STRESS ANALYSIS AROUND AN OPEN HOLE OF CFRP MODIEFIED WITH GNPs

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Outline

Carbon Fibre Reinforced Polymers (CFRPs)

Carbon nanofillers (CN)

Stress concentration properties of CN enhanced FRPs

Novelty – Scope

Techniques

Results

Conclusions

Carbon Fibre Reinforced Polymers (CFRPs)

PROS

- ✓ High strength-to-weight ratio
- ✓ Excellent fatigue properties
- ✓ Corrosion resistance
- ✓ Design flexibility

CONS

- – Sensitive in adverse environmental conditions
- – Low resistance to impact
- – Delamination
- – Susceptible to discontinuities/defects

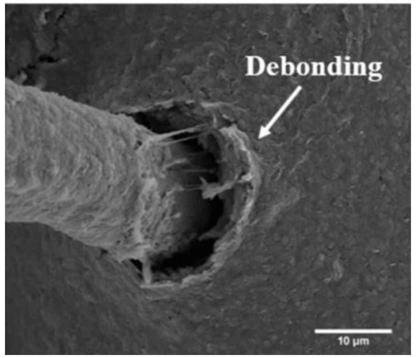
Stress concentration regions in CFRPs

Delamination: The layers of a composite material start to separate or peel apart.

Fiber-matrix debonding: Debonding between the fiber and matrix is weakened or lost.

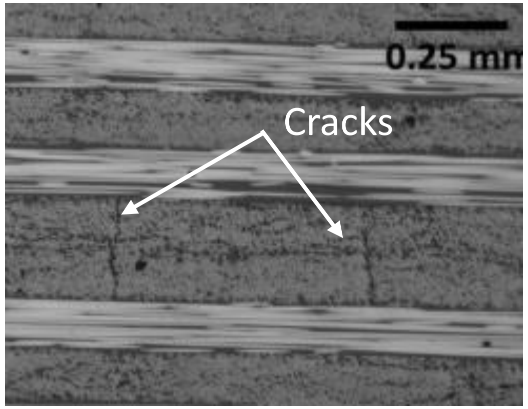
Cracks: Small or large fractures in the composite material.

Notches/Holes: Occur due to manufacturing errors, voids in the material, or damage caused during handling or use.

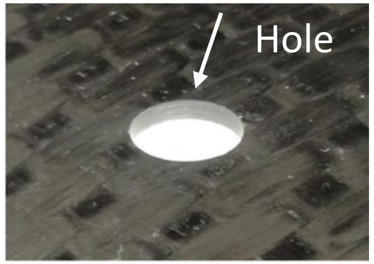


Ref. Fabrizio Sarasini et al. "Quasi-Static and Low-Velocity Impact Behavior of Intraply Hybrid Flax/Basalt Composites"

Ref. Chan-Joo Lee et al. "Design of Hole-Clinching Process for Joining CFRP and Aluminum Alloy Sheet"

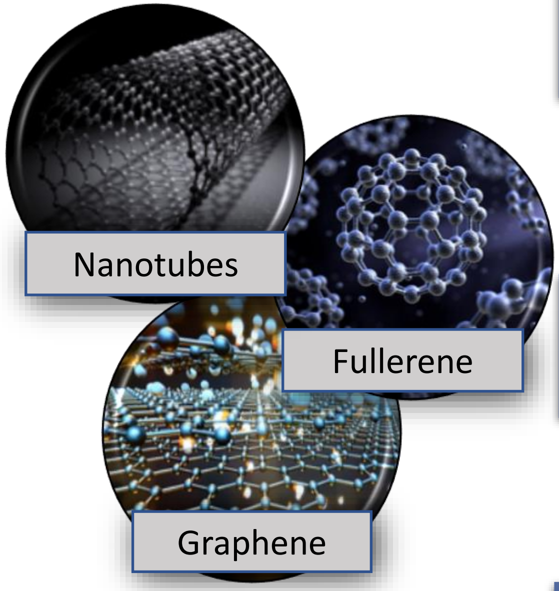


Ref. Christopher Baker *et al.* "Transverse cracking in carbon fiber reinforced polymer composites: Modal acoustic emission and peak frequency analysis"

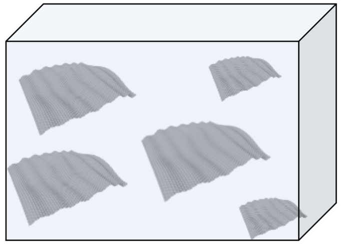


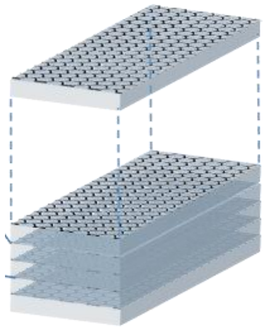
Need for quantifying and reducing those regions → Minimizing their effect on the performance of the CFRPs

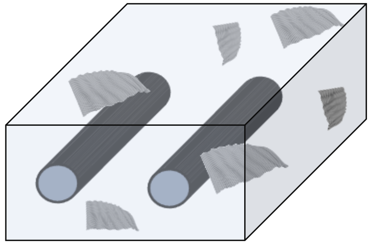
Carbon nanofillers (CN)



Reinforcement type	*Configuration*	*Classification*
Particle	*Additive*	**DISCONTINUOUS**
Layer	*Nanolaminate*	**CONTINUOUS**
Fibre	*CN-enhanced FRPs*	**HYBRID**







Stress concentration properties of CN enhanced FRPs

Type of Composite	***Nanofiller***	***Weight fraction %***	***Investigated properties***	***Improvement %***	***References***
CFRP	GNP	0.5	GI_C	61	Kostagiannopoulou et al. (2021), Engineering Fracture Mechanics
CFRP	GNP	0.5	GII_C	25	Kostagiannopoulou et al. (2021), Engineering Fracture Mechanics
CFRP	GNP	3	GI_C	60.4	Vijay K. Srivastava et al. (2017), Engineering Fracture Mechanics
CFRP	G0	0.5	GI_C	49	Kostagiannopoulou et al. (2015), Composites Science and Technology
GFRP	***CNT***	***0.1***	***Strength of an open hole composite***	***27***	***Pothnis J et al. (2021), Composites Part A: Applied Science and Manufacturing***

- Investigation of the damage evolution of open hole GFRP utilizing ***DIC*** method
- In-situ direct non-contact measurement of displacements/strains-Non distractive technique

Novelty - Scope

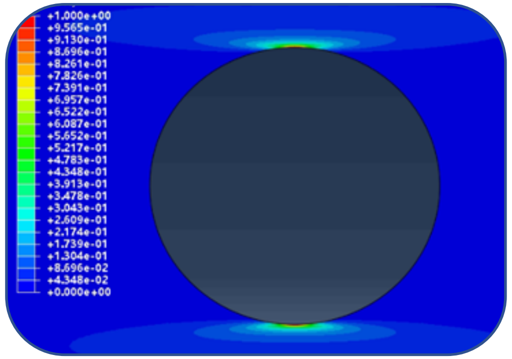
Addition of GNPs in notched CFRPs → Investigation of stress concentration around the circular notch via <u>Remote Raman technique</u>.

Remote Raman

- ✓ Non-destructive analysis
- ✓ Real-time analysis
- ✓ Large area coverage
- ✓ Flexibility
- ✓ Reduced safety risks

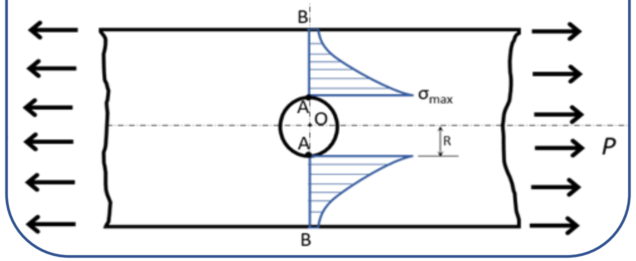
Validation of results

- Numerically, Finite Element Analysis

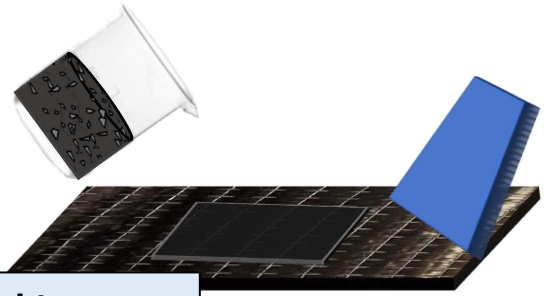


- Analytically, Tan’s FWC factor

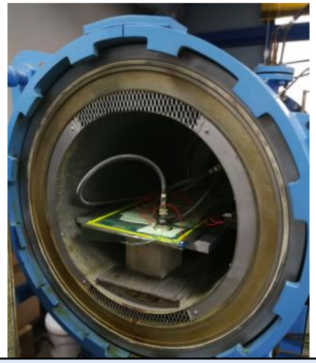
$$\frac{K_T}{K_T^\infty} = \left\{ \frac{3\left(1-\frac{2R}{w}\right)}{2+\left(1-\frac{2R}{w}\right)^3} + \frac{1}{2}\left(\frac{2R}{w}M\right)^6 (K_T^\infty - 3)\left[1-\left(\frac{2R}{w}\right)^2\right] \right\}^{-1}$$



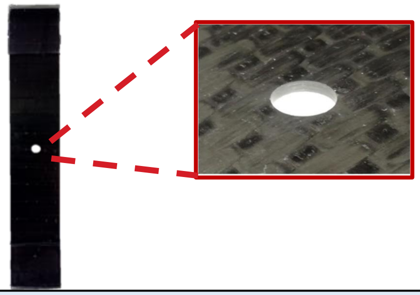
Fabrication and map of the experimental/theoretical work



Hand Lay-up



Curing under vacuum (Autoclave)

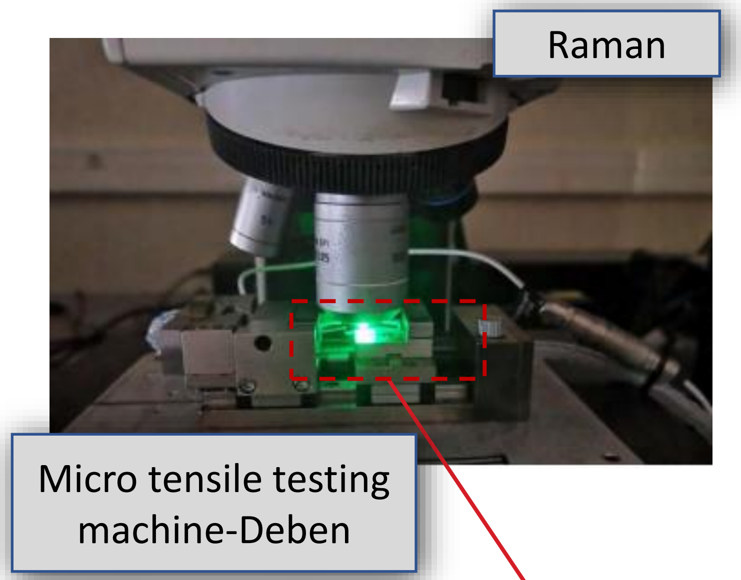


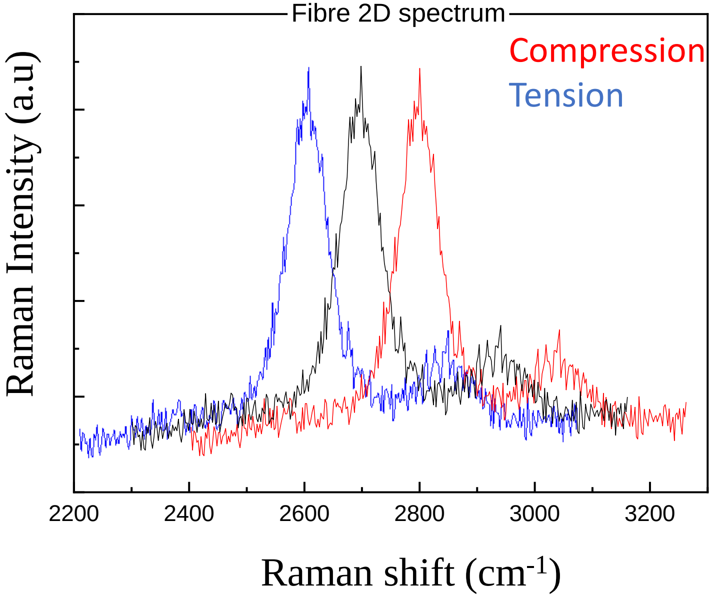
Shaped according to ASTM D5766

- CFRP Type
  - Neat
    - Strain Levels: 0.05%, 0.07%, 0.10%, 0.20%, 0.30%
  - Modified CFRP
    - GNPs content: 0.5 wt%, 1 wt%, 2 wt%
      - Strain Levels: 0.05%

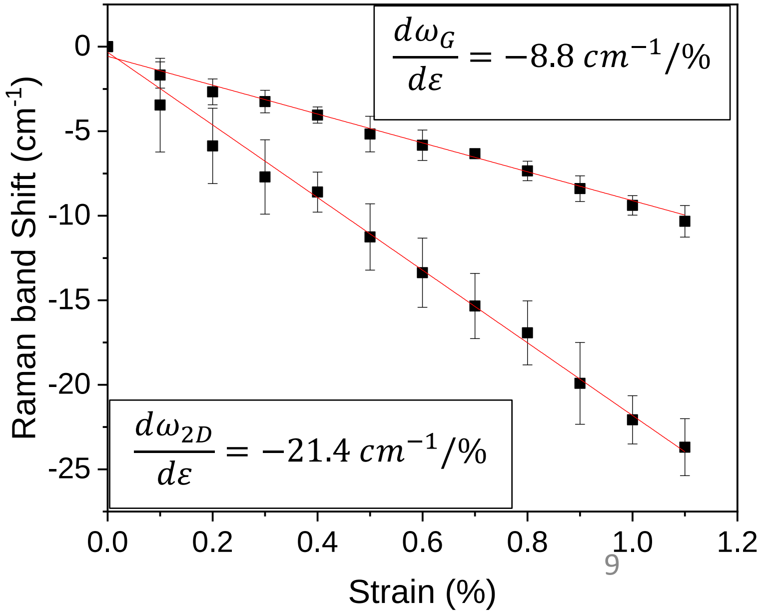
Raman Spectroscopy

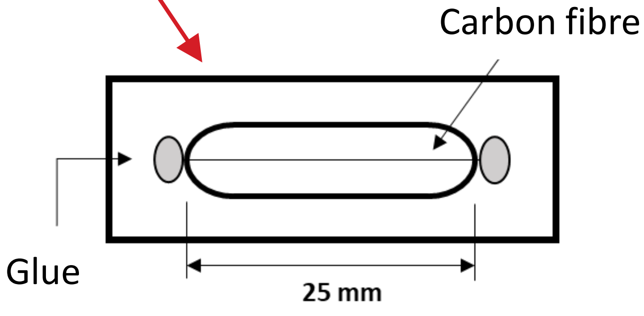
➢ Fibres' calibration curves





Different Strain Levels

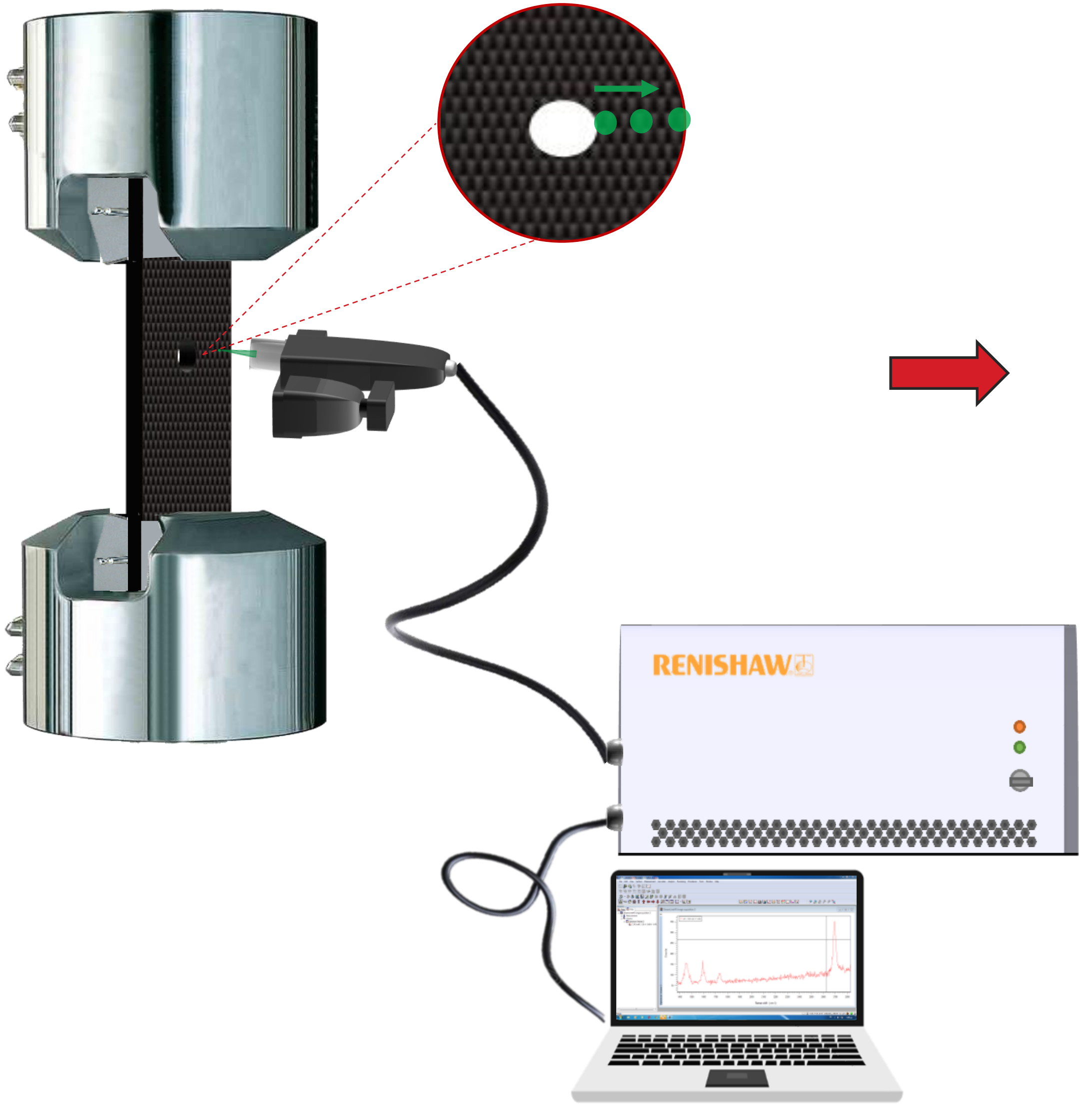


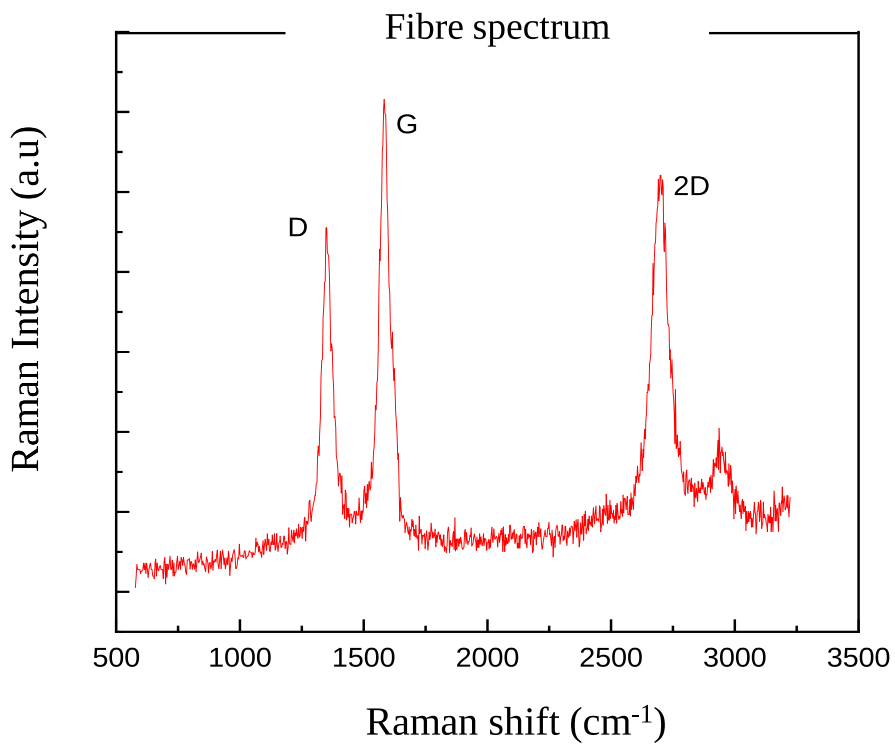


[ASTM D3379]

Remote Raman Spectroscopy

- Measurements for different applied strains





Fibre Calibration curves

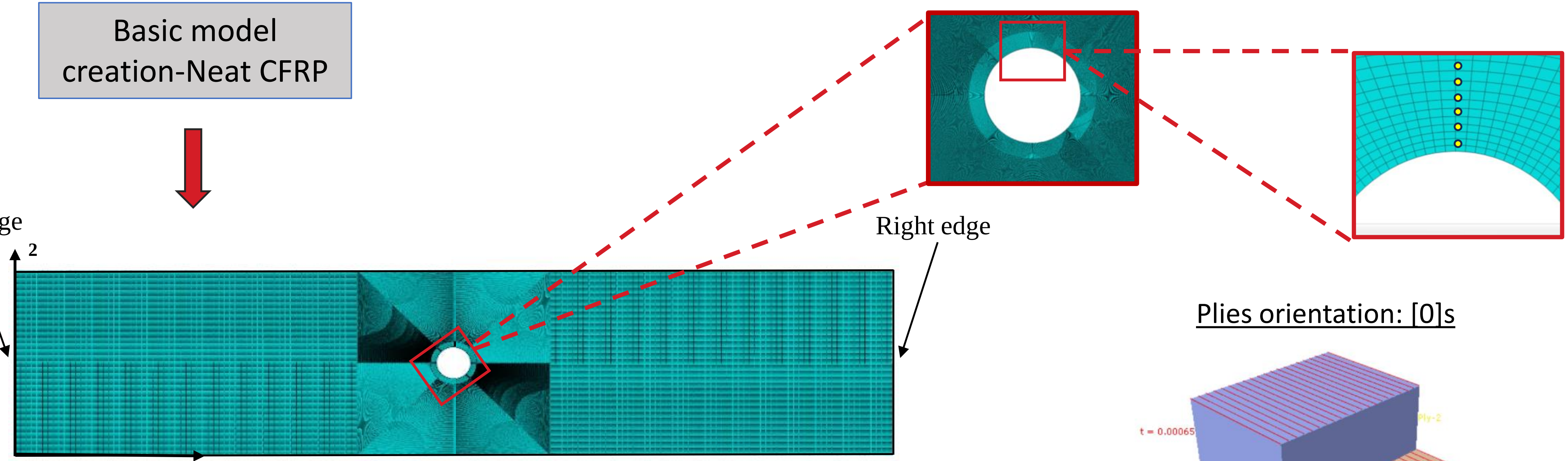
Stress/strain in fibres

Finite Element Analysis

Basic model creation-Neat CFRP

Left edge

Right edge



Boundary conditions:

$U_1=U_2=U_3=0$

$U_{R1}=U_{R2}=U_{R3}=0$

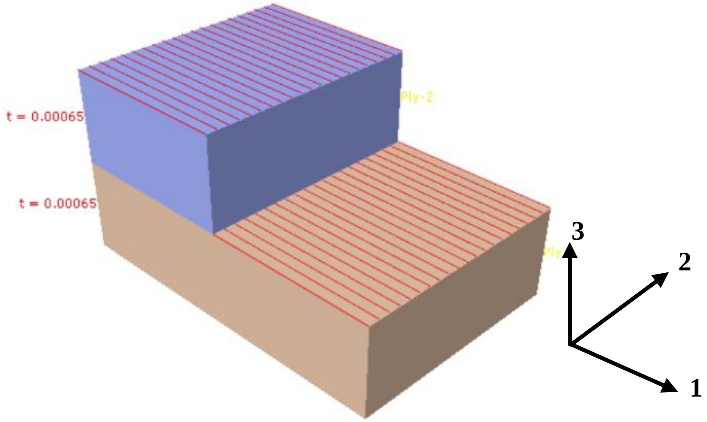
Boundary conditions:

U_1= Applied displacement

$U_2=U_3=0$

$U_{R1}=U_{R2}=U_{R3}=0$

Plies orientation: [0]s



Python scripting → Models' generation-Modified CFRPs → Python scripting → Stress/strain extraction

Tan's solution-Tan's Finite width correction factor (FWC)

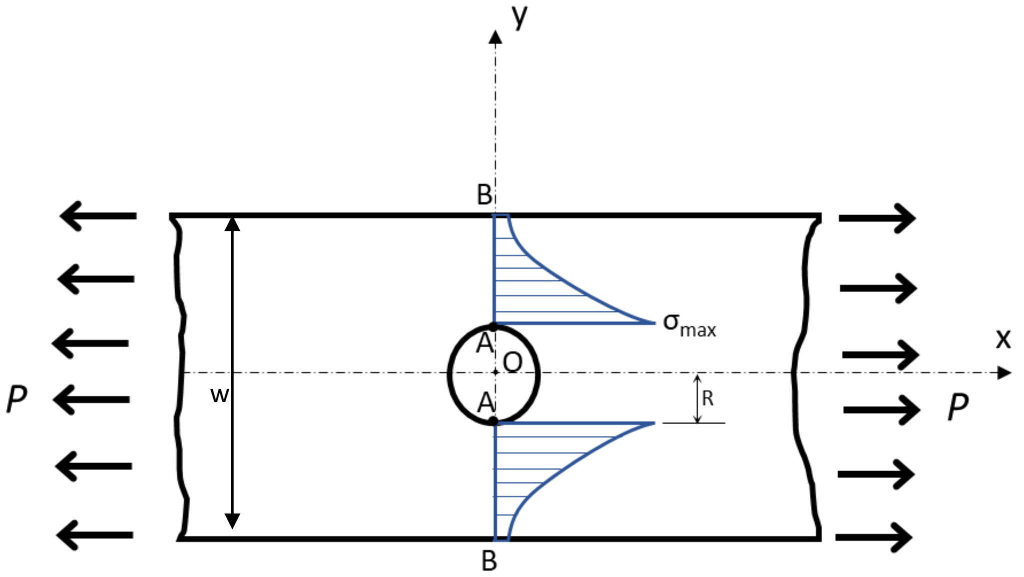
Axial stress for infinite plate

$$\sigma_{xx}\ (x=0,y) = P + \frac{P}{\beta_1-\beta_2} * \left\{ \frac{\beta_1^2}{1-\beta_1}\left[1-\frac{\beta_1 y}{\sqrt{R^2+\beta_1^2(y^2-R^2)}}\right] - \frac{\beta_2^2}{1-\beta_2}\left[1-\frac{\beta_2 y}{\sqrt{R^2+\beta_2^2(y^2-R^2)}}\right]\right\} \quad (1)$$

β_1, β_2 are related to elastic properties of the composite.

Tan's finite width correction factor (FWC)

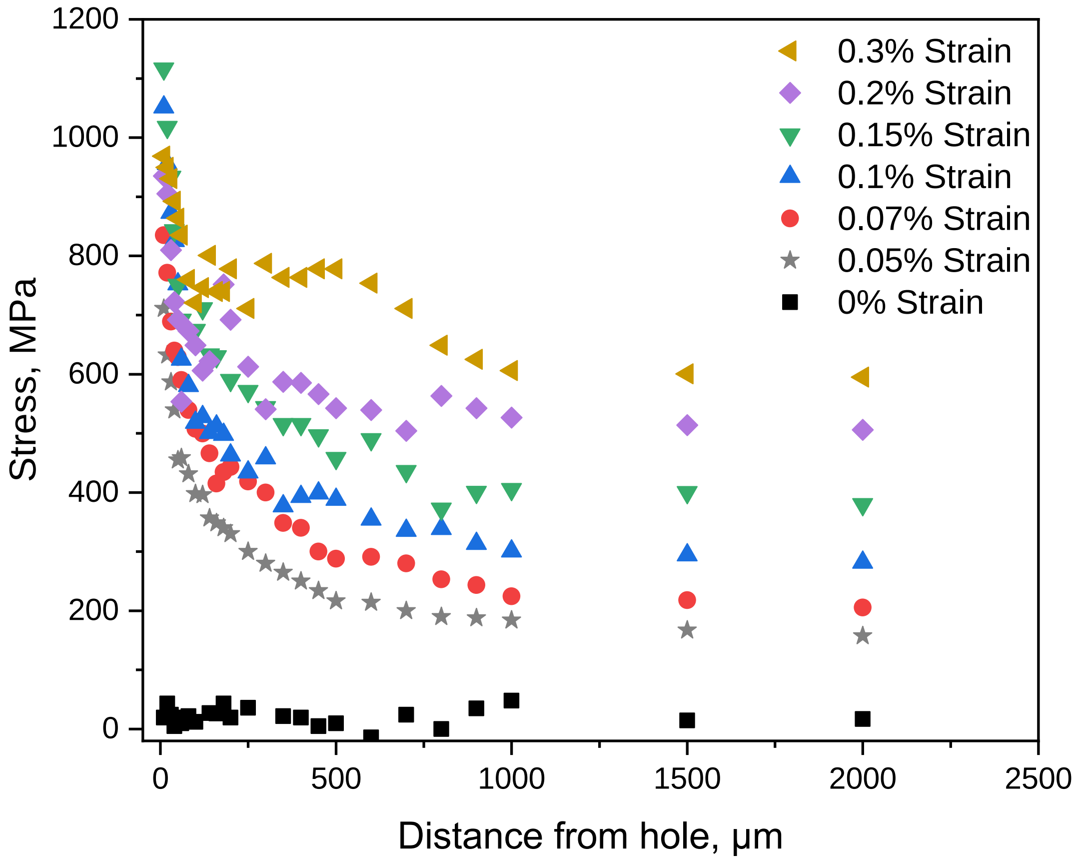
$$\frac{K_T}{K_T^\infty} = \left\{ \frac{3\left(1-\frac{2R}{w}\right)}{2+\left(1-\frac{2R}{w}\right)^3} + \frac{1}{2}\left(\frac{2R}{w}M\right)^6 (K_T^\infty - 3)\left[1-\left(\frac{2R}{w}\right)^2\right]\right\}^{-1} \quad (2)$$



Axial stress for finite plate

$\sigma_{xx,finite}\ (x=0,y)$=FWC* $\sigma_{xx}\ (x=0,y)$ (3)

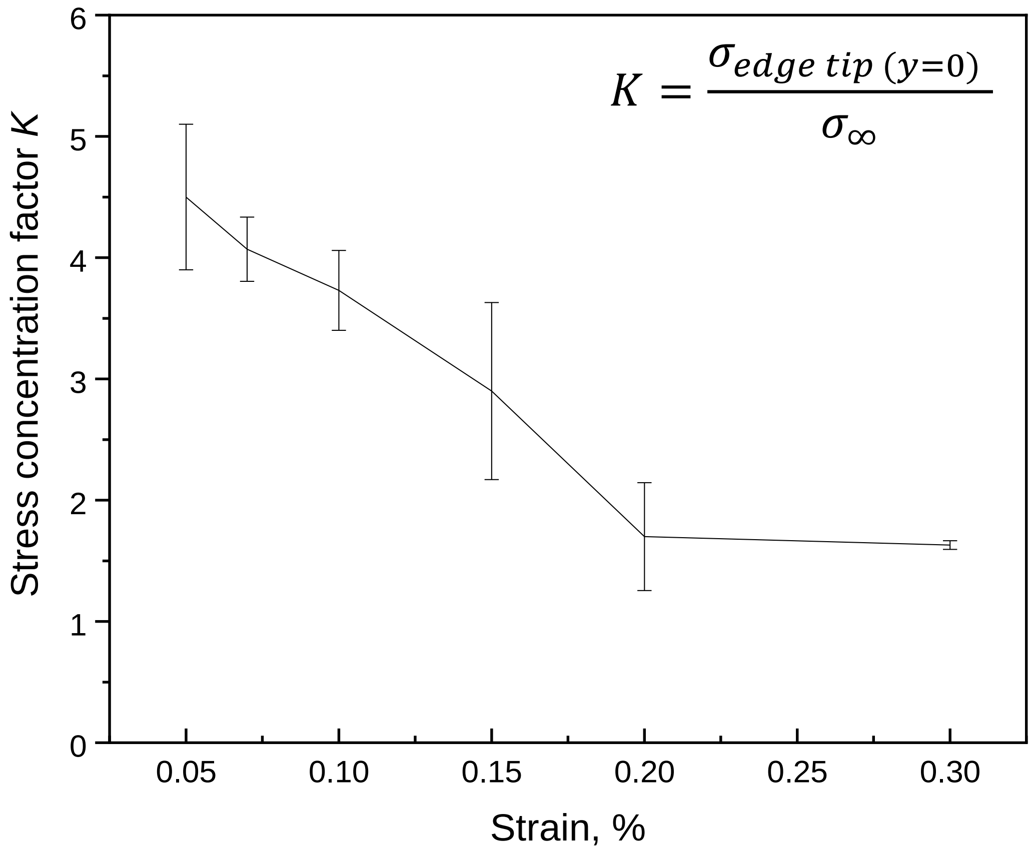
Neat Samples-Different Strain Levels



- Maximum stress is observed at the hole tip
- Max stress decays as the distance from the hole increases
- Stress reaches a plateau at distances greater than 1000 μm

Neat Samples-Different Strain Levels

Stress concentration factor *K* :



- Fibre fracture is assumed to occur between 0.15 and 0.2% of the external applied strain, where *K* decays dramatically
- Maximum *K* at the notch tip is observed in **0.05%** applied strain

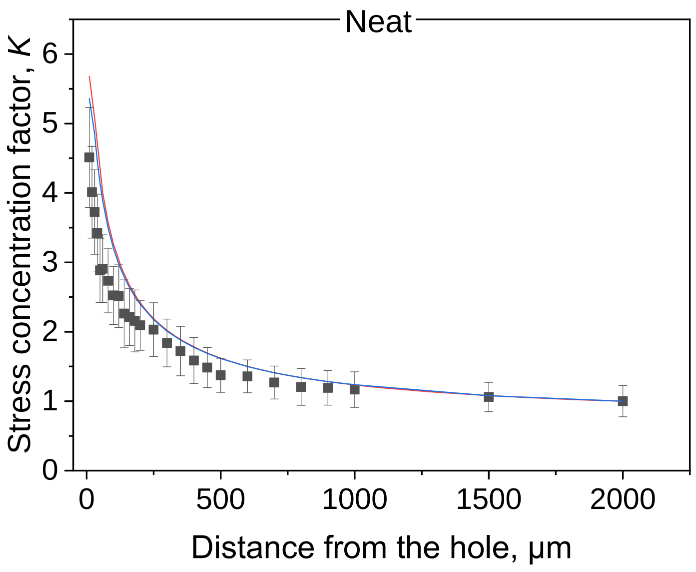
Selected strain step for all the following cases (Neat and GNPs enhanced CFRPs)

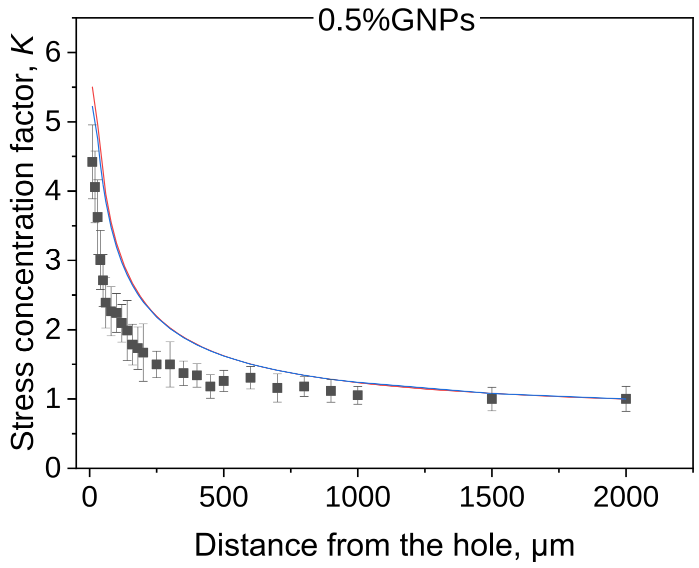
Determination of *K* reduction

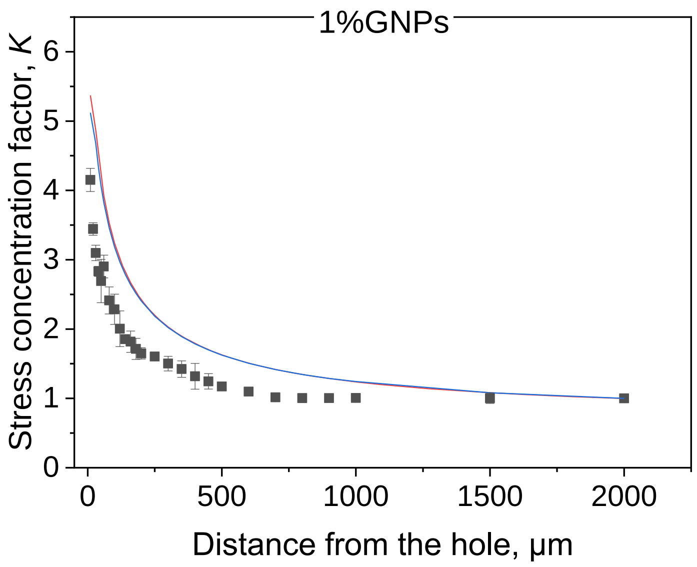
- **0.05% External applied strain**

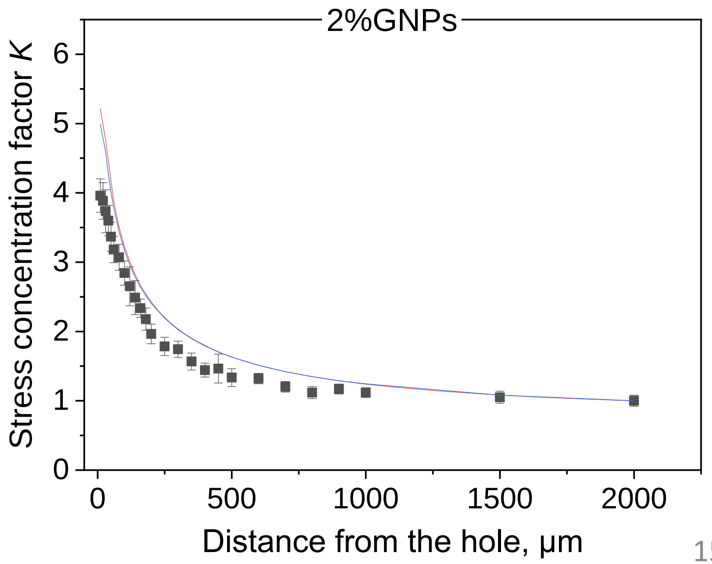
$$K = \frac{\sigma_{at\ any\ point}}{\sigma_{\infty}}$$

Analytical
Numerical
Experimental

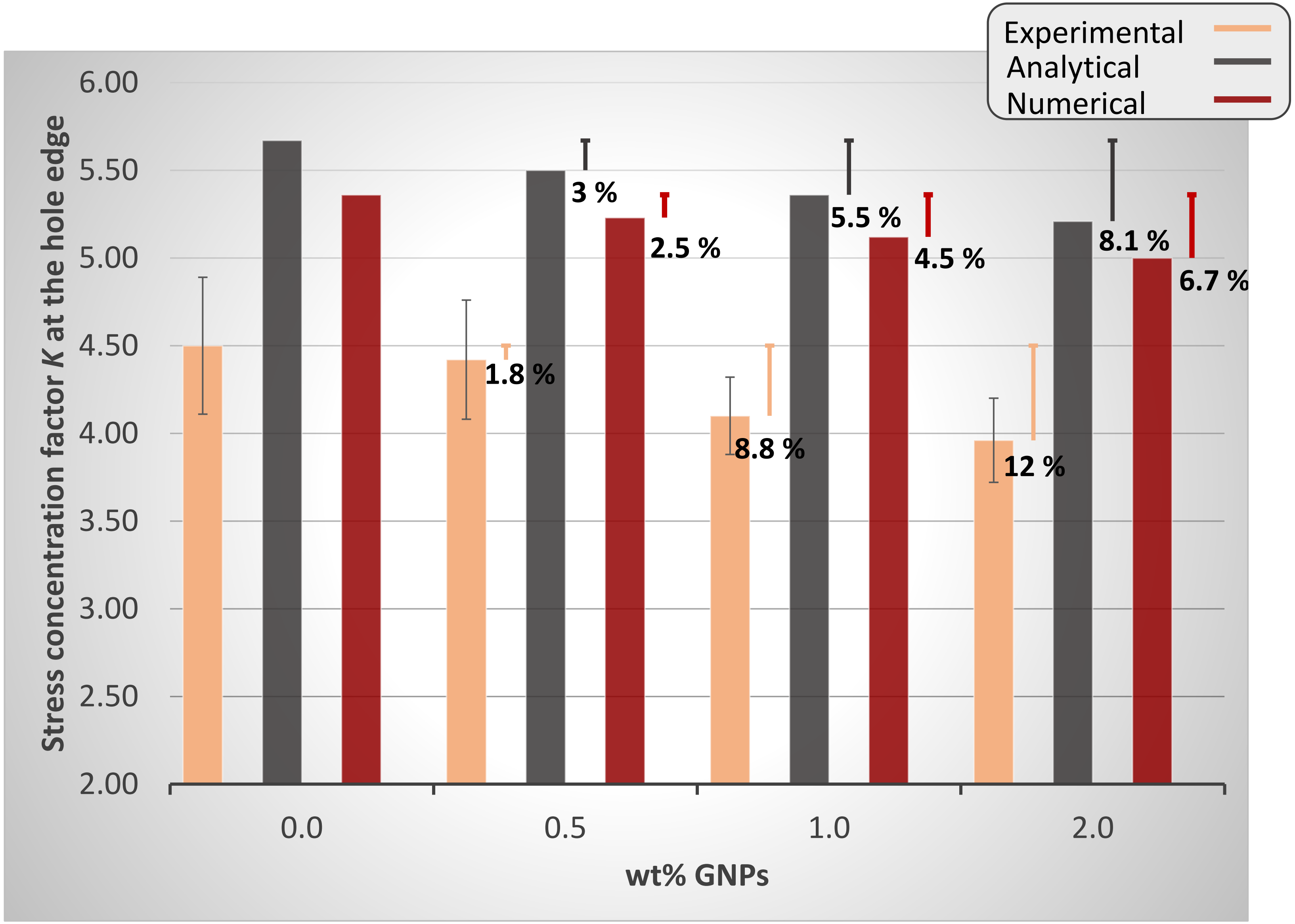








Determination of *K* reduction



Determination of *K* reduction

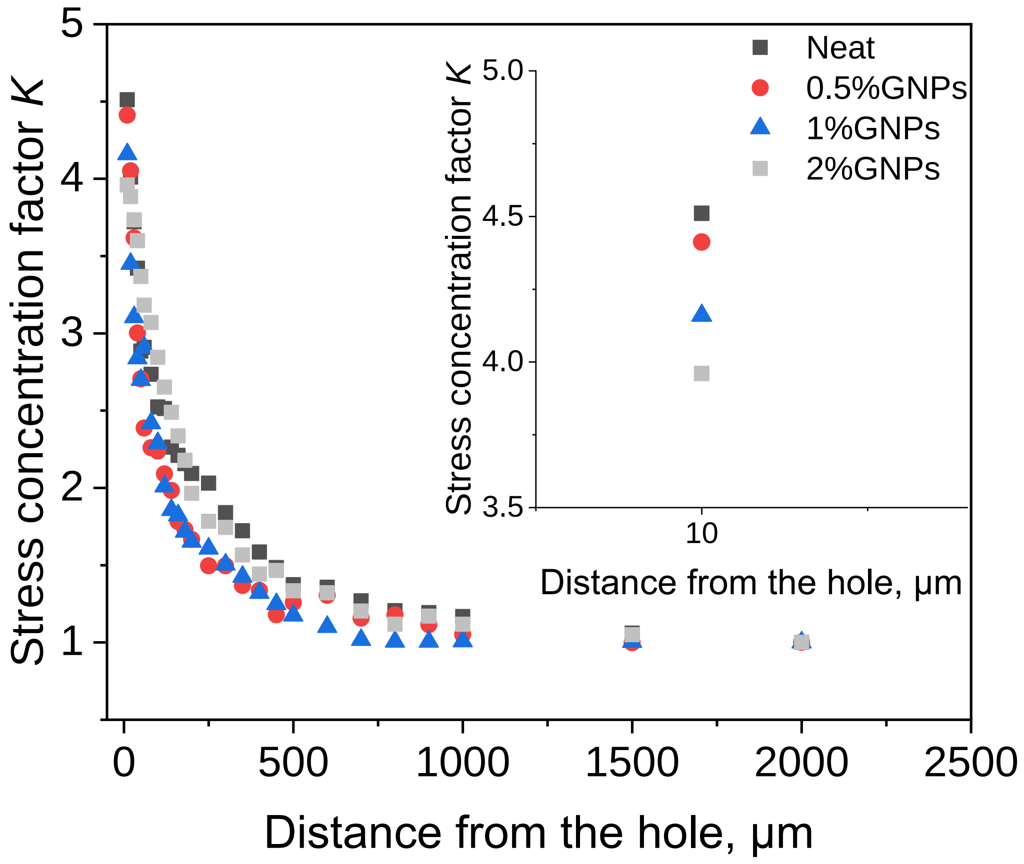
Remarks

- The experimental value of *K* at the notch tip, in neat CFRPs, equals to 4.5
- The analytical and numerical methods overestimate the *K* value up to 19% and 25%
- The experimentally defined stress concentration profile agrees with the analytical and numerical ones
- Similar behaviour of the *K* profile is presented for the modified CFRPs
- The analytical and numerical methods overestimate the *K* value up to 30% in case of 2wt% GNPs enhanced CFRP

	Numerical & Analytical Models	***Experiments***
Voids/ Inclusions/ Fibre breakages	X	√
GNPs Geometry	X	√
GNPs Orientation	X	√
GNPs Properties	√	√

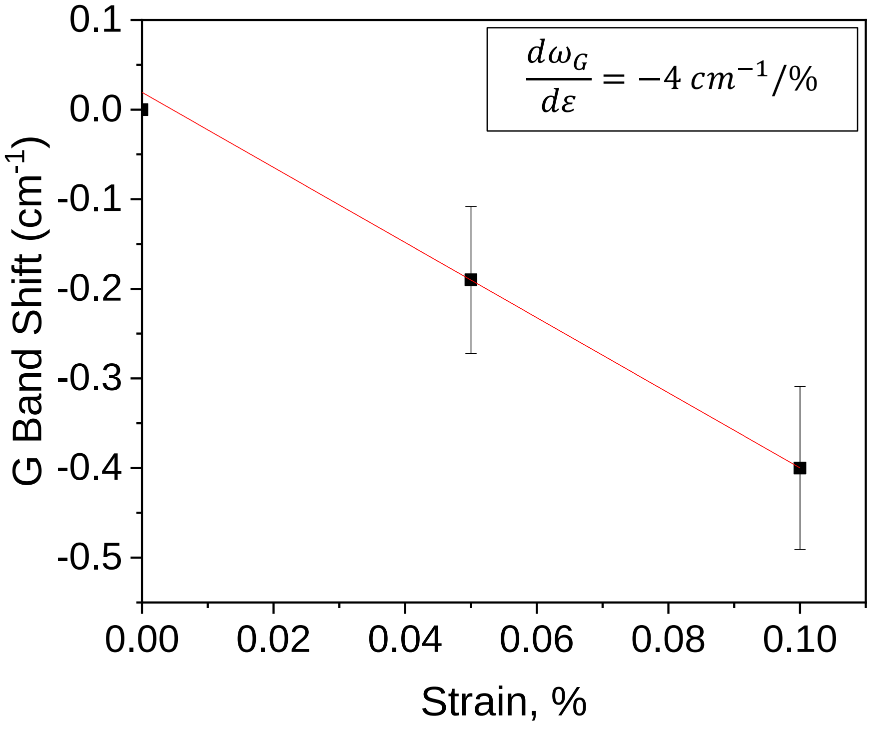
Determination of *K* reduction

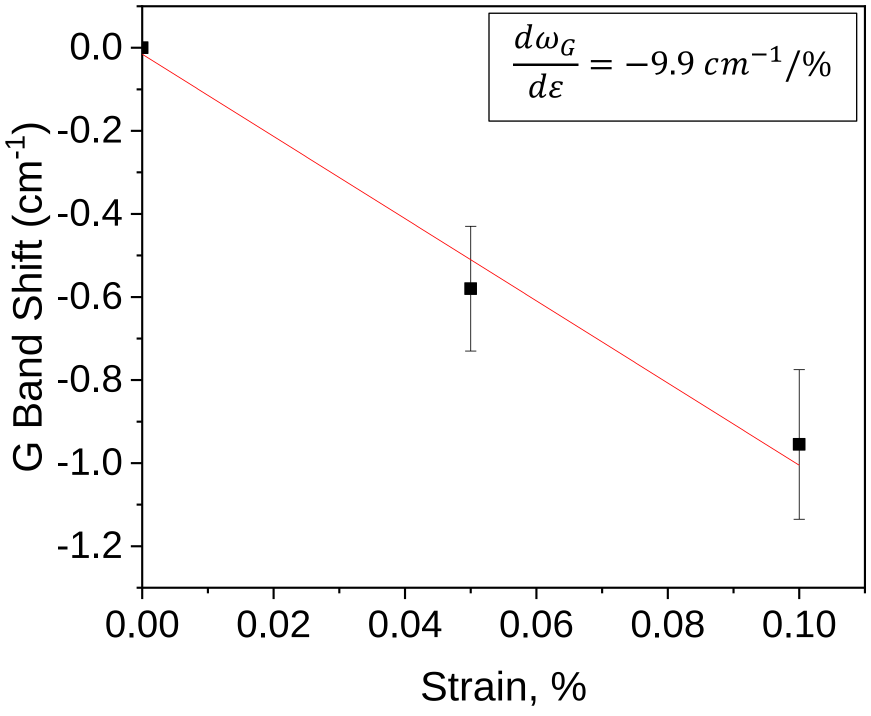
- <u>0.05% External applied strain</u>



- No significant difference of *K* values in the far field
- Apparent difference at the notch edge
- *K* decrease up to 2% for 0.5wt% GNPs enhanced CFRP
- *K* decrease up to 8.8% for 1wt% GNPs enhanced CFRP
- *K* decrease up to 12% for 2wt% GNPs enhanced CFRP

GNPs stress field into CFRPs





GNPs act as a good reinforcement → Part of the stress is distributed to the GNPs → The fibres bare less stresses → *K* reduction

GNPs have been deformed with a sensitivity of -4 cm-1/% far from the hole

GNPs have been deformed with a sensitivity of – 10 cm^{-1}/% around the hole

Conclusions

- Stress reaches a plateau at distances greater than 1000 μm
- The experimental value of *K* at the notch tip equals to 4.5 for the neat composite
- Maximum *K* decrease up to 12% for 2wt% enhanced CFRP as observed from experimental data
- Discrepancy between experimental and analytical/numerical K value at hole edge
- The experimentally defined *K* profile agrees with the analytical and numerical ones
- GNPs act as a good reinforcement since part of the stress is distributed to the GNPs ⇒ *K* reduction
- Remote Raman is a high-sensitivity method to in-situ measure the deformation via a non-destructive manner and provide the data in real time

THANK YOU

For your attention!!!

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