Round-Robin Mode-I Face/Core Fracture Toughness Characterization of Honeycomb Sandwich Composites using the SCB and DCB-UBM Test Methods

EASA Sandwich Structure Workshop
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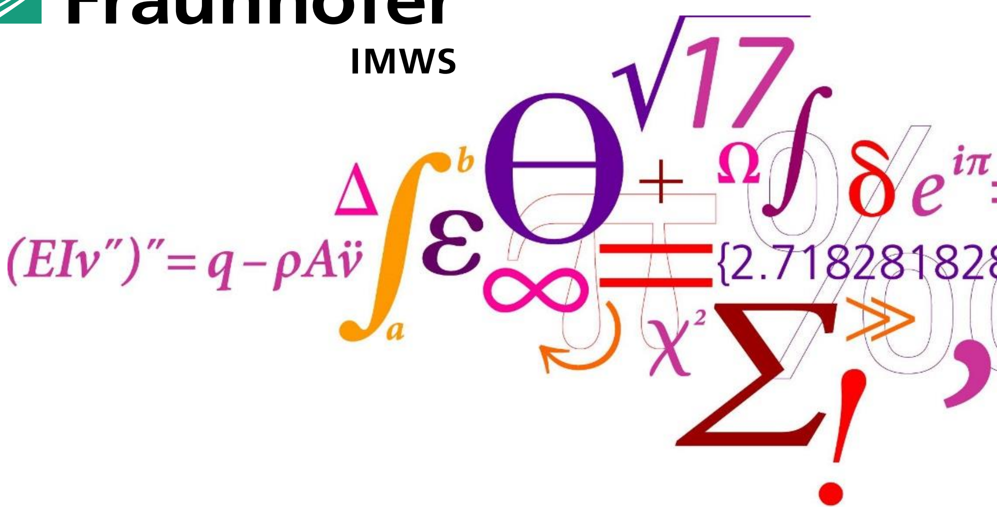
NATIONAL INSTITUTE OF AEROSPACE

Fraunhofer IMWS



DTU Mechanical Engineering
Department of Mechanical Engineering

Agenda

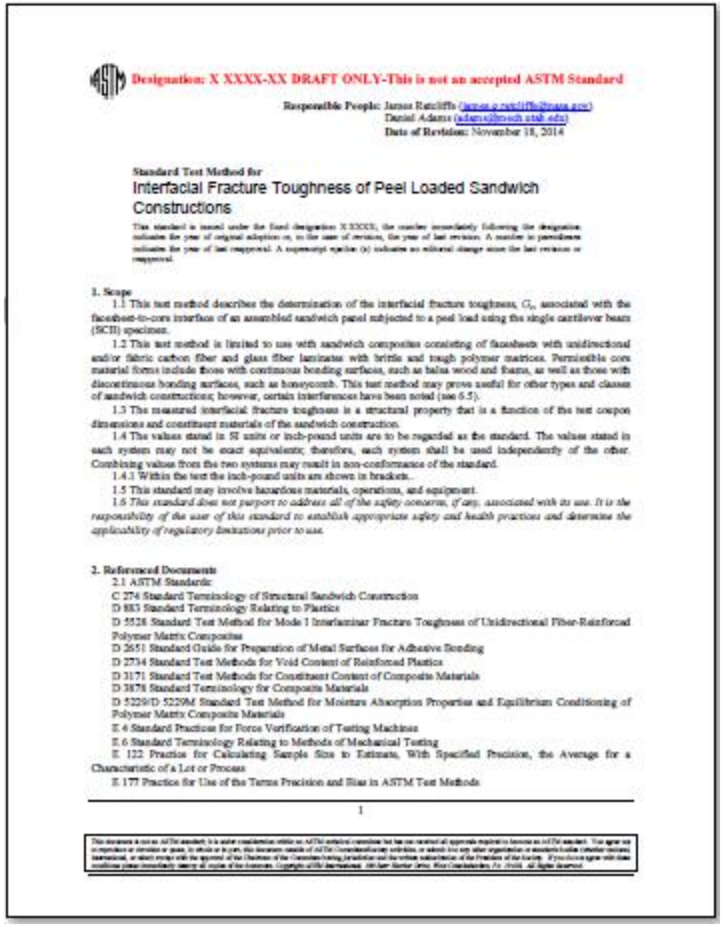
- Introduction
- Round-Robin details (SCB)
- Benchmark test details (DCB-UBM)
- Test matrix and results
- Conclusions

Introduction
Background

ASTM Committee D30 (WK 47682)

Standardized test method for peel-dominated interfacial fracture toughness of sandwich constructions (draft)

- Main responsible partners for draft the standard:
  - University of Utah
  - NASA Langley
- ASTM draft includes procedures to determine the SCB specimen dimensions (specimen length, face sheet, thickness, initial disbond length)
- Round-Robin initiated in 2014 involving seven laboratories in the USA and Europe from the CMH-17 Task Group
- *All testing just completed October 2016!*



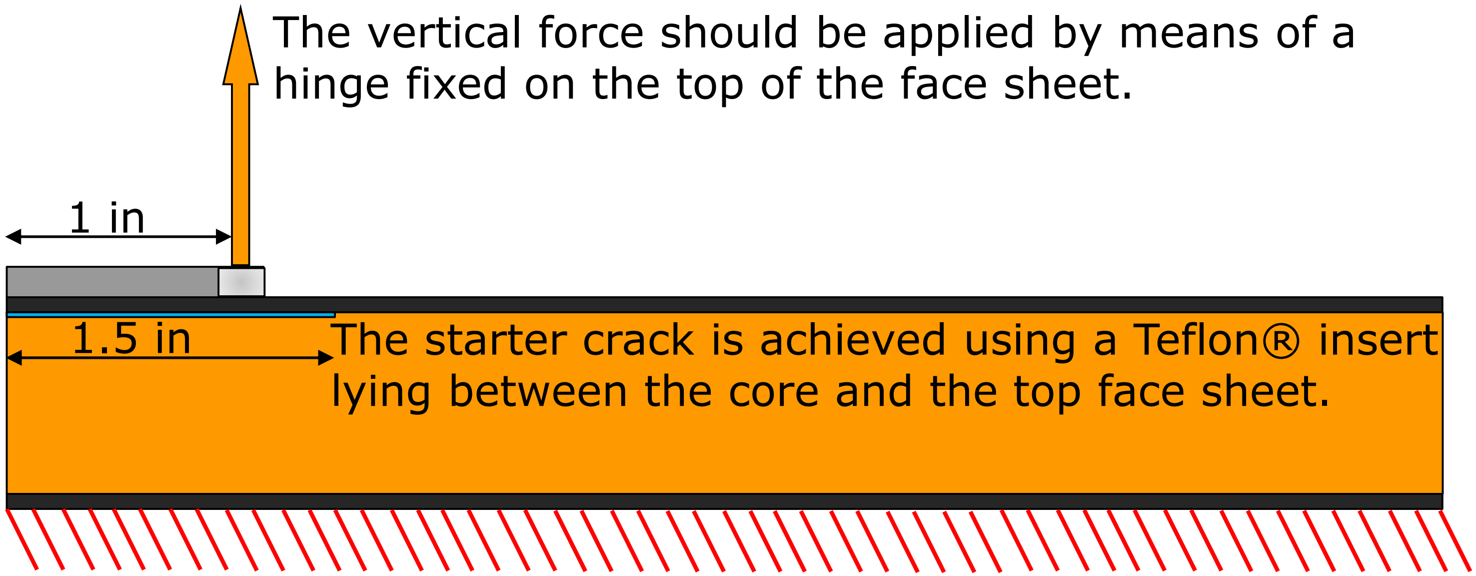
Introduction
Partners

The **Round-Robin** is an inter-laboratory activity involving seven independent testing laboratories use of the same general test method from the draft standard but utilizing different test equipment.

Lab ID	Name
Lab 1	University of Utah
Lab 2	NIAR
Lab 3	DuPont
Lab 4	NASA
Lab 5	Fraunhofer IMWS
Lab 6	Airbus
Lab 7	DTU

Round-Robin details (SCB)
Fixture demands

The vertical force should be applied by means of a hinge fixed on the top of the face sheet.



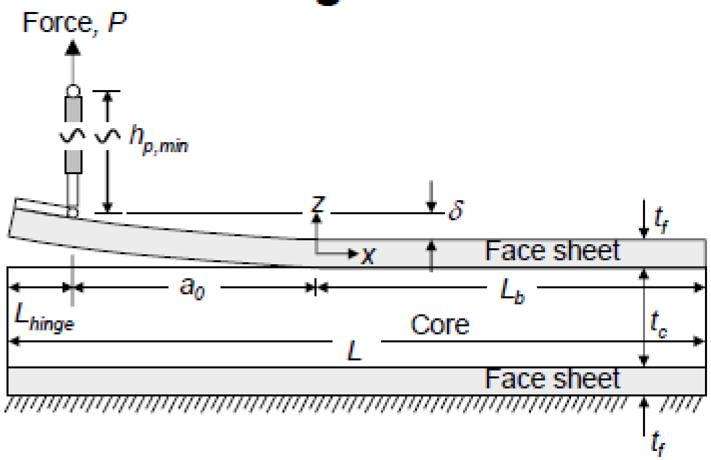
The face sheet on the bottom side of the sandwich specimen must be fixed on a <u>fixed</u> or <u>translatable</u> base using glue or a mechanical locking systems.

Each of the seven participating labs have developed their own specific test fixture complying with the above demands.

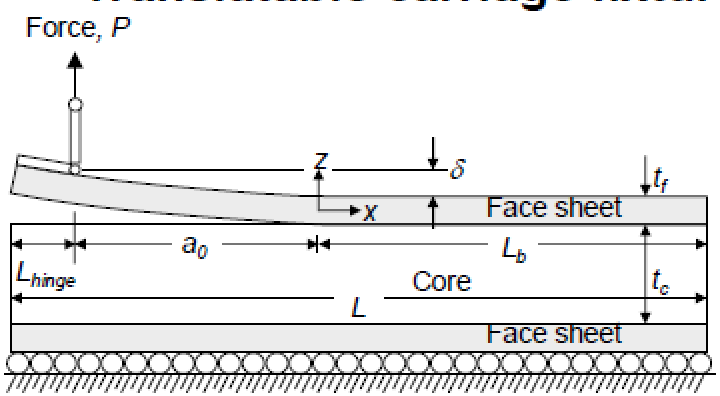
Round-Robin details (SCB)
Specimen geometry

Baseline Specimen parameters	
a_0	12.7 mm (0.5”)
width, b	50.8 mm (2.0”)
$h_{p,min}$	500 mm (20”)
L	305 mm (12”)
L_{hinge}	25.4 mm (1.0”)
t_c	25.4 mm (1.0”)
t_f	0.772 mm (0.0304”)
Face sheet	T650/5320 PW Layup (4 plies): $[45/0]_s$ 0-dir along specimen length
Core	HRH-10: Cell size = 3.2 mm (0.125”) Density = 3lb/ft^3 (48kg/m^3)

Loading offset fixture

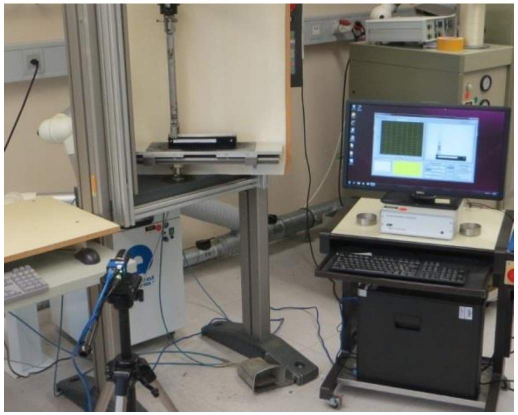


Translatable carriage fixture

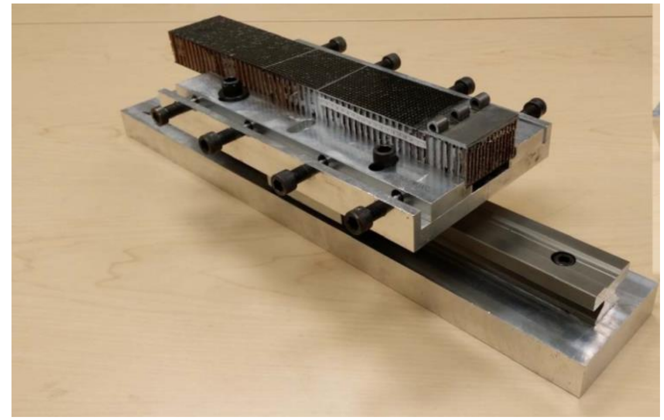


Round-Robin details (SCB)

Fixtures (DuPont, NIAR, NASA, Univ. of Utah)

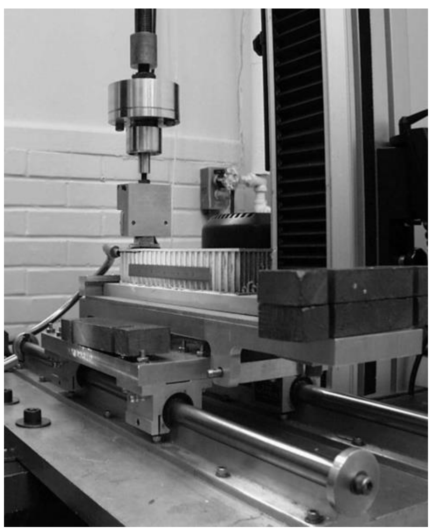


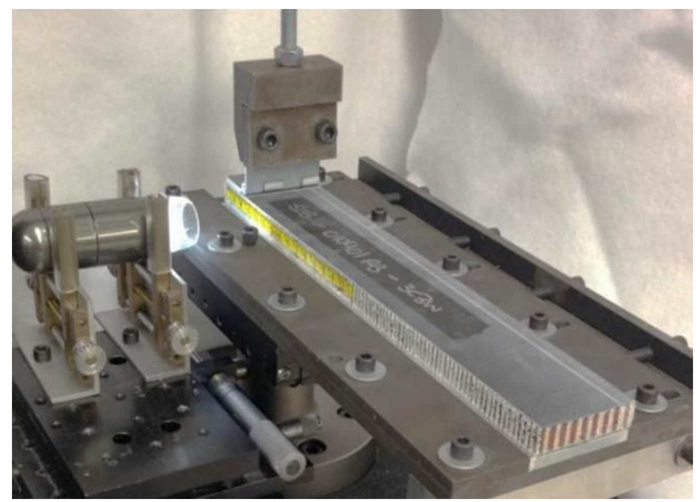
Lab 3, DuPont, Test rig setup



Lab 2, NIAR, Specimen clamping mechanism

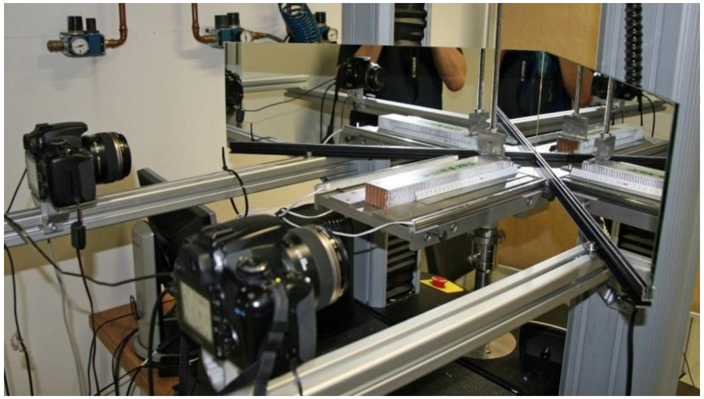
Lab 1, Utah, Test rig setup





Lab 4, NASA, Test rig setup

Round-Robin details (SCB)
Fixtures (Fraunhofer, Airbus)

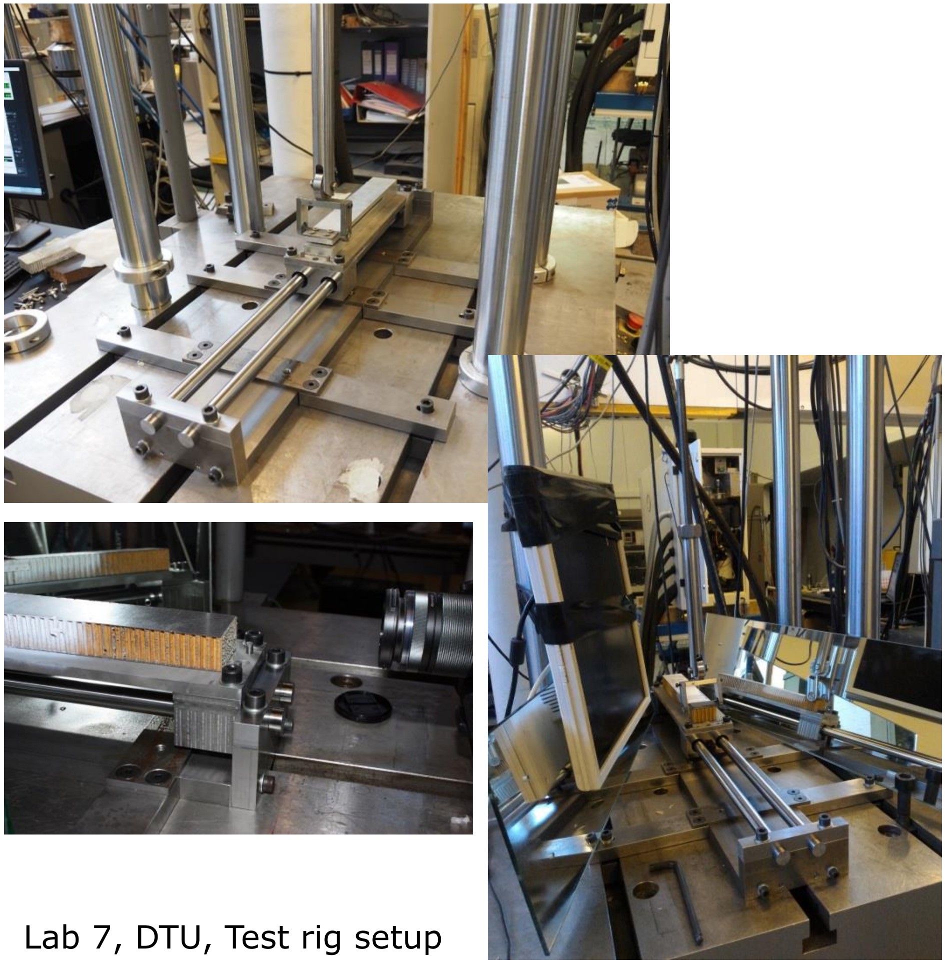

Lab 5, Fraunhofer, Crack detection system


Lab 5, Fraunhofer, Specimen clamping system

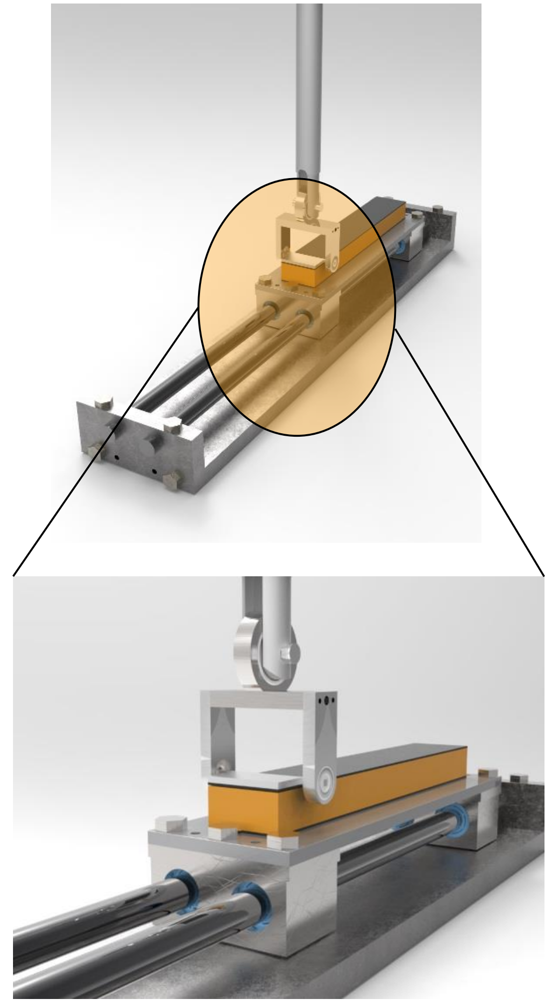
Lab 6, Airbus, Test setup

Round-Robin details (SCB)

Fixtures (DTU)



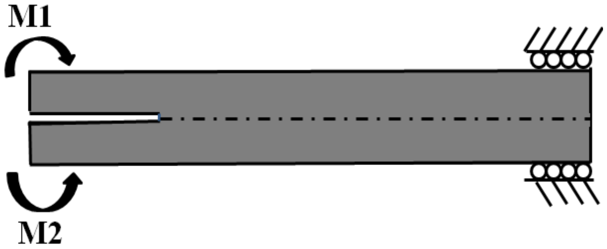
Lab 7, DTU, Test rig setup



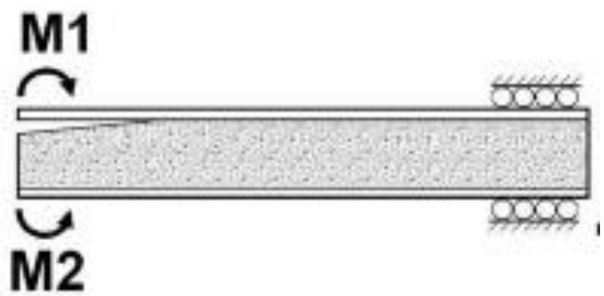
Lab 7, DTU, Load mechanism

Benchmark test details (DCB-UBM)
Key features

- Pure moments applied at the crack flanks
- Almost any mixed-mode ratio can be achieved!
- No transverse forces – no crack length needed!
- G-controlled by nature – good for fatigue!



- Extended for sandwich testing
- Analytical foundation (*Kardomateas et.al, 2013*)
  - Kinematic relations for a general asymmetric sandwich with moments
  - Closed form solutions for ERR and mode-mixity – good for future standard implementation!



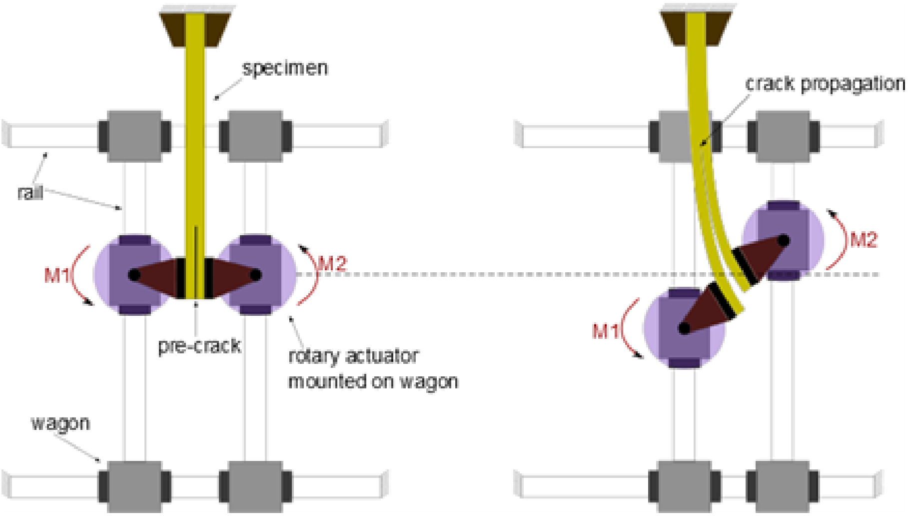
$$G = \frac{1-\nu_{f1}^2}{2E_{f1}}\left(\frac{P^{*2}}{h_{f1}} + E_{f1}^2 \frac{M_d^{*2}}{D_d^2}\frac{h_{f1}^3}{12}\right) + \left(\frac{P^{*2}}{(EA)_s^2}H_1 + \frac{P^* M_s^*}{(EA)_s D_s}H_2 + \frac{M_s^{*2}}{D_s^2}H_3\right)$$

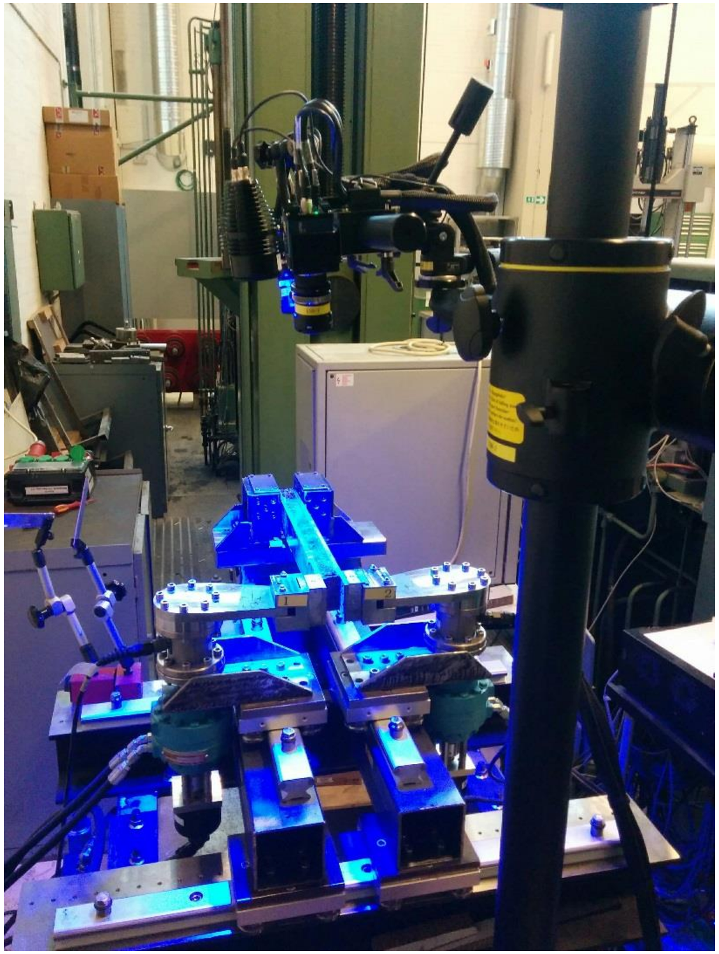
$$\psi = \tan^{-1}\left[\frac{\lambda \sin\omega - \cos(\omega+\gamma)}{\lambda\cos\omega + \sin(\omega+\gamma)}\right]$$

$$\lambda = -\frac{P^*}{M_d^*}\sqrt{\frac{a_1}{a_2}} \qquad \sin\gamma = \frac{-a_3}{2\sqrt{a_1 a_2}}$$

Benchmark test details (DCB-UBM)
Novel compact fatigue rated rig

- DTU high-fidelity bi-axial servo-hydraulic operated stand-alone rig
- Fatigue rated
- Capacity up to 565 [Nm]
- Able to apply any moment ratio
- Combined with ARAMIS 12M DIC system for high-resolution specimen monitoring

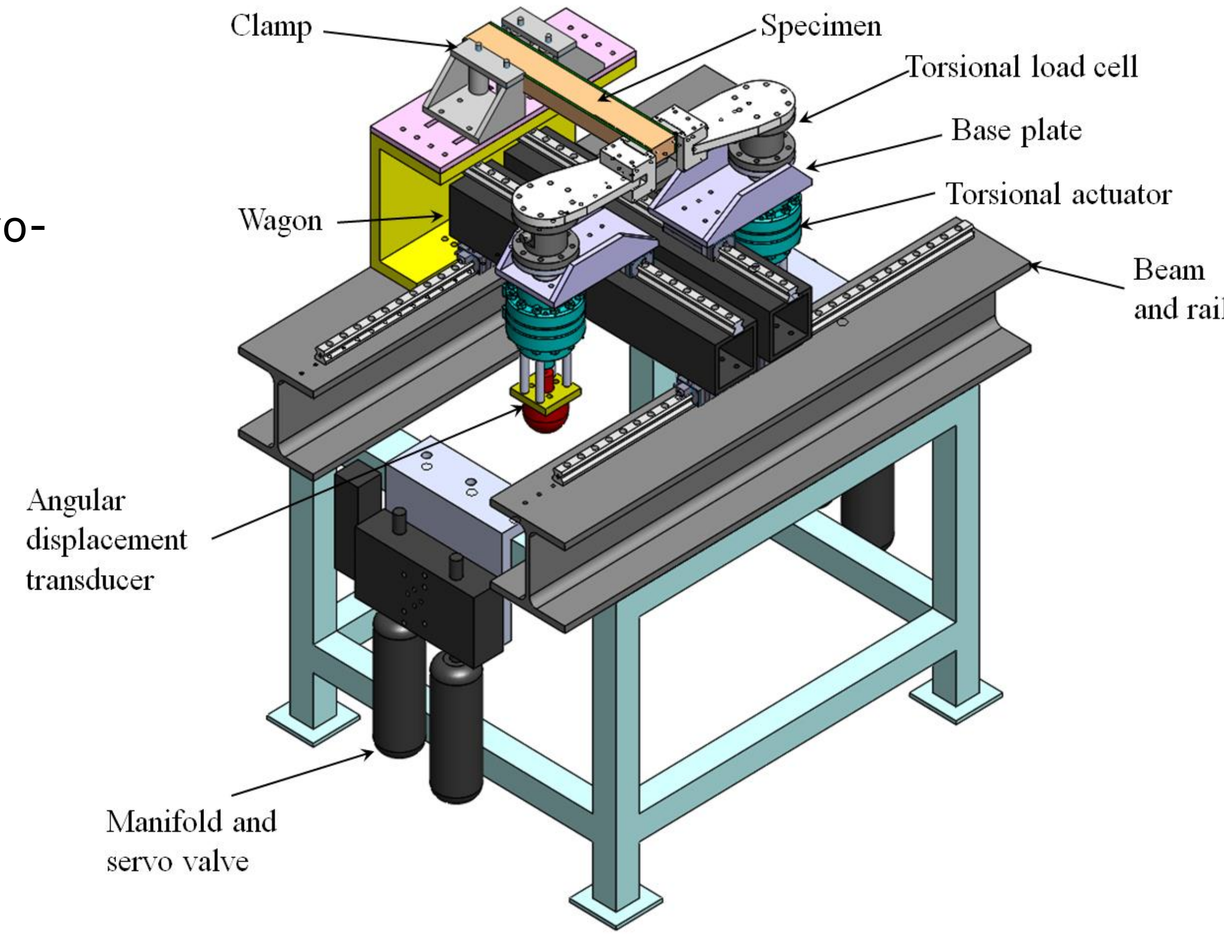




Benchmark test details (DCB-UBM)
Novel compact fatigue rated rig

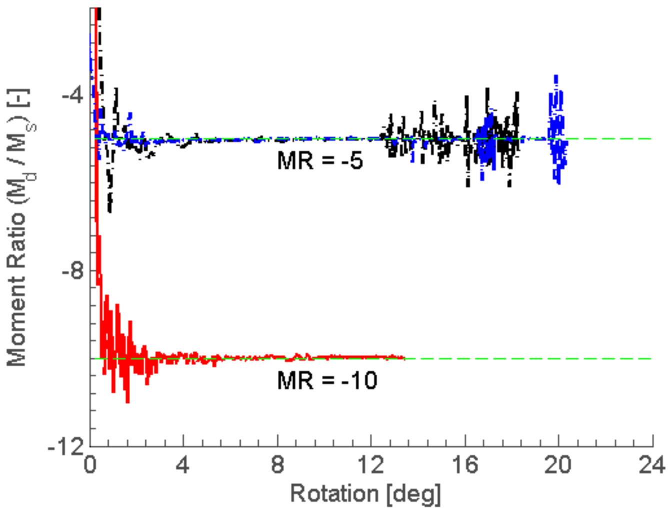
Specifications:

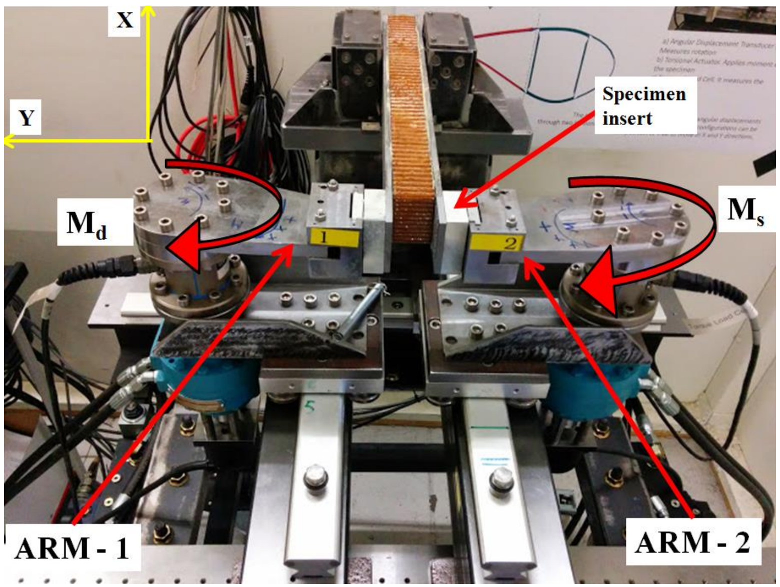
- Low friction roller wagon/rail system
  - Two torsional actuators (700 Nm)
  - Two 10 [L/min] servo-valves
  - Two 565 [Nm] torsional load cells
- Bi-axial servo-hydraulic controller (MTS FlexTest SE)
- Conditional control (CASCADE)
  - Rotation controlled tests

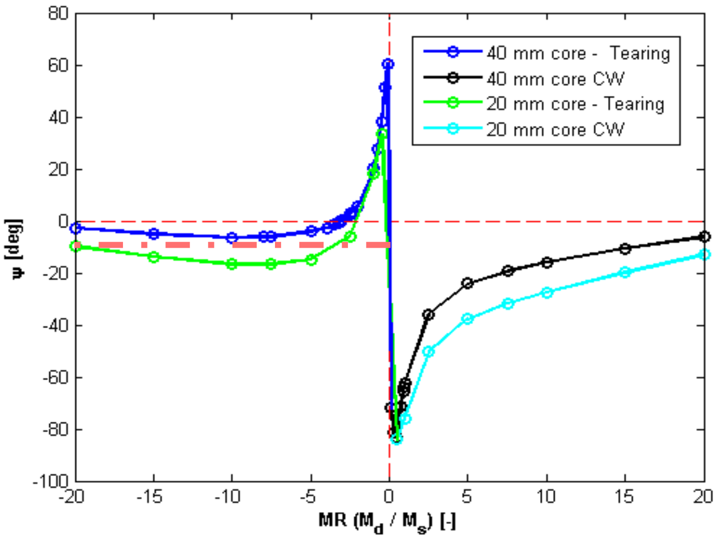


Benchmark test details (DCB-UBM)

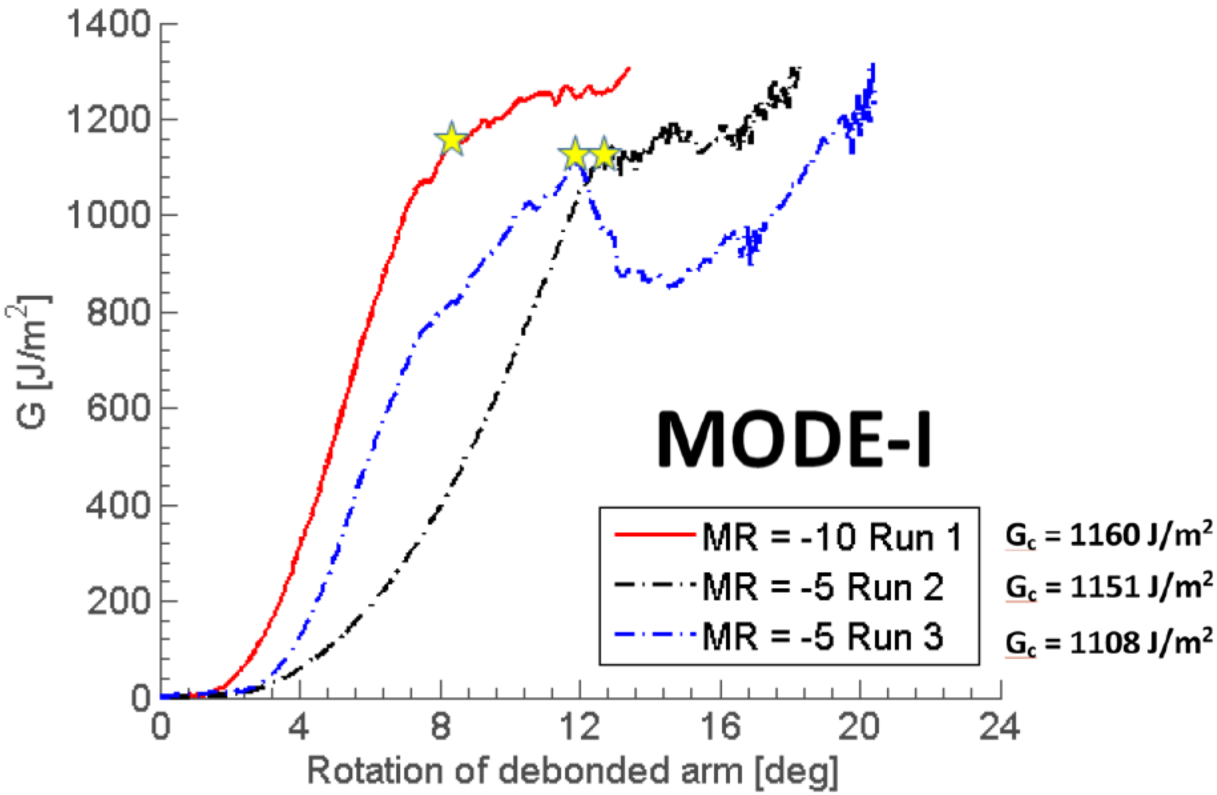
- Ratio of moments (MR = Md/Ms), determines the mode-mixity phase angle ψ
- Moment ratio held constant throughout the test
- Selection of MR from ψ vs MR map
- Round-Robin: MR = -10, -5 (predominant mode I conditions – *pending accurate material properties of the face sheets!*)

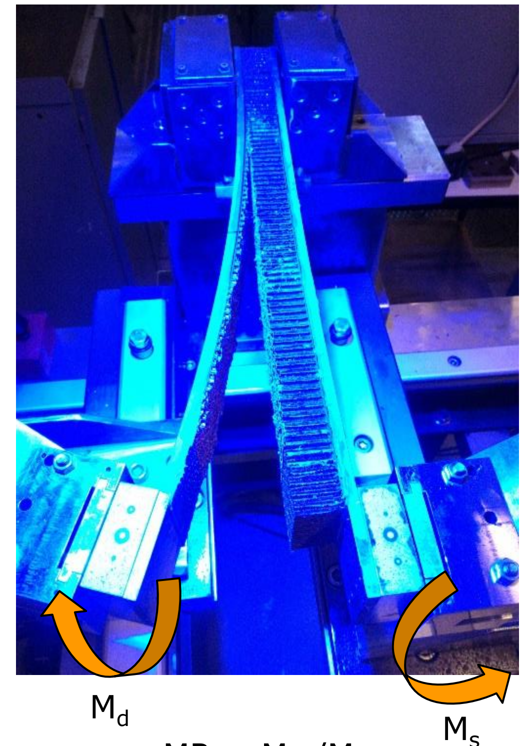






Benchmark test details (DCB-UBM)





$MR = M_d / M_s$

Interface crack

$$J = \sum_{p=1}^{10} \frac{E_p {M_b}^2}{6(A_b D_b - {B_b}^2)^2} \left[{A_b}^2 ({y_{p-1}}^3 - {y_p}^3) - 3A_b B_b ({y_{p-1}}^2 - {y_p}^2) + 3{B_b}^2 (y_{p-1} - y_p) \right]$$

[Lundsgaard et. al, 2008]

Test matrix and results (SCB + DCB-UBM)
Baseline

Lab #	Test protocol	Number of Specimens: Baseline	Number of Specimens: Additional	Additional Studies: L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

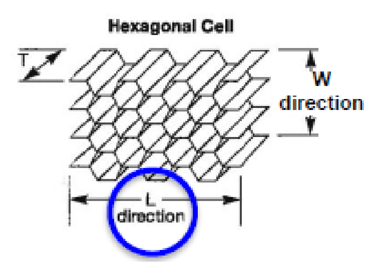
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading	5 mm/min	20,30 mm/min
unloading	30 mm/min	30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Dimensional Nomenclature

T = Thickness, or cell depth

L = Ribbon direction

W = Long direction, or direction perpendicular to the ribbon



+ 5 DCB-UBM benchmark specimens (DTU)

Test matrix and results (SCB + DCB-UBM)
Baseline

5 specimens

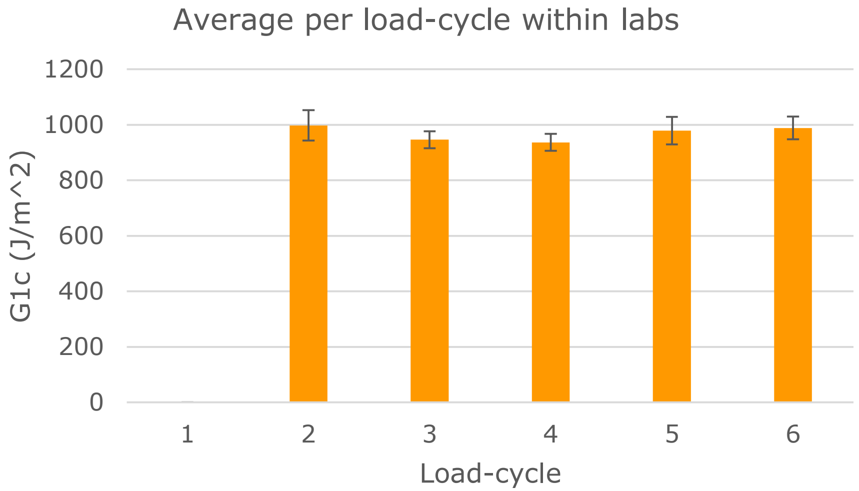
Lab	Load cycle	1	2	3	4	5	6	Average (2-6)
1	**G1c**	990,97	1012,21	983,34	965,79	930,53	964,31	**971,24**
	St.dev.	92,62	35,40	64,95	59,41	104,71	71,74	67,24
2	**G1c**	872,58	1199,99	979,76	1002,43	1109,53	1096,01	**1077,54**
	St.dev.	151,10	367,36	130,88	129,85	70,97	298,34	199,48
3	**G1c**	1182,16	829,16	832,92	833,95	839,86	868,12	**840,80**
	St.dev.	66,83	62,23	33,01	31,03	39,71	18,25	36,85
4	**G1c**	1066,33	912,34	881,87	900,78	929,25	899,91	**904,83**
	St.dev.	90,47	85,81	107,65	151,07	88,16	80,22	102,58
5	**G1c**	1004,86	1059,17	979,26	1029,31	1066,84	1067,01	**1040,32**
	St.dev.	93,39	51,88	79,42	72,09	63,35	69,35	67,22
6	**G1c**	1380,60	1025,41	951,81	909,53	890,38	957,96	**947,02**
	St.dev.	857,73	64,38	120,78	97,38	17,00	122,11	84,33
7	**G1c**	928,50	946,25	1015,69	917,69	1090,65	1069,15	**1007,89**
	St.dev.	176,63	63,10	112,15	92,79	143,36	144,87	111,25
Average		**1060,85**	**997,79**	**946,37**	**937,06**	**979,57**	**988,92**	
St. Dev.		159,45	109,55	60,27	61,74	99,46	82,875	

e.g. Lab 1 average G1c calculated from l-c 2 to 6 is …

Average G1c for load-cycle 1 is…

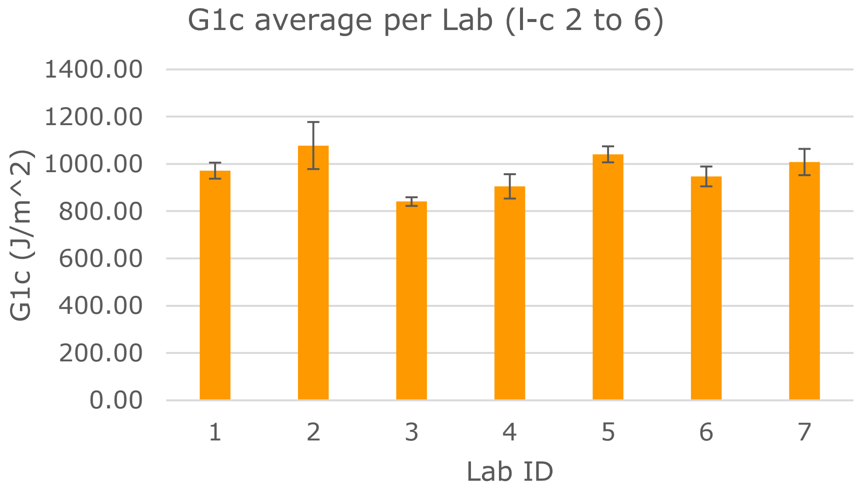
DCB-UBM	1140,00

Test matrix and results (SCB + DCB-UBM)
Baseline



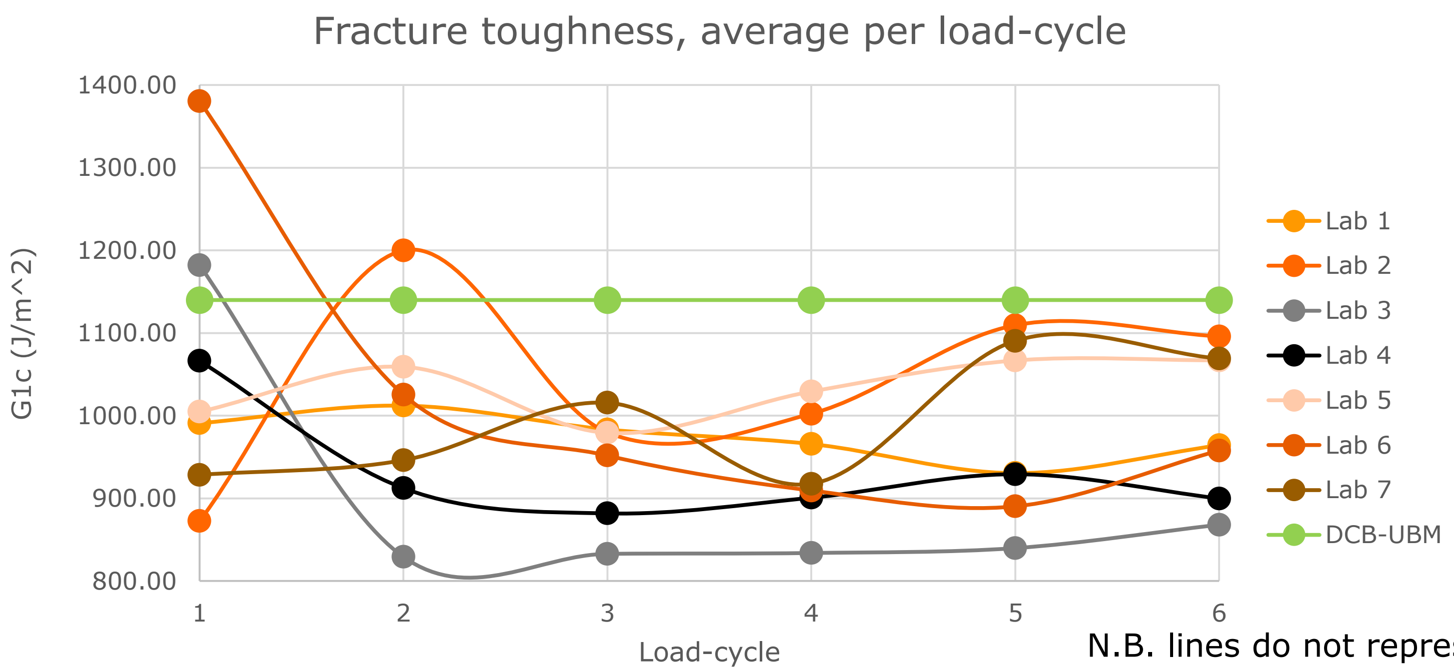
Load-cycle	*2*	*3*	*4*	*5*	*6*
G1c (J/m^2)	**997,79**	**946,38**	**937,07**	**979,58**	**988,92**

DCB-UBM	1140,00



Lab	*1*	*2*	*3*	*4*	*5*	*6*	*7*
G1c (J/m^2)	**971,24**	**1077,54**	**840,80**	**904,83**	**1040,32**	**947,02**	**1007,89**

Test matrix and results (SCB + DCB-UBM)
Baseline



N.B. lines do not represent progression between points.

- The artificial crack causes a greater results scatter
- Greater results consistency at load-cycle 3 and 4
- As the crack grows in length, the results diverge towards two different levels.

Test matrix and results (SCB)
Crack direction

Lab #	Test protocol	Number of Specimens		Additional Studies					Test Speed	
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	loading (mm/min)	unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

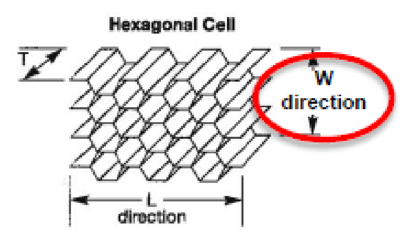
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	 5 mm/min 30 mm/min	 20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Dimensional Nomenclature

T = Thickness, or cell depth

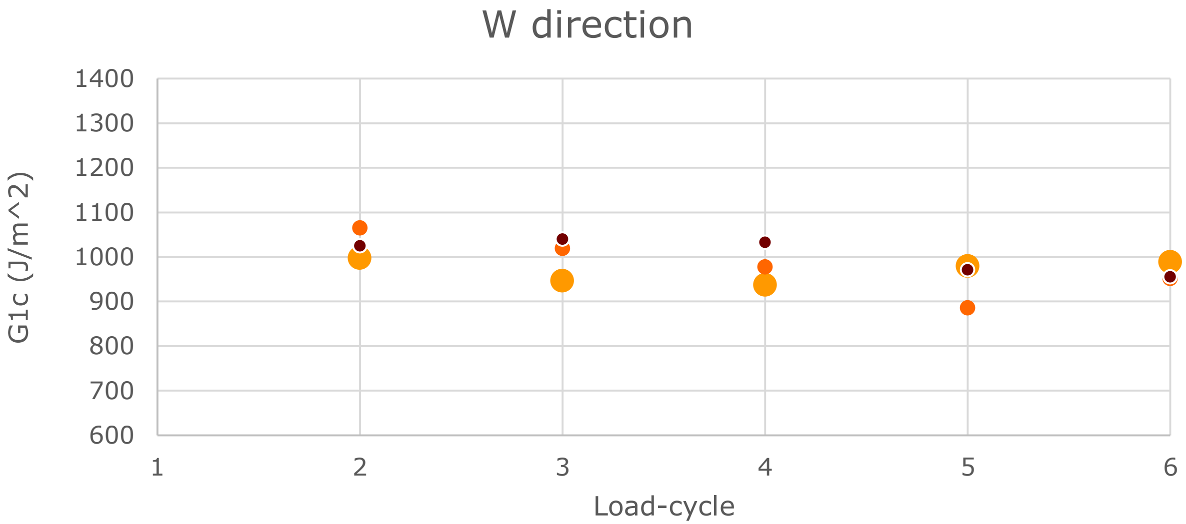
L = Ribbon direction

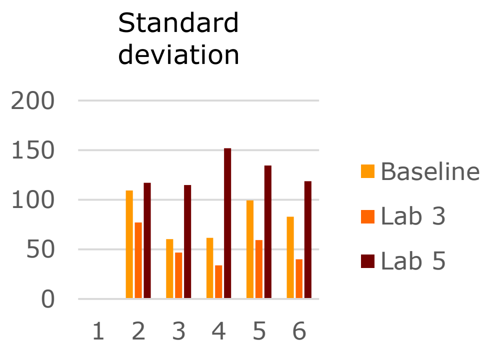
W = Long direction, or direction perpendicular to the ribbon



Test matrix and results (SCB)
Crack direction

Lab 3, Lab 5 studied the specimens in the W direction (baseline: L).



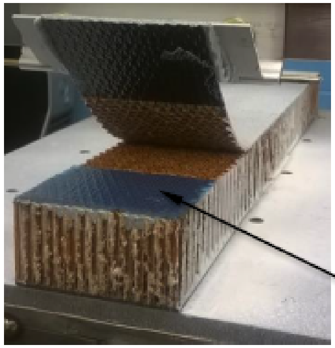


- After load-cycle 4 results are lower compared to the baseline
- N.B: Lab 3 has tested 4 specimens as data were lost in a black-out.

Test matrix and results (SCB)
Starter crack

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

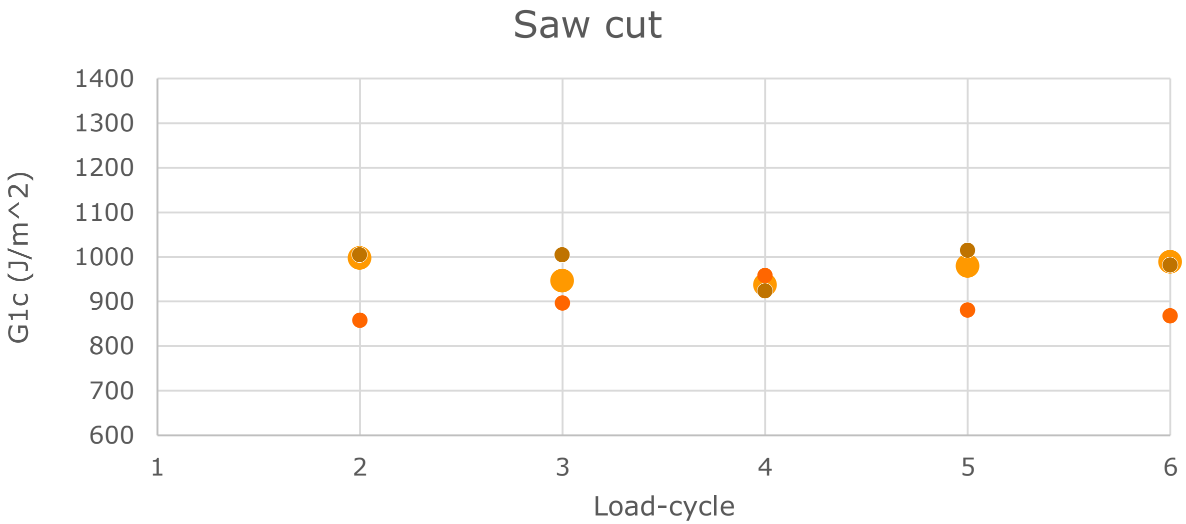


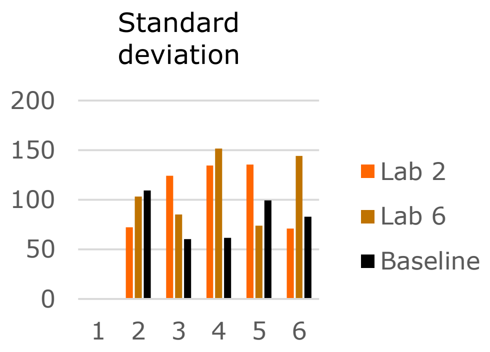
Teflon or saw cut

Test matrix and results (SCB)

Starter crack

Lab 2, Lab 6 have varied the starter crack parameter by introducing a saw-cut artificial crack (baseline: Teflon® insert).





- Load-cycle 4 is where the results match with the baseline
- It is expected that results will match the baseline after the pre-crack cycle.
- N.B: Lab 2 loading speed: 2.5mm/min, unloading speed: 5mm/min.

Test matrix and results (SCB)
Doublers

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

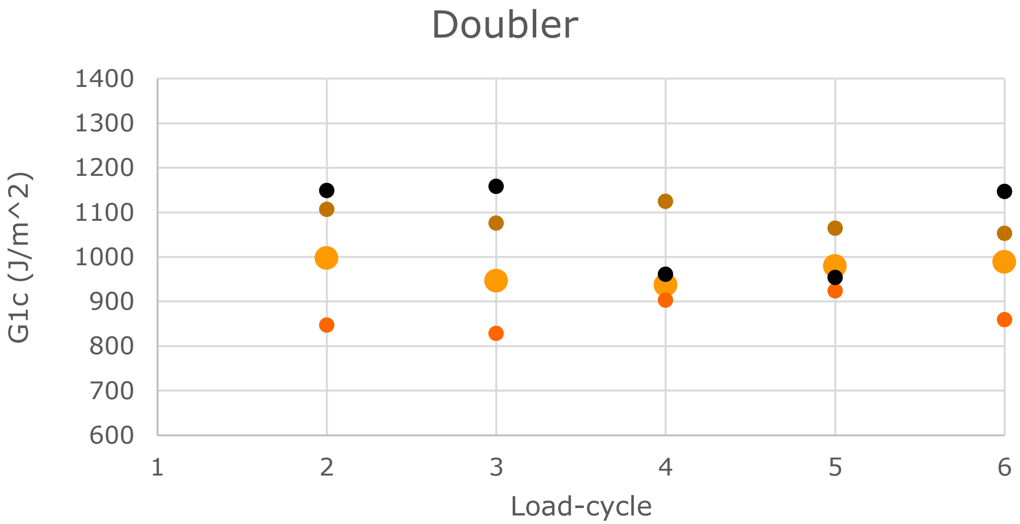
Thin face sheet tested without doubler

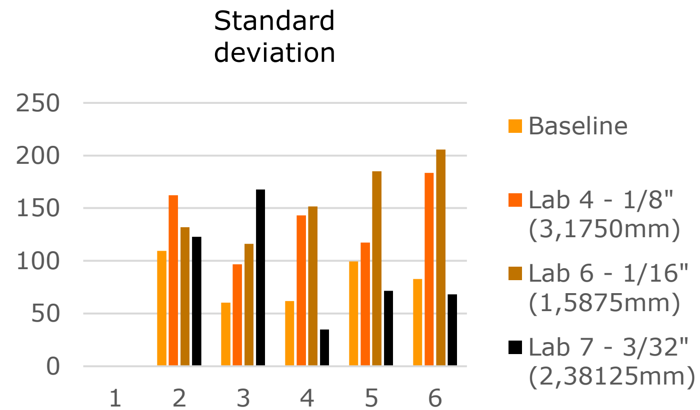
Thin face sheet tested with doubler

- **Reduces face sheet damage**
- **Creates unwanted core facture due to shear component**

Test matrix and results (SCB)
Doublers

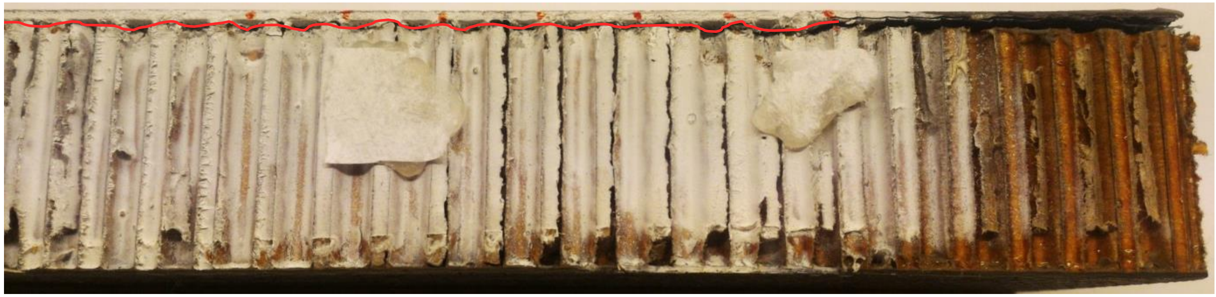
Lab 4, Lab 6, Lab 7 applied an additional GFRP layer of different thicknesses on top of the faces heet to reduce the rotation of the facesheet.

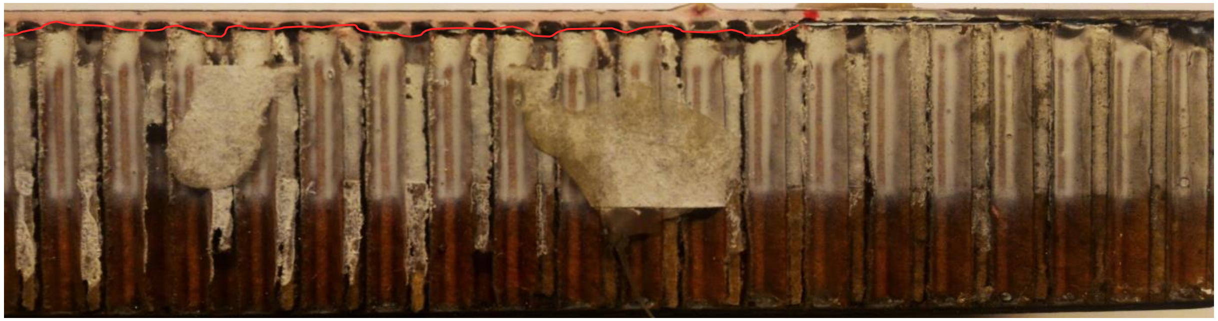


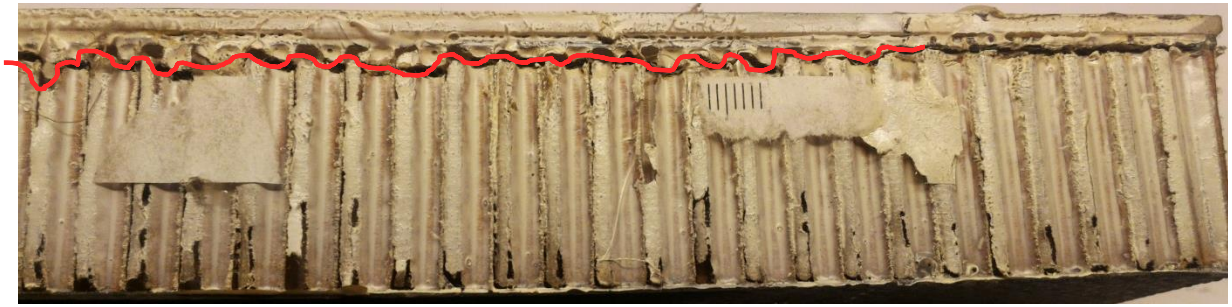


- Results with doubler layer differ greatly from the baseline
- The first two load-cycle suggest higher Gc for thickest GFRP layers
- The highest standard deviation is recorded.
- N.B: Lab 7 has discarded the results from one of the specimens tested.

Test matrix and results (SCB)
Doublers







- Baseline & slider:

the crack grows at the interface and does not show the tendency to grow towards the core.

- Doubler:

the crack propagates a bit further away from the face sheet and its path is less “smooth”

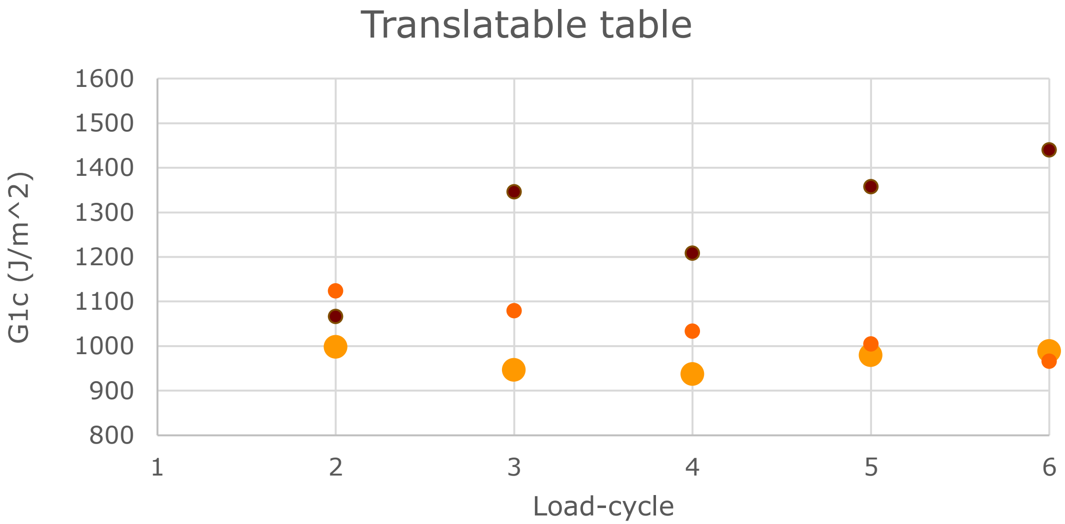
Test matrix and results (SCB)
Translatable table

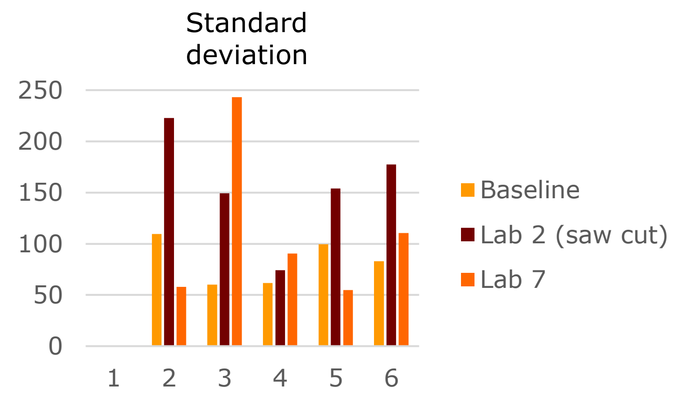
Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

Test matrix and results (SCB)
Translatable table

Lab 2, Lab 7 used a different specimen fixture which would allow the specimen to move forward as the crack grows.



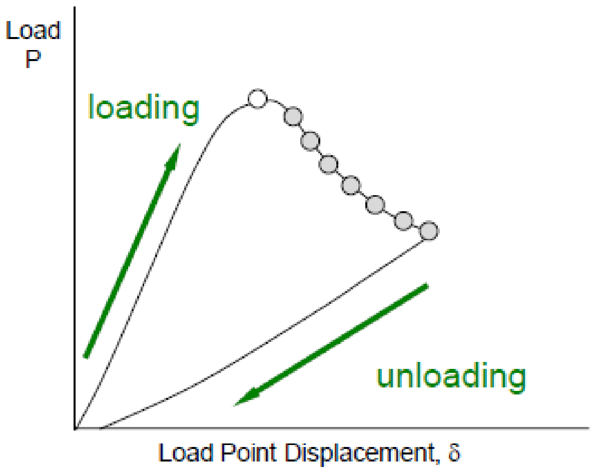


- Lab 2’s G1c’s are much higher than Lab 7’s and baseline.
- Somewhat higher GIc’s for Lab 7 compared to Baseline.
- Higher values due to friction in the bearings?

Test matrix and results (SCB)
Loading/unloading speed

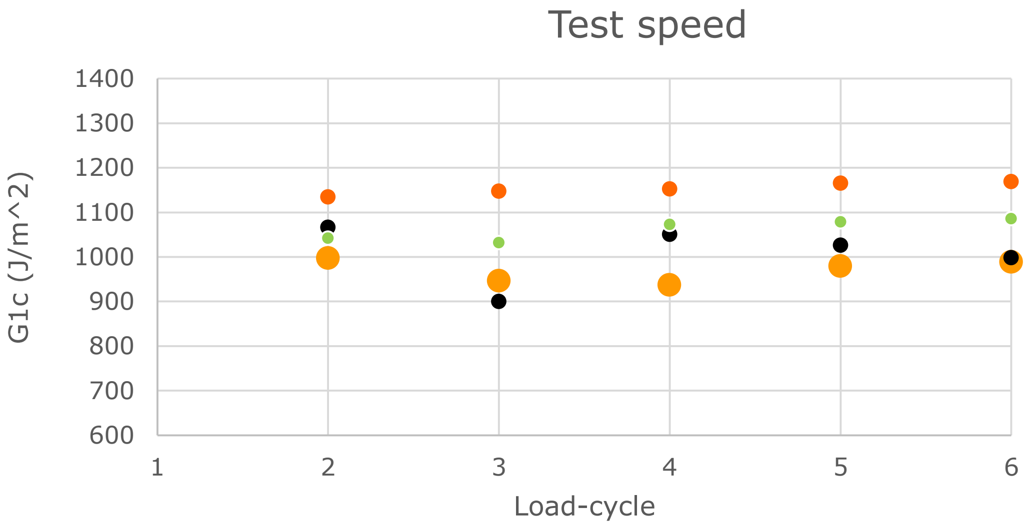
Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

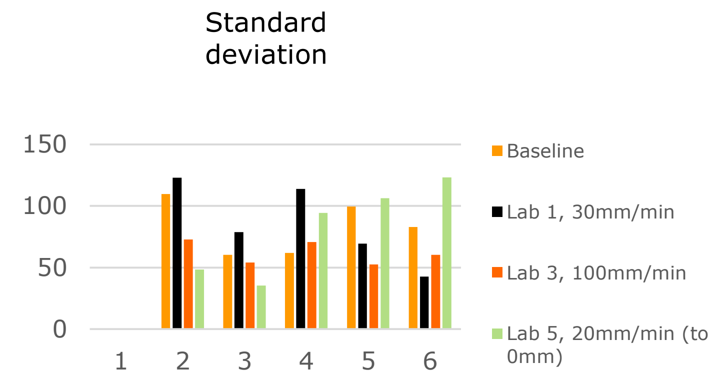
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm



Test matrix and results (SCB)
Loading/unloading speed

Lab 1, Lab 3, Lab 5 have tested specimens at an increased test speed of 30, 100 and 20mm/min (baseline: 5mm/min).





- Specimens tested at higher speed have recorded an higher fracture toughness compared to the baseline.
- N.B.: Lab 5 ends the unloading cycle at 0mm.

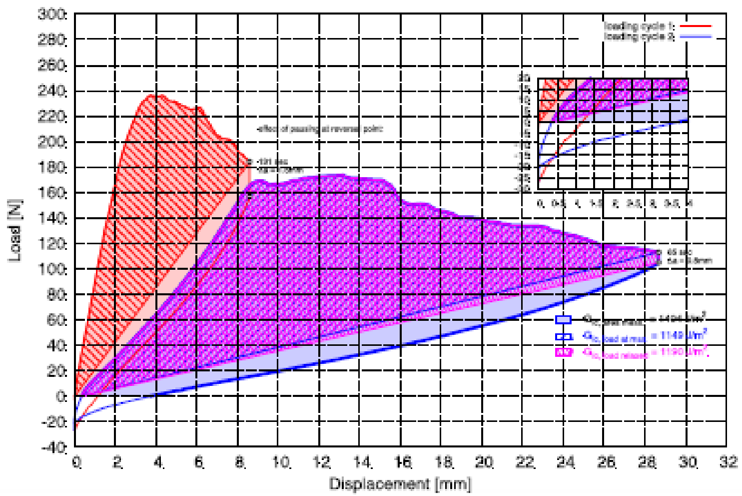
Test matrix and results (SCB)

Unloading to 0 mm

Lab #	Test protocol	Number of Specimens		Additional Studies						
		Baseline	Additional	L/W	Starter Crack	Doubler	Fixture	Unloading	Test Speed loading (mm/min)	Test Speed unloading (mm/min)
Lab 1 (Univ. Utah)		5A	10					0 mm	30	30
Lab 2 (NIAR)		5A	10		S		T			
Lab 3 (DuPont)	x	5A	10	W				0 mm	20+	30
Lab 4 (NASA)	x	5A	10			Y		0 mm	5	5
Lab 5 (Airbus)	x	5A	10	W				0 mm	20	30
Lab 6 (Fraunhofer)	x	5A	10		S	Y		0 mm		
Lab 7 (DTU)	x	5A	10			Y	T			

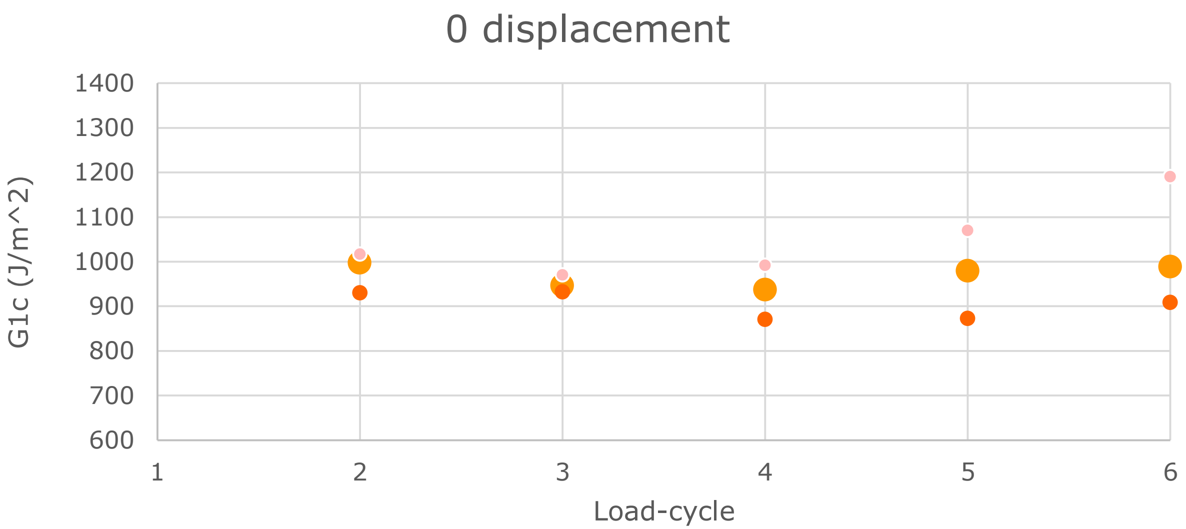
Specimen Category	Baseline	Additional
Dimensions	2 x 12-inch	
Crack Direction	L	W
Starter Crack	Teflon (T)	Saw Cut (S)
Insert Length	1.5-inch	
Doublers	No (N)	Yes (Y)
Fixture	Fixed (F)	Translate (T)
Test Speed loading unloading	5 mm/min 30 mm/min	20,30 mm/min 30, 5 mm/min
Δa for loop	10 mm (>3 cells)	
# of loops/cycles	>5	
Unloading	0 N	0 mm

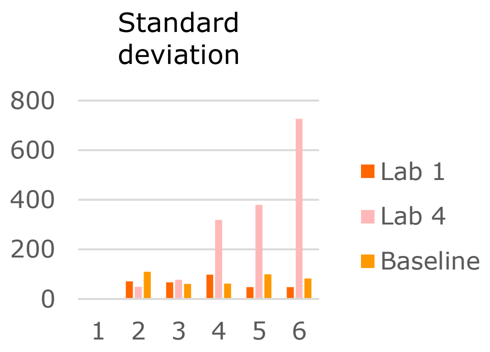
Will unloading to 0 mm create damage?



Test matrix and results (SCB)
Unloading to 0 mm

Lab 1, Lab 4 studied the case where the unloading phase ends at 0mm (baseline: 0N).





- G1cs diverge slightly at the second load-cycle
- Load-cycle 3 is where results converge with baseline
- From load-cycle 4 results increasingly diverge.
- N.B: Lab 4 has unloaded at 5mm/min.

Conclusions

- Baseline results are overall consistent between different laboratories and a fair agreement with the benchmark DCB-UBM results

- Not all parameters have the same impact on the fracture toughness measurements
    - Increased test speeds and the use of doubler layers lead to a greater divergence from the baseline results
    - Tests to 0mm, with W direction and saw cut are comparable to baseline results indicating neglectable influence.

- Some parametric studies seem to cause greater results scatter (resulting in higher st. dev.) than others, e.g. the use of doubler layer.

- Additional conclusions and discussions of the results during the group meeting tomorrow!

Thank you for your attention!