Experimental analysis of unfolding failure in curved composite laminates

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Outline

- Introduction to unfolding failure
- 4PBT
- Materials considered
- Traditional unfolding, UD test results
- Induced unfolding
- Test results: CP, QI
- Conclusions and future scope

Introduction

Unfolding failure

- Sudden delamination that occurs when subjected to opening bending moment
- Flatten the curvature, plies separate due to different lengths
- Opening bending moments induce out of plane stresses

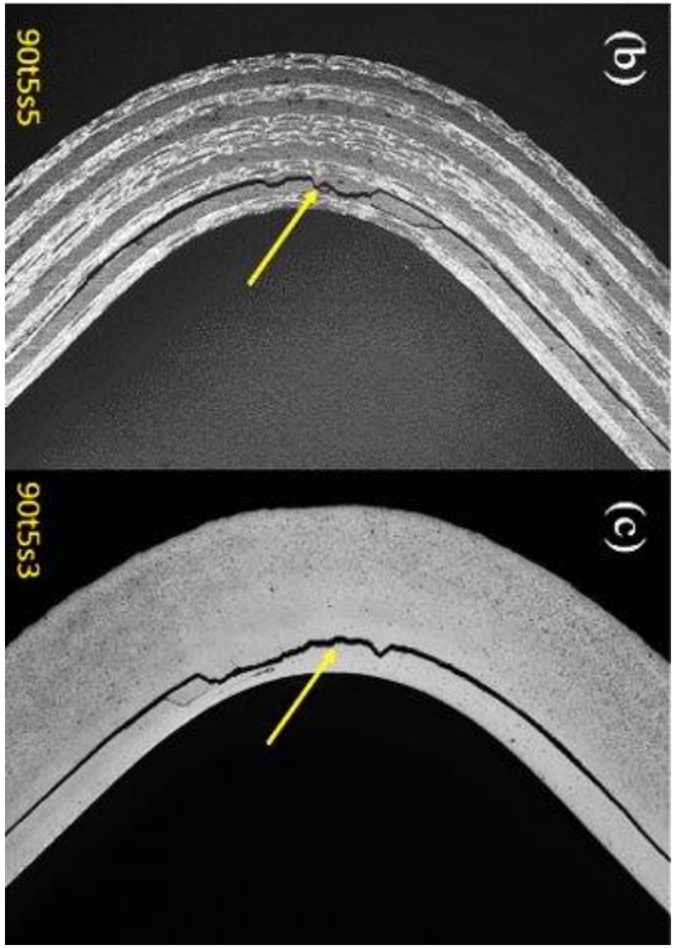


Fig 1: Representation of unfolding failure
[B.Tasdemir 19]

Four-point bending test

Test Standard: AITM1-0069 or ASTMD6415/D6415M–06a.

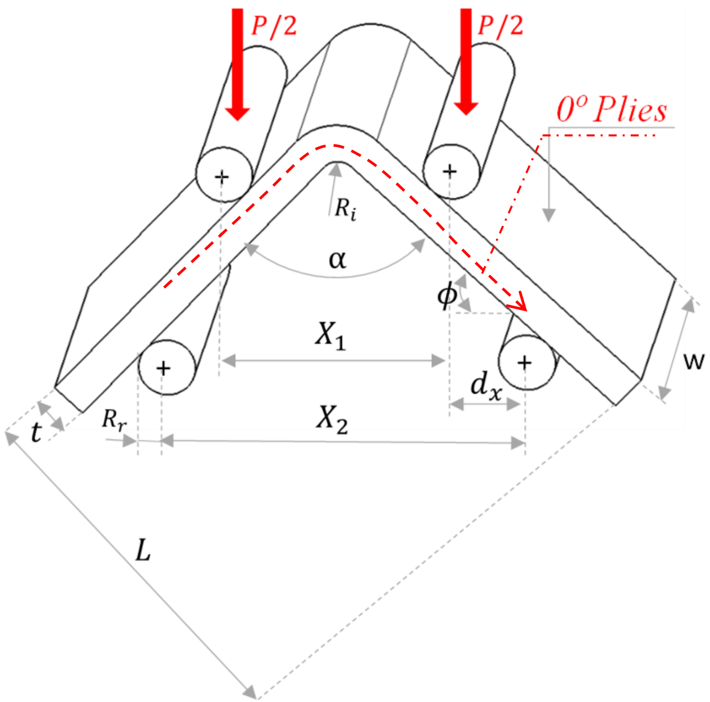
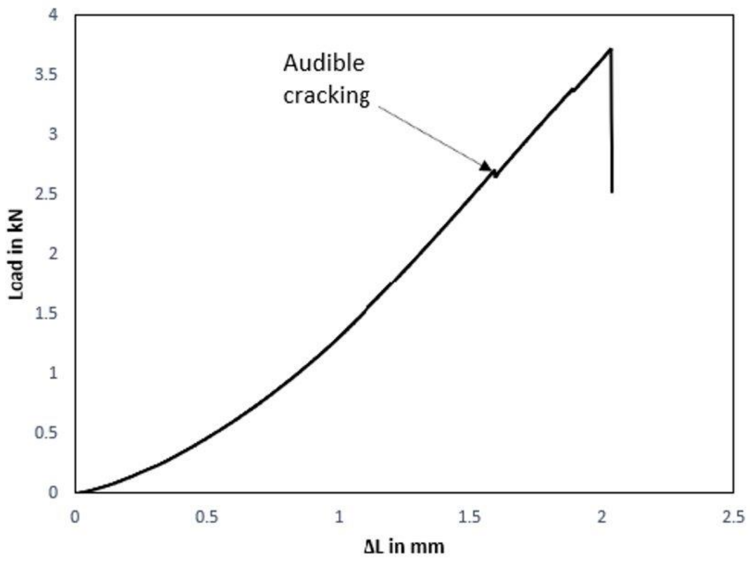


Fig 2: Specimen and fixture specifications

	Specimen dimensions	Preferred dimensions
Ri	Inner radius	10 ≥ Ri ≥ 5; depends on thickness
t	Thickness	Depends on stacking sequence
α	Opening angle	90° ± 3°
w	width	t < 5 = 25 ; 5 < t < 8 = 40 with ± 0.2 tolerance
L	Flange length	
	Test parameters	
X1	Distance of Upper rollers	
X2	Distance of lower rollers	
Rr	Roller radius	For 2 < t ≤ 6 = 5; 6 < t ≤ 12 = 10



Curved beam strength

$$CBS = \left(\frac{P}{2w\cos(\phi)}\right)\left(\frac{d_x}{\cos(\phi)} + (D+t)\tan(\phi)\right)$$

Interlaminar tensile strength

$$ILTS = \left(\frac{3.CBS}{2t\sqrt{R_i R_o}}\right)$$

Reference system

- Failure mechanism are analysed based on:
  - stresses associated with the failure loads
  - Location of cracks
- σ_{11} : Normal stresses along the fiber direction (0° fibers generally mean they follow the curvature and into the straight arms)
- σ_{22} : Normal stresses in the in-plane direction perpendicular to the fiber
- σ_{33} : Normal stresses in the direction of the thickness

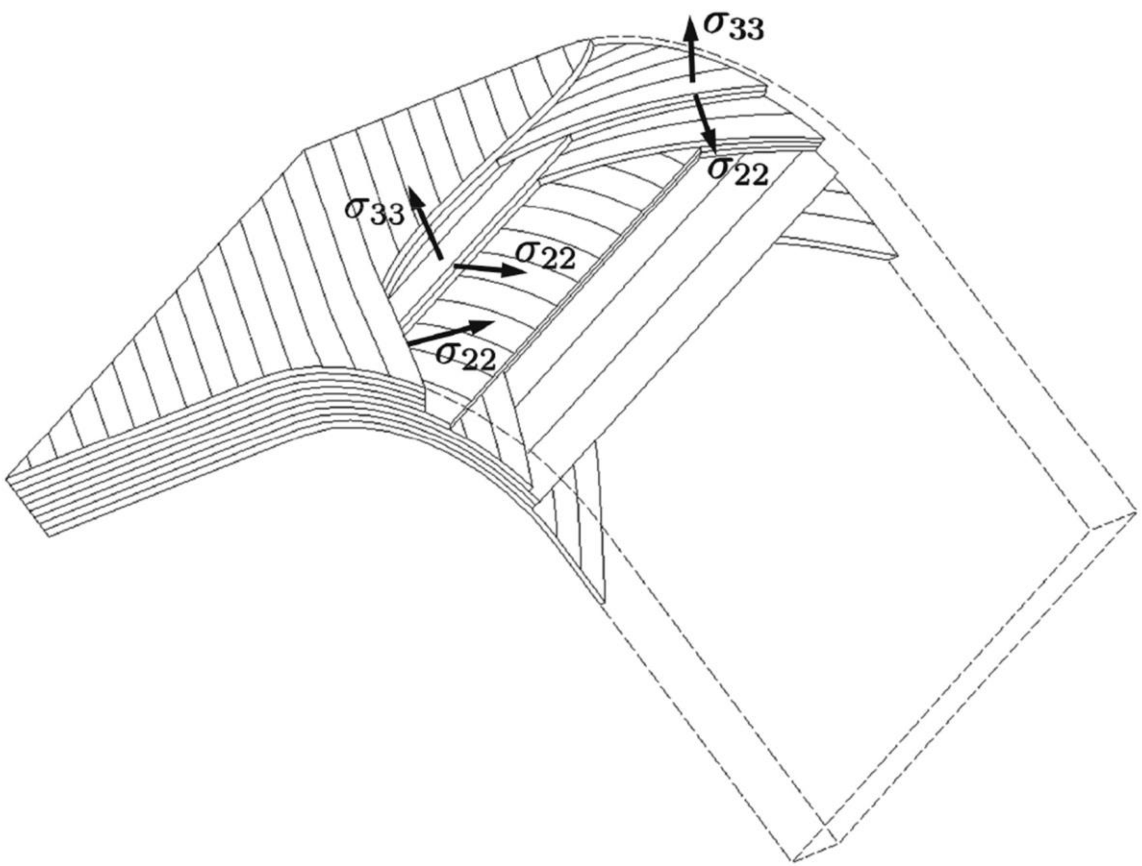


Fig 3: Representation of stress directions

(González-Cantero et al.,)

Materials considered

Thermoset materials

M1: AS4/8552

- From US (Zumaquero et al.,)
- Intermediate modulus
- $\Delta T=155$ K
- $S_{22al} < S_{33al}$
- Stacking sequences optimized specifically designed to study unfolding failure
- Ref: M1-UD, M1-CP, M1-QI

M3

(undisclosed because of confidentiality reasons)

- Self (Full experimental test campaign)
- High modulus
- $\Delta T=160$ K
- $S_{22al} < S_{33al}$
- Stacking sequences optimized specifically designed to study unfolding failure
- Ref: M3-UD, M3-CP, M3-QI

Traditional unfolding

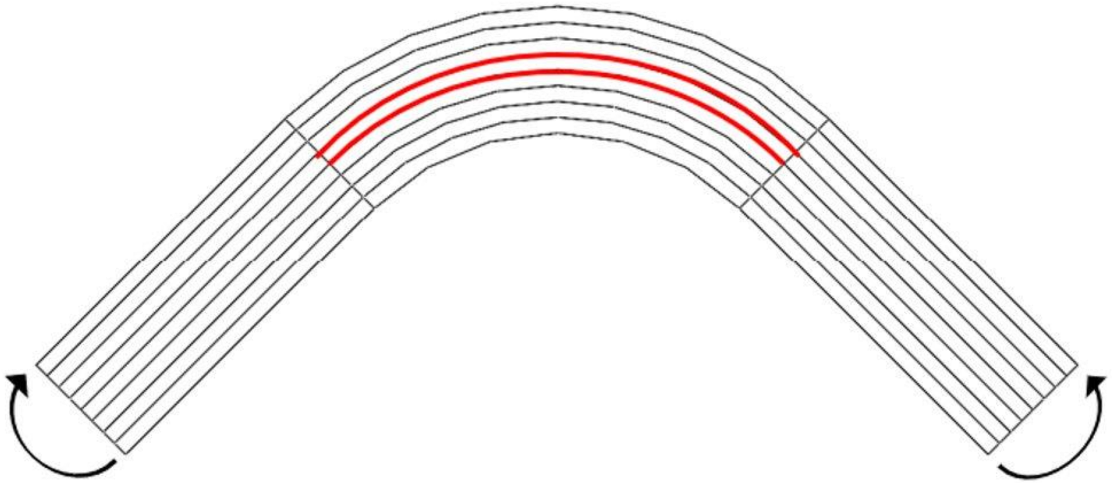


Fig 4: Schematic representation of Traditional unfolding

•Occurs in UD curved laminates

•Associated to interlaminar normal stresses(INS)

•When INS reaches its maximum allowable, initiates crack in the interlaminar direction

Traditional unfolding governed by

S_{33}(ILTS) & σ_{33}^{max}

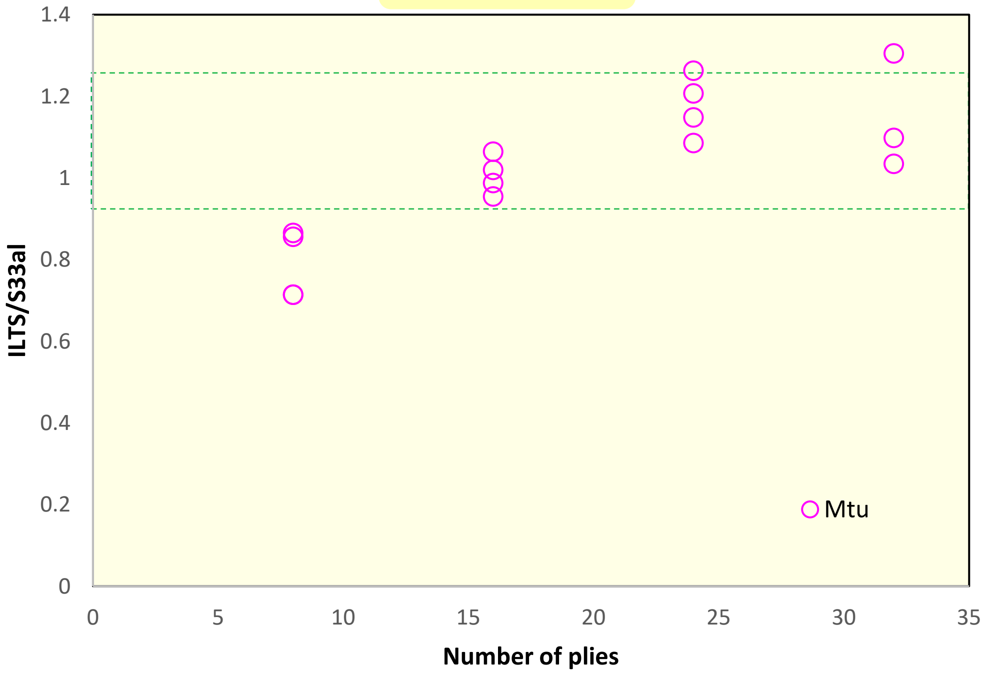
Interlaminar properties

Traditional unfolding: UD

Kim and Soni criterion

Condition: $\frac{\sigma_{33}^{max}}{S_{33}} = 1$ with $\sigma_{33}^{max} \geq 0$

M1-UD



Traditional unfolding: UD

Kim and Soni criterion

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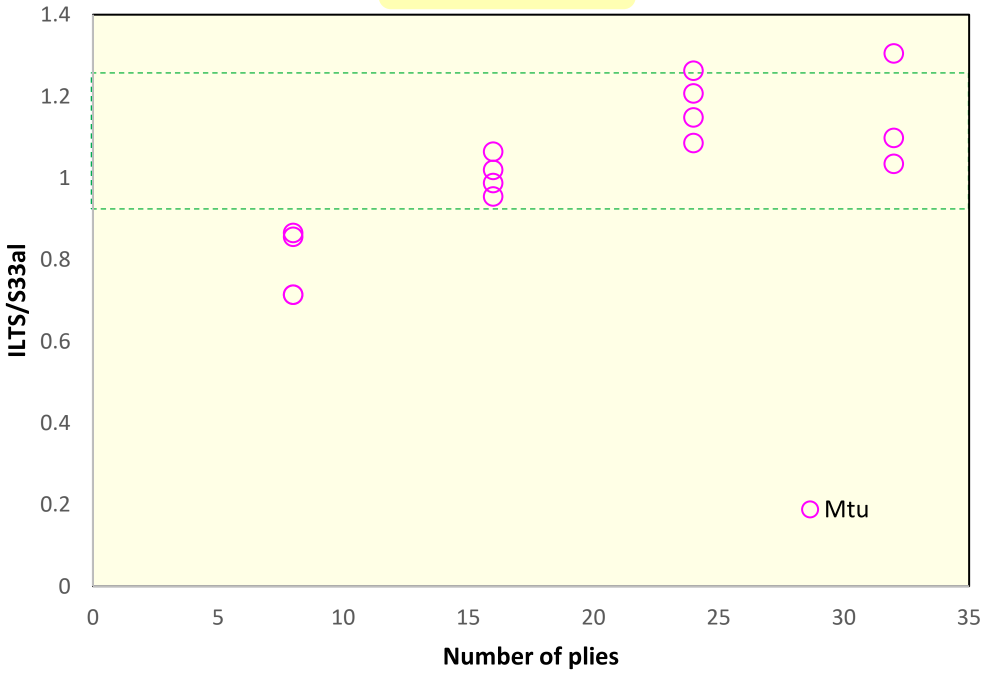
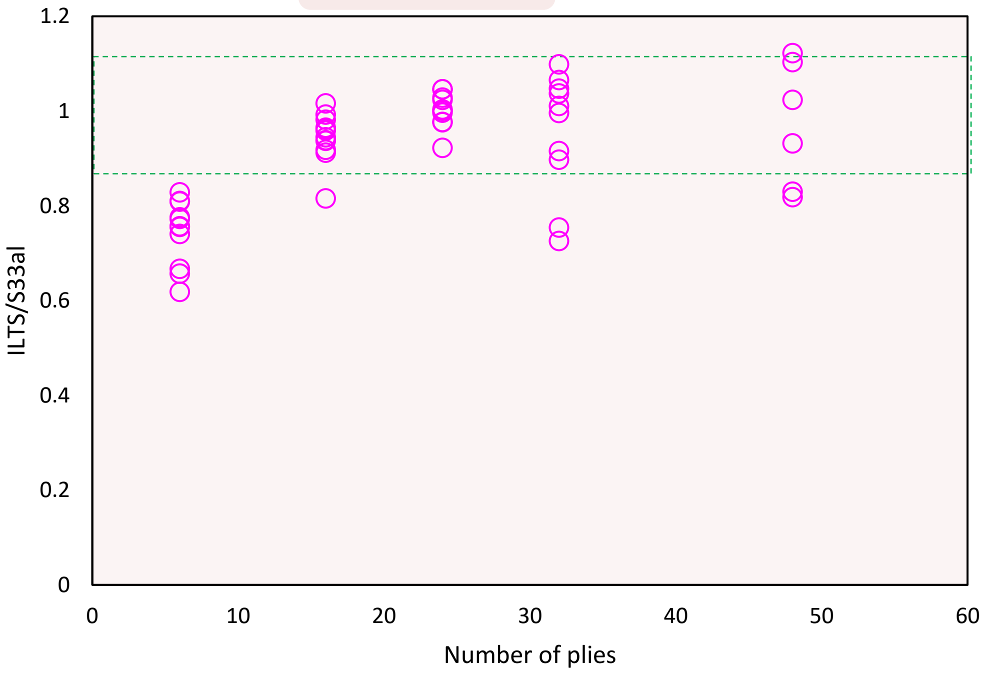
M1-UD



M3-UD



Traditional unfolding: UD

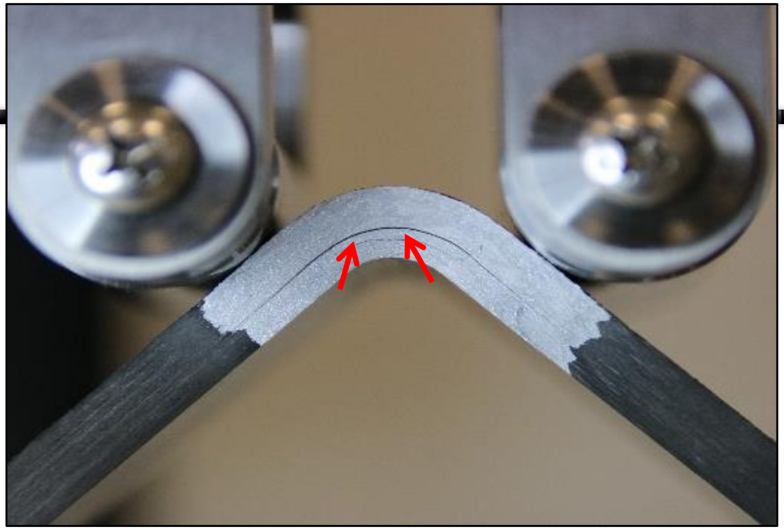
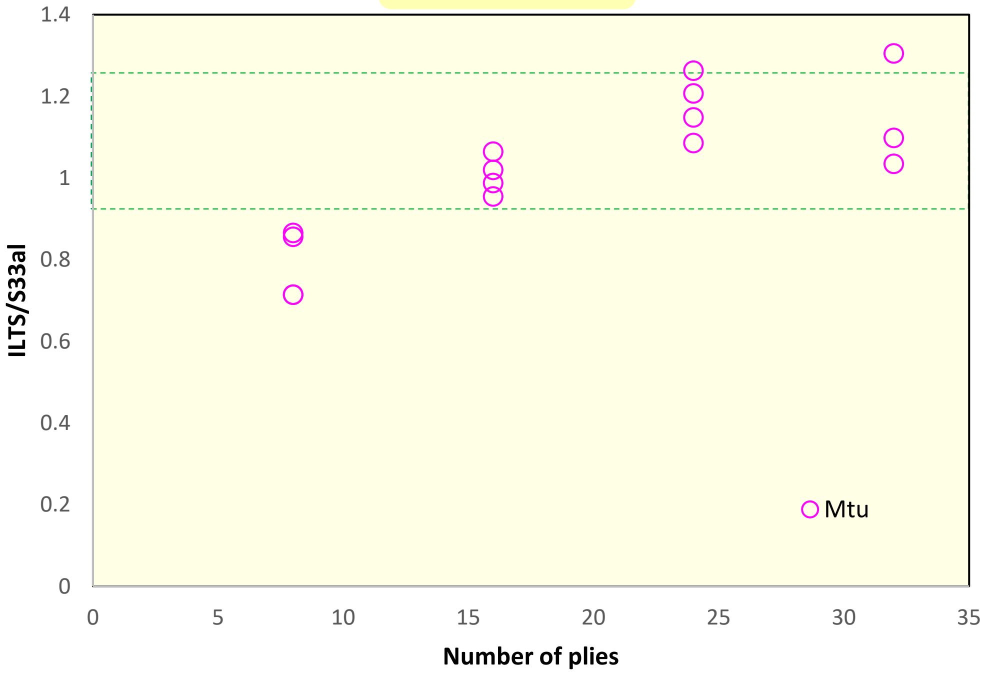


Fig 5: M3-UD32 specimen after failure

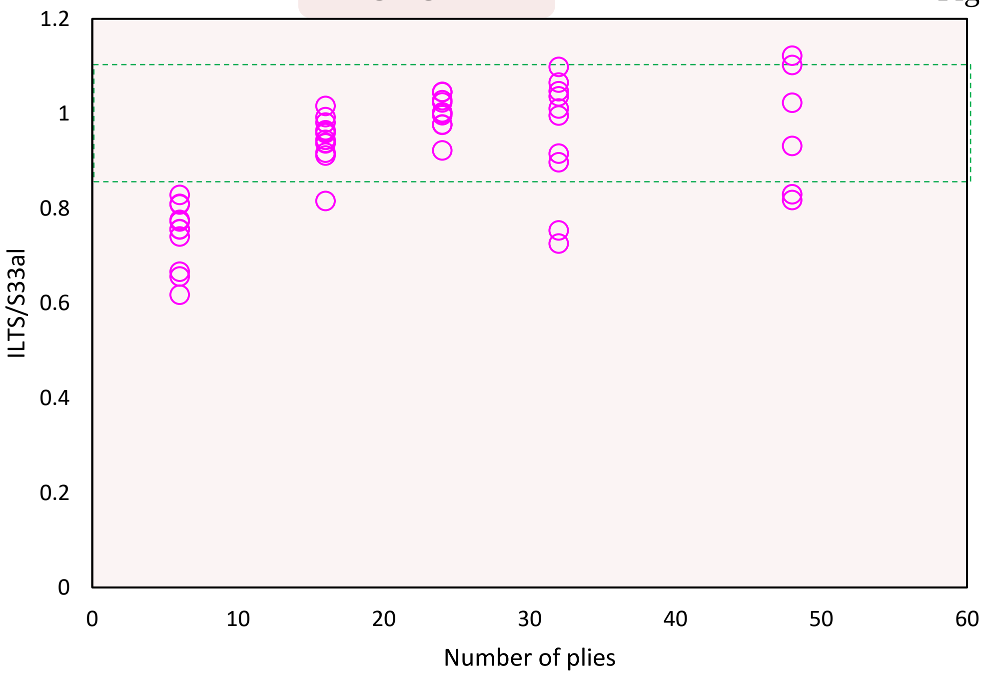
Kim and Soni criterion

Condition: $\frac{\sigma_{33}^{max}}{S_{33}} = 1$ with $\sigma_{33}^{max} \geq 0$

M1-UD



M3-UD



Traditional unfolding: UD

Kim and Soni criterion

Condition: $\frac{\sigma_{33}^{max}}{S_{33}} = 1$ with $\sigma_{33}^{max} \geq 0$

Traditional unfolding governed by

S_{33}(ILTS) & σ_{33}^{max}

Interlaminar properties

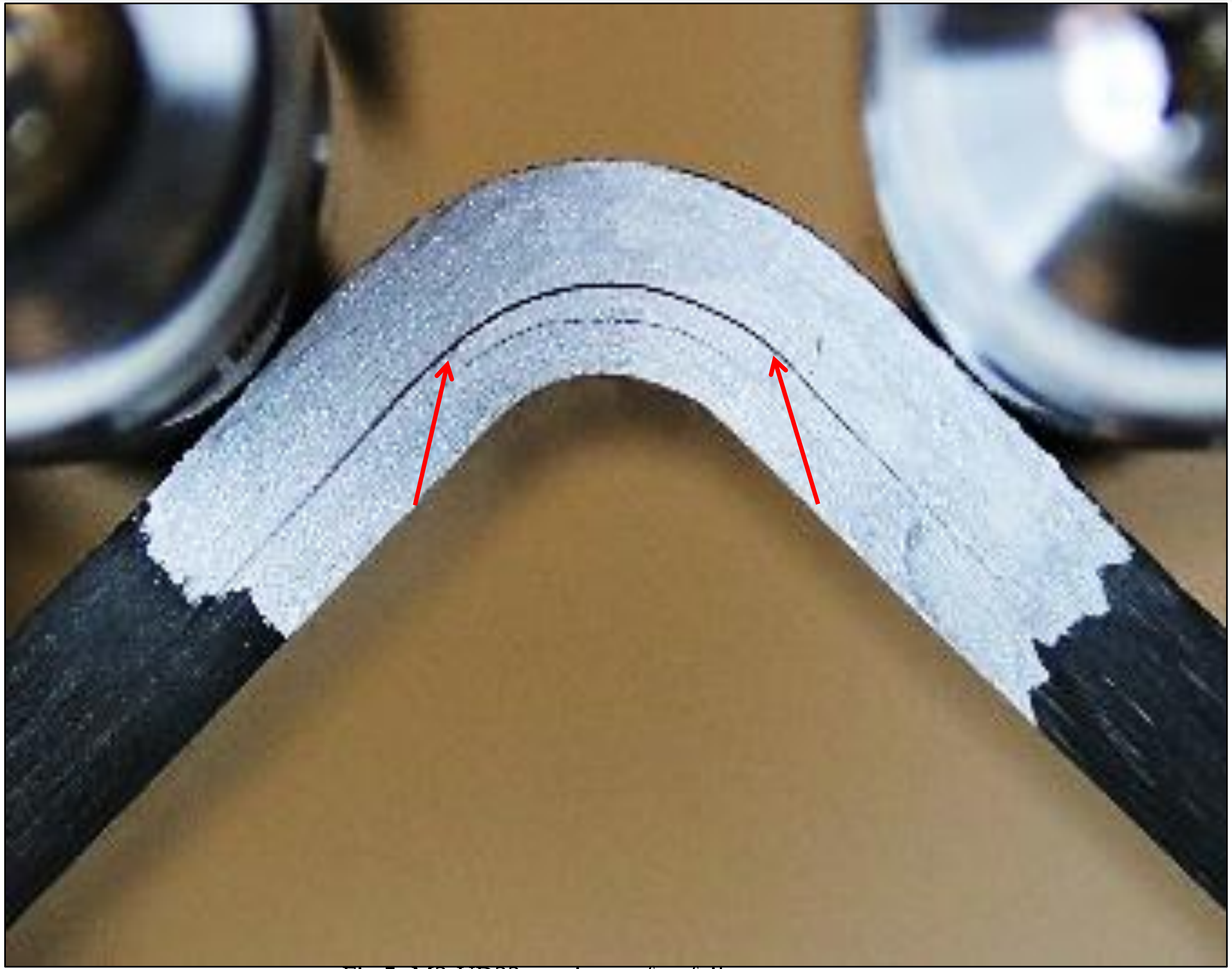


Fig 5: M3-UD32 specimen after failure

Traditional unfolding: UD

Kim and Soni criterion

Condition: $\frac{\sigma_{33}^{max}}{S_{33}} = 1$ with $\sigma_{33}^{max} \geq 0$

Traditional unfolding governed by

S_{33}(ILTS) & σ_{33}^{max}

Interlaminar properties

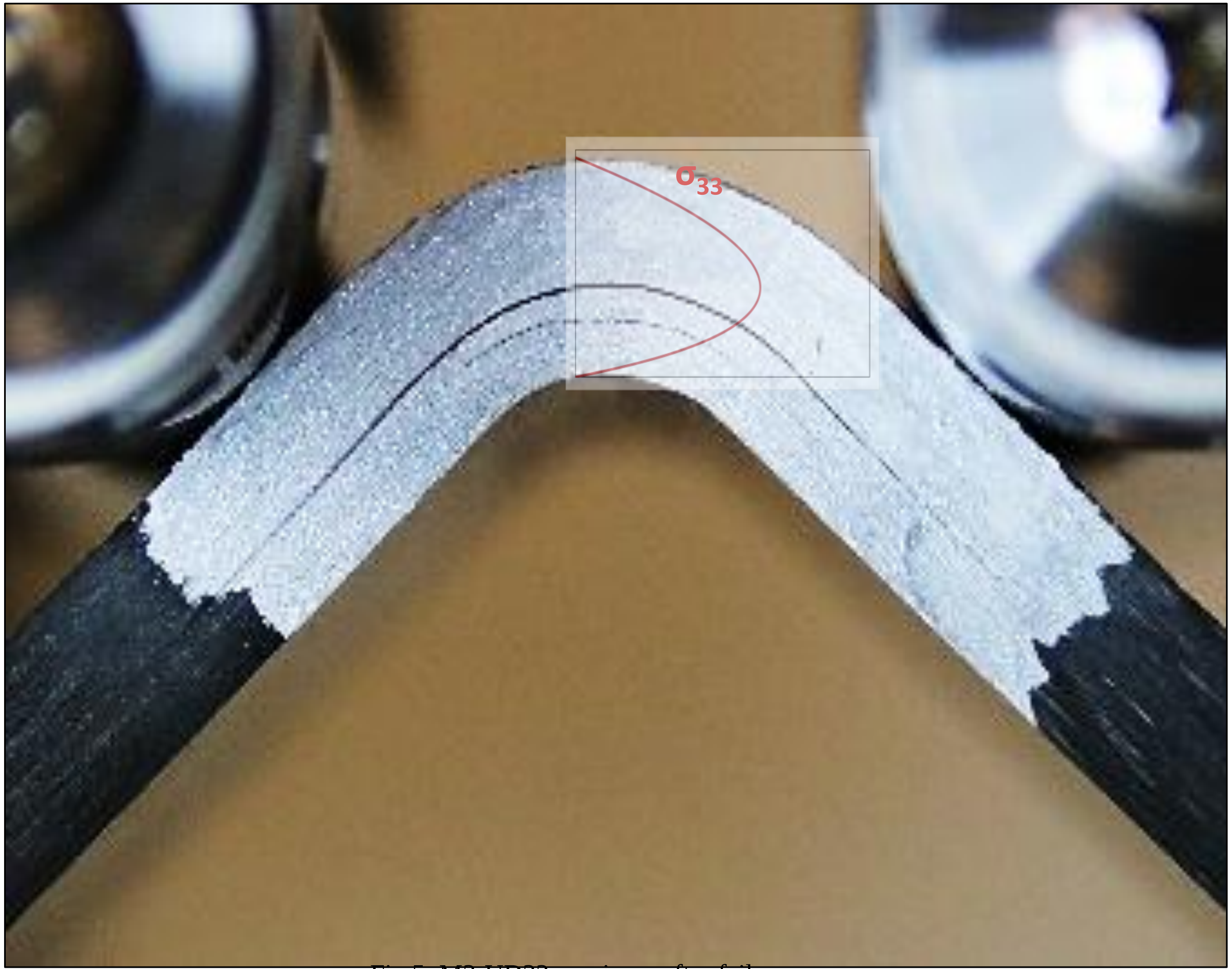


Fig 5: M3-UD32 specimen after failure

Traditional unfolding: UD

Kim and Soni criterion

Condition: $\frac{\sigma_{33}^{max}}{S_{33}} = 1$ with $\sigma_{33}^{max} \geq 0$

Traditional unfolding governed by

S_{33}(ILTS) & σ_{33}^{max}

Interlaminar properties

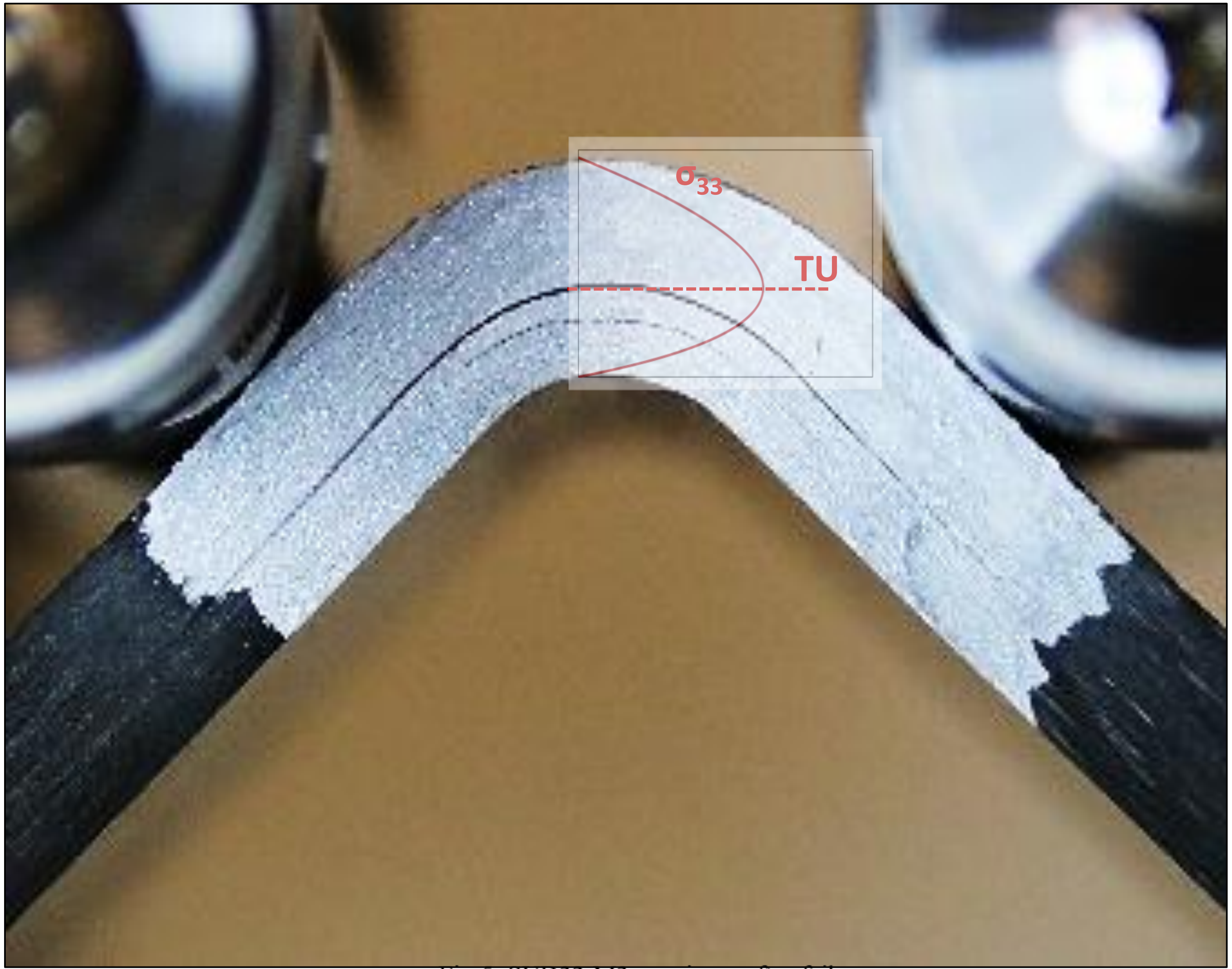


Fig 5: SUD32-M3 specimen after failure

Induced unfolding

- Occurs in non-UD curved specimens
- Damage is initiated by intralaminar failure which introduces crack
- Propagates as interlaminar delamination in the presence of sufficiently high INS
- Curvature induces sufficient value of INS for damage progression

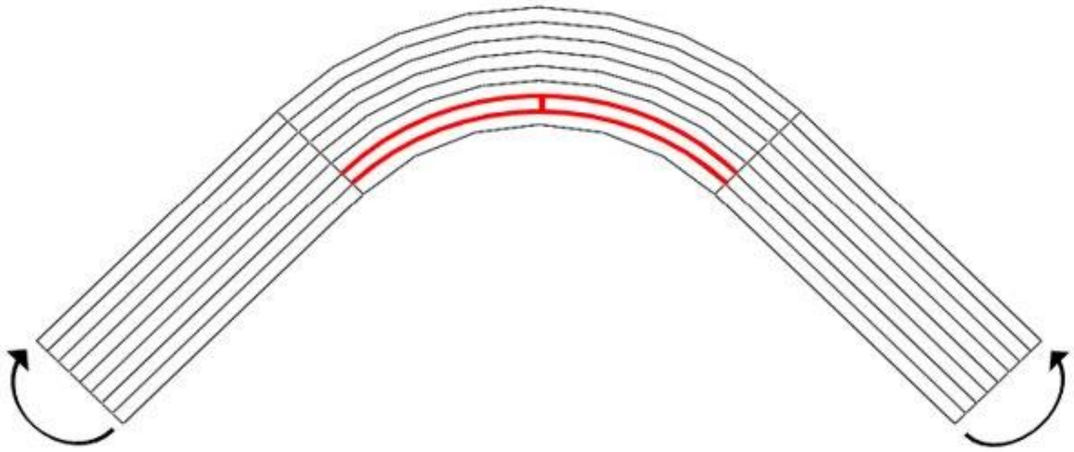


Fig 6: Schematic representation of Induced unfolding

Induced unfolding governed by S_{22} & σ_{22}^{max}

Induced unfolding condition $\sigma_{22}^{max} \geq S_{22\ non\text{-}UD}$

Intralaminar properties

Induced unfolding

Induced unfolding(IU)

First intralaminar damage

(ref: Mfid)

$$\frac{\sigma_{22}^{max}}{S_{22}} = 1$$

with

$$\sigma_{22}^{max} \geq 0$$

In any layer

Induced unfolding

(ref: Miu)

$$\frac{\sigma_{33}^{max}}{S_{33}} = 0.25$$

with

$$\sigma_{33}^{max} \geq 0$$

In inner 90º layers in which first intralaminar damage has already taken place

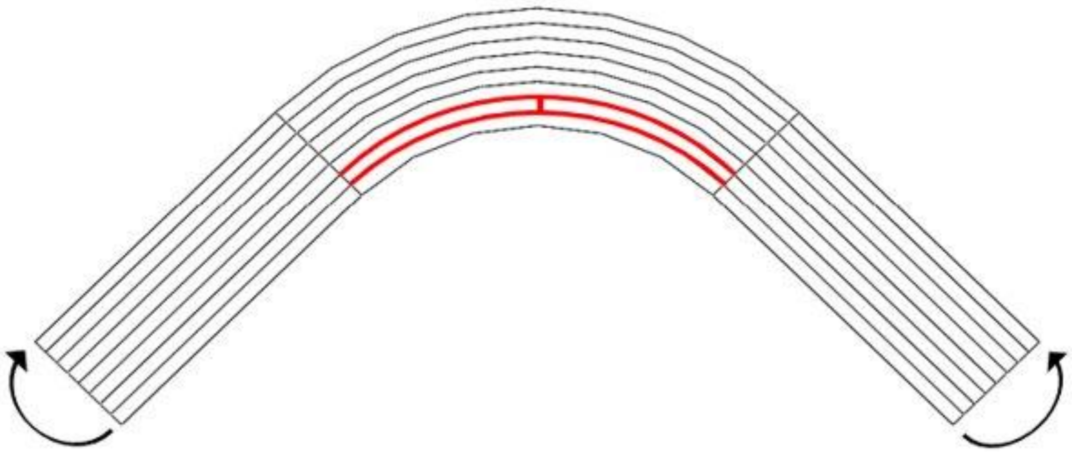


Fig 6: Schematic representation of Induced unfolding

Stress analysis

» The stresses for a certain applied moment M:

$$\sigma_{ij}(M,r) = \sigma_{ij}^{T} + M\sigma_{ij}^{M}$$

» The moment causing traditional unfolding

$$\sigma_{33}^{T} + M_{tu}\sigma_{33}^{M} = \sigma_{33}^{al}$$

» The moment causing first intralaminar damage

$$\sigma_{22}^{T} + M_{fid}\sigma_{22}^{M} = \sigma_{22}^{al}$$

» The moment causing induced unfolding (after f.i.d in inner 90º layers)

$$\sigma_{33}^{T} + M_{tu}\sigma_{33}^{M} = 0.25\ \sigma_{33}^{al}$$

(González-Cantero et al.,)

Stacking sequences

Cross-ply and Quasi-isotropic				
M1				
			Stacking sequence	
No. of plies(x)	W (mm)	Ri (mm)	Cross-ply Ref: M1-CP.x	Quasi-isotropic Ref:M1-QI.x
08	30	5	$[0, 90_2, 0]_S$	$[45, -45, 90, 0]_S$
16	30		$[0, 90_2, 0_5]_S$	$[45, -45, 90_2, 0, 45, -45, 0]_S$
24	30		$[0, 90_2, 0_9]_S$	$[45, -45, 90_2, 45, -45, 90, 0_2, 45, -45, 0]_S$
32	40		$[0, 90_2, 0_{13}]_S$	$[45, -45, 90_2, 45, -45, 90_2, 0, 45, -45, 0_2, 45, -45, 0]_S$

Cross-ply			
M3			
Ref	W(mm)	Ri(mm)	Stacking sequence
M3-CP.08	30	3	$[0, 90_2, 0]_S$
M3-CP.08	30	3	$[0, 90_2, 0_5]_S$
M3-CP.08	30	5	$[0, 90_2, 0_9]_S$
M3-CP.08	40	5	$[0, 90_2, 0_{13}]_S$
M3-CP.08	50	5	$[0, 90_2, 0_{21}]_S$

Quasi-isotropic			
M3			
Ref	W(mm)	Ri(mm)	Stacking sequence
M3-QI.10	30	5.00	[45, 90, -45, 0, 45, -45, 0, -45, 90, 45]
M3-QI.12	30	5.00	$[45, -45, 90, -45, 45, 0_2, 45, -45, 90, -45, 45]$
M3-QI.16a	30	5.00	[45, -45, 90, -45, 45, 0, 45, -45]s
M3-QI.16b	30	5.00	[45, 90, -45, -45, 45, 0, 45, -45]s
M3-QI.28a	40	6.00	$[45, -45, 90_2, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28b	40	10.00	$[45, -45, 90_2, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28c	30	6.00	$[45, 90, -45, 90, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28d	30	10.00	$[45, 90, -45, 90, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.36a	40	6.00	$[45, -45, 90_2, [-45, 45]_2, 0, [45, -45]_2, 0, [-45, 45]_2]s$
M3-QI.36b	40	6.00	$[45, 90, -45, 90, [-45, 45]_2, 0, [45, -45]_2, 0, [-45, 45]_2]s$

Stacking sequences

Cross-ply and Quasi-isotropic M1				
			Stacking sequence	
No. of plies(x)	W (mm)	Ri (mm)	Cross-ply Ref: M1-CP.x	Quasi-isotropic Ref:M1-QI.x
08	30	5	$[0, 90_2, 0]_S$	$[45, -45, 90, 0]_S$
16	30		$[0, 90_2, 0_5]_S$	$[45, -45, 90_2, 0, 45, -45, 0]_S$
24	30		$[0, 90_2, 0_9]_S$	$[45, -45, 90_2, 45, -45, 90, 0_2, 45, -45, 0]_S$
32	40		$[0, 90_2, 0_{13}]_S$	$[45, -45, 90_2, 45, -45, 90_2, 0, 45, -45, 0_2, 45, -45, 0]_S$

Cross-ply M3			
Ref	W(mm)	Ri(mm)	Stacking sequence
M3-CP.08	30	3	$[0, 90_2, 0]_S$
M3-CP.08	30	3	$[0, 90_2, 0_5]_S$
M3-CP.08	30	5	$[0, 90_2, 0_9]_S$
M3-CP.08	40	5	$[0, 90_2, 0_{13}]_S$
M3-CP.08	50	5	$[0, 90_2, 0_{21}]_S$

Quasi-isotropic M3			
Ref	W(mm)	Ri(mm)	Stacking sequence
M3-QI.10	30	5.00	[45, 90, -45, 0, 45, -45, 0, -45, 90, 45]
M3-QI.12	30	5.00	$[45, -45, 90, -45, 45, 0_2, 45, -45, 90, -45, 45]$
M3-QI.16a	30	5.00	[45, -45, 90, -45, 45, 0, 45, -45]s
M3-QI.16b	30	5.00	[45, 90, -45, -45, 45, 0, 45, -45]s
M3-QI.28a	40	6.00	$[45, -45, 90_2, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28b	40	10.00	$[45, -45, 90_2, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28c	30	6.00	$[45, 90, -45, 90, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.28d	30	10.00	$[45, 90, -45, 90, -45, 45, 0, [45, -45]_2, 0, -45, 45]s$
M3-QI.36a	40	6.00	$[45, -45, 90_2, [-45, 45]_2, 0, [45, -45]_2, 0, [-45, 45]_2]s$
M3-QI.36b	40	6.00	$[45, 90, -45, 90, [-45, 45]_2, 0, [45, -45]_2, 0, [-45, 45]_2]s$

Cross-ply curved specimen

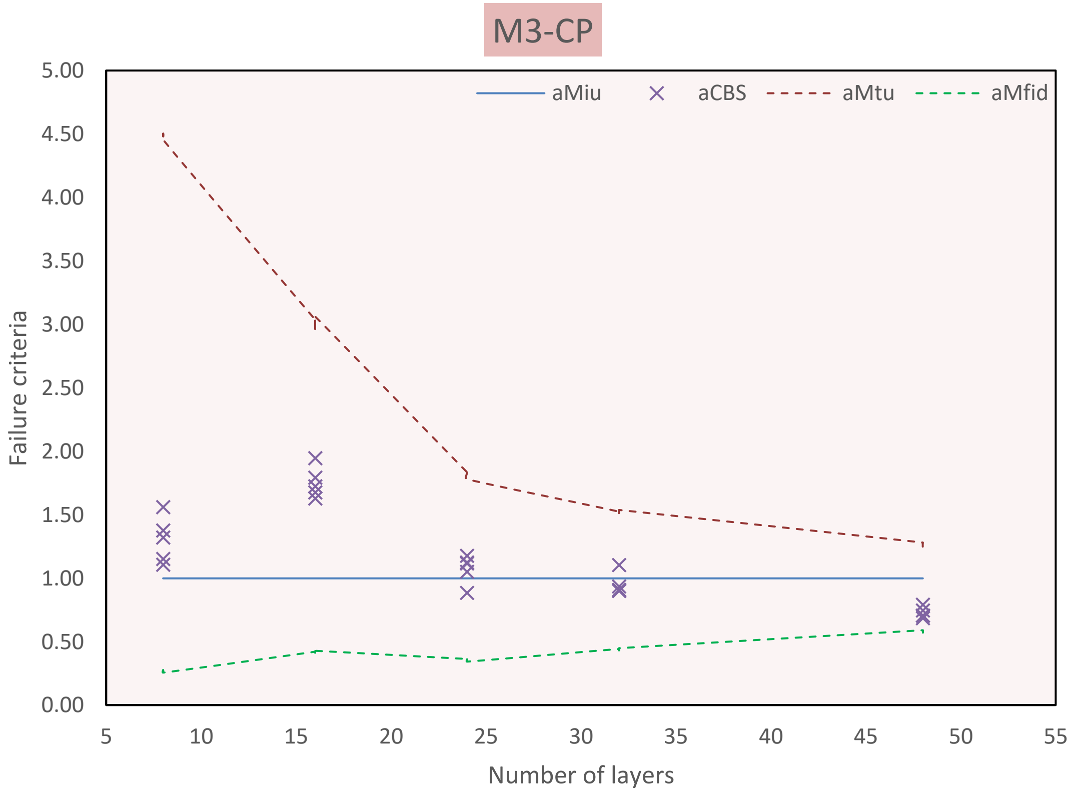
No. of layers	Stacking sequence
8	$[0,90_2,0]S$
16	$[0,90_2,0_5]S$
24	$[0,90_2,0_9]S$
32	$[0,90_2,0_{13}]S$
48	$[0,902,0_{21}]S$

aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

aMfid=Mfid/Miu ,

aCBS=CBS/Miu



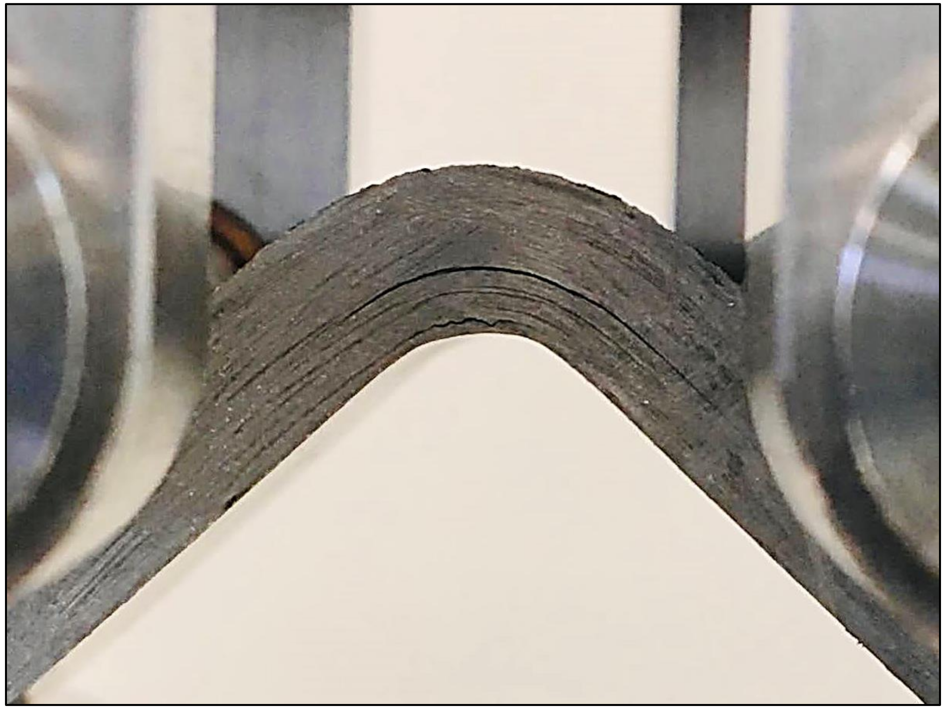


Fig 6:M3-CP.16 specimen after failure

Cross-ply curved specimen

No. of layers	Stacking sequence
8	$[0,90_2,0]S$
16	$[0,90_2,0_5]S$
24	$[0,90_2,0_9]S$
32	$[0,90_2,0_{13}]S$
48	$[0,902,0_{21}]S$

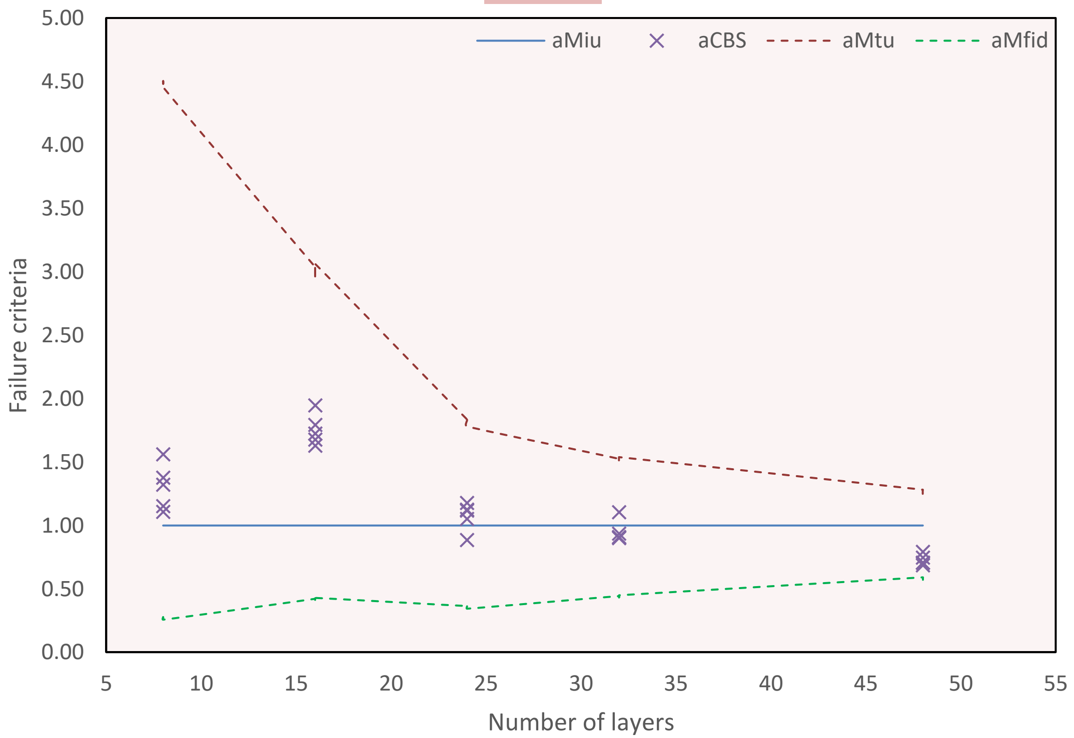
aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

aMfid=Mfid/Miu ,

aCBS=CBS/Miu

M3-CP



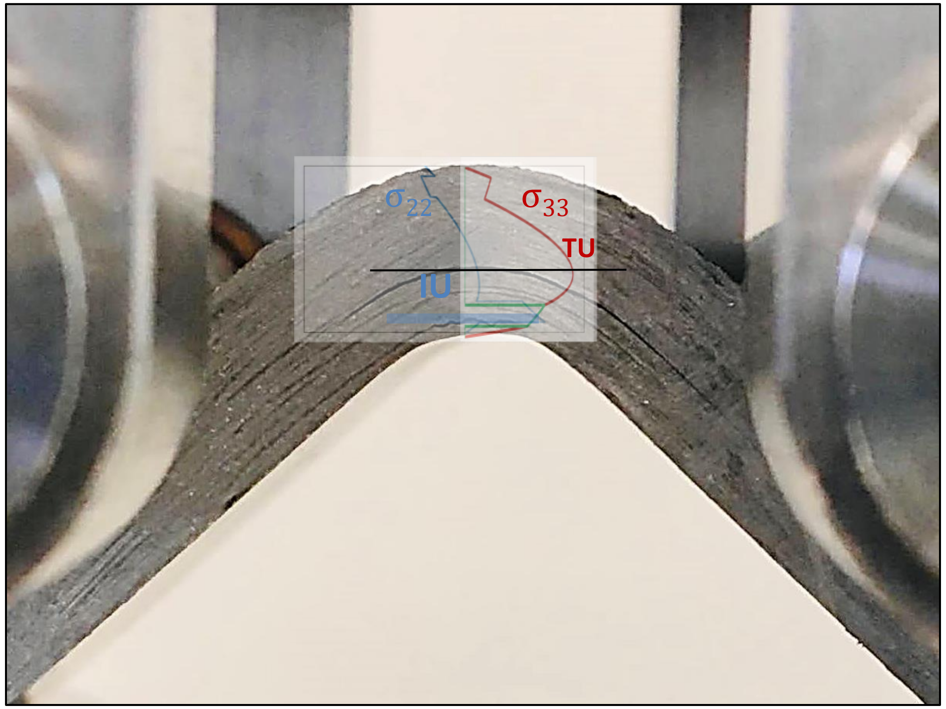
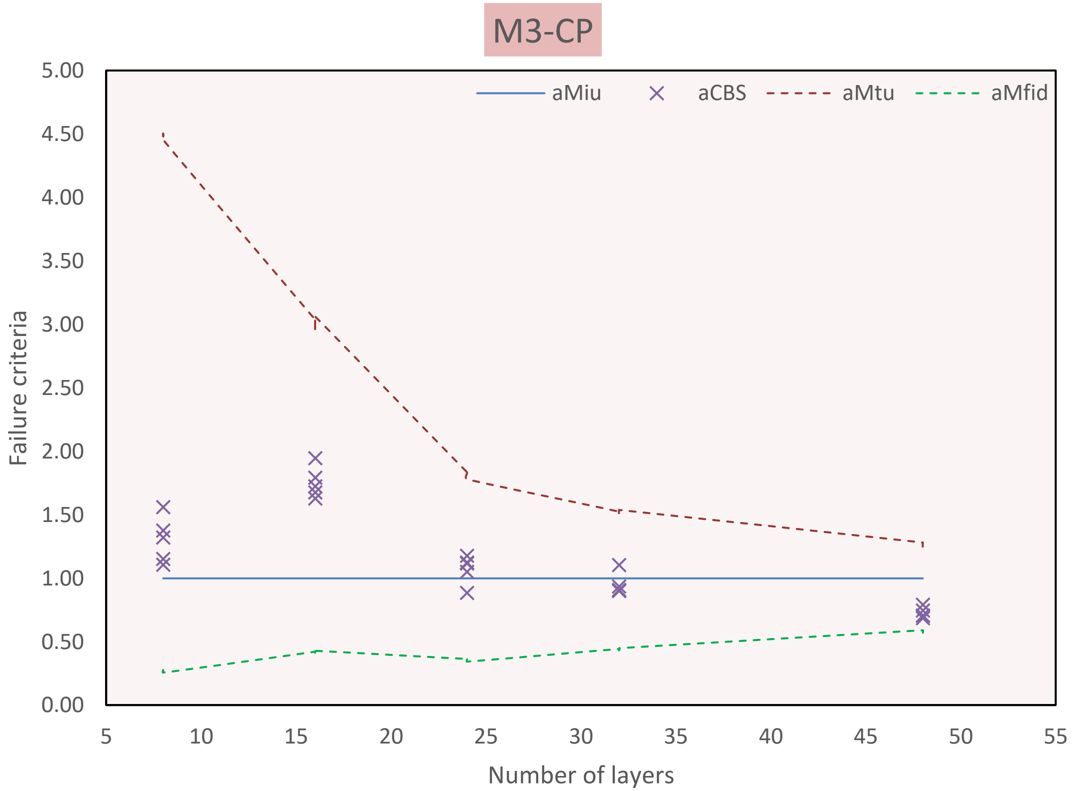


Fig 6:M3-CP.16 specimen after failure

Cross-ply curved specimen

No. of layers	Stacking sequence
8	$[0,90_2,0]S$
16	$[0,90_2,0_5]S$
24	$[0,90_2,0_9]S$
32	$[0,90_2,0_{13}]S$
48	$[0,902,0_{21}]S$



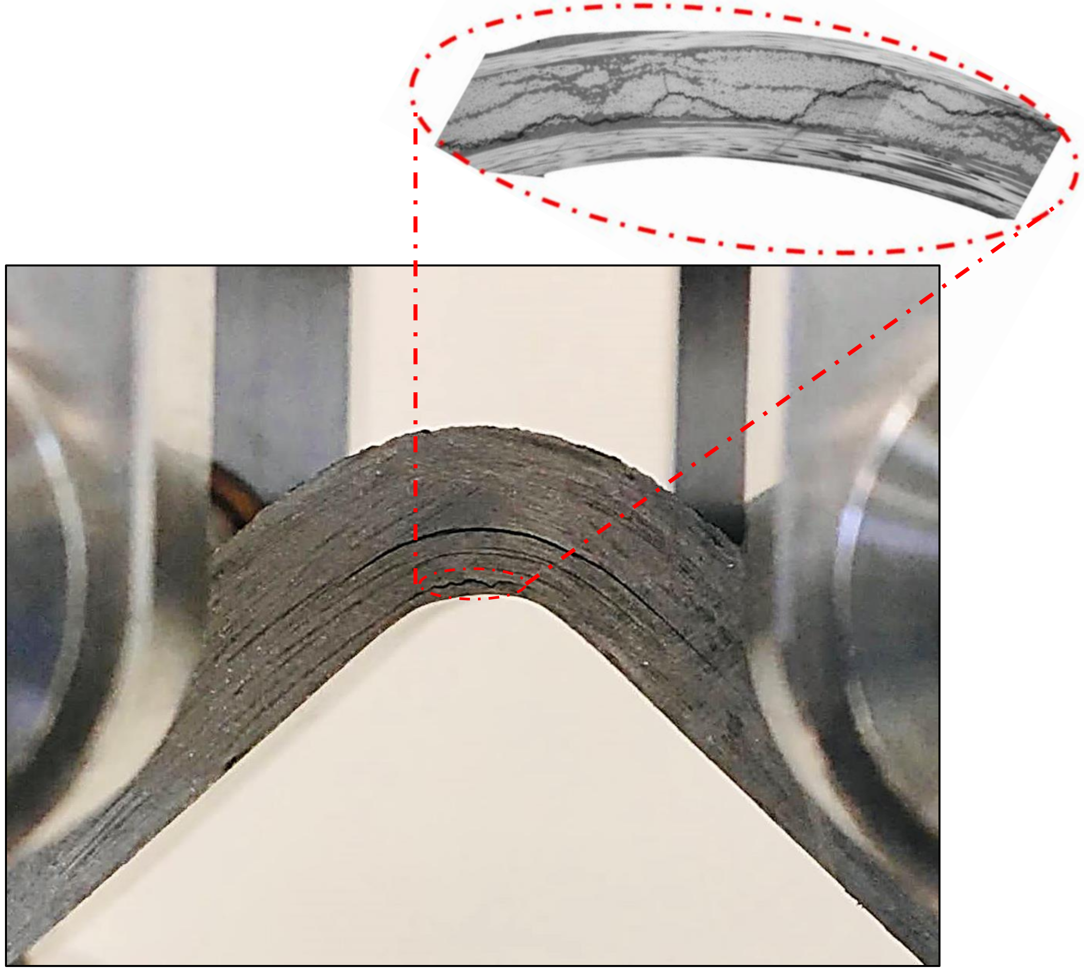


Fig 6:M3-CP.16 specimen after failure

Cross-ply curved specimen

No. of layers	Stacking sequence
8	$[0,90_2,0]S$
16	$[0,90_2,0_5]S$
24	$[0,90_2,0_9]S$
32	$[0,90_2,0_{13}]S$
48	$[0,902,0_{21}]S$

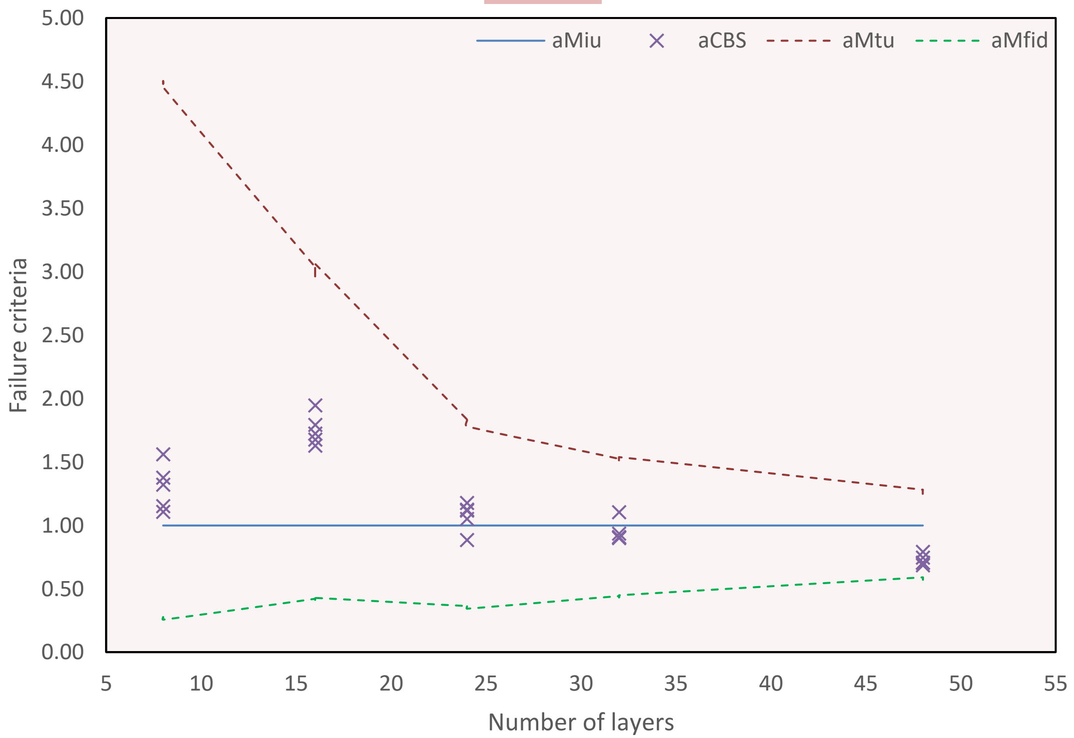
aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

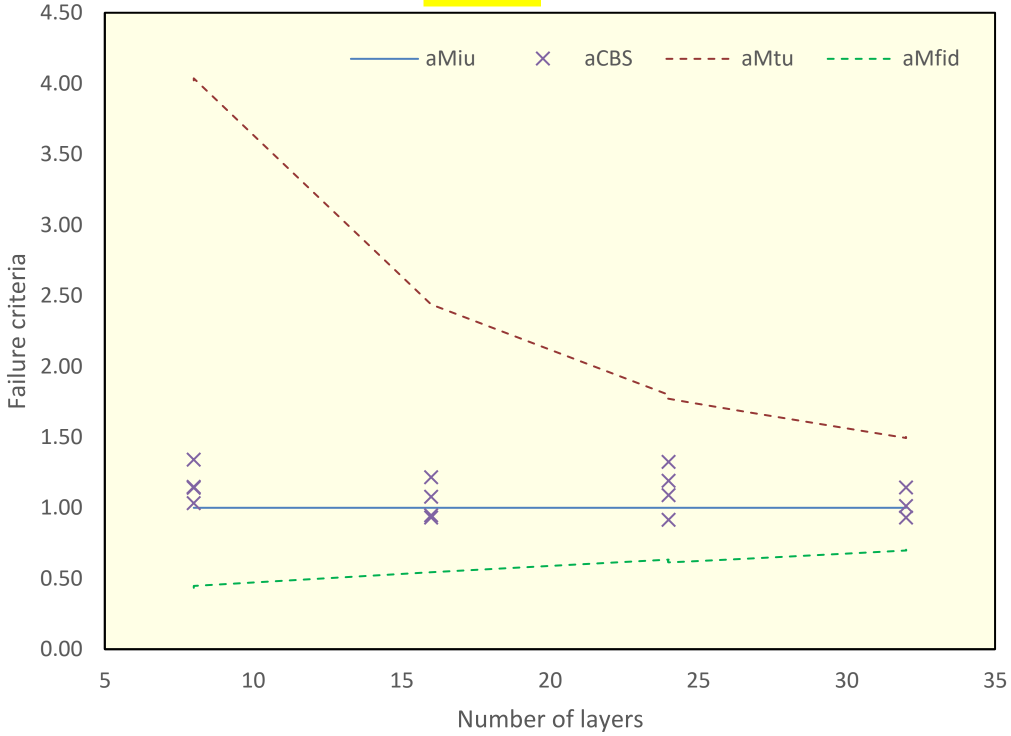
aMfid=Mfid/Miu ,

aCBS=CBS/Miu

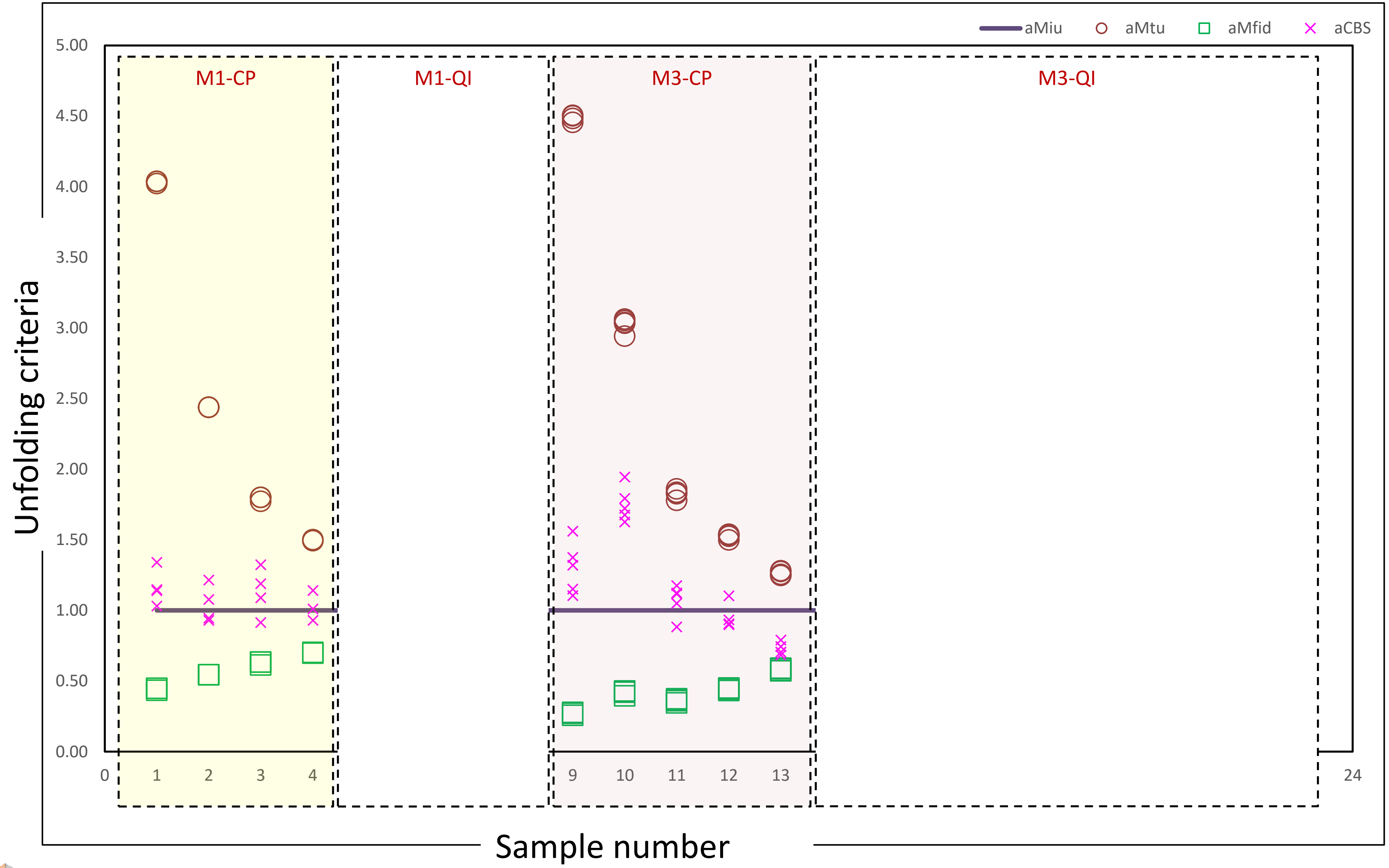
M3-CP



M1-CP



Cross-ply curved specimens



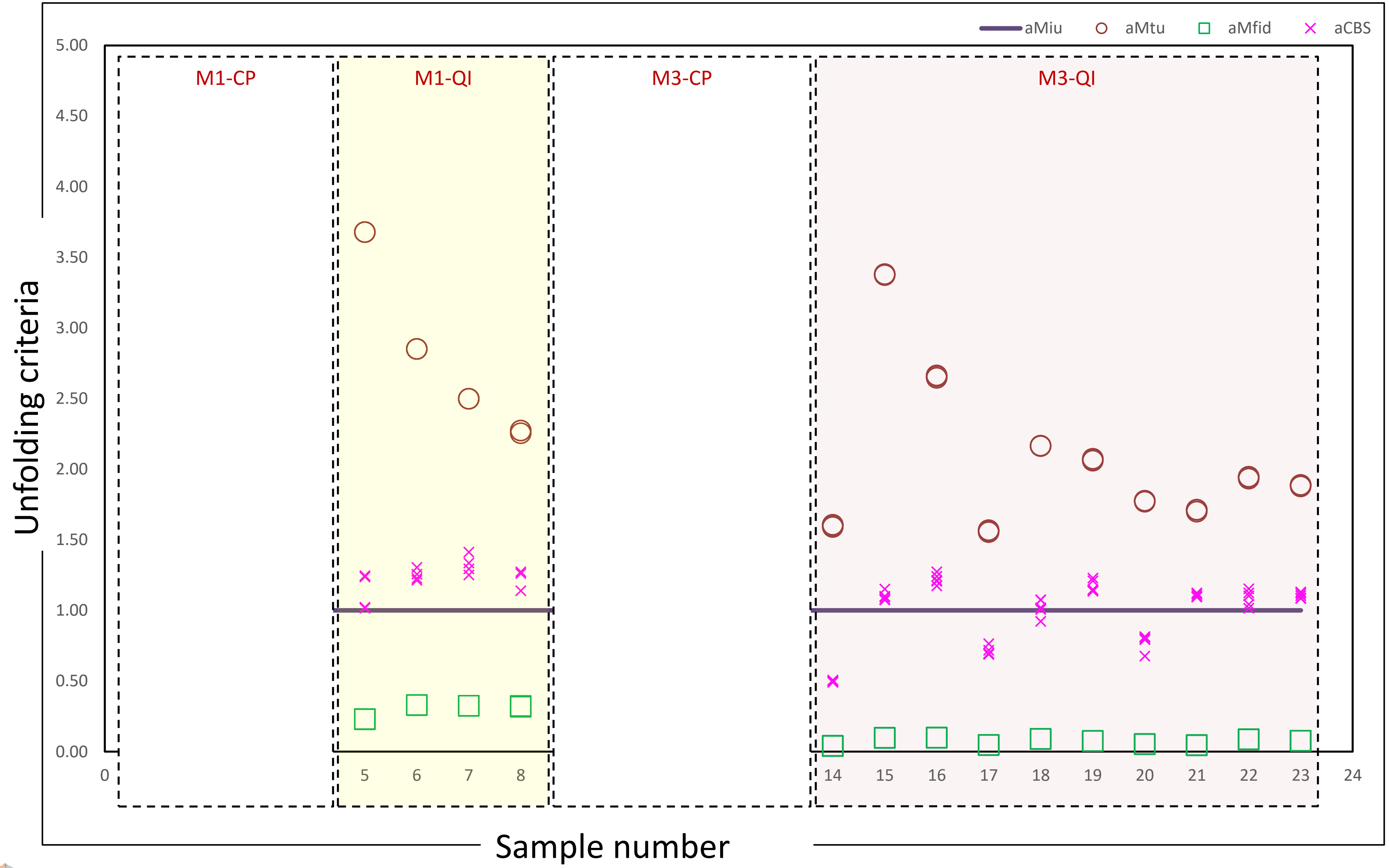
aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

aMfid=Mfid/Miu ,

aCBS=CBS/Miu

Quasi-isotropic



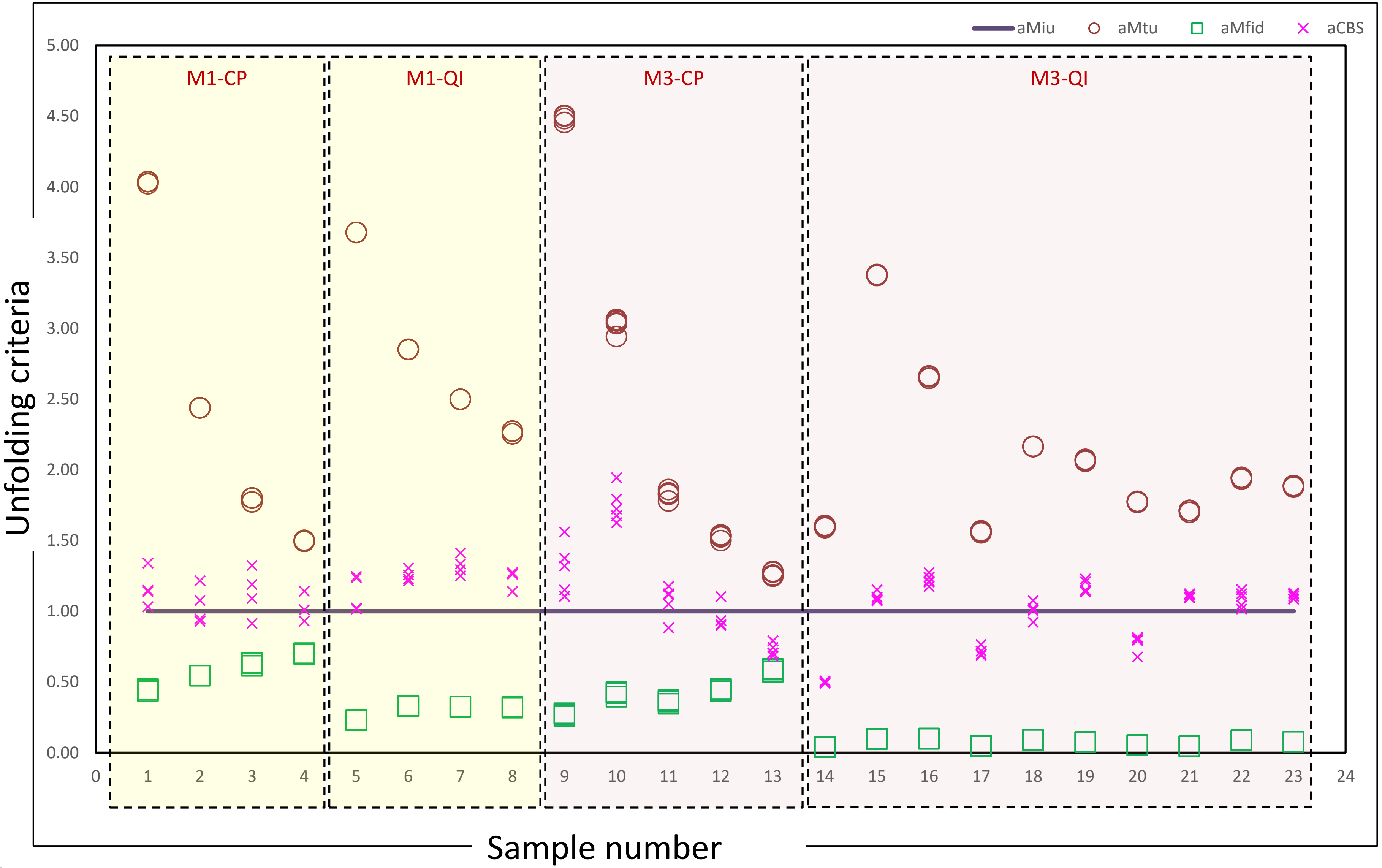
aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

aMfid=Mfid/Miu ,

aCBS=CBS/Miu

Experimental test results



aMiu=Miu/Miu=1 ,

aMtu=Mtu/Miu ,

aMfid=Mfid/Miu ,

aCBS=CBS/Miu

Comparison of actual delamination & it´s location

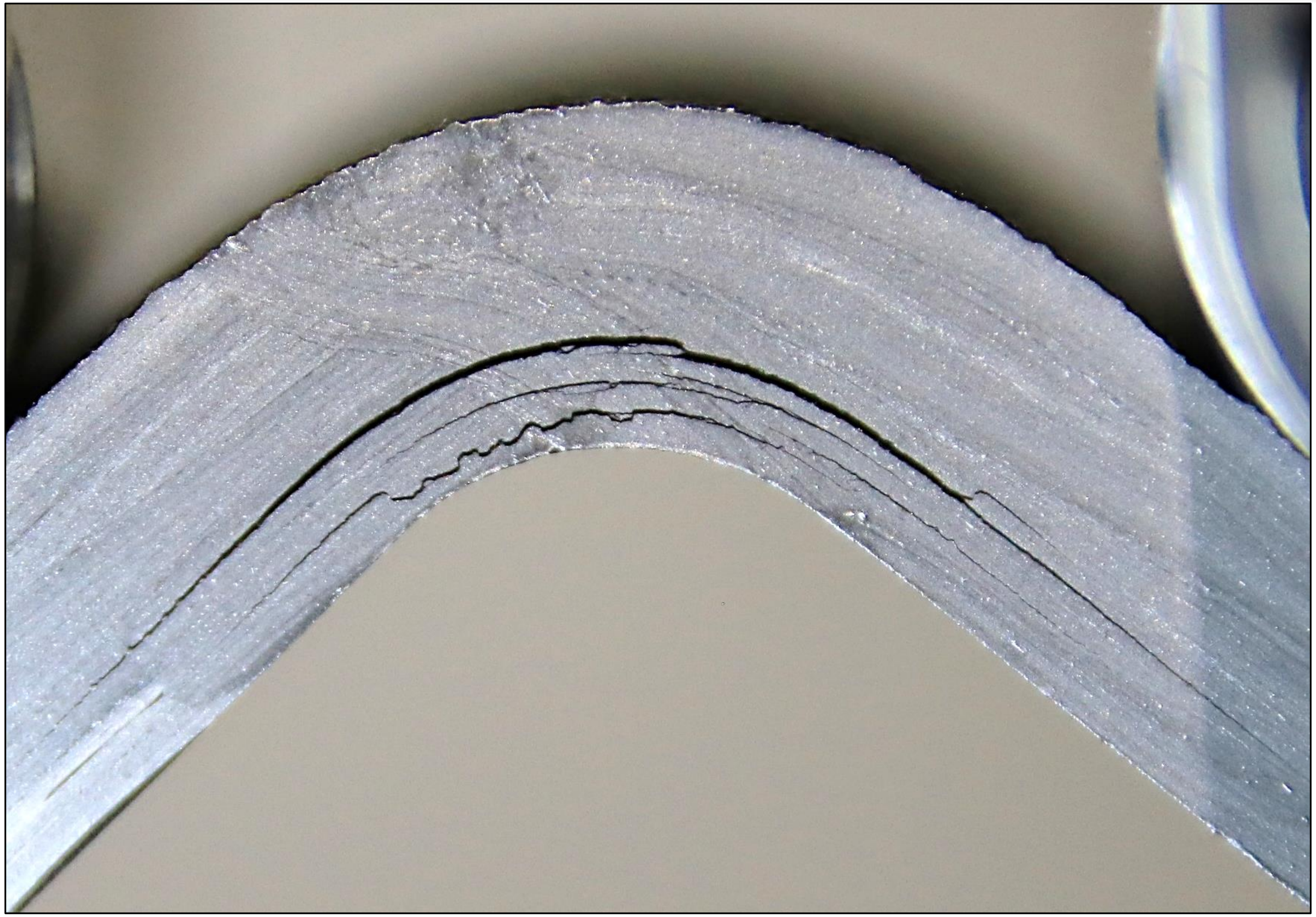


Fig 7: M3-QIa.36 specimen after failure

Stress representation w.r.t Miu

Comparison of actual delamination & it´s location

FIDAMC

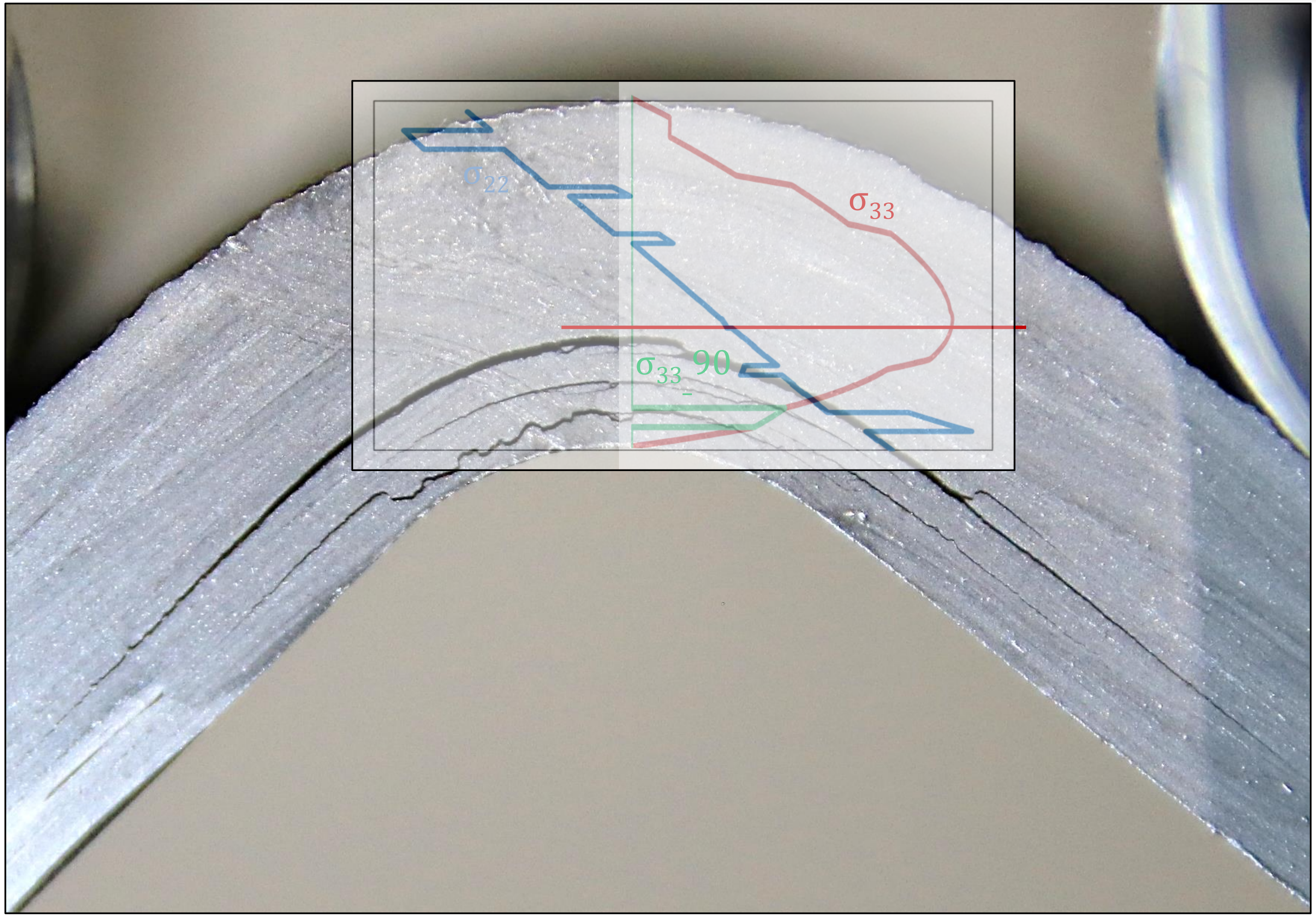


Fig 7: M3-QIa.36 specimen after failure

Stress representation w.r.t Miu

NewFrac Training Network

Conclusions and future scope

- Unfolding Failure has been analyzed taking into account three possible failure mechanisms (for which the failure moment predictions are analytically calculated based on the stress analysis):
  - Traditional Unfolding (Mtu): Failure occurs when $S_{33max} = S_{33al}$.
  - Instantaneous Induced Unfolding (Mfid): Failure occurs when $S_{22max} = S_{22al}$.
  - Delayed Induced Unfolding (Miu): Failure occurs when $S_{33max} = 0.25\ S_{33al}$ in the inner 90 layers.

- Results in UD laminates show a very good agreement between experimental results and Traditional Unfolding predictions.

- Results in multidirectional laminates show a very good agreement between experimental results and Delayed Induced Unfolding predictions.

- In all multidirectional laminates analyzed Miu > Mfid. The good agreement between experimental results and Miu values is in agreement with the assumption that a sufficiently high ILTS is needed to cause the intralaminar damage to propagate as a delamination.

Conclusions and future scope

Future scope:

- Interaction between intralaminar damage and subsequent delamination: Simple pointwise criteria (Requires detailed FE analysis)

References

[1] Tasdemir, B., and D. Coker. "Comparison of damage mechanisms in curved composite laminates under static and fatigue loading." *Composite Structures* 213 (2019): 190-203.

[2] González-Cantero, J. M., Graciani, E., López-Romano, B., & París, F. (2018). Competing mechanisms in the unfolding failure in composite laminates. *Composites Science and Technology*, *156*, 223–230. https://doi.org/10.1016/j.compscitech.2017.12.022

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Thank you for your attention!
Any questions?

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