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Prediction of adhesion failure of bonded joints using 3-point bending test and stress-energy coupled criterion

Presented by : Thiago Birro^{1,2}

Thiago.vasconcellos-birro@isae-superaero.fr

Co-authors: Frederic LACHAUD¹, Maëlen AUFRAY², Eric PAROISSIEN¹

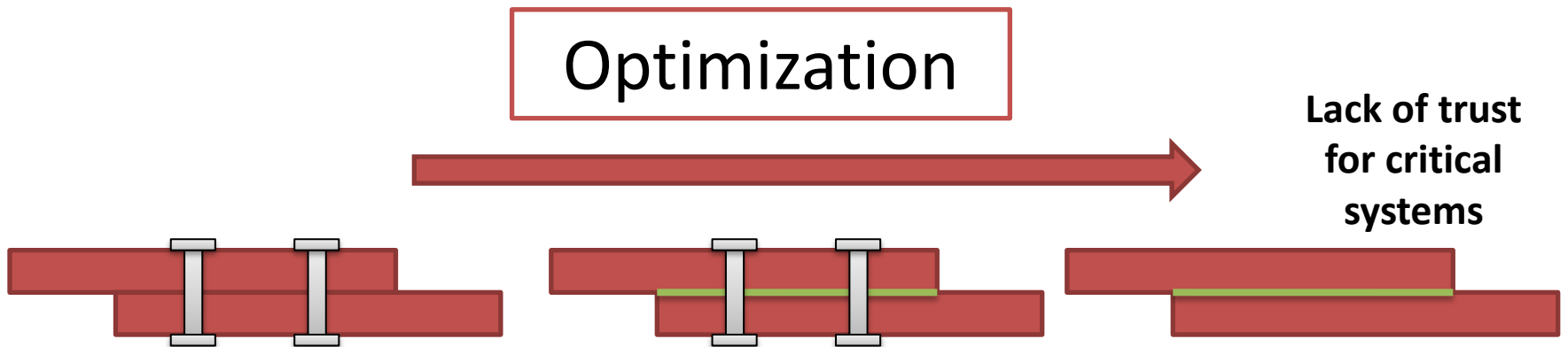
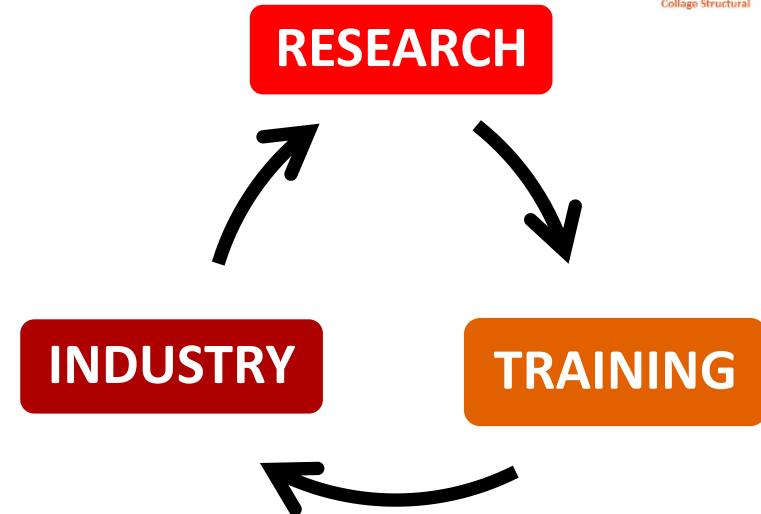
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²CIRIMAT, Université de Toulouse, CNRS, INPT, UPS, 4, allée Émile Monso -BP 44362, 31030 Toulouse Cedex 4, France.

- 1. Context**
- 2. Numerical approach**
 - **Coupled Criterion**
 - **Macro-Element**
 - **Validation**
 - **Dialogue experiment - simulation**
- 3. First Results**
- 4. Conclusion and perspectives**

Context

- TACCOS: *Toulouse Adhesion, Cohesion, Structural, Adhesive Bonding*
 - Collaboration between two institutions
 - “Adherence” at CIRIMAT and “Assembly” at ICA
 - Investigating the questions arisen from the structural adhesive bonding, basing on Chemistry and Mechanics



Mechanics of Adhesion

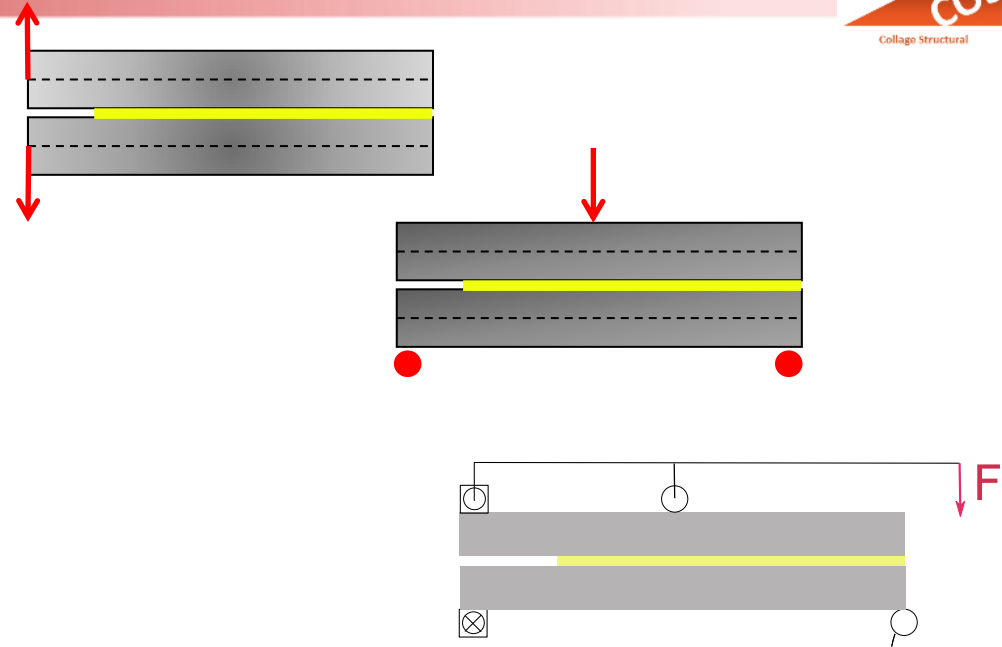
Fracture Test

Propagation

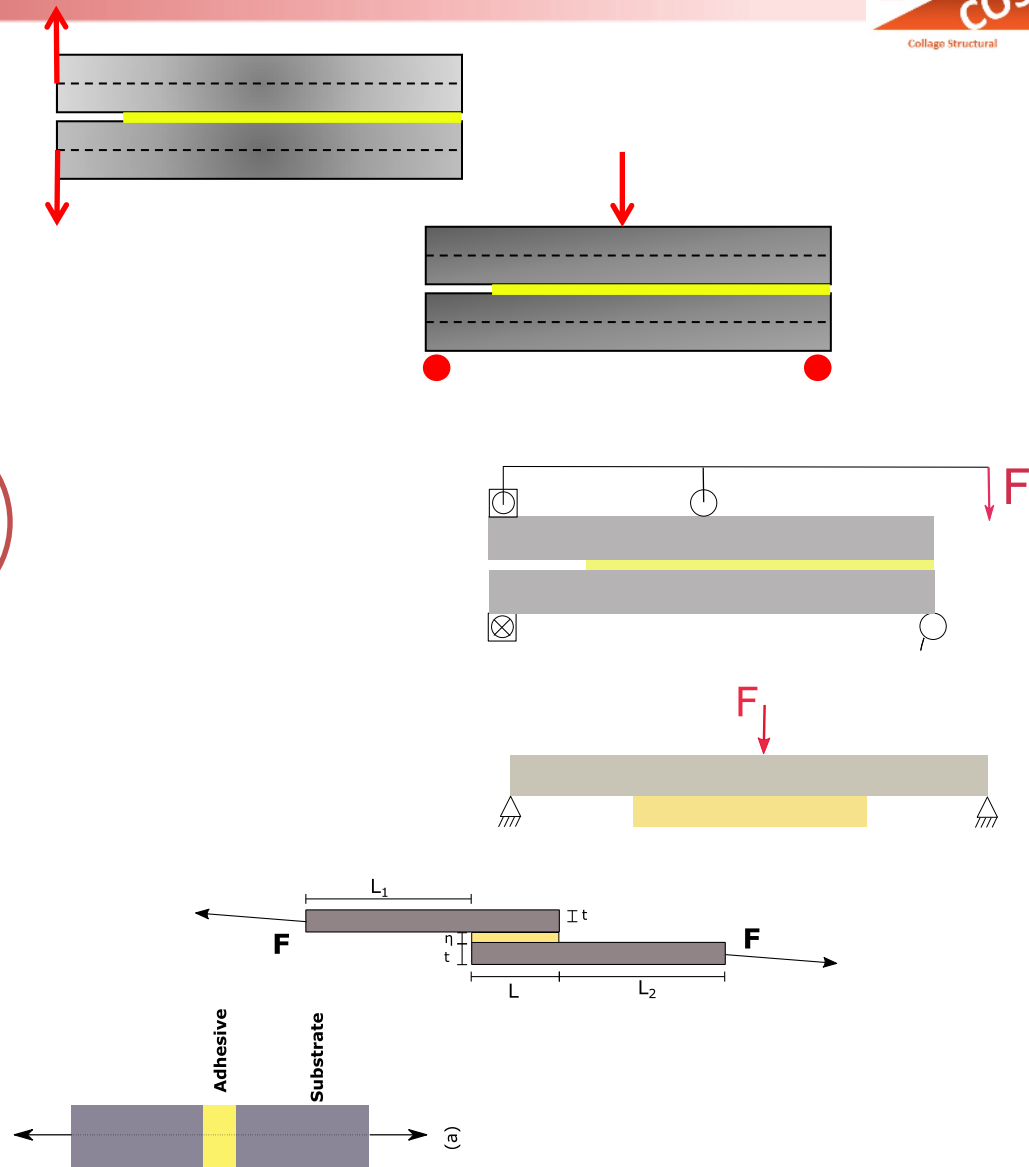
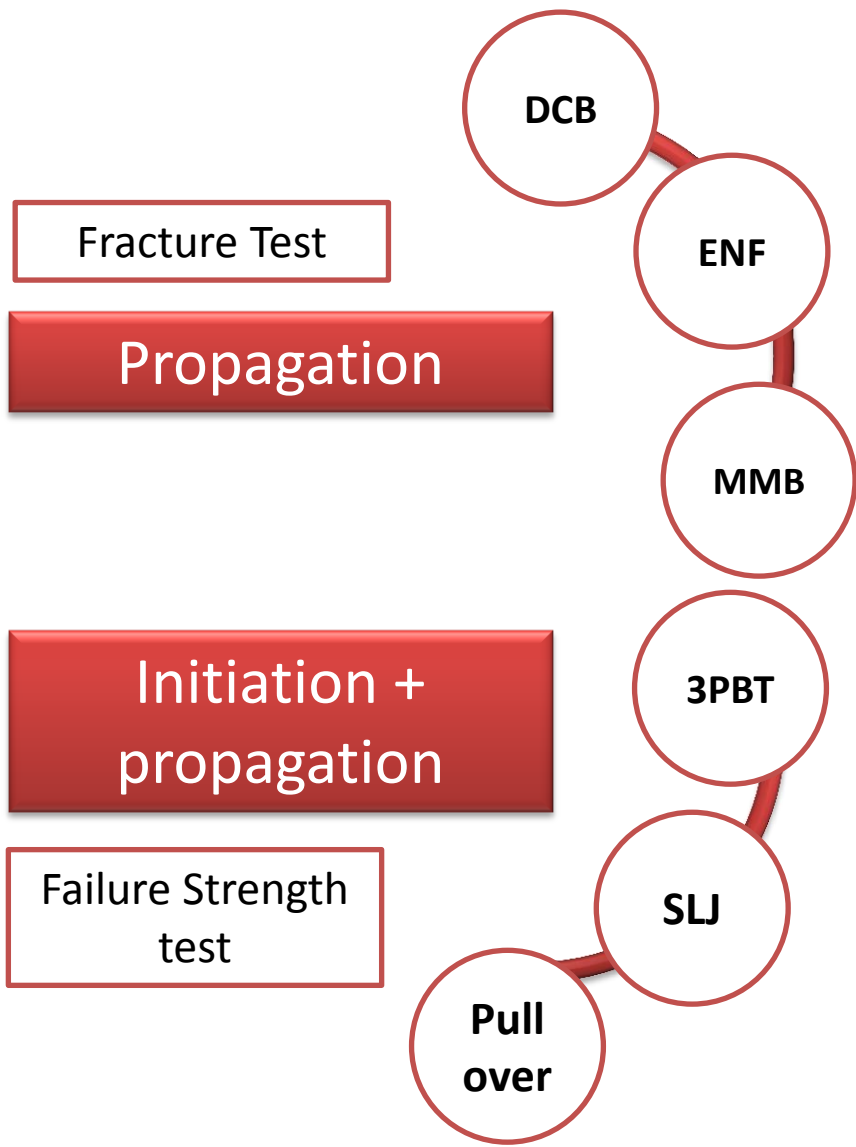
DCB

ENF

MMB



Mechanics of Adhesion



Mechanics of Adhesion

- ✓ Failure strength test:
 - ❑ Goal: Characterize adhesive failure
 - ❑ Provide initiation and also propagation

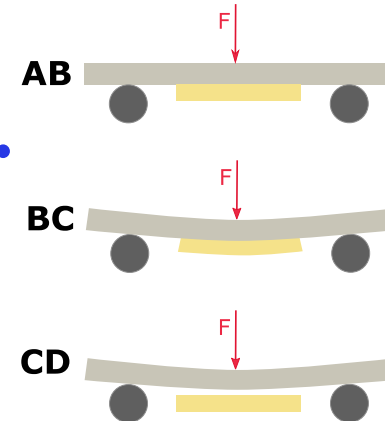
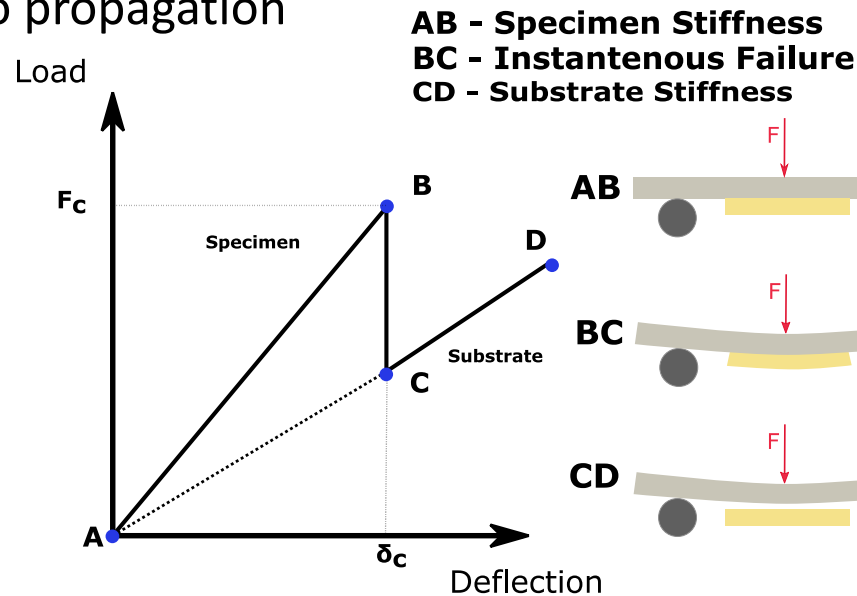
Cohesive failure within substrate



Cohesive failure within adhesive



Adhesive Failure



Mechanics of Adhesion

- ✓ Failure strength test:
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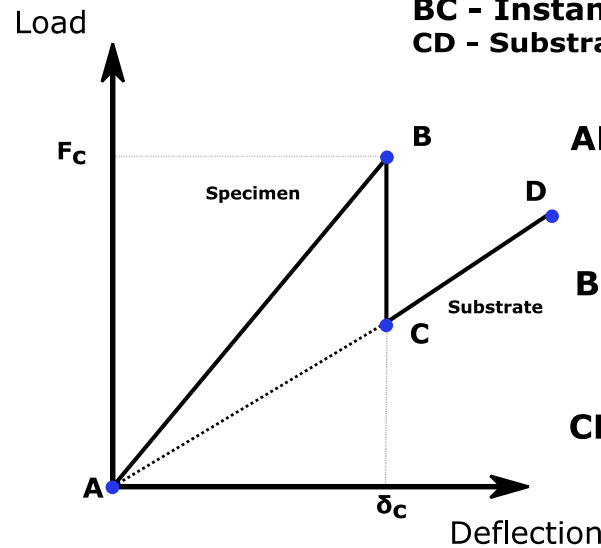
Cohesive failure within substrate



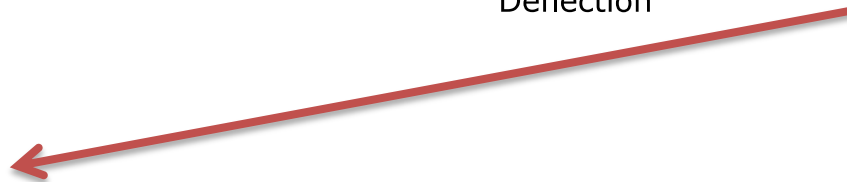
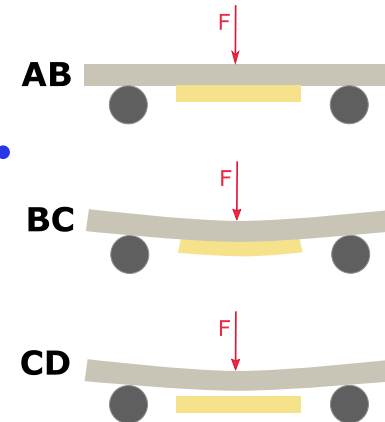
Cohesive failure within adhesive



Adhesive Failure



AB - Specimen Stiffness
BC - Instantaneous Failure
CD - Substrate Stiffness



Mechanics of Adhesion

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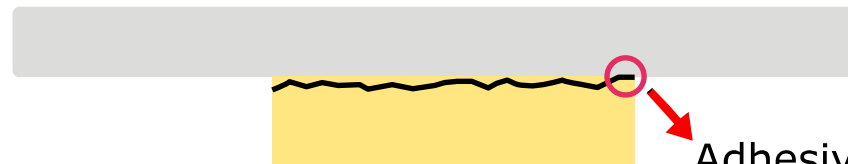
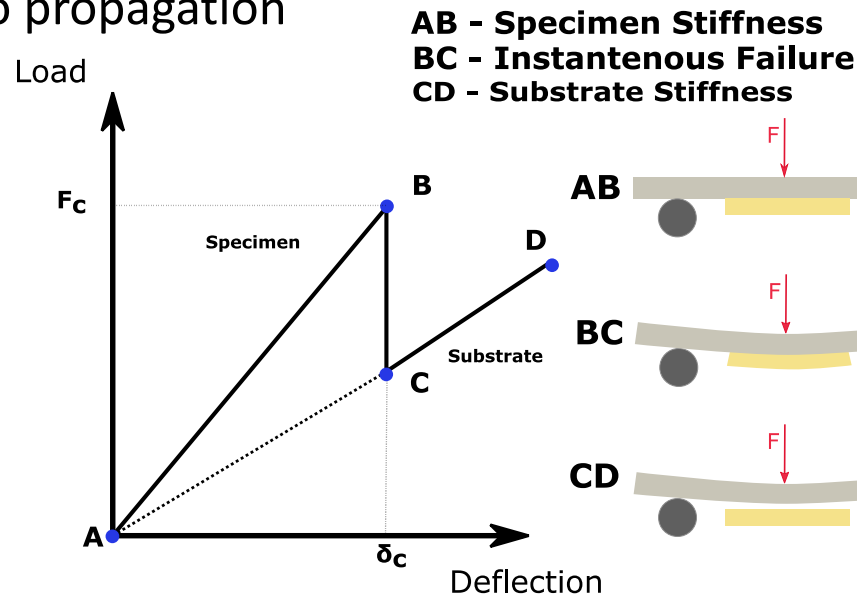
Cohesive failure within substrate



Cohesive failure within adhesive

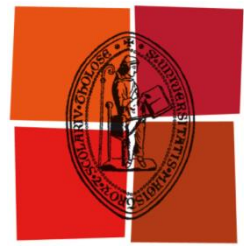


Adhesive Failure



Adhesive initiation

Propagation: adhesive or cohesive



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de Toulouse

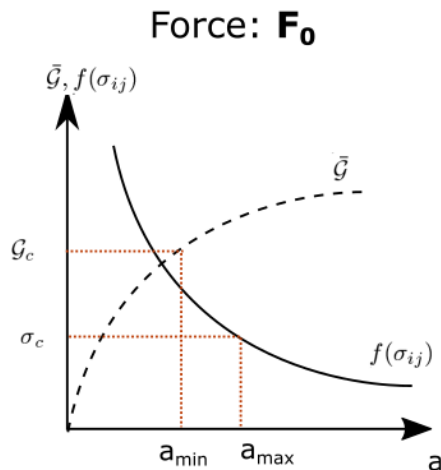
Numerical approach

Coupled Criterion

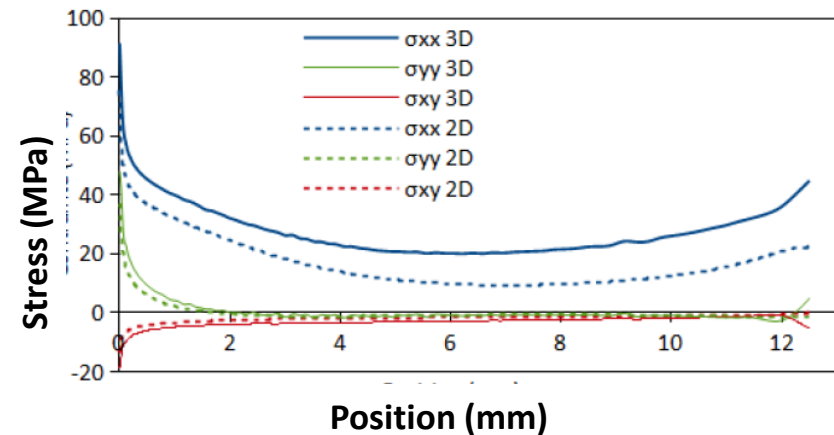
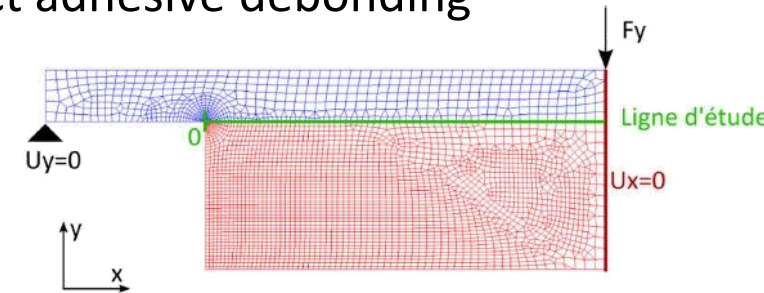
- ✓ New proposition: Coupled Criterion approach – **Leguillon (2002)**:
 - Energy and strength criteria
 - Only the strength criterion is unable to predict adhesive debonding
 - High stress concentration

Optimization problem **Weißgraeber (2013)**:

$$F_f = \min_{F,a} \{ F \mid f(\sigma_{ij}(x_i)) \geq \sigma_c \quad \forall x_i \in \Omega_c \quad \wedge \quad \bar{\mathcal{G}}(A = \Delta A) \geq \mathcal{G}_c \}$$



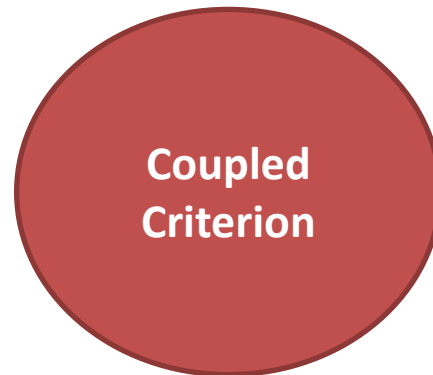
Lowest load satisfying both criteria ($a_{\min} = a_{\max}$)



Sauvage (2017)

State of the Art – Coupled Criterion

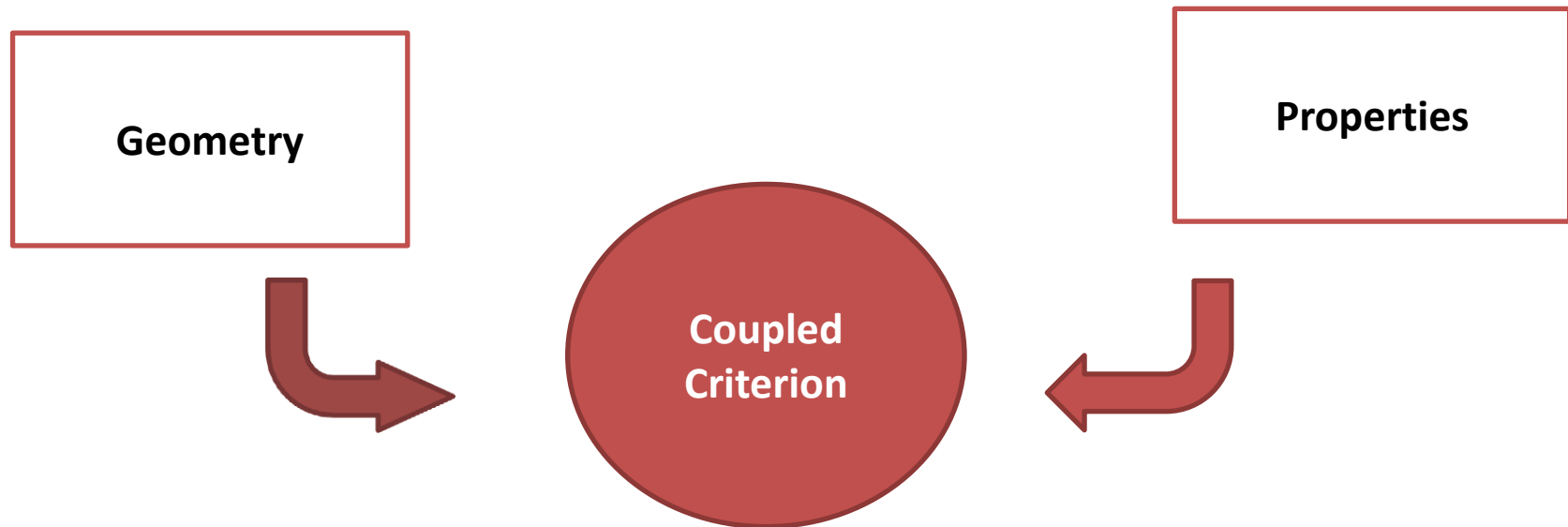
- A code was implemented on Matlab 



This algorithm can be coupled with different numerical methods for stress and energy determination

State of the Art – Coupled Criterion

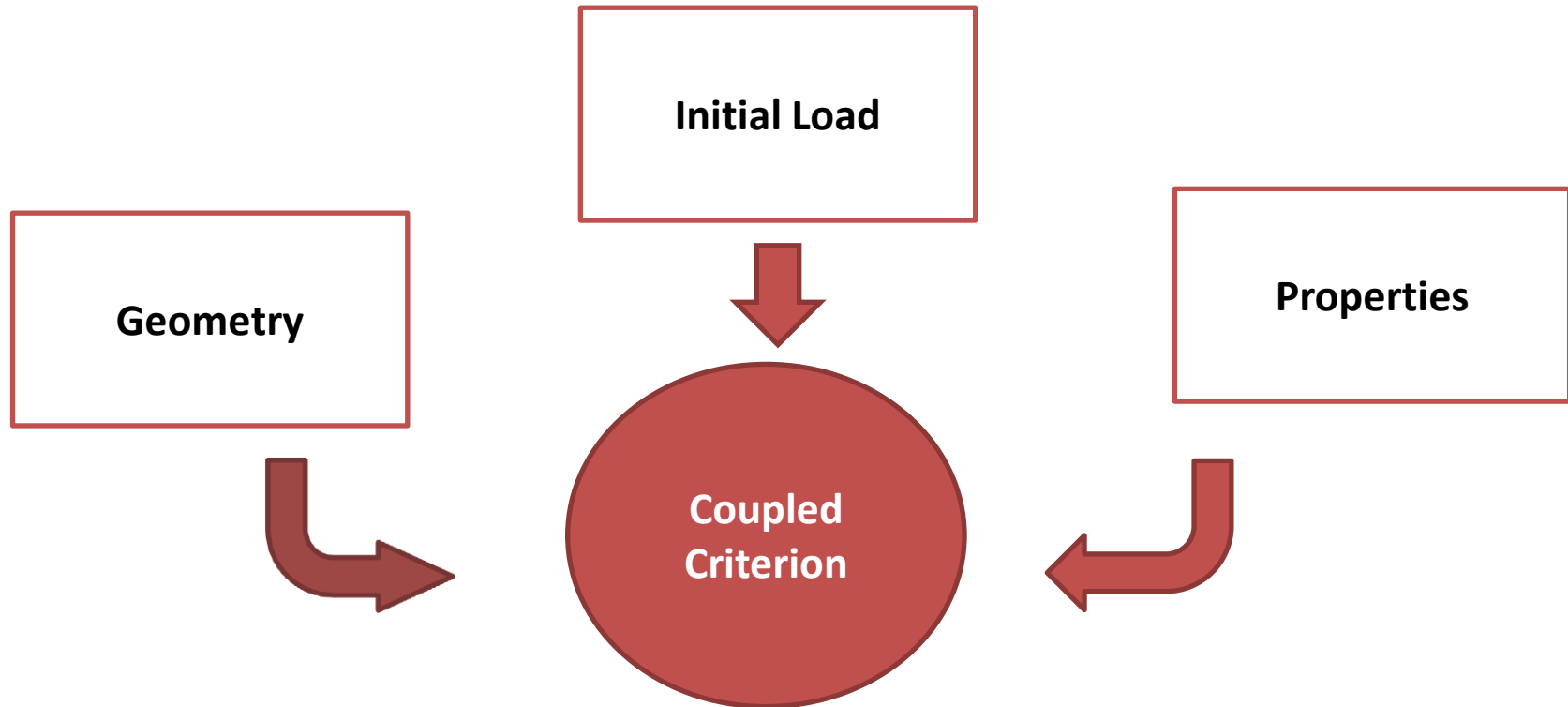
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State of the Art – Coupled Criterion

Critical stress

F_0

Energy release rate

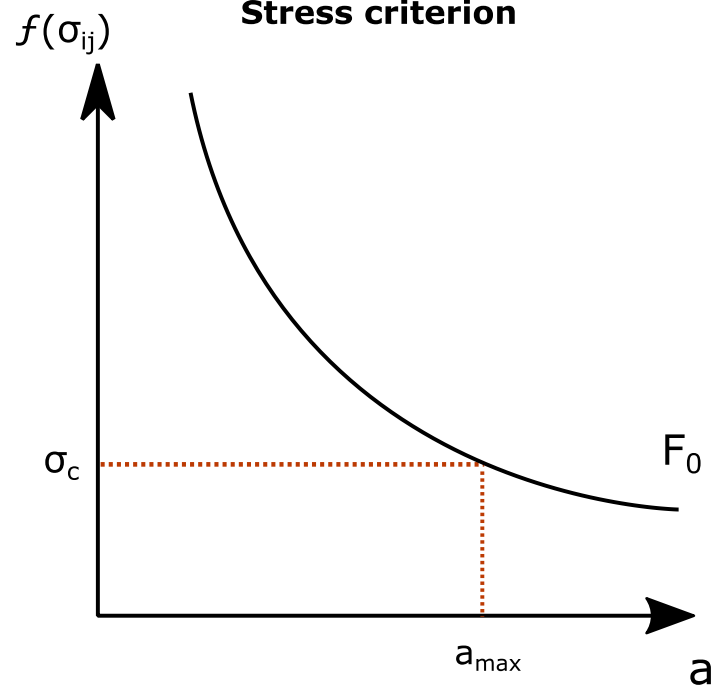
Normal assembly



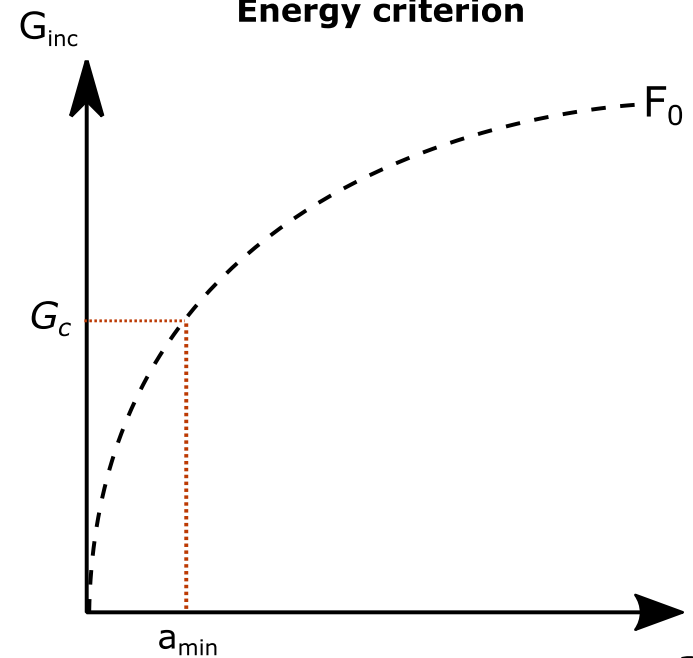
Pre-cracked assembly



Stress criterion



Energy criterion



State of the Art – Coupled Criterion

Critical stress

Normal assembly



F_0



F_1

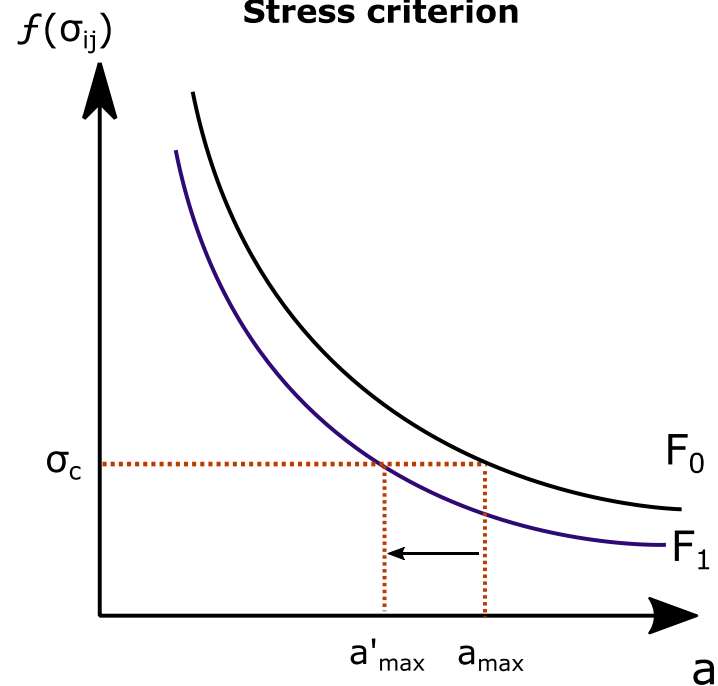
$$F_1 < F_0$$

Energy release rate

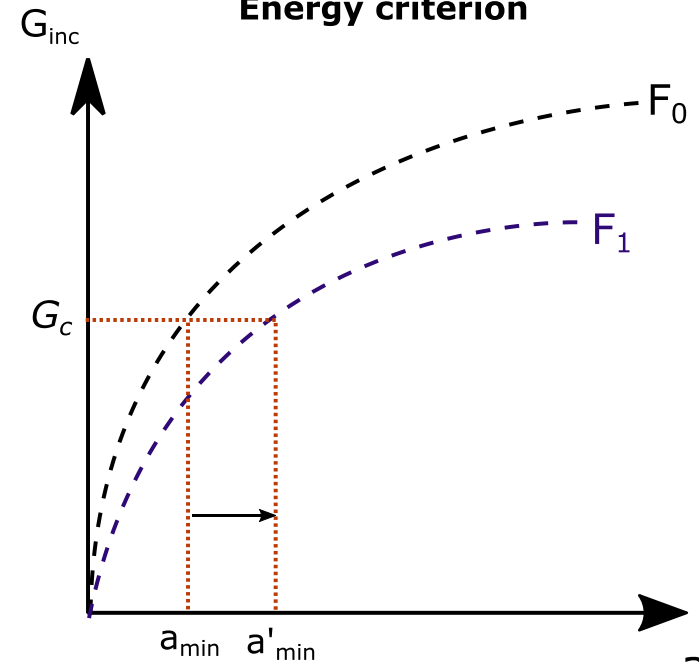
Pre-cracked assembly



Stress criterion

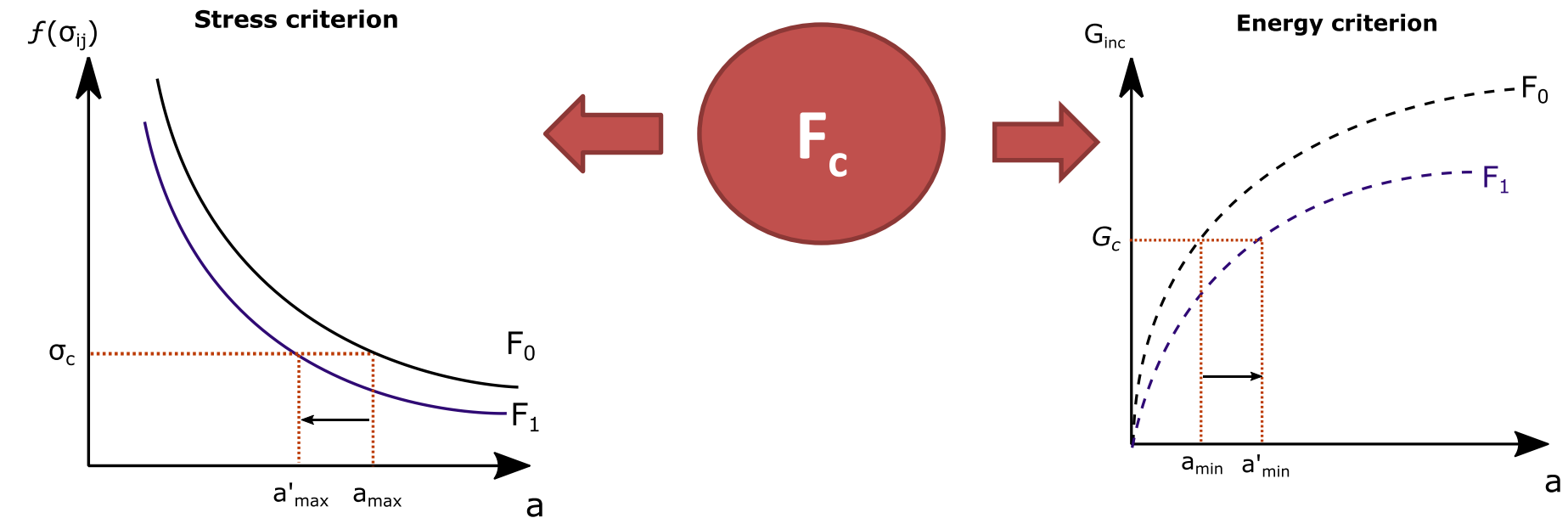


Energy criterion



State of the Art – Coupled Criterion

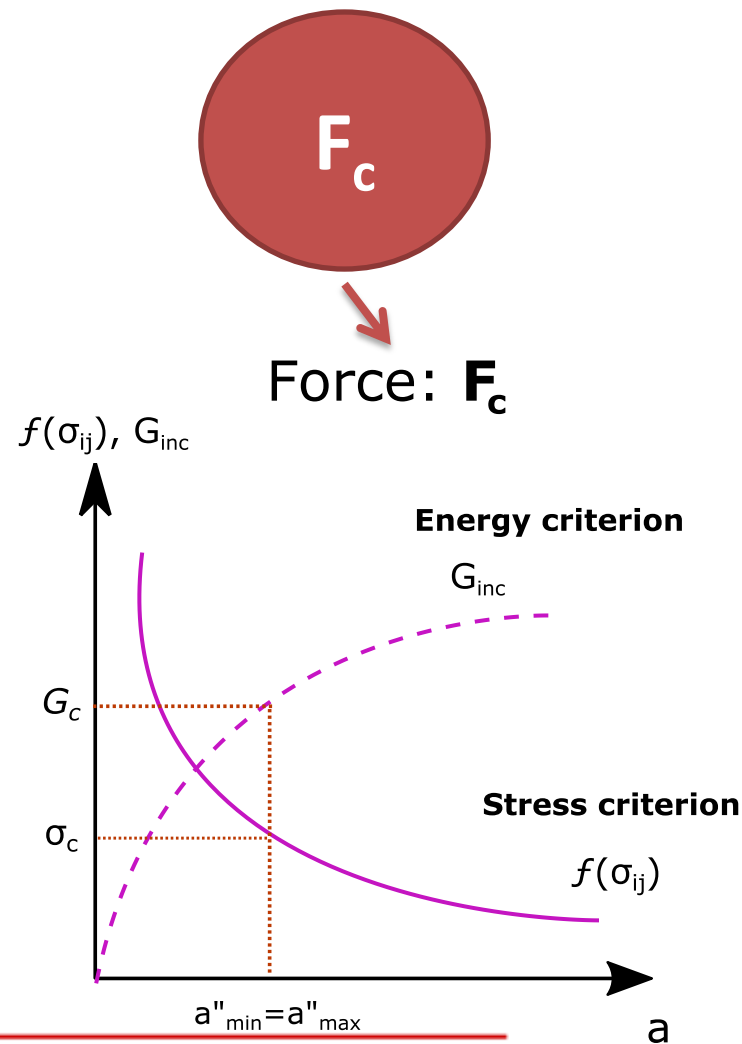
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$$F_f = \min_{F,a} \{ F \mid f(\sigma_{ij}(x_i)) \geq \sigma_c \quad \forall x_i \in \Omega_c \quad \wedge \quad \bar{\mathcal{G}}(A = \Delta A) \geq \mathcal{G}_c \}$$

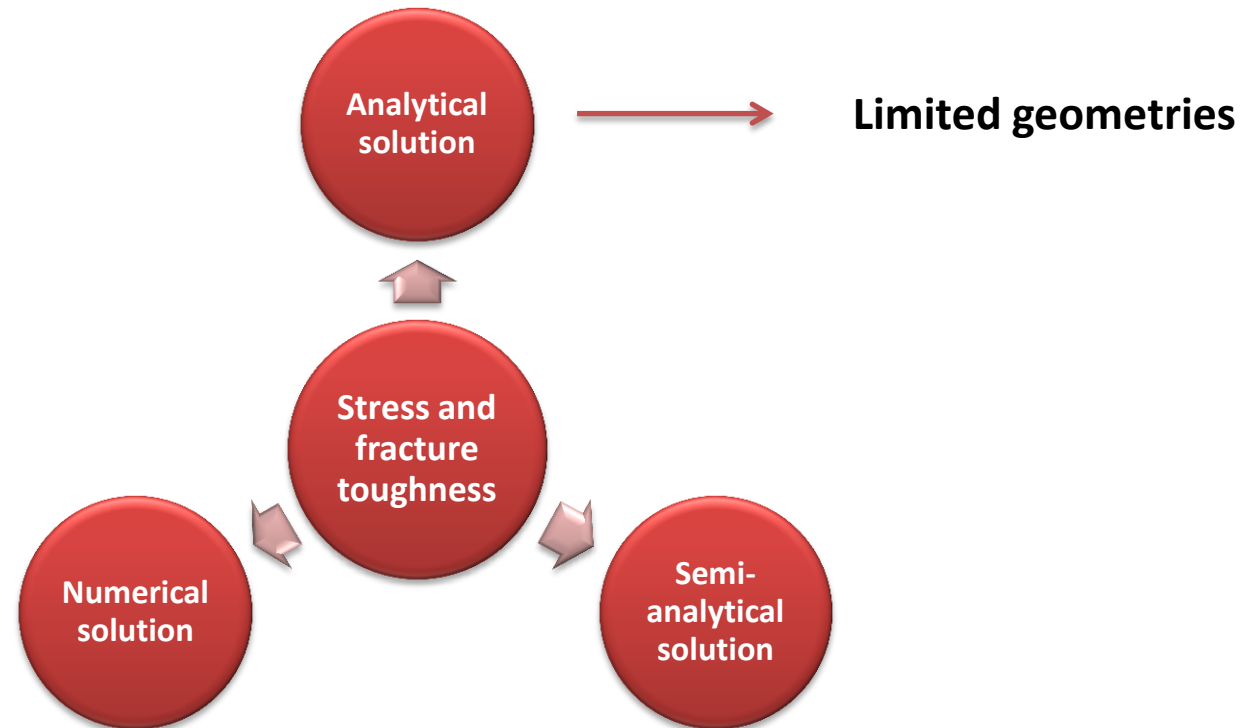
State of the Art – Coupled Criterion

- Main goal: Find the minimal load for satisfying both criteria :



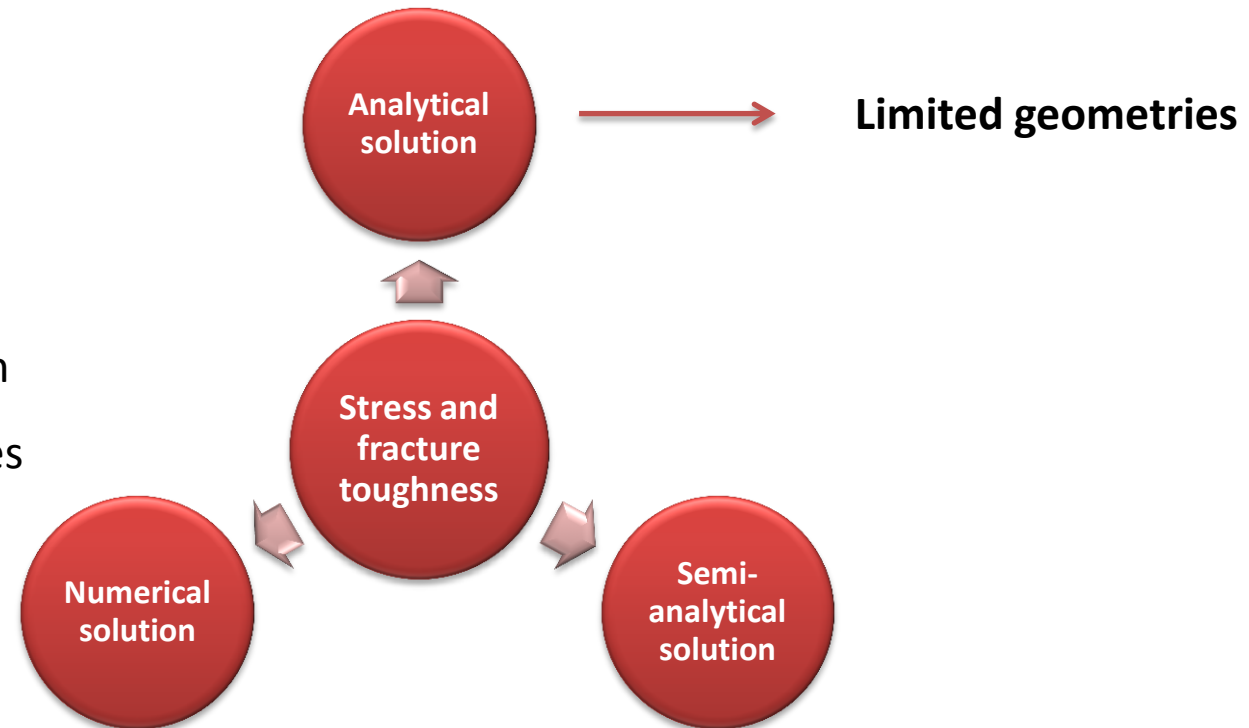
Coupled Criterion

- ✓ For stress and fracture toughness determination:



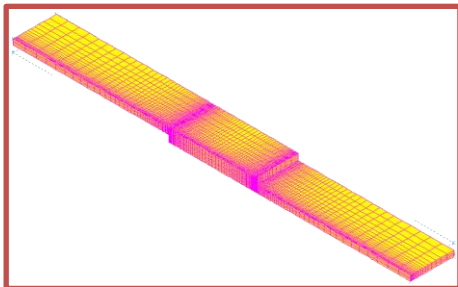
Coupled Criterion Implementation

✓ For stress and fracture toughness determination:



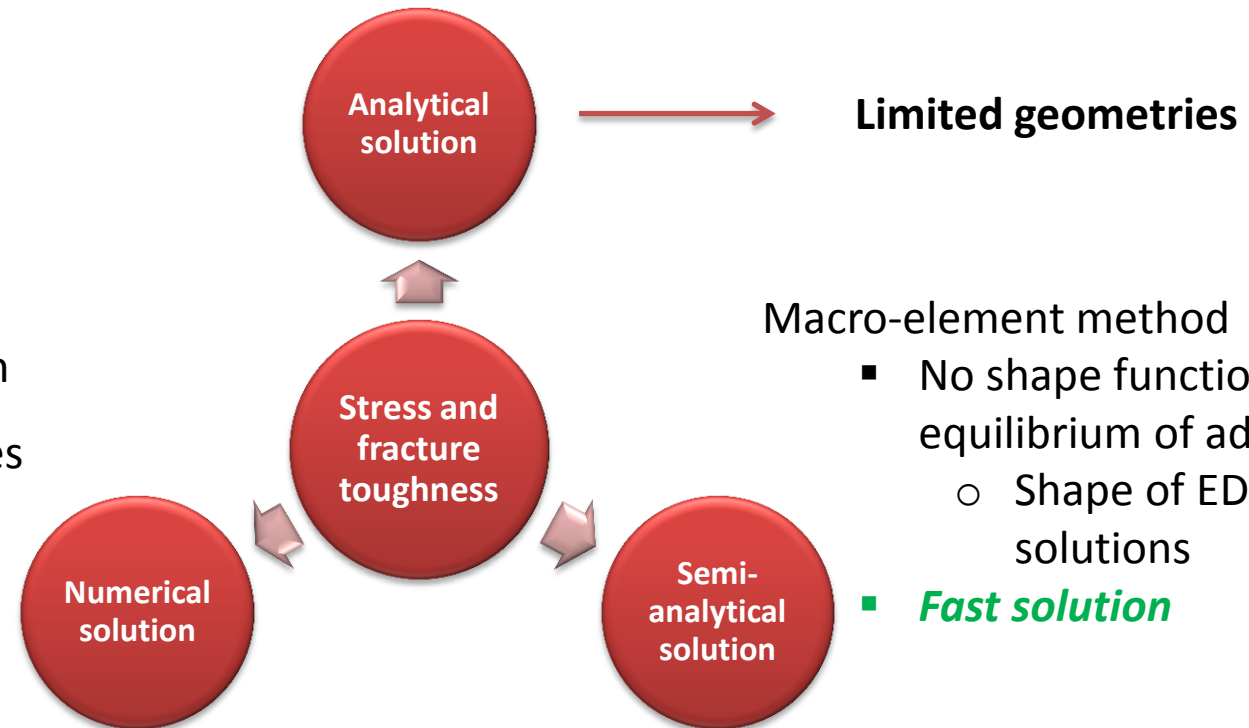
Finite element method

- Use shape function
- Include singularities
- ***Time consuming***



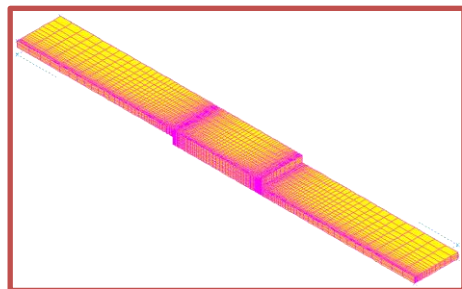
Coupled Criterion Implementation

✓ For stress and fracture toughness determination:



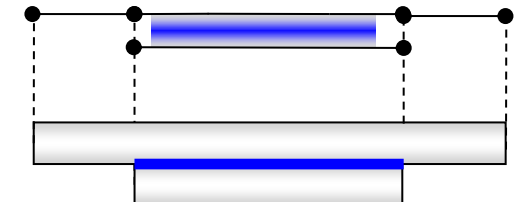
Finite element method

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- ***Time consuming***



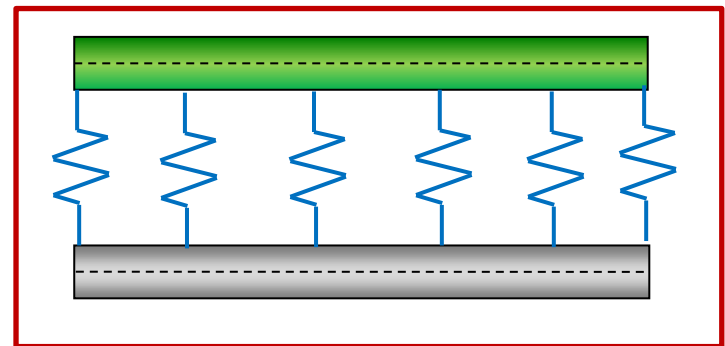
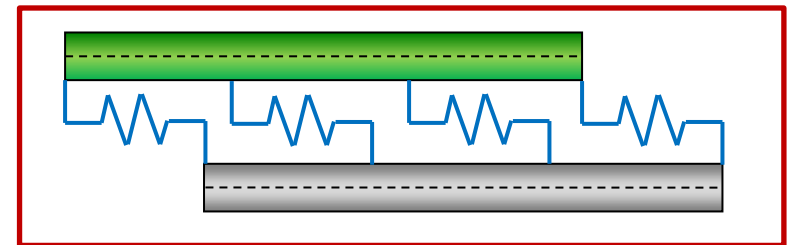
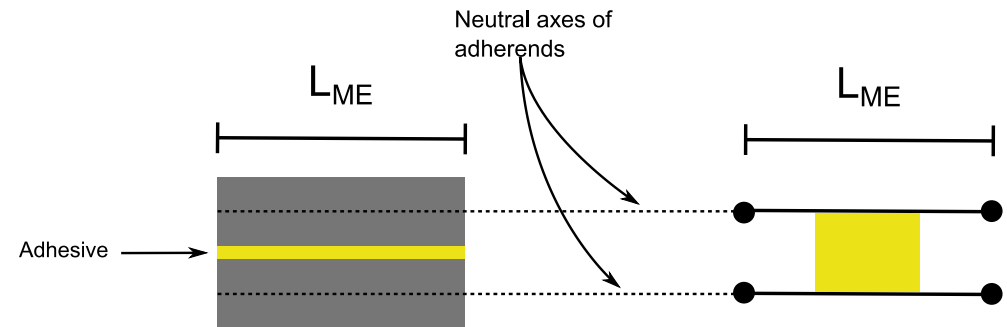
Macro-element method

- No shape function: Local equilibrium of adherents
 - Shape of EDO solutions
- ***Fast solution***



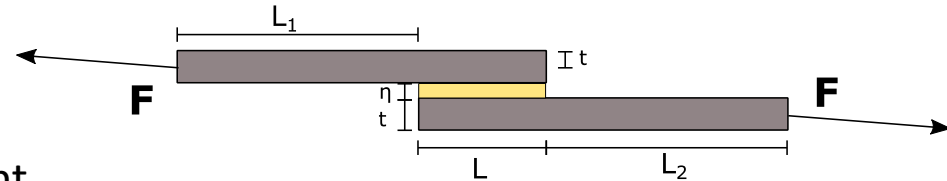
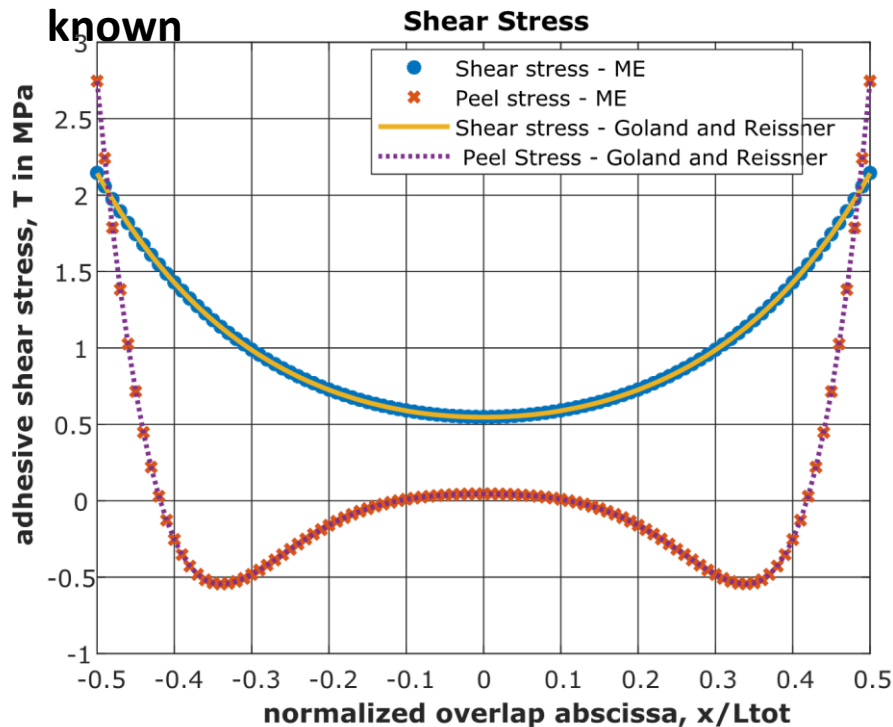
Macro-Element

- Macro-element analysis **Paroissien (2006)**:
 - Simplified approach for the stress analysis of bonded or hybrid (bolted/bonded) joints
 - No shape function: Force and displacement determined using local equilibrium
 - Bed of shear and peel springs
 - 1D Bar or 1D beam models



Macro-Element

- Validation of the new implementation:
Inspired by the work of [Wei graeber et al. \(2013\)](#)
- Algorithm was tested using a single lap joint configuration: **Analytical solution well known**



Strength criterion

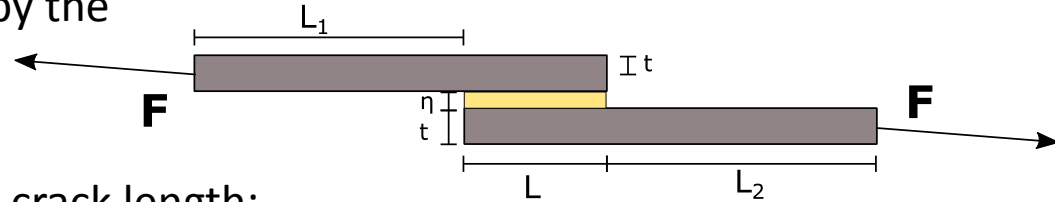
$$f(\sigma_{ij}) = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2} \geq \sigma_c$$

Energy criterion

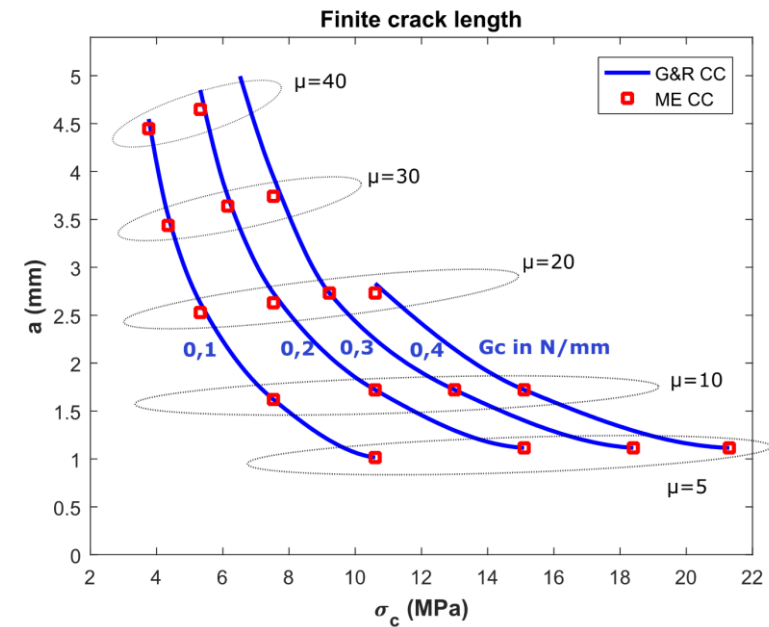
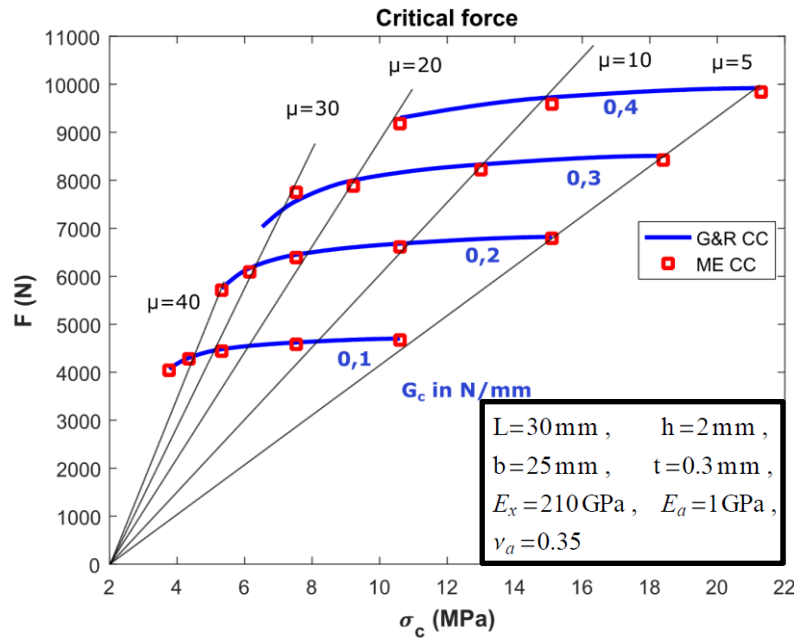
$$G_{inc} = \frac{1}{a} \int_0^a \frac{1}{2} \frac{\tau^2(\tilde{a})}{K_{II}} + \frac{1}{2} \frac{\sigma^2(\tilde{a})}{K_I} d\tilde{a} \geq G_c$$

Coupled Criterion Implementation

Validation of coupled criterion: Inspired by the work of [Weißgraeber et al. \(2013\)](#)



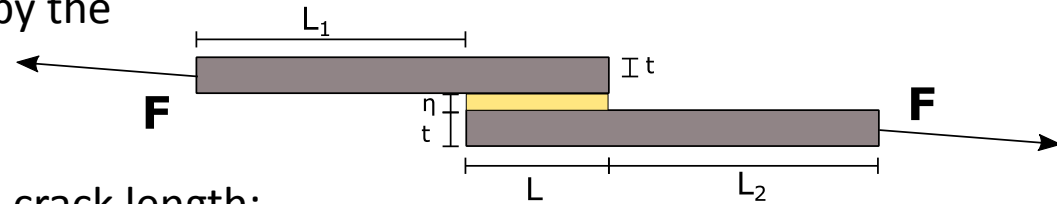
Effect of critical stress on failure load and crack length:



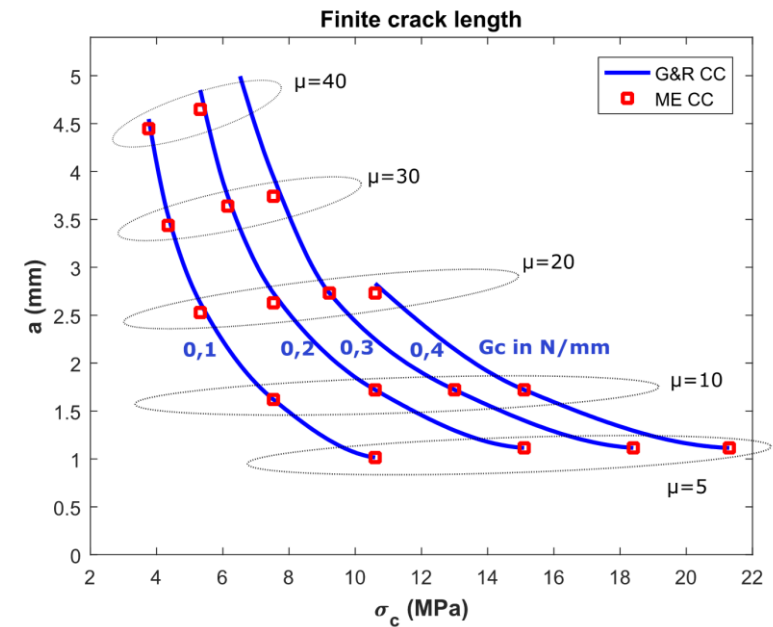
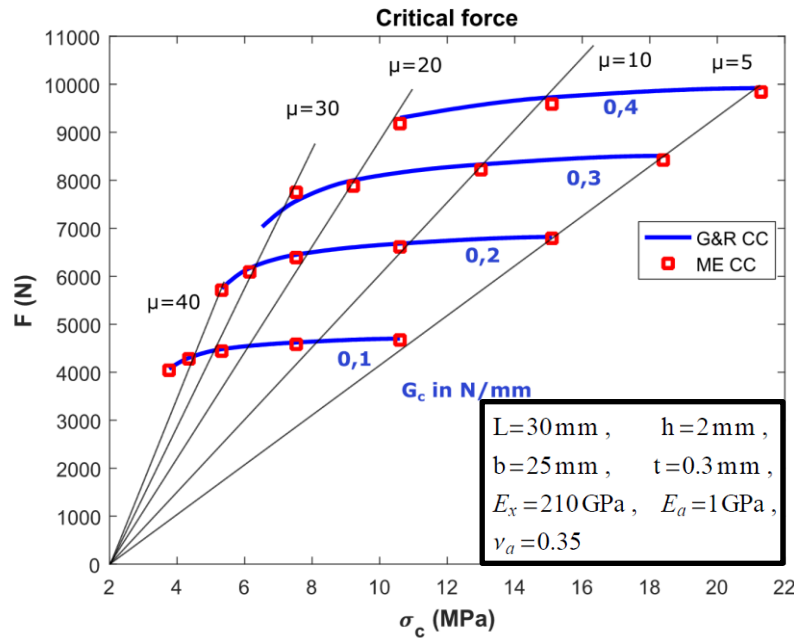
Fzero function -> bisection, secant, and inverse quadratic interpolation methods

Coupled Criterion Implementation

Validation of coupled criterion: Inspired by the work of [Weißgraeber et al. \(2013\)](#)



Effect of critical stress on failure load and crack length:



Brittleness number:

$$\mu = \frac{2K_I G_c}{\sigma_c^2}$$



Better results for low brittleness numbers – brittle adhesives

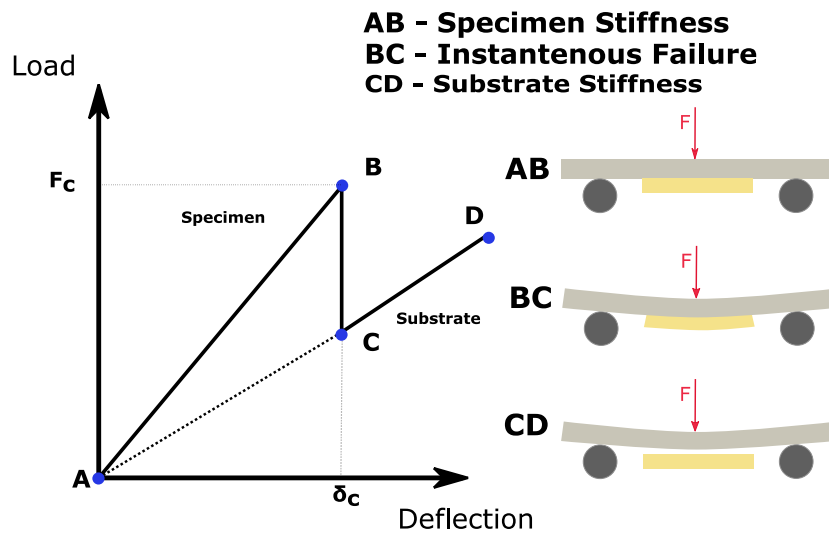
Dialogue experiment - simulation

- Application of CC for the 3 point bending test:
 - A direct scheme can be performed to determine the properties of interphase:

Dialogue experiment - simulation

- Application of CC for the 3 point bending test:
 - A direct scheme can be performed to determine the properties of interphase:

Macro scale

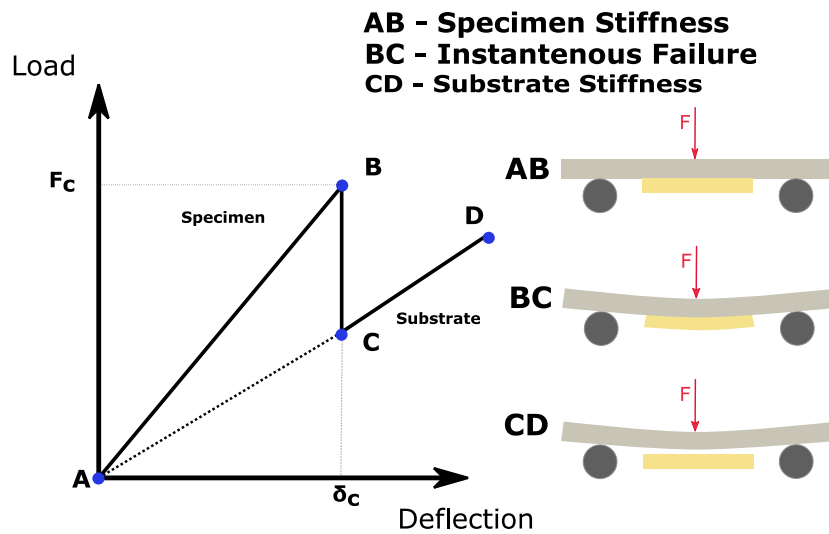


F_c and δ_c

Dialogue experiment - simulation

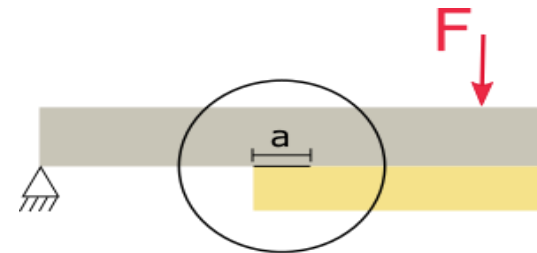
- Application of CC for the 3 point bending test:
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Macro scale



F_c and δ_c

Micro scale



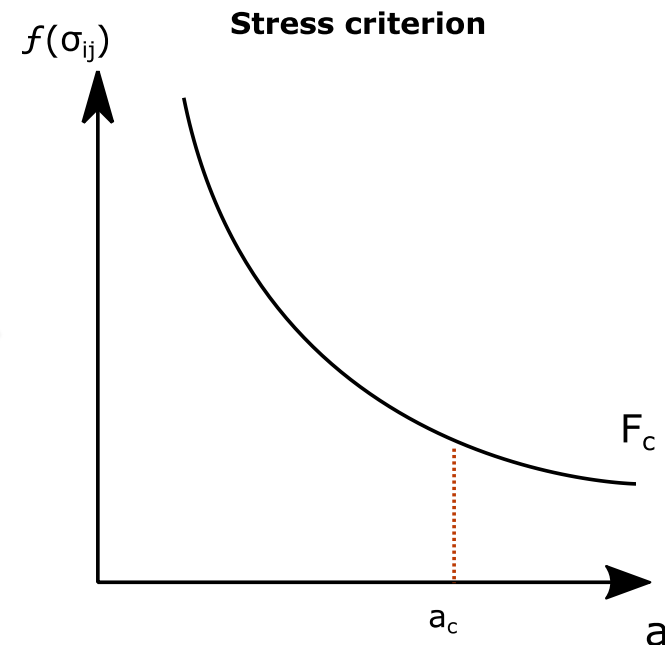
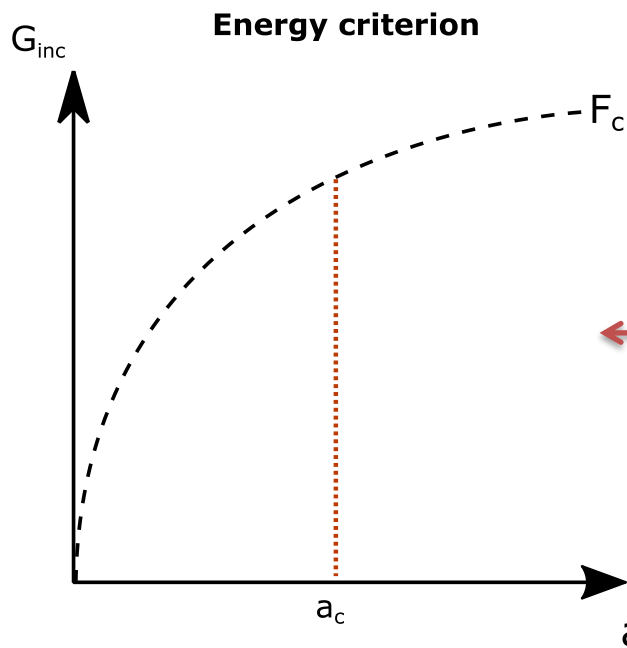
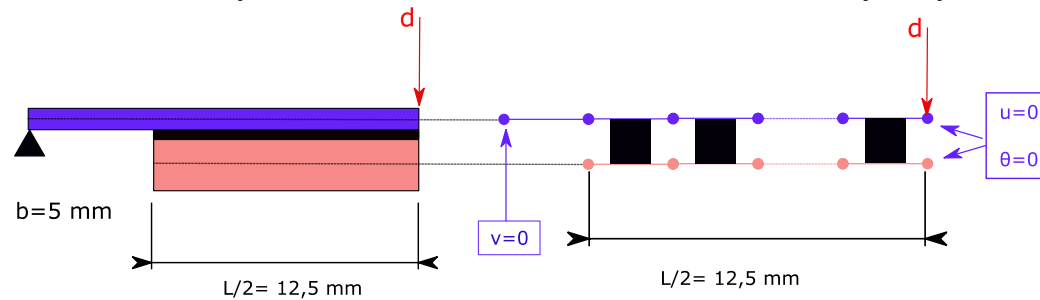
Post-Mortem analysis:



a_c

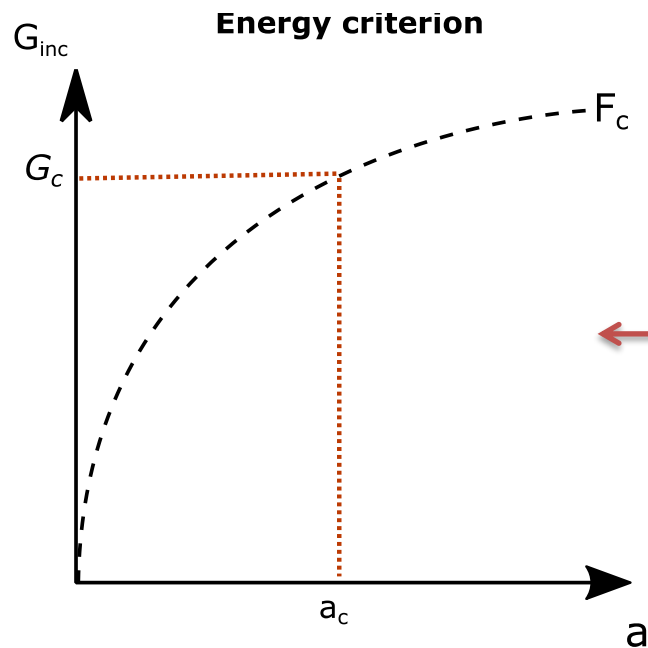
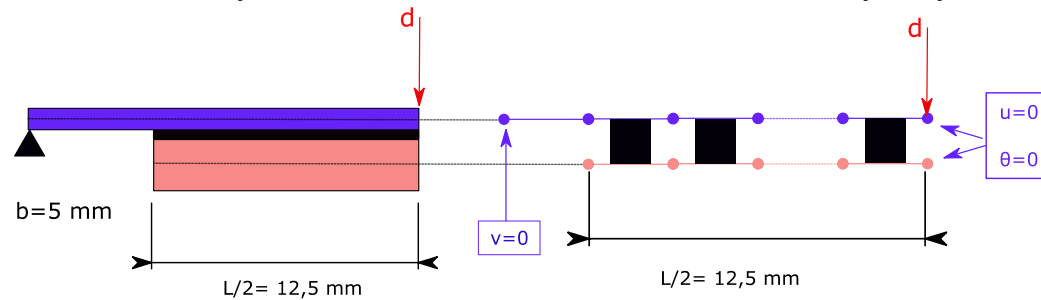
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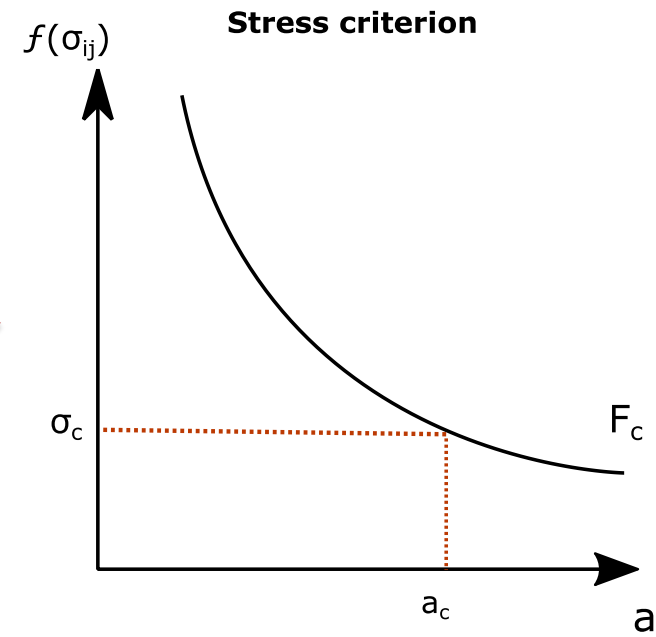


Dialogue experiment - simulation

- Application of CC for the 3 point bending test:
 - A direct scheme can be performed to determine the properties of interphase:



$F_c \text{ et } a_c$



First Results

- First results -> using inputs of **Sauvage (2017)**
 - Evaluation for different thickness of substrate

	F_c (N)	$a_c / 2$ (mm)
$e_{\text{subst}} = 1,0$ mm	86,0	0,055
$e_{\text{subst}} = 1,6$ mm	126,6	0,0559

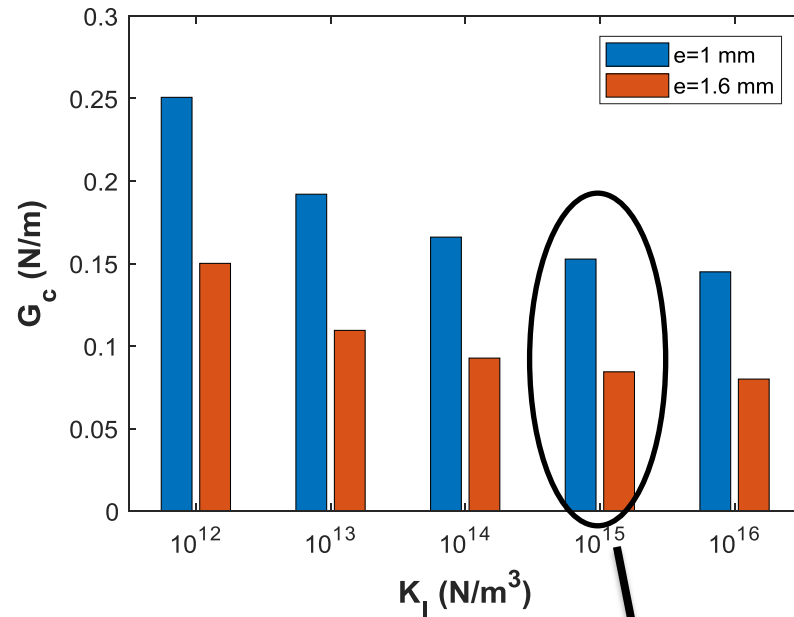
Substrate: **Al 2024- T3**
 Adhesive: **DGEBA/DETA**
 Surface treatment:
**Acetone degreasing+ HCl
 etching + Silane**



First Results

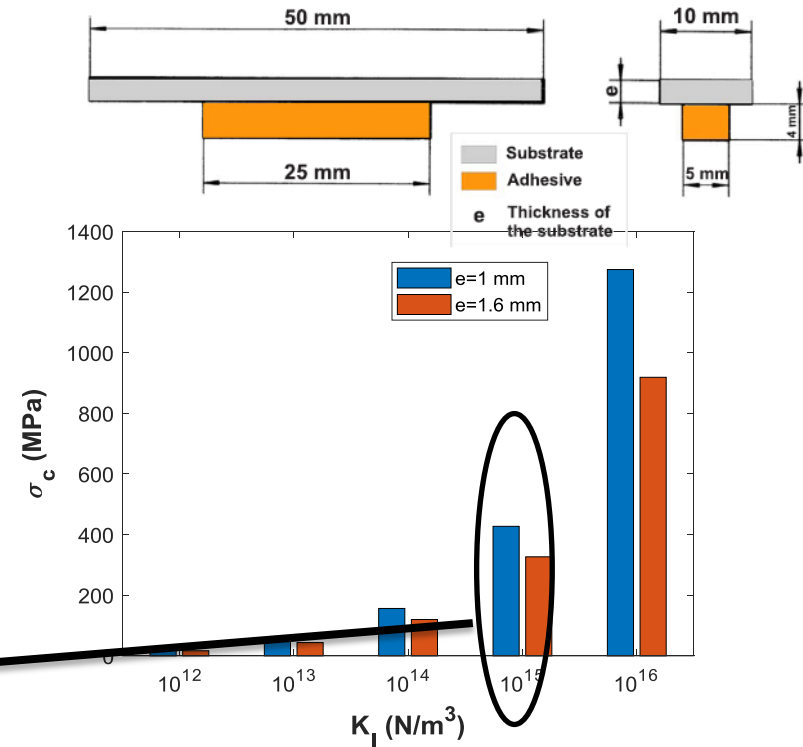
- First results -> using inputs of **Sauvage (2017)**
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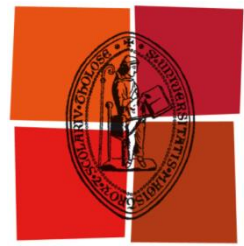
Substrate: **Al 2024- T3**
 Adhesive: **DGEBA/DETA**
 Surface treatment:
**Acetone degreasing+ HCl
 etching + Silane**



Perfect bonding: **High stiffness**

Threshold value





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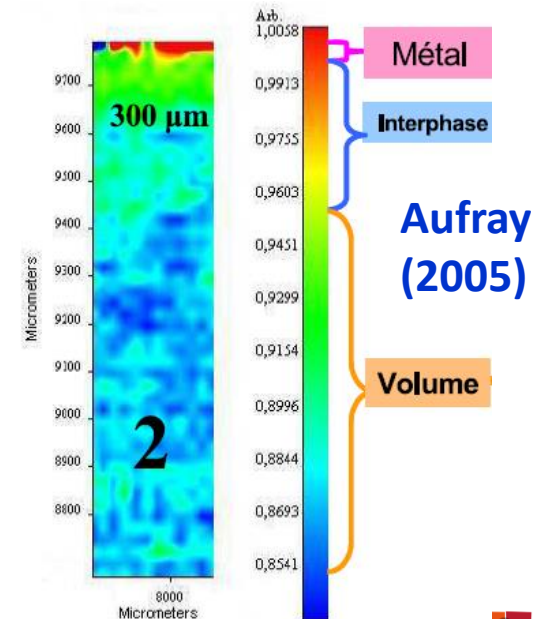
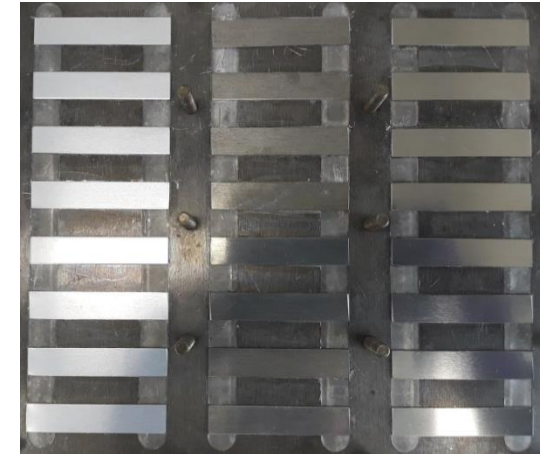
Conclusion and perspectives

Conclusion and perspectives

- ✓ Dispersions: they disallowed a complete equivalence of fracture toughness
- ✓ Fracture toughness of bulk polymer (DGEBA/DETA):

$$0,1 \text{ N/mm} \leq G_{Ic} \leq 0,333 \text{ N/mm}$$

- ✓ Find a simpler surface treatment to provide the initiation – **HOW?**
 - Nitric acid etching – Different duration and temperature
- Perspective:
 - ✓ Application for complex geometries
 - ✓ Include the mixed mode
 - ✓ Evaluation of residual stresses and the gradient of properties



Prediction of adhesion failure of bonded joints using 3-point bending test and stress-energy coupled criterion

Presented by : Thiago Birro^{1,2}

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¹Institut Clément Ader (ICA), Université de Toulouse, ISAE-SUPAERO, IMT MINES ALBI, UTIII, INSA, CNRS, 3 Rue Caroline Aigle, 31400 Toulouse, France.

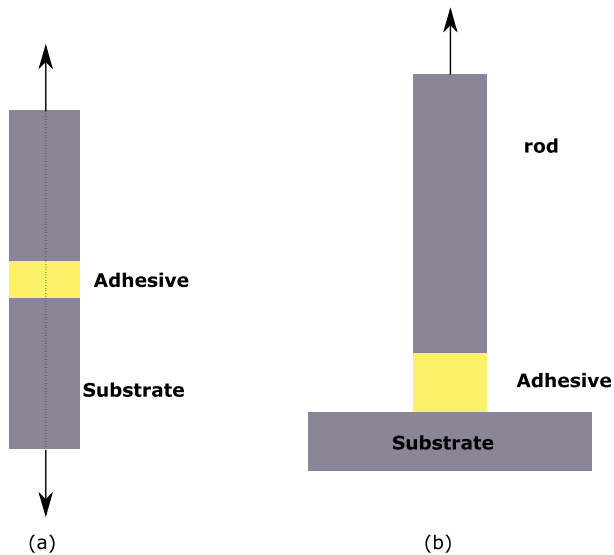
²CIRIMAT, Université de Toulouse, CNRS, INPT, UPS, 4, allée Émile Monso -BP 44362, 31030 Toulouse Cedex 4, France.

- Jean-Baptiste Sauvage et al. “Using the 3-point bending method to study failure initiation in epoxide-aluminum joints.” In: International Journal of Adhesion and Adhesives 75 (2017), pp. 181 –189.
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- N. Carrere, E. Martin, D. Leguillon, Comparison between models based on a coupled criterion for the prediction of the failure of adhesively bonded joints, Engineering Fracture Mechanics, Volume 138, 2015, Pages 185-201,
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- Dominique Leguillon. “Strength or toughness? A criterion for crack onset at a notch.” In: *European Journal of Mechanics - A/Solids* 21.1 (2002), pp. 61 –72

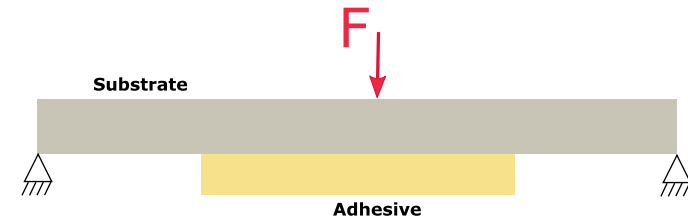
Experimental approach

- **Sauvage (2017)**: two mechanical test to characterize adhesive failure initiation:

Pull-over test



3-point bending test



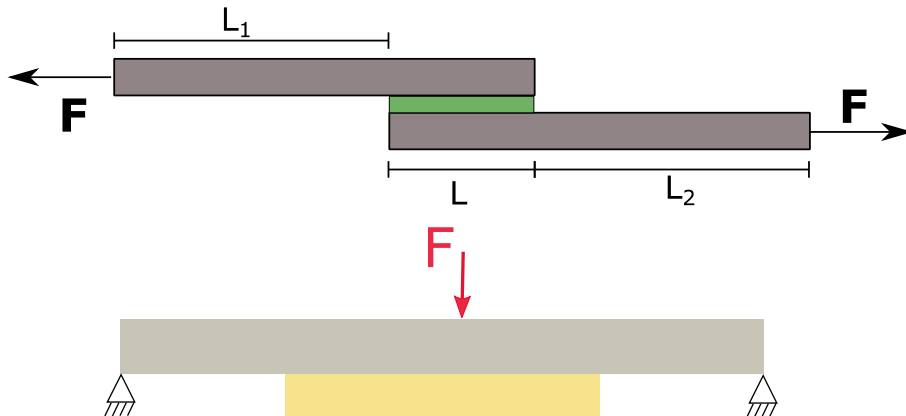
- No distinction of initiation/propagation
- Presence of mixed mode
- high three-dimensional state of stress distribution.
- Rod may be decentralized

- It can provide adhesive initiation failure
- Not used by general industry

State of the Art – Coupled Criterion

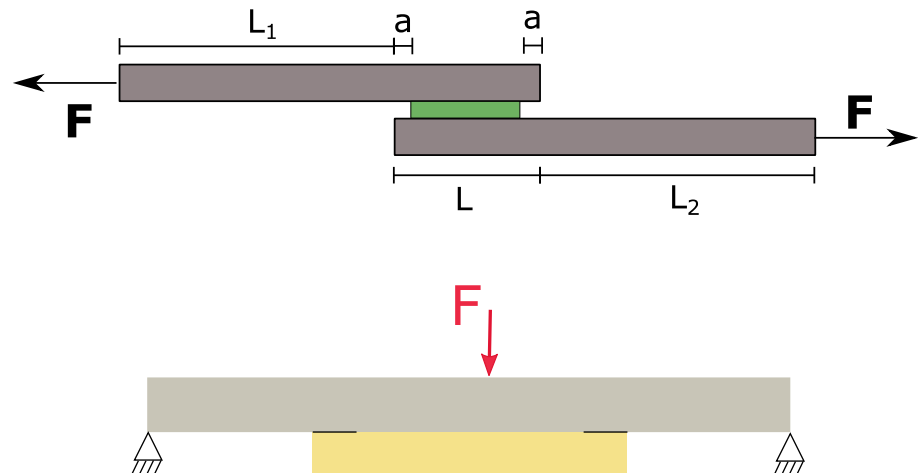
✓ physical point of view – **Carrere (2015):**

Strength criterion



Stress high enough to create
micro-cracks

Energy criterion



G_c high enough to propagate
micro-cracks on macro-cracks

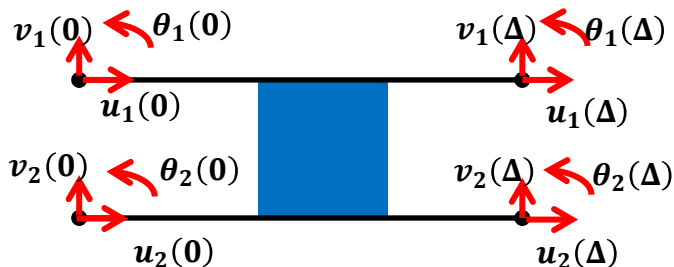
- Each macro-element has its stiffness matrix
- Shape of solution in displacements as function of integration constants
 - For each ME -> 12 DOF

Local equilibrium

$$\frac{dN_j}{dx} = (-1)^j bT$$

$$\frac{dV_j}{dx} = (-1)^{j+1} bS$$

$$\frac{dM_j}{dx} + V_j + b \frac{e_j}{2} T = 0$$



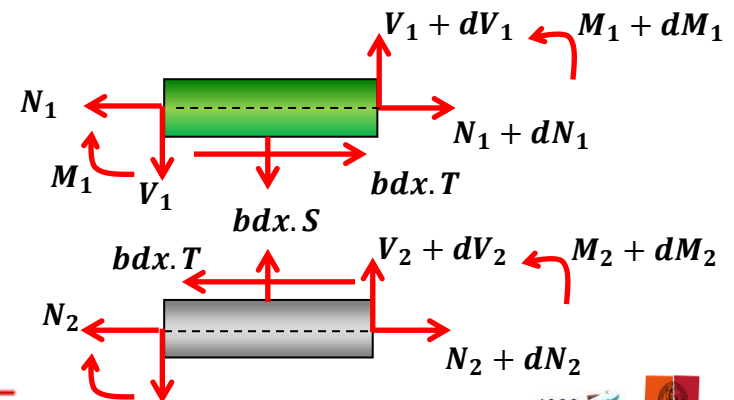
Constitutive equations

$$M_j = -B_j \frac{du_j}{dx} + D_j \frac{d\theta_j}{dx}$$

$$N_j = A_j \frac{du_j}{dx} - B_j \frac{d\theta_j}{dx}$$

$$\theta_j = \frac{dv_j}{dx}$$

$$T = \frac{G_a}{e_a} \left(u_2 - u_1 - \frac{e_2}{2} \theta_2 - \frac{e_1}{2} \theta_1 \right)$$



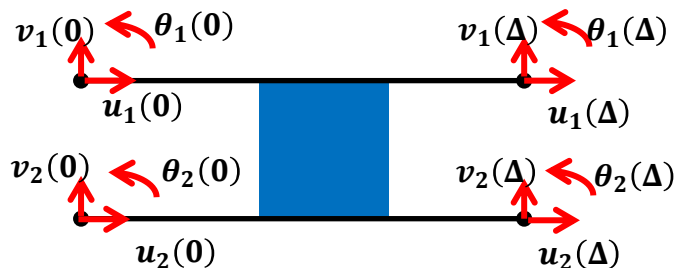
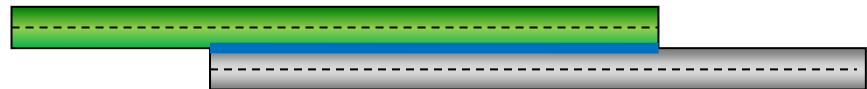
- Each macro-element has its stiffness matrix
- Shape of solution in displacements as function of integration constants
 - For each ME -> 12 DOF

$$\begin{pmatrix} -N_1(0) \\ -N_2(0) \\ N_1(\Delta) \\ N_2(\Delta) \\ -V_1(0) \\ -V_2(0) \\ V_1(\Delta) \\ V_2(\Delta) \\ -M_1(0) \\ -M_2(0) \\ M_1(\Delta) \\ M_2(\Delta) \end{pmatrix} = K_{PC} \begin{pmatrix} u_1(0) \\ u_2(0) \\ u_1(\Delta) \\ u_2(\Delta) \\ v_1(0) \\ v_2(0) \\ v_1(\Delta) \\ v_2(\Delta) \\ \theta_1(0) \\ \theta_2(0) \\ \theta_1(\Delta) \\ \theta_2(\Delta) \end{pmatrix}$$



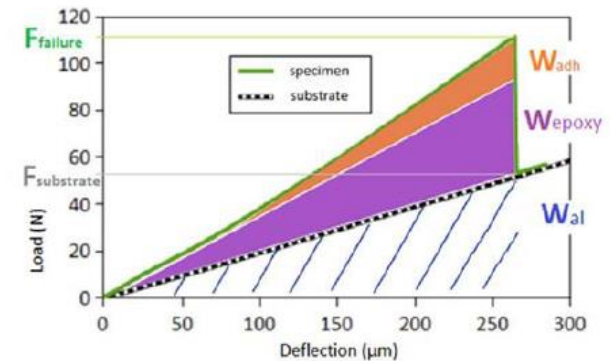
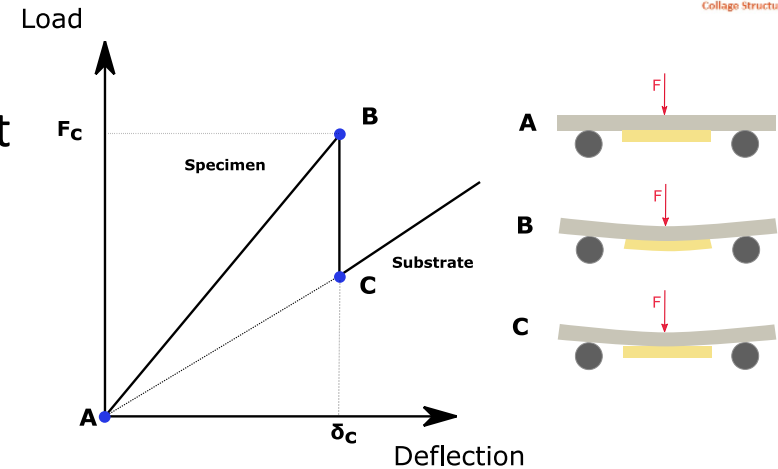
$$F_e = N_e M_e^{-1} U_e = K_{PC} U_e$$

A single macro-element can represent a whole bonded joints



Sauvage approach

- **3 point bending test: Roche (1986)**
 - Provide the critical force and displacement
 - Instantaneous failure
- Inconvenient: the results aren't generalized
- **Sauvage (2017)** has proposed an energetic approach:
 - Substrate energy
 - Bulk polymer energy
 - **Adhesive energy**



Comparison of adhesive energy for different substrate thickness

Formation of polymer/metal interphase

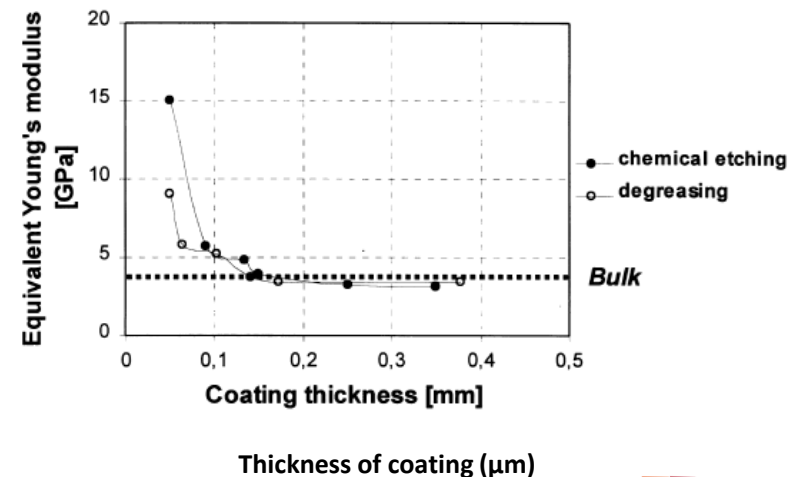
- Deposition of polymer into metallic surface: formation of a three-layer system



- Interphase region:
 - Important gradient of properties;
 - Residual stresses;
- The adhesive failure characterization:

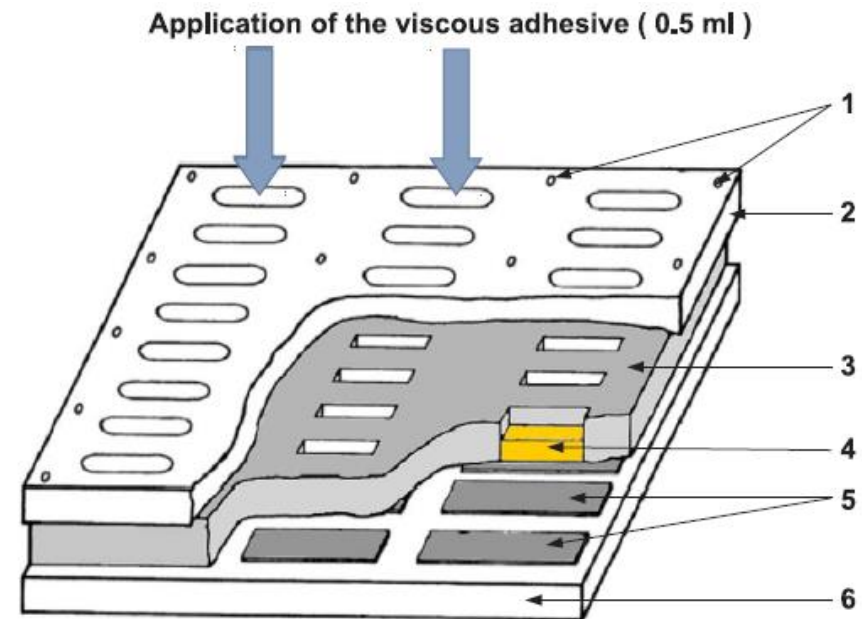
Determination of the role of the interface on the adhesive failure

Bouchet (2000):



Specimens

- Substrate: AA 2024-T3 Laminated
- Surface treatment
 - Acetone degreasing
 - Nitric acid etching: Different temperatures for different durations
 - De-ionized water at 100°C during 30 minutes
- Polymers:
 - DGEBA/DETA – 3 hours at room temperature and 1h at 140°C
 - Araldite - 3 hours at room temperature and 1h at 150°C

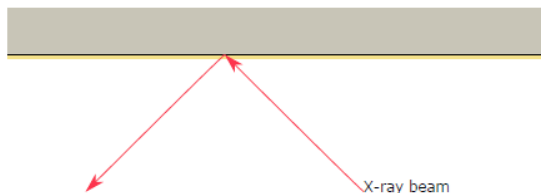


Formation of polymer/metal interphase

- Residual stresses
 - Thermal stresses **X**
 - Intrinsic residual stress **✓**

Indirect residual stresses measurement

Evaluation using x-ray diffraction



Direct residual stresses measurement

Evaluation of stiffness variation

Bouchet (2000):

