How pseudo-ductility influences the translaminar toughness and nominal strengths?

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Girona, 16/07/2021

Problem definition

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ANALYSIS AND ADVANCED MATERIALS FOR STRUCTURAL DESIGN

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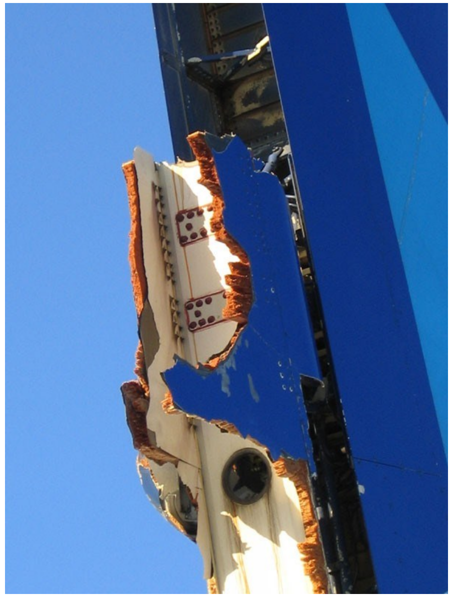
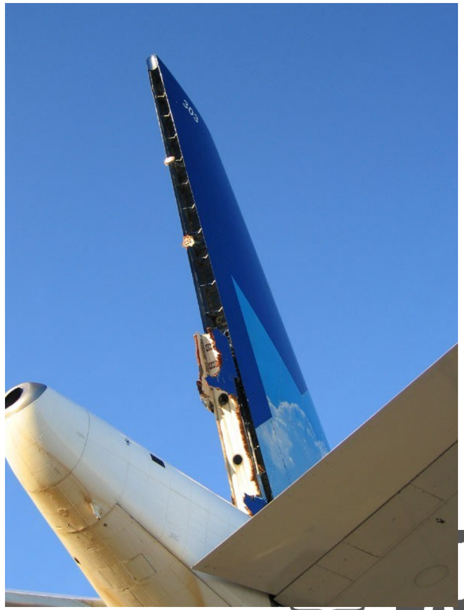
Problem definition

Composites

- **Brittle Failure is catastrophic and sudden.**

- EPSRC's (Engineering and Physical Sciences Research Council - UK) funded HiPerDuCT (High Performance Ductile Composite Technology)
  - **Main goal was to reduce the disadvantage from lack of ductility.**





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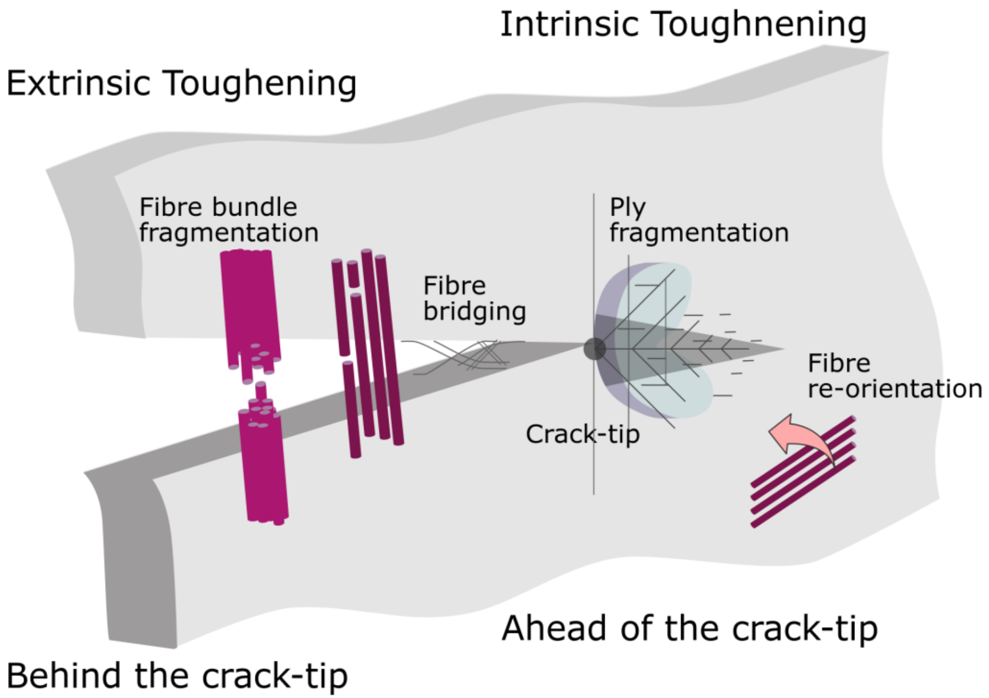
Introduction (1/2)

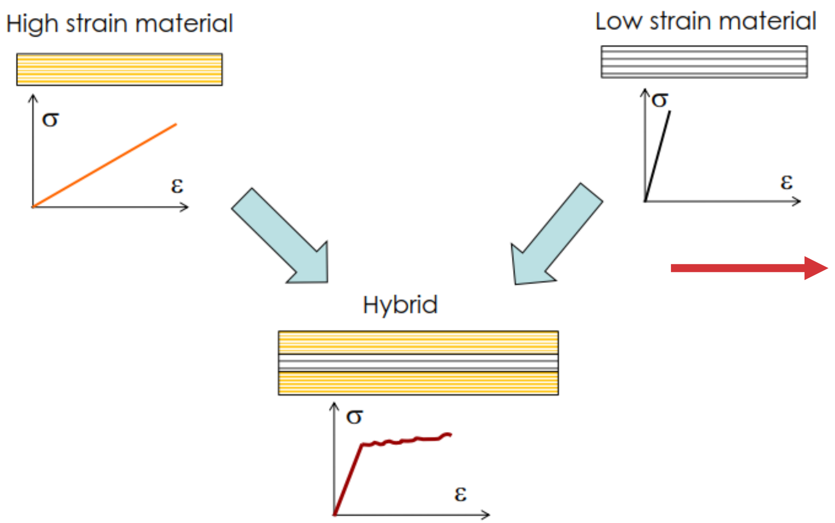
- Energy dissipation mechanisms can be broadly classified into extrinsic and intrinsic.
  - Intrinsic, occurring ahead of the crack-tip.
    - Crack need not be present for it to exert influence. E.g., Plasticity
  - Extrinsic, occurring behind the crack-tip
    - Crack is necessary. E.g., Fibre bridging, pull-out.
- Quasi-brittle materials like composites dissipate energy predominantly through *extrinsic dissipation mechanisms* like fibre-bridging, fibre pull-out, splitting, etc.,
- The intrinsic contribution can be several times (~up to 14) higher than the extrinsic contribution in total toughness [1].
  - Pseudo-ductility is shown to be a viable option to include intrinsic toughening in composite laminates.

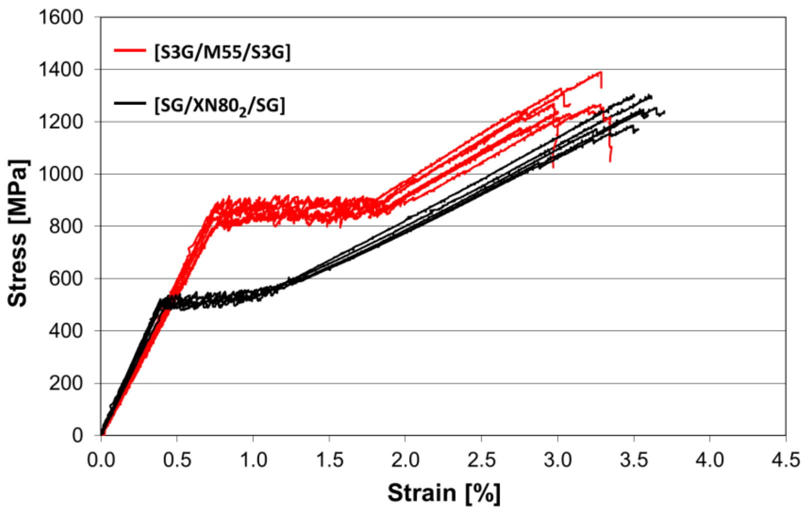


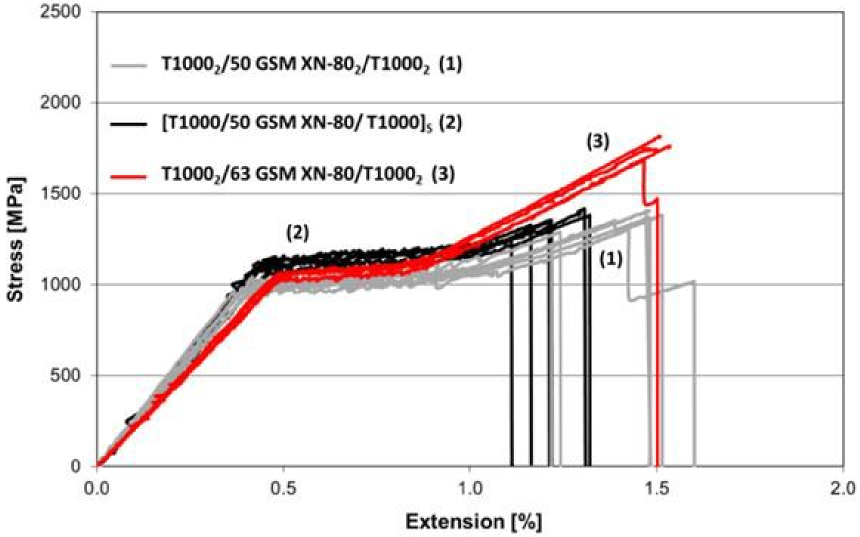
Re-drawn from Ritchie 2011(10.1038/nmat3115)

[1] Tvergaard 1992, 10.1016/0022-5096(92)90020-3

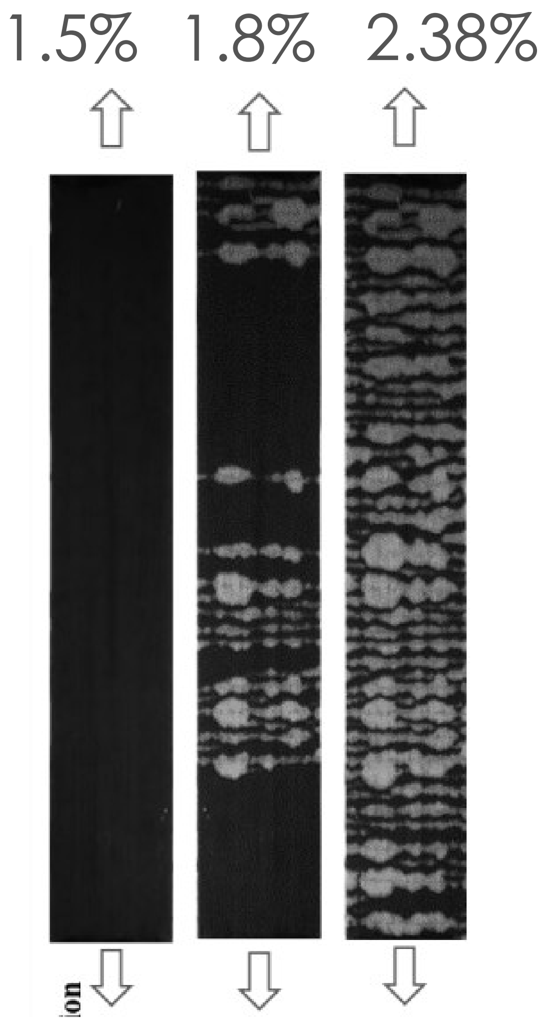
Introduction - Pseudo-ductile composites (2/2)







Tensile extension



Czel, 2016 (10.1016/j.compstruct.2016.02.010) & Fotouhi 2021, (Break the Borders @ KU Lueven)

Problem statement

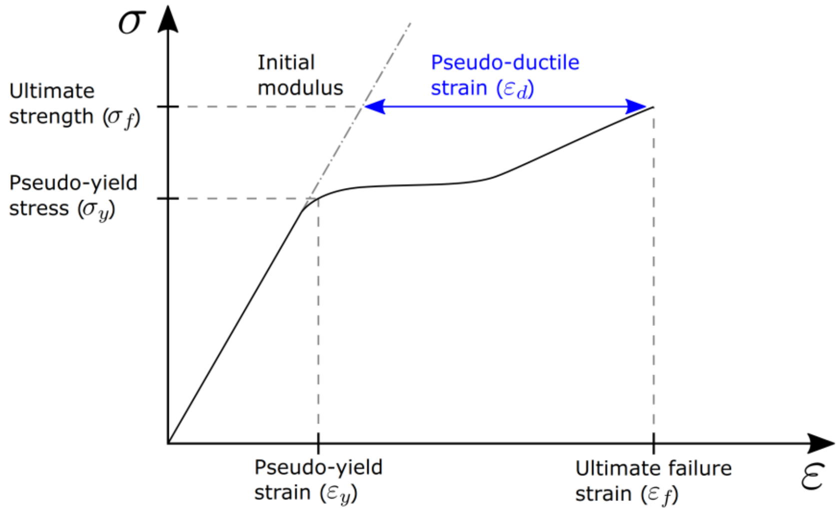
- Pseudo-ductile response has been demonstrated under tensile testing for both UD[1] and quasi-isotropic laminates[2],
  - there exists no work on their influence on toughness.
  - Needs thin plies (<60μm) and has narrow design space.
- It has yet to be quantified systematically to the improvements in other mechanical properties like nominal strengths of structural members like OHT or CCT.
  - Strengths of OHT/CCT were tested for a single radius [2]. But lacks information necessary to determine the size-effect law/limits.
- Numerical models will be used to understand the influence of material properties concerning to pseudo-ductility on,
  - The increment of fracture toughness $\left(\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}}\right)$ from the intrinsic contribution using CT specimen.
  - The Influence of pseudo-ductility on OHT and CCT strengths.

[1] Jalavand 2014 (j.compscitech.2014.01.013), Czél 2015 (j.compositesa.2015.01.019)
[2] Czél et al., (2018)], Fotouhi et al., (2018)

Dimensional analysis (1/4)

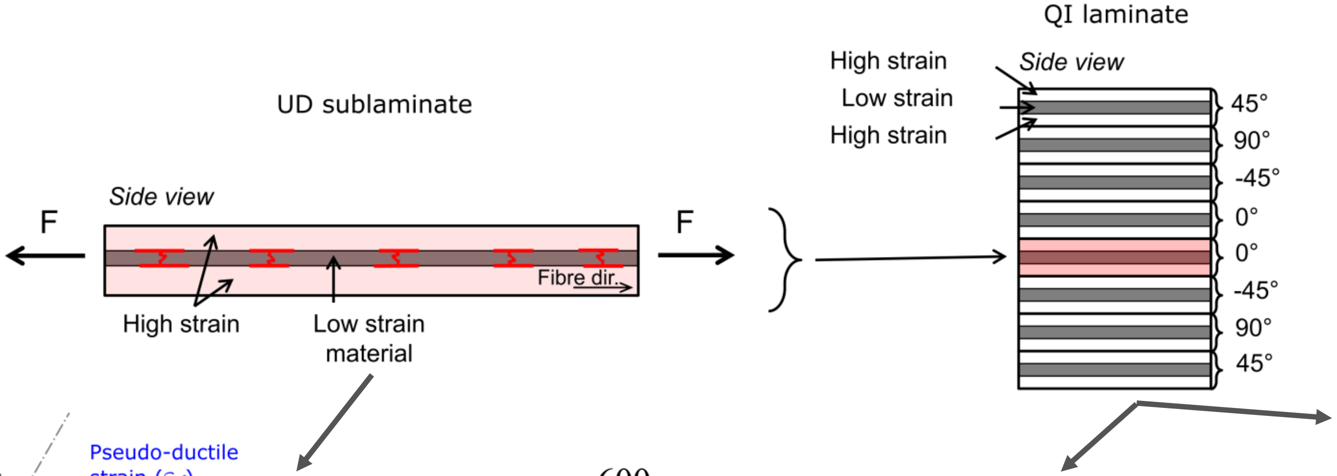
- Dimensional analysis is an efficient methodology to assess the influence of different input variables on a particular output variable of interest. It's carried using the principles of Buckingham π theorem.

- The ideal pseudo-ductile response has an intermediate plateau region before the "strain-hardening" leading to final failure.



Idealised tensile response of pseudo-ductile UD laminates

Dimensional analysis (2/4)



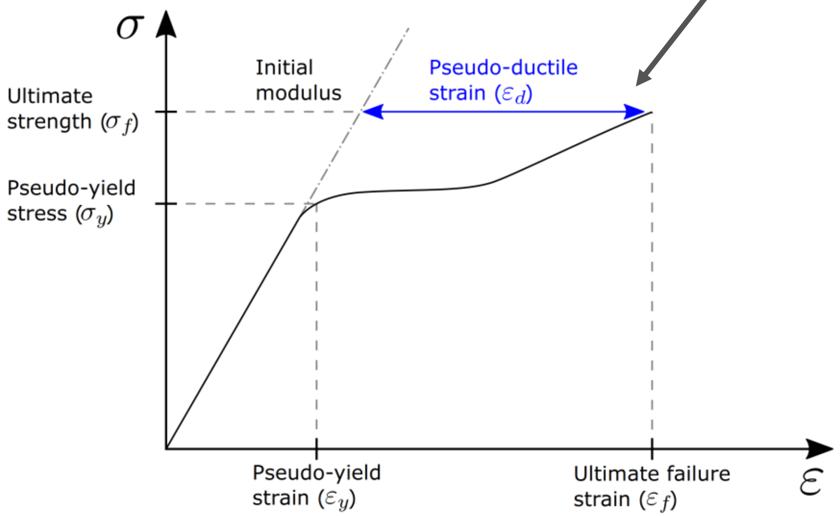
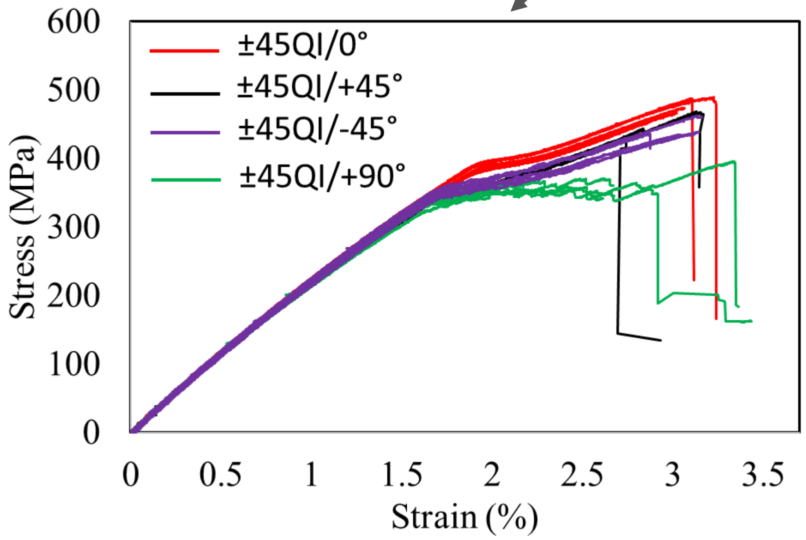
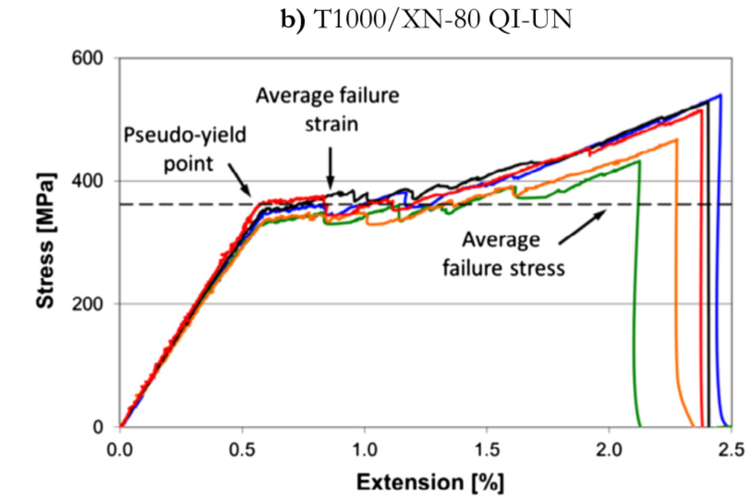


Figure 1: Idealised tensile response of pseudo-ductile QI laminates





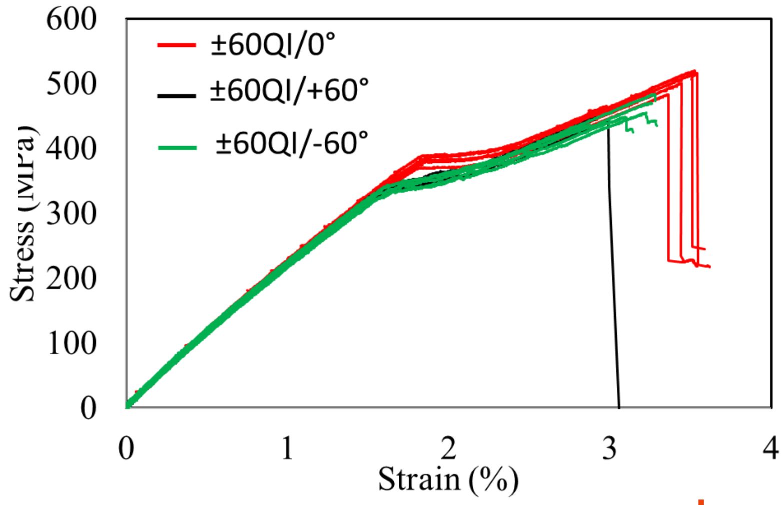
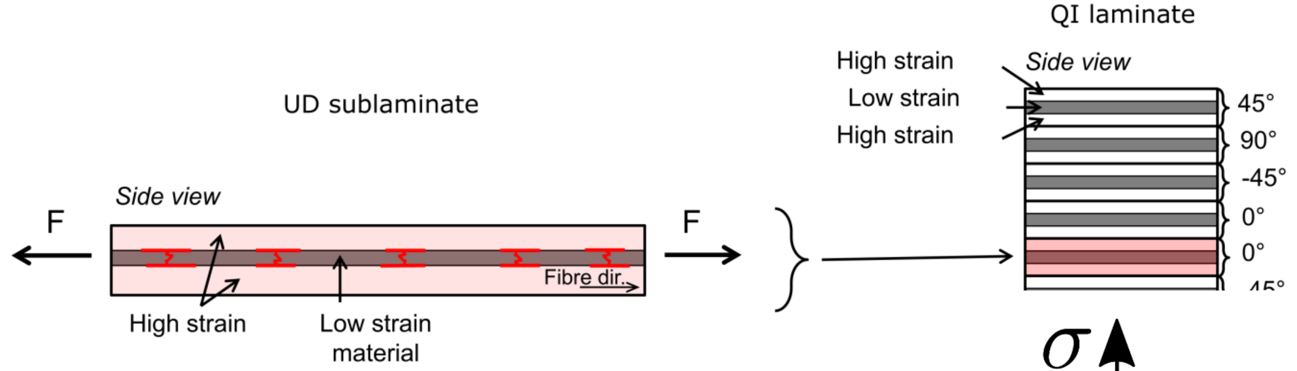


Figure 2: Tensile response of pseudo-ductile QI laminates

[1] Czel 2018 (j.compositesa.2017.10.028)
[2] Fotouhi 2017 (j.compscitech.2017.08.024)

Dimensional analysis (2/4)



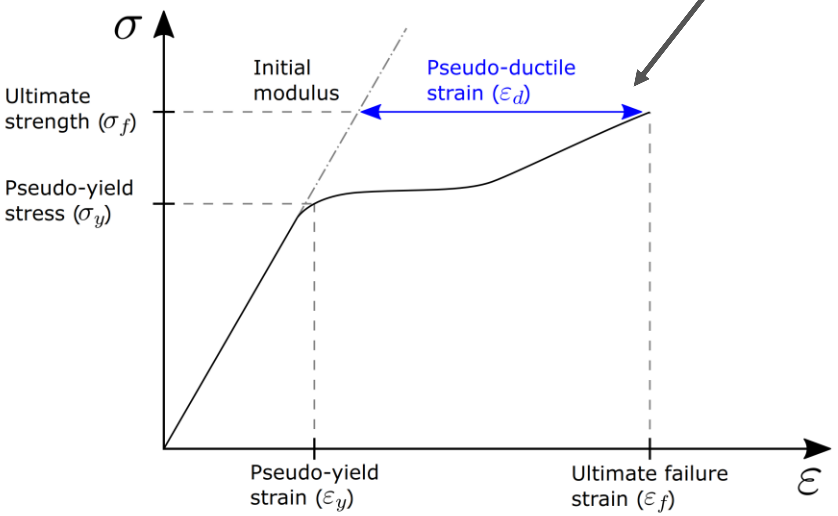


Figure 1: Idealised tensile response of pseudo-ductile QI laminates

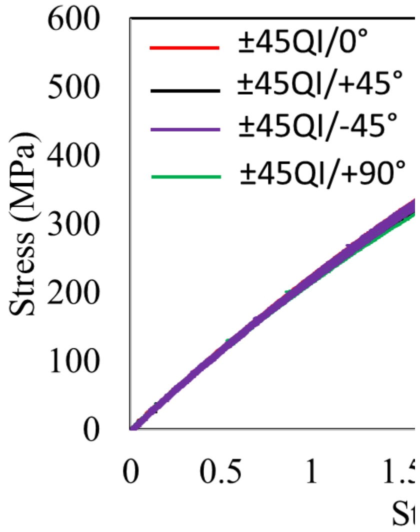
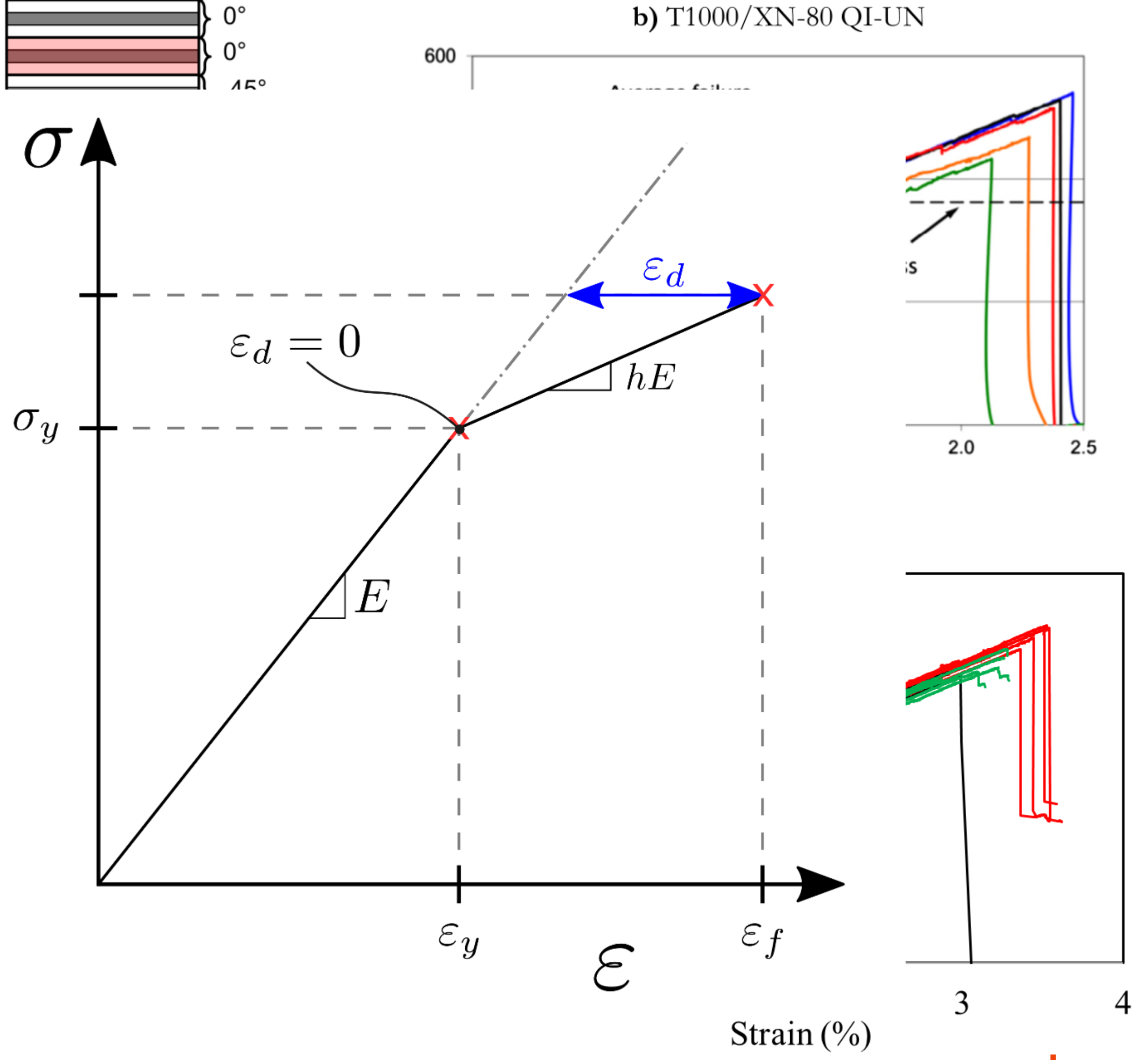


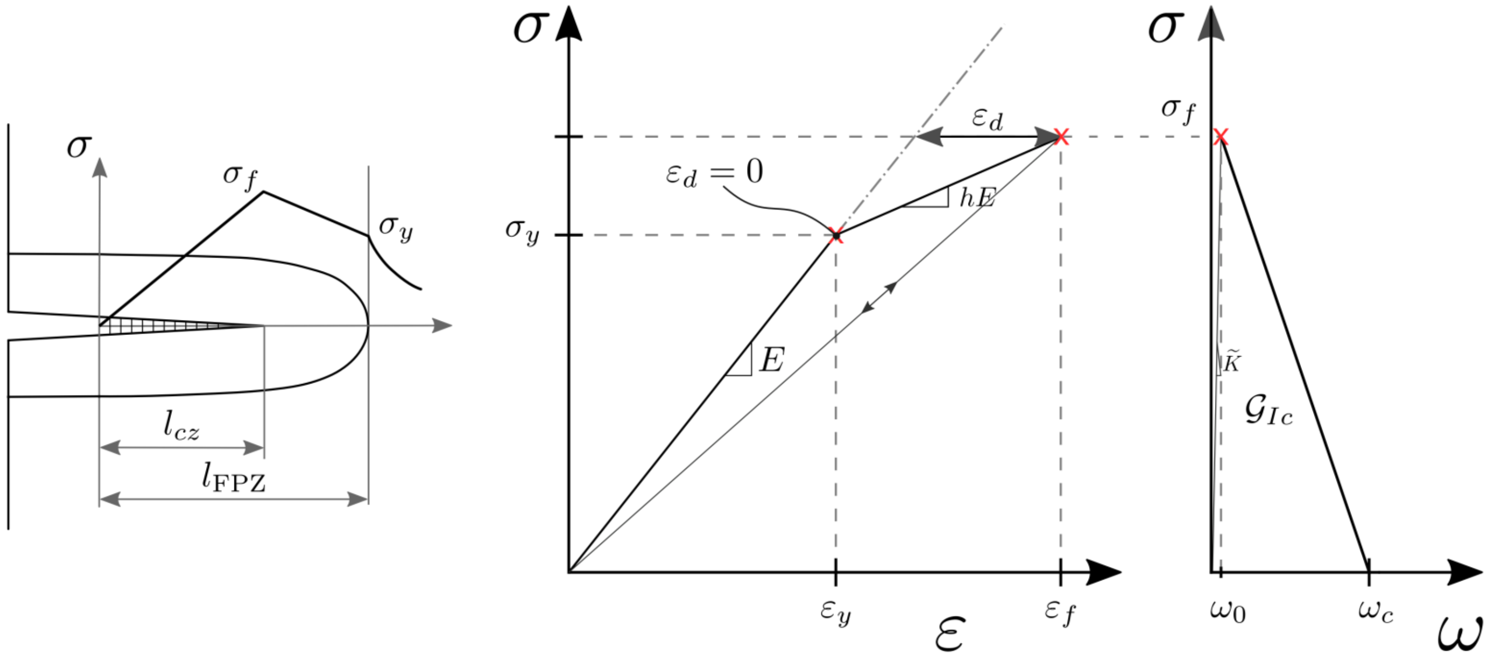
Figure 2: Tensil[e] pseudo-ductil[e] laminates



[1] Czel 2018 (j.compositesa.2017.10.028)
[2] Fotouhi 2017 (j.compscitech.2017.08.024)

Dimensional analysis (3/4)

- Linear elastic-linear hardening plastic material model for extrinsic separation (UMAT)
- Built-in traction-separation cohesive element for intrinsic separation.



Normalised pseudo-ductile uniaxial material response with degradation

Dimensional analysis (4/4)

- Influence of input variables on the fracture energy considering Compact Tension geometry. For a growing crack propagation, the model is of the form,

$$\mathcal{J}_\omega = f\left(E, \sigma_y, \varepsilon_d, \sigma_f, \mathcal{G}_{Ic}, \omega, W\right) \quad \dots (1)$$

Failure and cohesive strengths are assumed to be equal ($\sigma_f = \sigma_c$).

- At steady-state, $\frac{\sigma_y \omega_c}{2\mathcal{G}_{Ic}} \approx \text{constant}$, leading to,

$$\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}} = f\left(\varepsilon_y, \varepsilon_d, \frac{\sigma_f}{\sigma_y}\right) \quad \dots (2)$$

- Influence of ε_y is negligible in metals [1],

$$\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}} = f\left(\varepsilon_d, \frac{\sigma_f}{\sigma_y}\right) \quad \dots (3)$$

[1] Tvergaard 1992, 10.1016/0022-5096(92)90020-3, Brocks 2003, 10.1016/B0-08-043749-4/03102-5

Design of experiments

- The functional form has only 2 dependencies, therefore 2 studies were designed to determine their influence by keeping the other constant.

$$\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}} = f\left(\varepsilon_d, \frac{\sigma_f}{\sigma_y}\right)$$

$$** \; s_H = \frac{\sigma_f}{\sigma_y}$$

- Note that ε_{d4} and s_{H3} are equal.

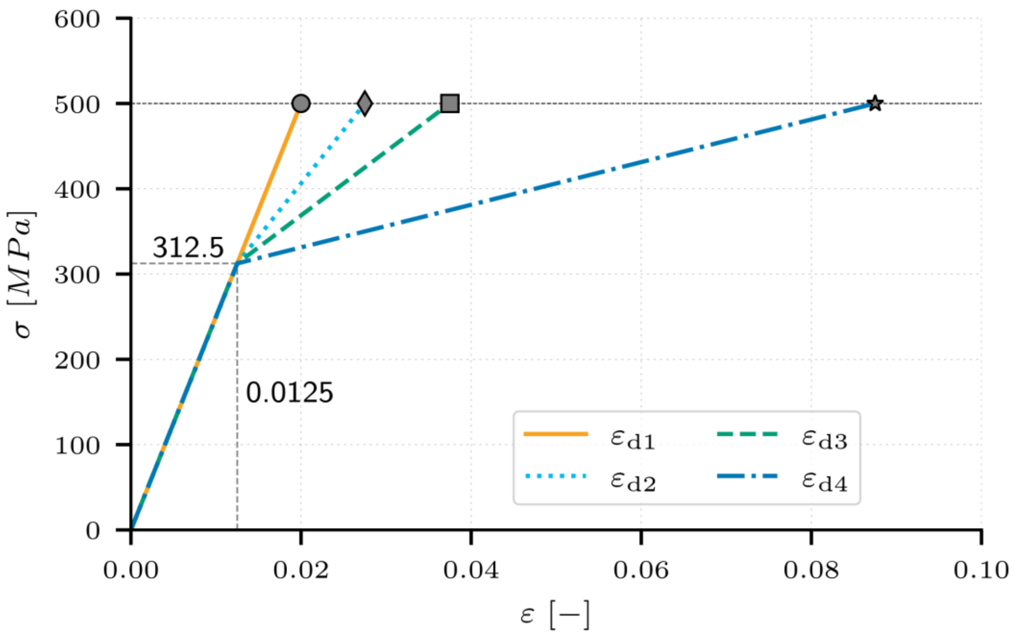


Figure 1: ε_{di} study: $f\left(\varepsilon_d, \frac{\sigma_f}{\sigma_y} = 1.6\right)$

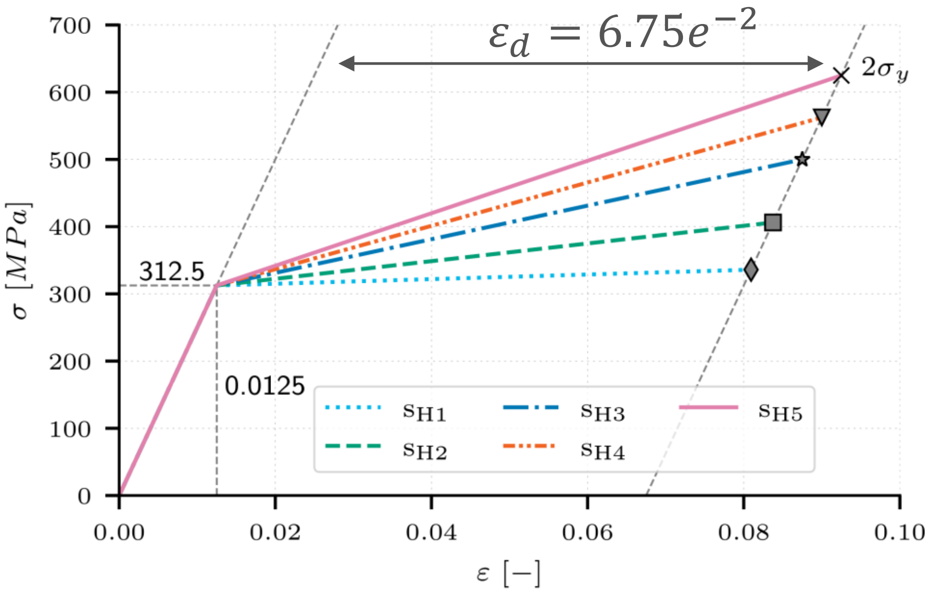


Figure 2: s_{Hi} study: $f\left(\varepsilon_d = 6.75e^{-2}, \frac{\sigma_f}{\sigma_y}\right)$

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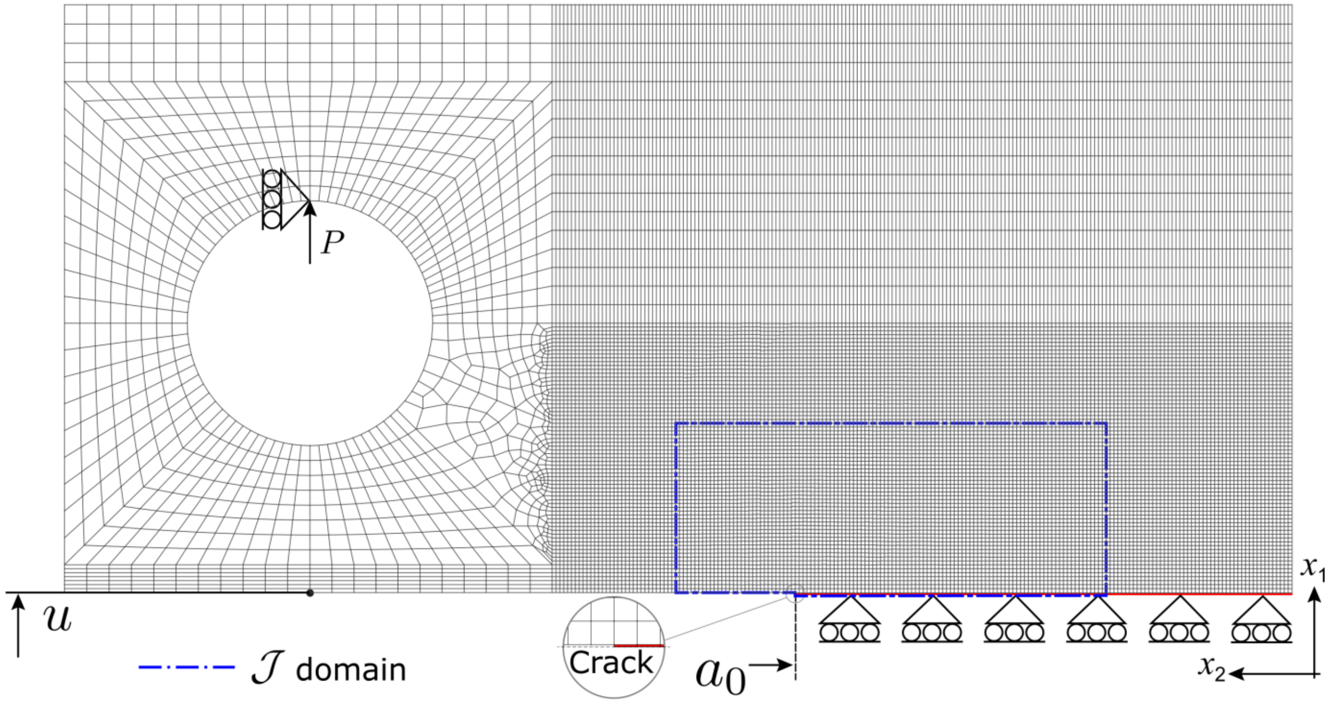
CT models

CT model (1/6)

- CT FE model with BC's and the domain used for J-integral calculation.
- Since only half the cohesive elements are modelled, so does the energy $0.5\mathcal{G}_{Ic}$.
- Only intrinsic behaviour is varied, extrinsic dissipation is kept constant using $\mathcal{G}_{Ic} = 75\frac{N}{mm}$.



CT model (2/6) – P-u behaviour of ε_{di} & s_{Hi} study.

- The LEFM P-u behaviour was drawn using the compliance and SIF relationships from Tada (2000) for a fixed $\frac{a}{W} = \frac{26}{51} = 0.51$.

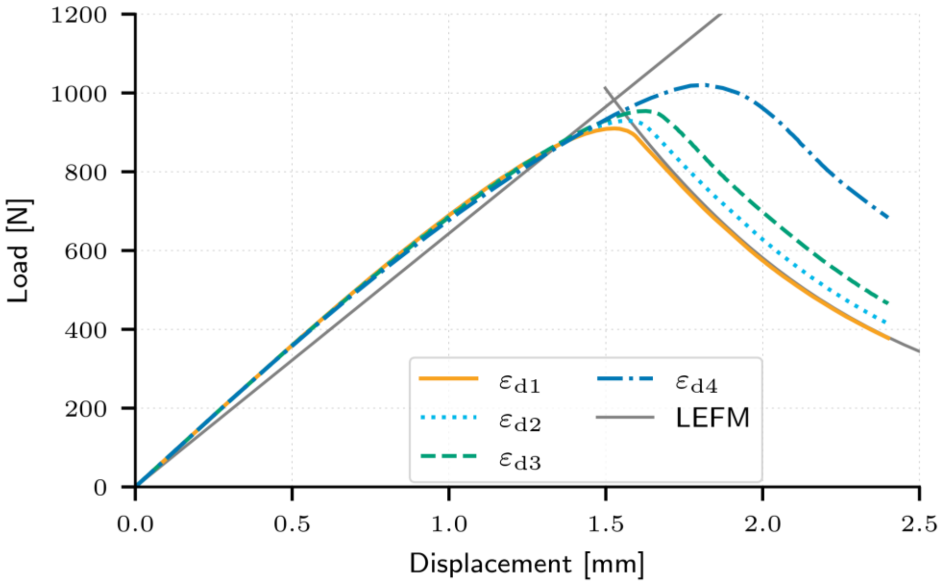


Figure 9: P-u behaviour of ε_{di} study cases with fixed $\frac{\sigma_f}{\sigma_y} = 1.6$

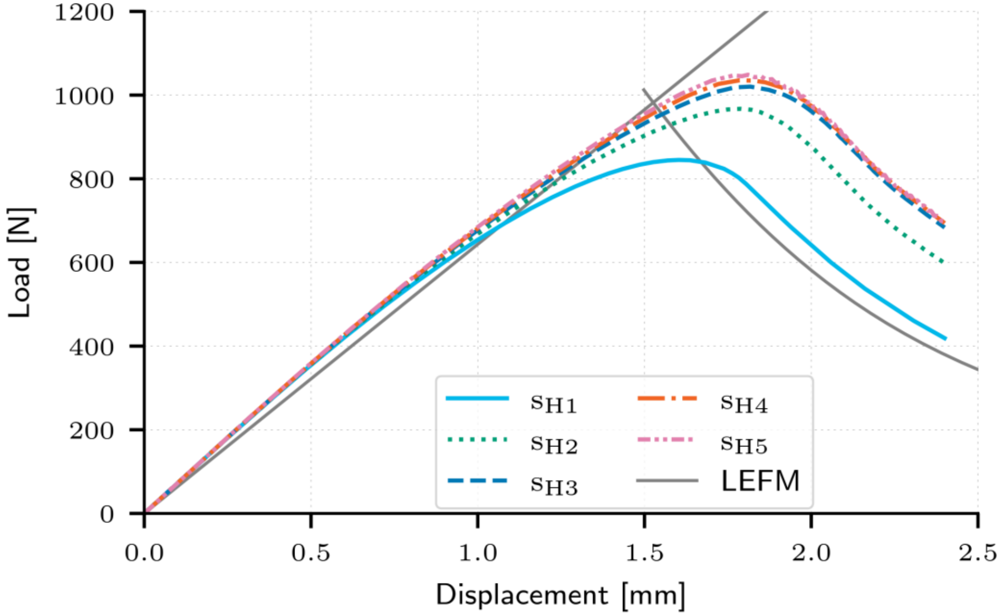


Figure 10: P-u behaviour of s_{Hi} study cases with fixed $\varepsilon_d = 6.75e^{-2}$

CT model (3/6) – $\frac{\mathcal{J}_\omega}{\mathcal{G}_{Ic}}$ behaviour of ε_{di} & s_{Hi} study.

- Normalised J-integral were obtained from the domain selected using the built-in area integral evaluation in Abaqus.

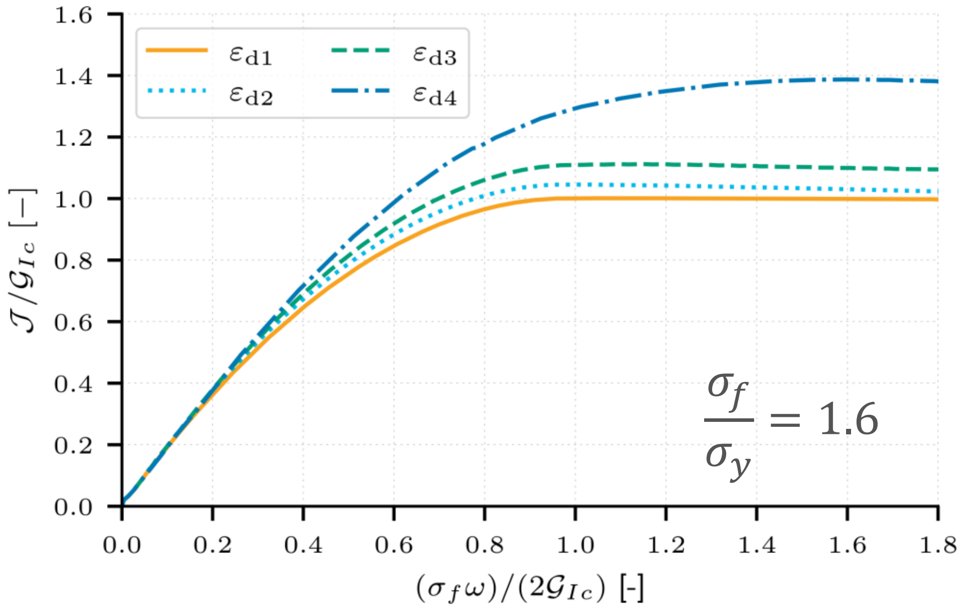


Figure 1: Normalised $\mathcal{J}_\omega$ behaviour of ε_{di} study cases with fixed $\frac{\sigma_f}{\sigma_y} = 1.6$

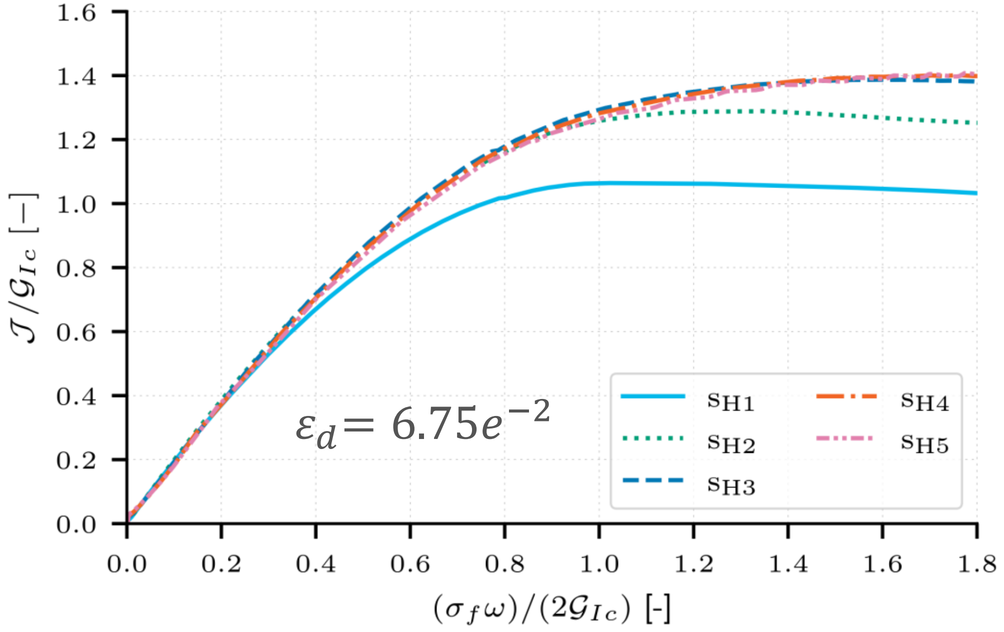
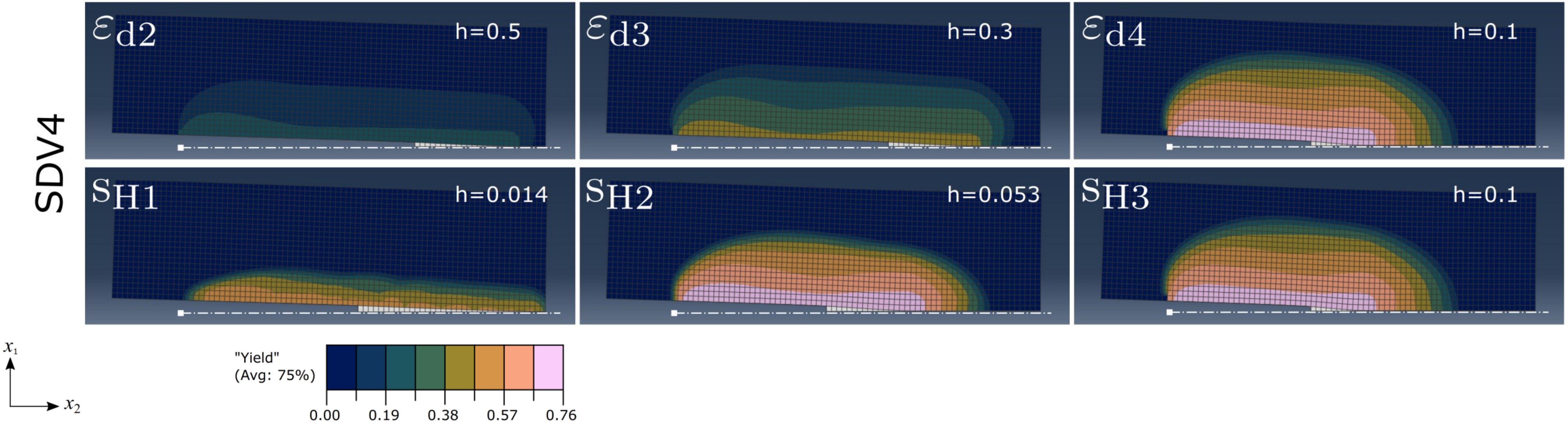
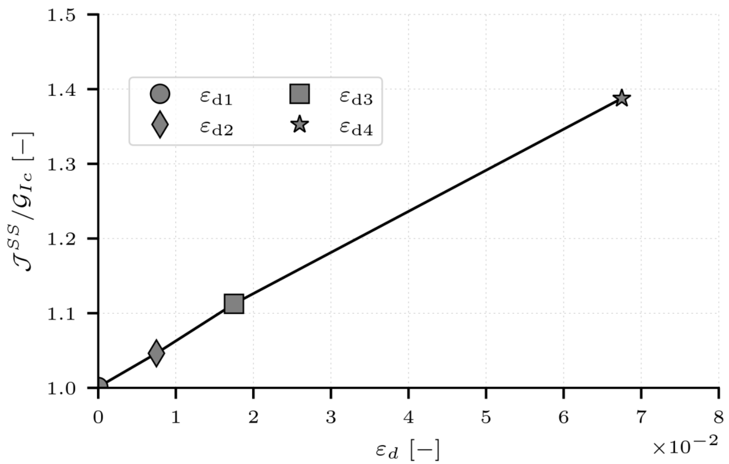


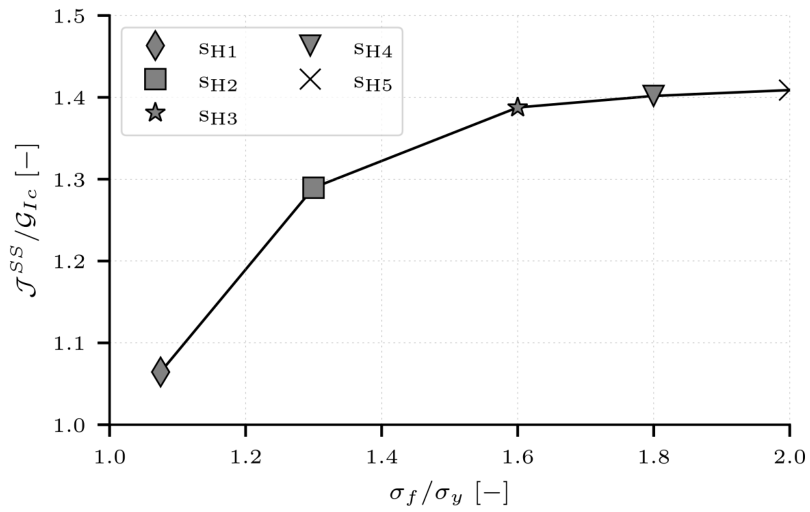
Figure 2: Normalised $\mathcal{J}_\omega$ behaviour of s_{Hi} study cases with fixed $\varepsilon_d = 6.75e^{-2}$

CT model (5/6) – Plastic zone shapes.



Plastic zone shapes of selected models.





CT model (6/6) - Conclusions

- From the functional form derived using dimensional analysis,

$$\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}} = f\left(\varepsilon_d, \frac{\sigma_f}{\sigma_y}\right)$$

- We can conclude that the
  - The pseudo-ductile strain(ε_d) has the linear influence on the toughness.
  - The normalised strengths ($\frac{\sigma_f}{\sigma_y}$) has significant influence initially then reaches a plateau.

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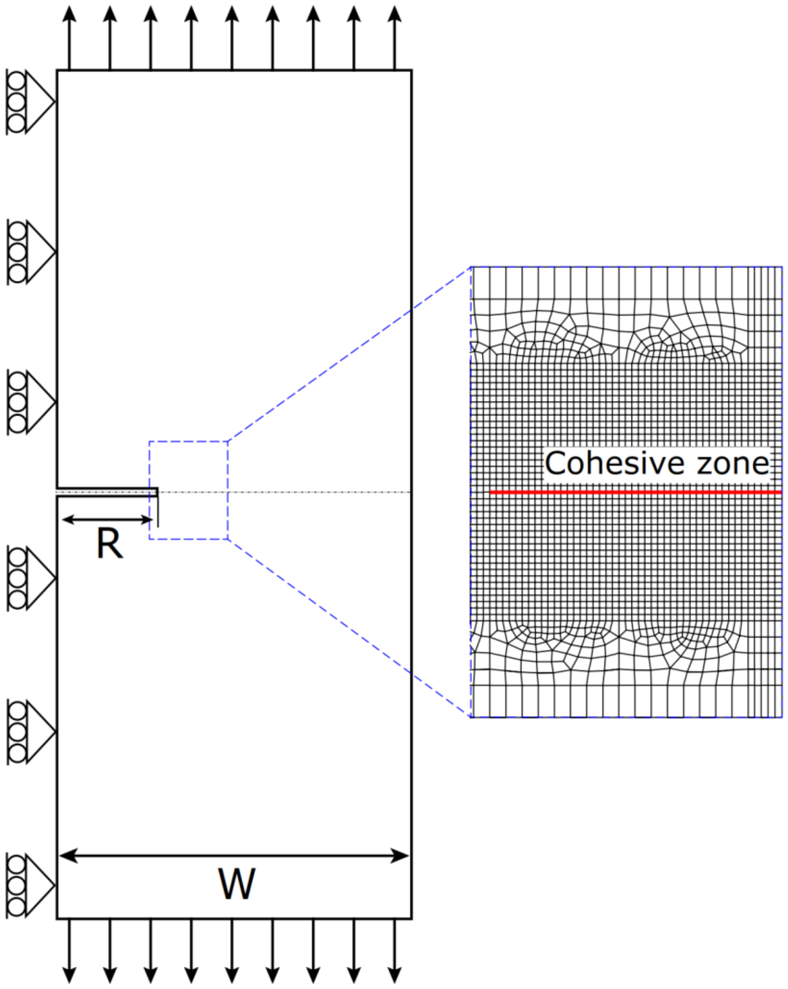
OHT & CCT models

OHT & CCT models

- Similar to CT models, half-symmetric plane stress models were developed for OHT and CCT specimens.
- It is assumed that the crack propagates in a straight line and cohesive elements were used to model them using traction separation behaviour. And the bulk material behaviour is modelled with the same elastic-plastic UMAT.
- Size effect were also considered, models with crack size/hole radius ranging from 0.2mm to 160mm (0.2, 0.5, 1, 4, 8, 12, 16, 80, 160mm). We assume a constant $\left(\frac{R}{W} = \frac{1}{6}\right)$.



Size effect law

- Bazant introduced SEL by asymptotically matching the strengths of smaller and larger specimens of similar geometries in relation to the FPZ length.

$$s_N = \frac{\sigma_N}{\sigma_f} = \left(\frac{K_t^{-r} + \bar{l}_{SEL}}{1 + \bar{l}_{SEL}}\right)^{\left(\frac{1}{2}\right)}$$

$$\bar{l}_{SEL} = \frac{E\mathcal{G}_{Ic}}{\sigma_u^2 F^2 R}$$

where $K_t \left(= \frac{\sigma_f}{\sigma_\infty}\right)$ is the stress concentration factor and F is the geometric correction factor to account for finite width effects.

[1] Pere 2012 (j.compscitech.2012.04.004)

Size effect law – CCT results

$$\frac{\sigma_N}{\sigma_f} = \left(\sqrt{\frac{1}{1+\bar{l}_{SEL}}}\right); \ \bar{l}_{SEL} = \frac{E\mathcal{J}^{ss}}{\pi R F^2 \sigma_f^2}$$

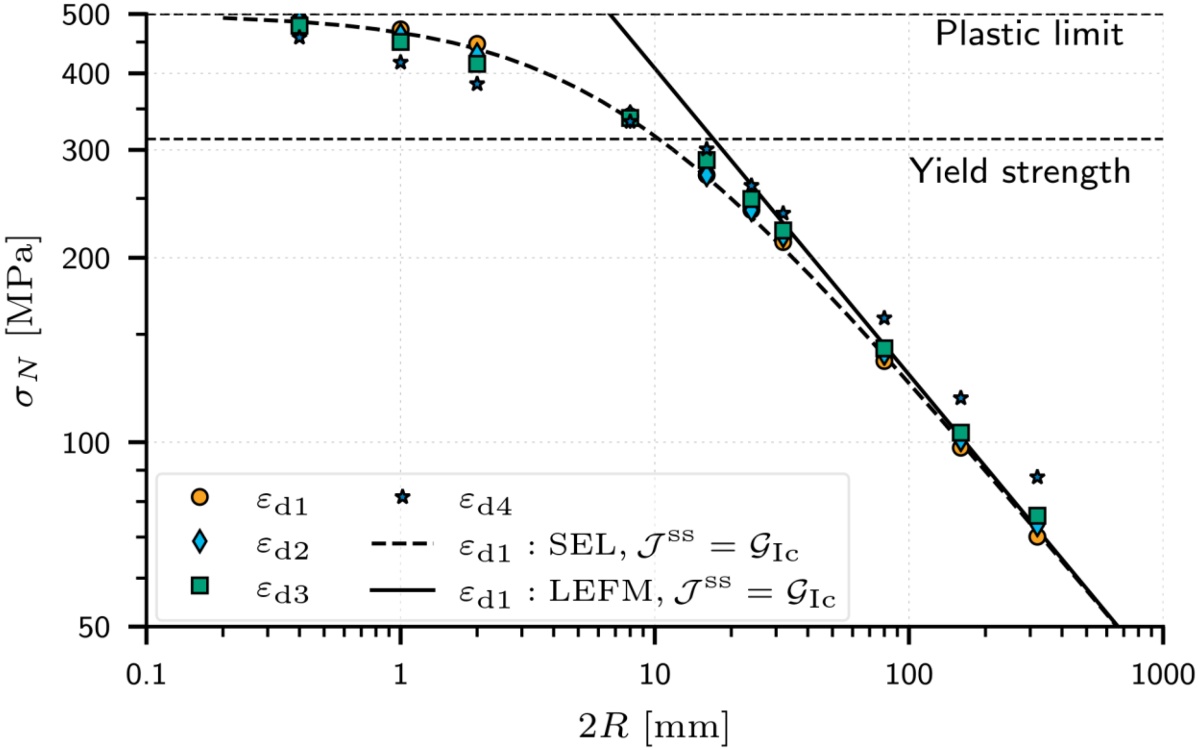


Figure 1: CCT nominal strengths of ε_{di} study cases with fixed $\frac{\sigma_f}{\sigma_y} = 1.6$

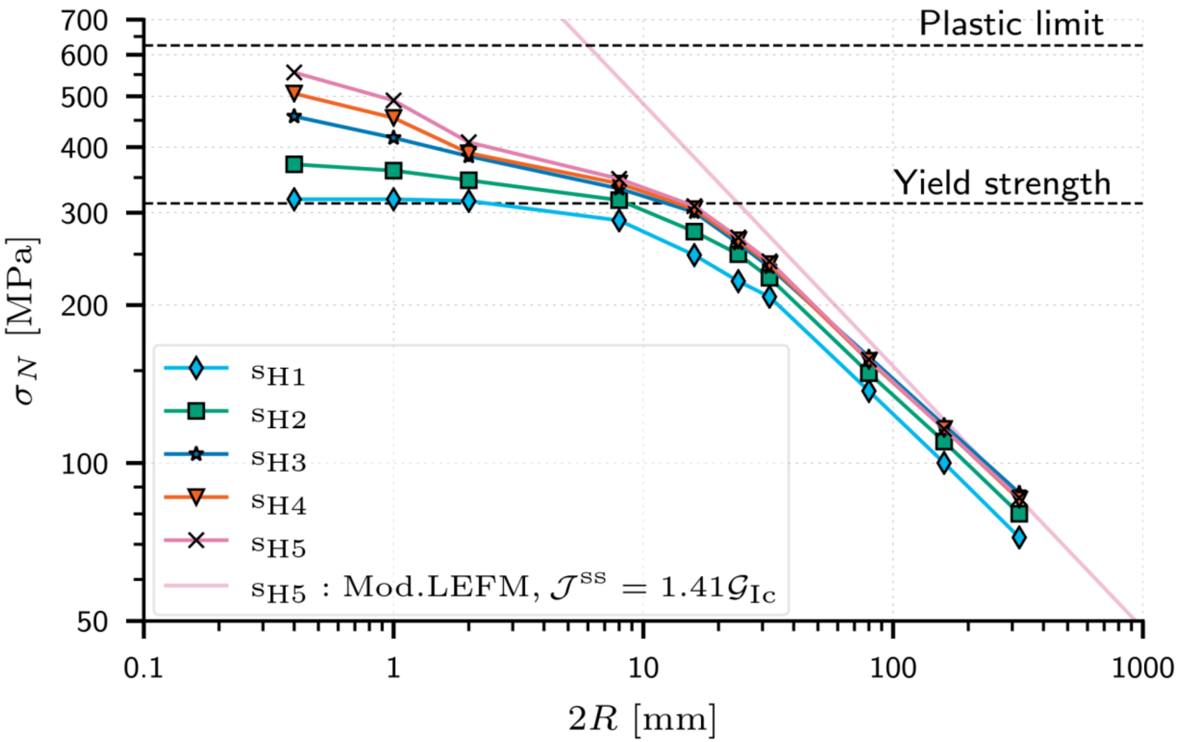
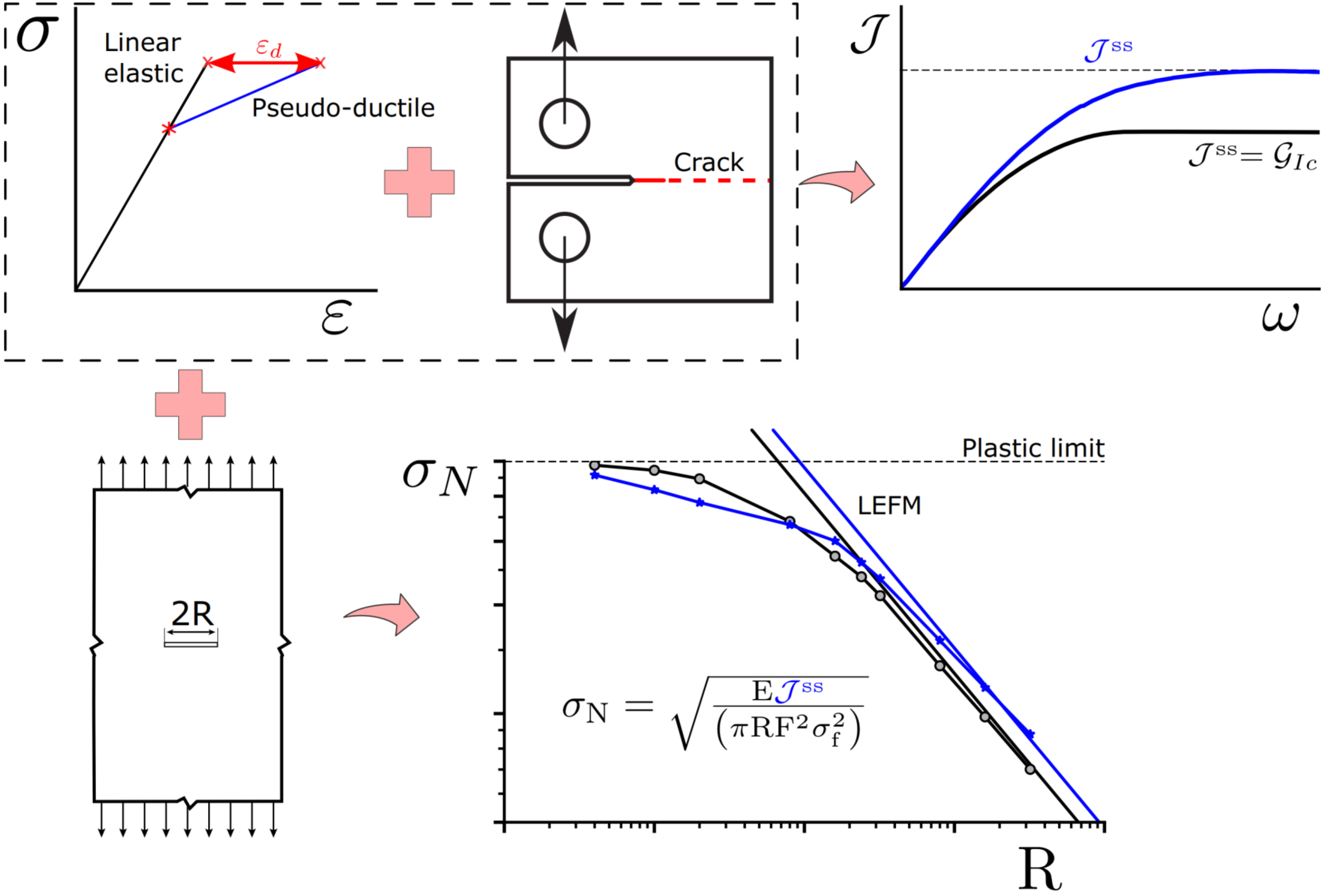


Figure 2: CCT nominal strengths of s_{Hi} study cases with fixed $\varepsilon_d = 6.75e^{-2}$

CCT RESULTS - CONCLUSIONS



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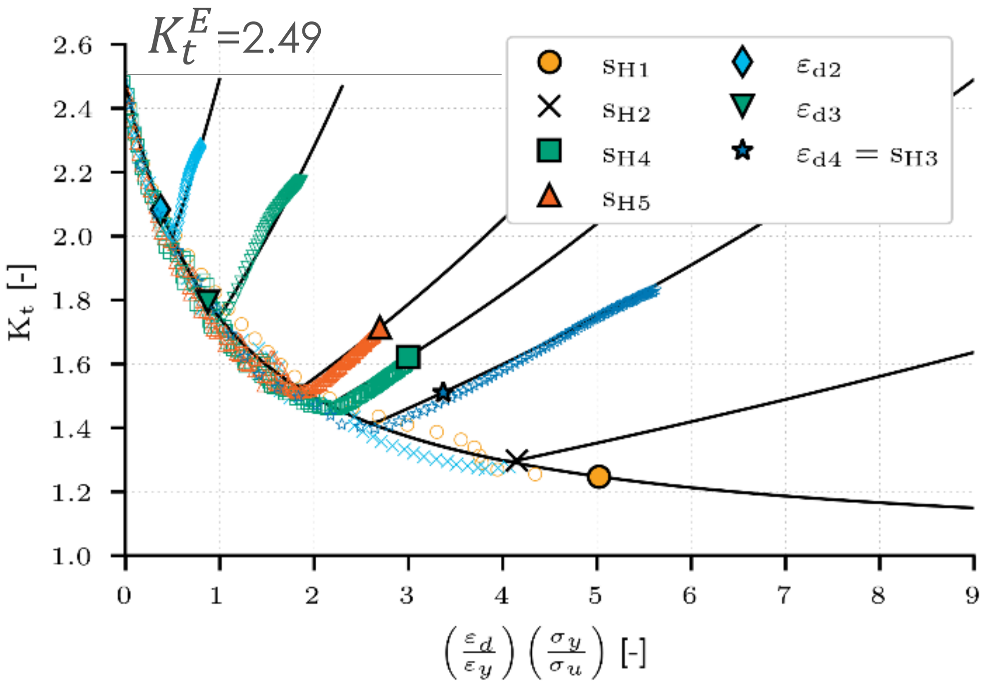
OHT models

Size effect law – Plastic SCF for all the cases

- Stowell proposed that the plastic stress-concentration factor, K_t^P,

$$K_t^P = 1 + (K_t^E - 1)\frac{E_{S,max}}{E_{S,\infty}}$$

$E_{S,max}$ is the secant modulus at the point of max. stress and $E_{S,\infty}$ is the secant modulus of far-field stress



Plastic stress concentration factors compared to the numerical results.

Stowell 1950, 978-1-68015-617-1

Size effect law – OHT results

$$s_N = \frac{\sigma_N}{\sigma_f} = \left(\frac{K_t^{-r} + \bar{l}_{SEL}}{1 + \bar{l}_{SEL}}\right)^{\left(\frac{1}{2}\right)} ; \ \bar{l}_{SEL} = \frac{E\mathcal{J}^{ss}}{\sigma_u^2 F^2 R}$$

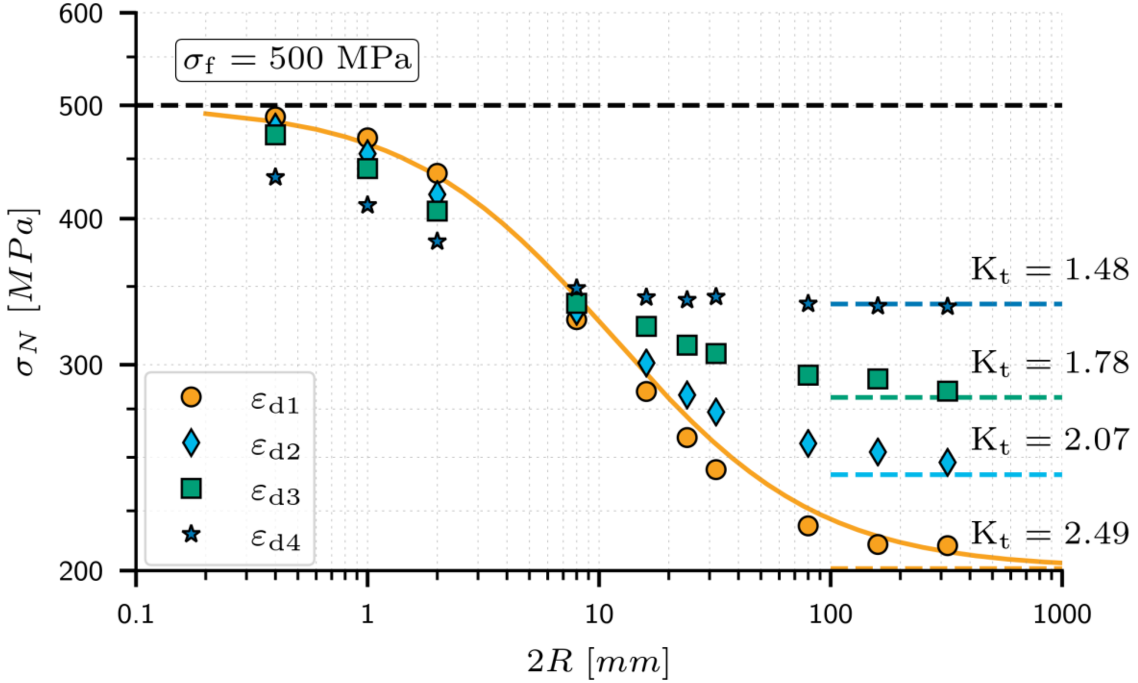


Figure 1: OHT nominal strengths of ε_{di} study cases with fixed $\frac{\sigma_f}{\sigma_y} = 1.6$

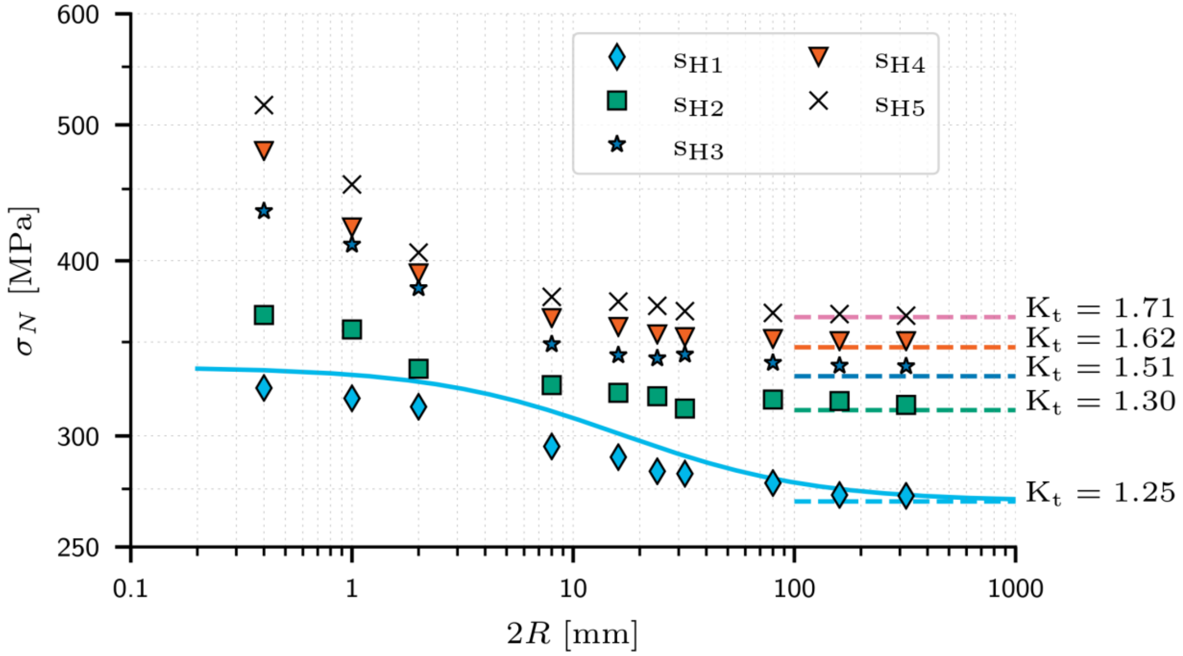
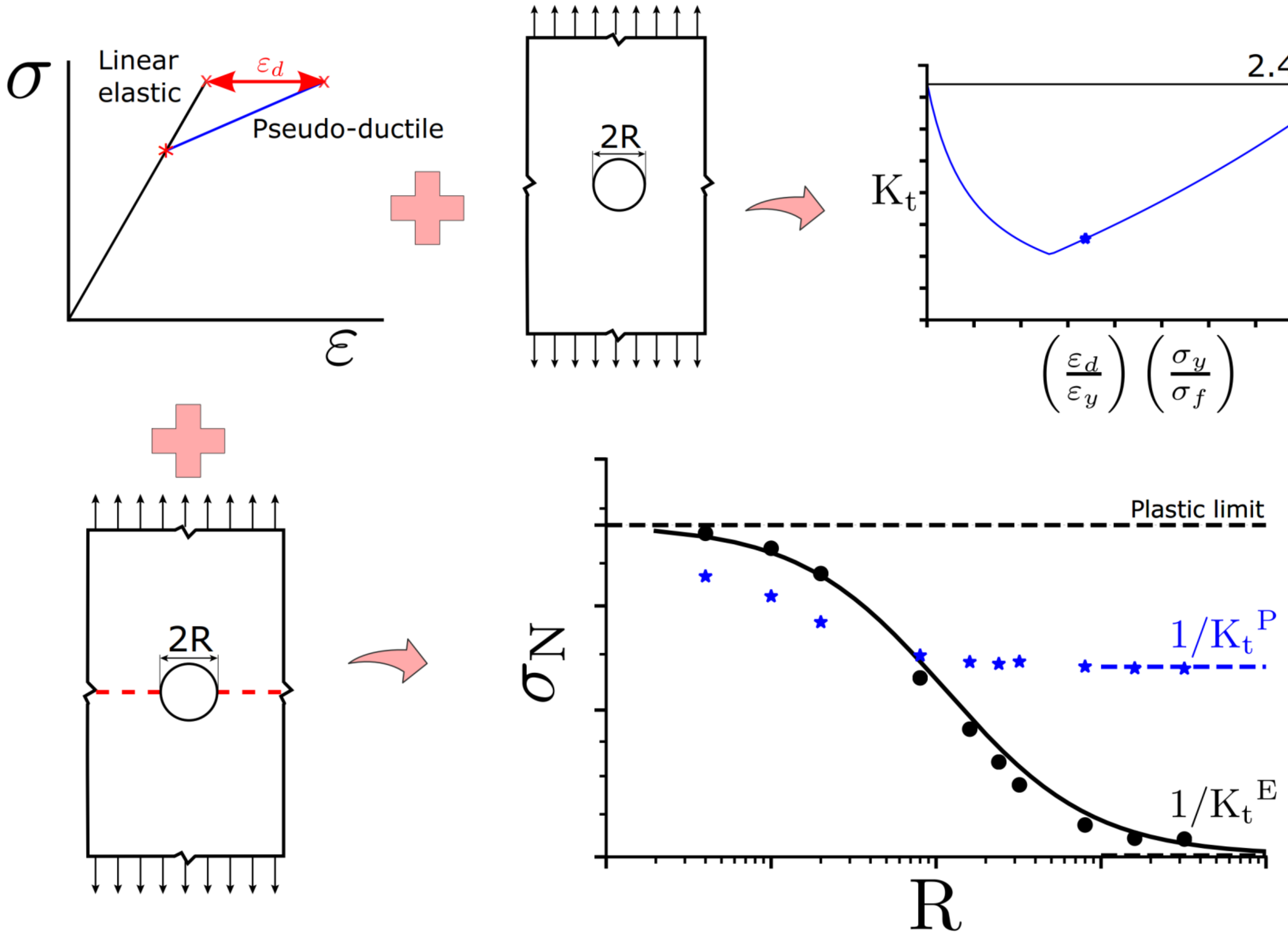


Figure 2: OHT nominal strengths of ε_{di} study cases with fixed $\varepsilon_d = 6.75e^{-2}$

OHT RESULTS - CONCLUSIONS



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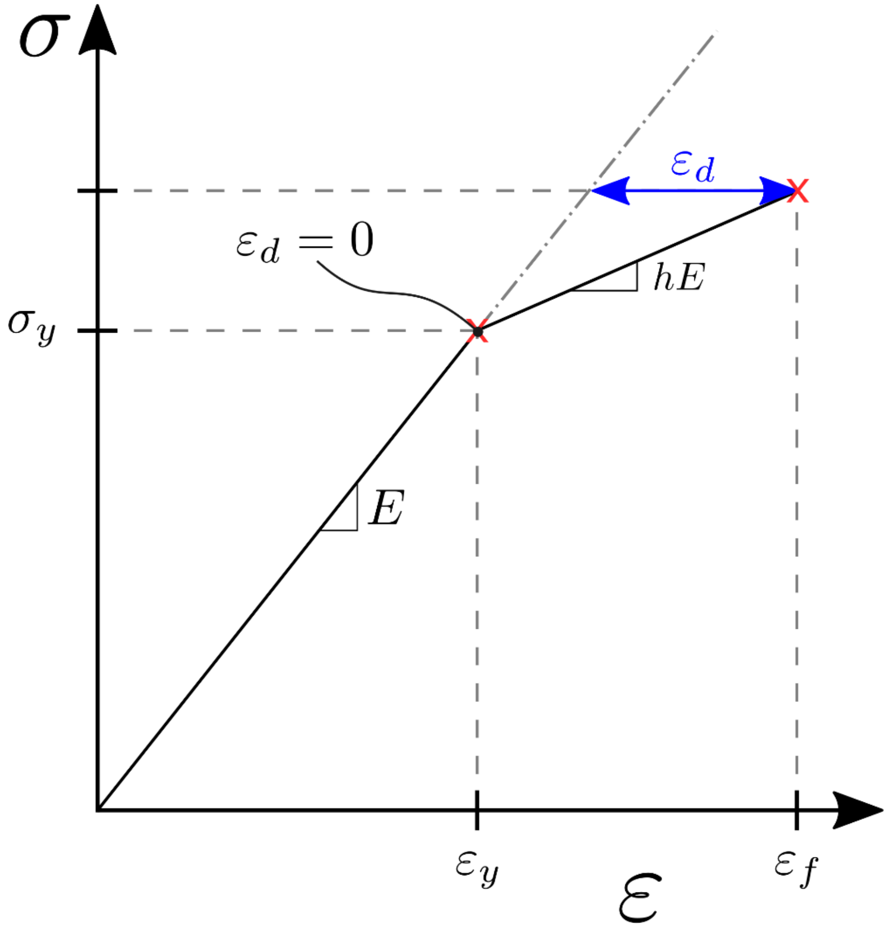
Dimensional analysis (3/5)

- However, they're virtually non-existent in the quasi-isotropic laminates.



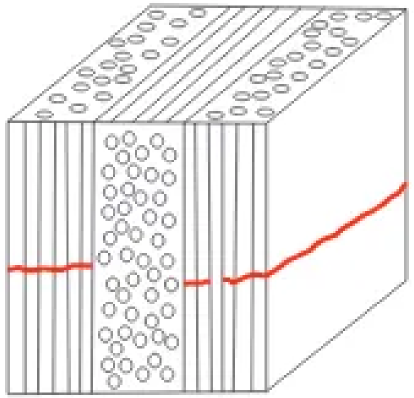
Idealised tensile response of pseudo-ductile QI laminates

Introduction (2/2)

- The translaminar toughness in conventional composite materials, is well understood. (For e.g., Ortega's work).
  - It can be conveniently modelled through cohesive law, $\mathcal{G}_{Ic} = \int \sigma(\omega) d\omega$

- From the EPSRC (UK) funded HiPerDuCT program, several researchers have demonstrated the possibility of creating pseudo-ductile behaviour in composite laminates through several methodologies.
  - Inter-ply and Intra-ply hybrids, Jalavand et al., (2014), Czél et al., (2015), Czél et al., (2018) and Fotouhi et al., (2018)
  - Angle-ply laminates e.g., $[\pm 27_7/0]_s$ Fuller et al., (2015), Wu et al., (2020)

Translaminar toughness



- Turner's definition, the energy dissipated by different mechanisms can be expressed as the sum of dissipated energies, i.e., irreversible strain energy (plasticity) and the energy dissipated in the creation of new crack surfaces [1].

$$R = \frac{dU}{dA} = \frac{dU_{sep}}{Bda} + \frac{dU_{plas}}{Bda} \quad \ldots (1)$$

- Without placing any restrictions on the size of plastic zone (SSY/LSY), for a non-linear material we can equivalently express eqn. 1 using $\mathcal{J}$-integral as,

$$\mathcal{J}^{ss} = \mathcal{J}_{CL} + \mathcal{J}_{pl} \ldots (2)$$

  - Under mode I loading, in the case of purely elastic material where the intrinsic contribution is 0 ($\mathcal{J}_{plas}$= 0), $\mathcal{J}^{ss} = \Gamma_0 = \mathcal{G}_{Ic}$.
  - By keeping the energy dissipated by the cohesive law ($\mathcal{J}_{CL}$) constant and altering the material properties, we could study its influence on the fracture toughness ($\mathcal{J}^{ss}$).

[1] Turner 1990, 978-0-947817-41-1;

CT model (4/6) – Steady state $\frac{\mathcal{J}^{SS}}{\mathcal{G}_{Ic}}$ behaviour.

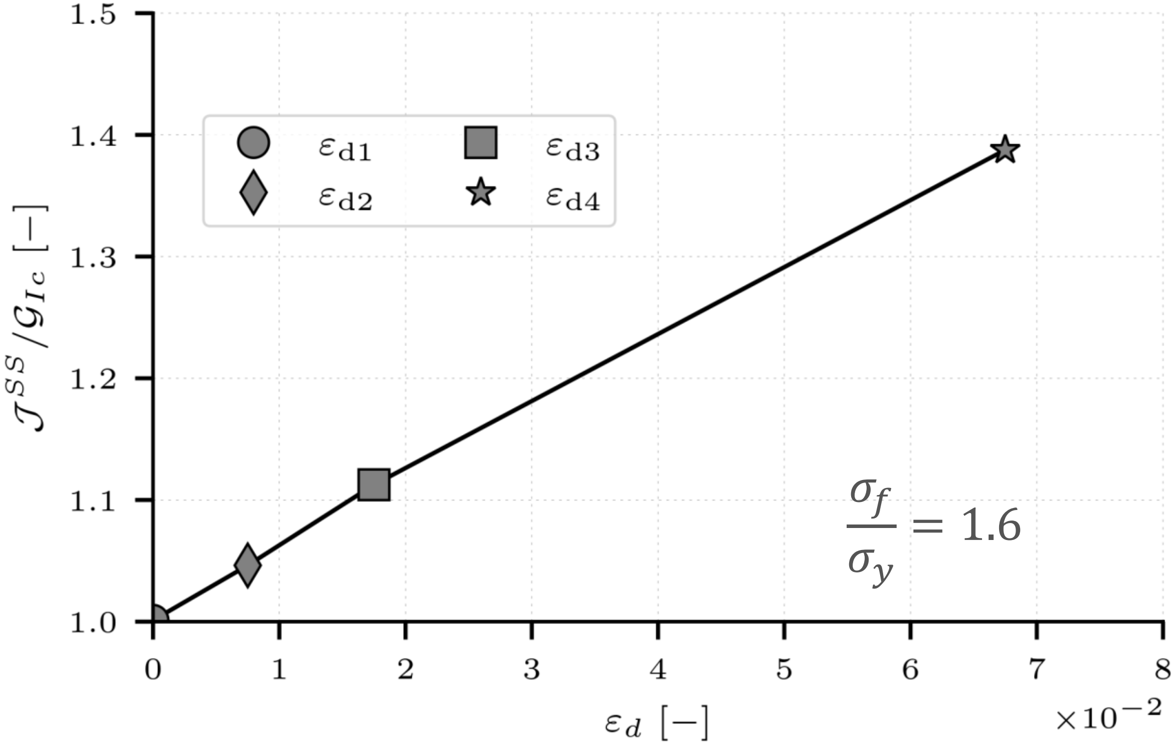


Figure 1: Influence of ε_d on normalised $\mathcal{J}^{SS}$ behaviour.

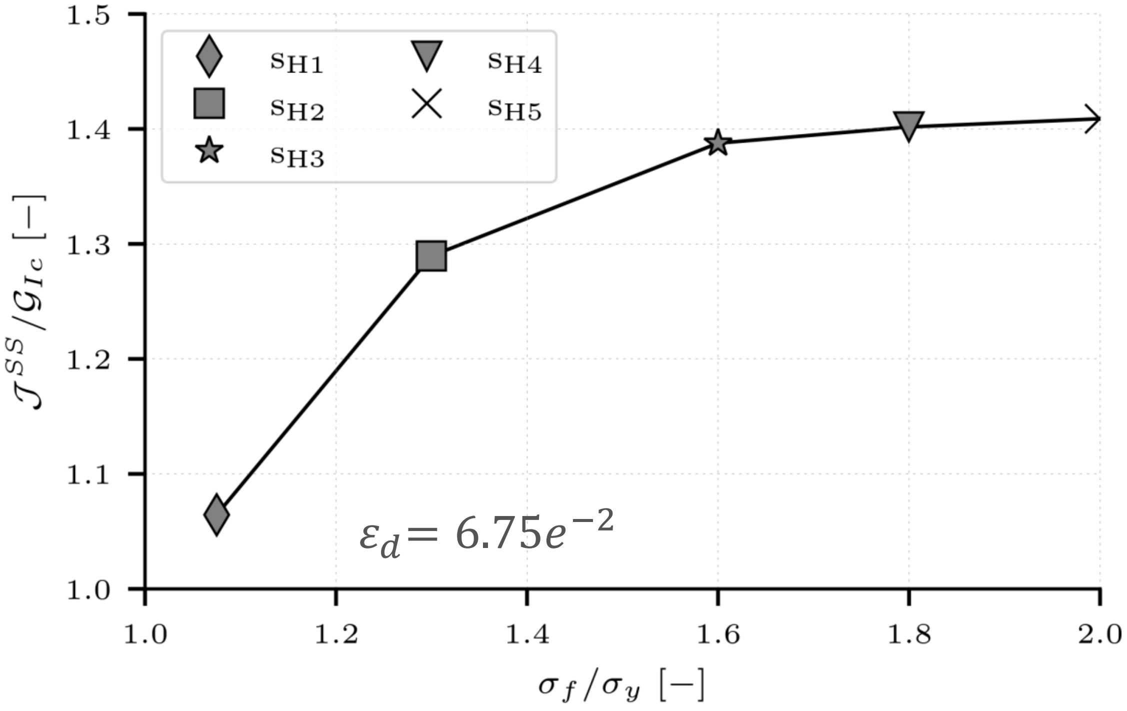


Figure 2: Influence of $\frac{\sigma_f}{\sigma_y}$ on normalised $\mathcal{J}^{SS}$ behaviour.

Modified size effect law – CCT results

- SEL

$$\frac{\sigma_N}{\sigma_f} = \left(\sqrt{\frac{1}{1+\bar{l}_{SEL}}}\right)$$

- Modified SEL

$$\frac{\sigma_N}{\sigma_f} = \left(\frac{\bar{l}_{SEL}(1-h)}{2s_H\left(\bar{l}_{SEL}+h\right)} + \sqrt{\left[\frac{\bar{l}_{SEL}(1-h)}{2s_H\left(\bar{l}_{SEL}+h\right)}\right]^2 + \frac{h}{h+\bar{l}_{SEL}}}\right)$$

$$\bar{l}_{SEL} = \frac{E\mathcal{J}^{ss}}{\pi RF^2\sigma_f^2};$$

$$h = \frac{H}{E};\, s_H = \frac{\sigma_f}{\sigma_y}$$