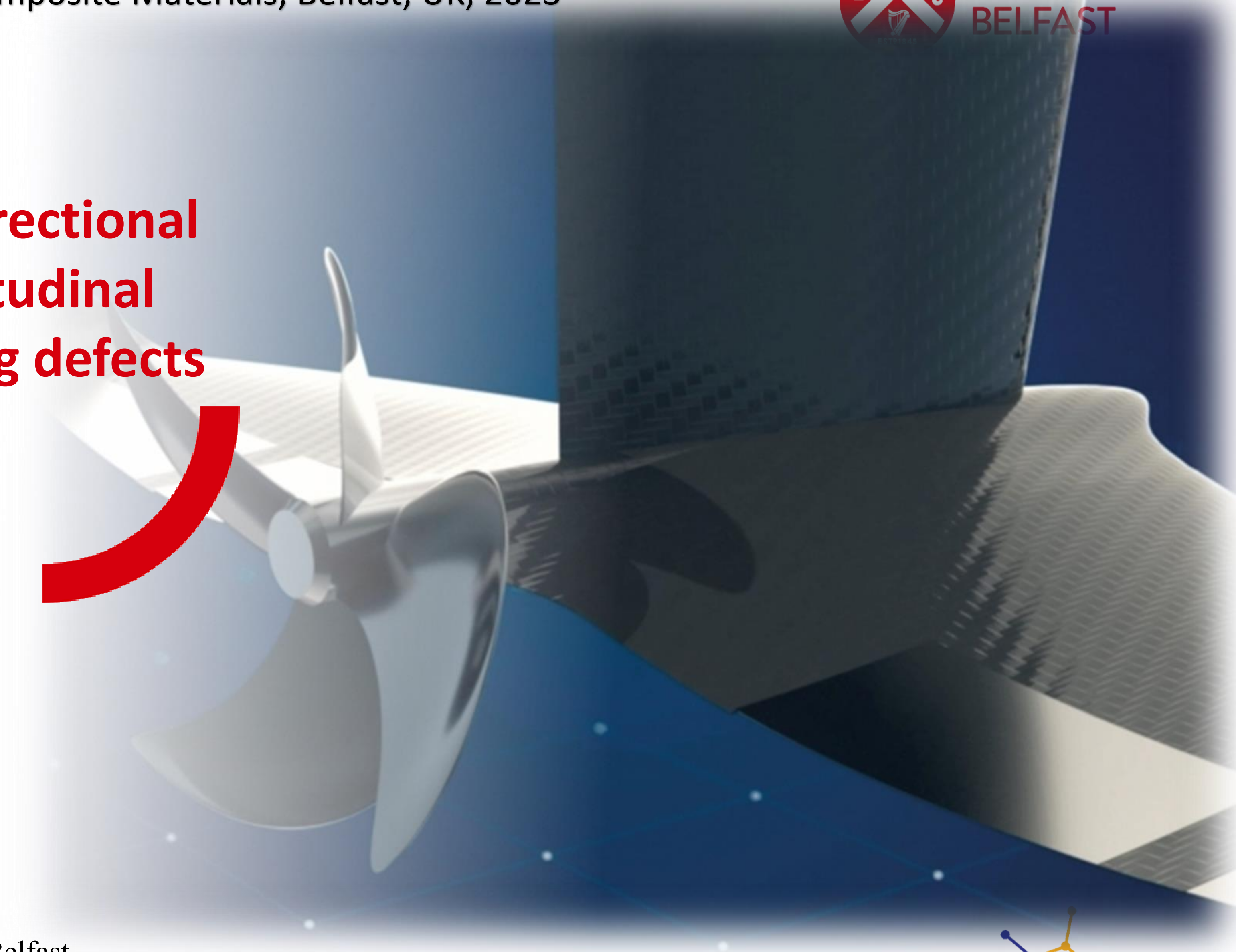
ICCM23: International Conference on Composite Materials, Belfast, UK, 2023

Failure analysis of unidirectional composites under longitudinal compression considering defects



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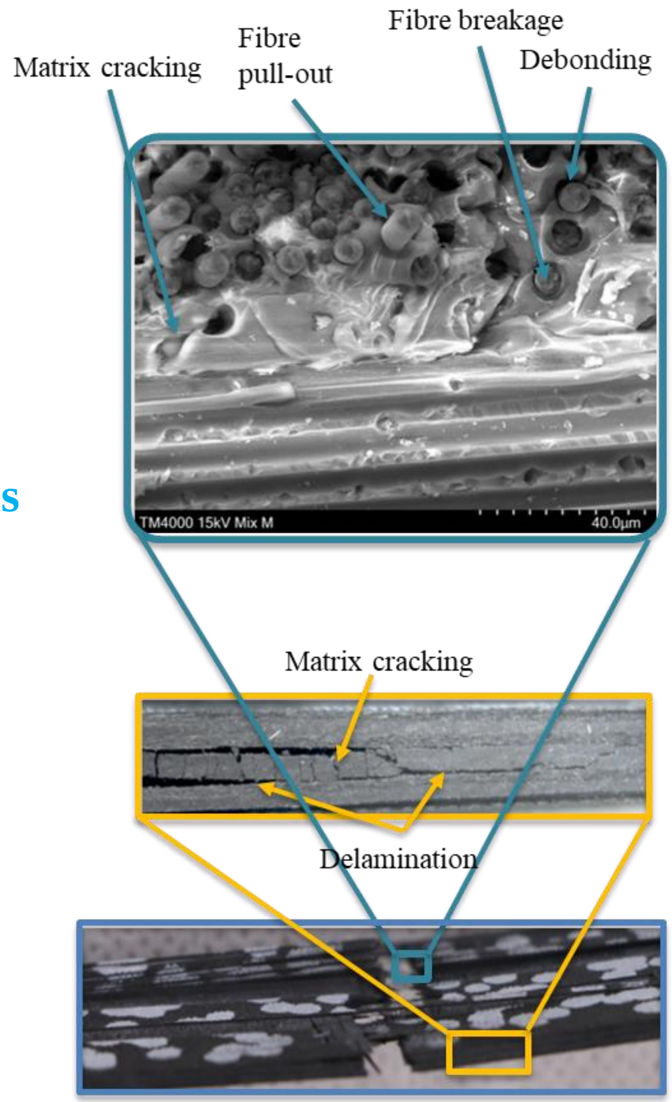
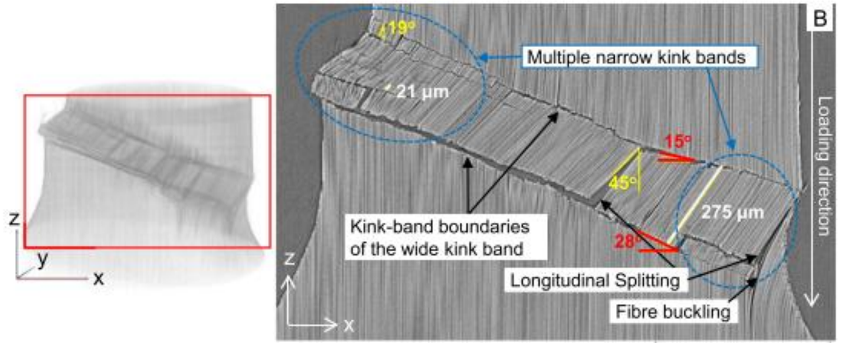
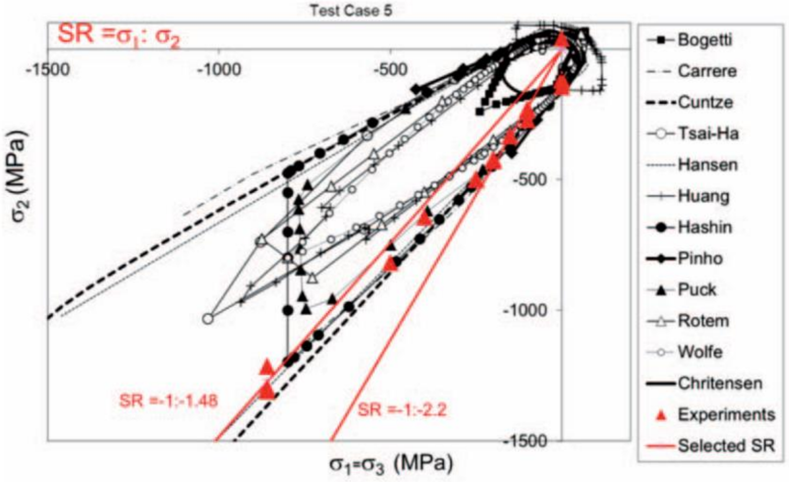
- Maximum stress Criterion
- Tsai-Wu criterion
- Hashin criterion
- Puck criterion
- LARC05
- ……



Typical failure pattern of cross-ply CFRP composite laminates



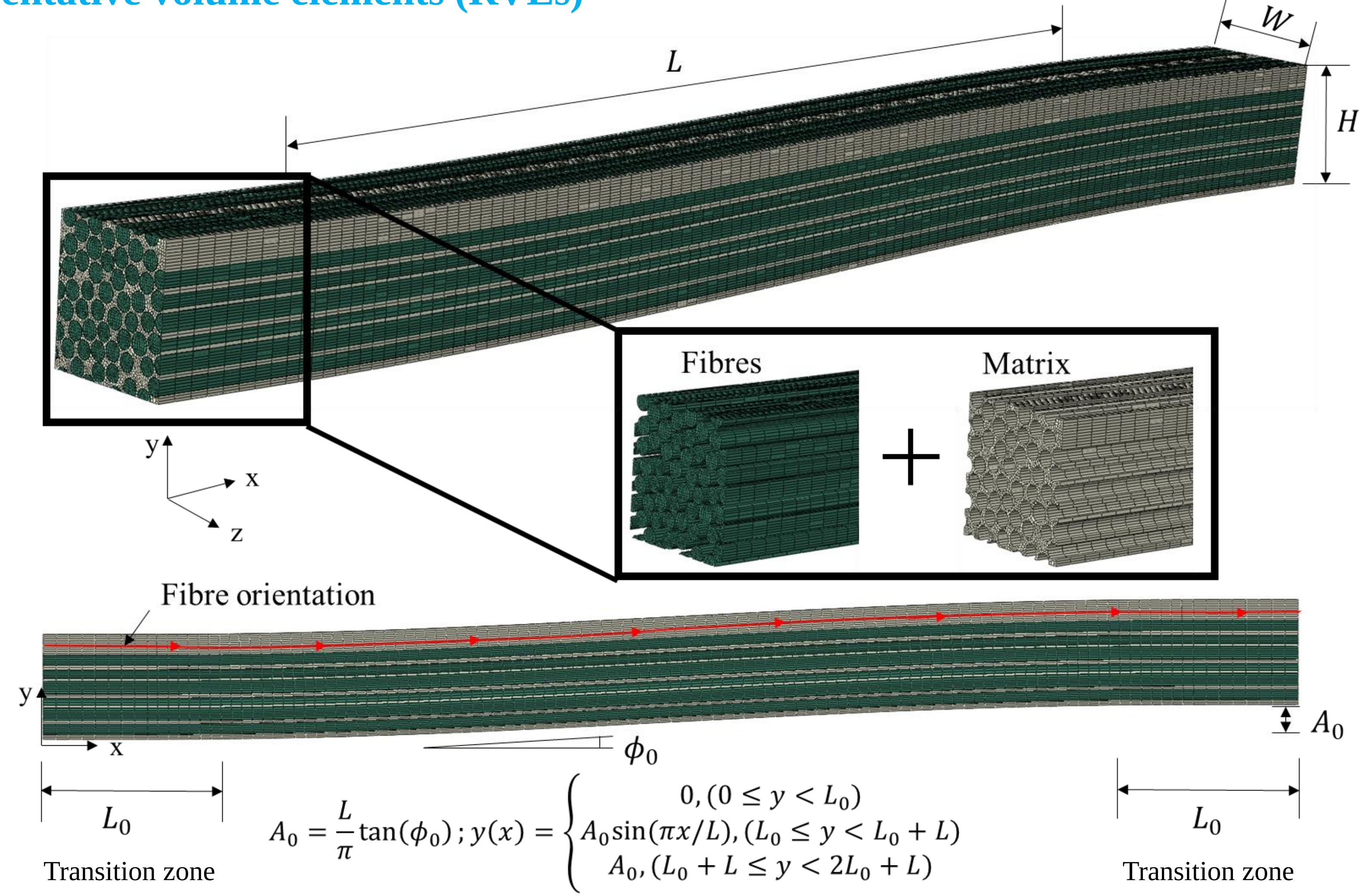
3D X-Ray micro-CT image of kink bands and associated damage mechanisms under longitudinal compression(Wang et al. 2017)



Failure criteria comparison under triaxial loading conditions from World Wide Failure Exercise – II (Kaddour et al. 2013)

❖ 3D high-fidelity micromechanical modelling

➢ Representative volume elements (RVEs)



$$A_0 = \frac{L}{\pi}\tan(\phi_0)\,;\, y(x) = \begin{cases} 0, (0 \le y < L_0) \\ A_0\sin(\pi x/L), (L_0 \le y < L_0 + L) \\ A_0, (L_0 + L \le y < 2L_0 + L) \end{cases}$$

❖ 3D high-fidelity micromechanical modelling

➢ Constitutive model of constituents

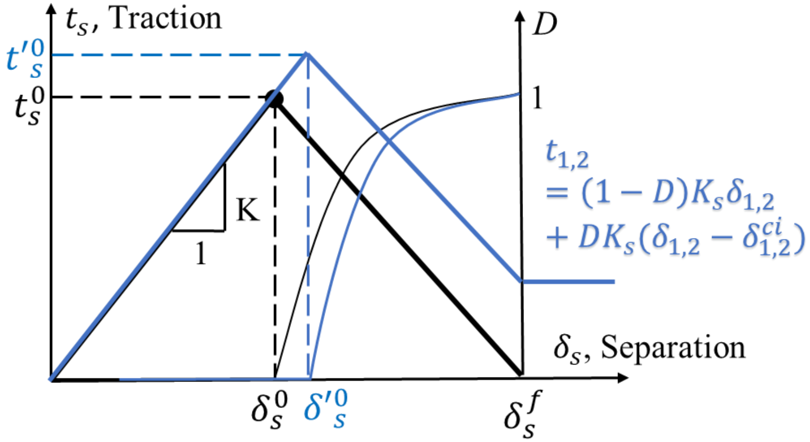
- **Fibres**

  Transversely isotropic, assumed to be elastic.

- **Fibre/matrix interface**

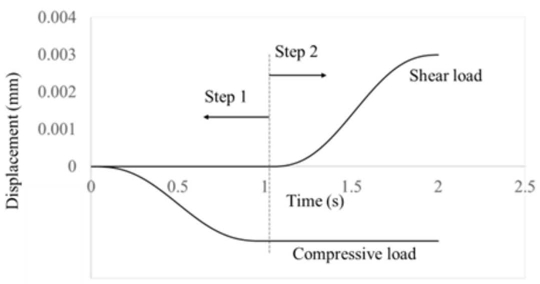
Original cohesive zone model — Friction effect under compression

$$\mathbf{t} = (1-D)\boxed{\begin{bmatrix} K_s & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_n \end{bmatrix}\begin{bmatrix} \delta_1 \\ \delta_2 \\ \delta_n \end{bmatrix}} + D\boxed{\begin{bmatrix} K_s & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_n \end{bmatrix}\begin{bmatrix} \delta_1-\delta_1^{ci} \\ \delta_2-\delta_2^{ci} \\ -<-\delta_n> \end{bmatrix}}$$

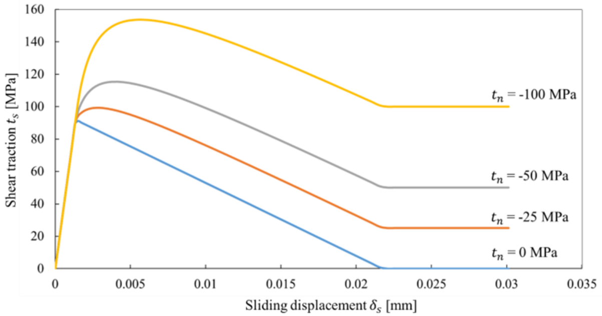


$$t_{1,2} = (1-D)K_s\delta_{1,2} + DK_s(\delta_{1,2}-\delta^{ci}_{1,2})$$

Cohesive surface



Shear stress under transverse compression



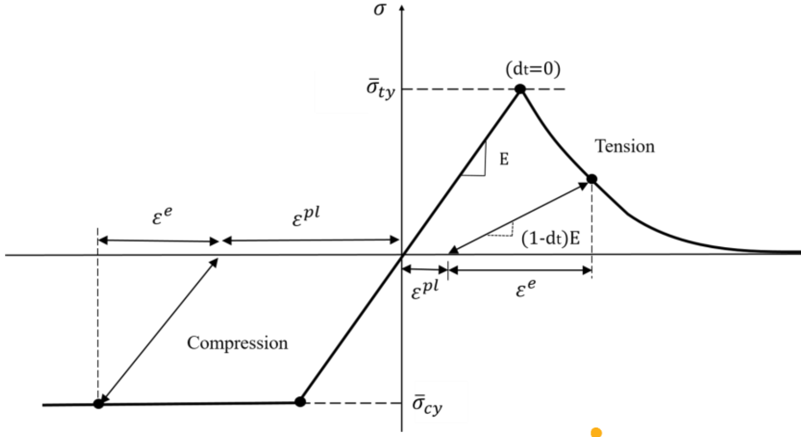
- **Matrix**

  Drucker-Prager plastic damage model

  - Brittle failure in uniaxial tension
  - Plastic behaviour in compression/shear
  - Influence of hydrostatic stress on the mechanical behaviour of polymer under multiaxial stress states

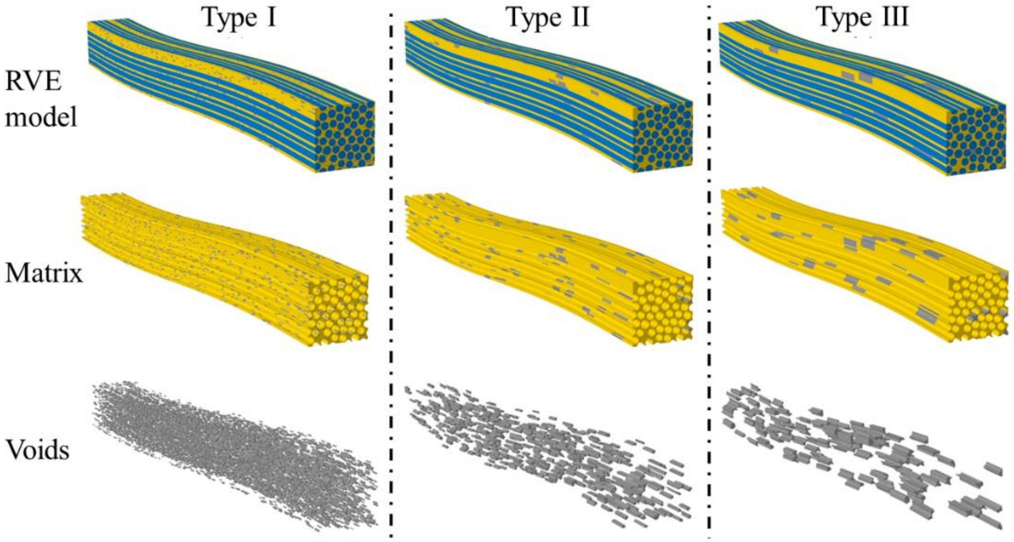
$$\Phi(I_1, J_2, \sigma_I, \beta, \alpha) = \frac{1}{1-\alpha}\left(\sqrt{3J_2} + \alpha I_1 + B\langle\sigma_I\rangle\right) - \sigma_{myc} = 0$$

I_1 stands for the first invariant of the stress tensor,
J_2 is the second invariant of the deviatoric stress tensor,
α is the **pressure-sensitivity** parameter of the Drucker-Prager yield criterion,
σ_I is the maximum principal stress.



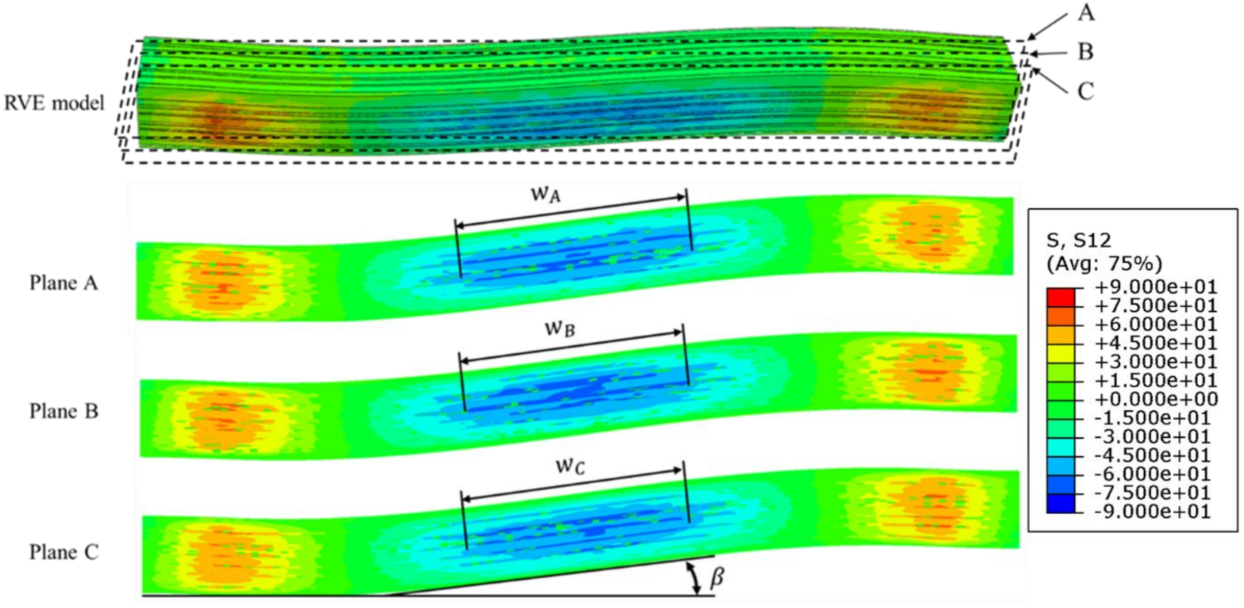
❖ Definition of voids and kink-band

➢ Definition of voids



Three types of voids (type I, type II and type III) in 3D RVE models with φ_0=5°, f_v=3%.

➢ Definition of kink-band width and fibre rotation angle

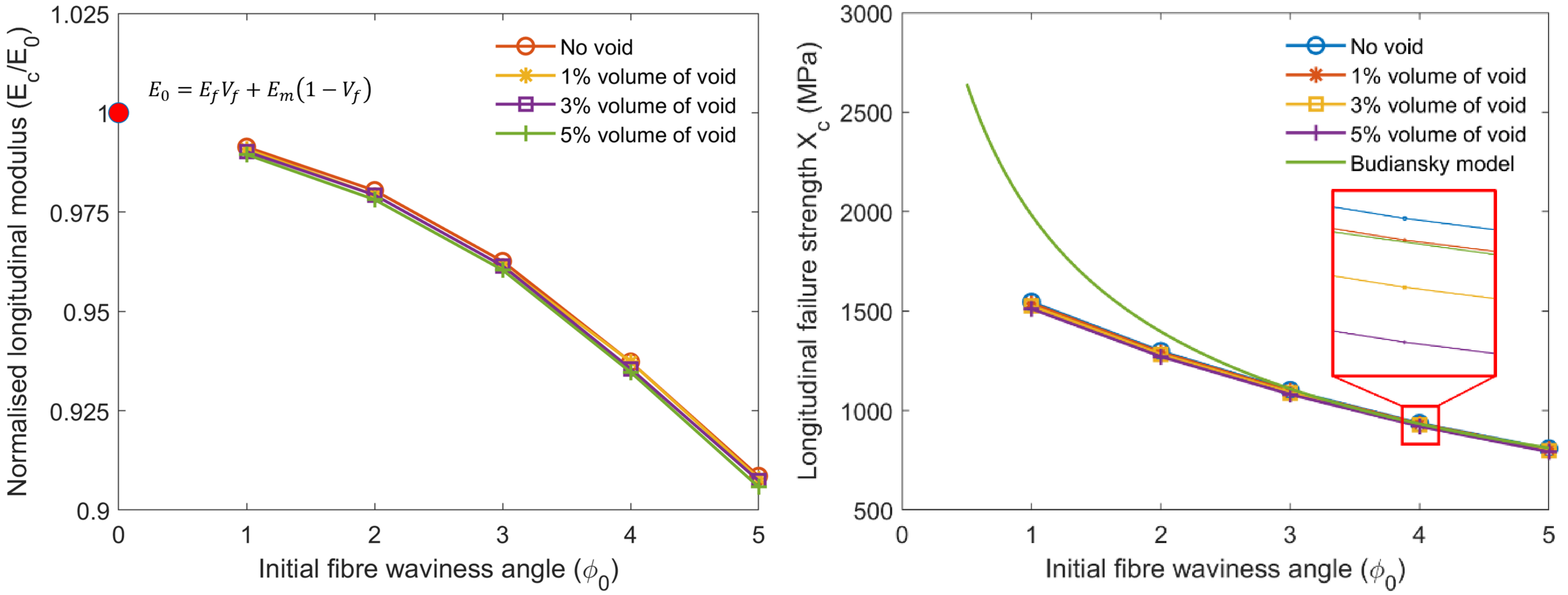


Kink-band width: $w = \frac{w_A+w_B+w_C}{3}$

Fibre rotation angle: β

❖ Numerical results under uniaxial longitudinal compression considering voids

➢ Influences of initial waviness angle and voids on the prediction of modulus and strength of composites



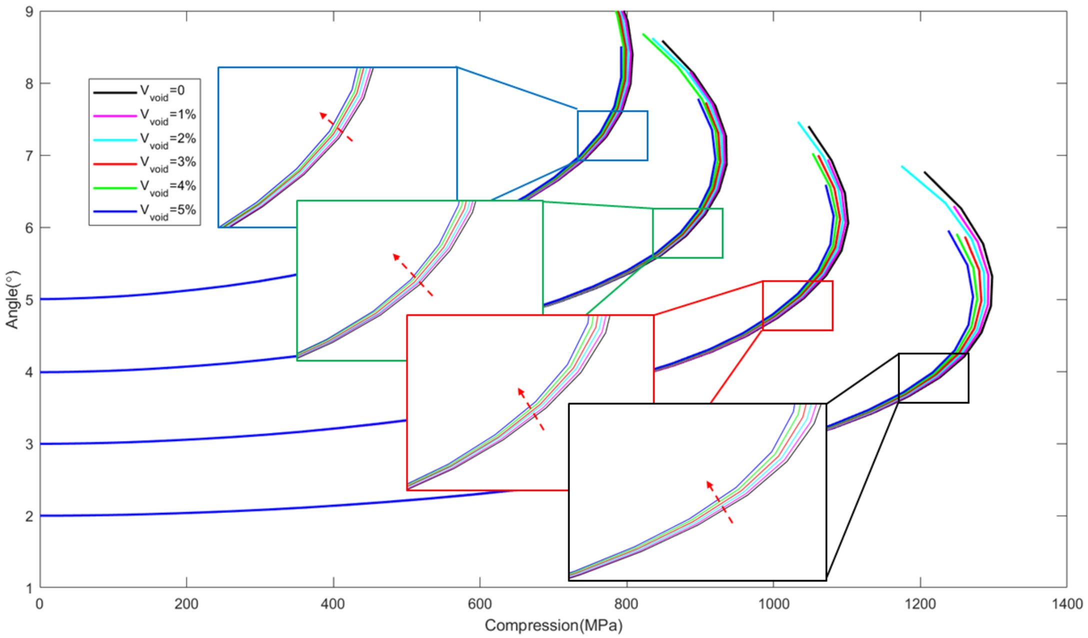
- Initial fibre waviness angle has significant influences on the longitudinal compressive modulus and failure strength.
- Volume fraction and type of voids have insignificant effects on the longitudinal compressive modulus and strength.

❖ Numerical results under uniaxial longitudinal compression considering voids

➢ Influences of uncertainties on in-situ kink-band width

Φ_0	Intact model		Void volume										
			1%			2%	3%			4%	5%		
			Void size										
			I	II	III	I	I	II	III	I	I	II	III
1°	—	—	—	—	—	—	—	—	—	—	—	—	—
2°	w_S	75.22	85.76			92.98	105.27			116.17	121.23		
3°	w_S	97.84	103.55	104.14	102.04	108.72	122.54	125.12	131.47	134.25	136.38	138.25	156.73
4°	w_S	132.82	135.78			143.37	149.2			154.12	160.45		
5°	w_S	143.4	150.57	148.86	149.75	159.04	158.17	159.95	173.07	171.82	158.59	174.99	169.93

➢ Influences of uncertainties on fibre rotation angle

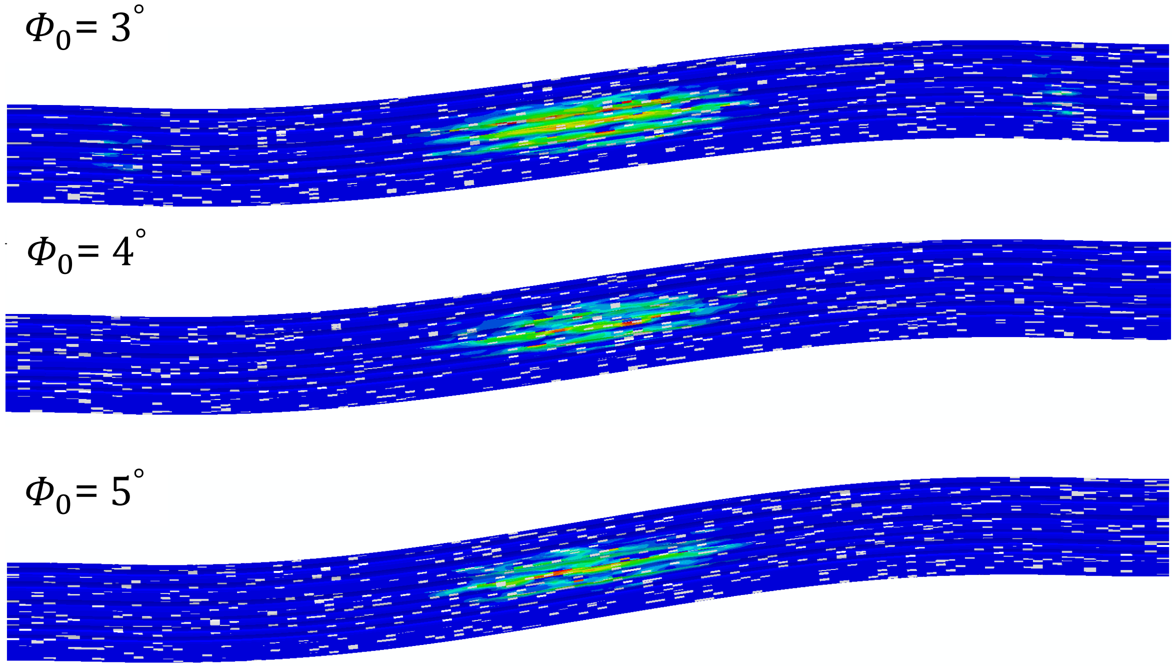


- Kinking phenomenon disappears when $\Phi_0 \leq 1^{\circ}$ as the failure mechanism is fibre failure
- In-situ kink-band width increases as the initial fibre waviness angle Φ_0 or volume fraction of voids increases
- The type of voids has insignificant effects on the in-situ kink-band width
- The volume fraction of voids does not influence fibre rotation angles at peak loads

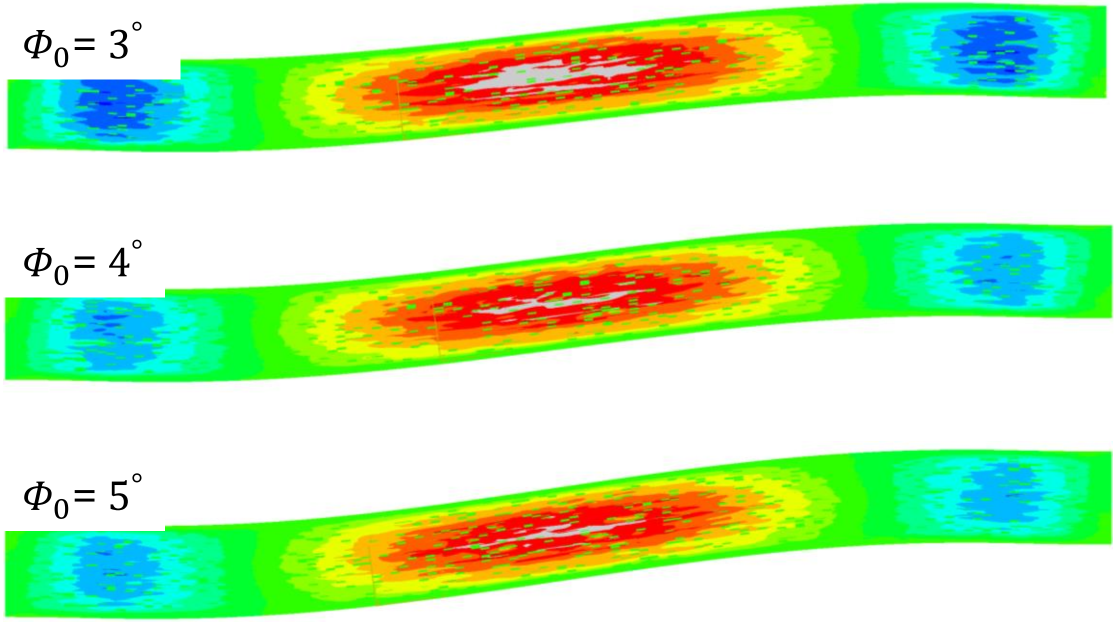
❖ Numerical results under uniaxial longitudinal compression considering voids

➢ Influences of the initial waviness angle on the failure of composites with f_v=3% and Type I

Tensile damage in matrix



Shear stress distribution in matrix

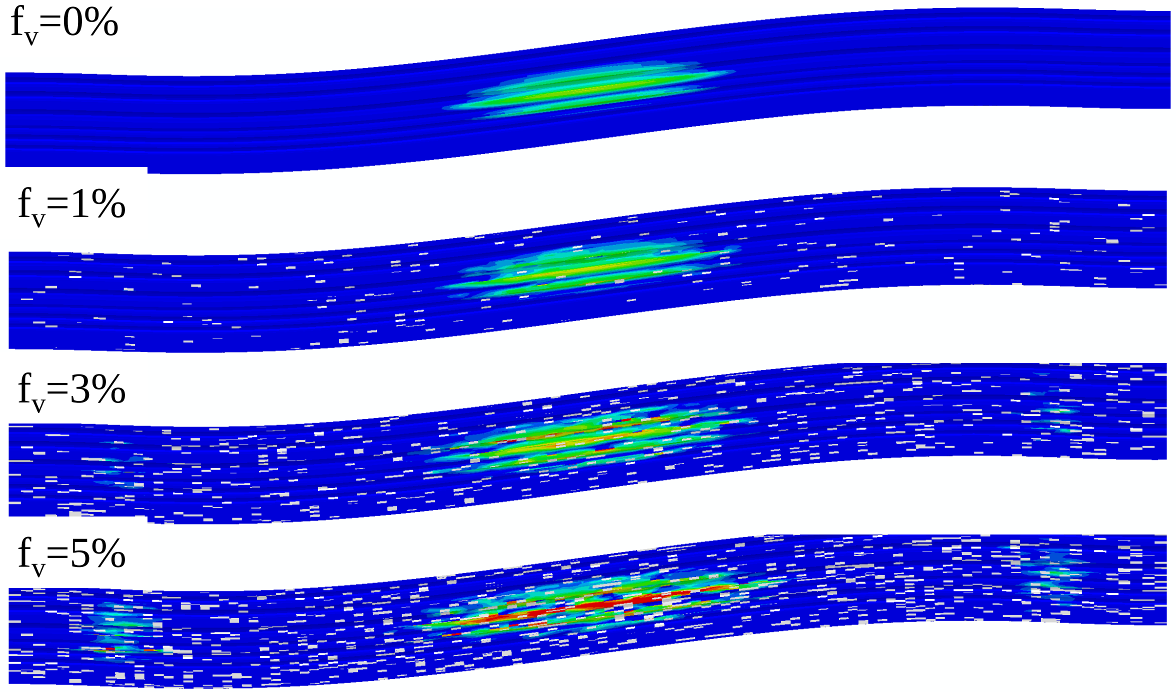


- Initial fibre waviness angle has insignificant influences on the final failure of composites under longitudinal compression

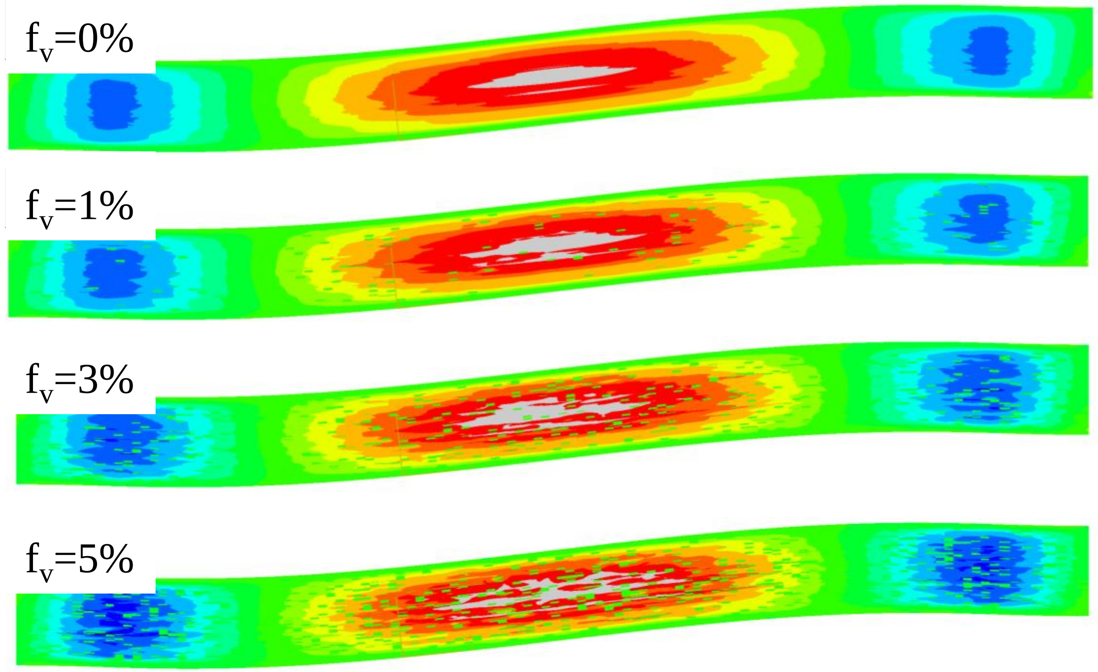
❖ Numerical results under uniaxial longitudinal compression considering voids

➢ Influences of the volume fraction of voids on the failure of composites with $\Phi_0 = 3^\circ$ and Type I

Tensile damage in matrix



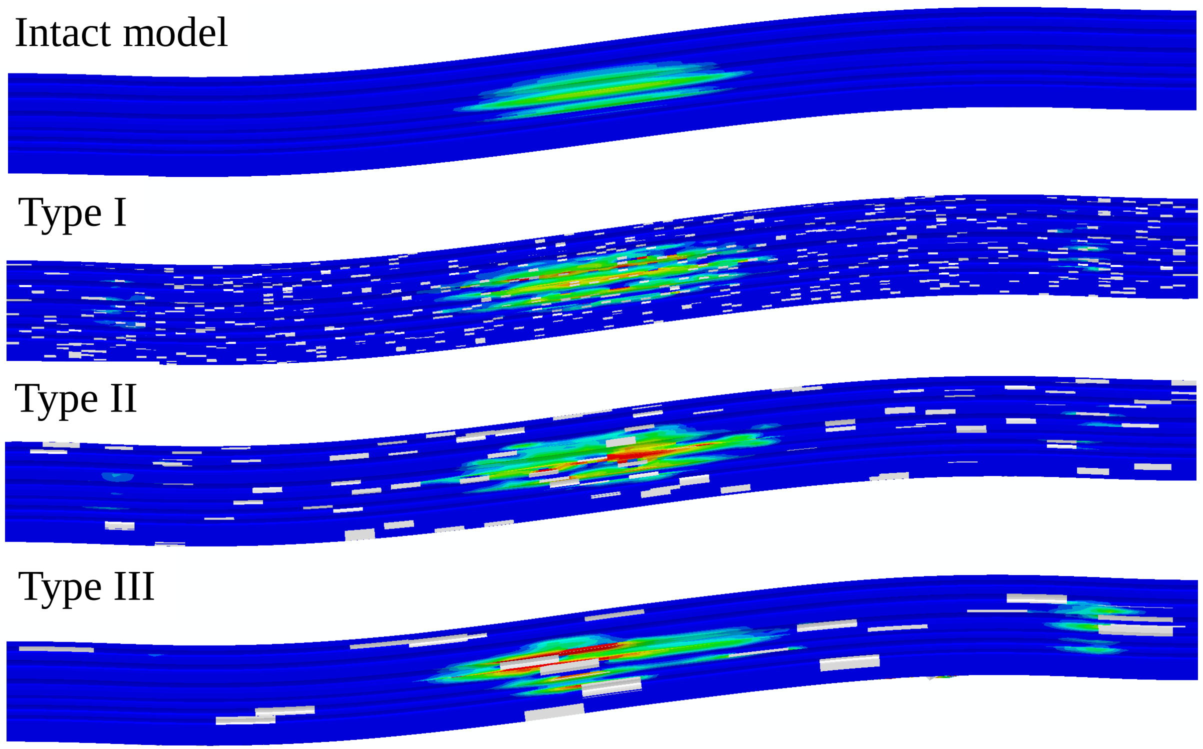
Shear stress distribution in matrix

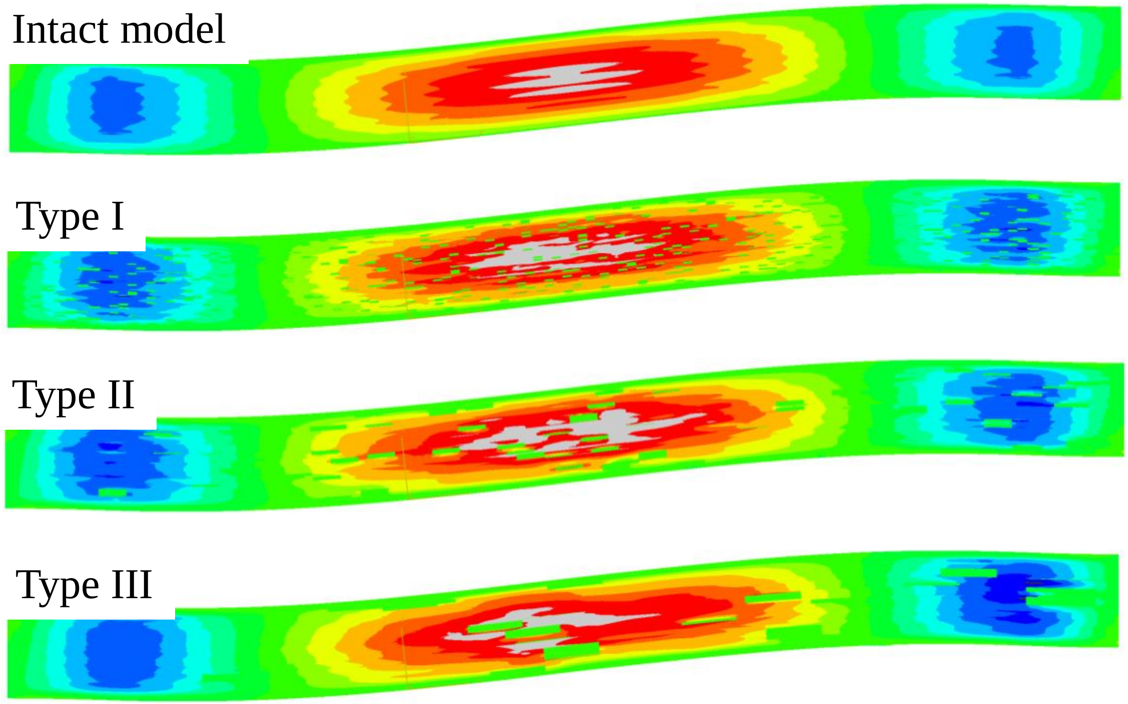


- The volume fraction of voids has significant effects on the damage initiation and propagation in the matrix
- The existence of voids has effects on the distribution of shear stress in the matrix

❖ Numerical results under uniaxial longitudinal compression considering voids

➢ Influences of the type of voids on the failure of composites with $\Phi_0 = 3^{\circ}$ and $f_v = 3\%$


Tensile damage in matrix

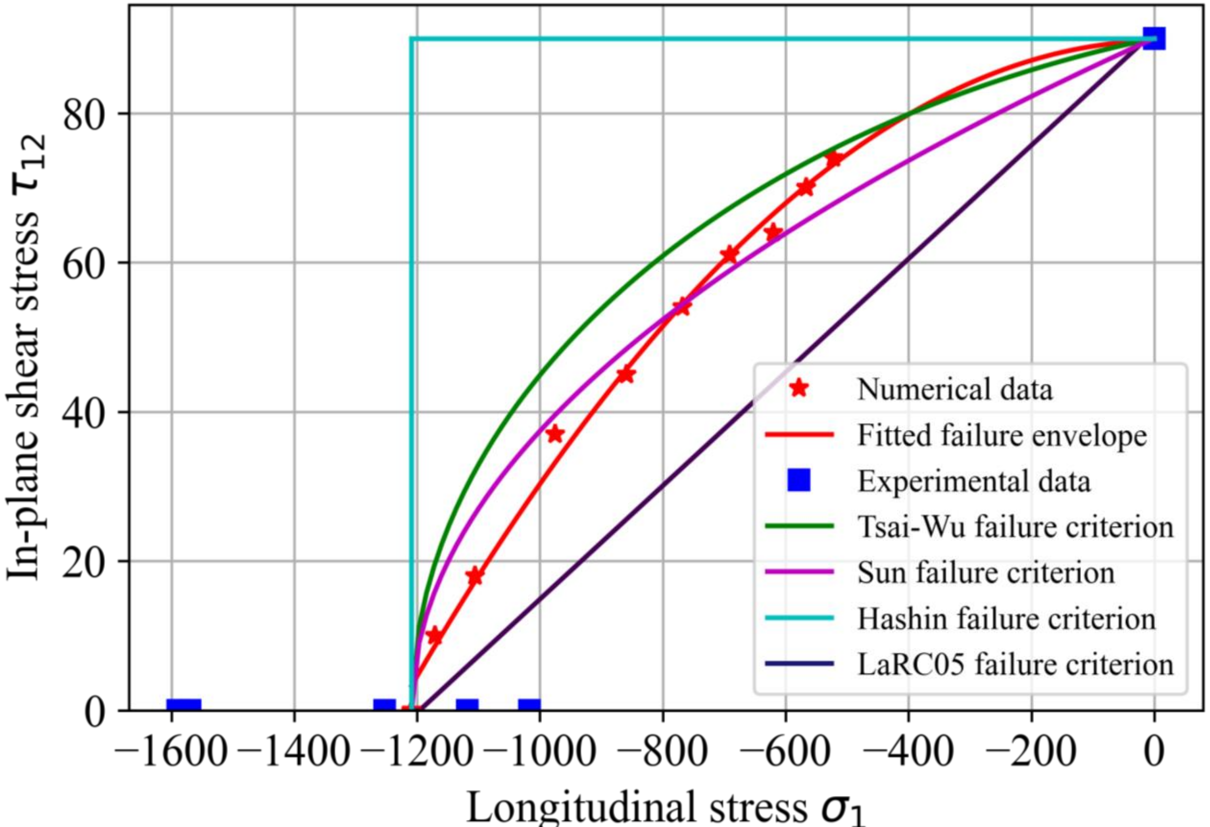

Shear stress distribution in matrix

- Damage easily initiates and propagates from the larger voids in the matrix
- The size of voids can influence the distribution of shear stress in the matrix

❖ Failure prediction under combined longitudinal compression and in-plane shear

➢ Failure strength prediction of composites and failure criteria comparison

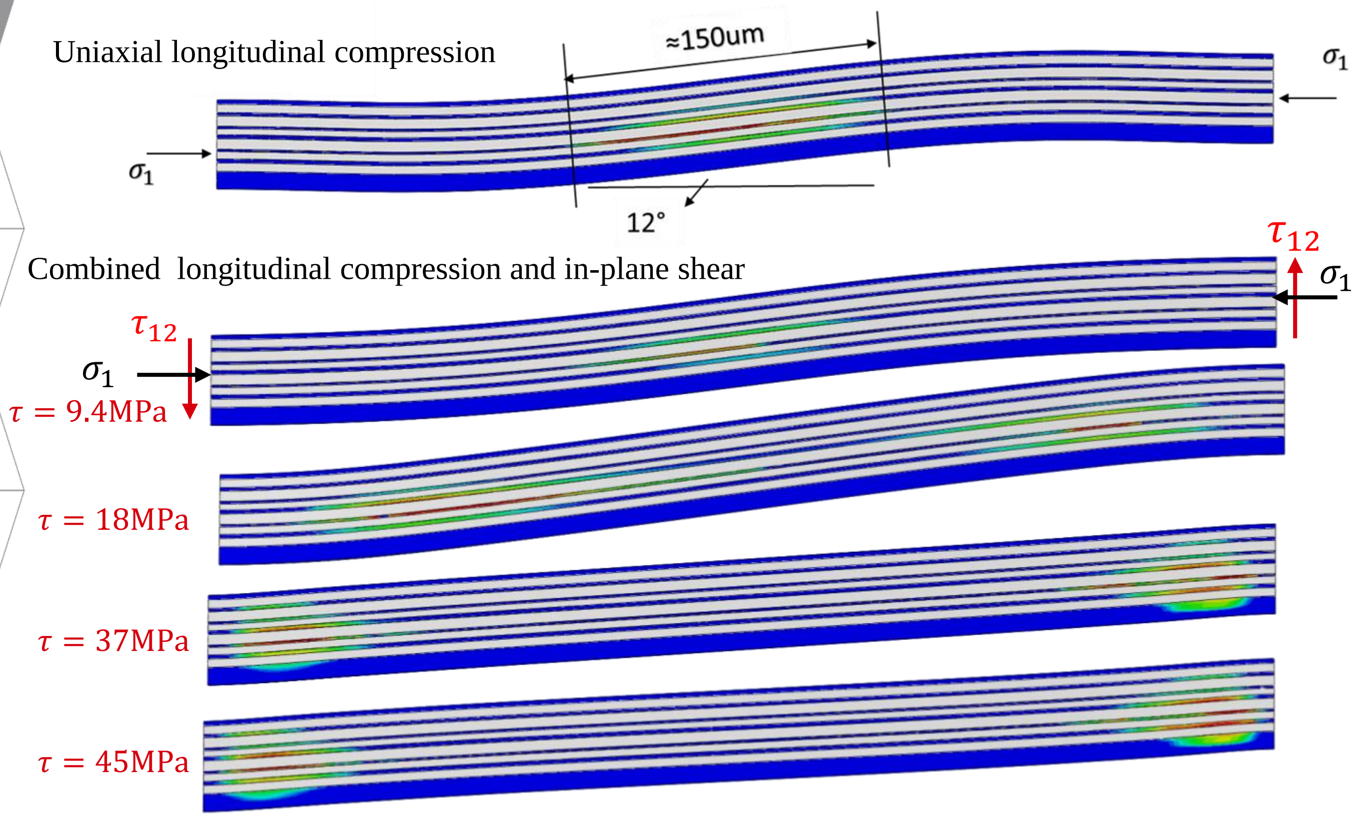
Shear stress	0	9.4	18	37	45	54	61	64	70	74
Failure point (MPa)	(1209,0)	(1171,9.4)	(1106,18)	(974,37)	(859,45)	(768,54)	(691,61)	(620,64)	(567,70)	(522,74)
Kink-band width (μm)	150	135	-	-	-	-	-	-	-	-
Fibre rotation angle	12°	14°	16°	-	-	-	-	-	-	-



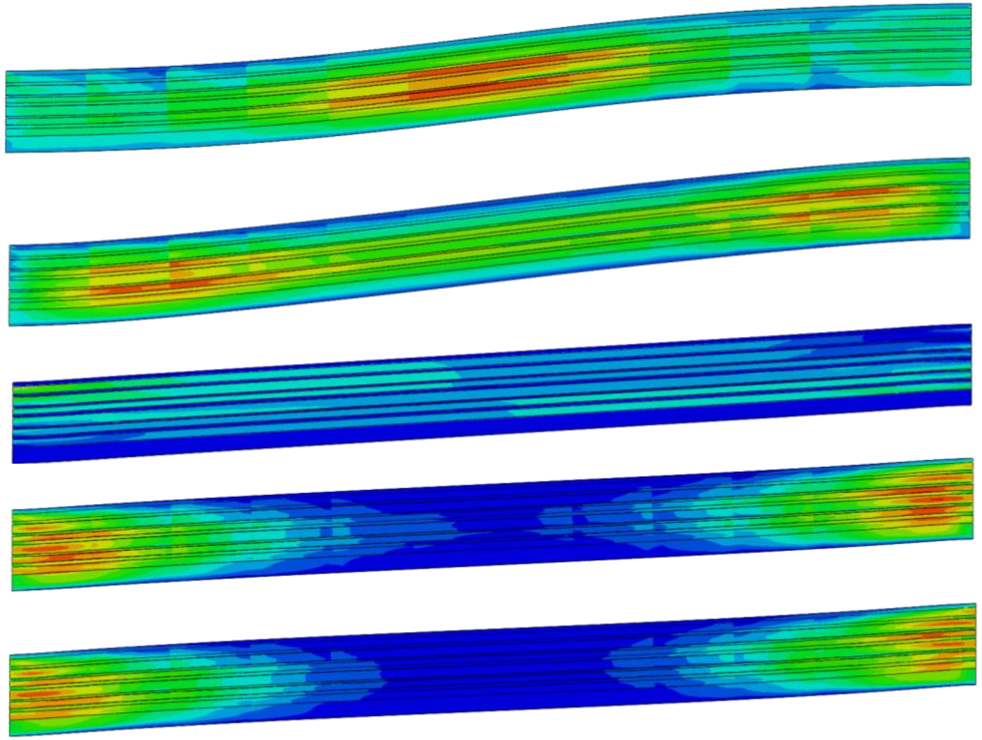
- In-situ kink-band width decreases as in-plane shear stress increases and disappears when the stress exceeds 18 MPa
- In-plane shear stress facilitates the fibre rotation under combined loading conditions when the stress is not larger than 18 MPa
- Hashin and Tsai-Wu failure criteria overestimate the failure strength under biaxial loadings while the LaRC05 failure criterion underestimates the strength.
- Sun Failure criterion has a better agreement with the failure strengths obtained from numerical simulations mainly due to its consideration of the initial waviness angle of fibres.

➢ Failure analysis of composites under combined loadings

Tensile damage in matrix



Shear stress distribution in matrix



- In-situ kink-band shrinks and shifts to both sides when in-plane shear stress increases
- The failure of composites is triggered by the matrix tensile failure in the form of splitting

❖ Conclusions:

- 3D high-fidelity micromechanical models can predict the failure of unidirectional composite materials in great detail under uniaxial longitudinal compression.
- A new approach is proposed for the measurement of in-situ kink band width for numerical studies
- Manufacturing-induced uncertainties, such as the initial waviness angle of fibres and voids, have a significant influence on the failure prediction of composites.
- In-plane shear stress influences the formation of kink bands and fibre rotation angle.
- Conventional failure criteria were assessed based on the failure strength under combined longitudinal compression and inn-plane shear and the Sun failure criterion performs best due to the consideration of initial waviness angle.

❖ Acknowledgement

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Thanks! Any question?