



Characterization of Adhesive Fracture Properties and Cohesive Laws Using Digital Image Correlation

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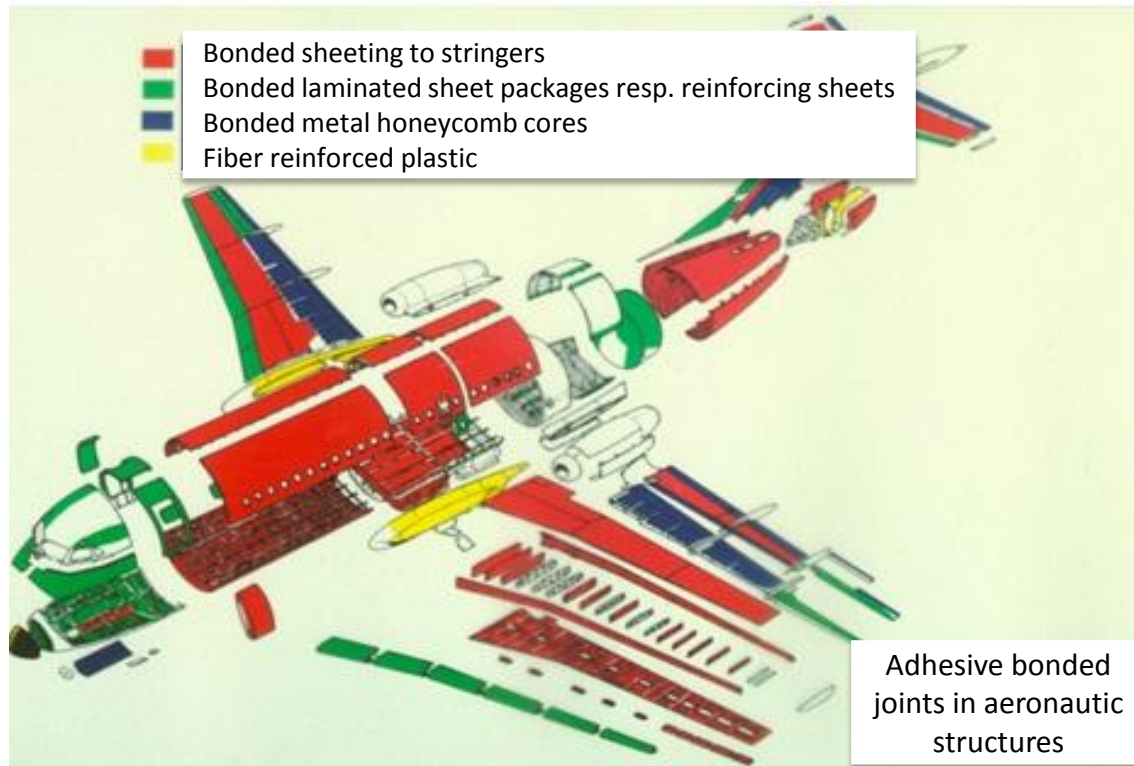
Outline



- **Introduction/Objectives**
- **Methodology**
- **Test Setups**
- **Cohesive Law/J-Integral**
- **Results**
- **Summary**

Introduction:

Adhesive Bonded Joints In Structural Composite Assemblies



➤ Some advantages over mechanical joints:

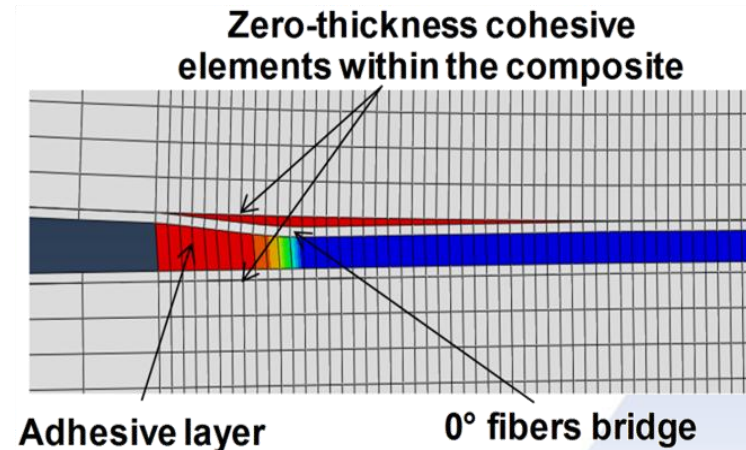
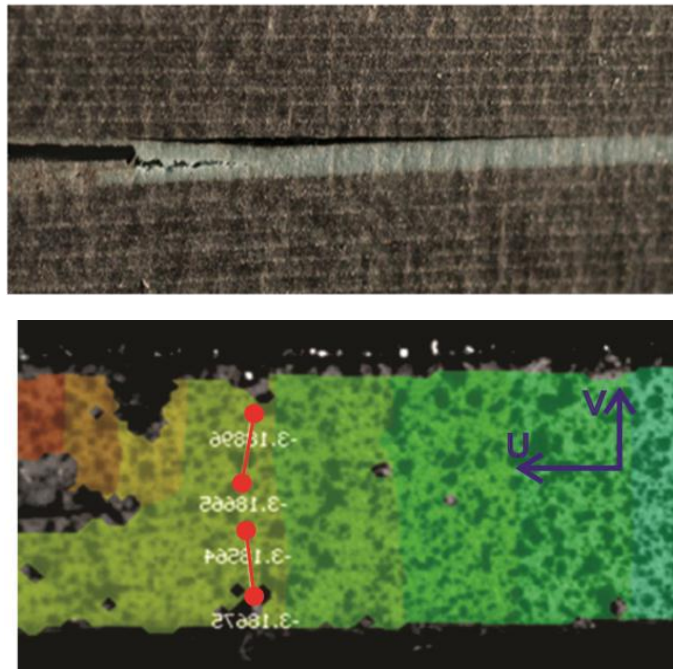
- Lower structural weight
- Lower manufacturing cost
- Improve damage tolerance

➤ However:

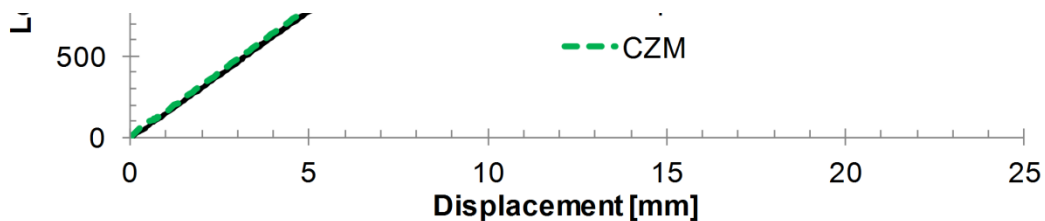
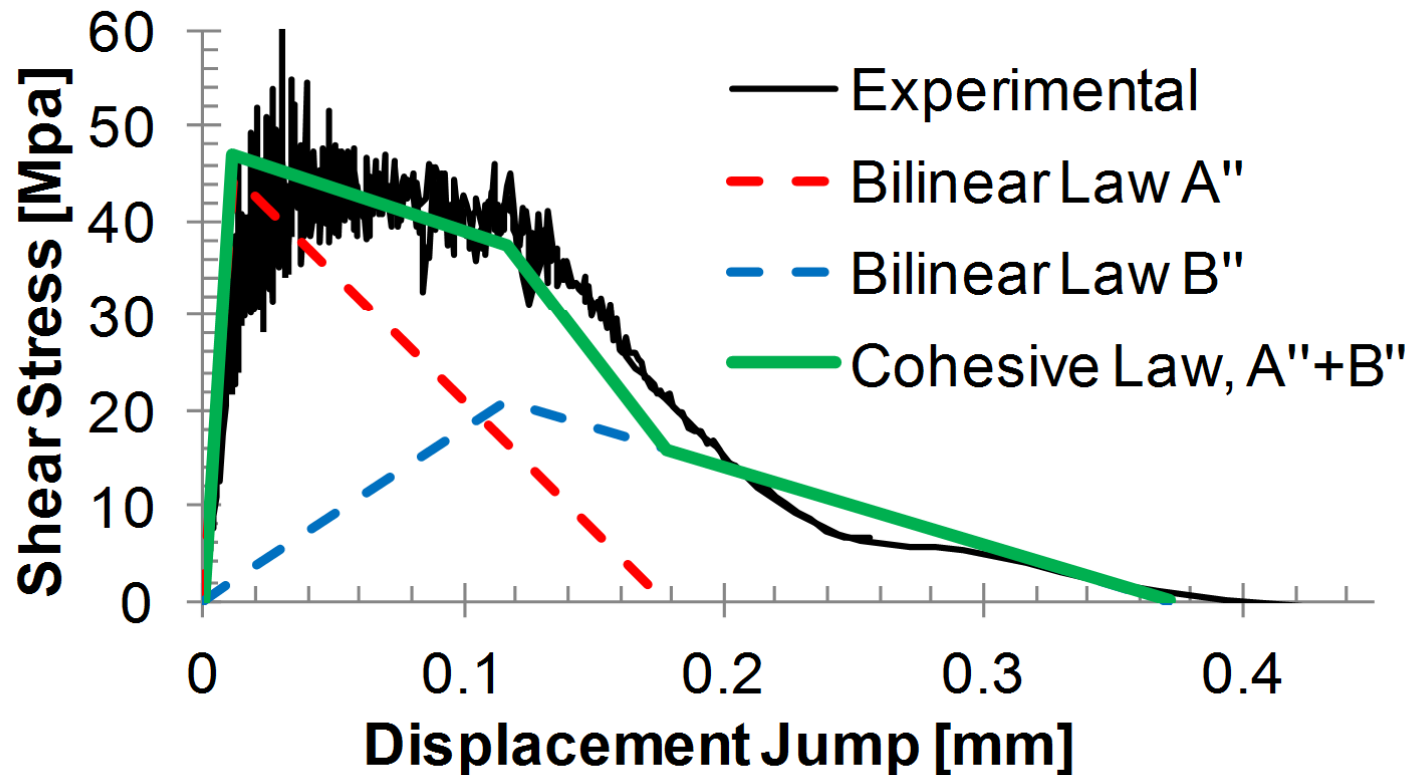
- Lack of failure criteria and material/structural validated models
- Lack of an accurate and reliable quality control

➤ Investigation of the failure mechanism of an adhesive layer in composite bonded joints

- Experimental: measurement of the cohesive laws for mode-I and mode-II debonding through Digital Image Correlation (DIC)
- Numerical: model the failure of the composite bonded joint through a Cohesive Zone Model (CZM) based on the experimental cohesive laws



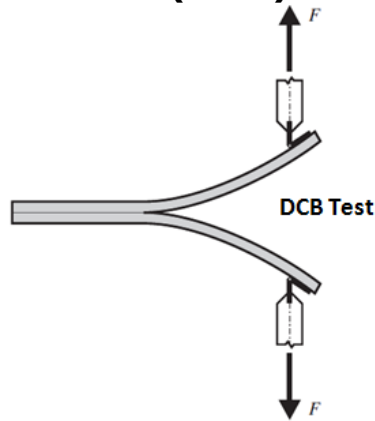
COHESIVE LAW



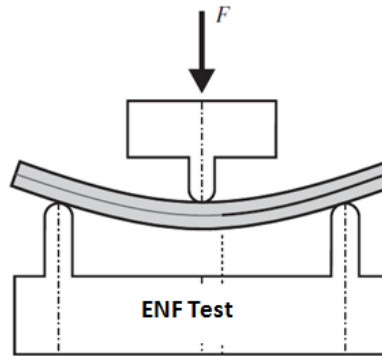
- The cohesive law represents the non-linear fracture properties of the adhesive material
- The global structural response is used for validation

- Delamination failure modes are studied through standard experiments:

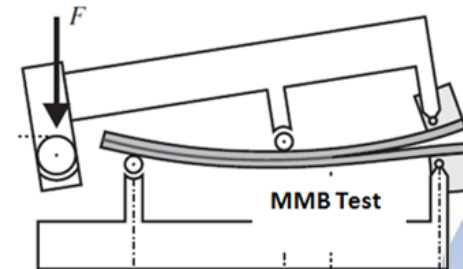
•Mode-I:
Double Cantilever Beam
(DCB)



•Mode-II:
End Notched Flexure
(ENF)

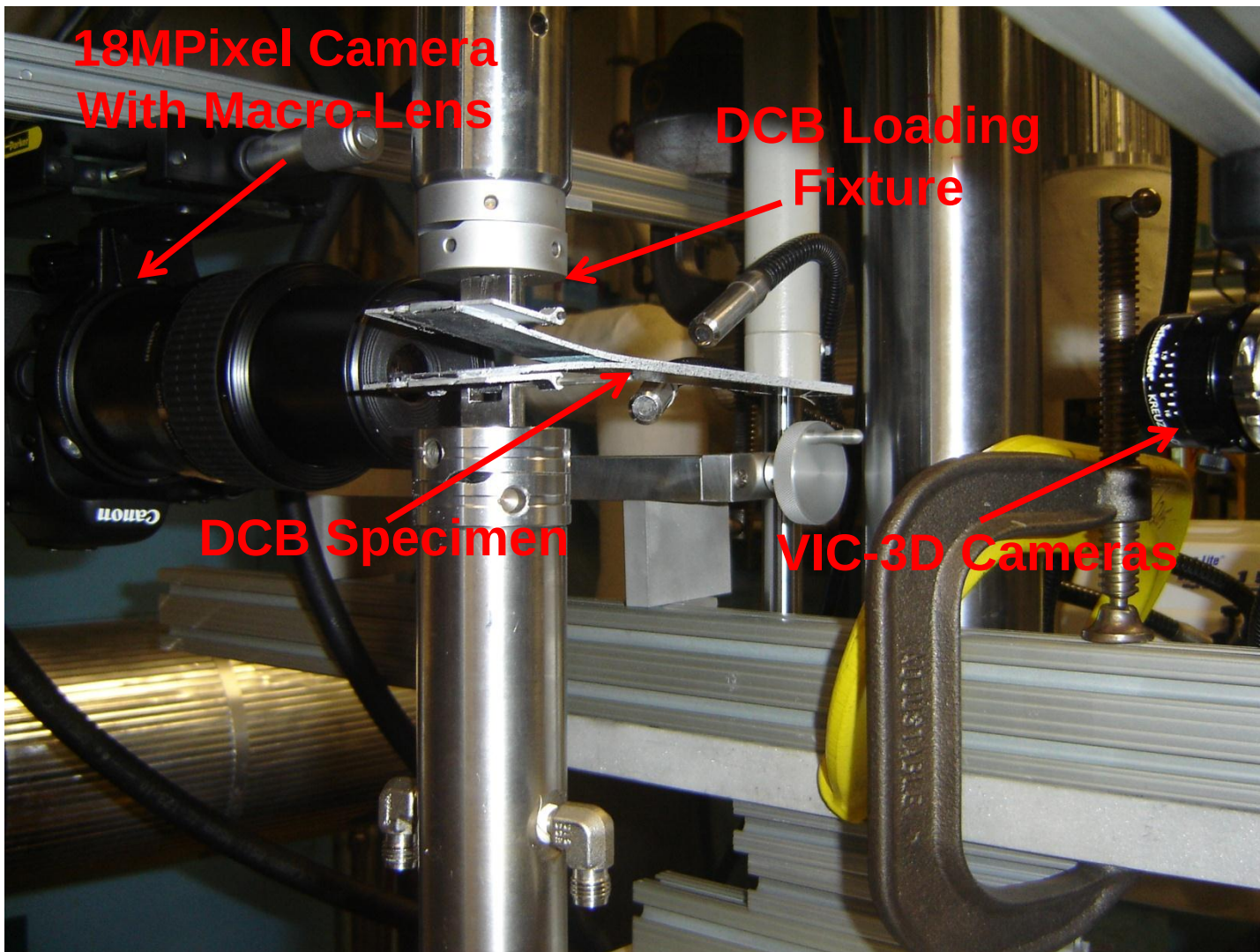


•Mixed-Mode I/II:
Mixed-Mode Bending
(MMB)

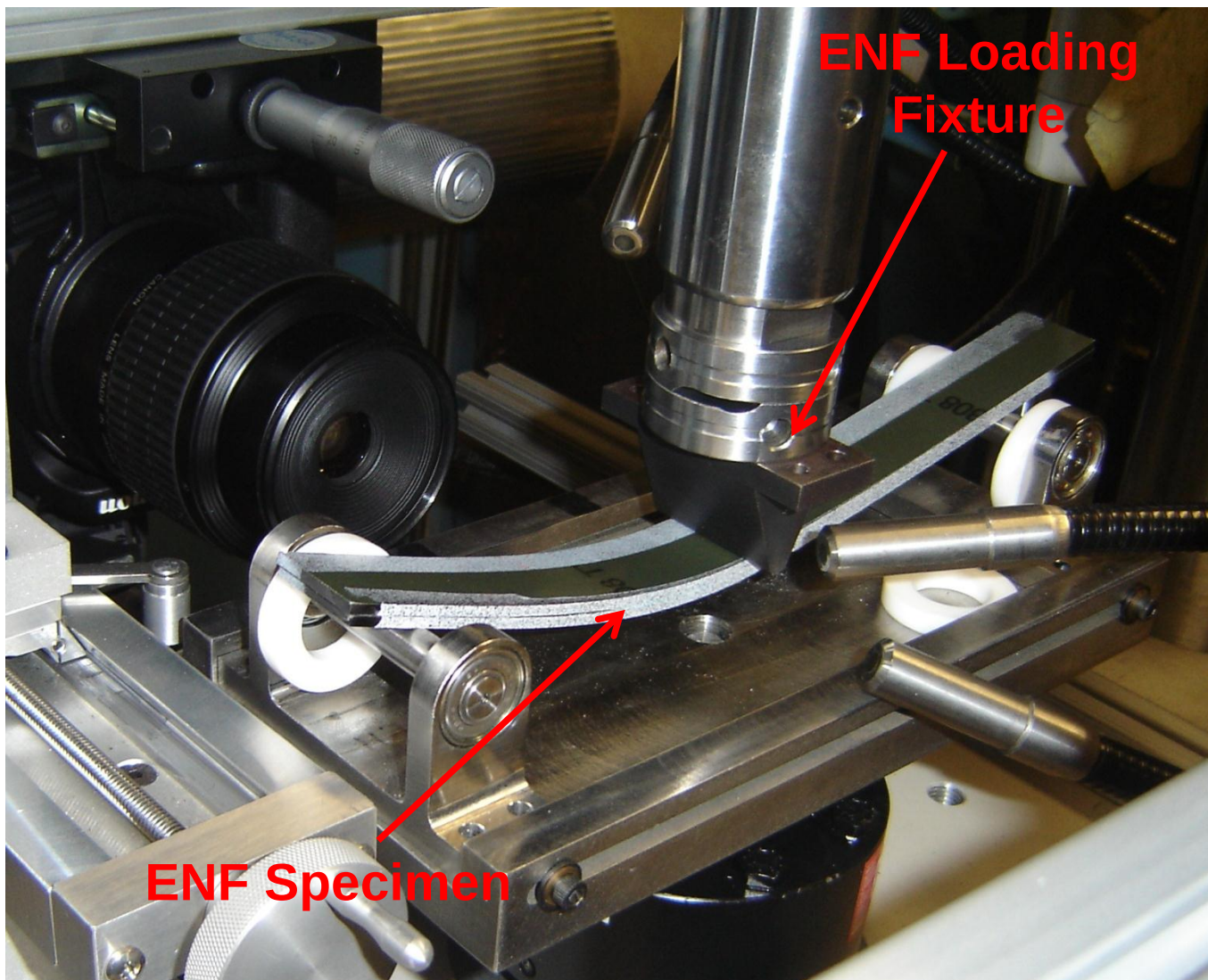


- The standards, based on Linear Elastic Fracture Mechanics (LEFM) assumptions, were developed for brittle fracture in composite laminates and originally were not meant to test adhesives.

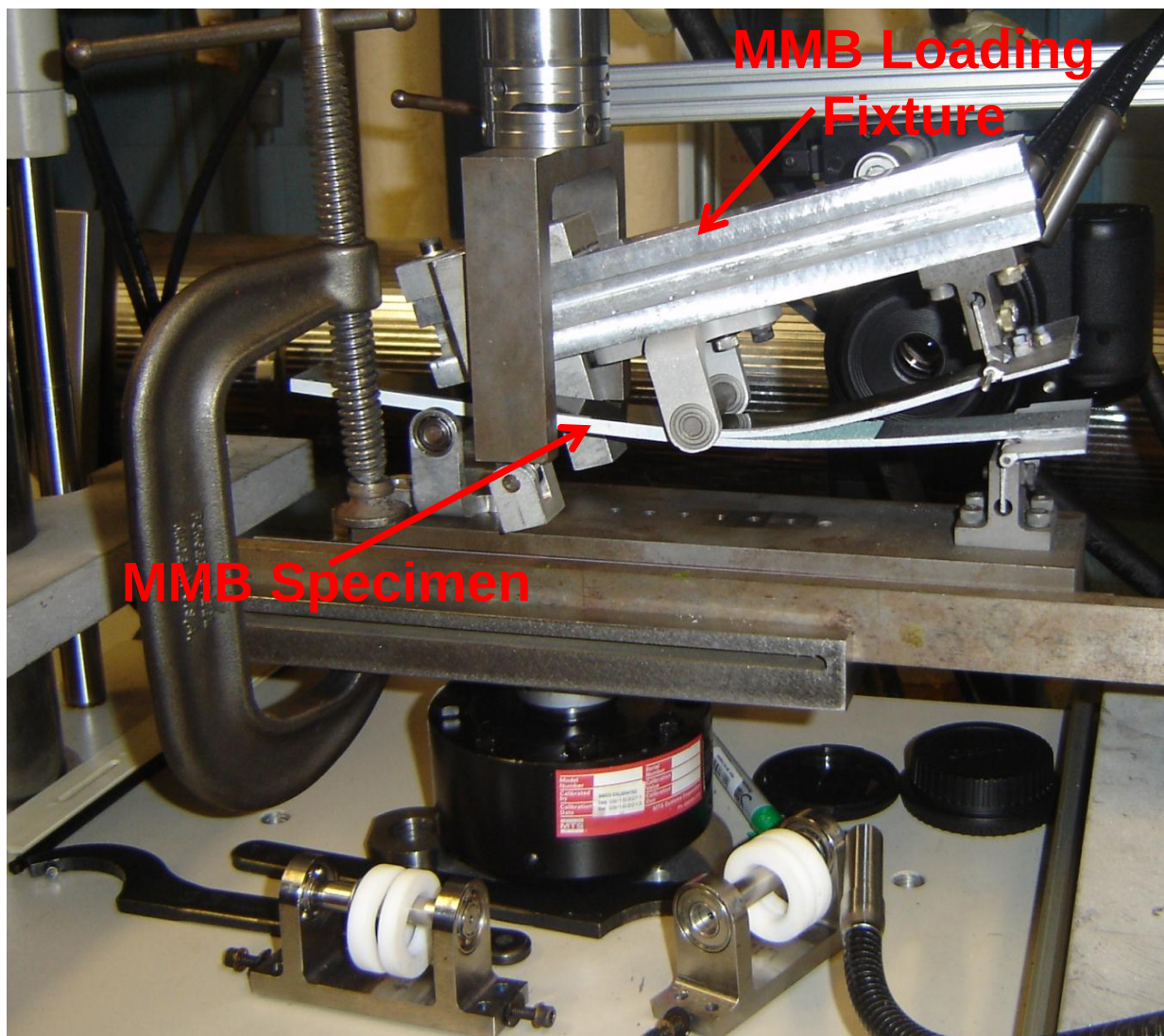
DCB Test setup



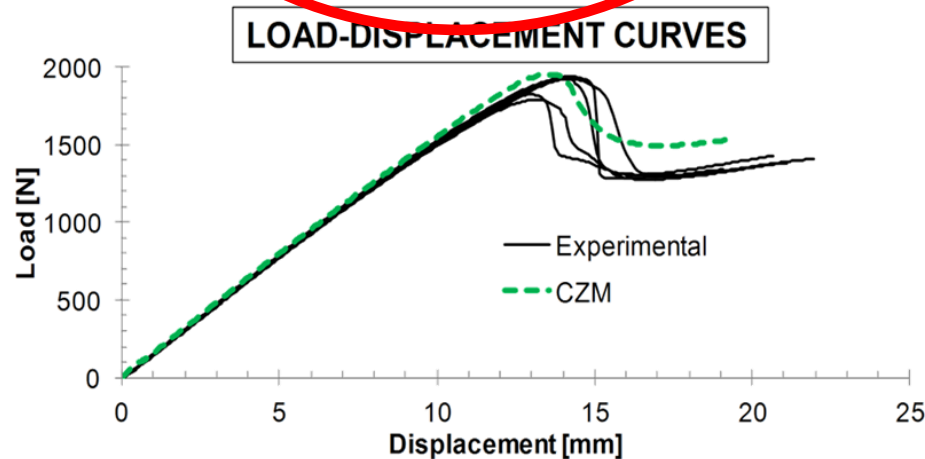
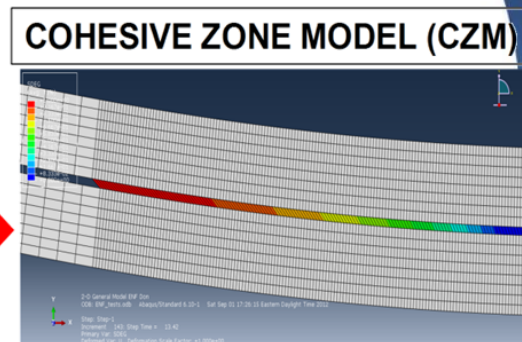
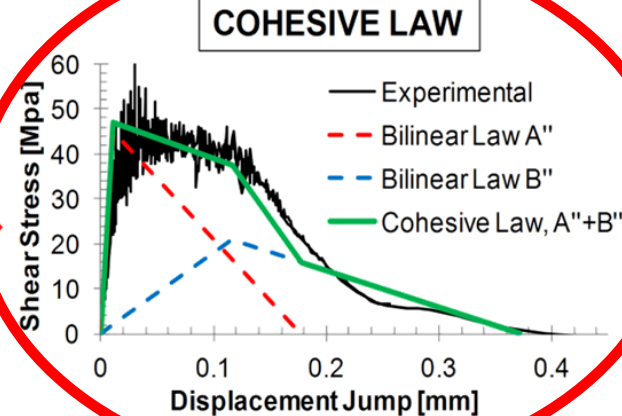
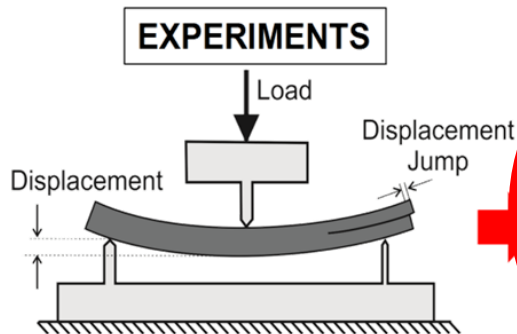
ENF Test Setup



MMB Test Setup

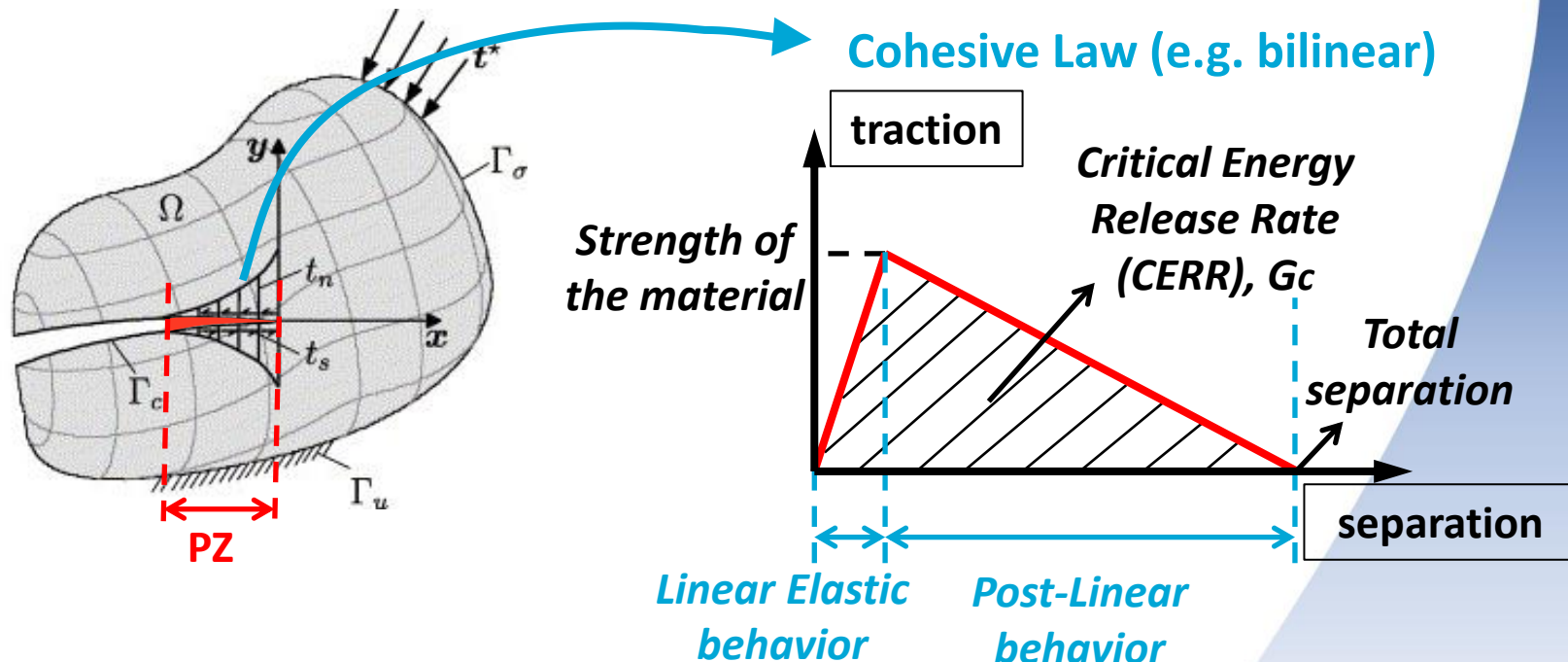


Cohesive Laws





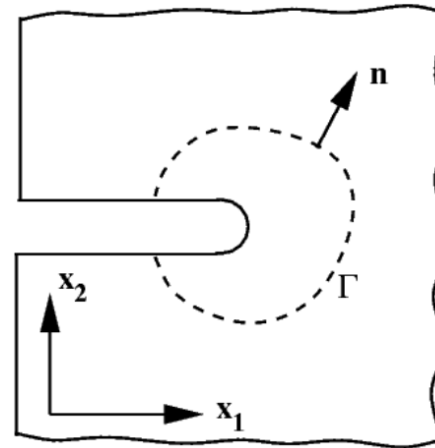
- Cohesive laws are the relation between the traction and the displacement – jump (or separation) in the “Process Zone” (PZ).
- The PZ is the region ahead the crack tip where the material softens and separates creating fresh surfaces.



- The Critical Energy Release Rate (CERR) or Fracture Toughness, G_c is the energy dissipated during fracture of the material;
- G_c can be estimated through a mathematical tool named “J-integral”.

- A contour integral estimated around the crack tip:

$$J_c := \int_{\Gamma} \left(w dx_2 - \underline{t} \frac{\partial \underline{u}}{\partial x_1} ds \right)$$

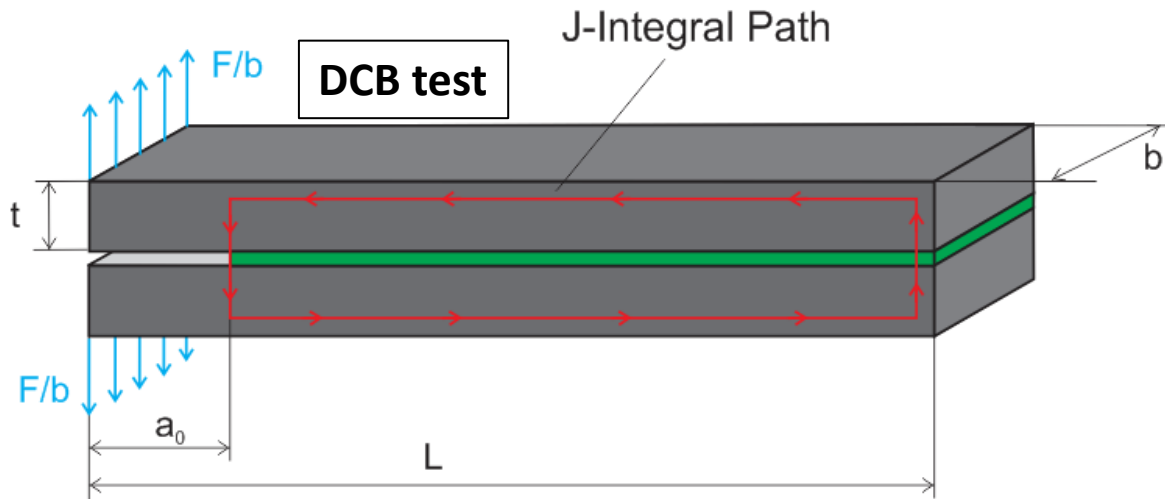


- w is the strain energy density;
- $\underline{t}$ is the surface traction vector;
- $\underline{u}$ is the displacement vector.

- Path independent, i.e. two independent integration paths will give the same result;
- Equal to G_c ;
- The derivative with respect to the displacement-jump coincides with the traction displacement functions;

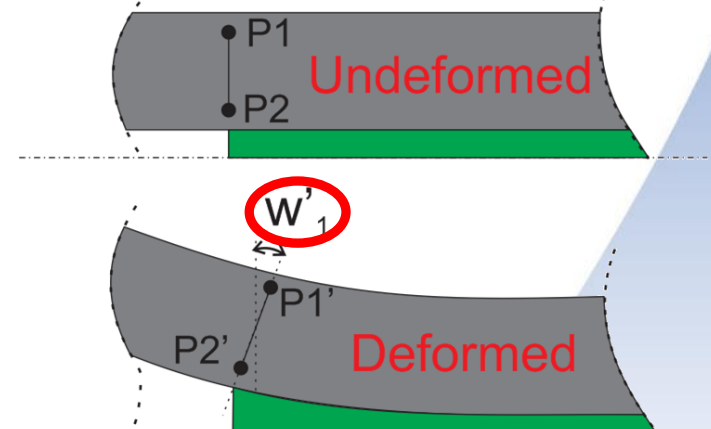
$$J_c = G_c = \int_0^{\delta_c} \sigma(\delta) d\delta \quad \longrightarrow \quad \frac{dJ}{d\delta} = \sigma(\delta)$$

J-Integral for a Mode-I Specimen

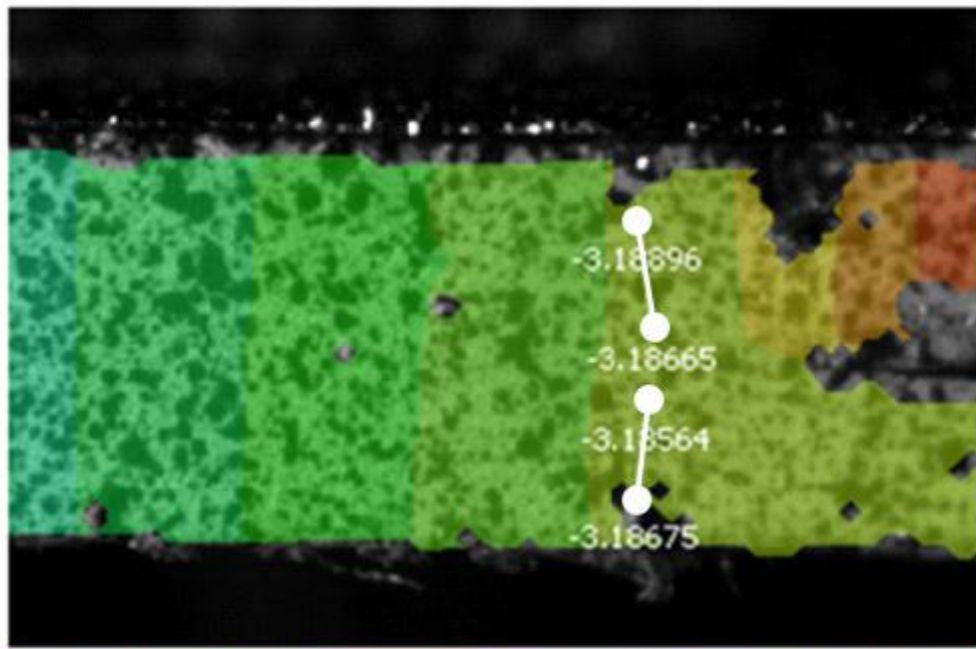


$$J_{DCB} = \frac{12}{Et} \frac{F a_0}{b t} \frac{\ddot{\theta}^2}{\theta} + \frac{F a_0}{b} \left| w'_1 - w'_2 \right|$$

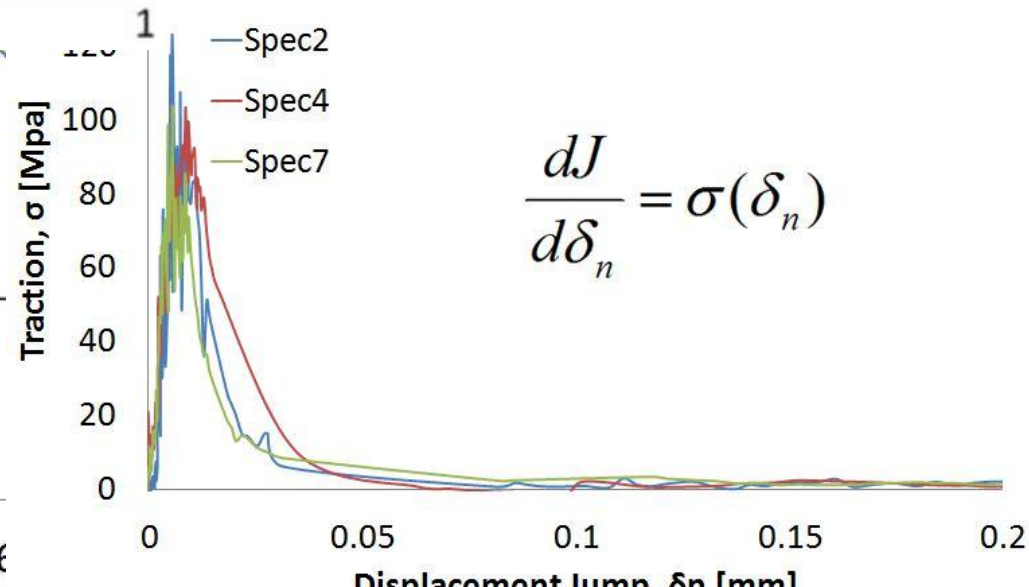
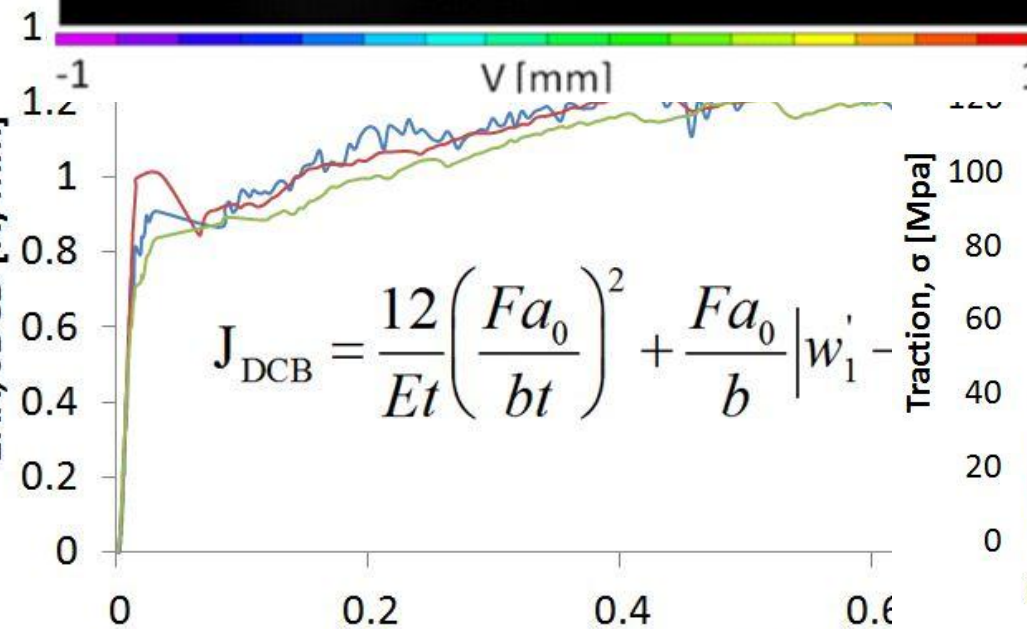
Pure Mode-I deformation



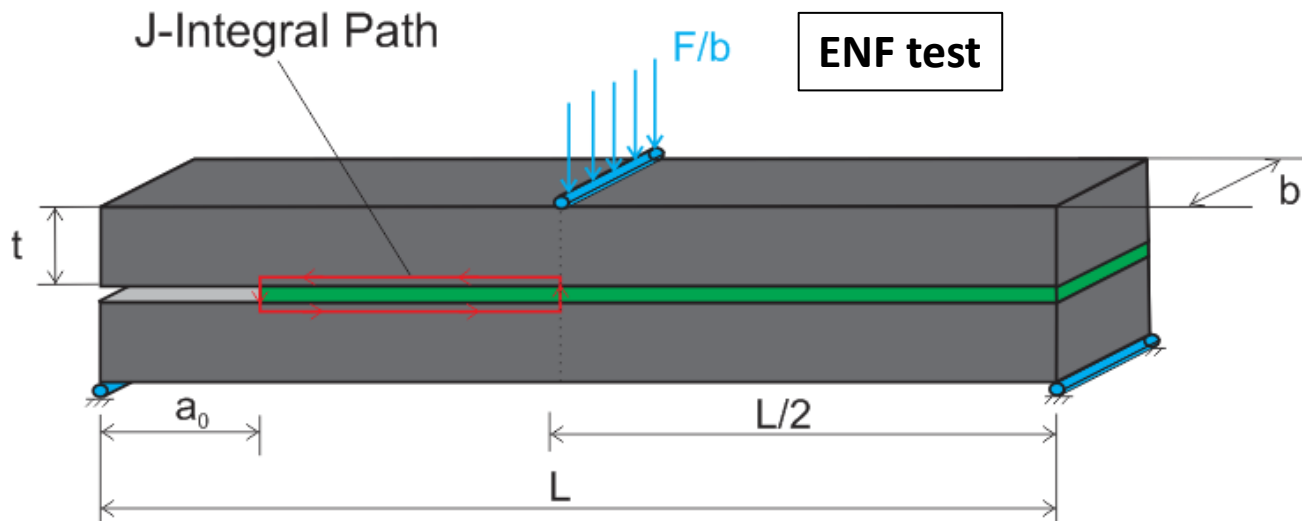
w' is the rotation of the arm measured through the DIC



Mode-I Cohesive Law



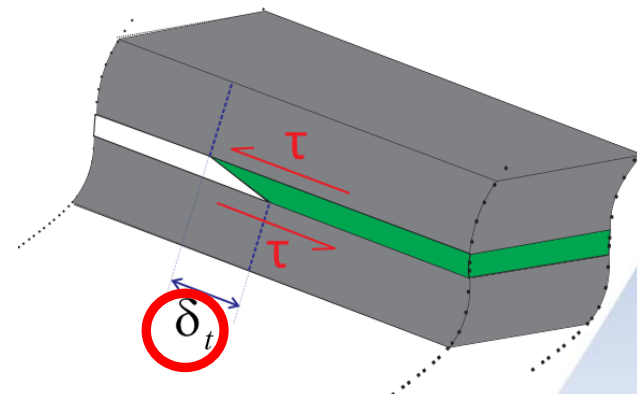
J-Integral for a Mode-II Specimen



Pure Mode-II deformation

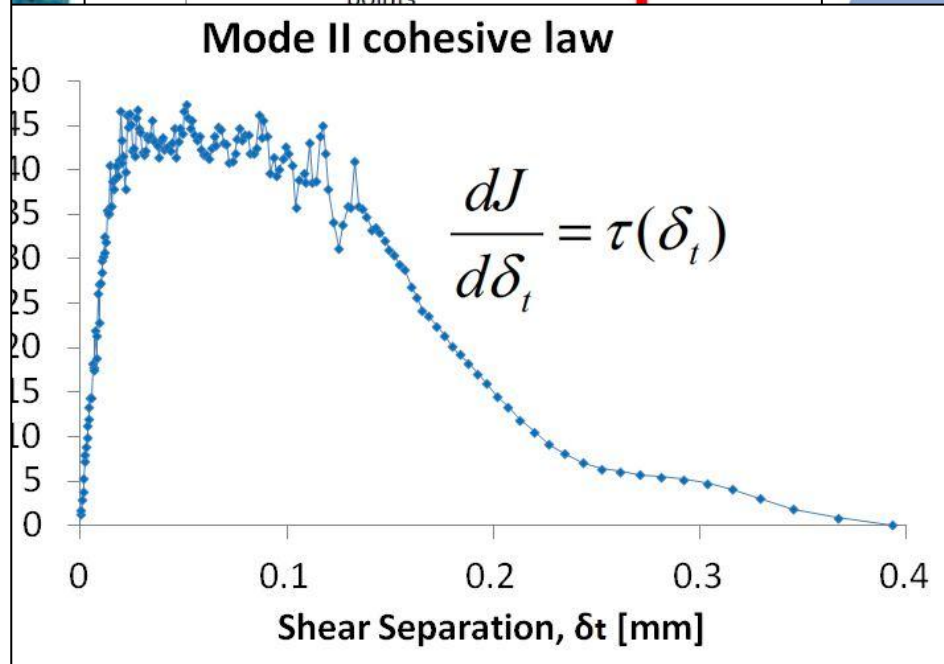
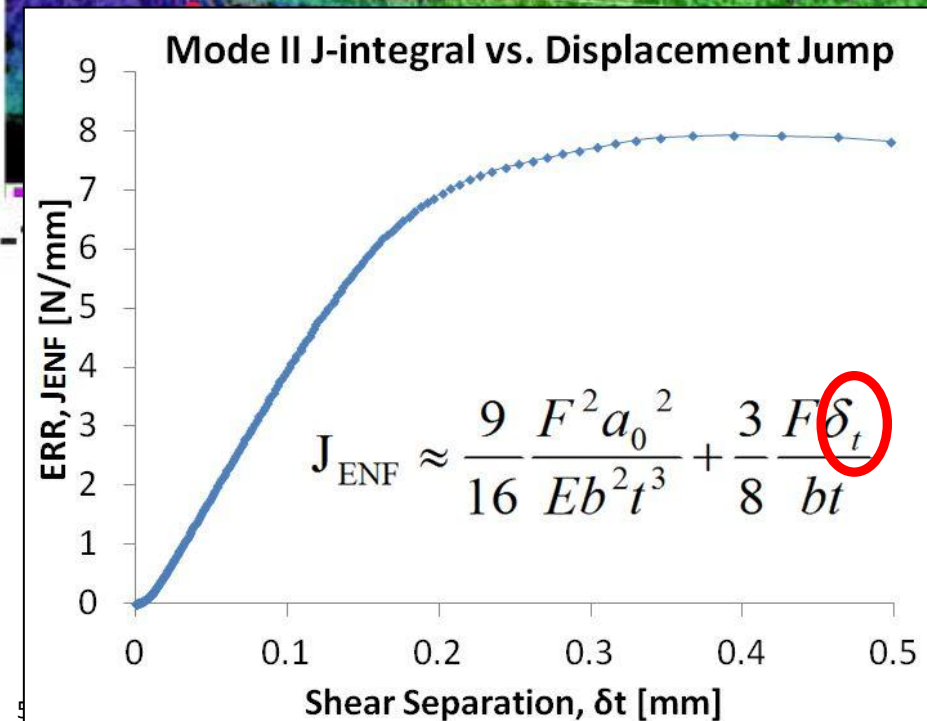
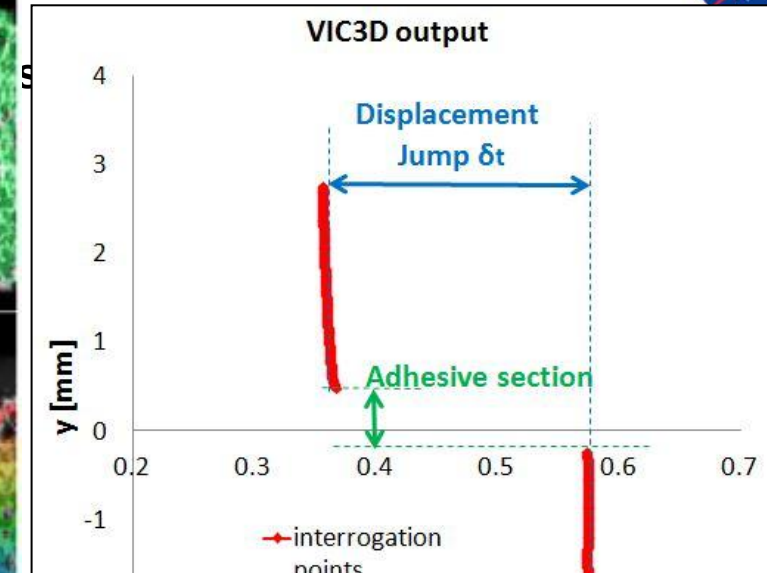
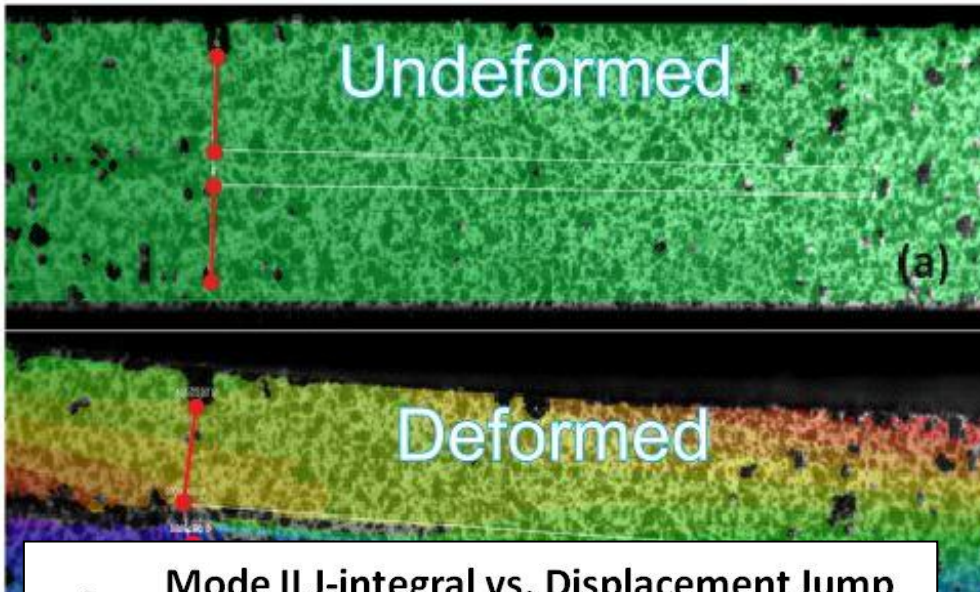
$$J_{\text{ENF}} \approx \frac{9}{16} \frac{F^2 a_0^2}{Eb^2 t^3} + \frac{3}{8} \frac{F \delta_t}{bt}$$

K. Leffler, 2007

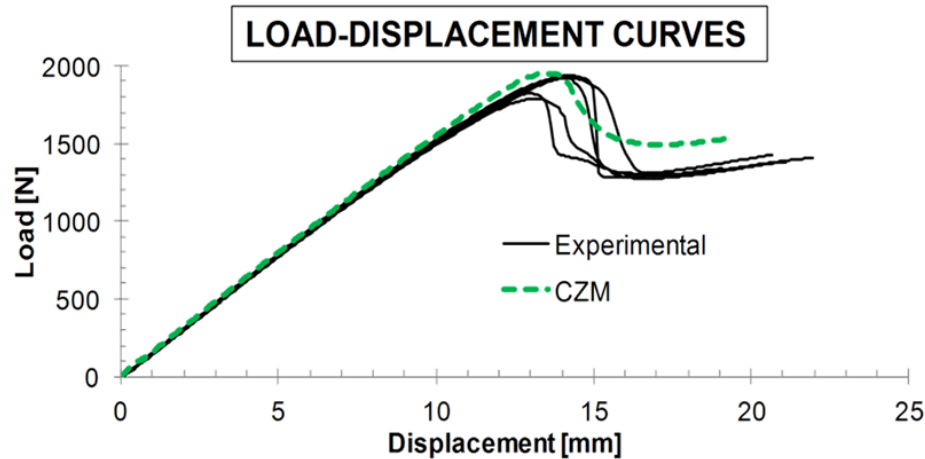
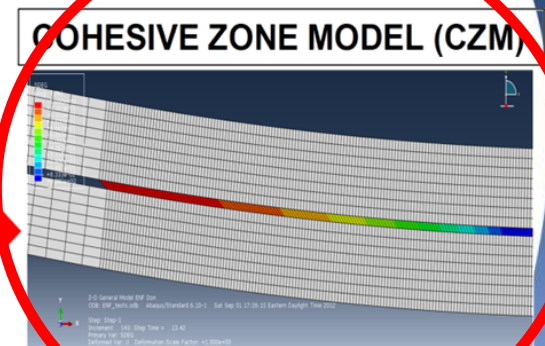
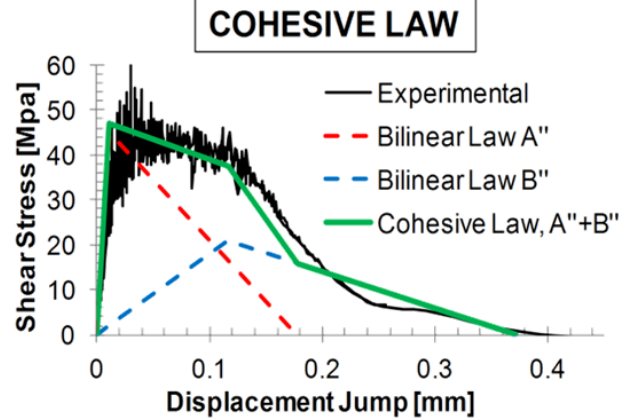
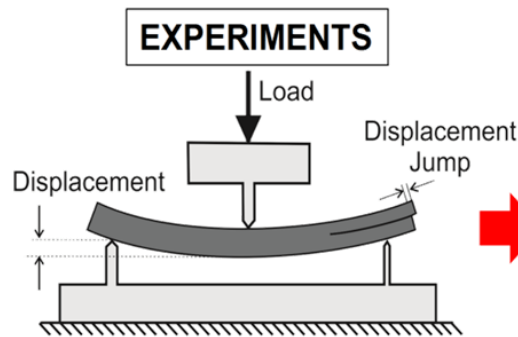


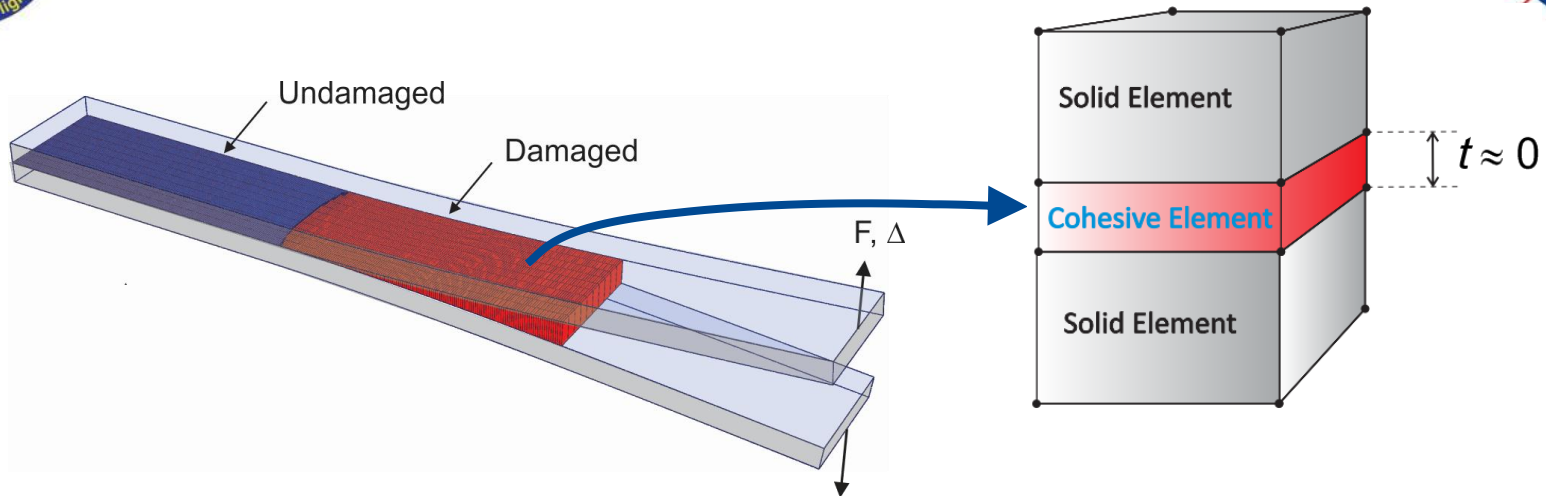
δ_t is the shear displacement jump
(or shear *separation*), measured
through the DIC

ENF J-Integral from DIC

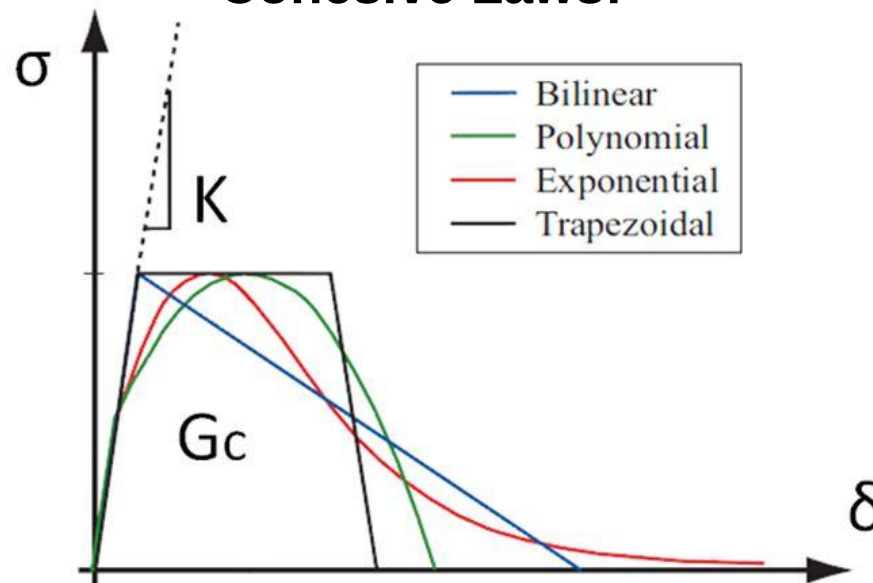


Cohesive Zone Model (CZM)





Cohesive Laws:

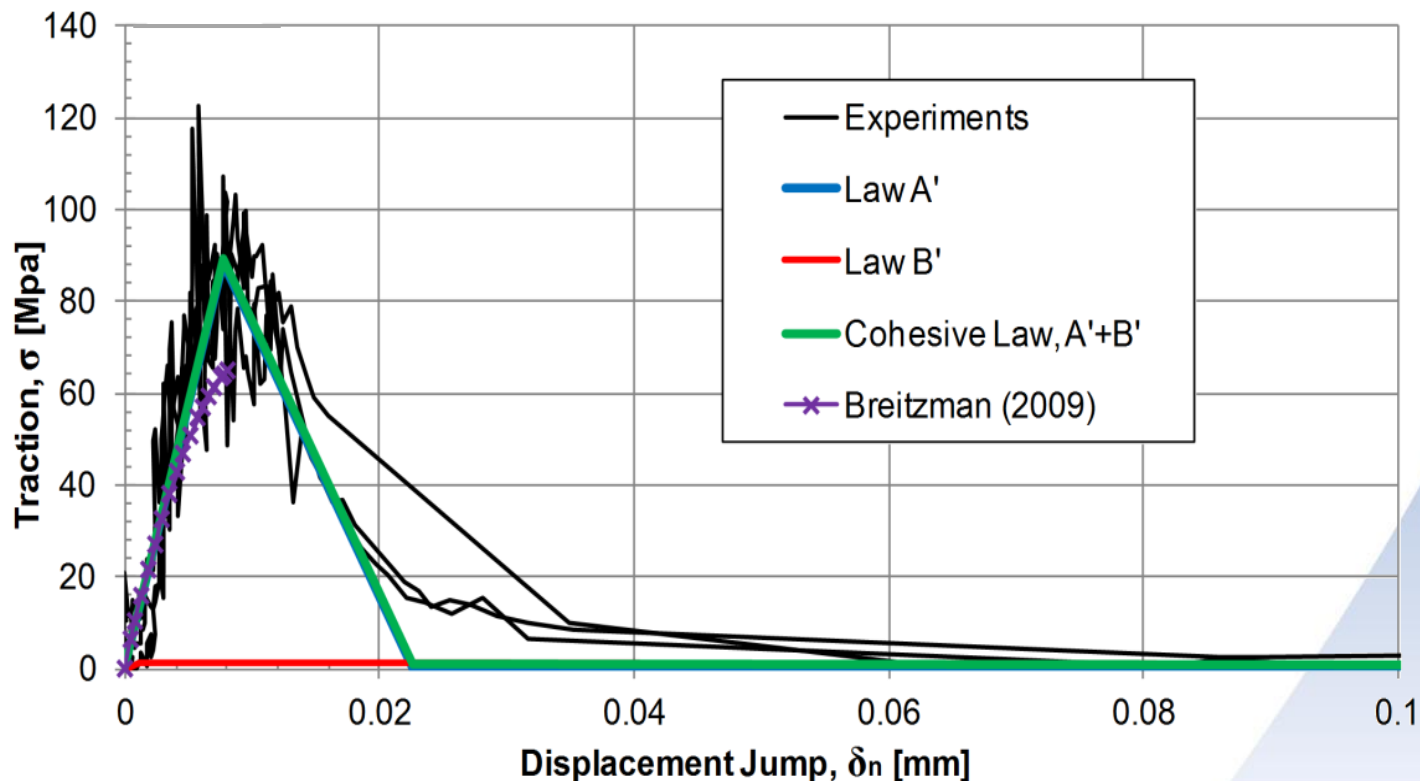




Modeling the Cohesive Law Through the Superposition of Two Bilinear Laws, Mode-I

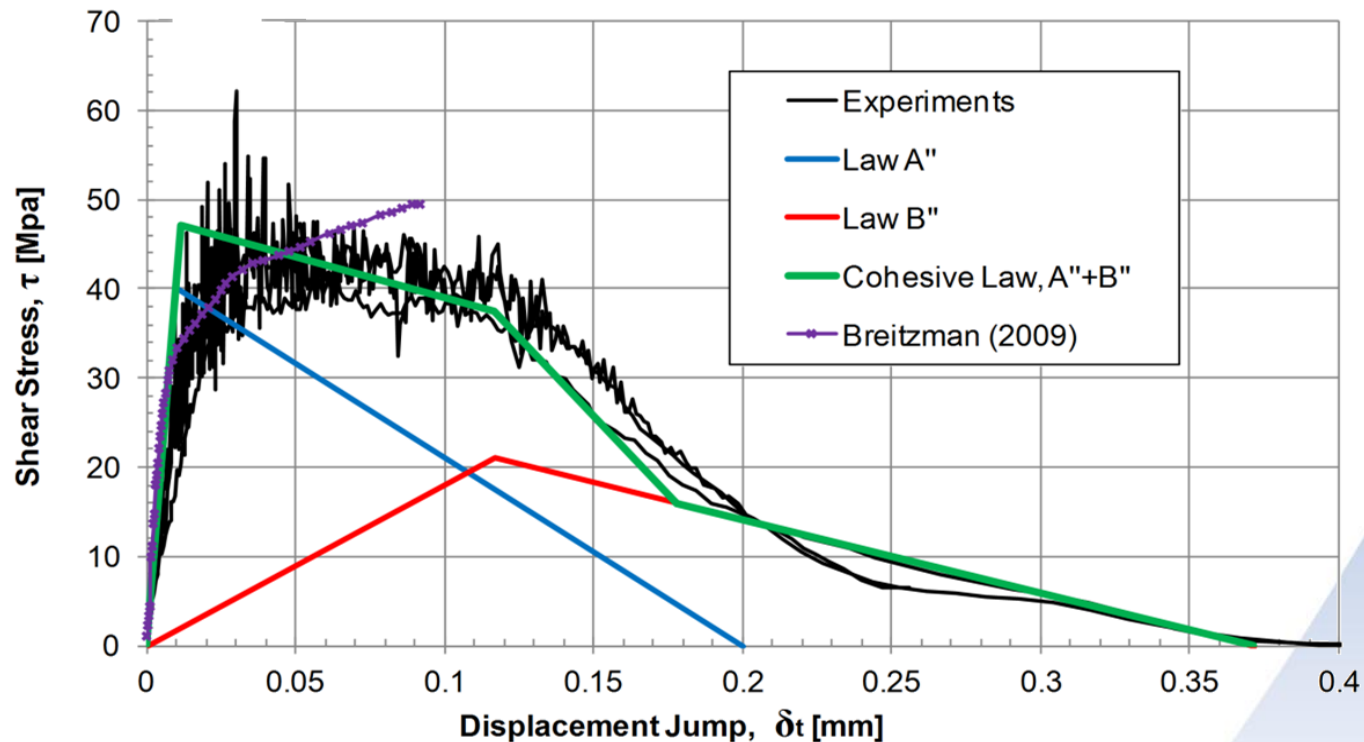


- Cohesive law obtained by superposing two bilinear laws
- Elastic response of the material in agreement with Breitzman et al. (2009)



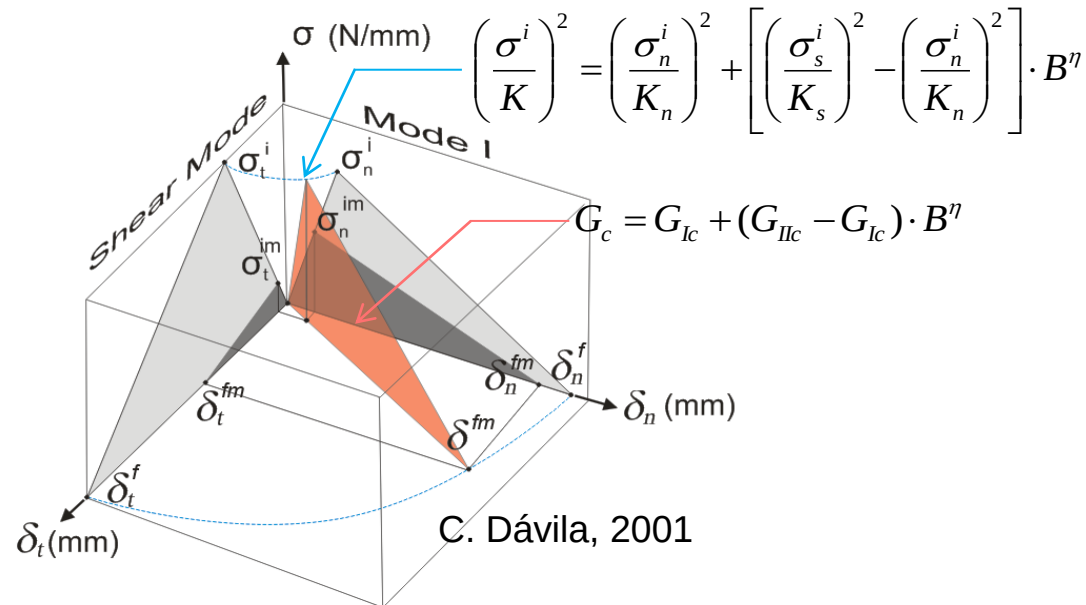
Modeling the Cohesive Law Through the Superposition of Two Bilinear Laws, Mode-II

- Cohesive law obtained by superposing two bilinear laws
- Elastic response of the material in agreement with Breitzman et al. (2009)

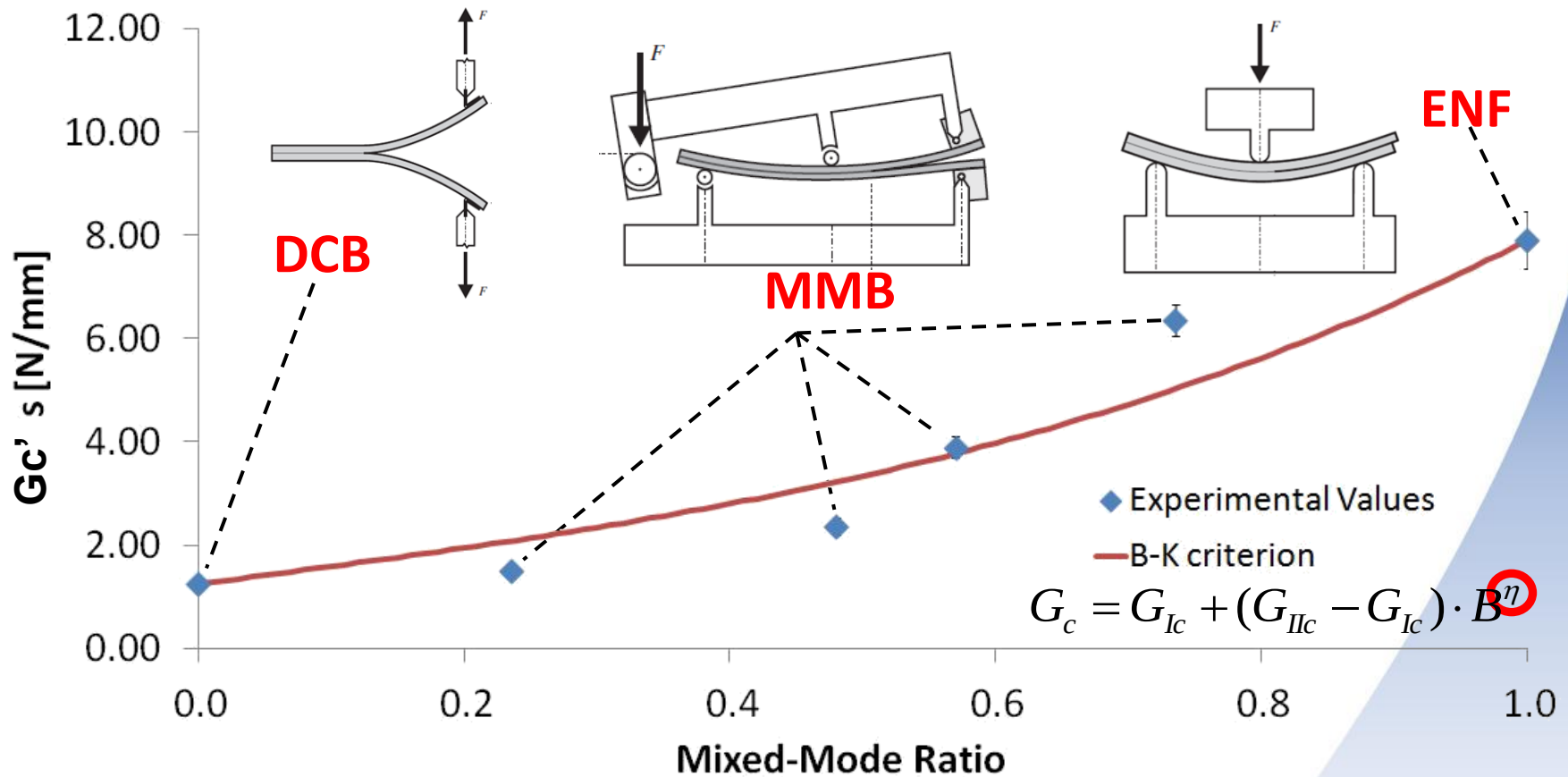


Mixed-Mode Delamination Model

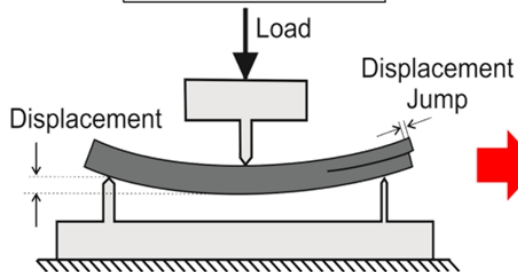
- Both initiation and propagation of failure in mixed-mode are based on the Benzeggagh-Kenane (B-K) criterion:



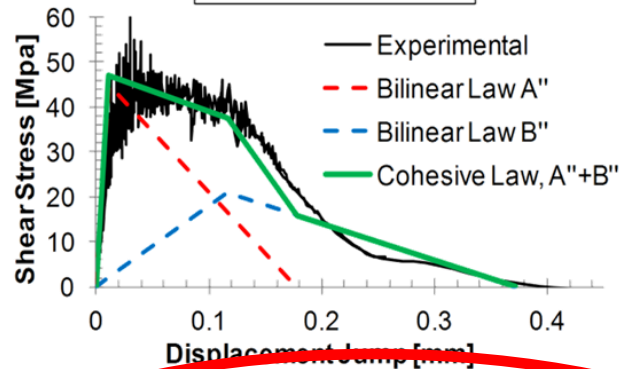
- The B term represents the “mixed-mode ratio”, defined as the fraction of the total ERR dissipated in pure mode-II delamination.



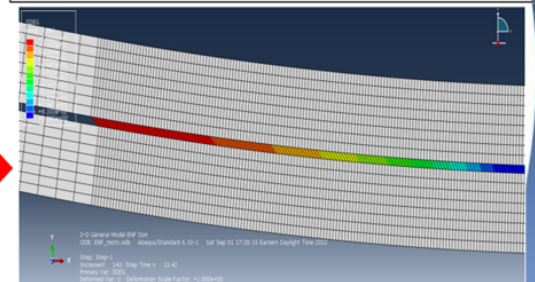
EXPERIMENTS



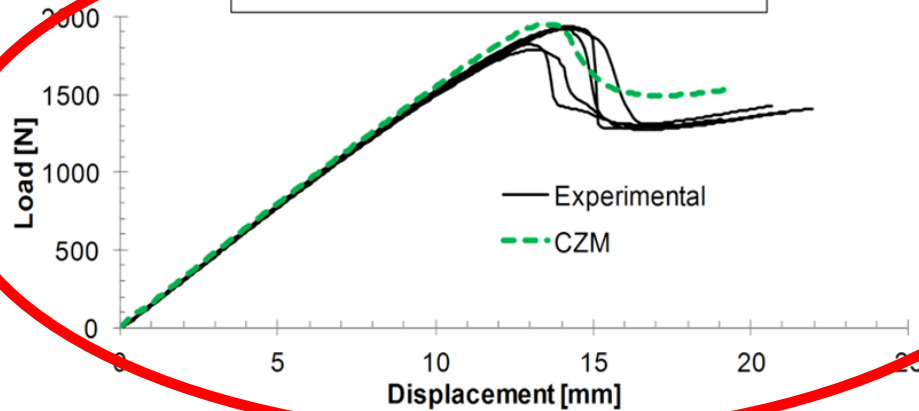
COHESIVE LAW



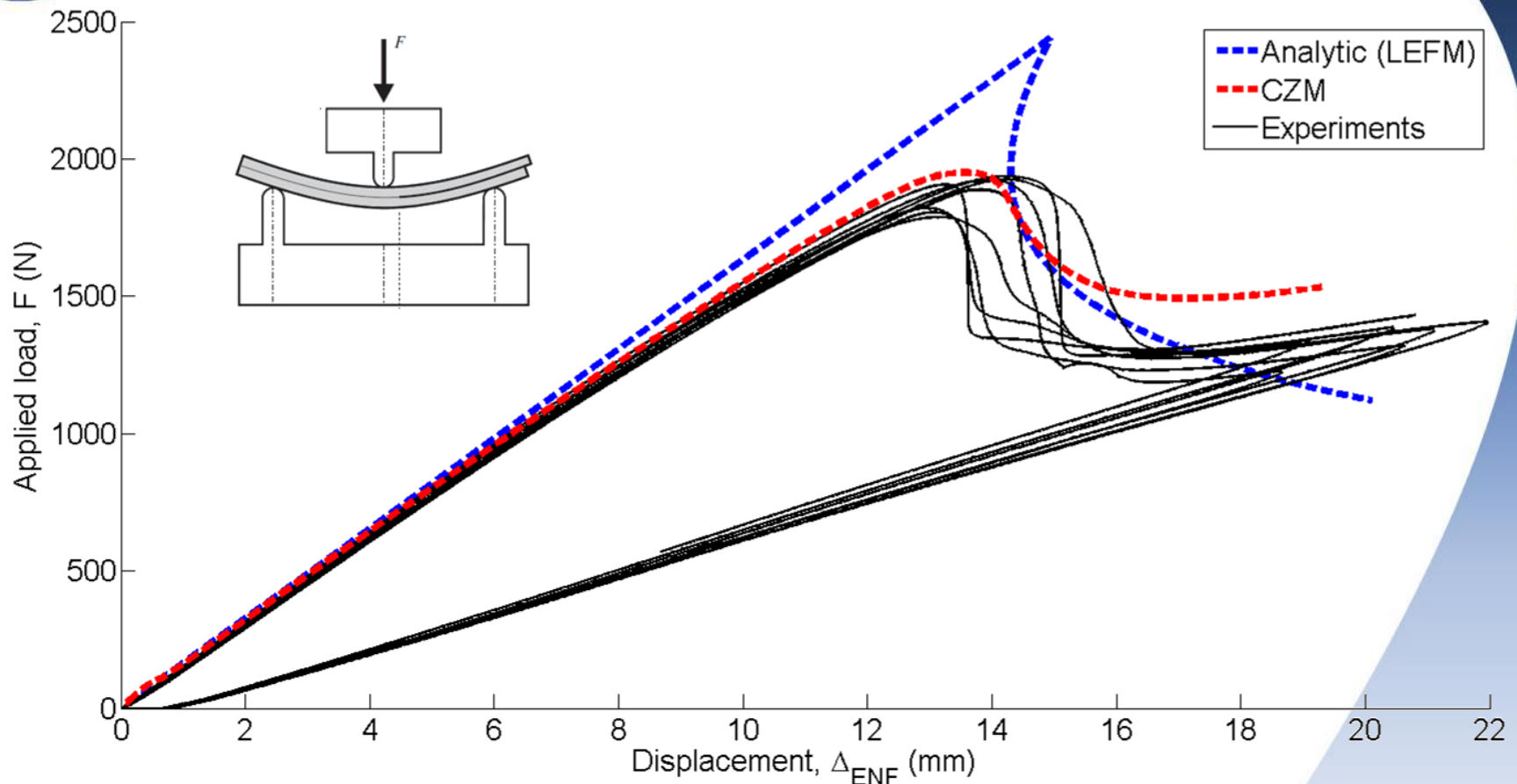
COHESIVE ZONE MODEL (CZM)



LOAD-DISPLACEMENT CURVES

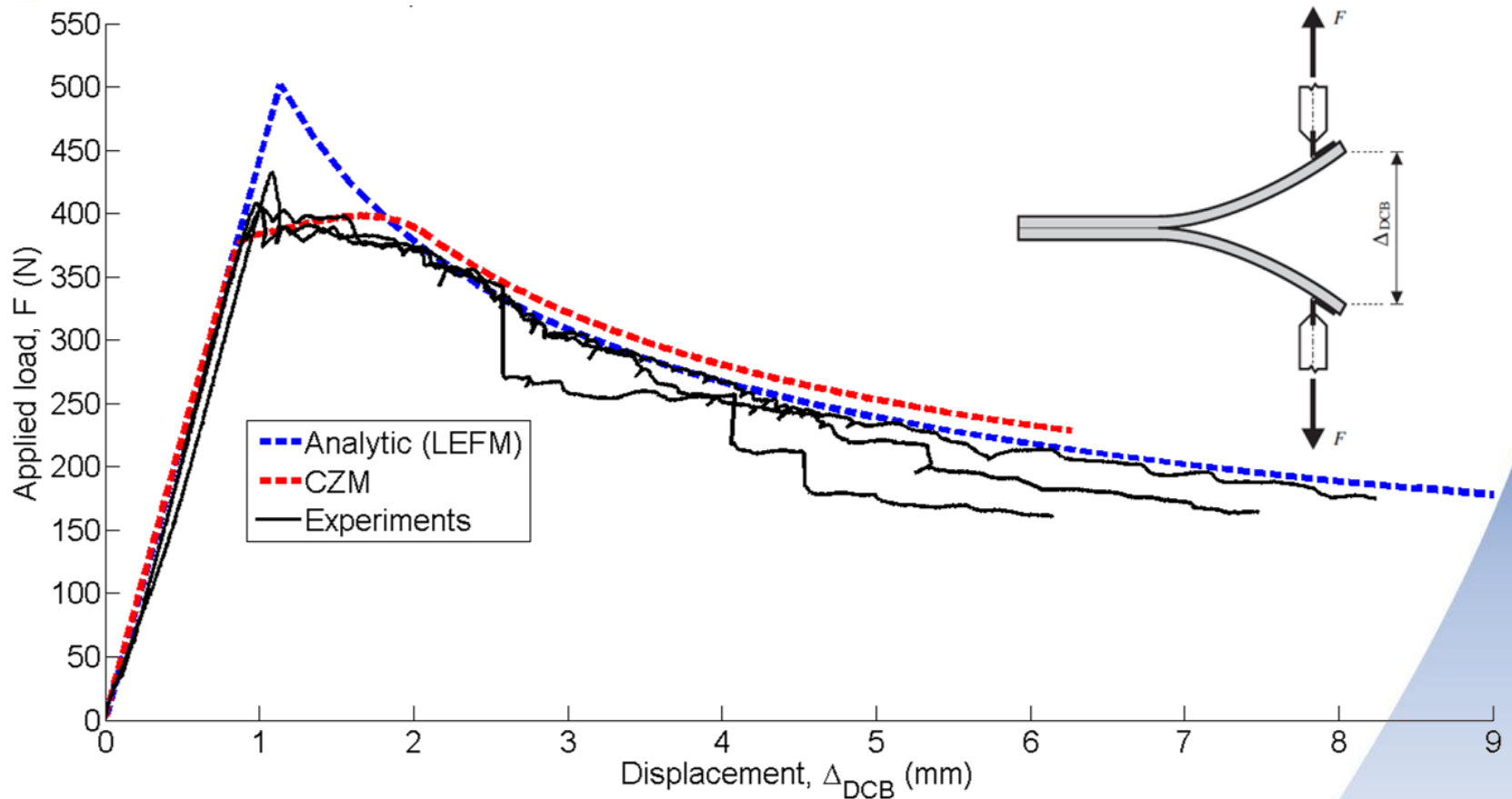


Correlation of the Analytical, Experimental and Numerical Load-Displacement Curves for ENF

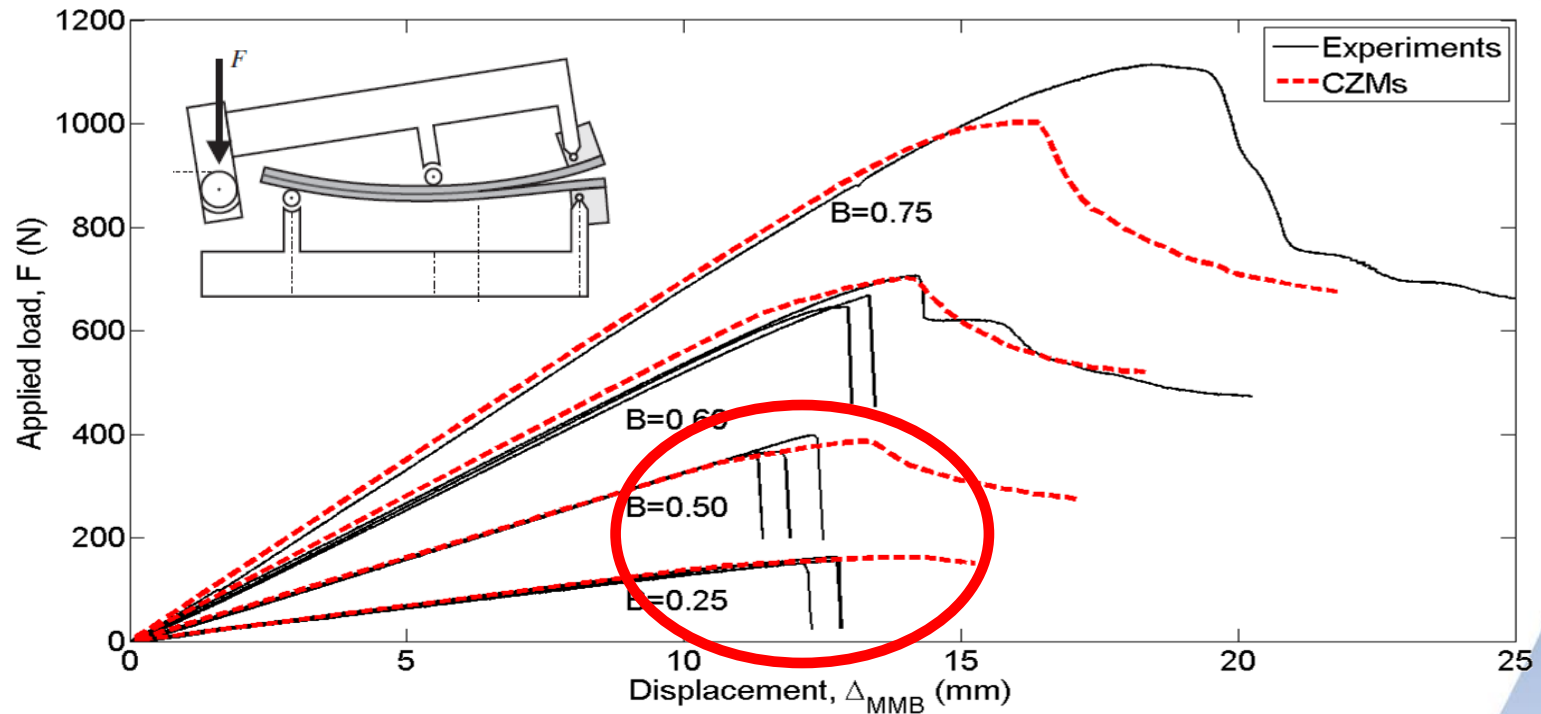


- Good correlation both in terms of failure load and load-displacement history
- Linear Elastic Fracture Mechanics (LEFM) does not address the non-linear response of the material

Correlation of the Analytical, Experimental and Numerical Load-Displacement Curves for DCB



- Good correlation both in terms of failure load and load-displacement history
- Linear Elastic Fracture Mechanics (LEFM) does not address the non-linear response of the material

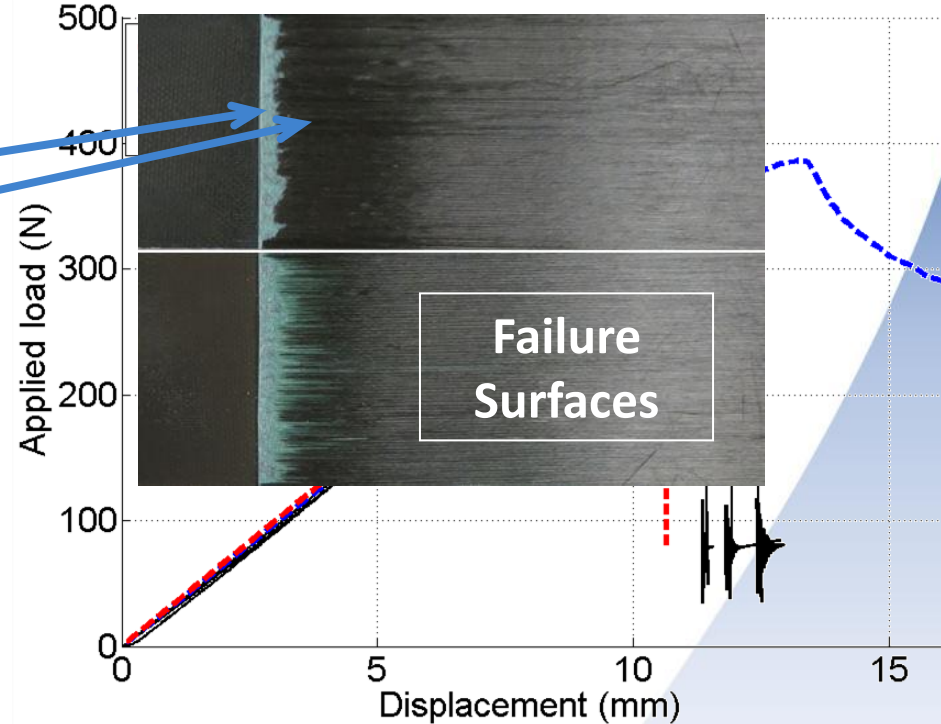
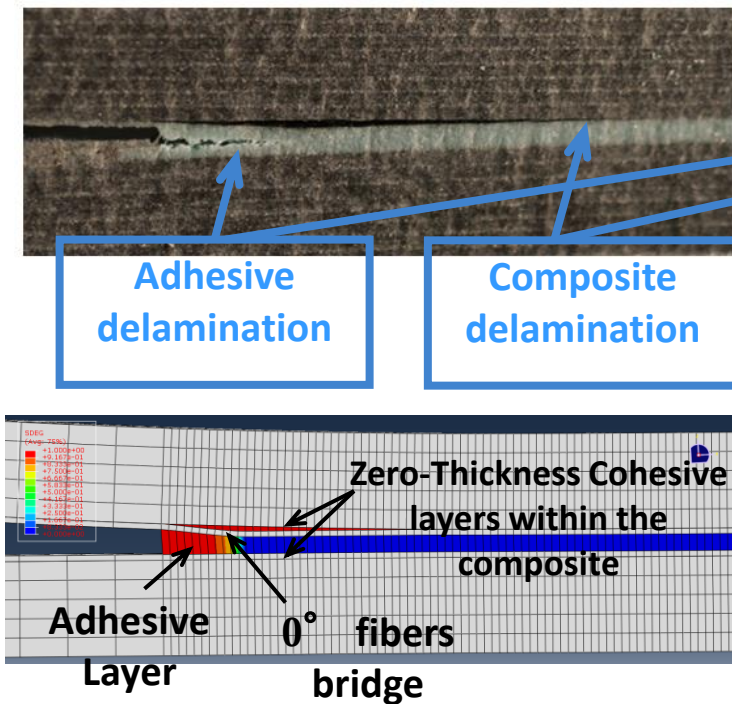


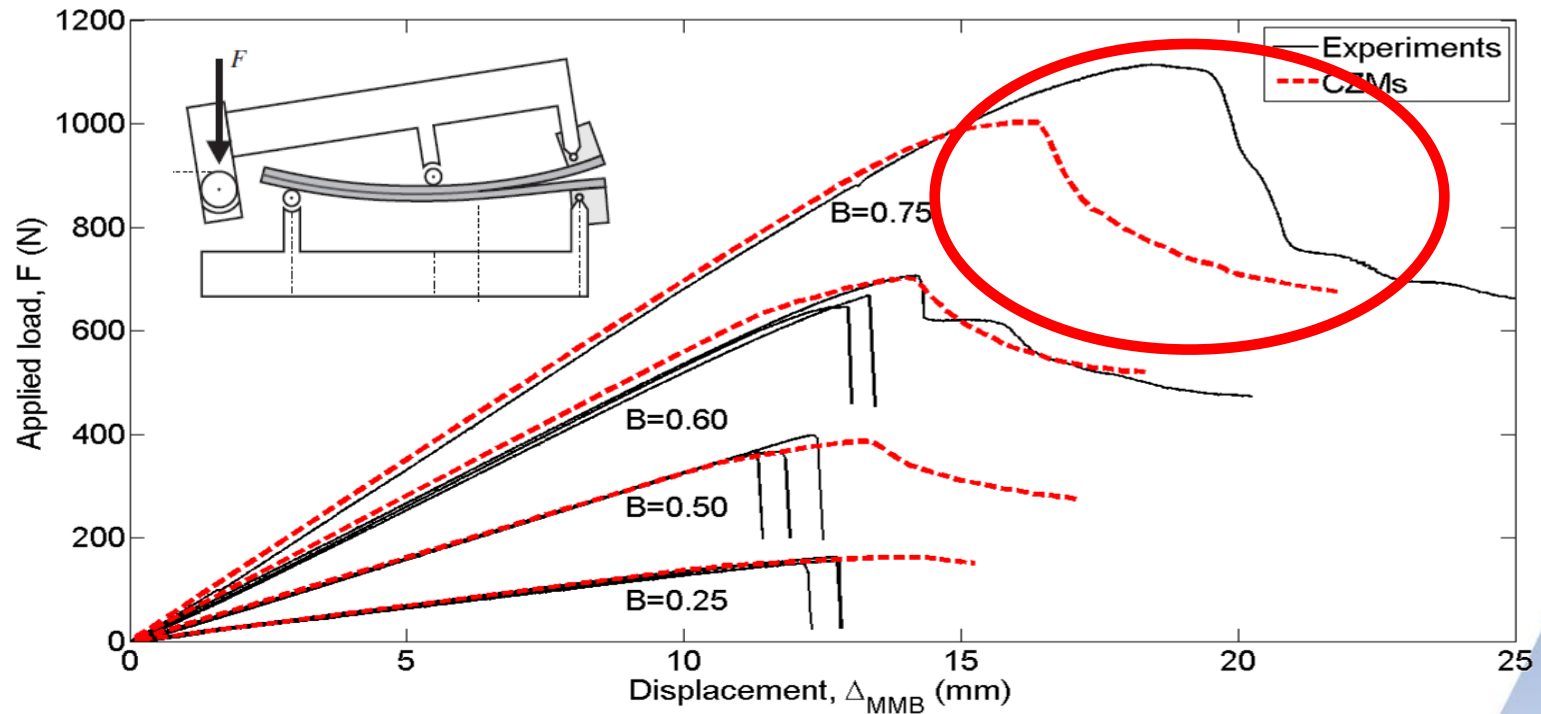
➤ Good correlation in terms of failure loads and load-displacement history except for:

- $B=0.25$; 0.50 ; drop in the load-displacement curve, consequence of an unconventional brittle failure mechanism named “Double Delamination”

Double Delamination

- Unexpected failure mechanism
- Numerical model to capture the Double Delamination
- Two additional cohesive layers within the composite arms
- Better results compared to the original model



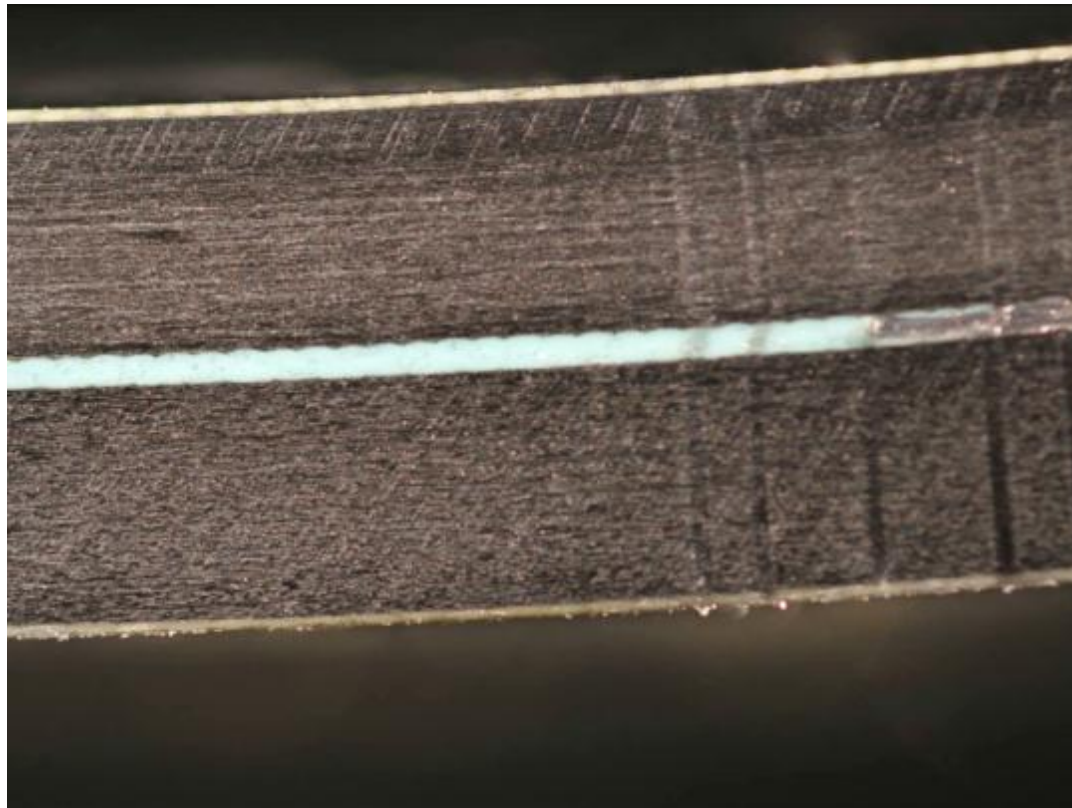


➤ **Good correlation in terms of failure loads and load-displacement history except for:**

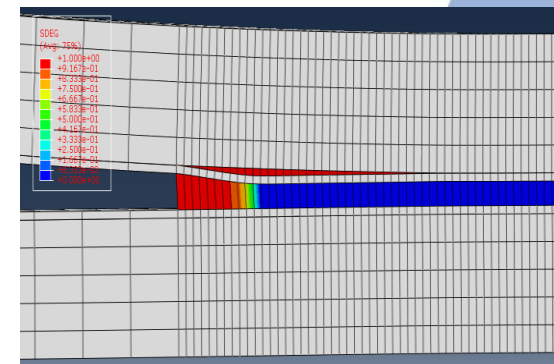
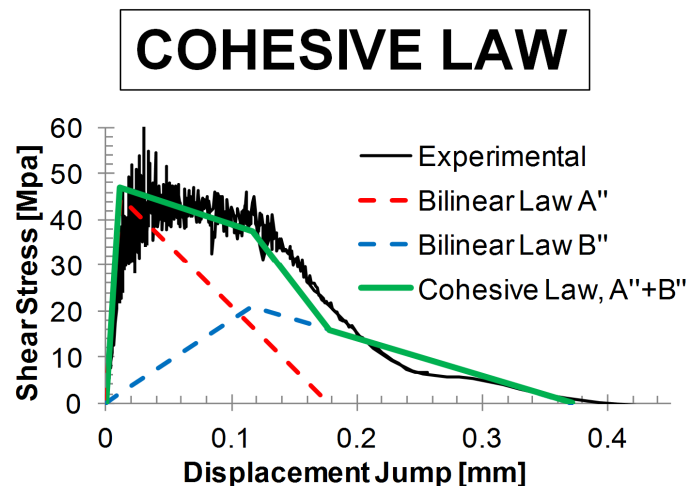
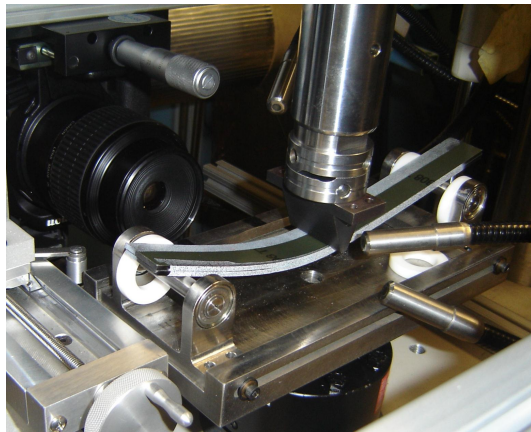
- $B = 0.75$; underestimation of the failure load, probably consequence of an underestimation of the pure mode-II G_c due to a peel opening during the ENF test

Peel Opening in an ENF Test

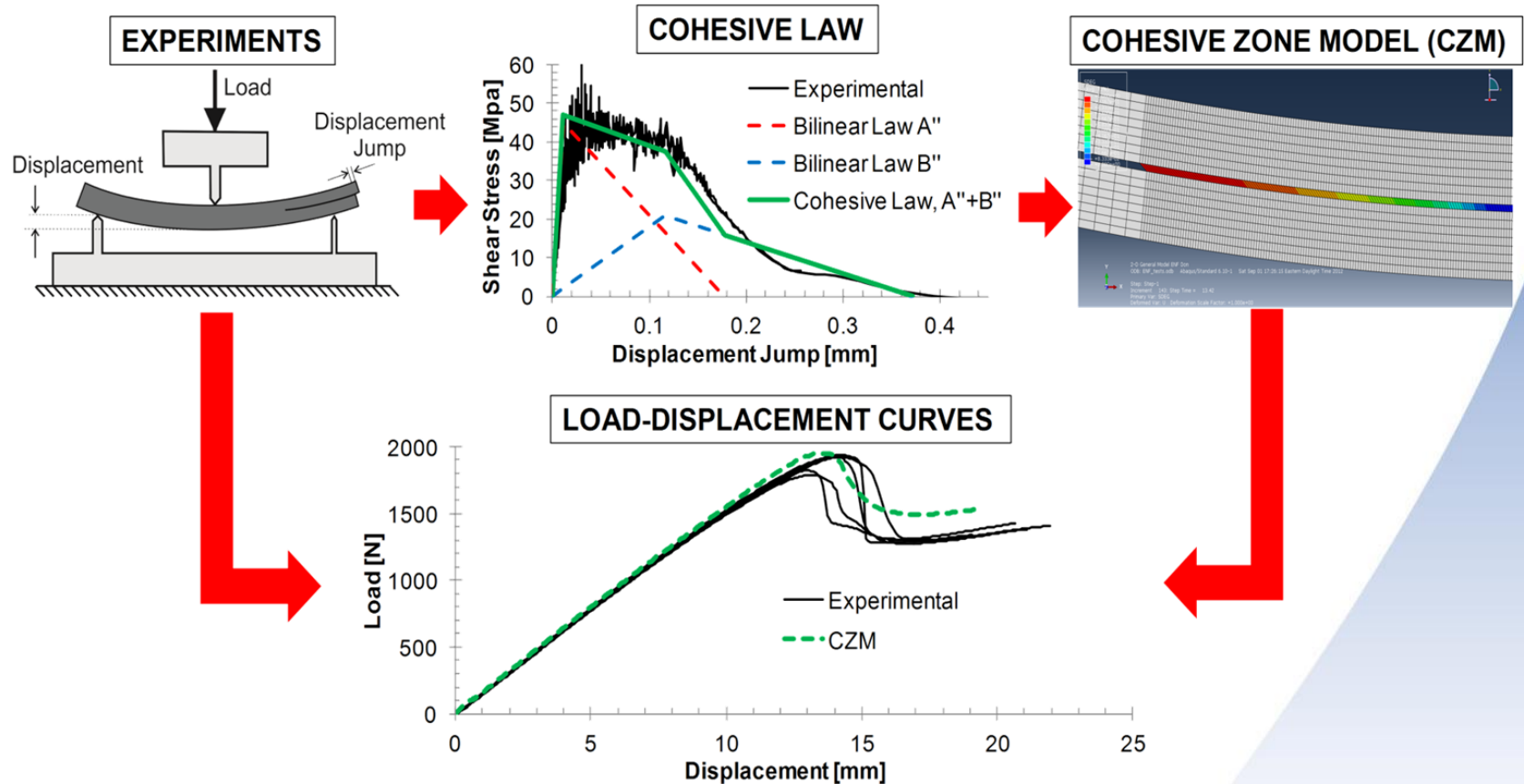
- The adhesive layer, initially subjected to only shear at the crack tip, starts to open in mode-I at a shear displacement jump of about 0.15 mm



- Experimental tests to characterize adhesive debonding in mode-I, mode-II and mixed-mode I/II
- Measurement of the cohesive laws for pure mode-I and pure mode-II debonding of an adhesive layer using DIC and the J-Integrals
- Development of a mixed-mode CZM (through User Defined Elements) to simulate the progression of damage in the adhesive layer of a composite bonded joint



- The experimental and numerical methodologies are linked through the cohesive laws (i.e. the local structural response) and show the same global structural response





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STIEP



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Education Program (STIEP)

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North Carolina State University



NC STATE UNIVERSITY

- **Prof. Adriaan Beukers, Dr. Sotiris Koussios,**
Delft University of Technology





Questions?



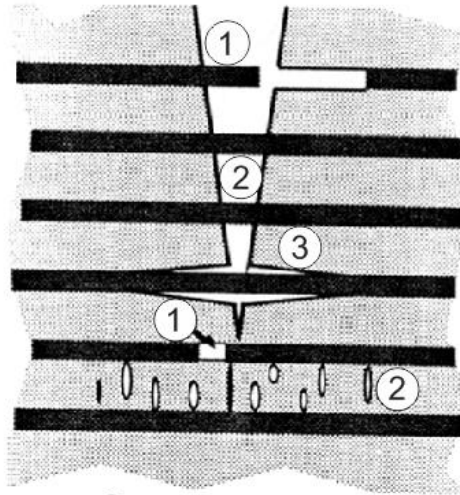


Next slides are for possible questions

Failure Modes of a Composite Bonded Joints

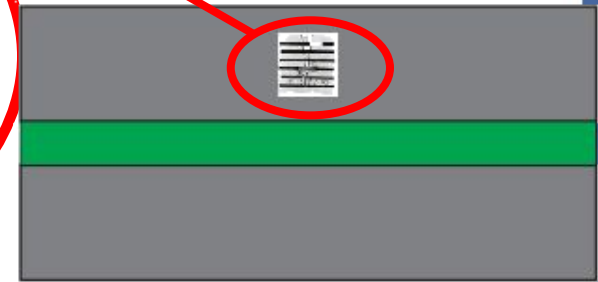
Nomenclature: Debonding mechanisms

- Cohesive Failure, i.e. failure within the adhesive layer



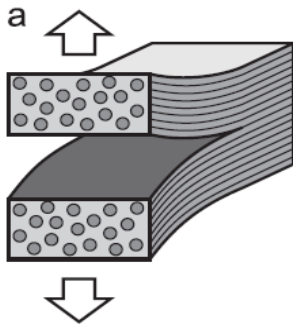
- ① Fibers damage
- ② Matrix damage
- ③ Delamination

- Structural Failure

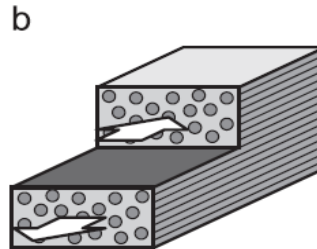


Debonding mechanisms can be classified in the “classic” delamination modes:

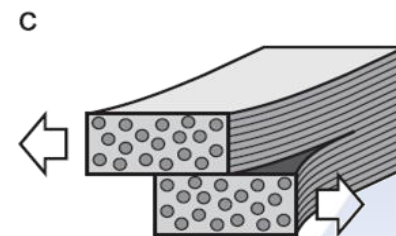
- Crack opening, Mode-I



- In plane shear, Mode-II

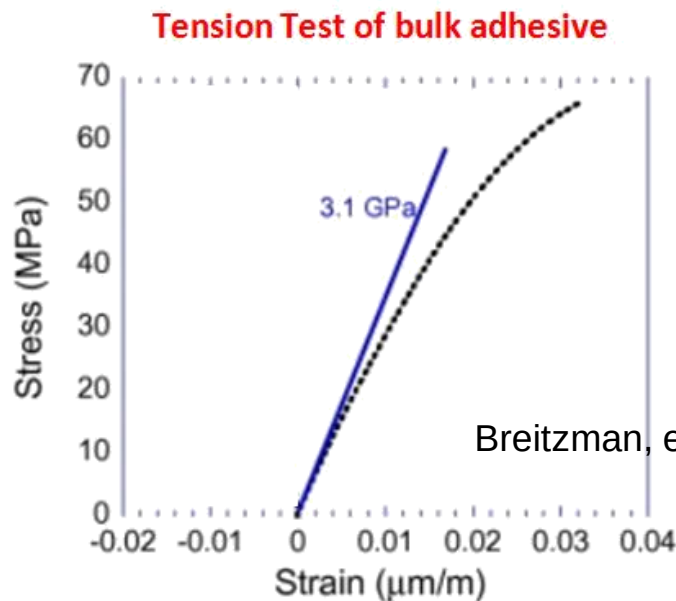


- Tearing, Mode-III

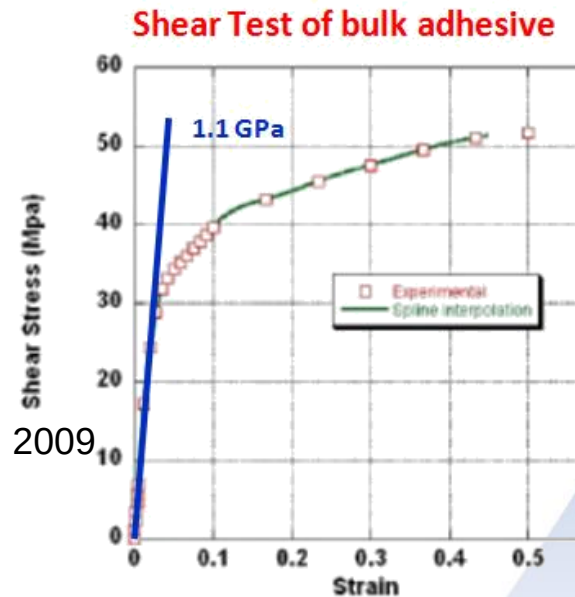


- Mode-II and Mode-III are usually assumed to have the same mechanical response;

- In order to model the damage within the adhesive layer:
- Cohesive elements have a finite thickness;
 - Penalty stiffnesses are not “infinite” but represent the elastic moduli of the material; in addition, penalty stiffnesses for mode-I and mode-II are different.

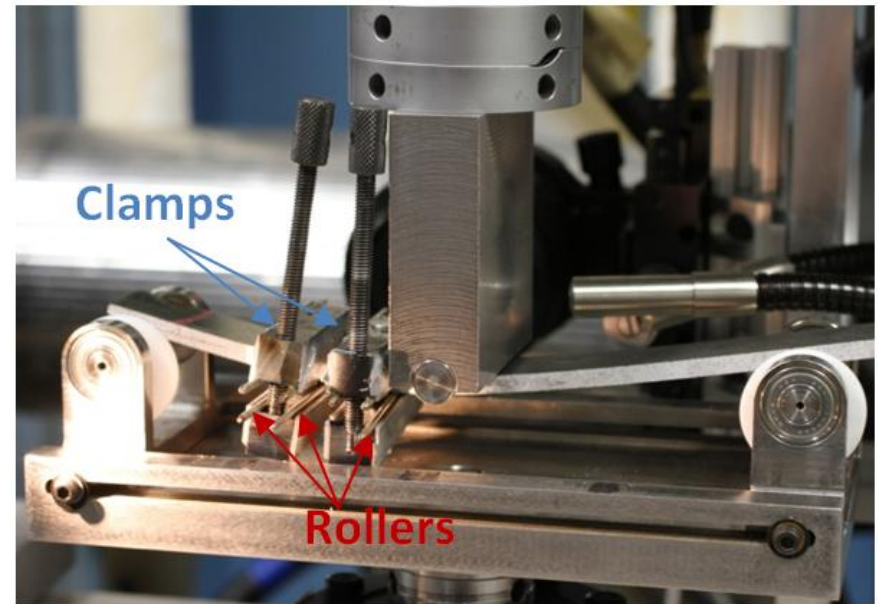
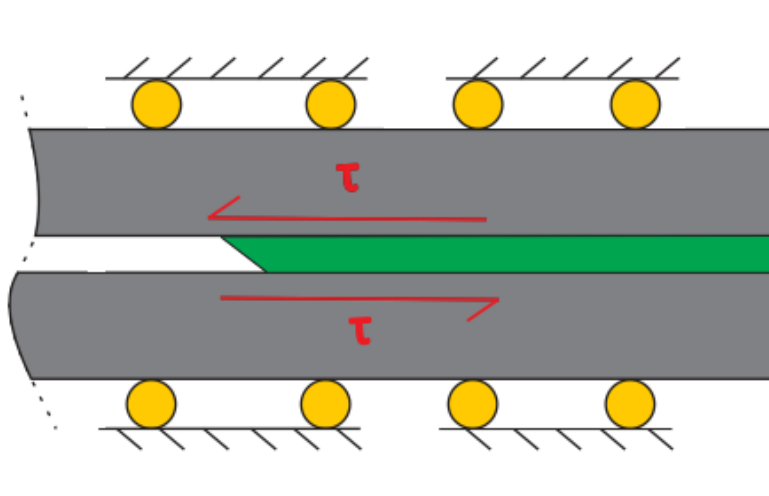


Breitzman, et al. 2009

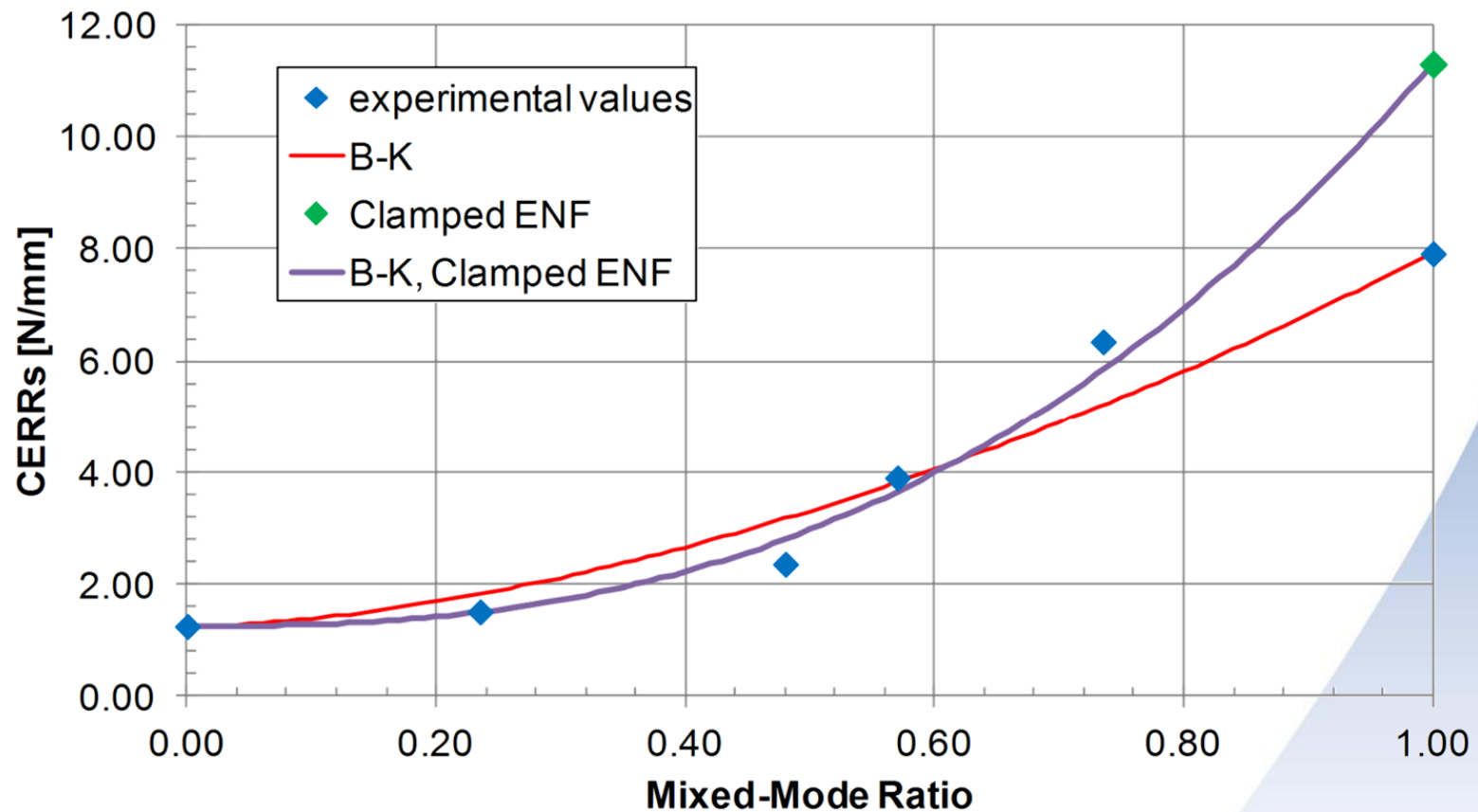


ENF Test with Constrained Mode-I Opening

- ENF specimen tested with constrained peel-opening;
- Constraints given by two clamps, each “touching” the specimen in four points near the crack tip without applying compression forces.



- With the new mode-II ERR the B-K criterion fits better the mixed-mode measurements;



- The ENF test with peel opening constraint gave $G_{IIC} \approx 11.3 \text{ N/mm}$

