Assessment of the Residual Strength of Marine Laminate Panels

05/07 16.10hr Room 5.5
Every paper 20 minutes - Including 5 minutes discussion

*Claire De Marco Muscat-Fenech**
*Jan Bonello**
Stephane Champagne +

**University of Malta, Malta*
+*Universite` de Nantes*

UNIVERSITY OF MALTA
L-Università ta' Malta

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Introduction

Motivation of work

- marine grade laminates are subjected to a wide variety of impacts
- objects of all shapes and sizes
- different impact energy levels
- impact - barely visible impact damage (BVID) to complete laminate penetration
- damage sustained will influence the residual properties of the composite material

Intended Application

- According to BS EN ISO 12215-5:2008: Small Craft - Hull Construction and Scantlings
    - Hull length < 24m
    - CE design category C
    - Operate in shore seas
    - Significant wave heights 2m
    - Beaufort Scale ≤ 6

Buccaneer 180

- Designed for:
    - Planing Speed : 35 knots (max)
    - Panel Sizes: (0.7m x 0.3m) to (2.1m x 0.9m)
    - Hull Pressure (planing mode): 7.5 kN/m^2 to 36 kN/m^2

Materials Used

- PPG E-glass
  - CSM 300 and CSM 450 - mass density - 300 and 450 g/m^2
  - average fibre diameter of 11 μm of up to 50 mm length
  - with an emulsion binder
  - Woven 600 g/m^2
  - s.g. - 2.56
  - tensile strength - 3.45 GPa
  - tensile modulus - 72 GPa
  - poisson ratio – 0.22

- Marine grade Reichhold POLYLITE® 440-M850 orthophtalic polyester resin
  - s.g. – 1.1
  - tensile strength – 0.05 GPa
  - tensile modulus – 4.6 GPa
  - poisson ratio – 0.37

Fabrication & Laminate Panels

Laminate Panel Hand Layup Sequence - ASTM D5687

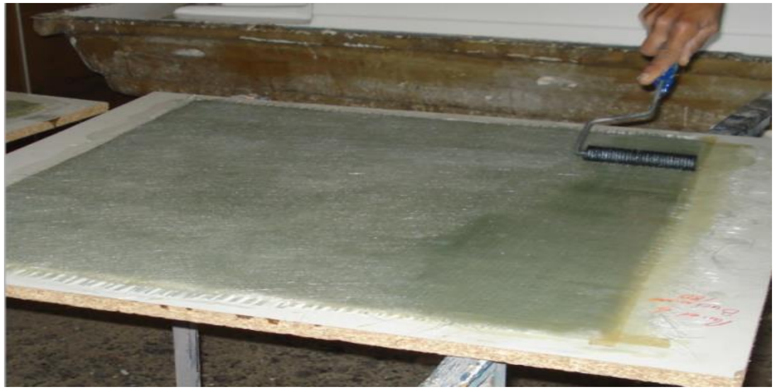
(temperature of 18^{o}C and a relative humidity of 80%)

Layer No.	1	2	3	4	5	6	7
Layer Type	CSM	CSM	CSM	WR	CSM	CSM	CSM
Areal Density: g/m^2	300	300	450	600	450	300	300

mean thickness: t = 4.72 mm

fibre mass fraction = 0.40 → fibre volume fraction = 0.23

Wetting the reinforcement fabric with resin



Applying pressure on the laminate using a consolidation metal roller

Characterisation Testing

Tensile Test
ISO 527:1997

Compressive - IITRI fixture
ASTM D3410M

Flexure Testing
ASTM D790-03

Ultimate tensile strength	149.6 MPa
Tensile modulus	9.89 GPa
Ultimate compressive strength	171.59 MPa
Compressive modulus	12.60 GPa
Ultimate flexural strength	189.2 MPa
Flexural modulus	6.92 GPa

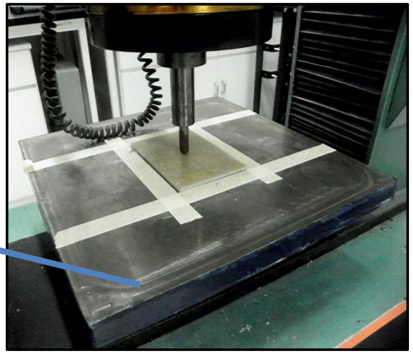
Quasi-Static Indentation Impact

ASTM D6264M - *Standard Test Method for Measuring Damage Resistance of Fiber-Reinforced Polymer-Matrix Composite to Concentrated Quasi-Static Indentation Force*

Standard 12.7 mm diameter hemisphere indentor

flat rigid base plate 300mm x 300mm x 30mm, thickness greater than the expected max indentor displacement for **procedure A**

support plate 200mm x 200mm x 40mm, with a 12.7mm diameter opening for **procedure B**



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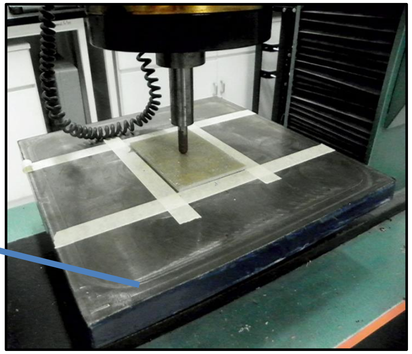

- Instron 4206 Universal tensile Testing Machine
- testing load rate is 1.25 mm/min
- attains maximum force within 1 to 10 min

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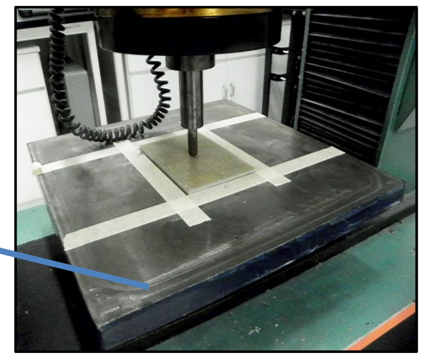

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12.7 mm ⌀ hemispherical pyramid (30º apex) 15mm ⌀ cylindrical

QSI indentors - EN24, surface hardened to 60-62 HRC

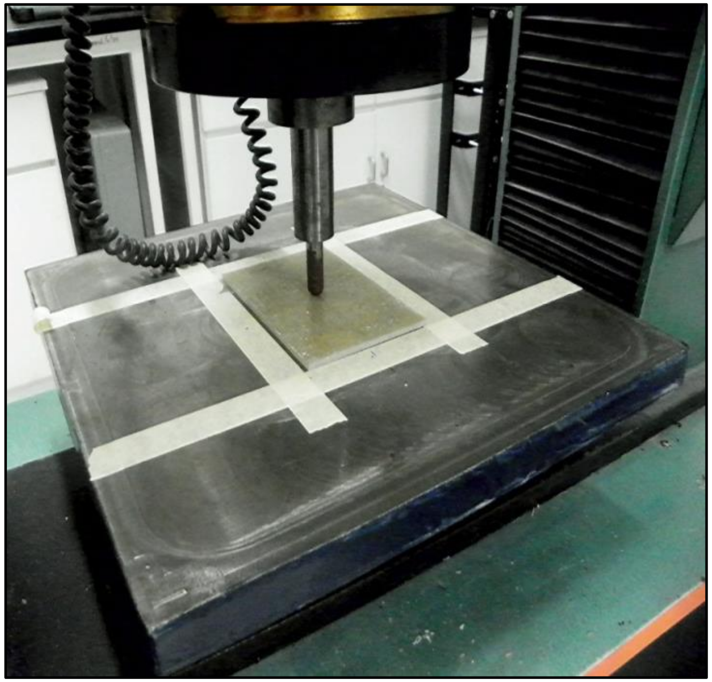
Quasi-Static Indentation Impact

ASTM D6264-M Procedure A: **Rigid support**

- hemisphere and cylinder

- the sharp pointed pyramid indentor

does not produce sufficient damage since the damage is very highly localised and the laminate thickness will be penetrated immediately and will cause apparatus damage



Quasi-Static Indentation Impact

to analyse visible impact controlled damage

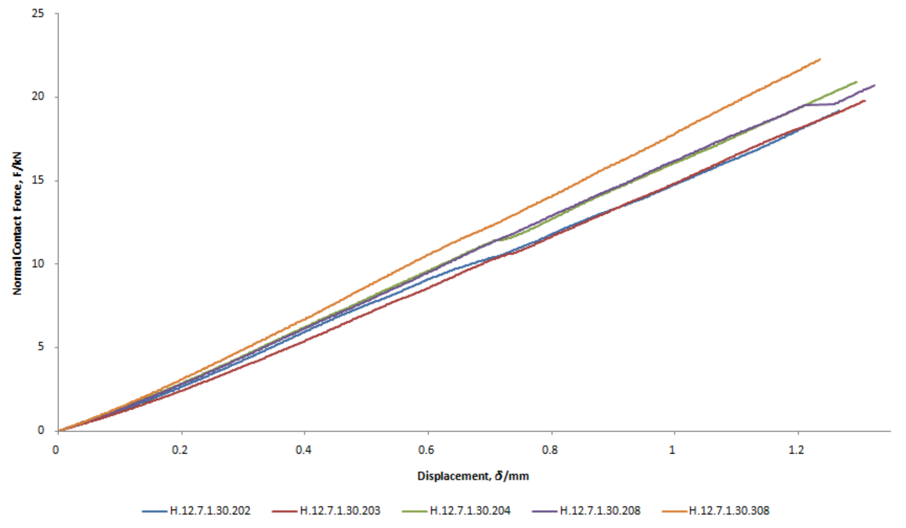
- two values of the indentation depth of 0.93 mm and 1.30 mm approximately to 20 and 28% of the mean laminate thickness

- to impart a certain degree of “controlled damage” of delamination, matrix cracking, fibre-matrix de-bonding and fibre breakage

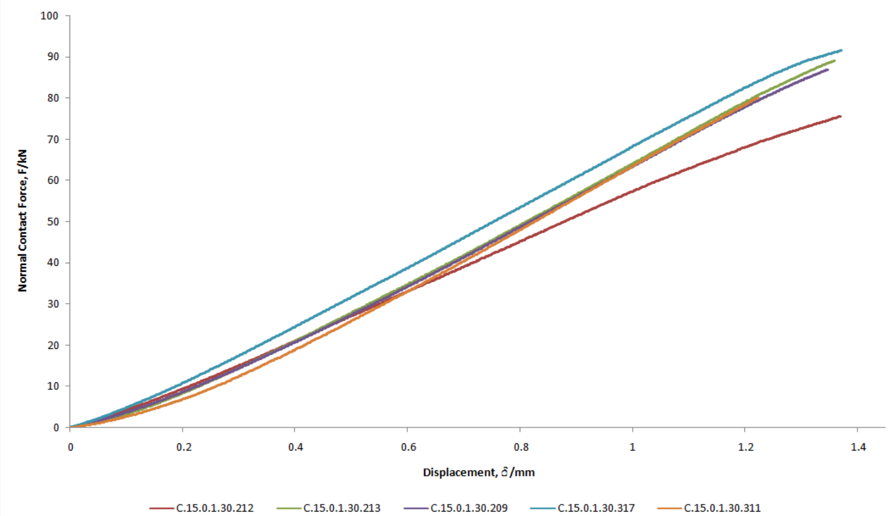
Quasi-Static Indentation Impact

Normal force vs crosshead displacement curves.

Hemisphere indentation



Cylinder indentation



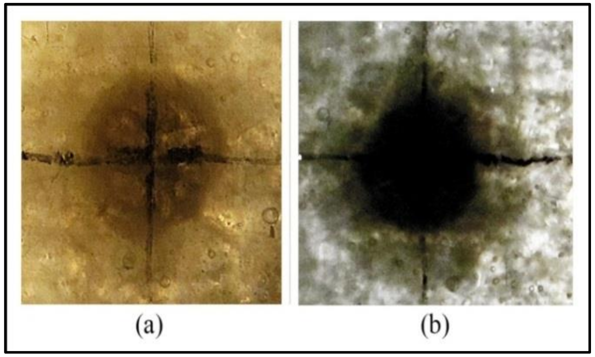
The contact laws for quasi-static indentation follow:

Hemispherical: $F = (16.76 \pm 2.03\ kN/mm)\alpha^{1.06 \pm 0.03}$ $R^2 = 0.998$

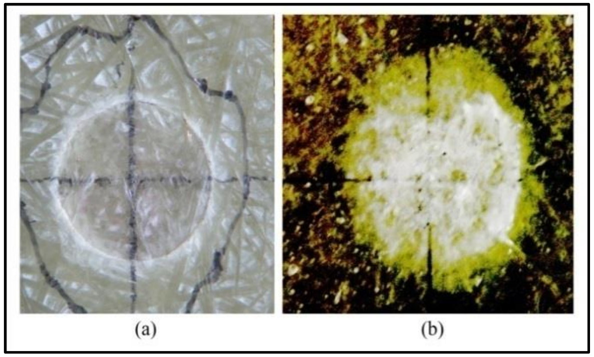
Cylindrical: $F = (63.59 \pm 4.52\ kN/mm)\alpha^{1.23 \pm 0.1}$ $R^2 = 0.999$

Quasi-Static Indentation Impact

Damage



Hemisphere – depth 1.30 mm (a) front (b) back
(photo enhanced to highlight the delaminated areas)



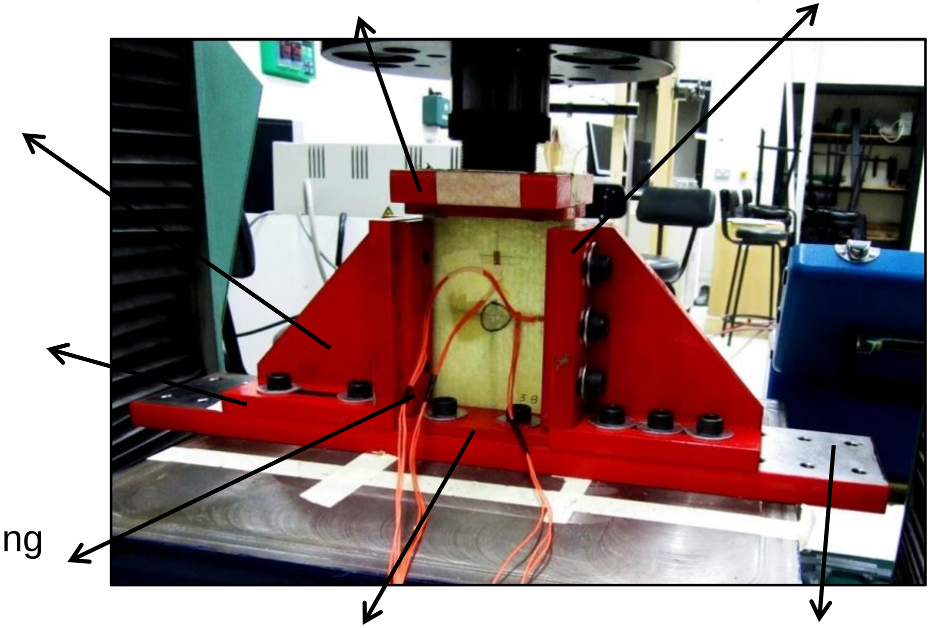
Cylinder - depth 1.30 mm (a) front (b) back
(photo enhanced to highlight the delaminated areas)

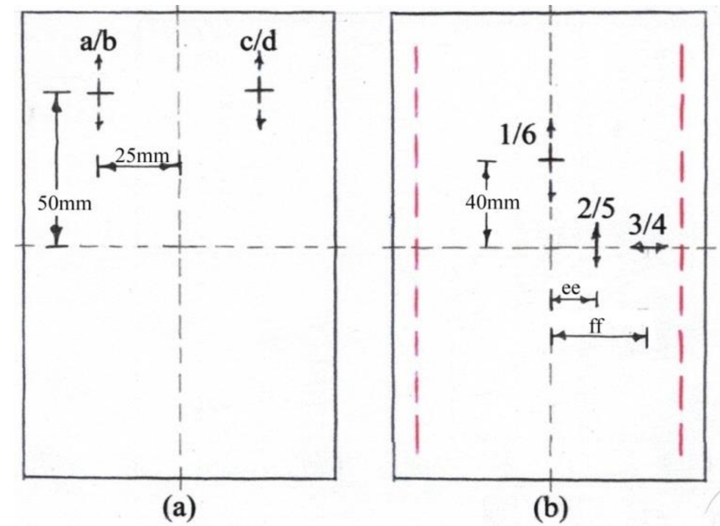
Indentor	Mean Indentation Depth/mm	Mean Damage Area/mm^2
Hemispherical (12.7mm diameter)	0.88 ± 0.04	134.33 ± 17.38
Hemispherical (12.7mm diameter)	1.27 ± 0.04	166.17 ± 22.60
Cylindrical (15.0mm diameter)	0.98 ± 0.03	144.6 ± 64.50
Cylindrical (15.0mm diameter)	1.36 ± 0.02	270.33 ± 24.32

Compression after Impact: CAI

***Compression after impact (CAI)*, ASTM D7137M -** on the damaged laminate

CAI apparatus - *ASTM D7137M*





Strain gauge arrangement:

(a) ASTM D7137M

(b) Modified positions -

1/6 strain gauges are placed along the specimen vertical centre line

2/5 immediately outside the damage zone

3/4 are placed midway between the supported edge (red-line) and strain gauges 2/5

Compression after Impact: CAI

Compression after impact (CAI), ASTM D7137M - on the damaged laminate

to characterise the specimen failure after an in-plane compression

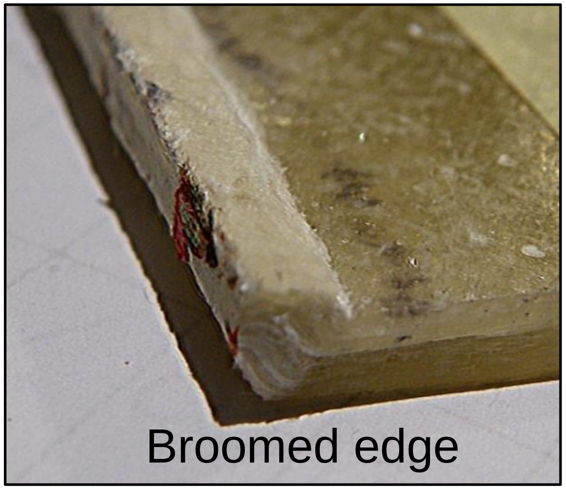
- *mode of specimen failure*
- *residual compressive strength*, $F_{CAI} = \frac{P_{MAX}}{A}$
- *effective compressive modulus*, $E_{CAI} = \frac{P_{3000} - P_{1000}}{(\varepsilon_{3000} + \varepsilon_{1000}).A}$
- *strength reduction factor*, $SRF = \frac{F_{CAI}}{F_C}$
- *modulus reduction factor*, $MRF = \frac{E_{CAI}}{E_C}$

Compression after Impact: CAI

mode of specimen failure - ASTM D7137M - three letter code

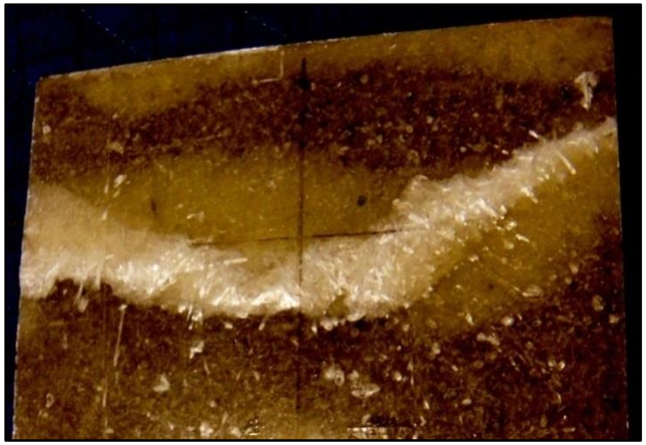
- LAT represents lateral failure at the top edge of the specimen
- KAT represents kink-band failure at the top edge of the specimen
- OGM represents a failure type within the gauge length (the unsupported length of the specimen) towards the middle of the specimen
- LGM represents lateral failure away from the damage site but in the middle
- LDM represents lateral failure through the damage site towards the middle of the specimen

The modes of *unacceptable failure* are end-crushing, edge-restrained delamination growth and panel instability. Panels failing in any of the latter modes were not considered

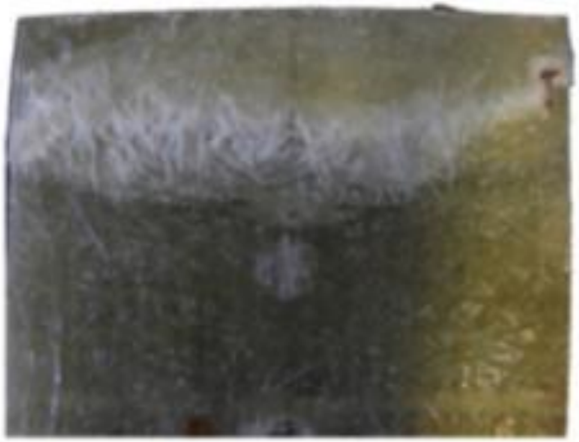

Broomed edge

Compression after Impact: CAI

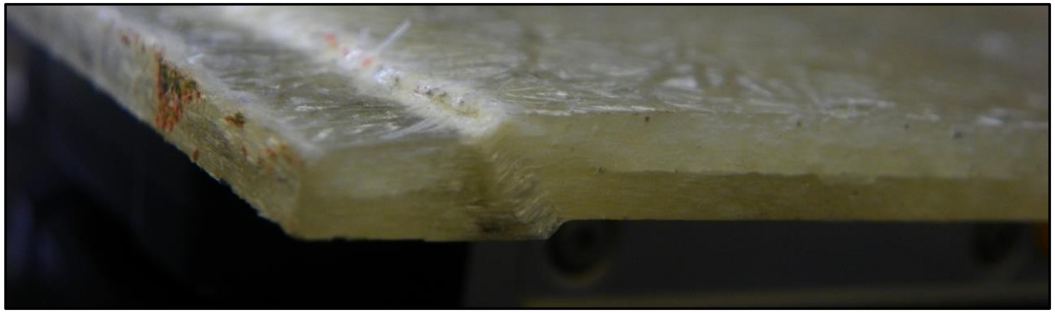
acceptable mode of specimen failure - ASTM D7137M



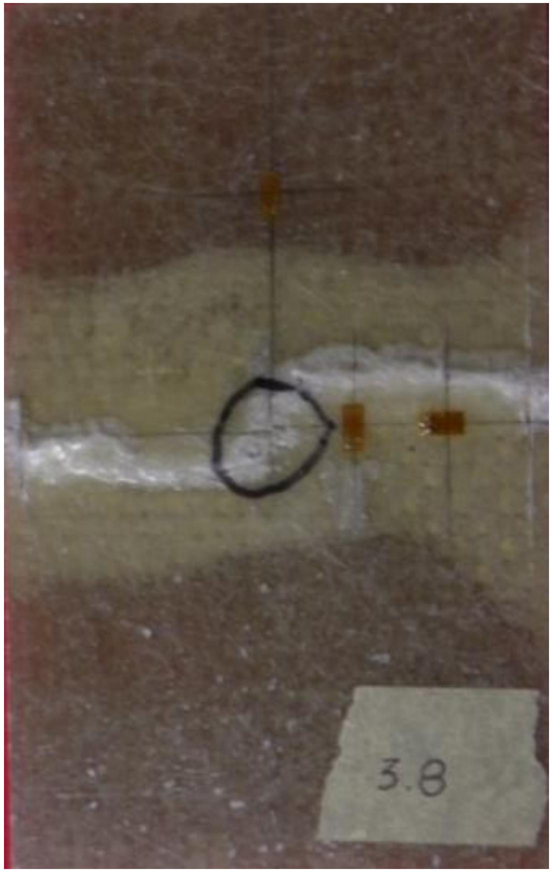
LGM



LAT



KAT



LDM

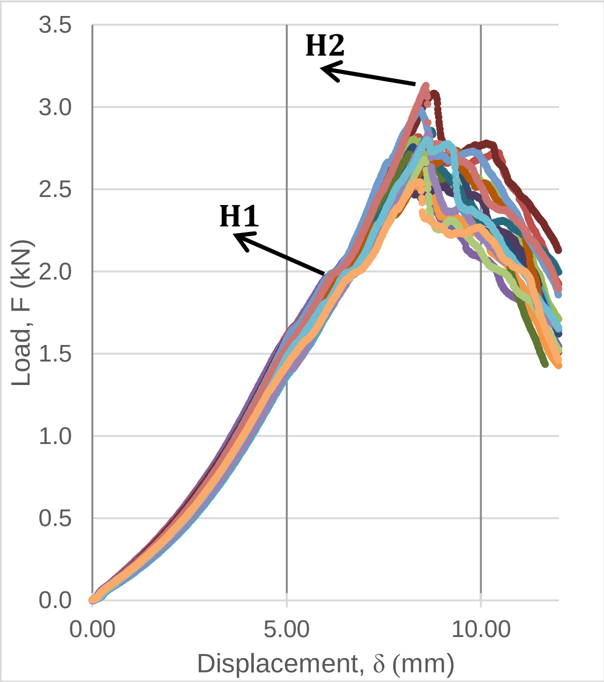
Compression after Impact: CAI

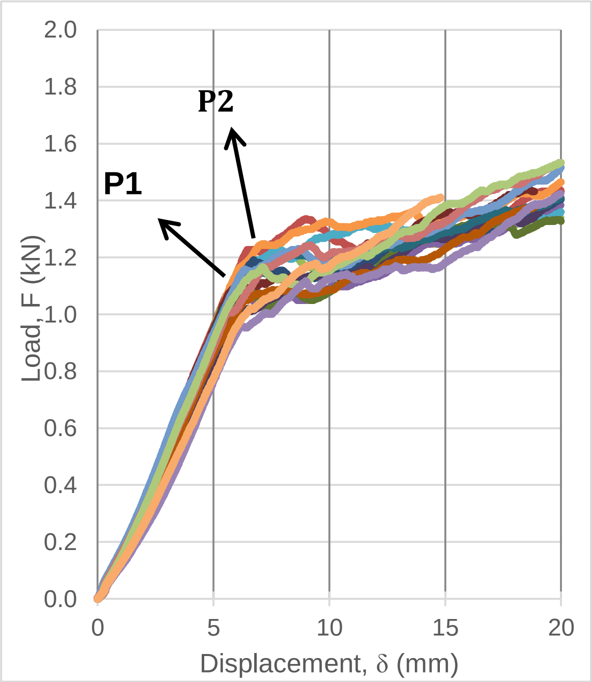
CAI Experimental Results	Specimen	Specimen Failure Code	Ultimate Compressive Residual Strength (F_{CAI})		Strength Retention Factor (SRF)		Effective Compressive Modulus (E_{CAI})		Modulus Retention Factor (MRF)	
			Mean Value	Standard Deviation	Mean Value	Standard Deviation	Mean Value	Standard Deviation	Mean Value	Standard Deviation
			MPa	MPa (%)			GPa	GPa (%)		
	Hemishpere 0.93 mm indentation	KAT LAT OGM	89.6 ± 0.1 (0.125%)	9.5 (10.6)	**0.52**	0.08	8.001± 0.001 (0.00001%)	2.956 (36.95)	**0.63**	0.23
	Hemishpere 1.30 mm indentation	LAT LDM LAT LDM	106.6 ± 0.1 (0.139%)	7.9 (7.4)	**0.62**	0.06	12.074± 0.001 (0.00001%)	8.576 (7.103)	**0.95**	0.07
	Cylinder 0.93 mm indentation	LDM LAT LAT LDM LDM	103.4 ± 0.2 (0.168%)	10.1 (9.8)	**0.60**	0.08	9.545 ± 0.001 (0.00001%)	1.662 (17.416)	**0.76**	0.13
	Cylinder 1.30 mm indentation	LDM LAT KAT LGM	90.1 ± 0.1 (0.157%)	16.8 (18.6)	**0.53**	0.14	11.003 ± 0.001 (0.00001%)	1.644 (14.950)	**0.87**	0.13
Experimental Results [FACTS]			Ultimate Compressive Strength (F_C)				Compressive (Young's) Modulus (E_C)			
			171.59 MPa				12.60 GPa			

Quasi-Static Indentation Impact

ASTM D6264-M Procedure B: Simply supported

Laminate Characteristics		Ultimate tensile strength	192 MPa
Fibre mass fraction	0.475	Tensile modulus	11.1 GPa
Fibre volume fraction	0.280	Ultimate flexural strength	256 MPa
Thickness	3.45 mm	Flexural modulus	8.7 GPa

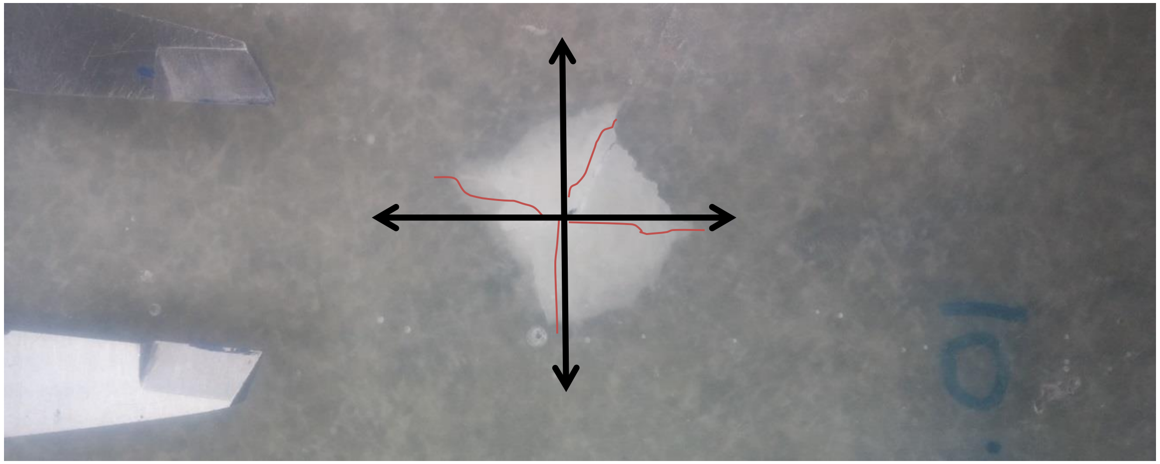




Quasi-Static Indentation Impact

- damage sustained far exceeds what is characteristic of BVID, with a large white delaminated visible area
- called - Visible Indentation Damage (VID)

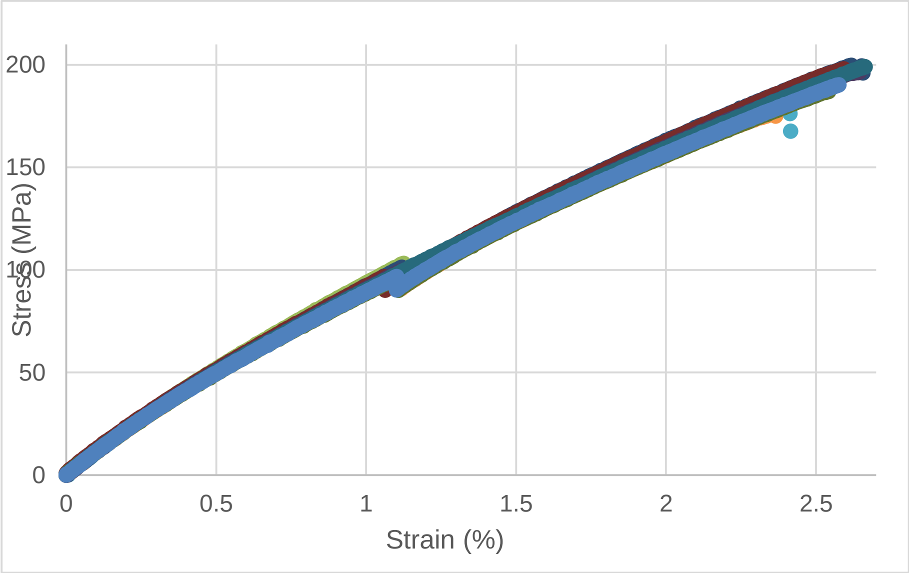
Indentor	Max load at yield (kN)	Average VID Width (mm)	Average Front Hole Width (mm)
Hemisphere	2.8 ± 0.2	36 ± 4	12.70 ± 0.01
Pyramid	1.1 ± 0.1	27 ± 3	12 ± 1

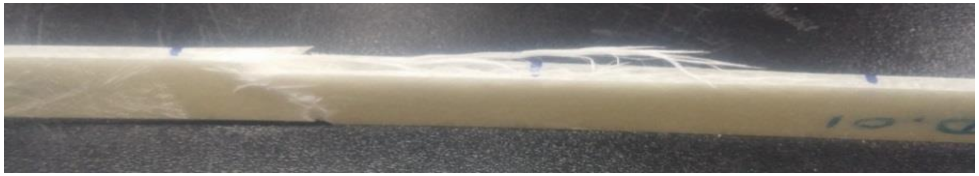


VID for pyramid indentor

Characterisation after Impact

- **Tensile -** tensile strength before (original) TBI vs after (damaged) TAI





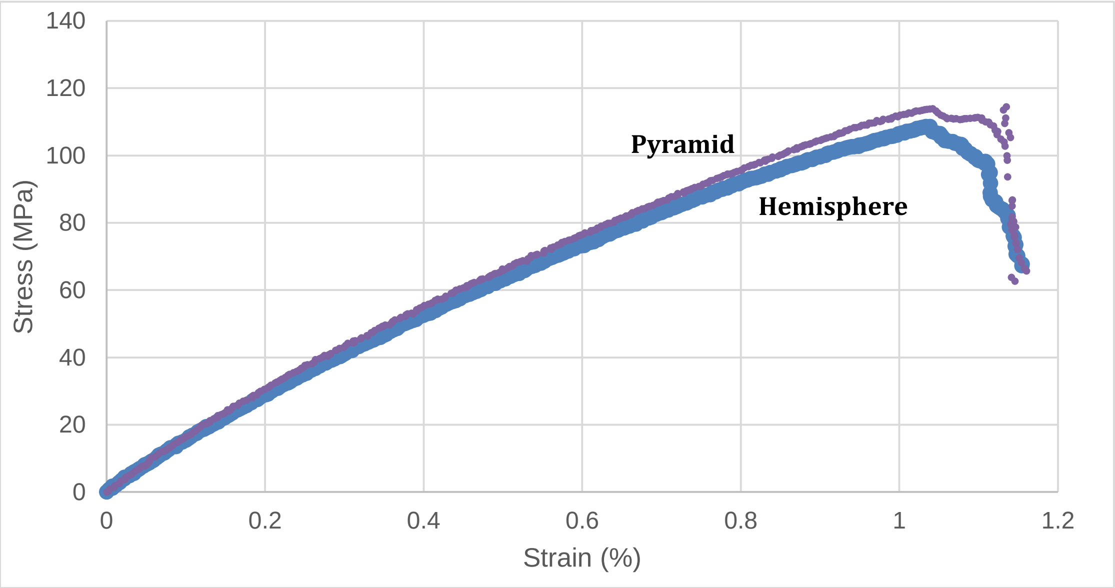
TBI - matrix failure, fibre pull out and delamination

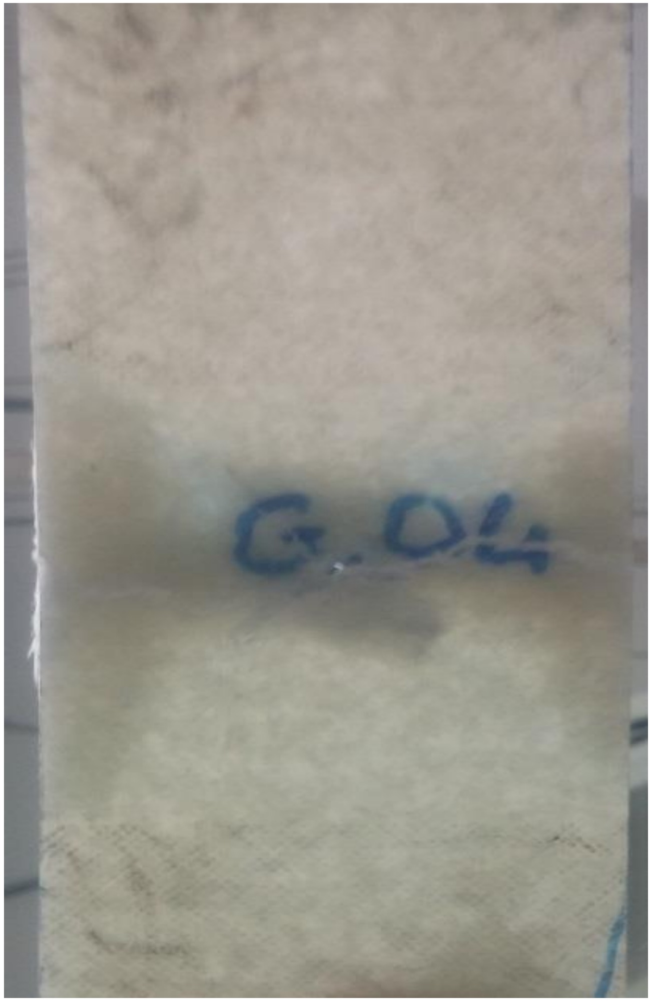
Characterisation after Impact

- **Tensile -** tensile strength before (original) TBI vs after (damaged) TAI

TAI Specimen

- based on the damaged diameter, *a* the laminate was cut to a width *w*,
- each resulting specimen had the same ratio of *a/W* = 0.5
- a geometric characteristic used in fracture mechanics testing in cracked bodies





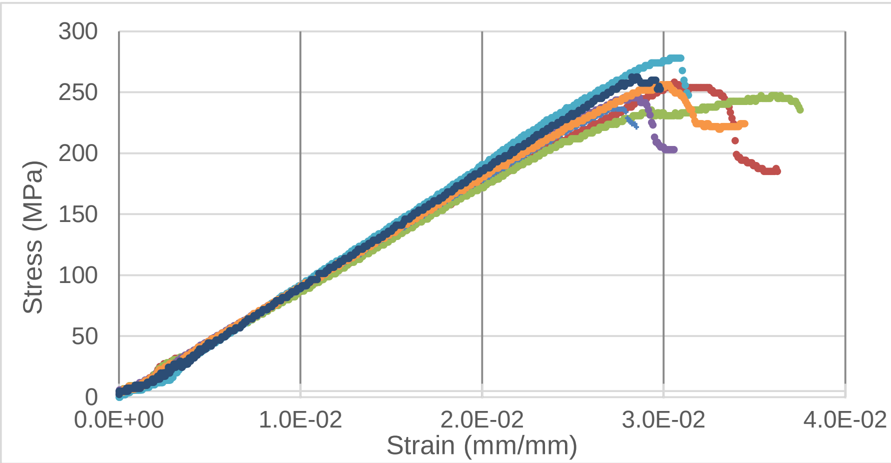
Characterisation after Impact

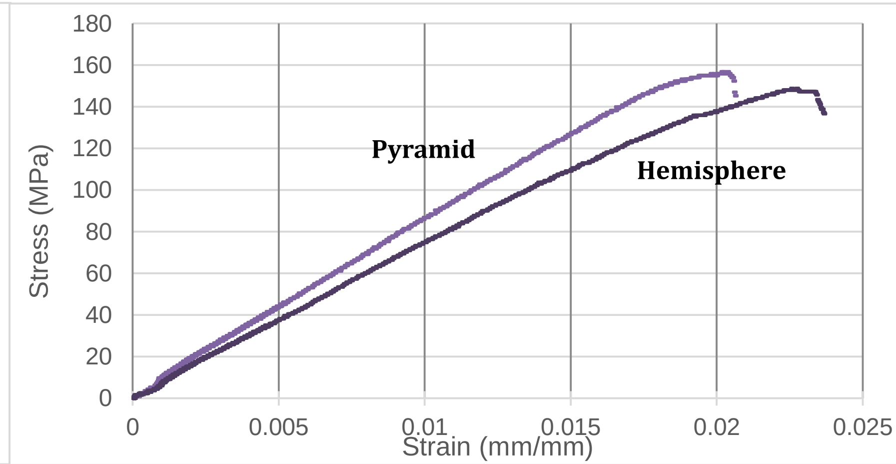
- **Tensile -** tensile strength before (original) TBI vs after (damaged) TAI

<table>
<tr><th rowspan="3">TBI</th><th colspan="4">Ultimate Tensile Strength (MPa)</th><th colspan="4">Tensile Modulus (GPa)</th></tr>
<tr><th colspan="2">Mean Value</th><th colspan="2">Standard Deviation (%)</th><th colspan="2">Mean Value</th><th colspan="2">Standard Deviation (%)</th></tr>
<tr><td colspan="2">192</td><td colspan="2">11 (5.7)</td><td colspan="2">11.1</td><td colspan="2">0.8 (7.2)</td></tr>
<tr><th rowspan="4">TAI</th><th colspan="4">Ultimate Residual Tensile Strength (MPa)</th><th colspan="4">Residual Tensile Modulus (GPa)</th></tr>
<tr><th rowspan="2">Mean Value</th><th rowspan="2">Standard Deviation (%)</th><th colspan="2">Strength Retention Factor (SRF)</th><th rowspan="2">Mean Value</th><th rowspan="2">Standard Deviation (%)</th><th colspan="2">Modulus Retention Factor (MRF)</th></tr>
<tr><th>Mean Value</th><th>Standard Deviation (%)</th><th>Mean Value</th><th>Standard Deviation (%)</th></tr>
<tr><td>108</td><td>12 (11.1)</td><td>0.56</td><td>0.05 (8.4)</td><td>6.8</td><td>0.6 (8.8)</td><td>0.61</td><td>0.05 (8)</td></tr>
</table>

Characterisation after Impact

- **Flexural -** flexural strength before (original) FBI vs after (damaged) FAI





<table>
<tr><td rowspan="3">FBI</td><td colspan="4">Ultimate Flexural Strength (MPa)</td><td colspan="4">Flexural Modulus (GPa)</td></tr>
<tr><td colspan="2">Mean Value</td><td colspan="2">Standard Deviation (%)</td><td colspan="2">Mean Value</td><td colspan="2">Standard Deviation (%)</td></tr>
<tr><td colspan="2">256</td><td colspan="2">13 (5.1)</td><td colspan="2">8.7</td><td colspan="2">0.8 (9.1)</td></tr>
<tr><td rowspan="4">FAI</td><td colspan="4">Ultimate Residual Flexural Strength (MPa)</td><td colspan="4">Residual Flexural Modulus (GPa)</td></tr>
<tr><td rowspan="2">Mean Value</td><td rowspan="2">Standard Deviation (%)</td><td colspan="2">Strength Retention Factor (SRF)</td><td rowspan="2">Mean Value</td><td rowspan="2">Standard Deviation (%)</td><td colspan="2">Modulus Retention Factor (MRF)</td></tr>
<tr><td>Mean Value</td><td>Standard Deviation (%)</td><td>Mean Value</td><td>Standard Deviation (%)</td></tr>
<tr><td>154</td><td>8 (5.2)</td><td>0.60</td><td>0.03 (5.2)</td><td>7.9</td><td>0.4 (5.1)</td><td>0.91</td><td>0.05 (8)</td></tr>
</table>

Characterisation after Impact

Compressive Characteristics Evaluation

- *ASTM D3410* compression before impact (CBI) - Traditionally the ultimate compressive strength and compressive modulus are determined through the ASTM D3410 standard testing procedures

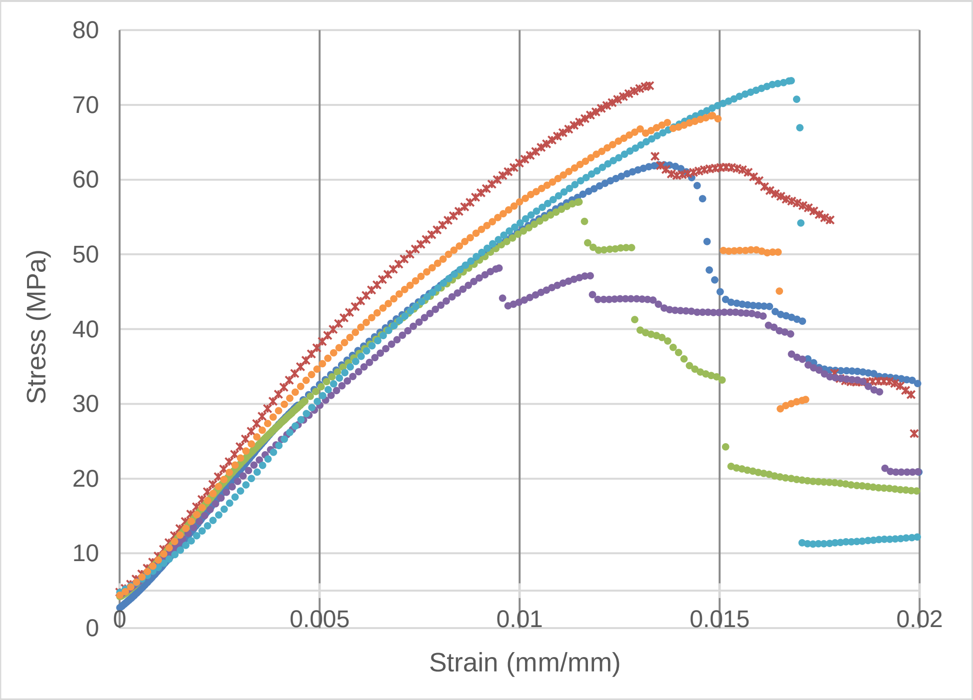
- *ASTM D7137M* describes the CAI testing of the damaged laminates, to obtain the *SFR* and *MRF*

- In the first instance a different approach is being adopted here, and the CBI properties of the undamaged specimens are to be tested in the CAI fixture and to evaluate if such an option may produce valid and reliable information

Characterisation after Impact

CBI testing in the CAI apparatus

slopes show a scatter of compressive modulus and the ultimate compressive stress and corresponding strain



Characterisation after Impact

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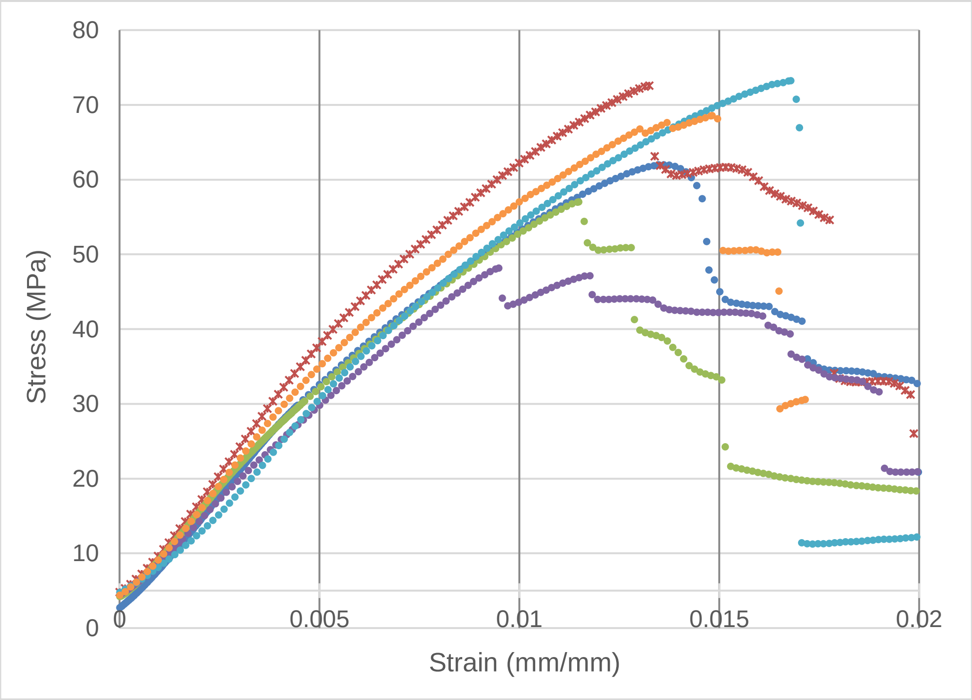
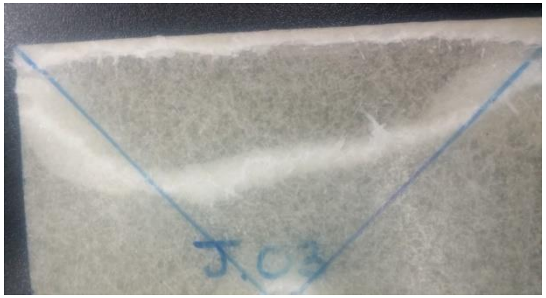
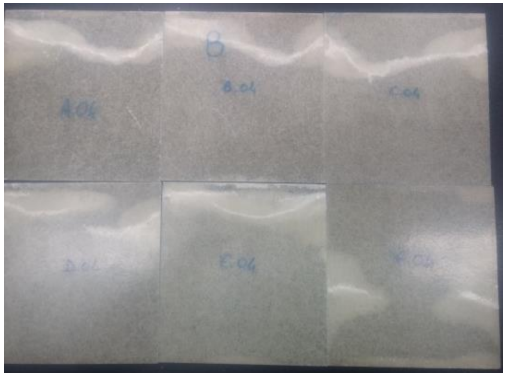




Damaged CBI Specimens showing end-crushing, edge-restrained delamination growth or by panel instability.

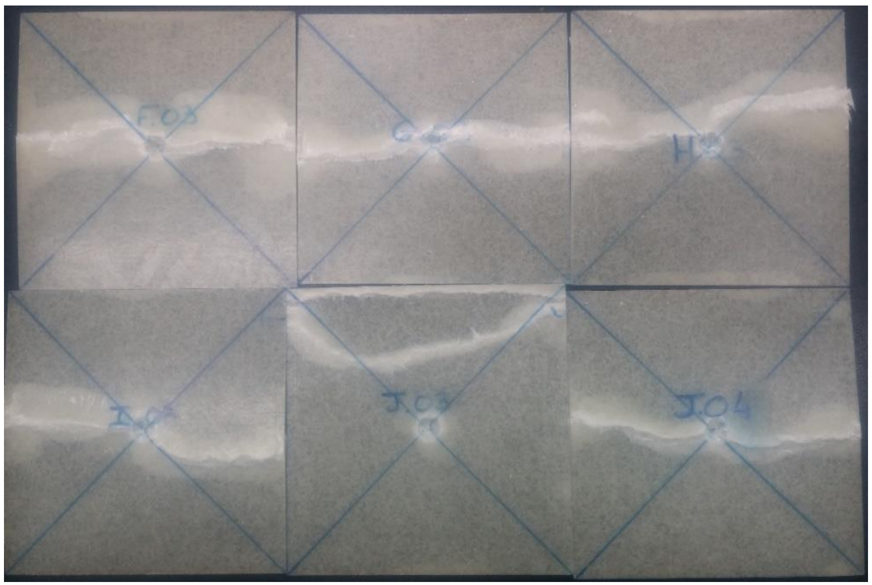
These modes of failure, according to ASTM D7137M are considered invalid



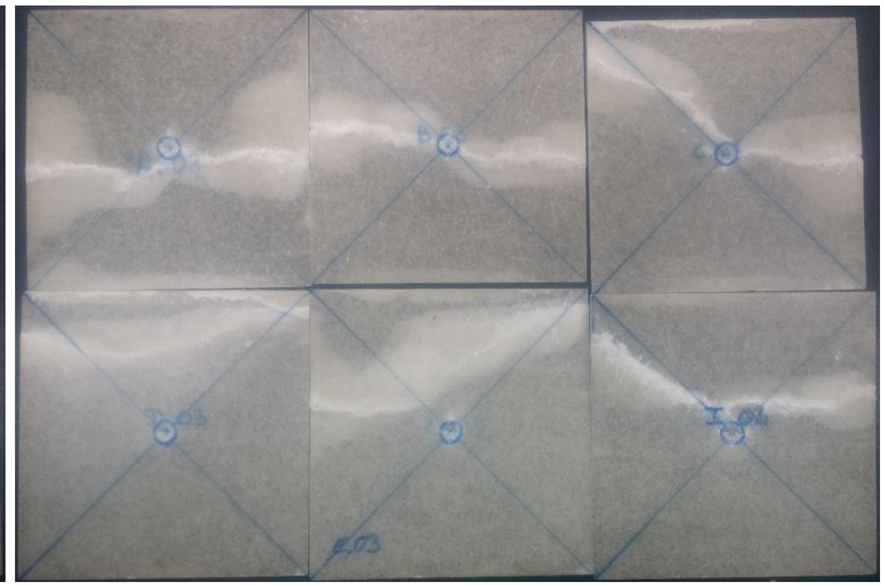
Concluding that ***testing the compressive properties, CBI within the CAI apparatus is not appropriate and must not be undertaken***

Characterisation after Impact

Compressive - compressive strength before (original) CBI (ASTM D3410) vs after (damaged) CAI (ASTM D7137M)



hemisphere



pyramid

CAI testing

All specimen failure according to ASTM D7137M

Characterisation after Impact

Compressive - compressive strength before (original) CBI (ASTM D3410) vs after (damaged) CAI (ASTM D7137M)

	Indentor Type	Specimen Failure Code	Ultimate Residual Compressive Strength (MPa)			Residual Compressive Modulus (GPA)		
			Mean Value	Standard Deviation (%)	Strength Retention Factor (SRF)	Mean Value	Standard Deviation (%)	Modulus Retention Factor (MRF)
CAI Results - ASTM D7137	Hemisphere	LDM LDM LDM LDM LAT LDM	66	4 (6.1%)	**0.38**	6.3	0.6 (9.5)	**0.50**
	Pyramid	LDM LDT LAT LGT LGM	71	5 (7.1%)	**0.41**	6.3	0.7 (11.1)	**0.50**
ASTM D3410			Ultimate Compressive Strength (MPa)			Compressive Modulus (GPa)		
			171.59			12.6		

Conclusions

- laminates tested & characterised using standard test procedures

- QSI: A - rigid backed, hemisphere & cylinder - 20 & 28% of thickness
  - **CAI testing -** *mode of specimen failure*, F_{CAI}, E_{CAI}, *SRF, MRF*

- QSI: B – simply supported, hemisphere & pyramid – 100% thickness
  - TBI vs TAI → tensile SRF & MRF
  - FBI vs FAI → flexural SRF & MRF

  { Specimen dimensions based on the damaged diameter, *a* the laminate was cut to a width *w*, such that each resulting specimen had the same ratio of $a/W = 0.5$

  - CBI testing in the CAI apparatus - not recommended procedure
  - CBI vs CAI → compressive SRF & MRF

Conclusions

ASTM D6264M QSI Testing Procedure A: Rigid Support		ASTM D6264M QSI Testing Procedure B: Simply Supported	
Characteristic	Indentor	Indentor	Characteristic
Hemisphere		Hemisphere	
		0.56	Tensile SRF
		0.61	Tensile MRF
		0.60	Flexural SRF
		0.91	Flexural MRF
Compressive SRF	0.57	0.38	Compressive SRF
Compressive MRF	0.79	0.50	Compressive MRF
Cylinder		Pyramid	
		0.56	Tensile SRF
		0.61	Tensile MRF
		0.60	Flexural SRF
		0.91	Flexural MRF
Compressive SRF	0.57	0.41	Compressive SRF
Compressive MRF	0.82	0.50	Compressive MRF

Thank you for your kind attention