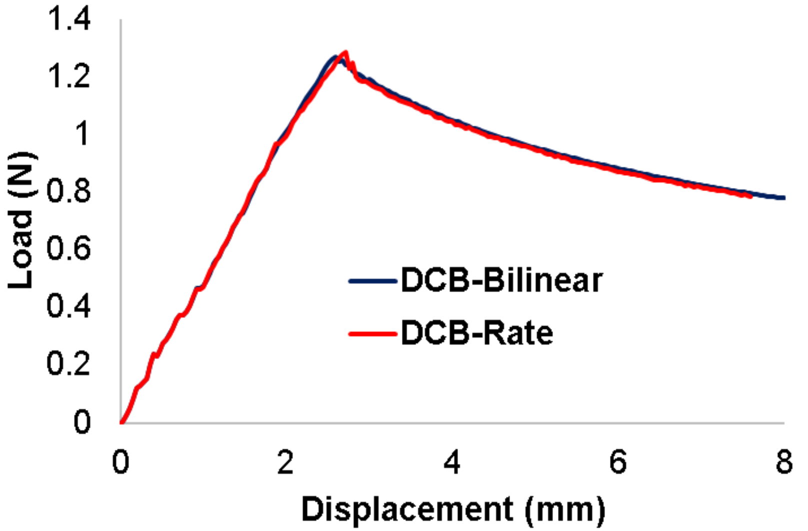
Loading rate = 1 *mm/S*

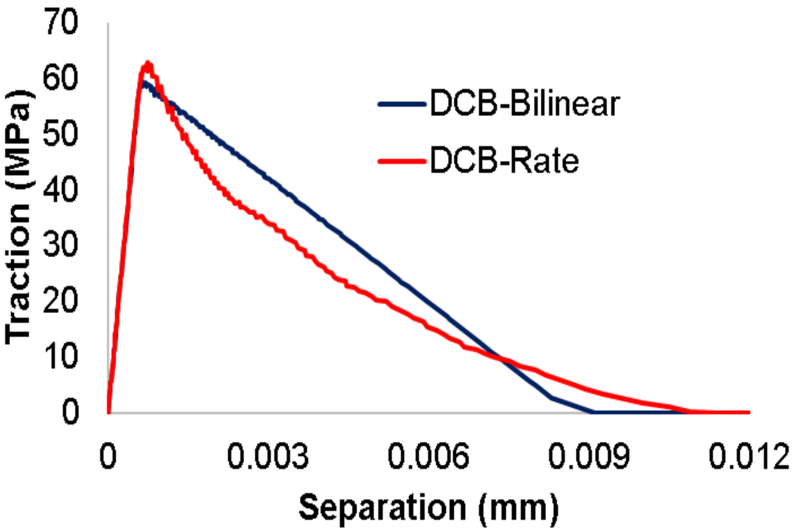
U= 114000 *J/mol* *and* σ_0= 168 *MPa*

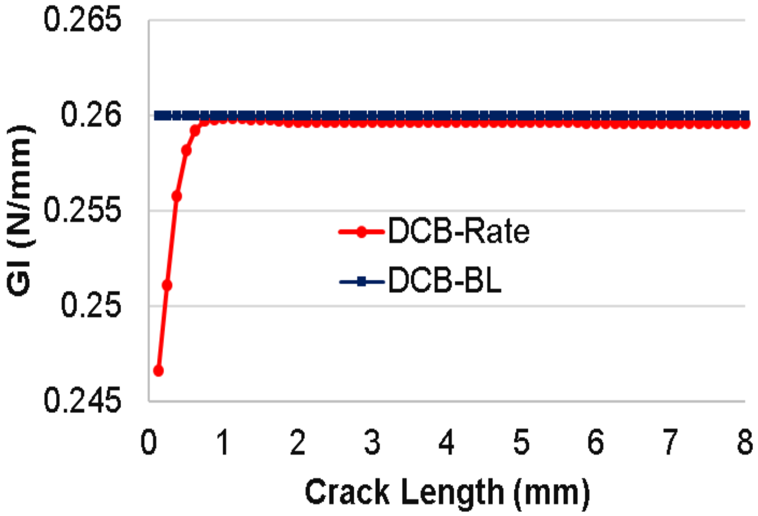
E_1 =100000 *N/mm^3 and* E_2 =1000 *N/mm^3*

τ = 6 *S and* p=-2.85







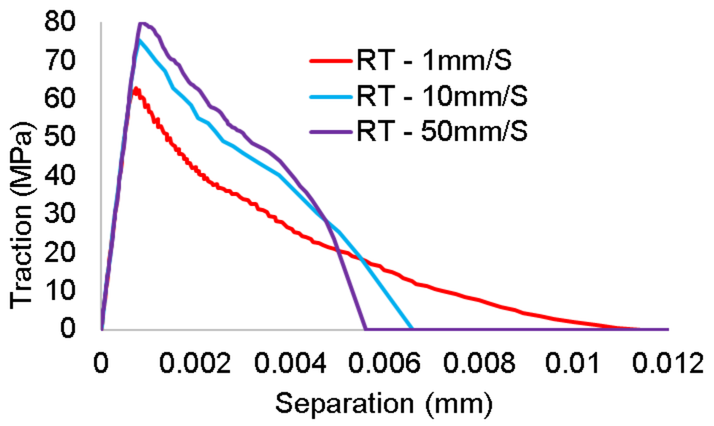


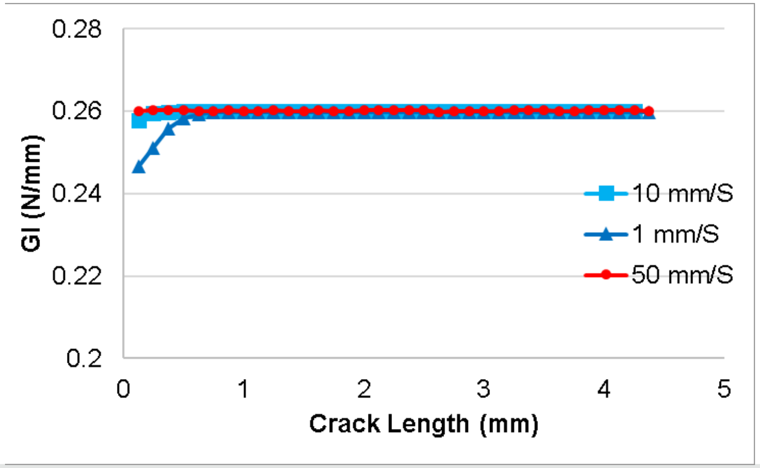
*Paul W. Harper, Stephen R. Hallett, Cohesive zone length in numerical simulations of composite delamination, Engineering Fracture Mechanics, 2008

Proposed model capability – Mode I - DCB

Effect of loading rate

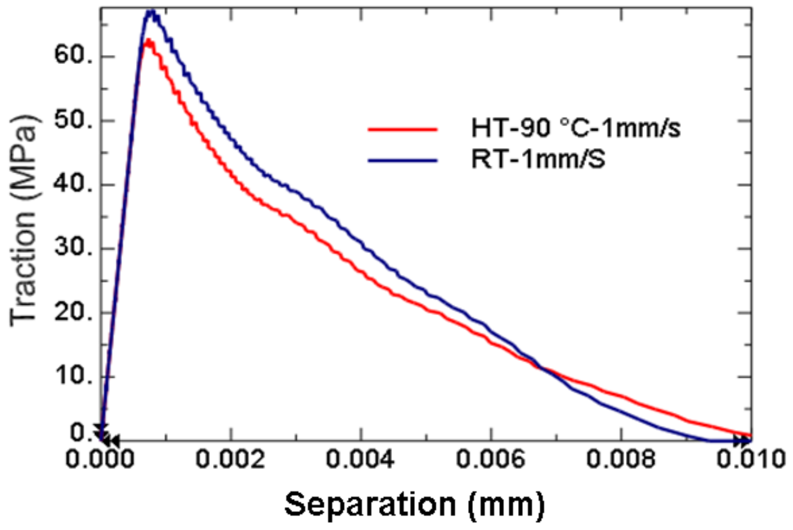
- Critical energy kept constant
- Peak traction increases with loading rate





Effect of Temperature

- Critical energy assumed to be constant
- Peak traction decreases as temp. increases

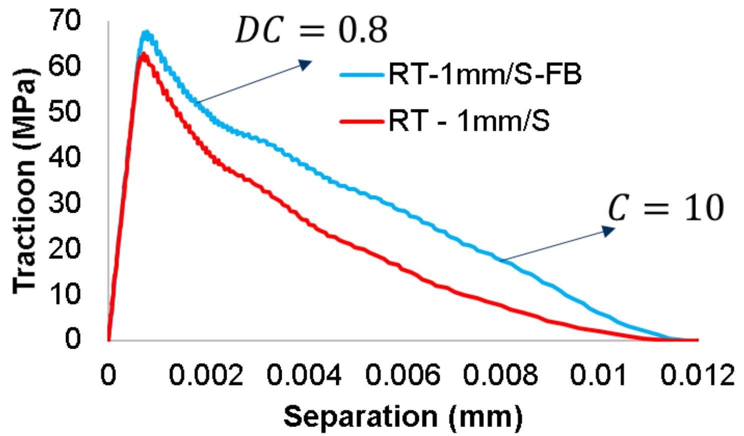


Fibre bridging effects

Effective damage rate constant

$$A(t,T)_{eff} = \frac{A(t,T)_M}{1+\exp[C(D(T,t)-DC)]}$$

DC *is* Damage index at fibre bridging initiation



Model validation against Bilinear CZM – Mode II

End Notch Flexure

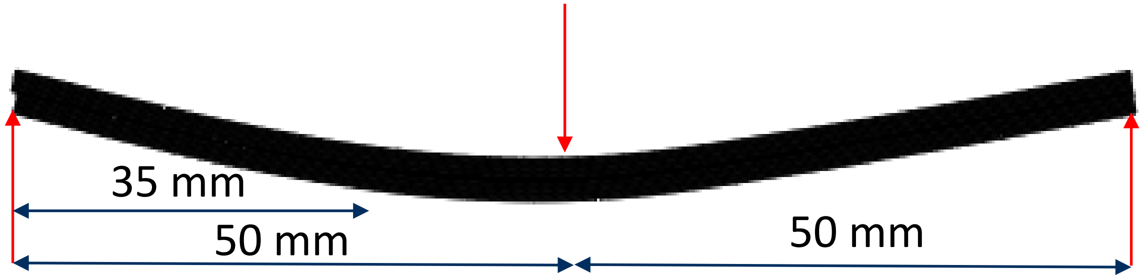
Material - HTA6376/C *

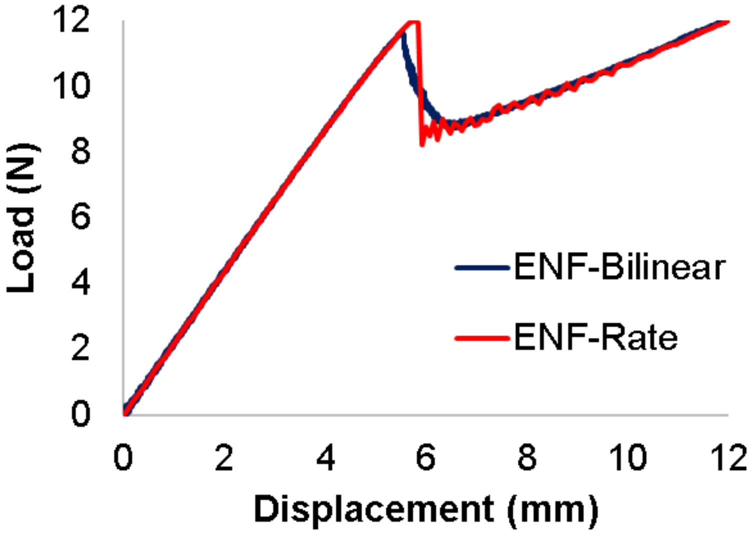
Loading rate = 1 *mm/S*

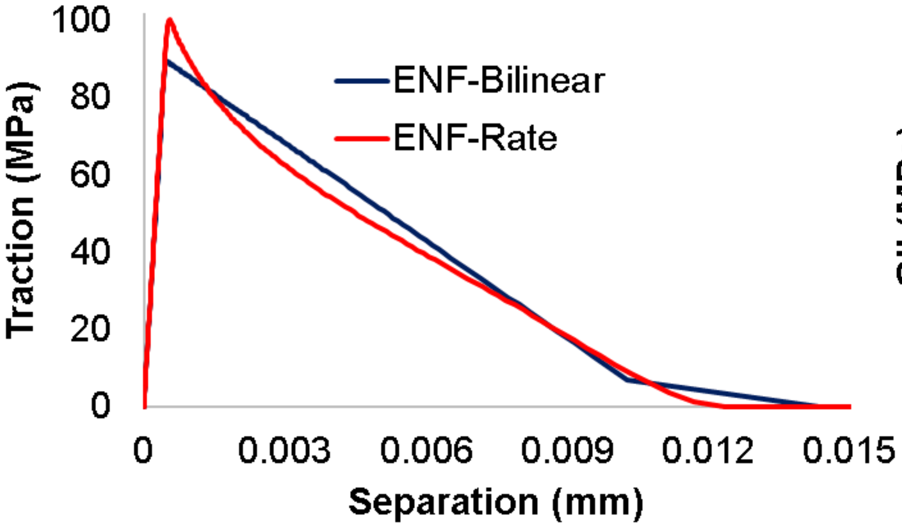
U= 124000 *J/mol* *and* σ_0= 230 *MPa*

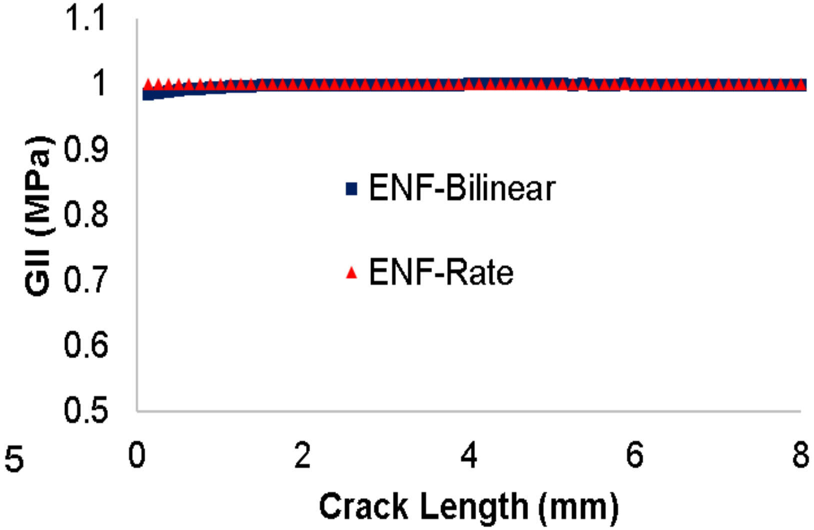
E_1 =100000 *N/mm^3 and* E_2 =1000 *N/mm^3*

τ = 6 *S and* p=-2.9









*Paul W. Harper, Stephen R. Hallett, Cohesive zone length in numerical simulations of composite delamination, Engineering Fracture Mechanics, 2008

Mixed-mode viscoelastic CZM model

Mixed-mode traction

$$\sigma_m(T,t) = \left(1 - D_m(T,t)\right)^{*}\sigma_m(T,t)$$

Updated damage function

$$\frac{dD_i(T,t)}{dt} = \left(1 - D_m(T,t)\right)^{p_i} A(T,t);\; i = I, II$$

Updated traction function

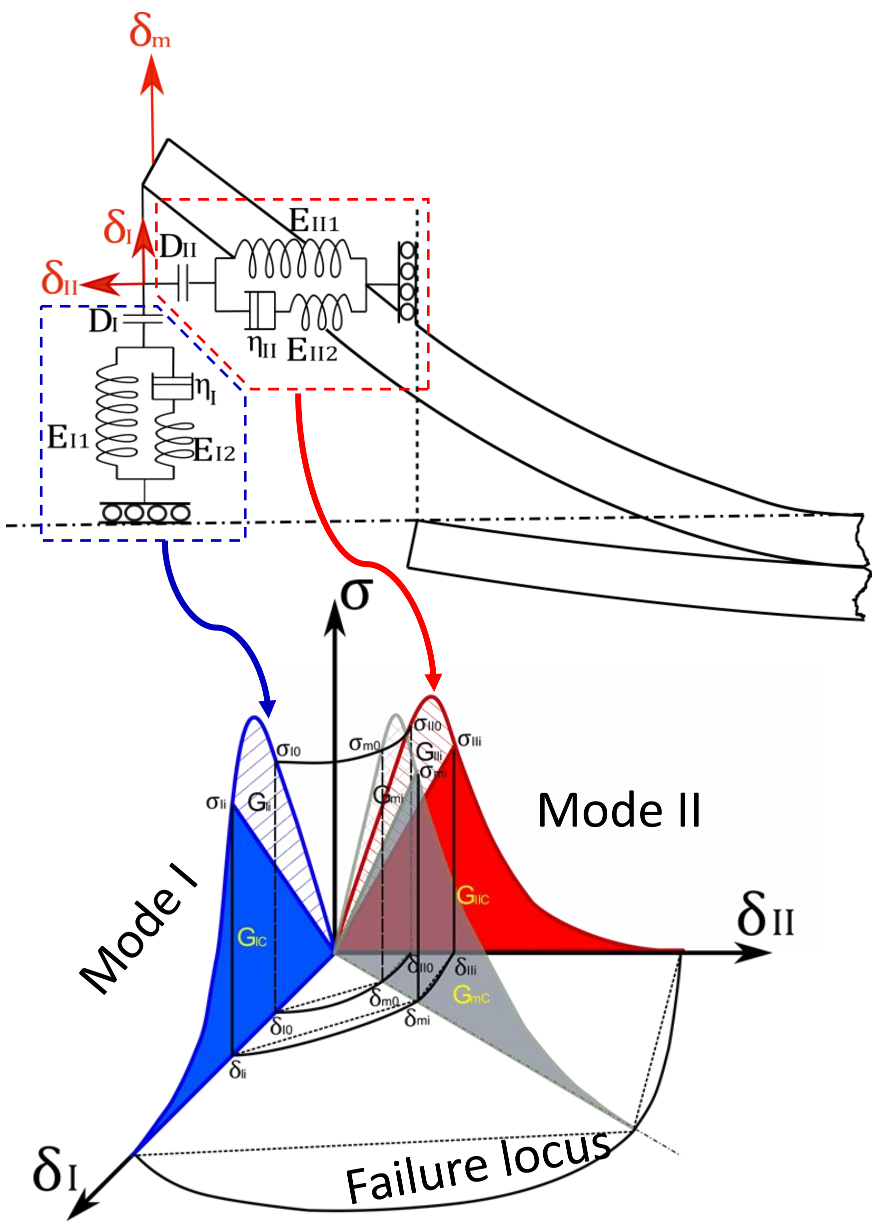
$$\sigma_i(T,t) = \left(1 - D_i(T,t)\right)^{*}\sigma_i(T,t)$$

Energy based mixed-mode damage

$$G_{mi} = G_{mC} - \int_0^{\delta} \sigma_{mi}\, d\delta$$

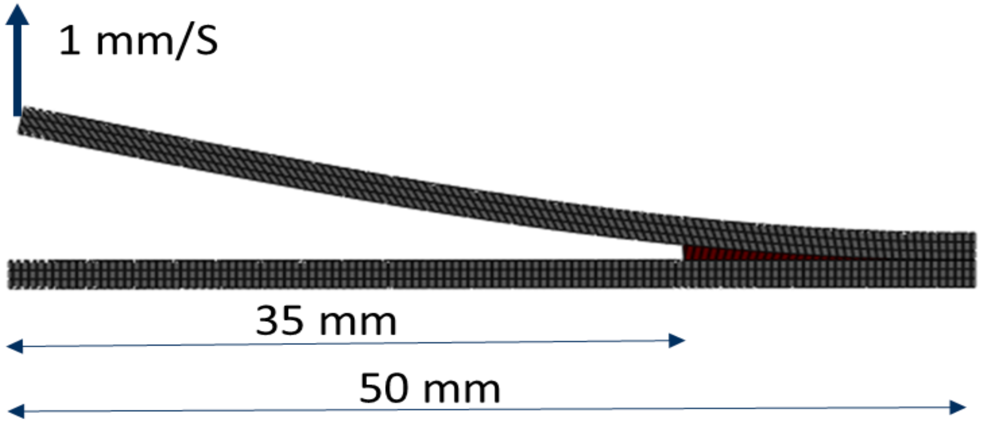
$$G_{mi} = G_{mC} - \left(\int_0^{\delta_{mi}} (1 - D_m)k\delta d\delta + \int_{\delta_{mi}}^{\delta} (1 - D_m)k\delta d\delta\right)$$

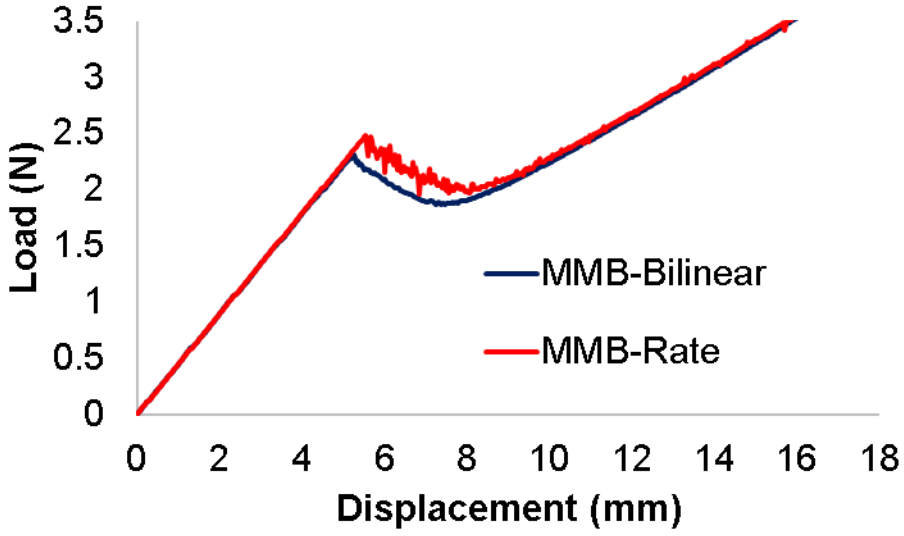
$$\boxed{D_m = 1 - \left(1 - \frac{G_{mi}}{G_{mC}}\right)\left(\frac{\delta_{m0}}{\delta_m}\right)}$$

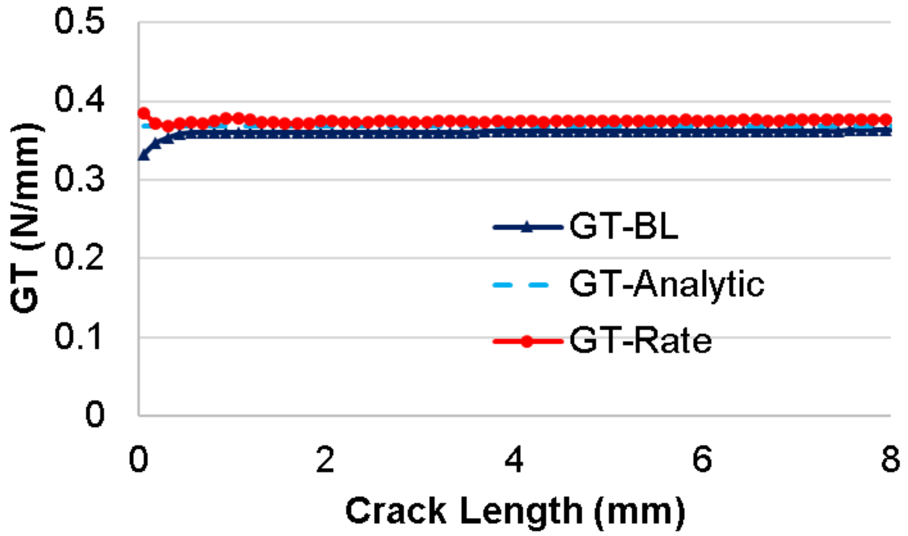


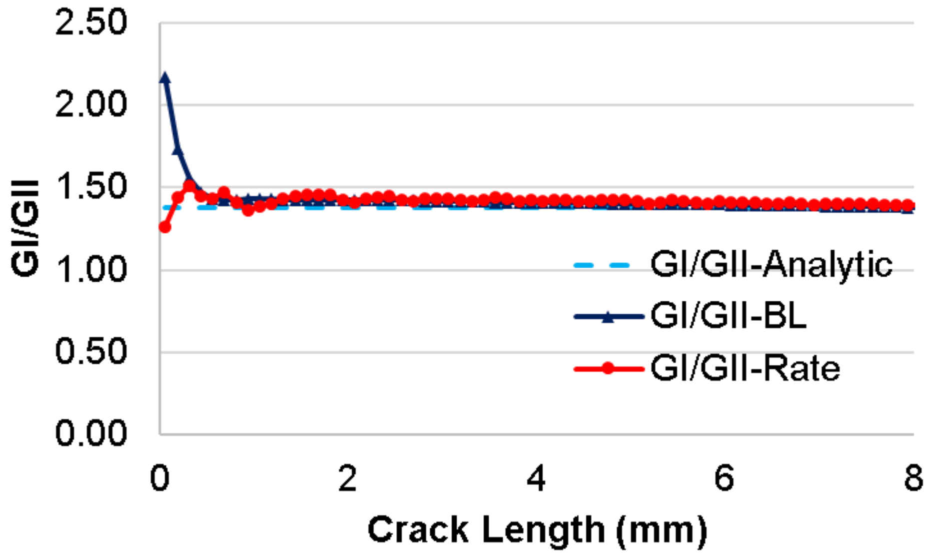
Mixed-mode viscoelastic CZM model

Fixed Ratio M-mode, GI/GII=1.33, HTA6376



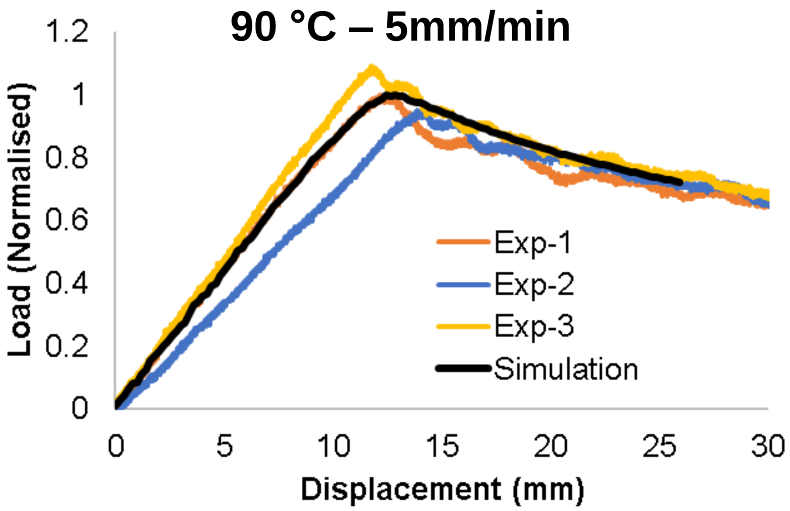


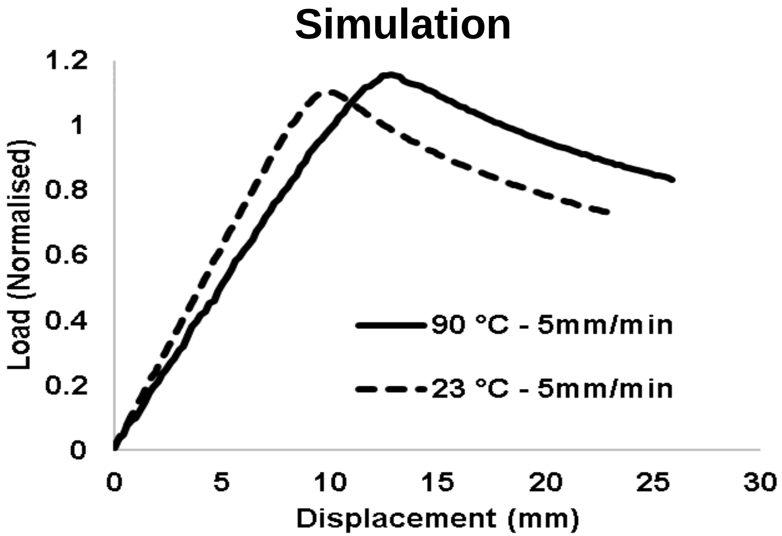




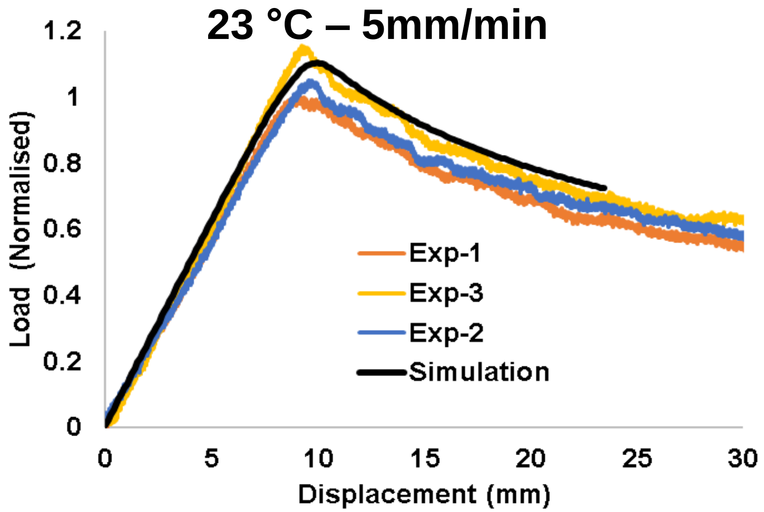
Validation - a carbon/epoxy material – DCB-Mode-I

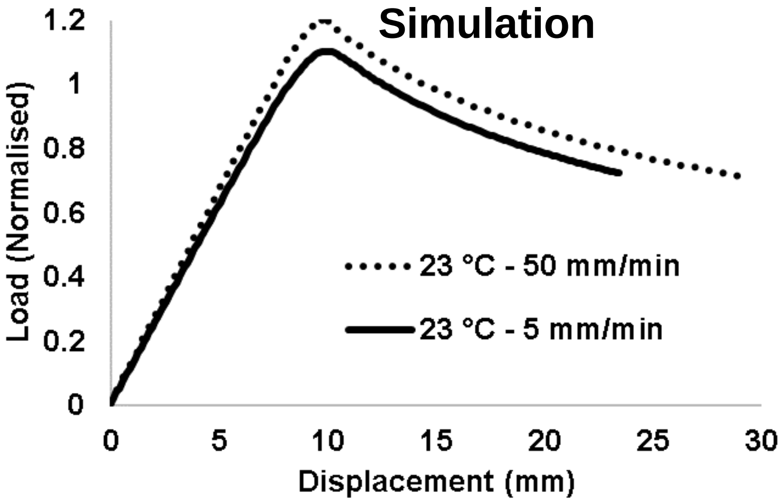
Effect of Temperature





Effect of Loading Rate





Summary

- A viscoelastic Cohesive Zone Model (CZM) with loading rate and temperature dependent traction-separation is developed and implemented as a VUMAT subroutine
- The proposed model is compared against the bilinear CZM for mode-I and mode-II delamination cases
- An energy-based mixed-mode CZM framework is proposed and compared against bilinear CZM for a fixed ratio mode-mixity
- The VECZM model is validated for a carbon/epoxy laminate under mode-I delamination at different loading rates and temperatures
- The rate and temperature dependent simulation results are in good agreement with the experimental results

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University of BRISTOL
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Thank you

Email.gana.ammasaisengodan@bristol.ac.uk