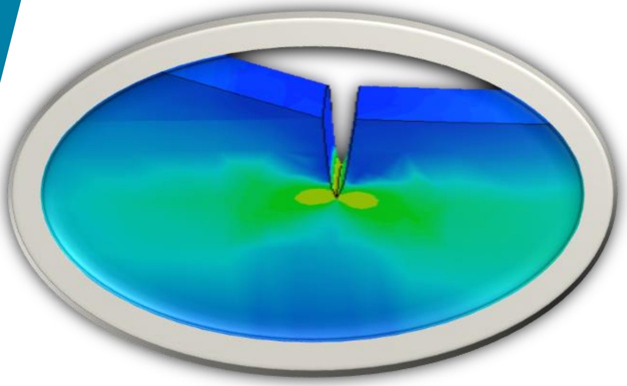
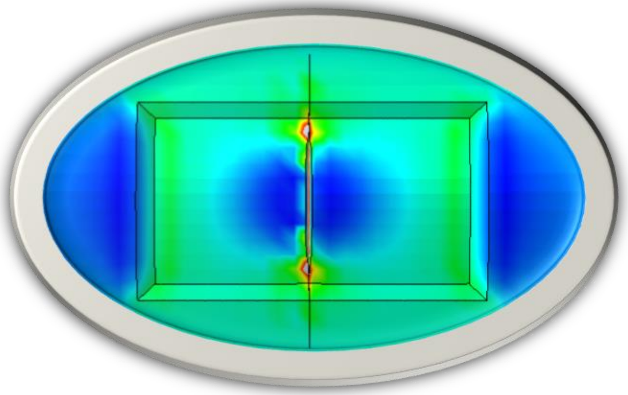
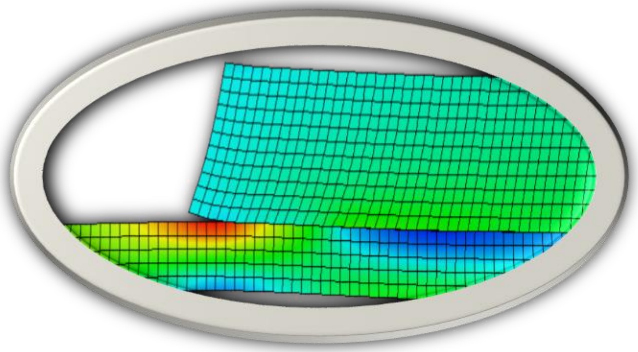

# Evolution of Crack Stress Fields in Composite Repaired Section

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# Introduction

## Low installation cost
Compared to steel sleeve repair.

## Safe
Eliminates hot work hazards

## Non disruptive
No operation interruption.

## Increased utilization
A spike in investor interests

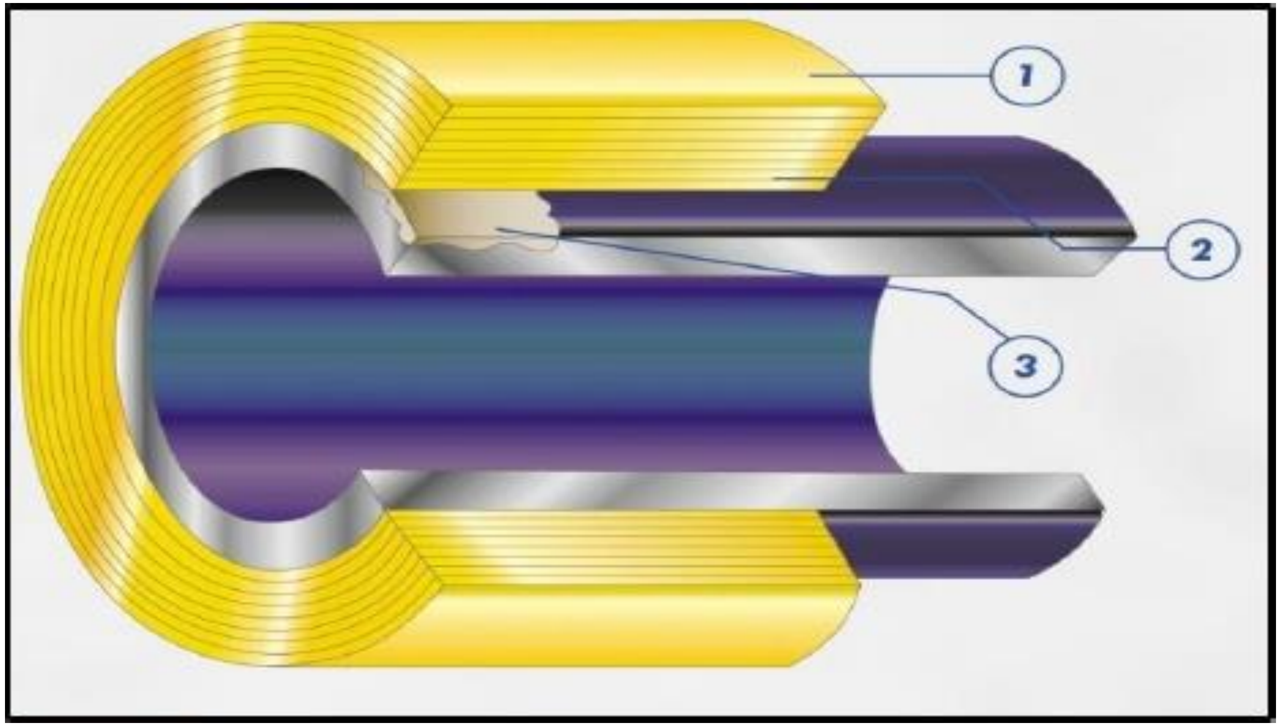
## >25 years
Industry application

## Internationally standardized
ISO/TS 24817, ASME PCC-2

## Diverse applications
Sewer, water, oil and gas, offshore structures

## Continuous development
JIP, research insights

# Repair system




1. Fibre-reinforced polymer (FRP) sleeve: primary load carrying component, high strength
2. Interlayer adhesive: primary load transfer component (defect free pipe section – sleeve)
3. Grout (putty): primary load transfer component (defect pipe section – sleeve), ensure uniform profile for the composite layer.

# Research questions???

**Known:**

- The stresses upstream and downstream the composite repair section are functions of nature of loading, repair strategy, repair thickness, ply orientation, putty properties, surface finishing, etc [1].
- The stresses at the repaired section are primarily dependent on the status of the interlayer between the pipe and the composite [2].
- Residual stresses can lower interlayer shear limit, leading to poor load transference and higher stresses at the repaired section [3].

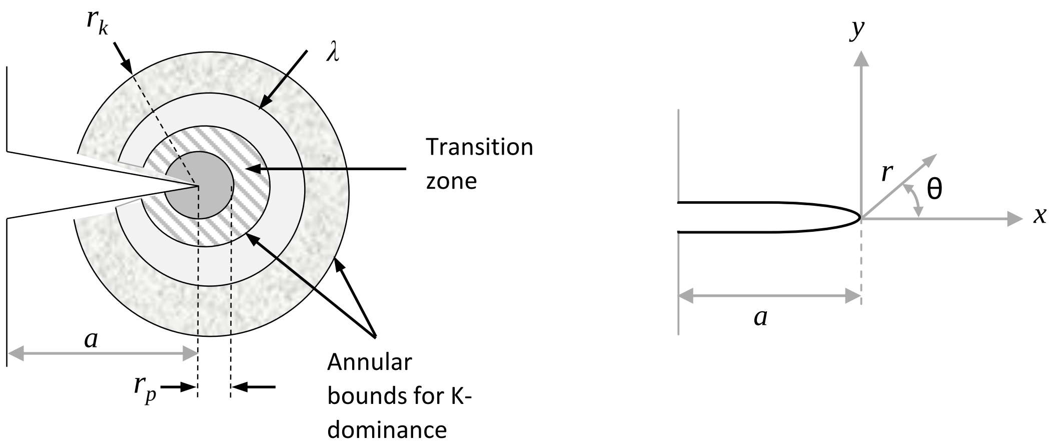
# Research questions???

**Unknown:**

- The relationship between degradation of interlayer stiffness and crack nucleation at the repaired section.
- The relationship between crack location and its stress intensity.
- The relationship between damage evolution of the interlayer and crack propagation at the repaired section.

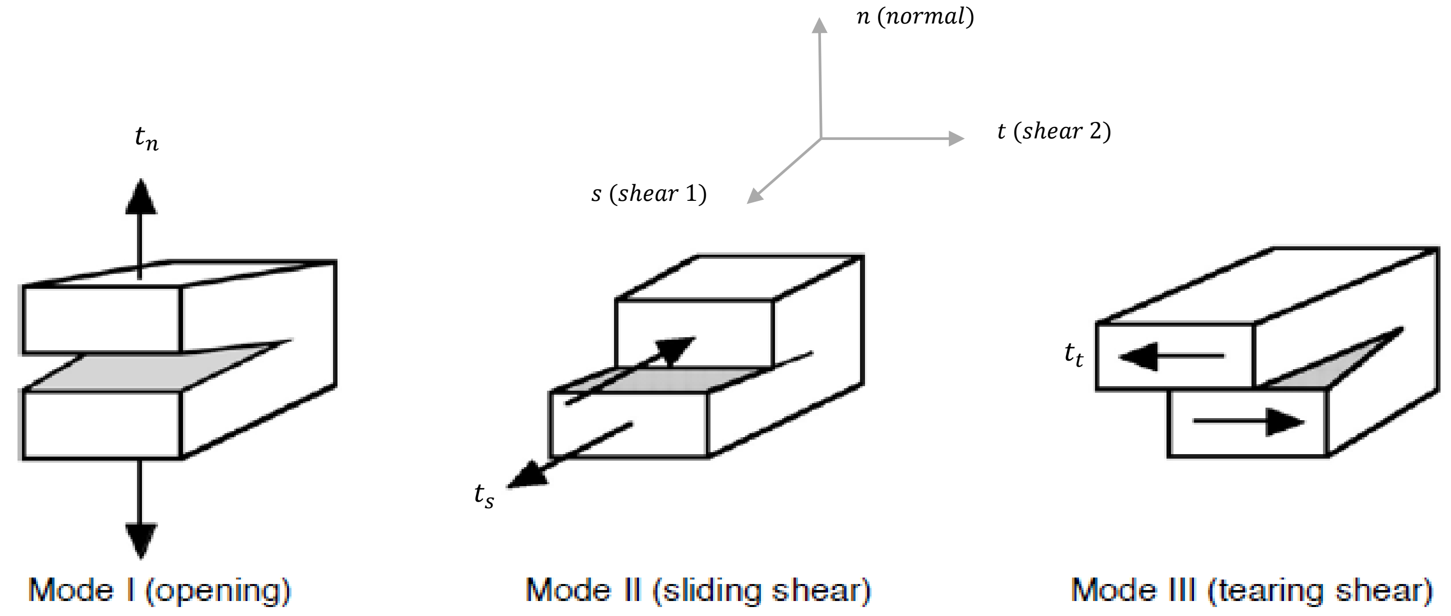
# Theoretical basis

For a brittle crack, the linear elastic fracture mechanics asymptotic solution allows for the characterisation of the local crack-tip stress fields using solely the elastic stress intensity factor K.




$$\lim_{r \to 0} \sigma_{ij}(r,\theta) = \frac{1}{(2\pi r)^{1/2}}\left[K_I f_{ij}^{I}(\theta) + K_{II} f_{ij}^{II}(\theta) + K_{III} f_{ij}^{III}(\theta)\right]$$

# Crack initiation in bulk materials can be simplified using three distinct modes and a damage initiation criterion based on traction separation laws

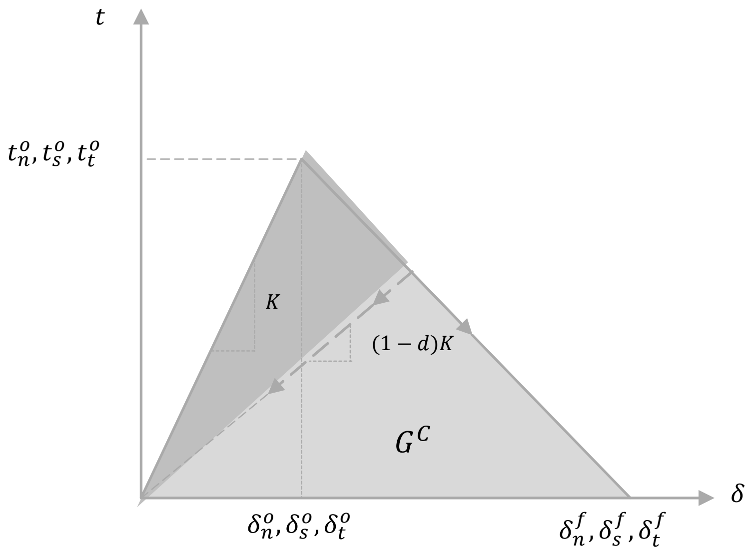


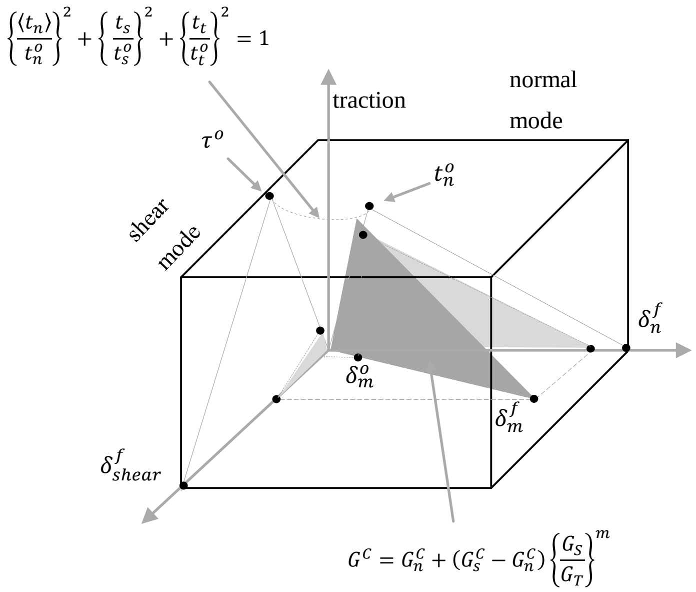

The quadratic damage initiation criterion is given as $$\left\{\frac{\langle t_n \rangle}{t_n^o}\right\}^2 + \left\{\frac{t_s}{t_s^o}\right\}^2 + \left\{\frac{t_t}{t_t^o}\right\}^2 = 1$$

Crack propagation in bulk materials can be simplified using the Benzeggagh-Kenane (B-K) expression for damage evolution based on the critical energy release rate $G^C$ at a material point [4]

$$G^C = G_n^C + (G_s^C - G_n^C)\left\{\frac{G_S}{G_T}\right\}^m$$

$$strain\ energy\ release\ rate\ ratio\ (SERRR) = \frac{strain\ energy\ release\ rate\ (SERR)}{critical\ energy\ release\ rate\ (G^C)}$$



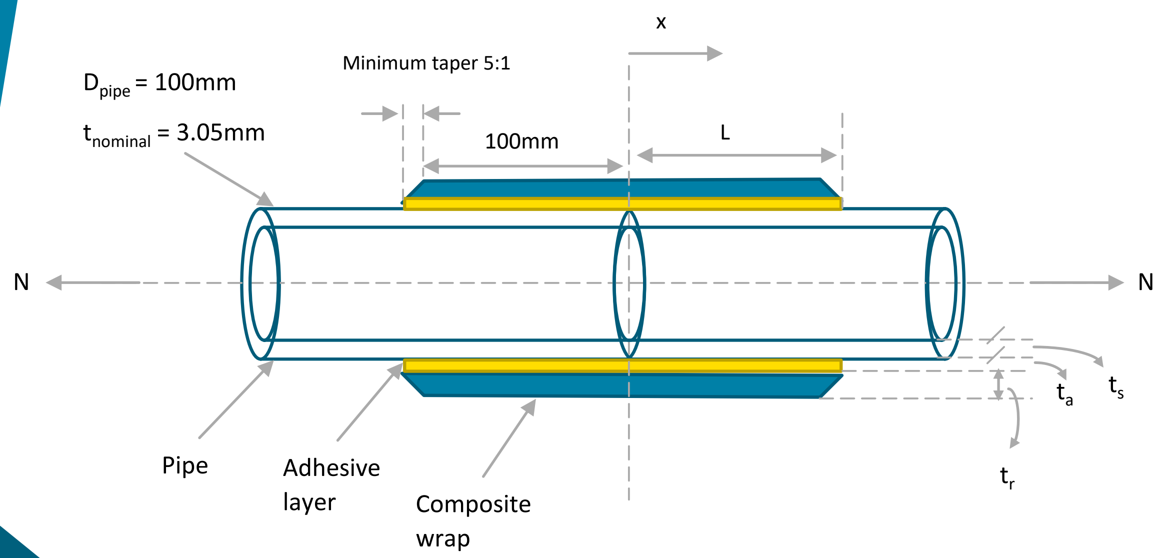
# Methodology

- The finite element (FE) fracture mechanics approach was employed via the virtual crack closure technique (VCCT) and the extended finite element method (XFEM).
- All analysis were carried out using CAE software Abaqus.
- Post processing was carried out automatically using Python scripts.

# Validation models

## Adhesive strength validation: Pull out test

- Repair: length = 215mm, thickness = (7, 9, 15)mm
- 3 ½ in, Sch 10, 3.05mm WT



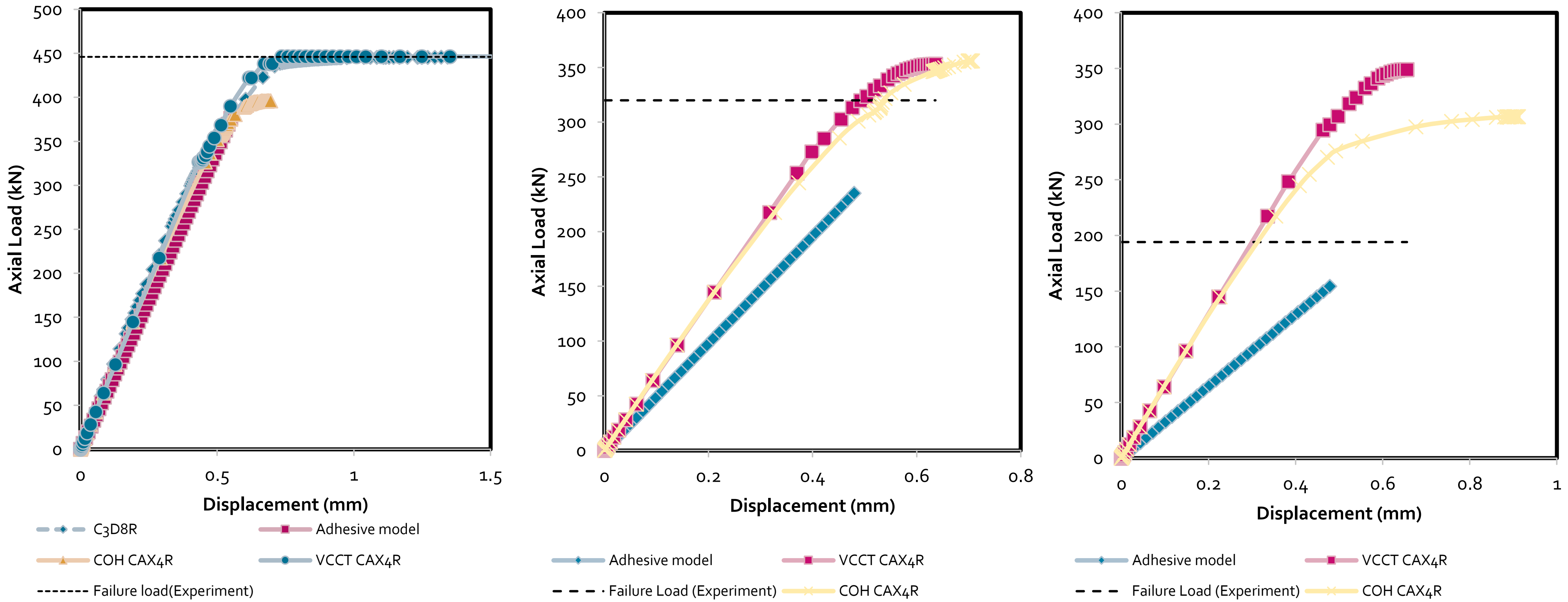

### Adhesive layer theory [5]

$$G_i = K_{i,int}\frac{1}{2}\left(\frac{1}{E_r}+\frac{1}{E_s}\right)\left(\frac{2\alpha_m - 1}{\alpha_m^2}\right) \quad for\ i = I, II$$

$$\alpha_m = \frac{E_S}{E_r\left(2+\frac{E_S}{2}\left(\frac{1+v_r}{E_r}-\frac{1+v_S}{E_S}\right)\right)}$$

E = Elastic modulus
v = Poisson's ratio
$K_{i,int}$ = Stress intensity factor for mode i
$_{r,\, s}$ = repair, substrate

## Figure: Axial limit for different repair thickness




$t_r$=15mm　　$t_r$=9mm　　$t_r$=7mm

## Mesh sensitivity studies: XFEM

- Element characteristic dimension as a function of h-refinement partition.
- Convergence of stress fields at enriched region for XFEM application.
- For an elliptical crack, convergence issues associated with crack front occurring at element tangential plane / not cutting through sufficient element supports.

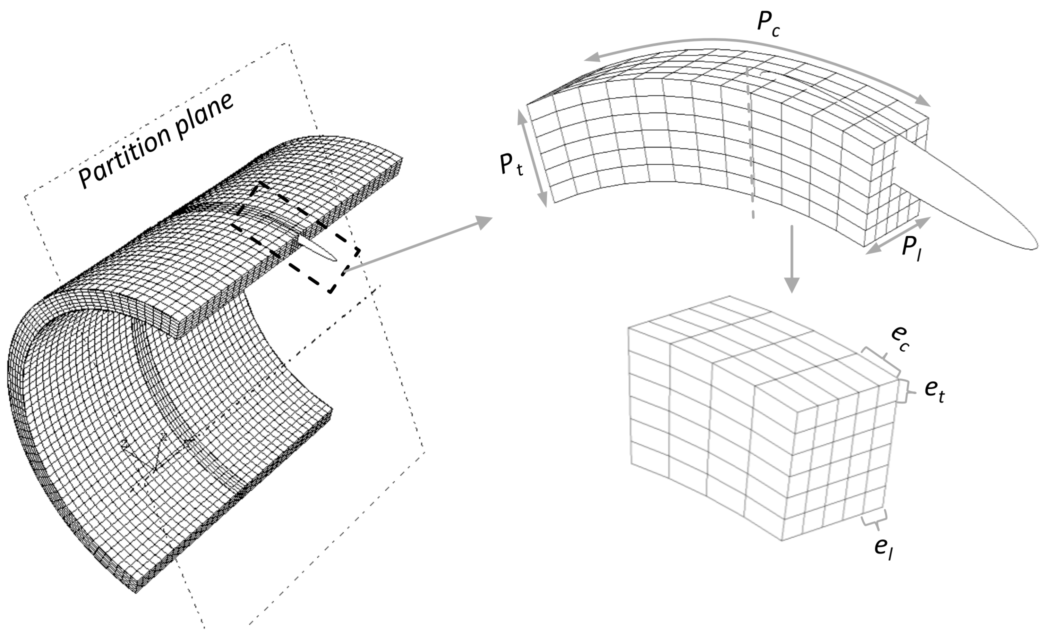


Table: Influence of element dimension on solution and mesh convergence

| Model | $e_t/a$ | $e_l/a$ | $e_c/a$ | $N_C$ | $K_I$ $[MPa\sqrt{m}]$ | $\varepsilon_{ref}(\%)$ R6 | $\varepsilon_{ref}(\%)$ BS7910 | STD $[MPa]$ | $\varepsilon_{rel}(\%)$ |
|---|---|---|---|---|---|---|---|---|---|
| **M1** | 0.2 | 0.2 | 0.2 | 5 | 21.98 | 17.15 | 14.57 | 0.07 | 12.48 |
| **M2** | 0.12 | 0.12 | 0.12 | 8 | 19.48 | 3.82 | 1.53 | 1.34 | -0.32 |
| **M3** | 0.09 | 0.09 | 0.09 | 11 | 19.31 | 2.94 | 0.67 | 0.82 | -1.17 |
| **M4** | 0.06 | 0.06 | 0.06 | 15 | 19.54 | 4.15 | 1.86 | 1.97 | Ref |

Comparison between analytical limit load solutions [6] for constant depth circumferential crack and XFEM limit load

Table: Axial and moment capacity

| | **Normalized axial limit** | **Normalized moment capacity** |
|---|---|---|
| **Closed form solution** | 0.816 | 0.165 |
| **FE results (this study)** | 0.777 | 0.152 |
| **Relative error (%)** | 4.68 | -7.78 |

# 1. Adhesive failure and crack properties

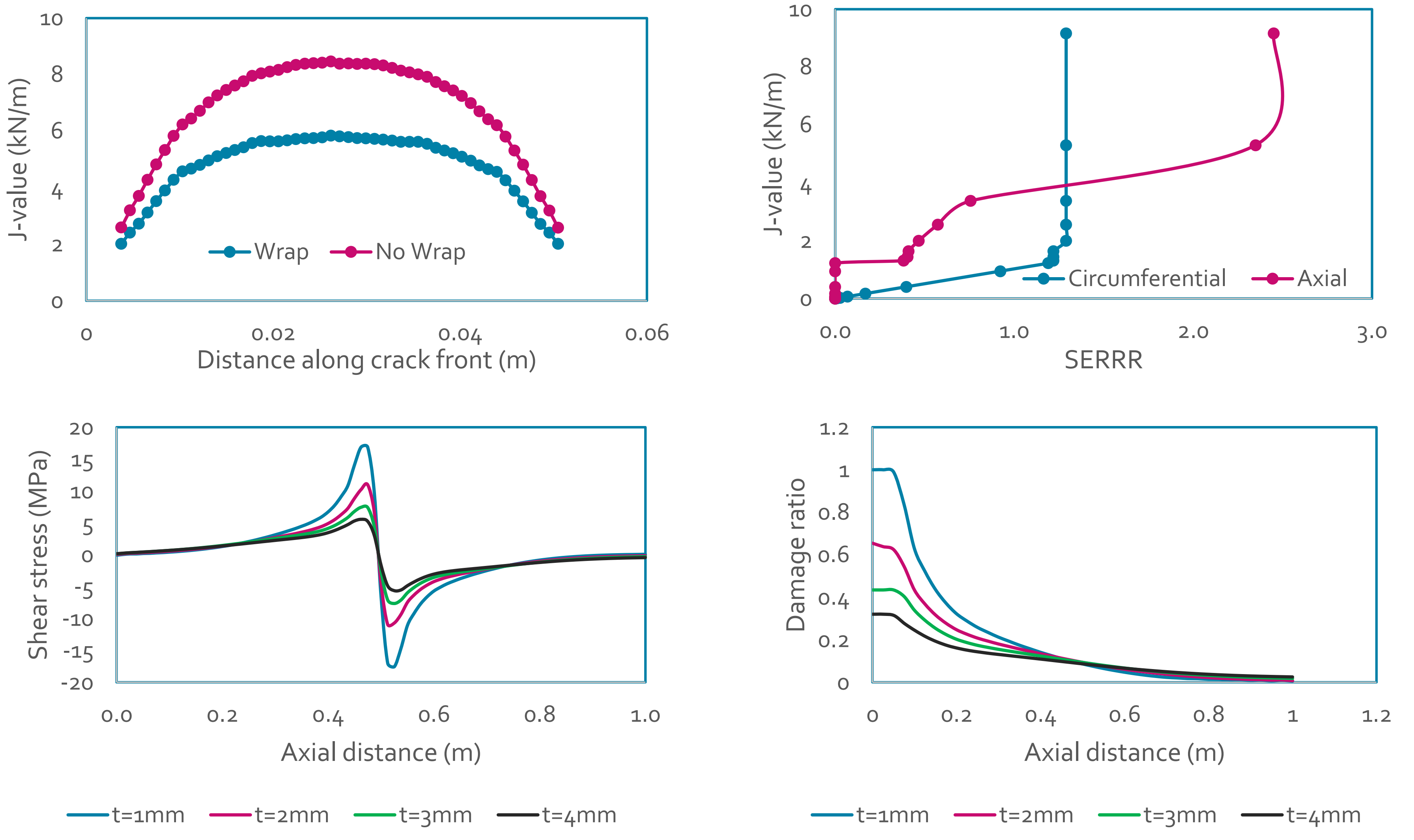



Figure: (a) Variation of J-value along crack path (b) influence of tension on adhesive failure and propagation direction (c) shear stress distribution (d) Damage ratio along repair length

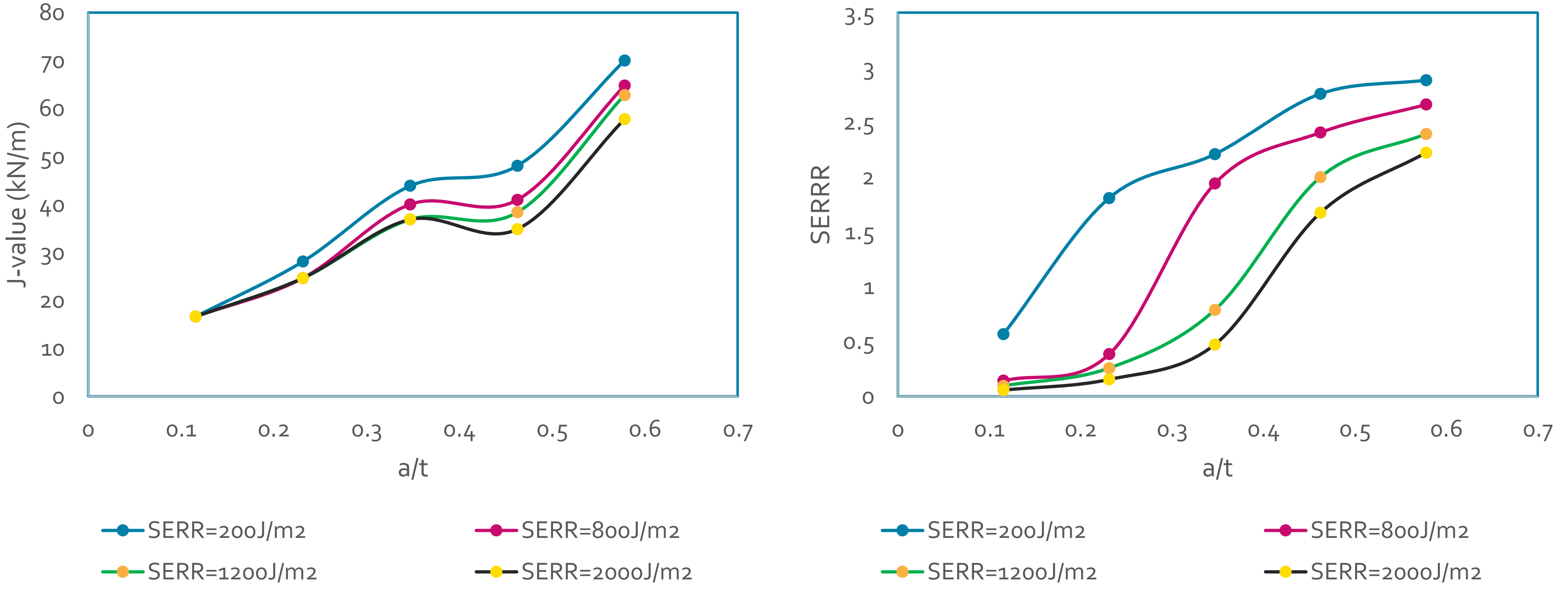
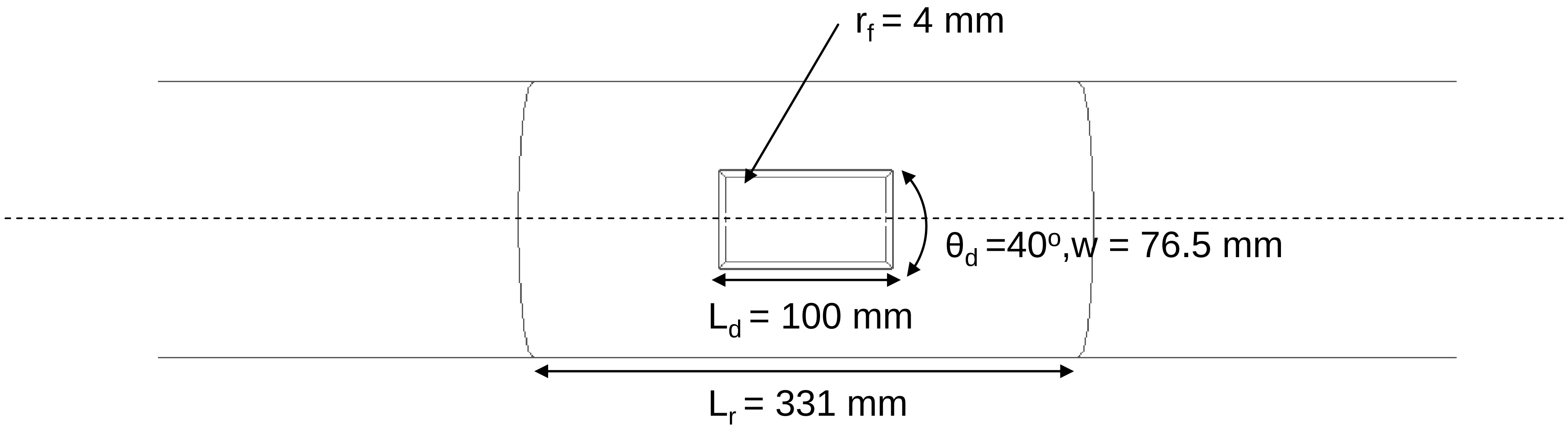



Figure: (a) Influence of adhesive strength on J-value (b) ) Influence of adhesive strength on maximum SERRR

# 2. Repaired defect and stress fields

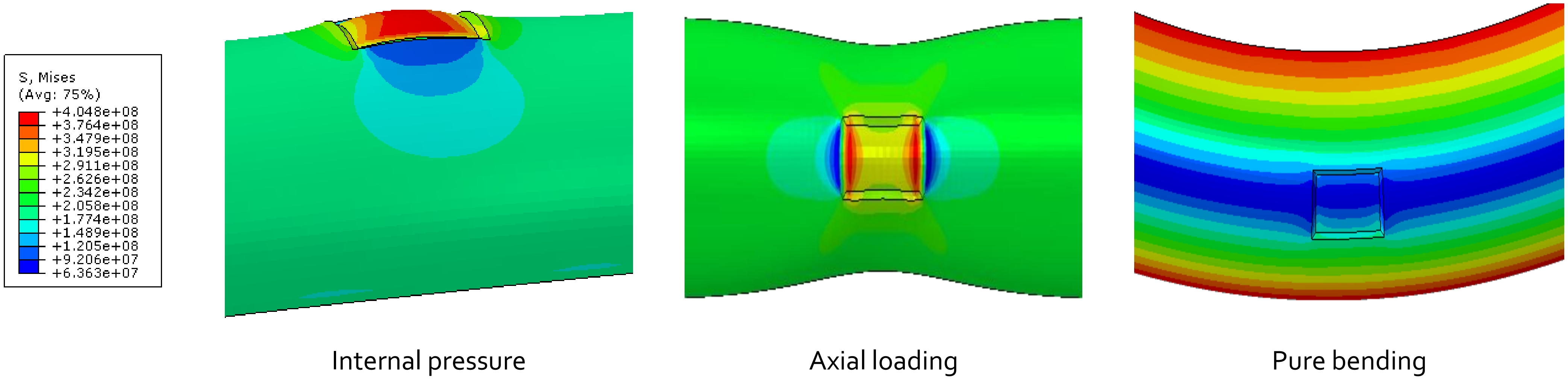



**Pipe (AISI 1010)**: $D_o = 219.1\ mm,\ t = 12.7\ mm,\ E = 205\ GPa, v = 0.29, \sigma_y = 315\ MPa, \sigma_{UTS} = 430\ MPa,$
$\varepsilon_f = 29\%, K_{IC} = 43\ MPa\sqrt{m},\ G_c = 8.26kN/m$

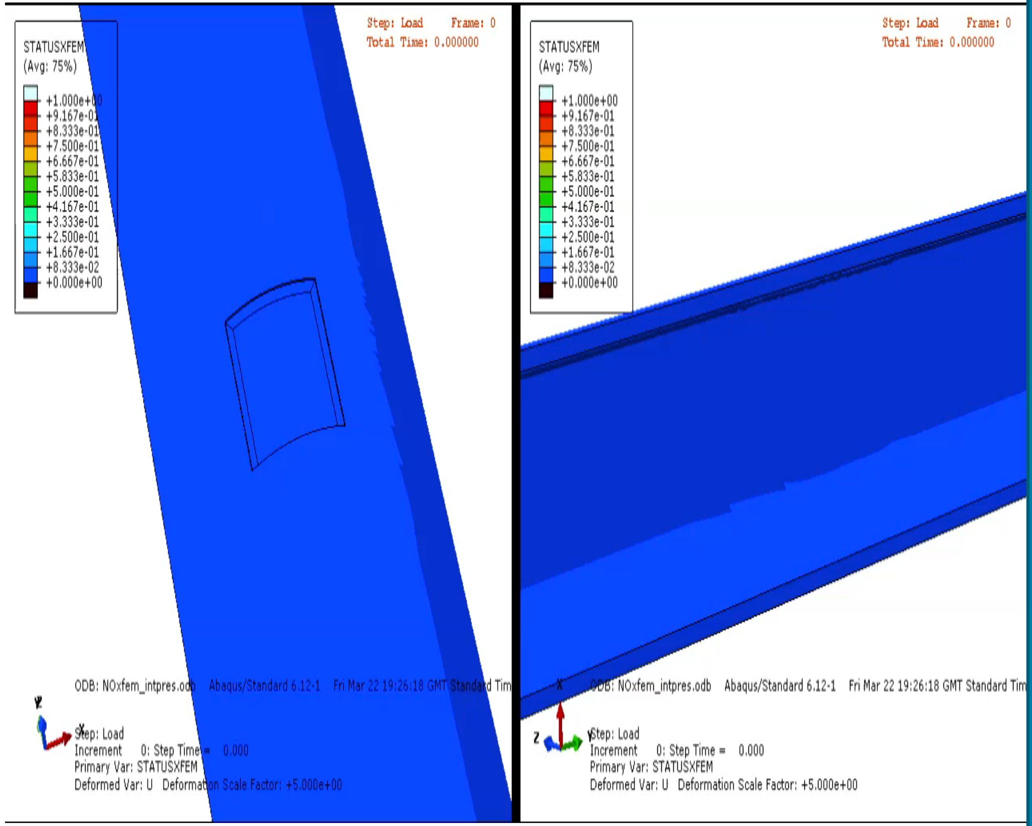
**Grout**: $E = 8\ GPa, v = 0.36, \sigma_{UTS} = 60\ MPa, \sigma_{UCS} = 1.5\sigma_{UTS}$

**Repair wrap (GFR)**: $E_{hoop} = 18.2\ GPa, E_{axial} = 12.7\ GPa, v_{12} = v_{13} = 0.2, v_{23} = 0.38, G_{12} = G_{13} = 5\ GPa,$
$G_{23} = 2.4\ GPa, t_{ply} = 0.625mm$

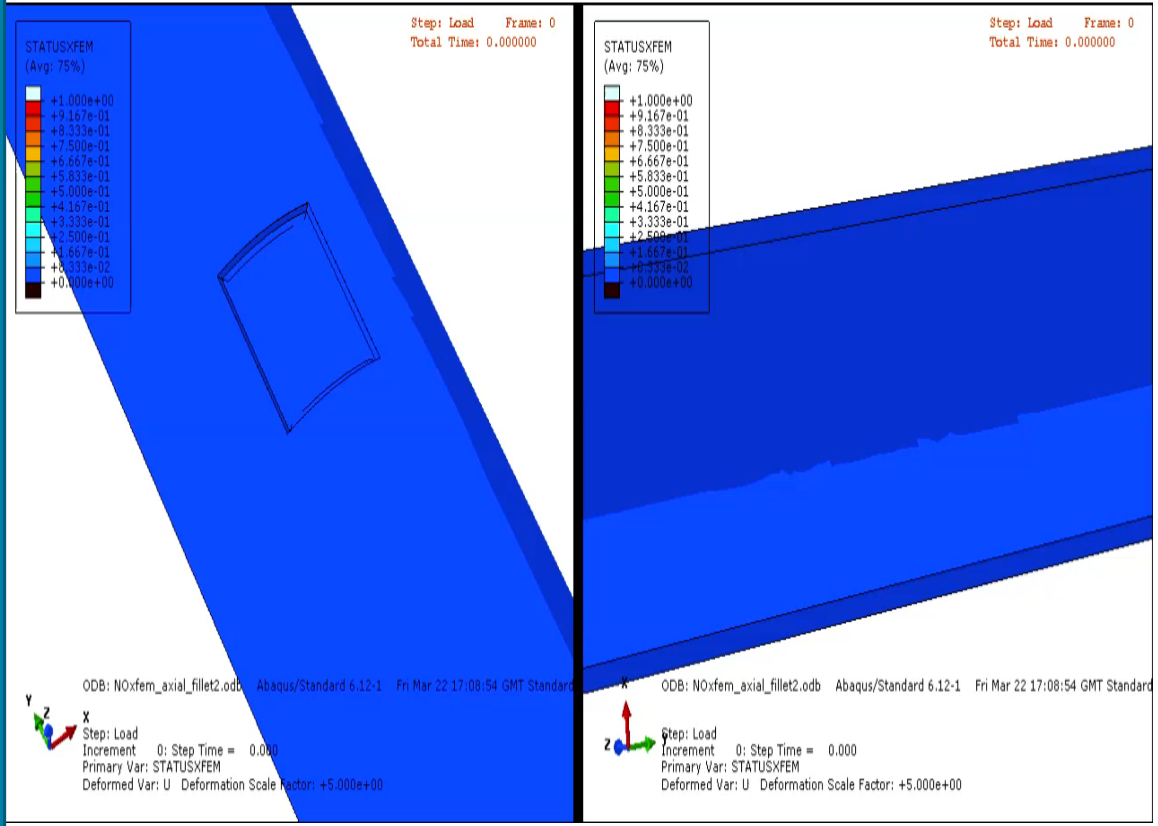
## Deformation modes and equivalent stress distribution




- It is general knowledge that the capacity of the load transfer mechanism between the wrapped pipe section and the composite determines the stress distribution and critical hotspots at the repaired section.
- Generally, high strength reinforcing materials, high speed curing and performance adhesives and high compressive strength grout are required to achieve an optimum repair system.



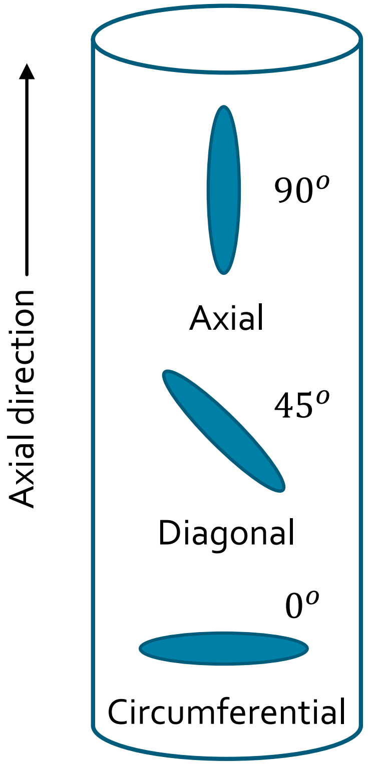

Internal pressure

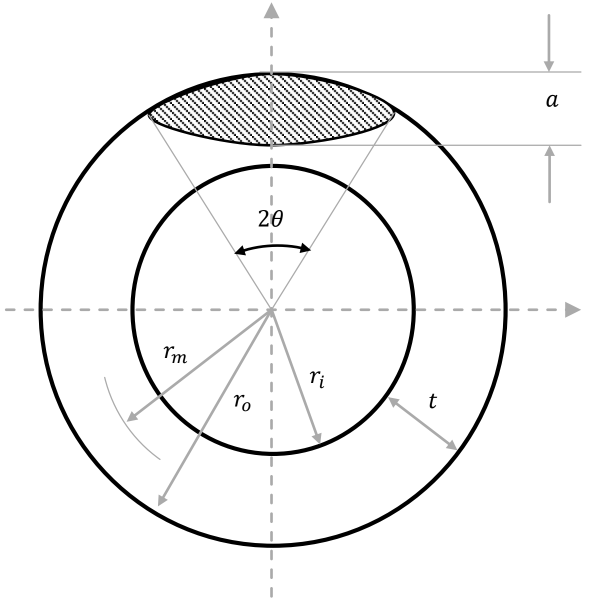



Tension

# 3. Repaired defect and crack stress fields

Crack configurations




Crack geometric labels

$a$= crack depth

$2c$= crack front length

$2c = 2\theta r_o$ ($2\theta$ in radians)

For LEFM in homogenous 3D bodies, the intensity of the crack tip stress field can be expressed by the effective stress intensity factor

$$K_{eff} = \sqrt{K_{\mathrm{I}}^2 + K_{\mathrm{II}}^2 + \frac{K_{\mathrm{III}}^2}{(1-\nu^2)}}$$

$$K_r = \frac{K_{eff}}{K_{mat}}$$

# Influence of contact stiffness

$$\beta = \frac{\text{Default contact stiffness } S}{\text{Sampled contact stiffness } S_n}$$

$$\varphi = \frac{\text{Shear stress } \tau_n}{\text{Default shear strength } \tau}$$

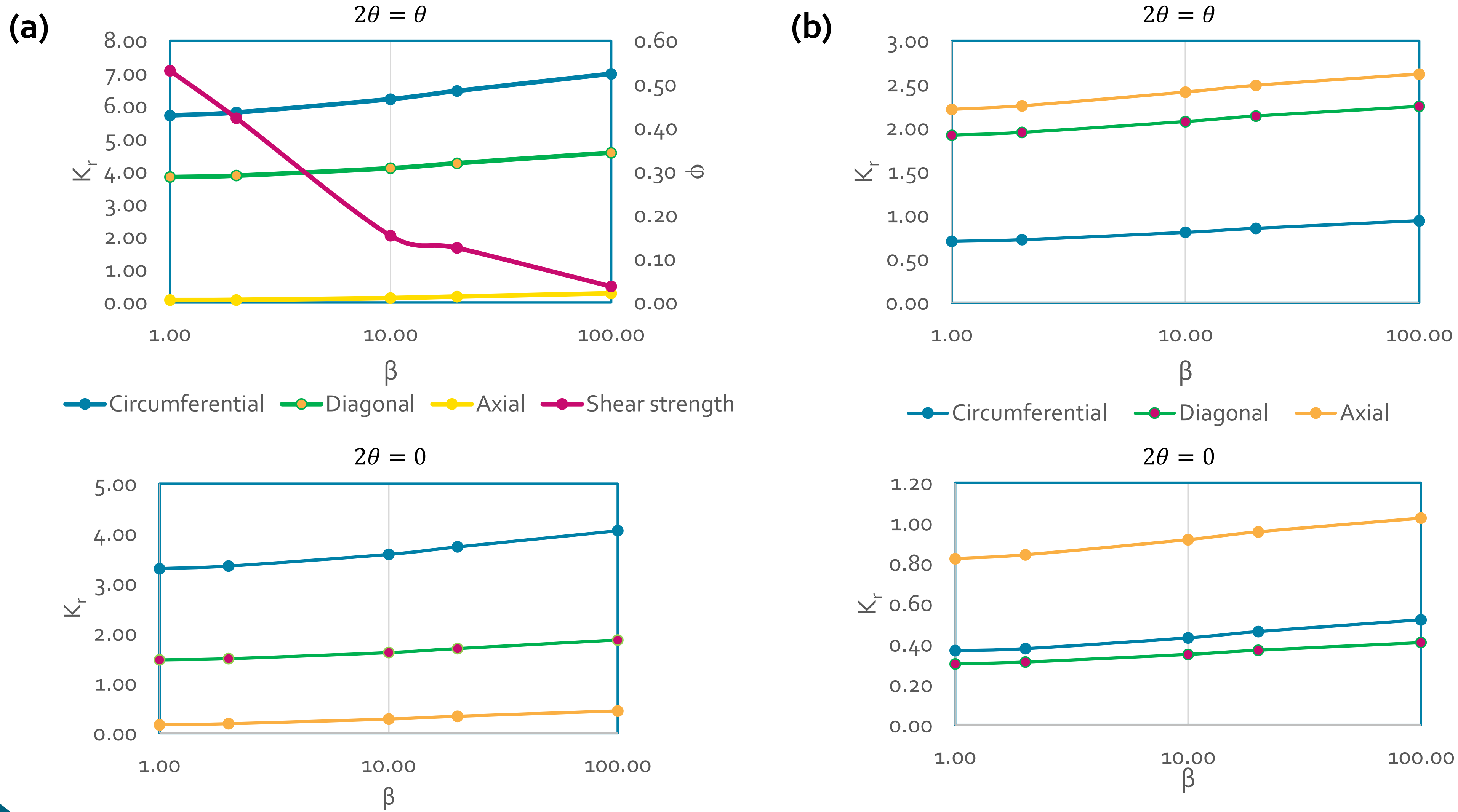
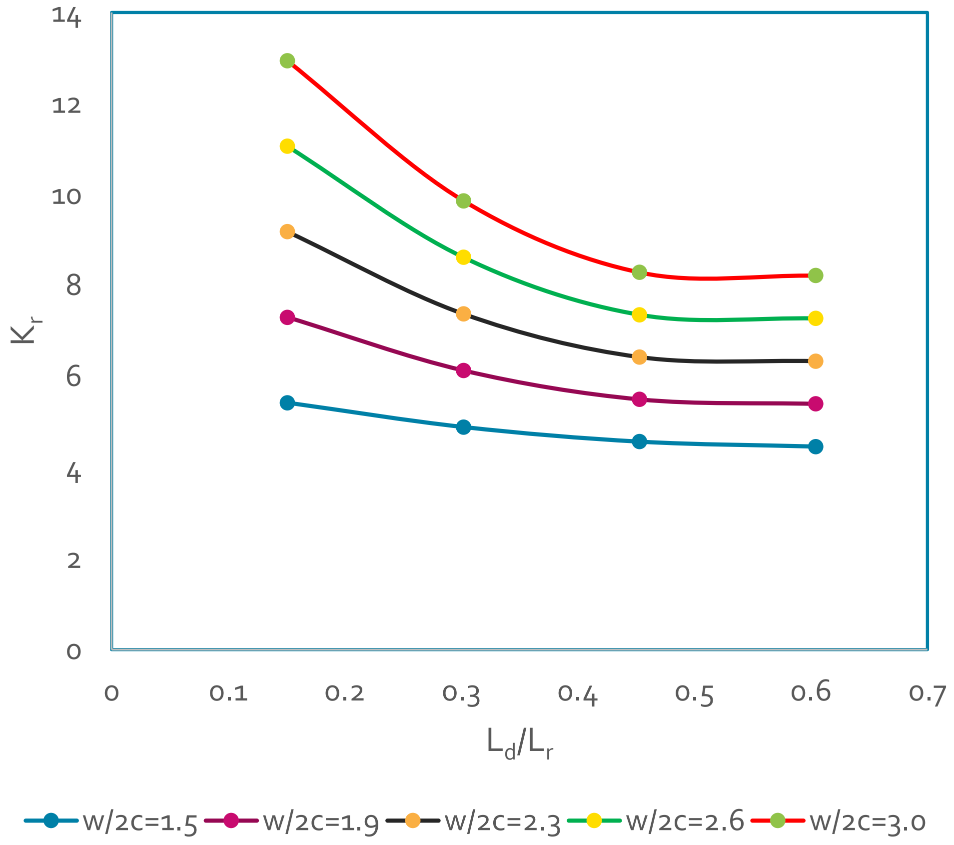



Figure: Influence of contact stiffness on crack tip stress intensity (a) Tension (b) internal pressure

## Defect and crack geometry effect



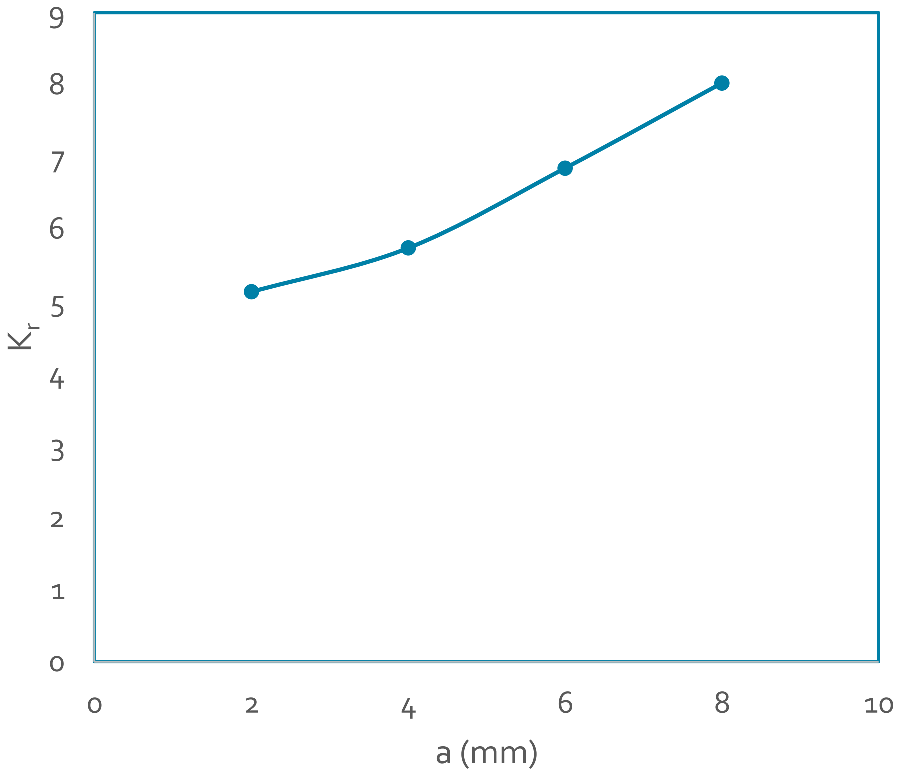




Figure: Influence of defect dimension and crack depth on the crack stress field intensity for a $0^o$ crack under tension

# Grout stiffness effect

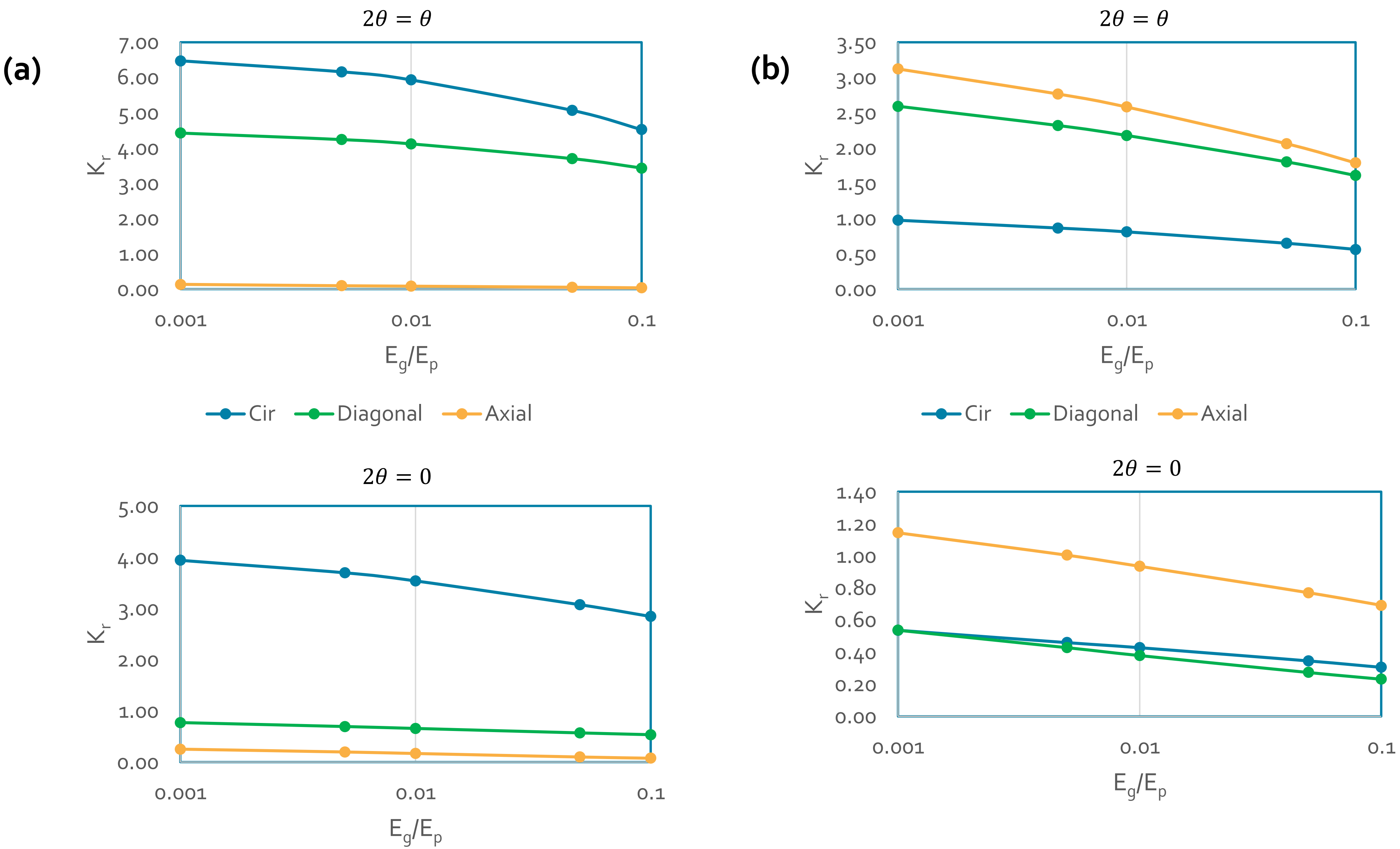
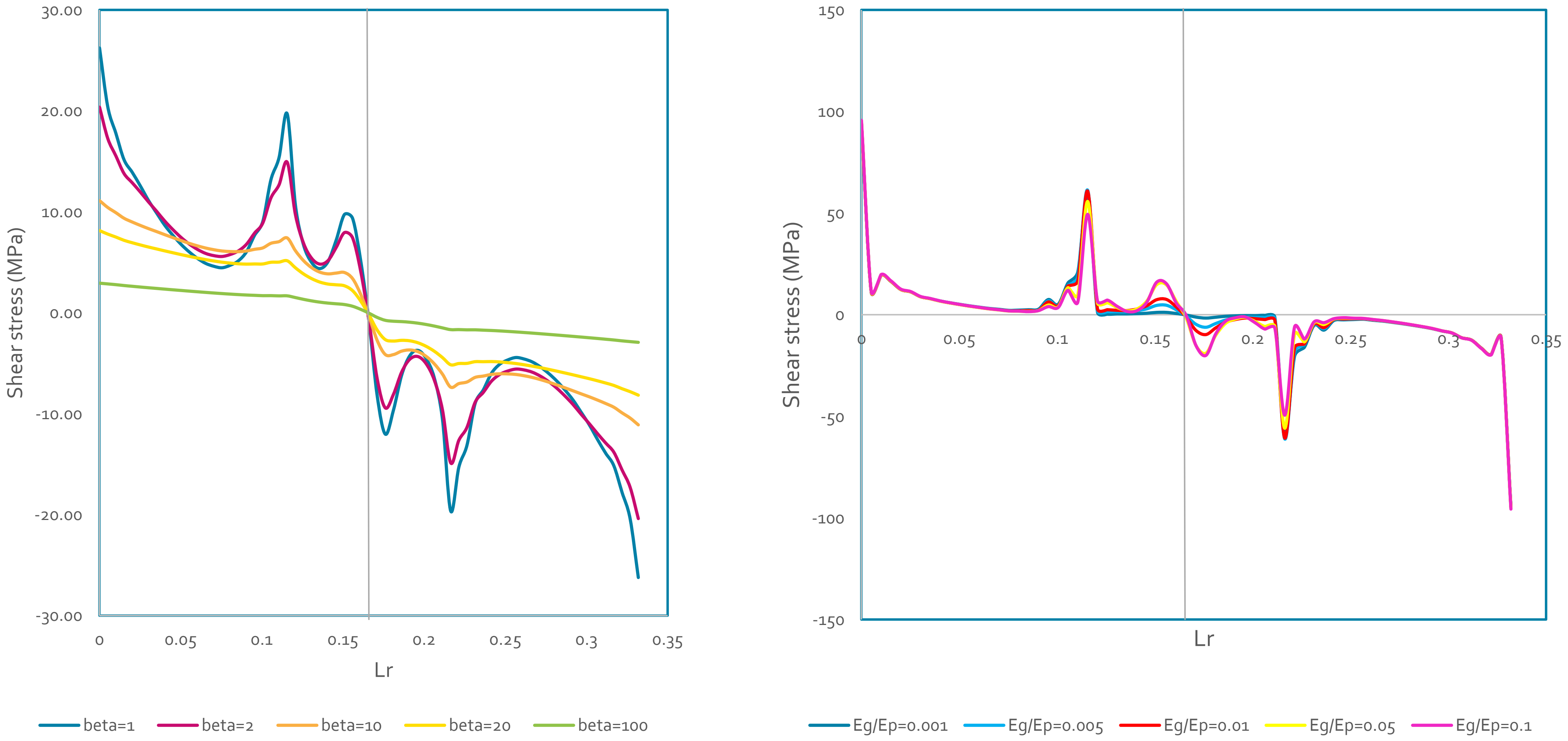
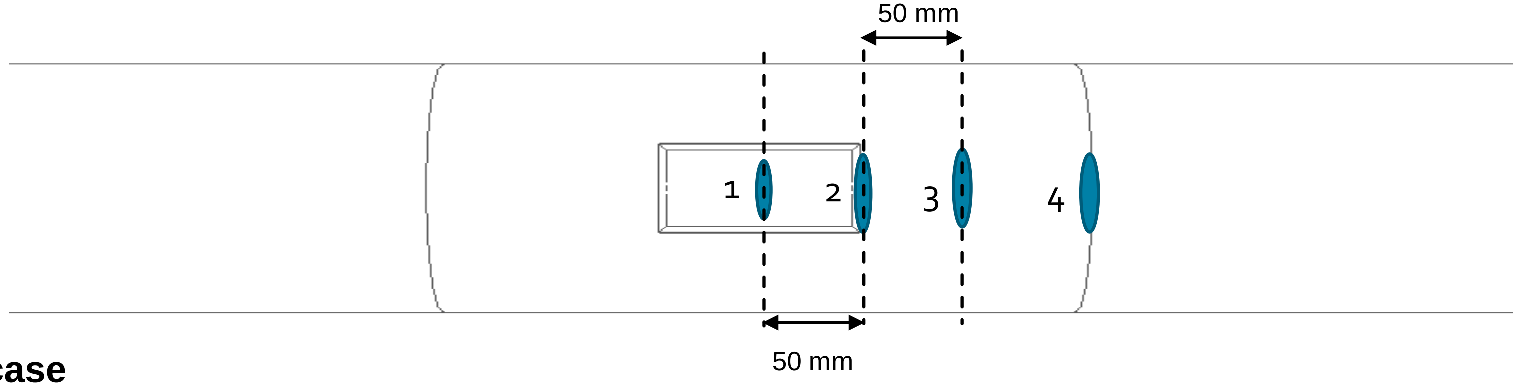



Figure: Influence of grout stiffness on the crack stress field intensity (a) tension (b) internal pressure

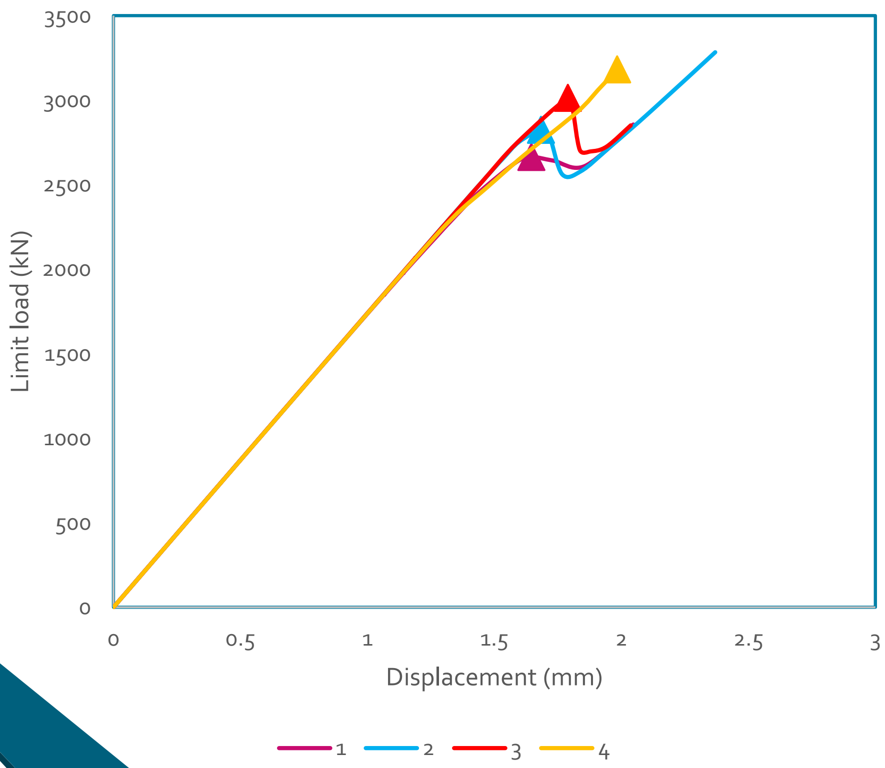


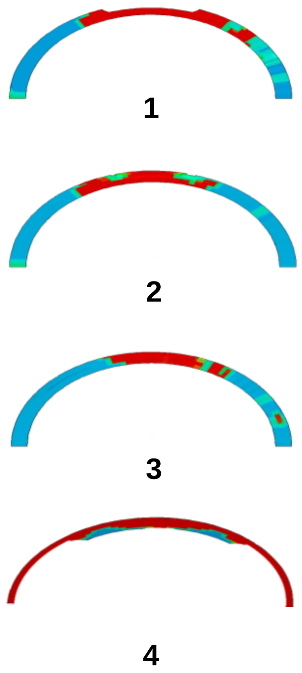

<u>Figure: Influence of (a) contact stiffness (b) grout stiffness on the shear stress distribution</u>

# 4. Influence of crack location

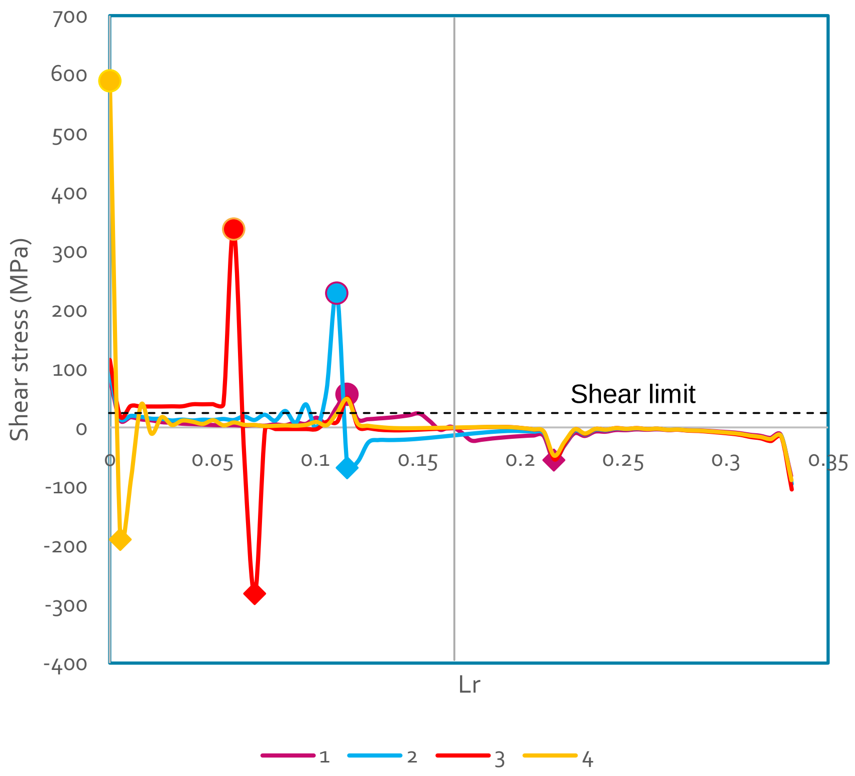



**Tension case**




Red contour: failed elements



# Conclusions

1. The load transfer between the defect pipe and the repair wrap signifies the most important factor in determining the severity of the crack stress fields.
2. The influence of the crack orientation on the crack stress fields depends on the direction of the maximum principal stress and the crack plane.
3. For axial load cases with circumferential cracks, a geometric factor can be used as a quantitative measure of the evolution of the stress fields as a function of repair design variables.
4. Utilizing a high compressive strength/stiffer grout improves load transference, and thus lowers the magnitude of the crack stress fields.
5. For a repair system under internal pressure, a properly machined defect can arrest circumferential crack propagation. For the same system under tension, the defect finishing has insignificant influence on crack propagation.

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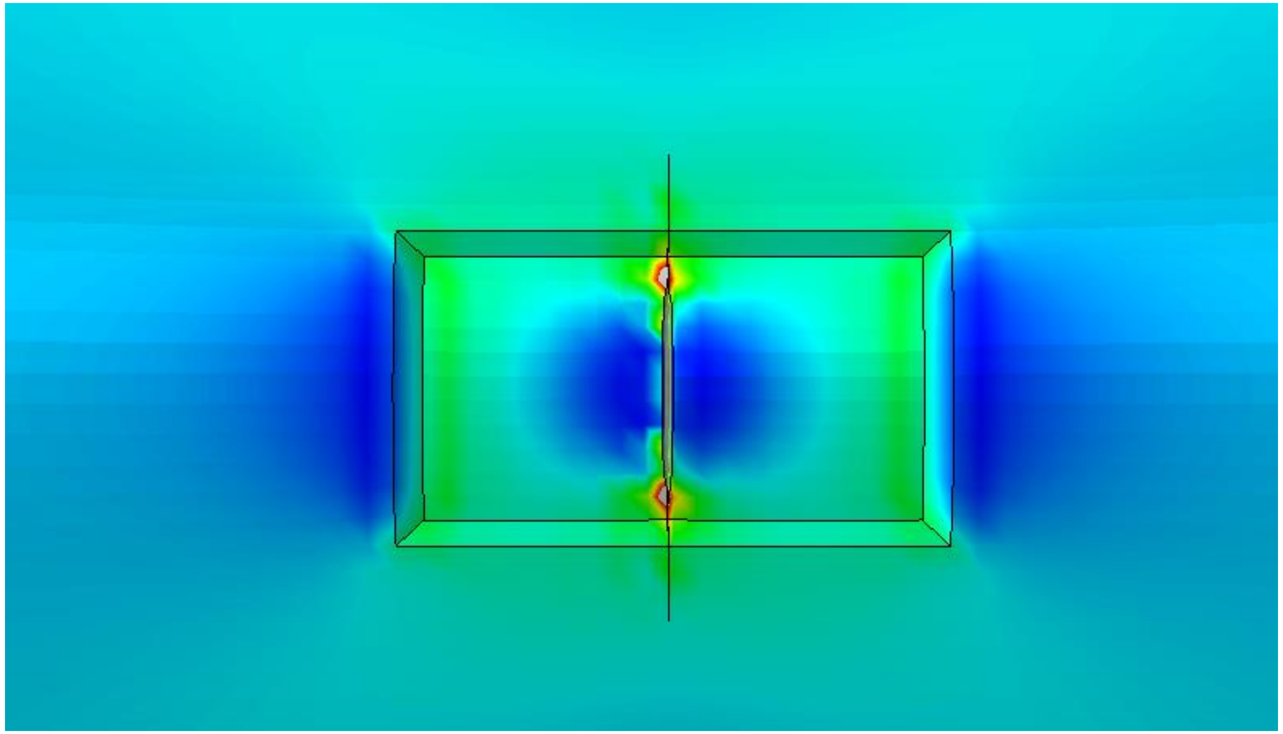
# THANKS FOR YOUR AUDIENCE



# QUESTIONS?????