Failure of a pre-cracked adhesive sandwich layer in shear

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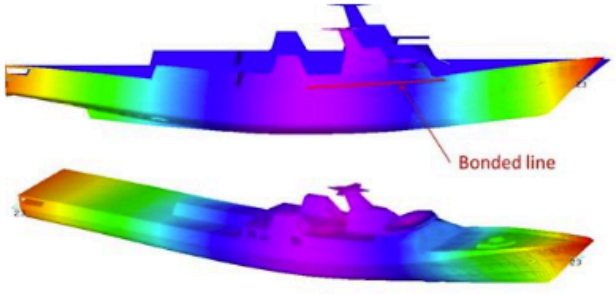
Motivation

Ship building industry is looking into steel/composite hybrid adhesive joints due to number of reasons:

- Higher stability
- Higher speed
- Less fuel consumption
- Less CO_2 emission
- Higher corrosion resistance

Assembly in shipyard



25 years at sea

Problem statement and case study

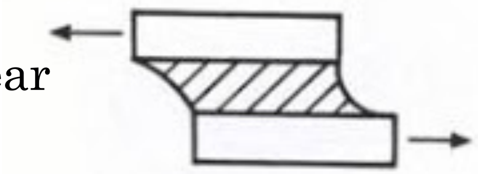
- A joint is designed connecting composite superstructure to steel hull
- Performance of these joints are under evaluation
- Adhesive layer thickness is 8-12 mm
- Adhesive layer is under shear loading

Tests aim at evaluation the shear properties of adhesives

- There is a need to develop predictive tools and test geometries for the failure of joints under macroscopic shear.
- Two classes of test exist for adhesives in shear: torsional shear and combined tension-shear.
- Torsional shear tests include the napkin ring test (ASTM E 229)
- Tensile-shear geometries: single-lap shear test, double-lap shear test, Thick Adherend Shear Test (TAST)

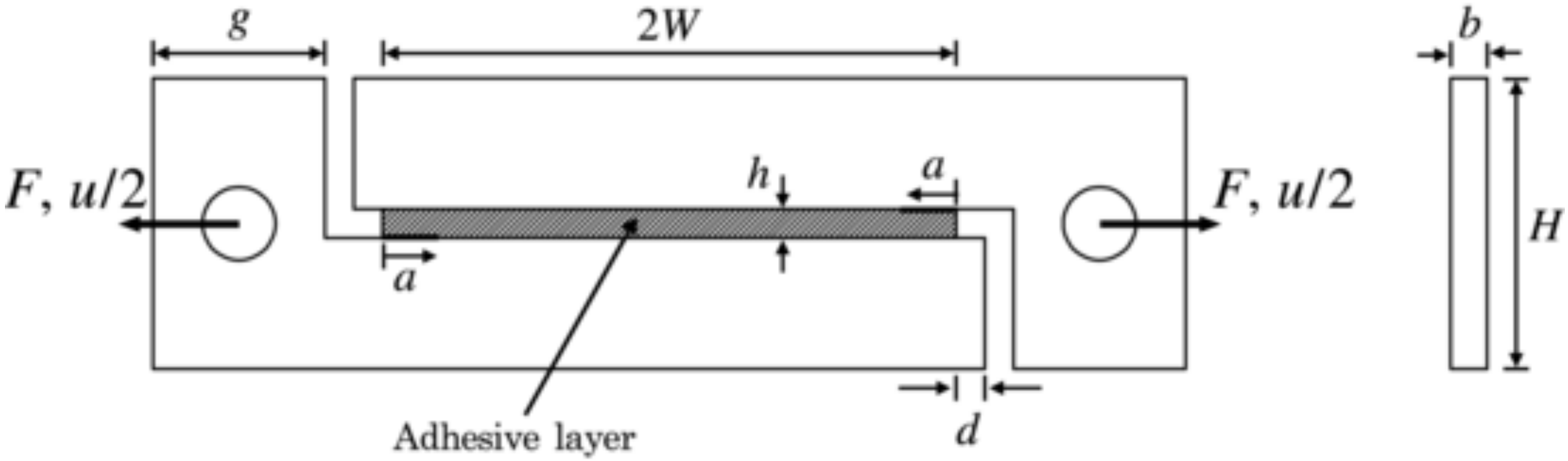
Torsion

Tension-shear



Simplification of the problem and experiment design

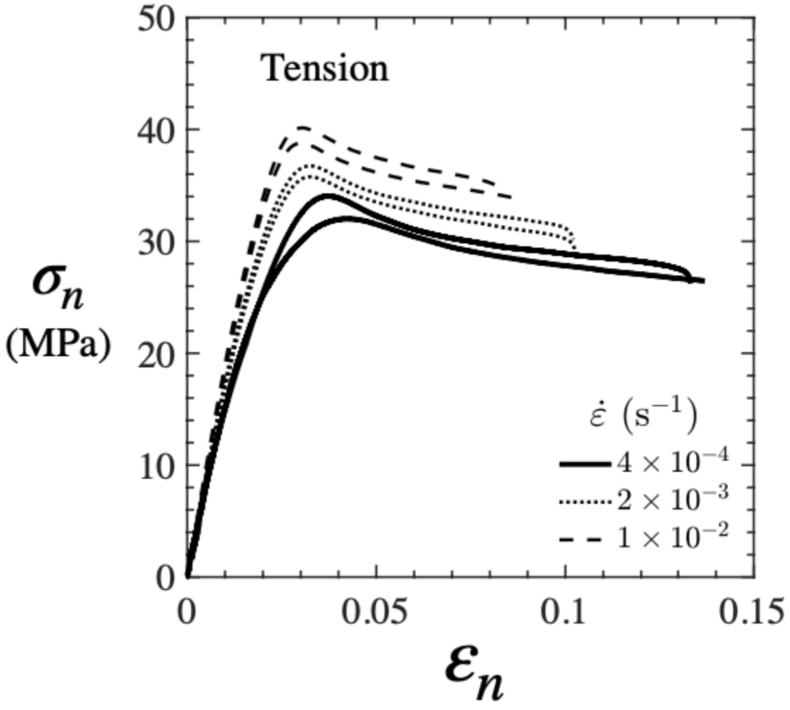
- The imposition of pin-loading, aligned with the mid-plane of the joint, prevents the development of an unknown bending moment and shear force at the ends of the specimen.



Adhesives under investigation

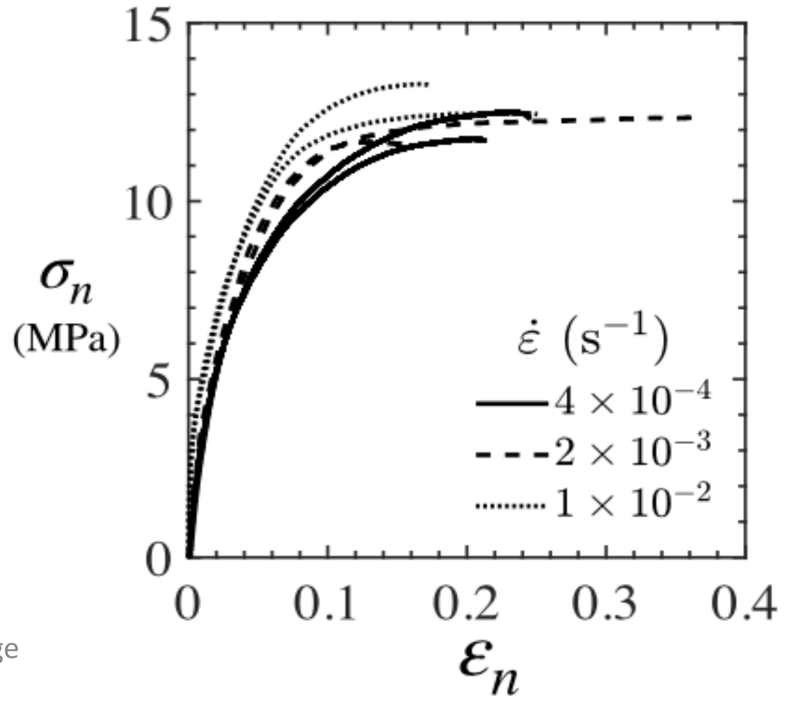
A two part epoxy:

- Tensile strength 30-40 MPa
- Modulus 1.5-2.5 GPa
- Strain at failure 0.08-0.15
- Elastic-plastic behaviour
- Low adhesive/steel interfacial toughness



An MMA-based adhesive:

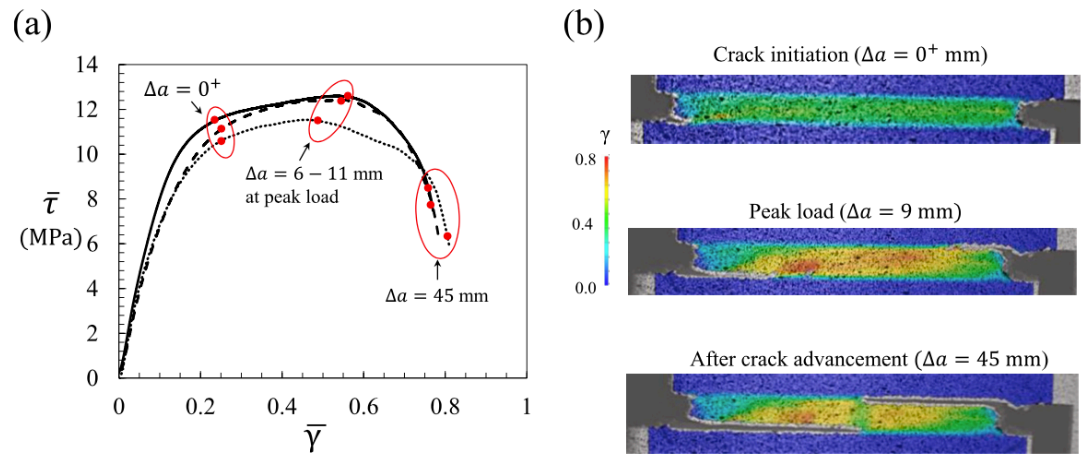
- Tensile strength 12-15 MPa
- Modulus 245-380 MPa
- Strain at failure 0.2 – 0.4
- Non-linear behaviour
- High adhesive steel interfacial toughness



Measured response of TAST joints

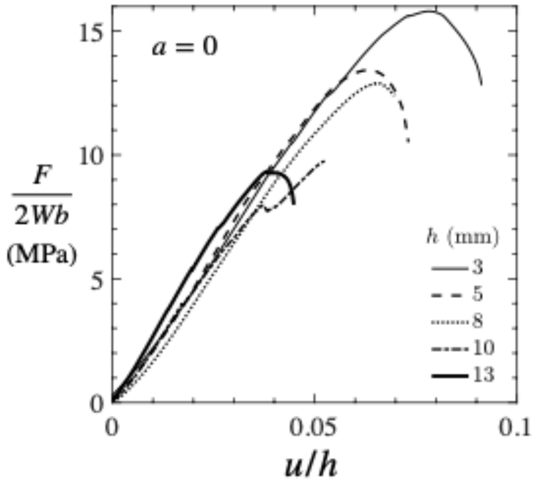
MMA-based adhesive/steel joint:

- Gradual crack growth
- Failure inside the adhesive in vicinity of adhesive/steel interface
- Crack resistant behaviour
- Adhesive undergoes plastic deformation



Epoxy adhesive/steel joint:

- Sudden failure
- Failure at the adhesive/steel interface
- Adhesive is elastic prior to failure

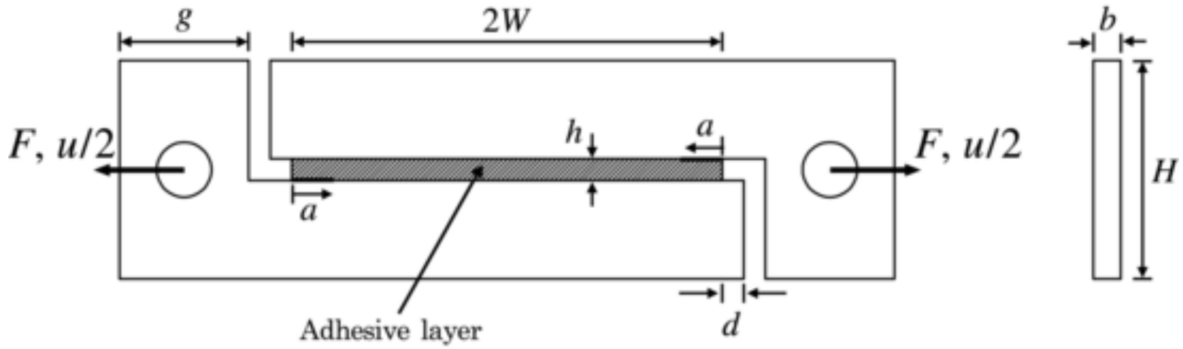


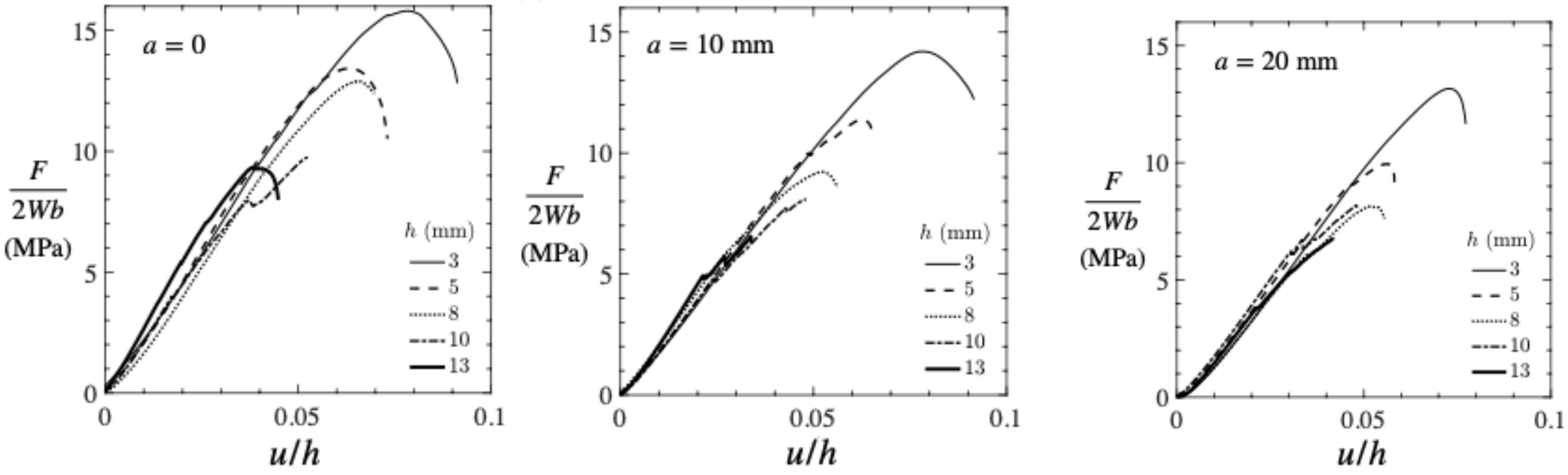
Why so different?

We aim to understand the mechanics of these failures

Now let's focus on the epoxy/steel joints

- Linear Elastic Fracture Mechanics is valid for these joints.
- What is the effect of pre-cracks on these joints?

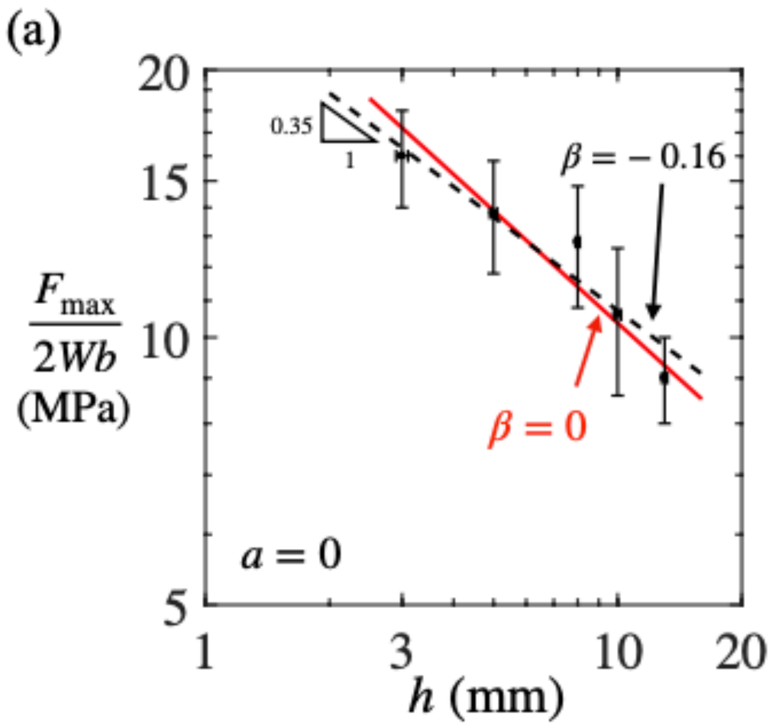




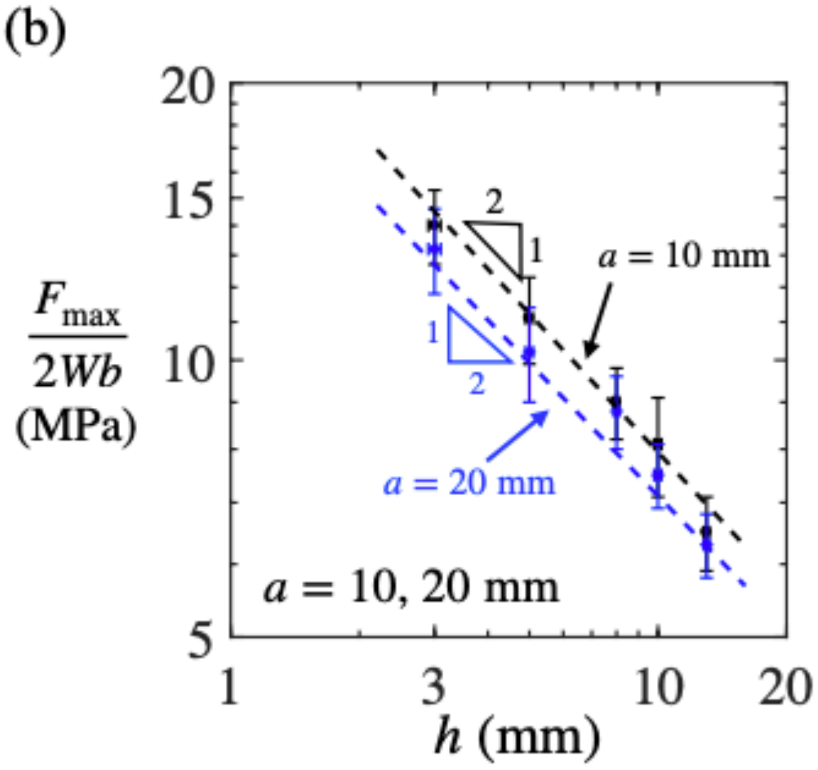
- Strength of the joints and the strains at failure decreases as the pre-crack length increases
- Anything exciting?

Average failure strength versus adhesive layer thickness

- The power law dependency of failure strength on adhesive layer thickness is different in specimens with no pre-crack compared to the ones with long pre-cracks.



$$\tau_c^{\infty} \propto h^{-0.35}$$



$$\tau_c^{\infty} \propto h^{-0.5}$$

In specimens with long pre-crack

If we consider a semi-infinite interfacial crack along the adhesive steel interface for an infinite layer of adhesive, of height h, sandwiched between two rigid substrates (Mart´ınez-Pan˜eda et al., 2020; Rice and Rosengren, 1968), the dependence of failure strength to $h^{-0.5}$ is consistent with the prediction by a straightforward calculation of the energy release rate G.
The upper substrate is displaced in a sliding direction with respect to the lower substrate by an amount $h\gamma$ where γ is the shear strain in the intact layer, upstream of the crack tip. Then the upstream strain energy density of the sandwich layer, per unit area, reads

$$W^u = \frac{1}{2}\frac{{\tau^{\infty}}^2 h}{\mu}$$

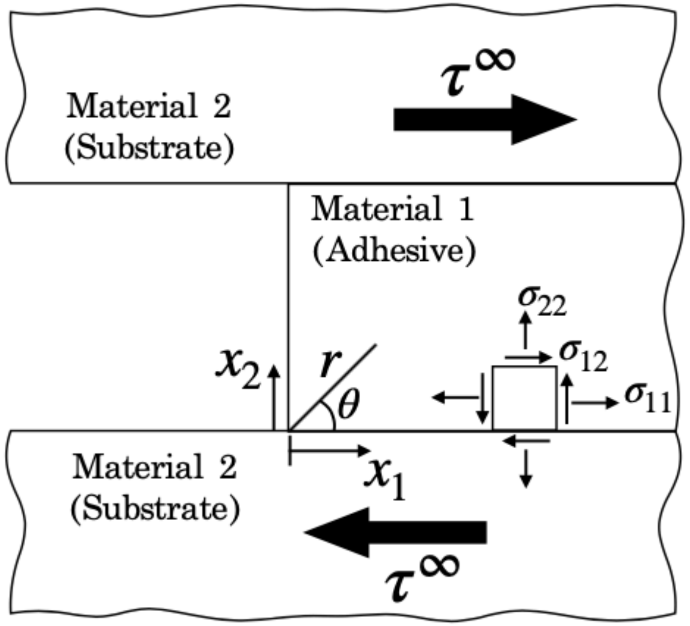
$$G = W^u$$

$G \equiv \Gamma$ interfacial toughness

$$\tau_c^{\infty} = \left(\frac{2\mu\Gamma}{h}\right)^{\frac{1}{2}}$$

This analysis shows that the failure in the specimens with long pre-crack is governed by the K-field. How about the specimens with no pre-crack?

Order of singularity at a sharp corner



$$\sigma_{ij} = H\, r^{\lambda-1}\, f_{ij}(\lambda, \theta)$$ Stress field at the sharp corner

$$u_i = H\, r^{\lambda}\, g_i(\lambda, \theta)$$ Displacement field at the sharp corner

$$\sigma_{12} = H\, r^{\lambda-1}\, f_{12}(\lambda, \theta = 0)$$

$$\sigma_{22} = H\, r^{\lambda-1}\, f_{22}(\lambda, \theta = 0)$$

where $$H = \tau^\infty\, h^{1-\lambda}\, b(\alpha, \beta)$$

and $$\alpha = \frac{\mu_1\,(1-\nu_2) - \mu_2\,(1-\nu_1)}{\mu_1\,(1-\nu_2) + \mu_2\,(1-\nu_1)} \qquad \beta = \frac{1}{2}\,\frac{\mu_1\,(1-2\nu_2) - \mu_2\,(1-2\nu_1)}{\mu_1\,(1-\nu_2) + \mu_2\,(1-\nu_1)}$$

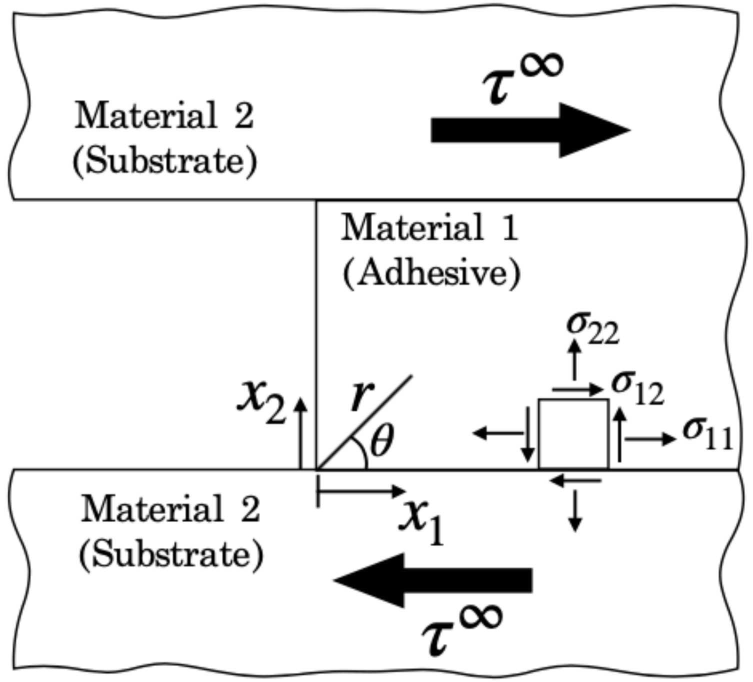
Effect of Dundurs parameters on order of the 90° corner singularity

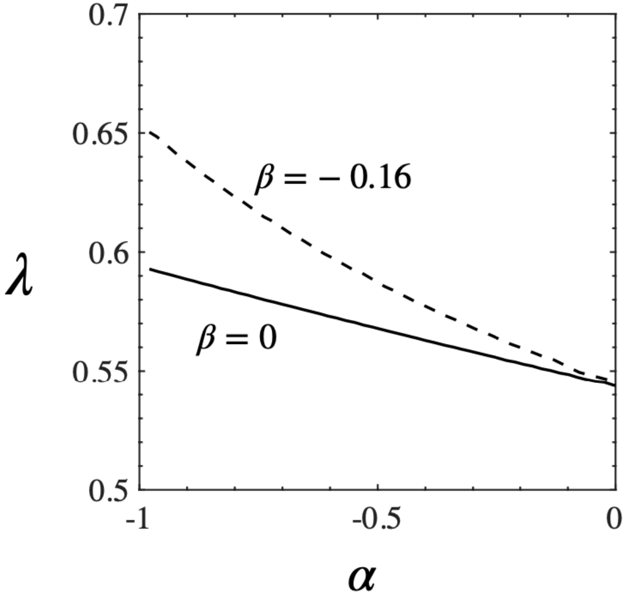
$$\sigma_{\theta\theta}^{(1)} - i\sigma_{r\theta}^{(1)} = \sigma_{\theta\theta}^{(2)} - i\sigma_{r\theta}^{(2)} \qquad \text{along } \theta = 0$$

$$u_r^{(1)} + iu_\theta^{(1)} = u_r^{(2)} + iu_\theta^{(2)} \qquad \text{along } \theta = 0$$

$$\sigma_{\theta\theta}^{(1)} - i\sigma_{r\theta}^{(1)} = 0 \qquad \text{along } \theta = \frac{\pi}{2}$$

$$\sigma_{\theta\theta}^{(2)} - i\sigma_{r\theta}^{(2)} = 0 \qquad \text{along } \theta = -\pi$$





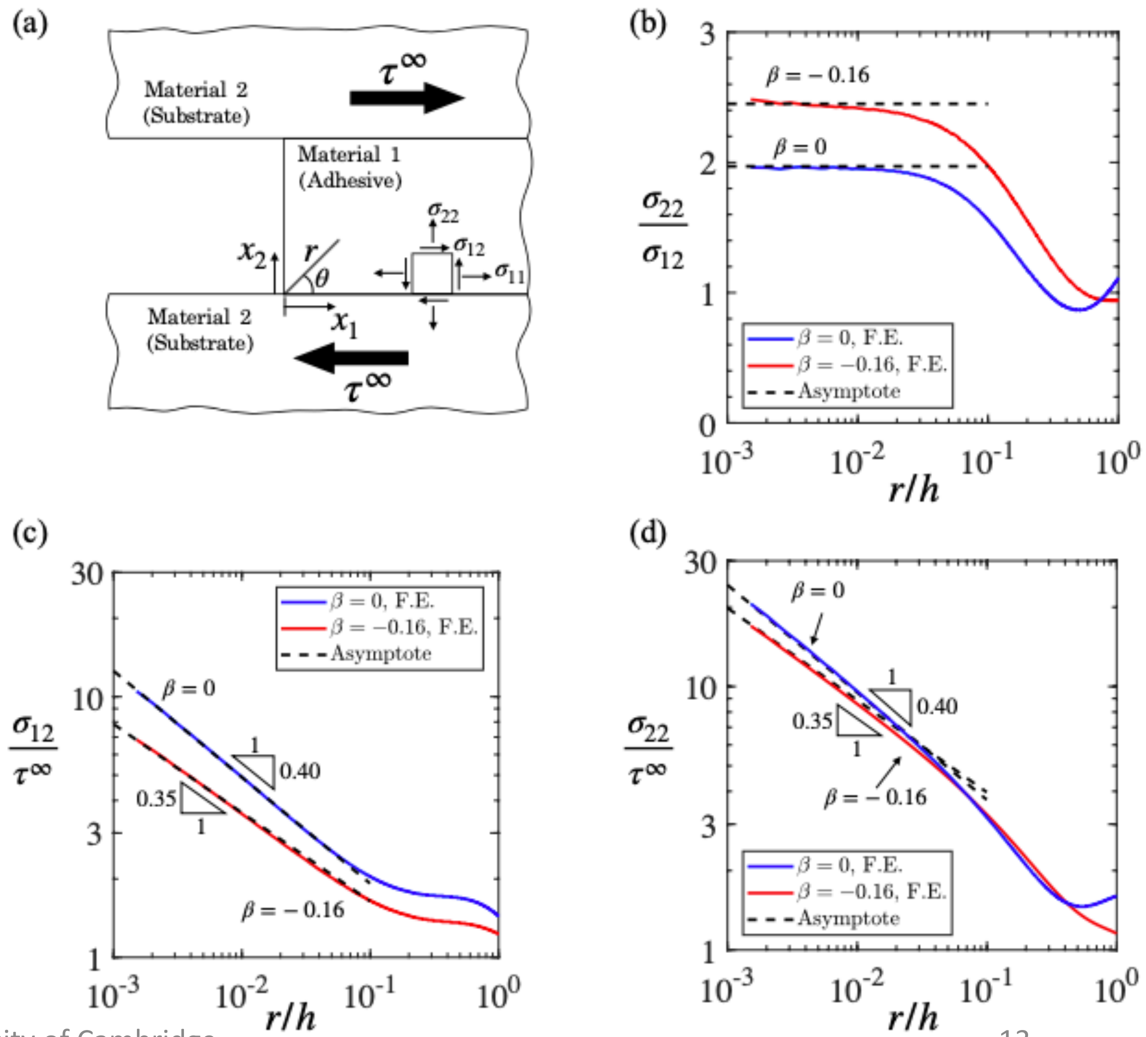
$$\alpha = \frac{\mu_1(1-\nu_2) - \mu_2(1-\nu_1)}{\mu_1(1-\nu_2) + \mu_2(1-\nu_1)} \qquad \beta = \frac{1}{2}\frac{\mu_1(1-2\nu_2) - \mu_2(1-2\nu_1)}{\mu_1(1-\nu_2) + \mu_2(1-\nu_1)}$$

Stress field at the 90° corner

$$\sigma_{12} = \tau^{\infty}(\frac{r}{h})^{\lambda-1} b f_{12}$$

$$\sigma_{22} = \tau^{\infty}(\frac{r}{h})^{\lambda-1} b$$

- Using FEM calculations we can fit the analytical solutions and find constant values of b and f for this configuration.
- The corner singularity domain is extended up to 0.1 h.
- Stress field at the interface in the sharp corner highly depends on the value of β.



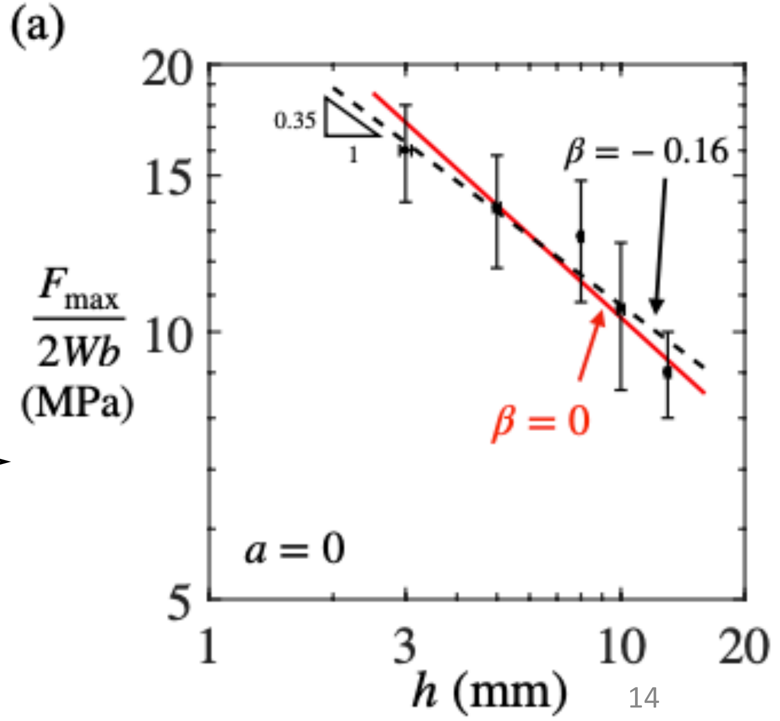
Failure is governed by *H*-field

- The idea is that failure in sharp corners is governed by H-field instead of K-field as far as the plastic zone size is smaller than corner singularity domain. . Hence, we can write that there is a critical value of H_c at which failure happens, then according to

$$H = \tau^{\infty} h^{1-\lambda} b(\alpha, \beta)$$

$$\tau_c^{\infty} = H_c h^{\lambda-1}/b$$

For our material combination: λ= 0.65 $\Rightarrow$ $\tau_c^{\infty} \propto h^{-0.35}$ $\Rightarrow$



Now let’s focus on the MMA-based adhesive/steel joints

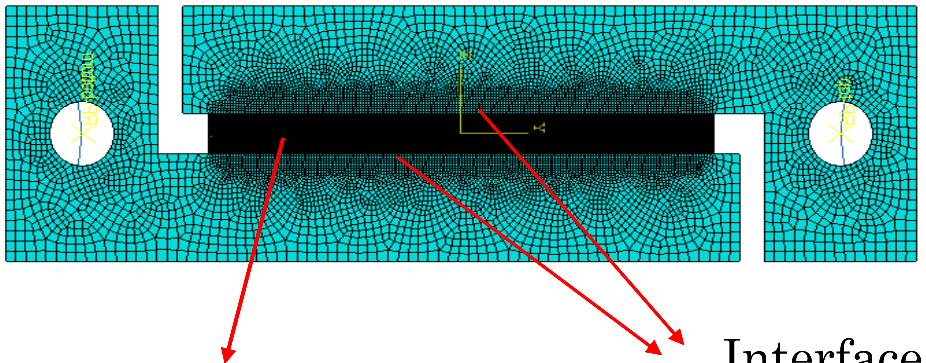
- LEFM is NOT valid for these joints
- Corner singularity analysis is not valid for this case since the plastic zone size is much larger than the corner singularity domain:

$$r_p = \frac{E\Gamma_1}{\left(3\pi{\sigma_y}^2\right)} \approx 5\ \text{mm}$$

Hence, in this case another approach is adapted to predict the mechanical response of joints.

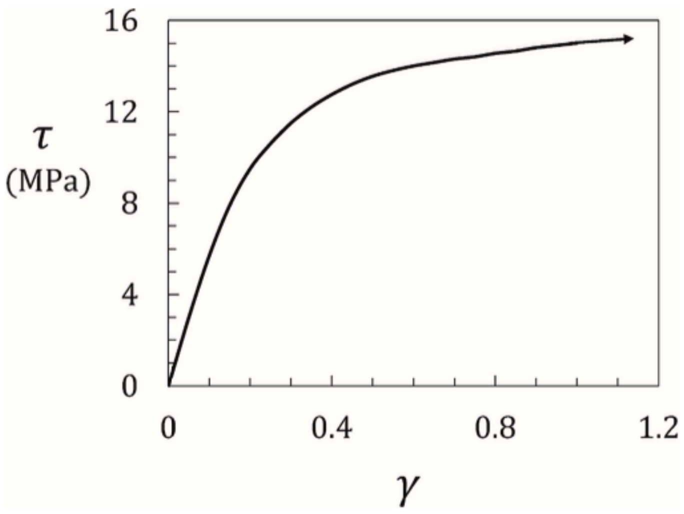
Finite element modelling

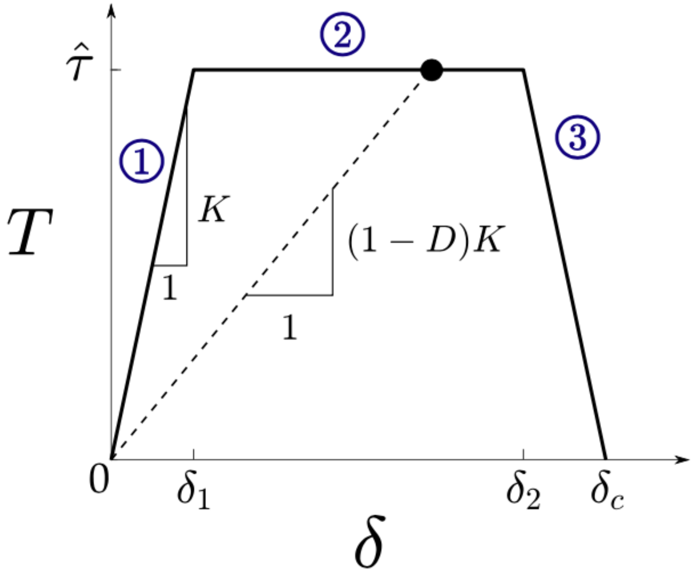
- The shear stress versus shear strain behaviour of adhesive was deduce from experiments by eliminating the effect of cracks.
- A calibrated traction-separation model is needed.



Adhesive

Interfaces





$$T = \begin{cases} K\delta & \text{if } \delta \le \delta_1 \\ \hat{\tau} & \text{if } \delta_1 \le \delta \le \delta_2 \\ \hat{\tau}\left(1 - \frac{\delta-\delta_2}{\delta_c-\delta_2}\right) & \text{if } \delta_2 \le \delta \le \delta_c \end{cases}$$

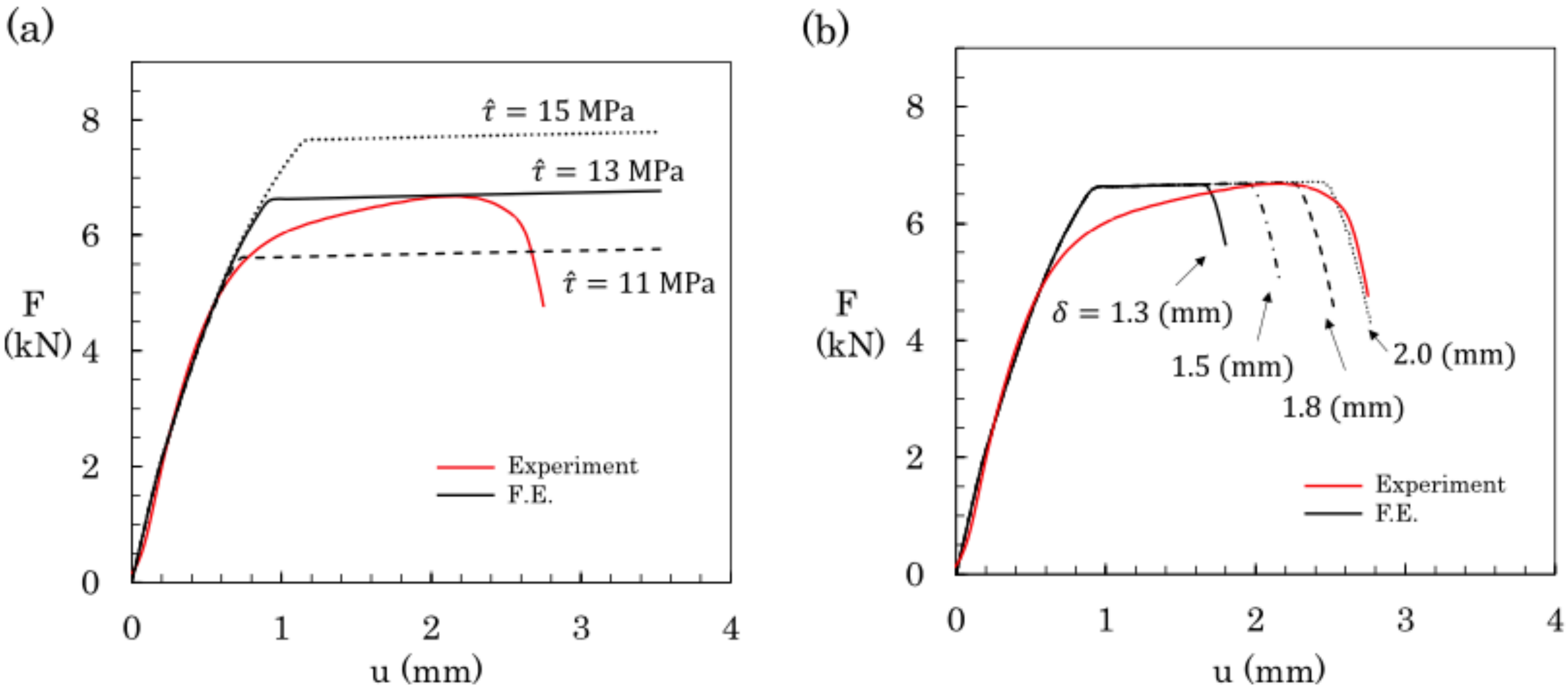
$$\boldsymbol{T/\delta = (1 - D)K}$$

$$D = \begin{cases} 0 & \text{if } \delta \le \delta_1 \\ 1 - \frac{\hat{\tau}}{K\delta} & \text{if } \delta_1 \le \delta \le \delta_2 \\ 1 - \frac{\hat{\tau}}{K\delta}\left(1 - \frac{\delta-\delta_2}{\delta_c-\delta_2}\right) & \text{if } \delta_2 \le \delta \le \delta_c \end{cases}$$

Model calibration

- Traction: 13 MPa
- Separation: 2 mm

- These values seem to lead to an acceptable prediction of force-displacement curve.



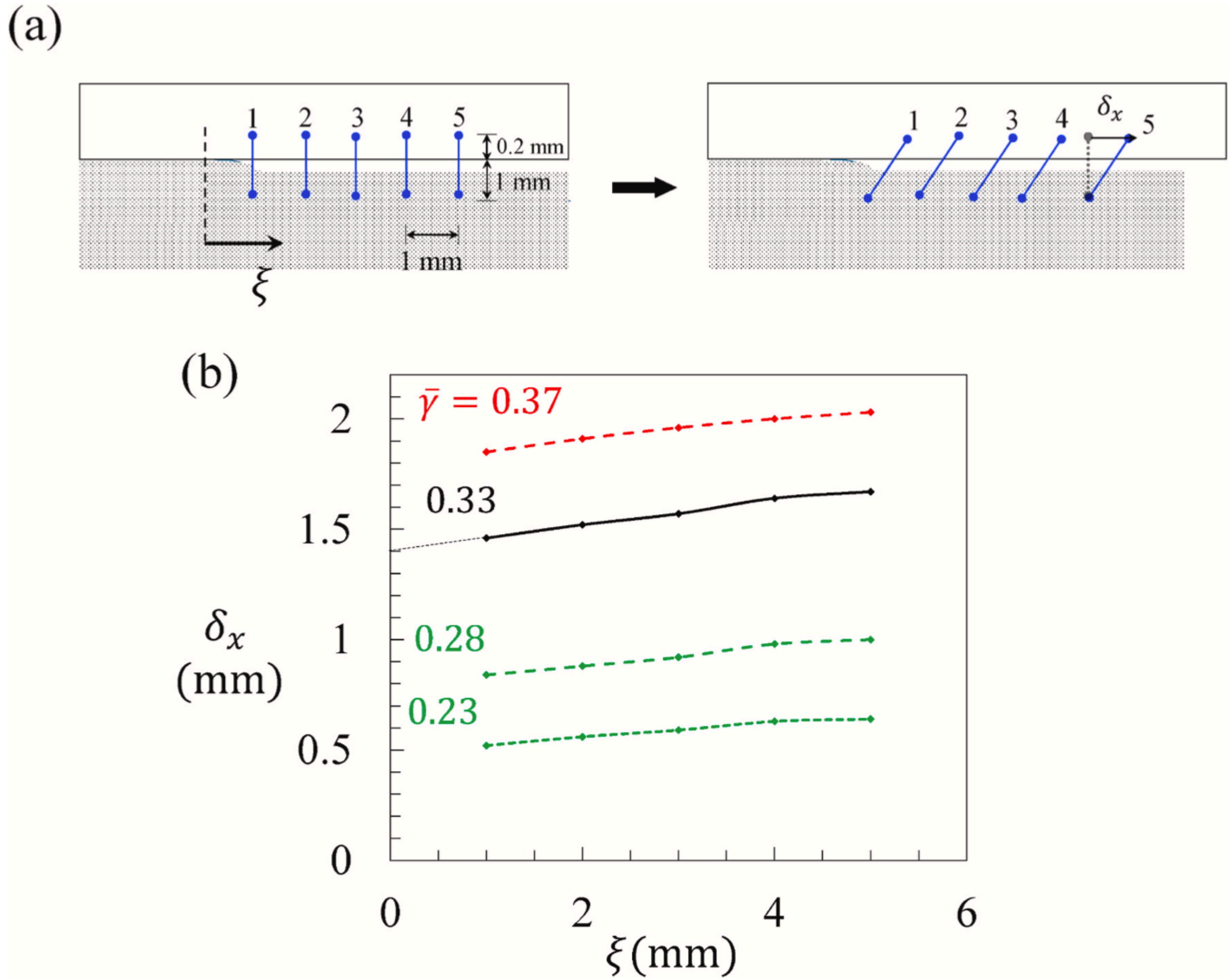
Experimental measurement of δ_c

- The magnitude of the critical shear displacement at the crack tip of a pre-crack, at the onset of crack growth, is measured by means of DIC.

- Five digital gauges are placed behind the crack tip. The spacing of the gauges is 1 mm, and the first one is 1 mm behind the crack tip.

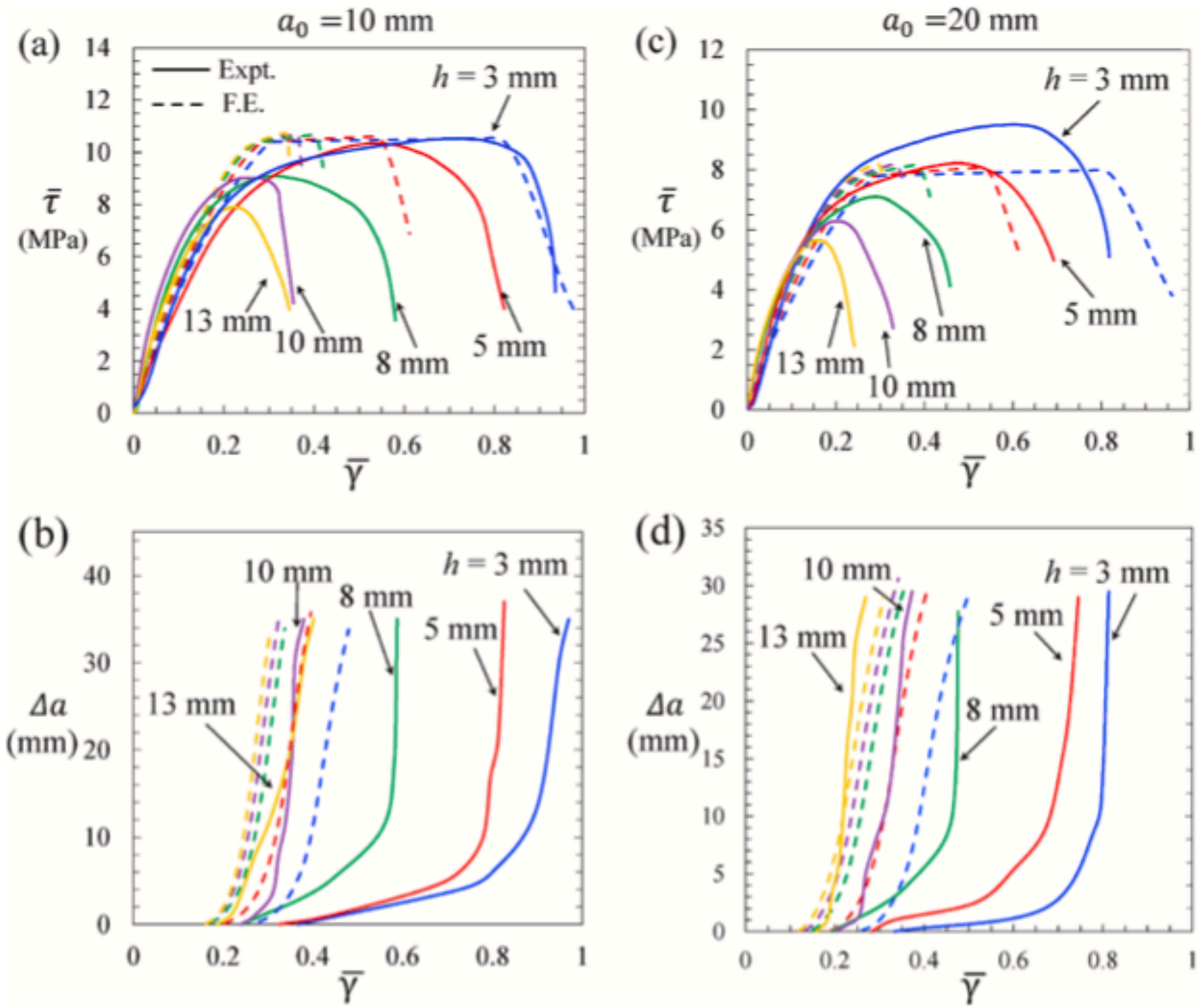
- Sliding displacement profile for the choice h = 8 mm, a_0 = 20 mm, is shown.

- Note, in (a), the finite opening of the pre-crack along the crack flanks; it is due to the saw-cut in manufacture.



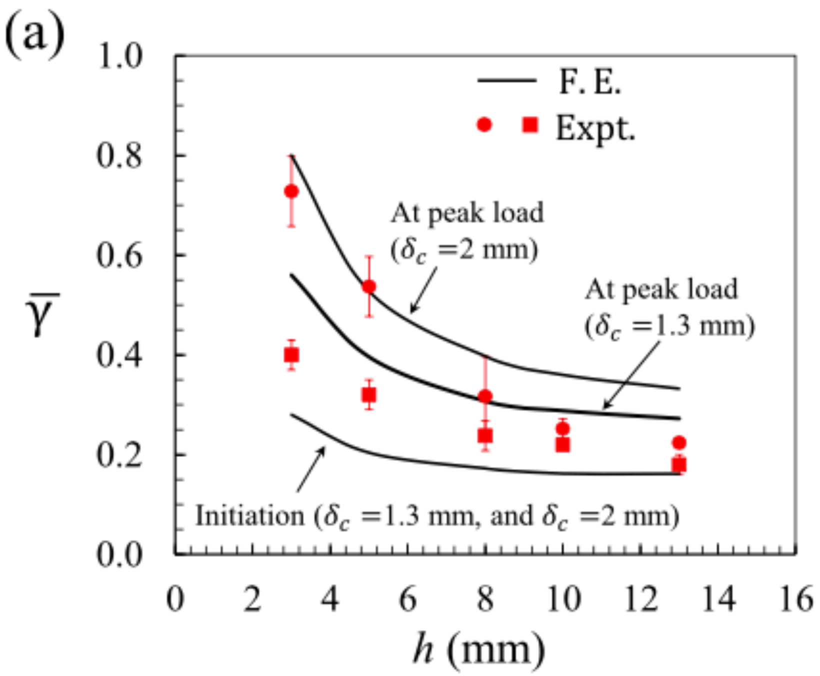
Experiments versus simulations

- Although the maximum force and deformation is nicely predicted, the models are not capable of capturing crack growth as a function of shear deformation.

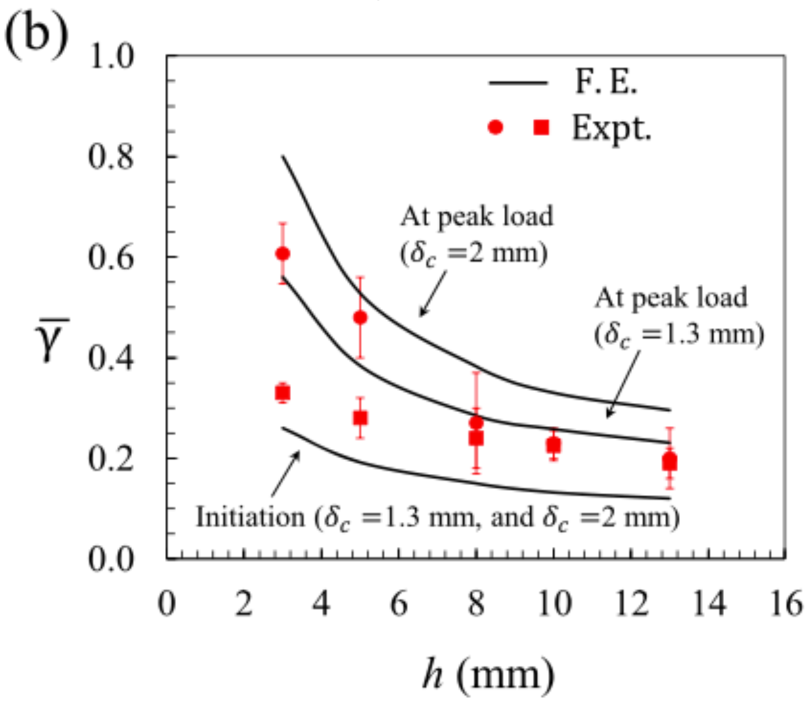


Critical results

$a_0 = 10$ mm



$a_0 = 20$ mm



We can conclude that for these joints, the shear deformation for initiation of crack is 0.2. This number can be used as a design parameter for the MMA-based adhesive/steel joints.

Conclusions

- In joints with linear elastic adhesives and low interfacial toughness, sharp corners act almost as a crack.
- Singularity order for cracks is 0.5 and for sharp corner is 0.65
- Cohesive zone modelling can be used for joints made of flexible adhesives, however the predictions are not fully accurate
- CZM can be adjusted in order to predict some critical engineering parameters

Thank you!

Advisor: Prof. Norman Fleck

Collaborators: Dr. Emilio Martinez-Paneda, Dr. Ivan Cuesta

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