WCCM XI - ECCM V - ECFD VI
BARCELONA 2014

11th. World Congress on Computational Mechanics (WCCM XI)

5th. European Conference on Computational Mechanics (ECCM V)
6th. European Conference on Computational Fluid Dynamics (ECFD VI)

20 – 25 July 2014 - Barcelona, Spain

- Fracture and Contact Mechanics for Interface Problems -

Dynamic nonlinear debonding at interfaces in thin-walled layered systems

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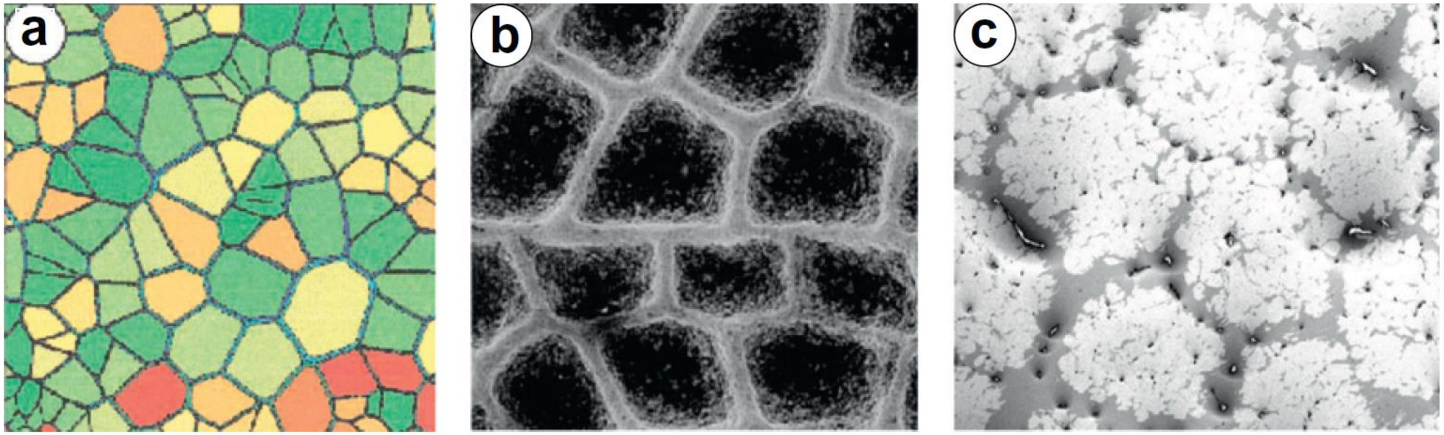
Outline

- Finite thickness interfaces in material microstructures and in composite laminates
- Modelling fracture in finite thickness interfaces
- Dynamic crack propagation in systems with finite thickness interfaces

Finite thickness interfaces

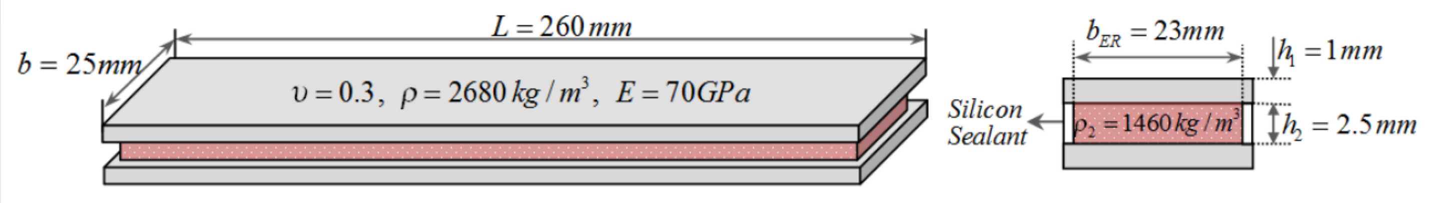
- **Finite thickness interfaces in material microstructures**



Polycrystalline Copper **Two-phase hard metal** **WC-Co/PCD material**

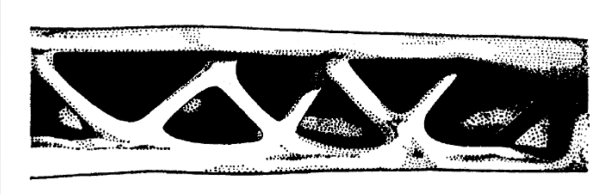
D.J. Benson et al. (2001) ***Mater Sci Eng A***, Vol. 319-321, 854-861.
Z.K. Fang et al. (2001) ***Int J Refr Metals & Hard Mat***, Vol. 19, 453-459.

- **Finite thickness interfaces in composites to control structural damping**



A. Arikoglu, I. Ozkol (2010) ***Comp Struct,*** 92, 3031-3039.

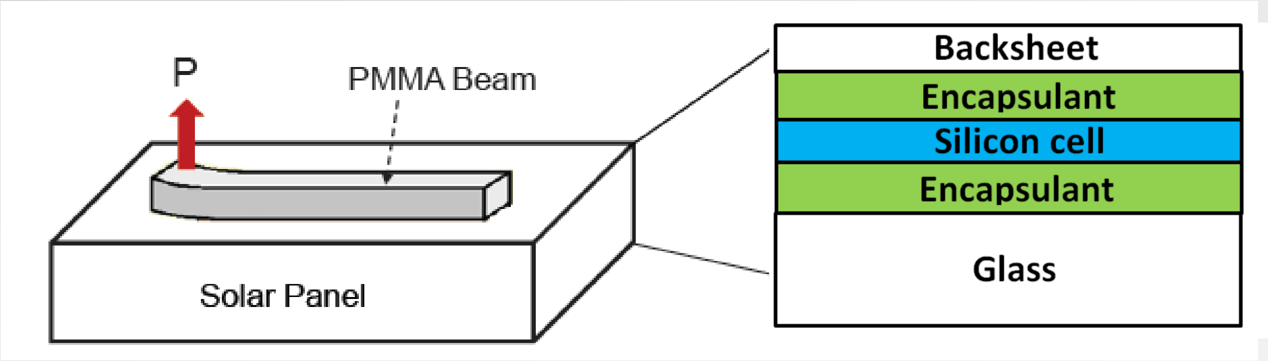
- **Truss-like interfaces with specific inertial properties to filter elastic waves**



D. Bigoni, A.B. Movchan (2002) ***Int J Solids Struct,*** 39, 4843-4865.

Glass-silicon cell delamination in photovoltaic modules

F. Novo et al. (2012) ***2012 PV Module Reliability Workshop***.



FIRB Future in Research 2010: *"Structural mechanics models for renewable energy applications"*

Principal investigator: Prof. Marco Paggi

Modelling interfaces

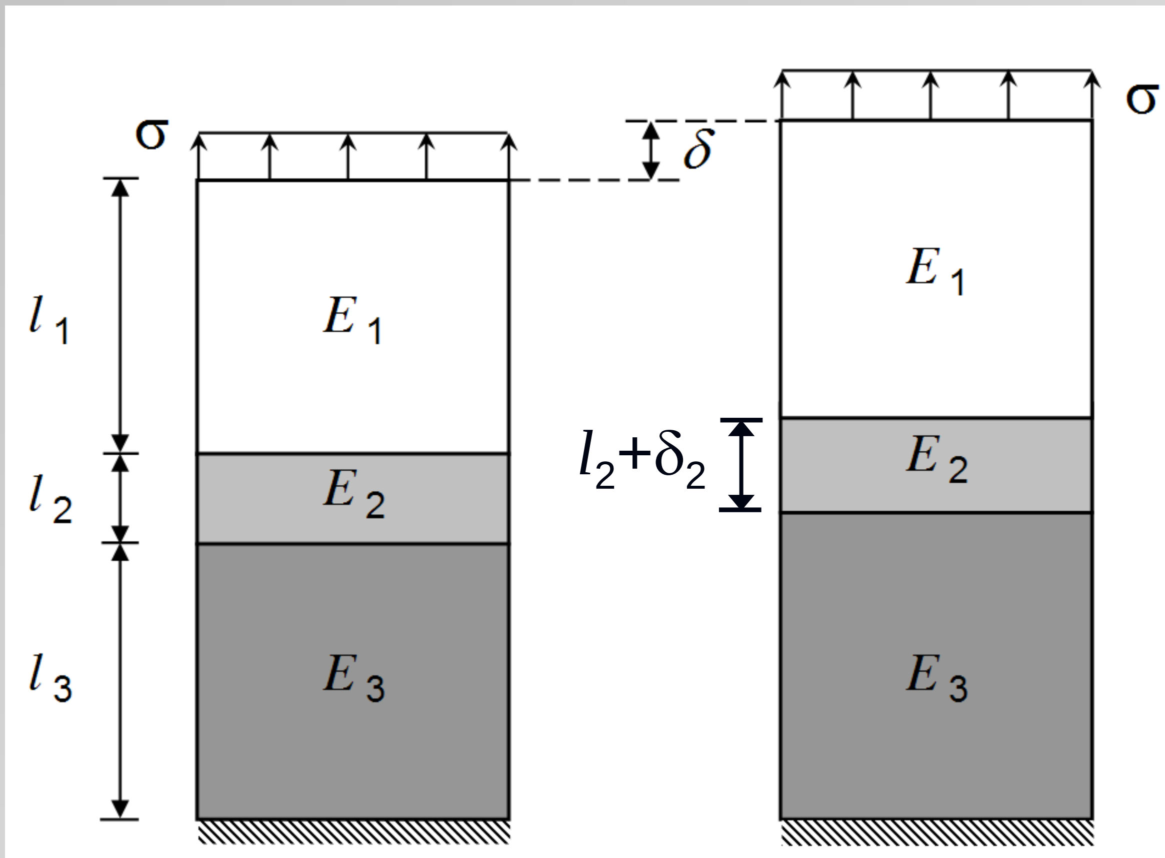
• **Interfaces are usually modelled by means of the Cohesive Zone Model**

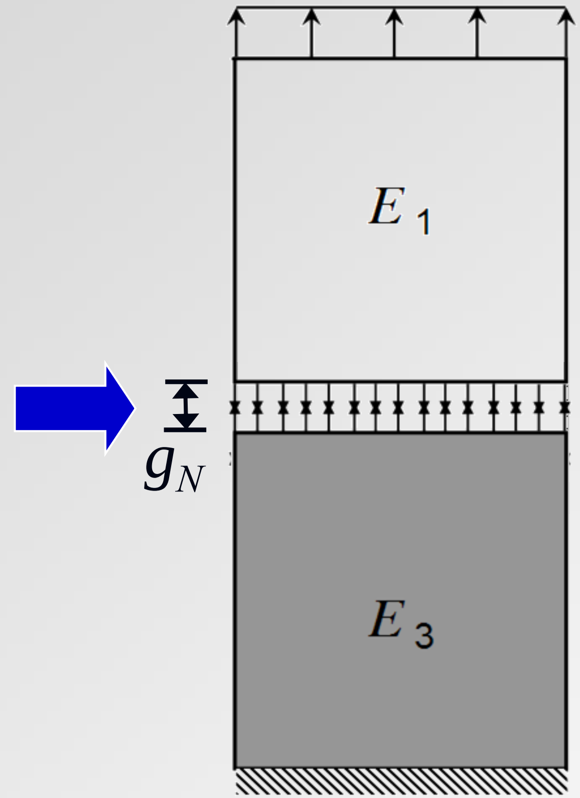
- **A detailed finite element discretization of the interface microstructure is very often too expensive from the computational point of view.**

- **The available CZMs apply to zero-thickness interfaces**
  - As simple as possible for numerical reasons rather than being physical meaningful
  - Inverse methods
  - Molecular dynamics simulations (Yamakov et al. (2006), ***JMPS***, Vol. 54, 1899-1928)
  - Multiscale approaches (C.B. Hirschberger et al. (2009), ***EFM***, Vol. 76, 793-812; M.G. Kulkarni et al. (2009), ***MOM***, Vol. 41, 573-583.)

- **Definition of a CZM that accounts for the finite thickness properties of the interfaces**

Nonlocal CZM based on damage mechanics





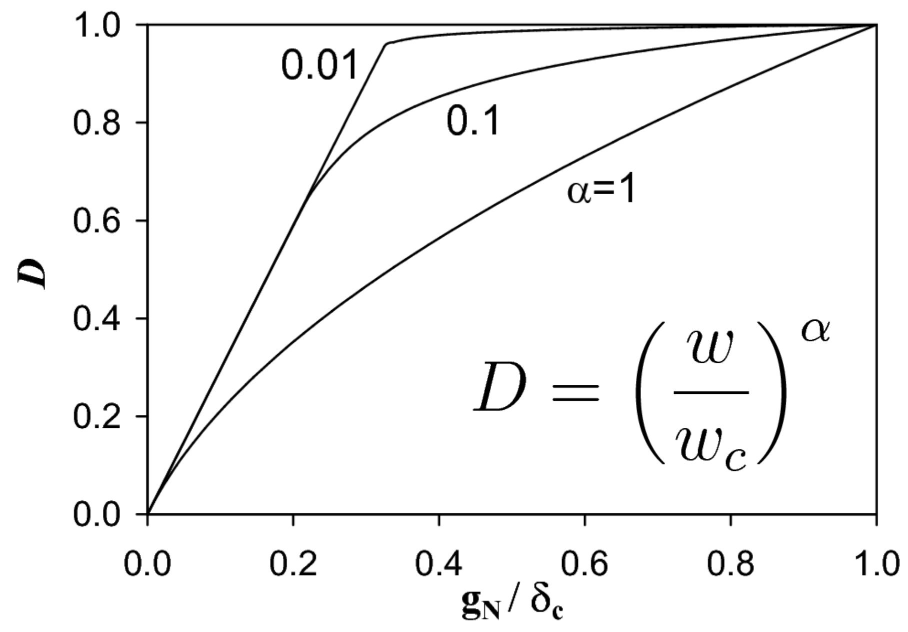
$$\delta = \left[\frac{l_1}{E_1} + \frac{l_2}{E_2(1-D)} + \frac{l_3}{E_3}\right]\sigma$$

$$\boxed{\sigma = \frac{E_2}{l_2}\frac{1-D}{D}g_N}$$

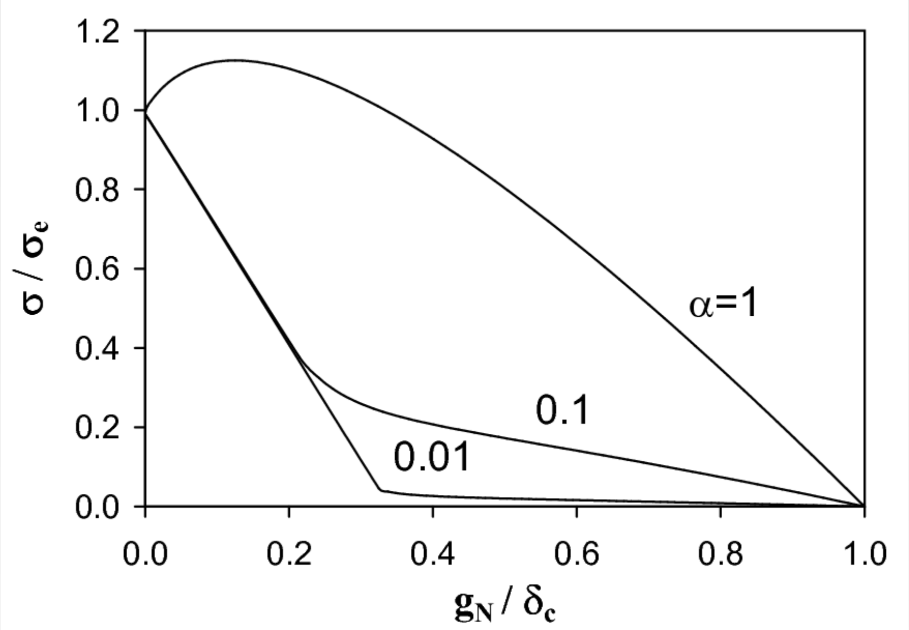
M. Paggi, P. Wriggers (2011) ***Computational Mater Sci***, Vol. 50, 1625-1633.

Nonlocal CZM based on damage mechanics

- No need of meshing the interface region with continuum elements (computational gain)
- The shape of the CZM depends on the damage evolution law (physically motivated)



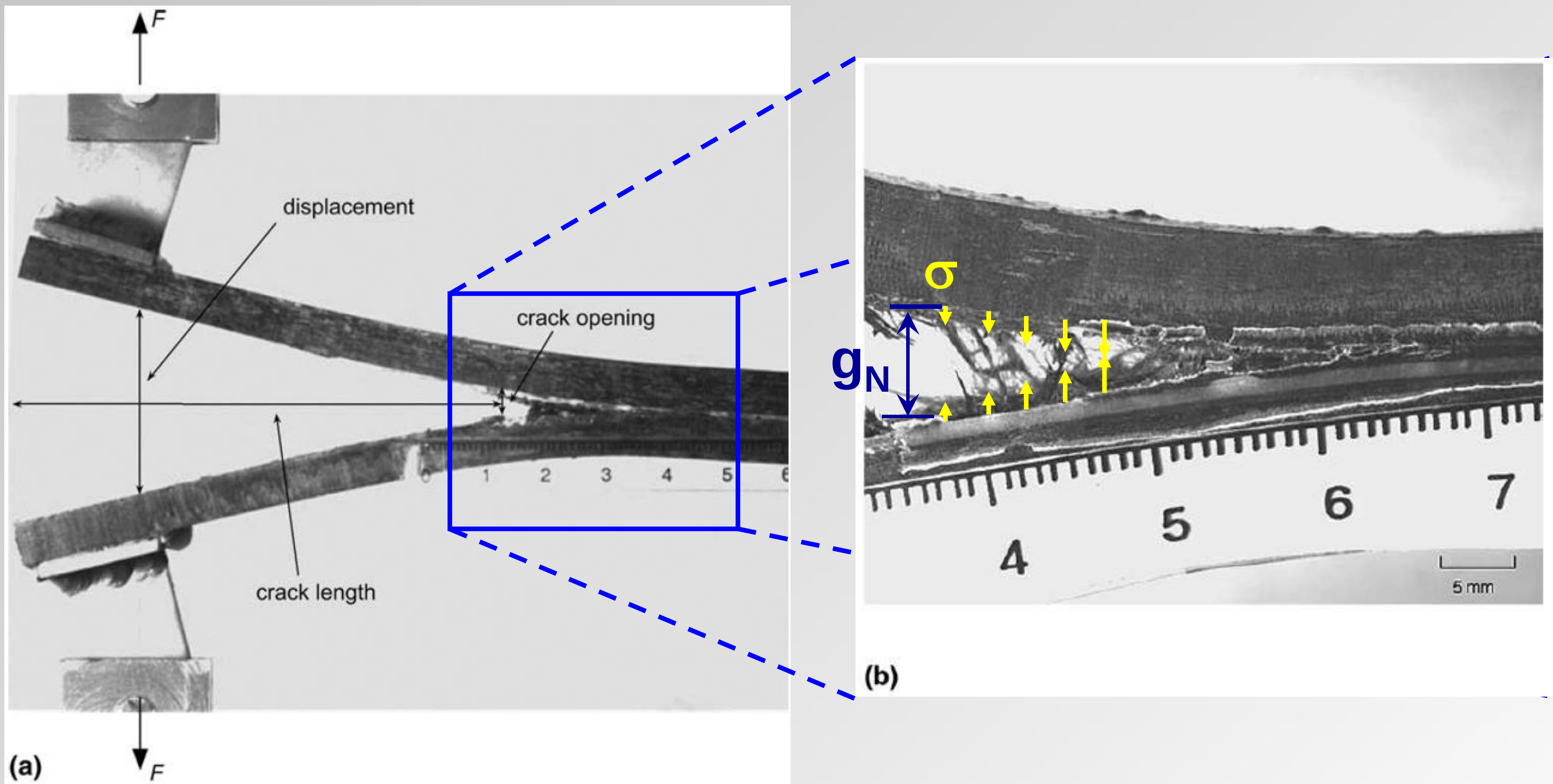
Damage vs. crack opening



Shape of the nonlocal CZM

The DCB test

Composite laminates with adhesive



S. Li, M.D. Thouless, A.M. Waas, J.A. Schroeder, P.D. Zavattieri (2005) ***Comp Sci Tech,*** Vol. 65, 281-293.

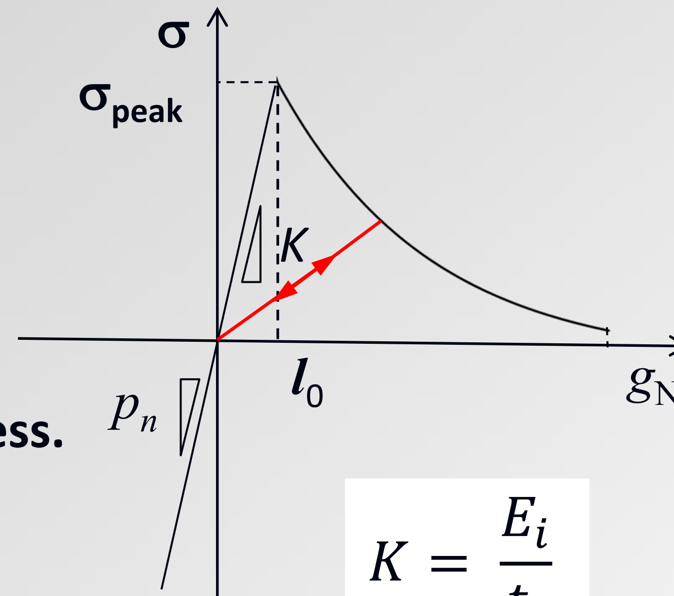
Interface fracture: Mode I CZM

Mode I: irreversible cohesive law

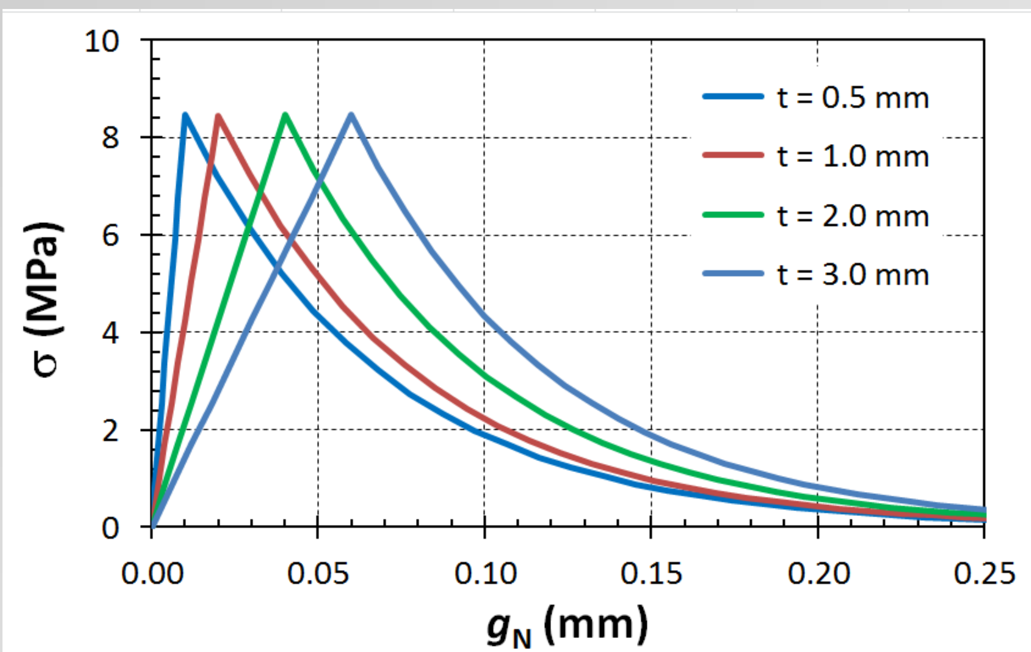
Elastic branch: $$\sigma = \sigma_{max} e^{\left(\frac{-l_0 - g_T}{rms}\right)} \frac{g_N}{l_0}$$

Softening curve: $$\sigma = \sigma_{max} e^{\left(\frac{-g_N - g_T}{rms}\right)}$$

Compression response governed by a penalty stiffness.



$$K = \frac{E_i}{t_i}$$

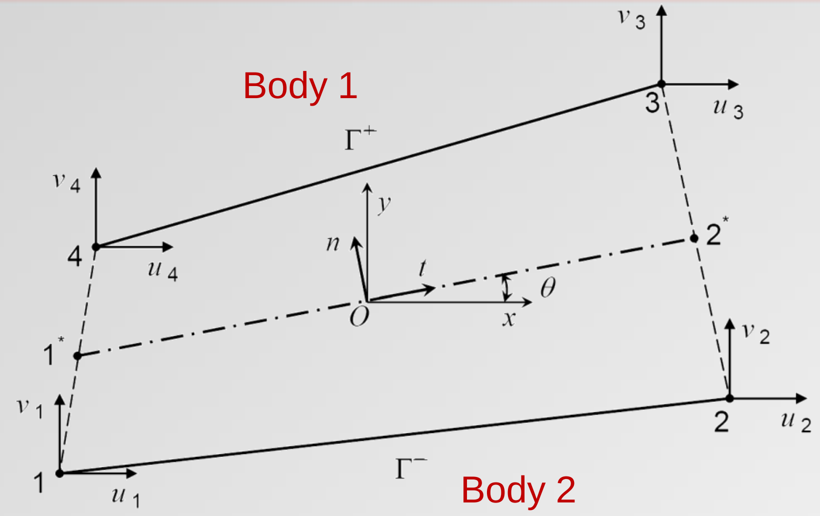


t (mm)	l_0 (mm)	$K \equiv p_n$ (N/m^3)
0.5	0.01	8.46 x 10^{11}
1.0	0.02	4.23 x 10^{11}
2.0	0.04	2.12 x 10^{11}
3.0	0.06	1.41 x 10^{11}

FE implementation

Interface contribution to the weak form:

$$G_{\mathrm{int}} = \int_S \delta\mathbf{g}^{\mathrm{T}}\mathbf{p}\,\mathrm{d}S = \int_S (\delta g_{\mathrm{T}}, \delta g_{\mathrm{N}}) \begin{pmatrix} \tau \\ \sigma \end{pmatrix} \mathrm{d}S$$



The nonlinear dependency between the vector *p* and the gap vector *g* has to be linearized for the application of the Newton-Raphson method:

$$\Delta G_{\mathrm{int}} = \int_S (\delta g_{\mathrm{T}}, \delta g_{\mathrm{N}})\,\mathbf{C} \begin{pmatrix} g_{\mathrm{T}} \\ g_{\mathrm{N}} \end{pmatrix} \mathrm{d}S$$

Tangent interface constitutive matrix C:

$$\mathbf{C} = \begin{bmatrix} \dfrac{\partial \tau}{\partial g_{\mathrm{T}}} & \dfrac{\partial \tau}{\partial g_{\mathrm{N}}} \\ \dfrac{\partial \sigma}{\partial g_{\mathrm{T}}} & \dfrac{\partial \sigma}{\partial g_{\mathrm{N}}} \end{bmatrix}$$

M. Ortiz, A. Pandolfi (1999) ***Int J Num Meth Eng***, Vol. 44, 1267-1282.
M. Paggi, P. Wriggers (2011) ***Comp Mat Sci***, Vol. 50, 1634-1643.

Discretized equation of dynamic equilibrium:

$$\mathbf{M}\boldsymbol{a} + \mathbf{R}^{\mathbf{int}}(x) = \mathbf{R}^{\mathbf{ext}}(t)$$

Mass matrix, **M**, lumped, both for elastic continuum and interfaces.

Mass of the interface defined as a function of the interface thickness and density:

$$\mathbf{M}_{\mathrm{i}} = \frac{\rho t l}{4}\mathbf{I}$$

Implicit solution scheme in space and time:

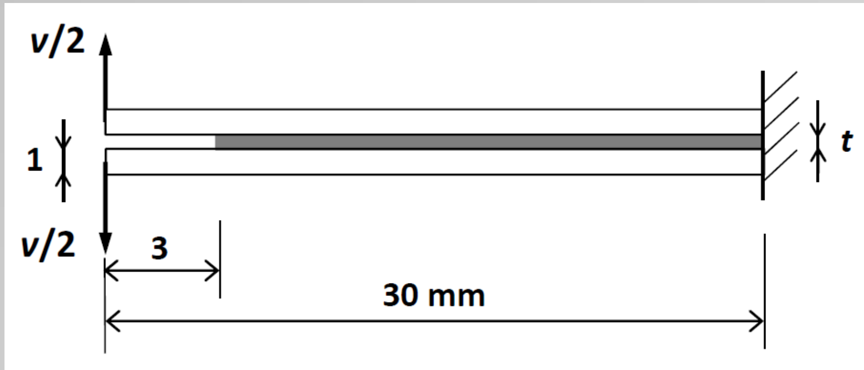
- Integration over time: Newmark constant-average-acceleration scheme

  (β=0.5, γ=0.25)

- Solution of the equilibrium equations: Newton-Raphson method

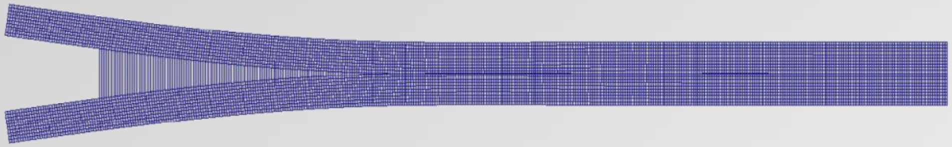
Case study

- Specimen geometry



t = 0.5, 1.0, 2.0, 3.0 mm

- FE model



2D plane strain model

4-node isoparametric FEs

Finite element size:

75 x 100 μm

Time step: Δt = 0.5 μs

- Mechanical properties

Laminae

E = 70 GPa

ν = 0.3

ρ = 2700 kg/m^3

Interface

E_i = 0.42 GPa

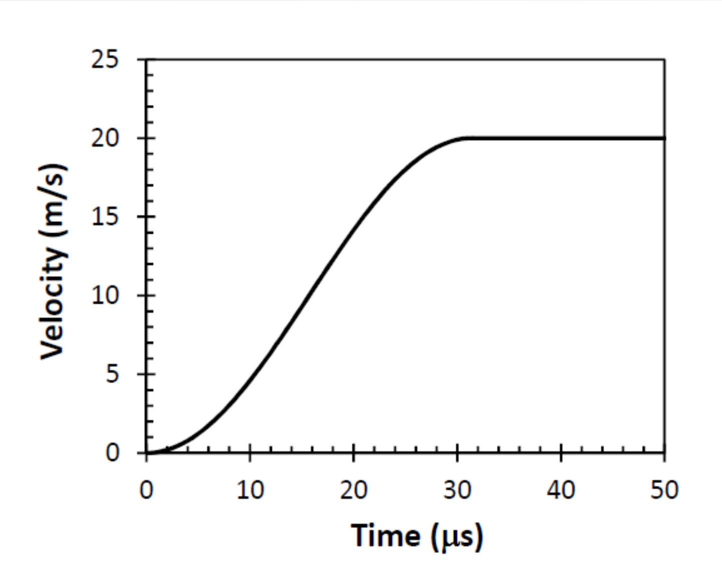
σ_{peak} = 8.5 MPa

g_{Nc} = 3 x 10^{-4} m

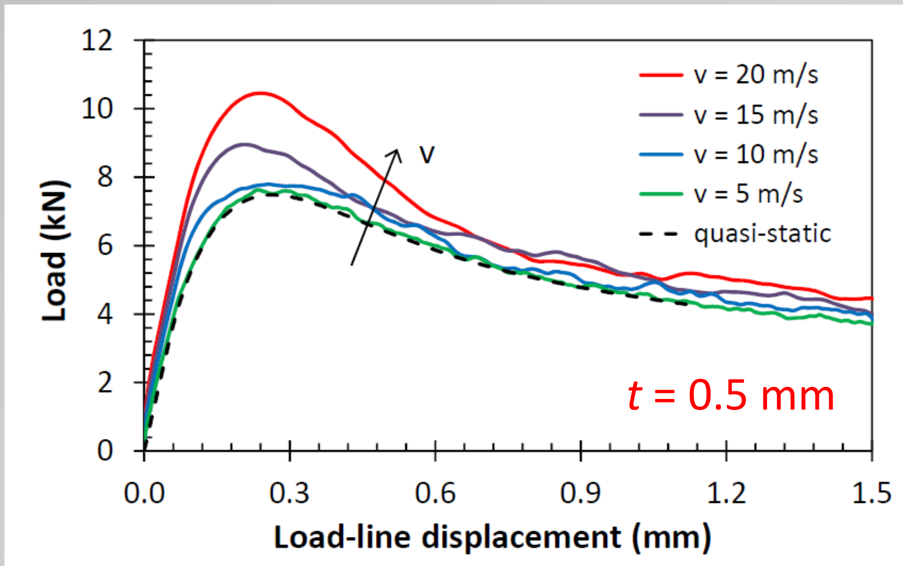
G_F = 600 N/m

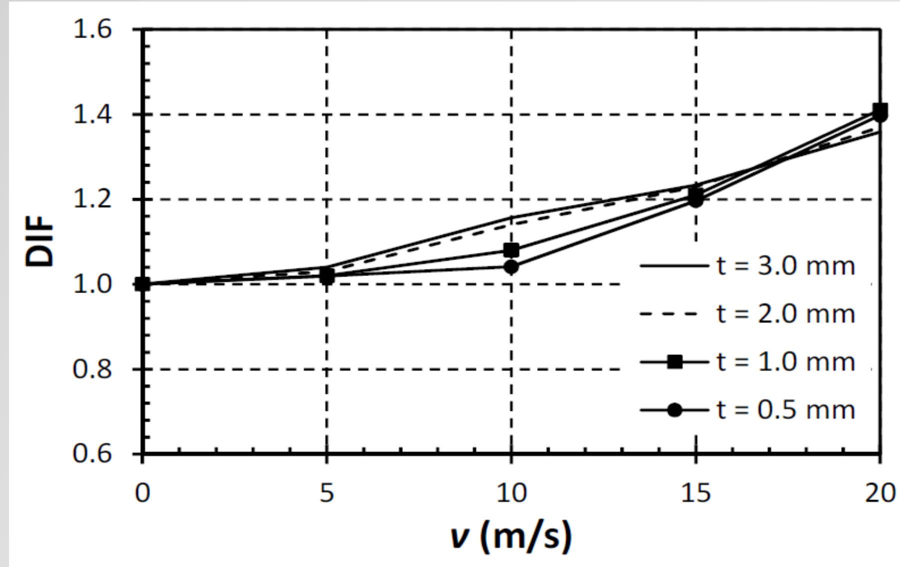
ρ = 2700 kg/m^3

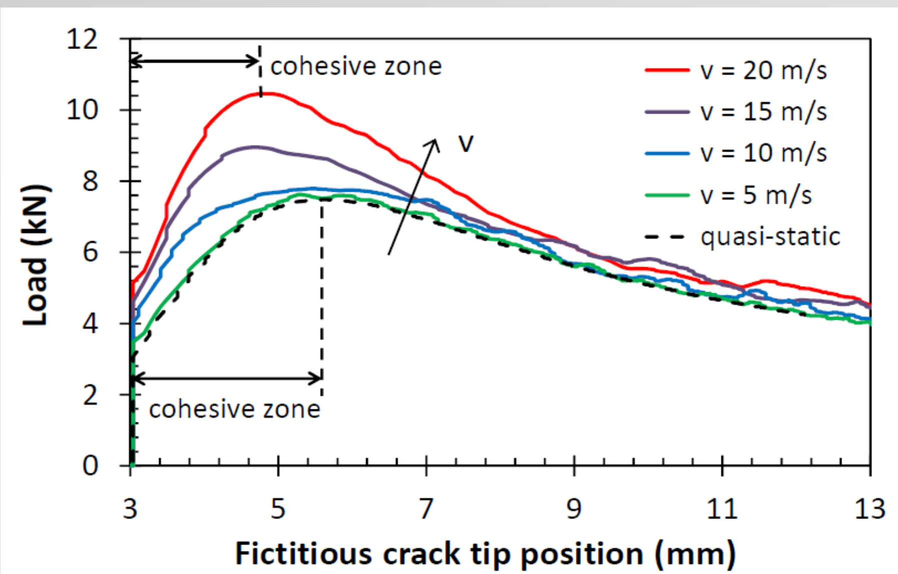
- Displacement-controlled loading

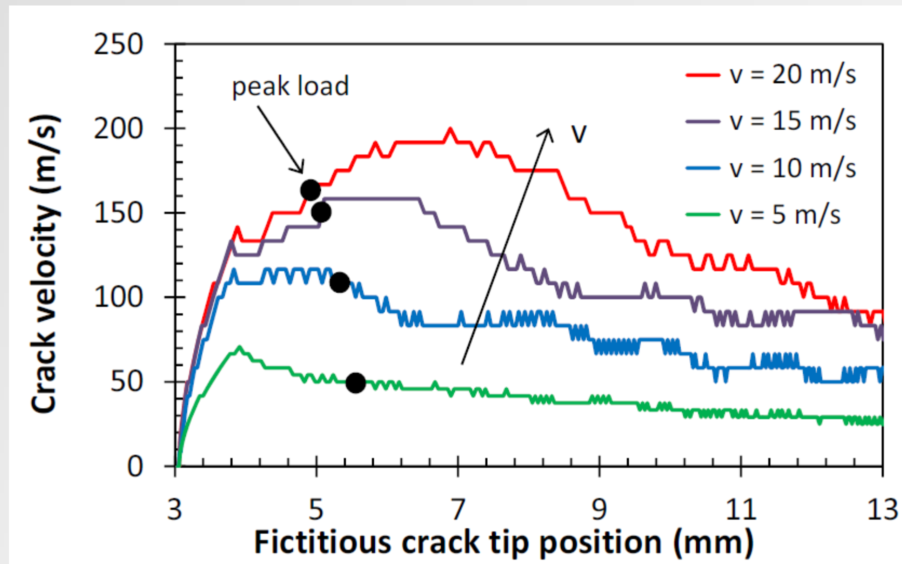


The loading rate

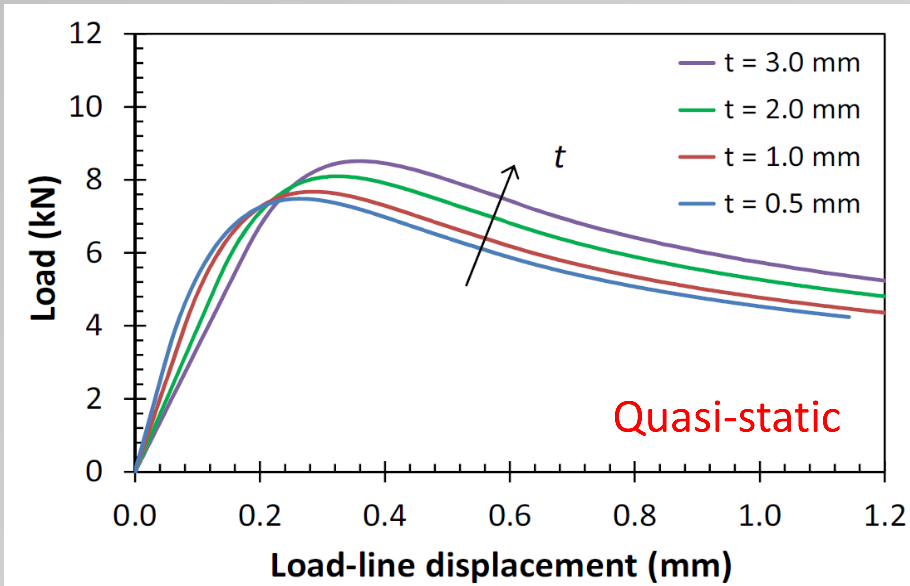


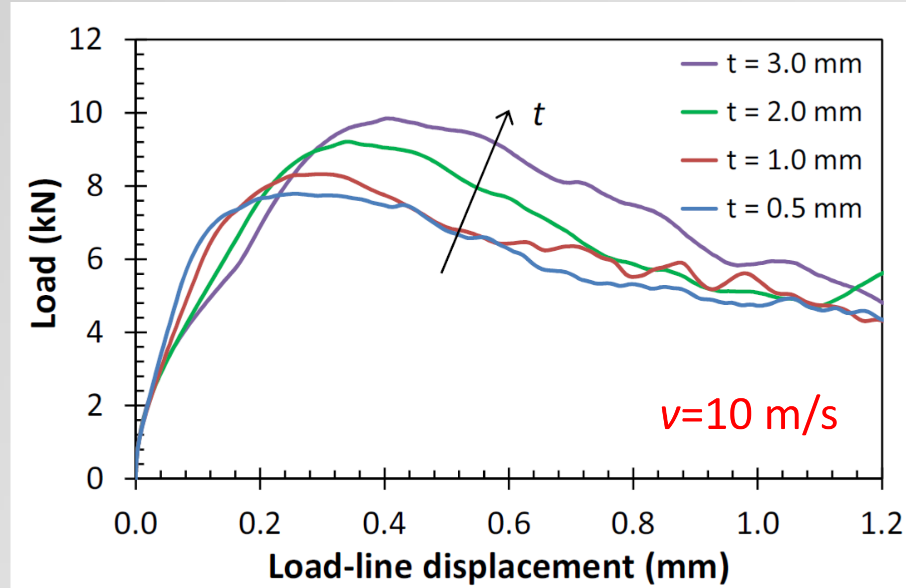


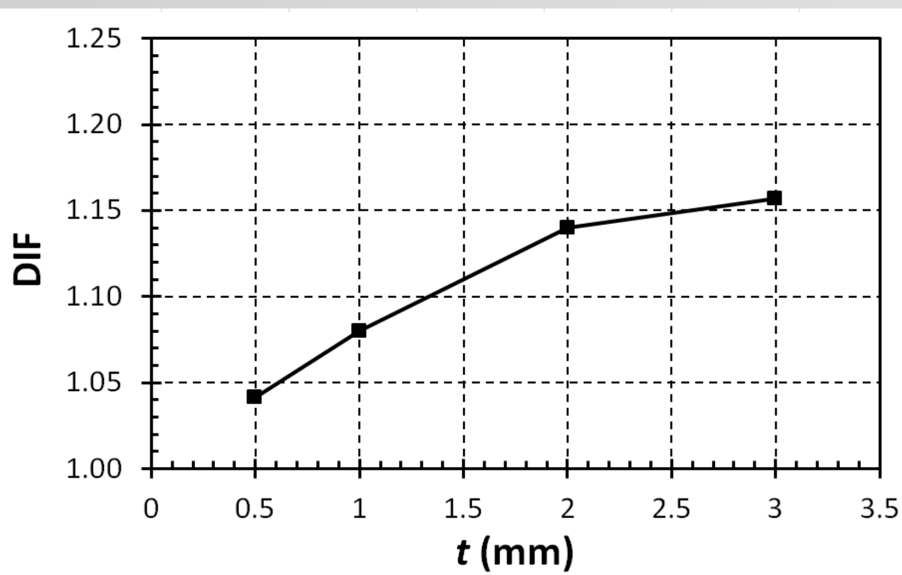


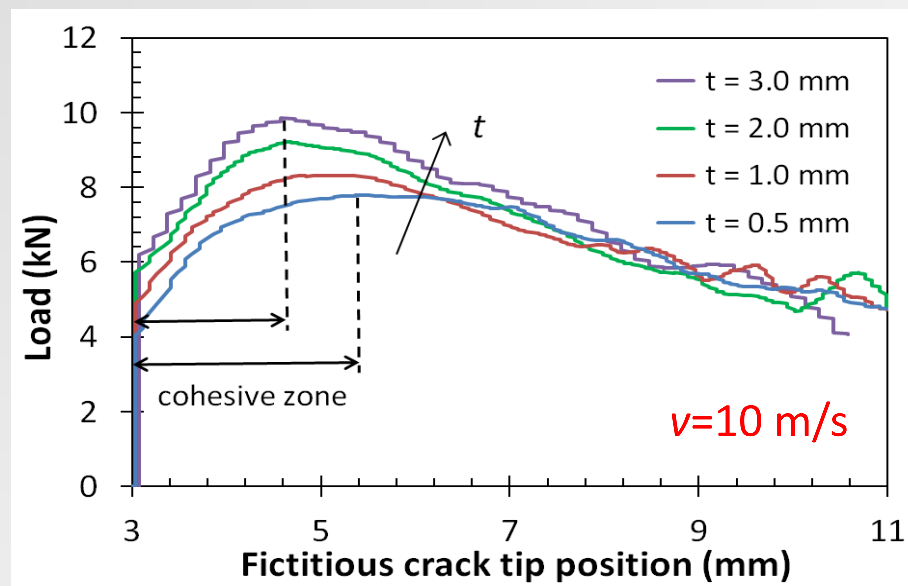


The adhesive thickness



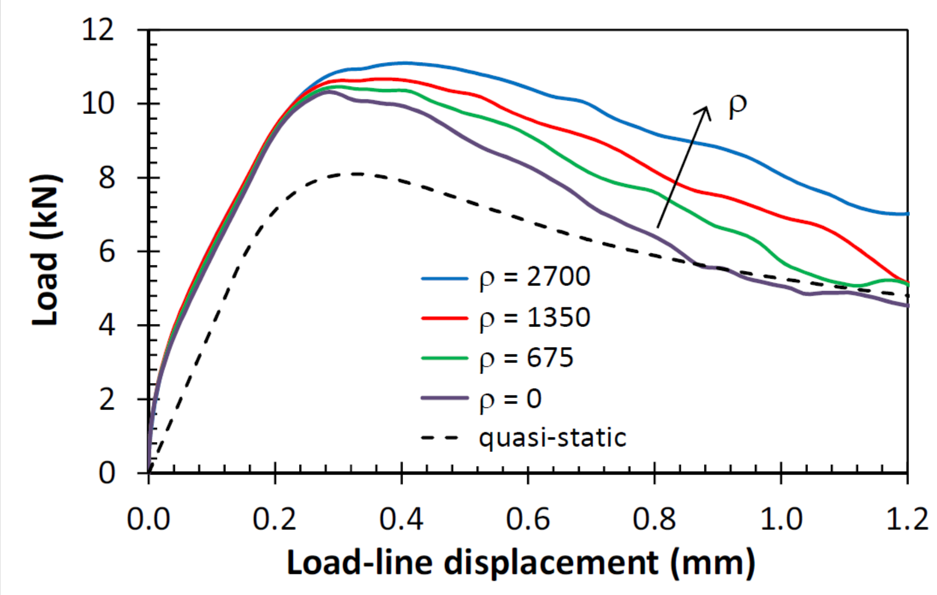


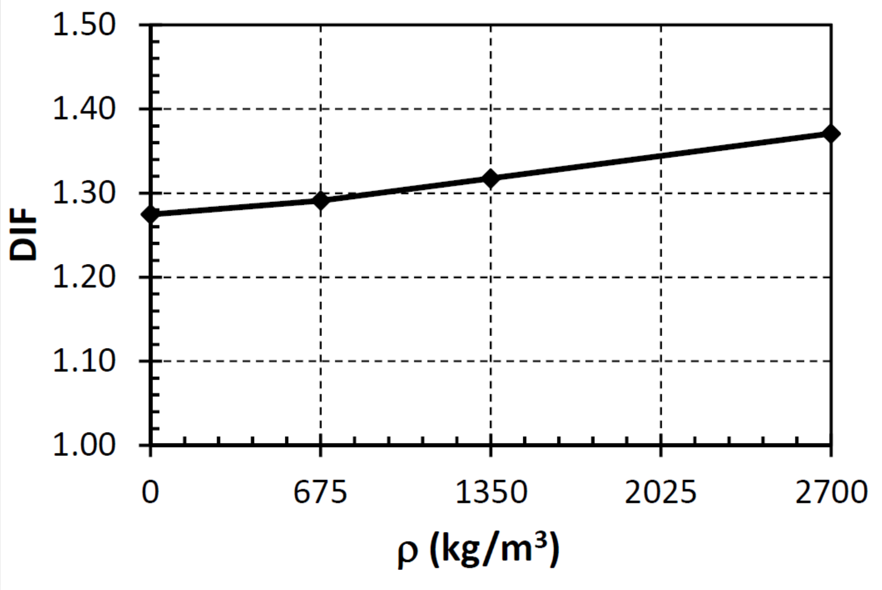




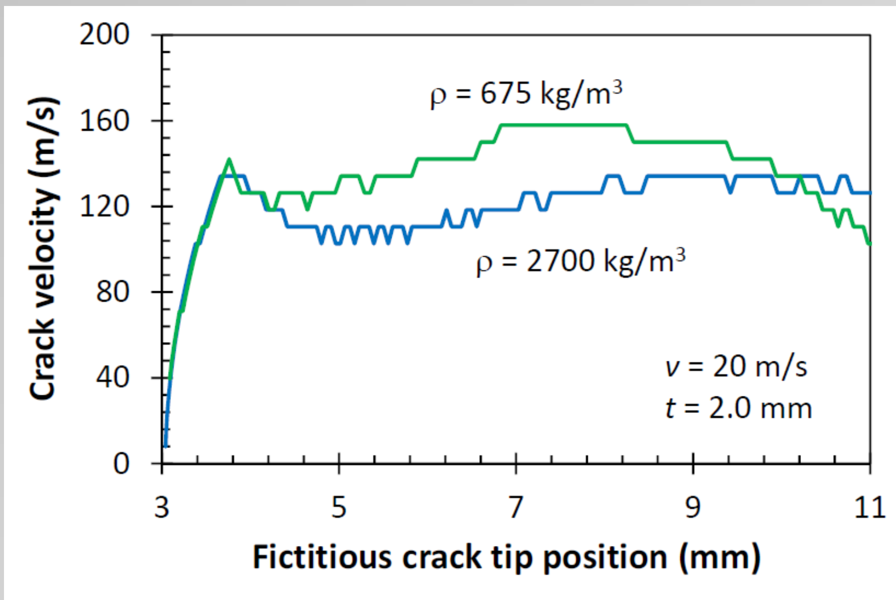
The adhesive mass density

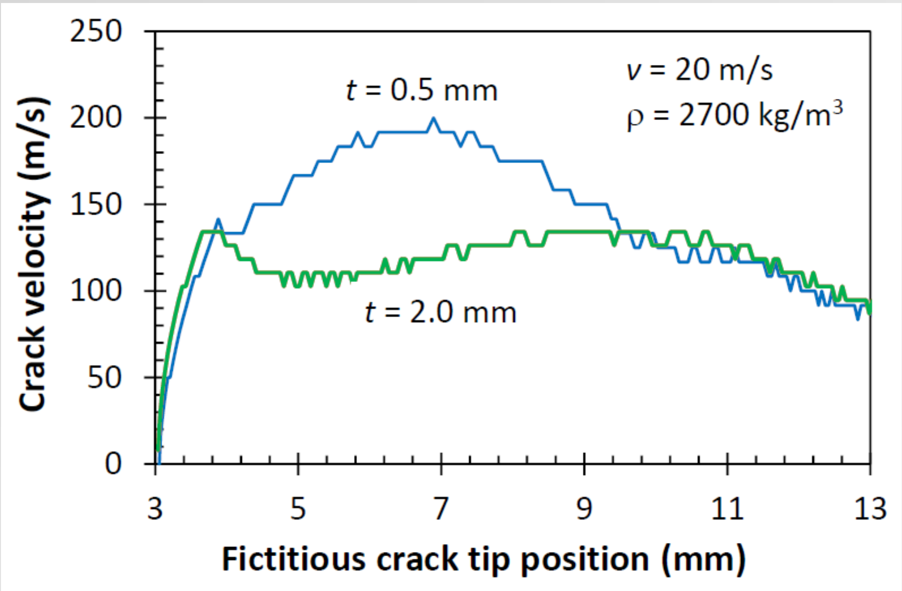
t = 2 mm; v = 20 m/s





The crack velocity





In both cases the interface mass is varied by a factor of 4 times

The combined effect of varying both interface stiffness and mass has a larger effect on the crack velocity as compared to the case when only the mass is modified

Conclusions

Dynamics of finite thickness interfaces:

(1) Nonlinear fracture dynamics of laminates with finite thickness adhesives is investigated

(2) Both mass and stiffness of the adhesive layer are considered in the dynamic equilibrium equations

(3) Inertia of the interface has a non-negligible effect on the dynamic strength increase factor

(4) Inertia of the adhesive has a remarkable effect on crack growth kinetics

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THANK YOU FOR YOUR KIND ATTENTION!