Future Variable Mixed Mode Sandwich Debond Characterisation Methods for Standards Implementation

CMH-17 European Bonded Structure Meeting
EASA, Cologne, June 13-14th 2013

Christian Berggreen
Head of Group Lightweight Structures
Associate Professor, PhD

DTU Mechanical Engineering
Department of Mechanical Engineering

Contributors

Technical University of Denmark, Department of Mechanical Engineering:
- Christian Berggreen, Associate Professor, PhD

Florida Atlantic University, Dept. of Ocean and Mechanical Engineering:
- Leif A. Carlsson, Professor, PhD

Georgia Institute of Technology, School of Aerospace Engineering:
- George A. Kardomateas, Professor, PhD

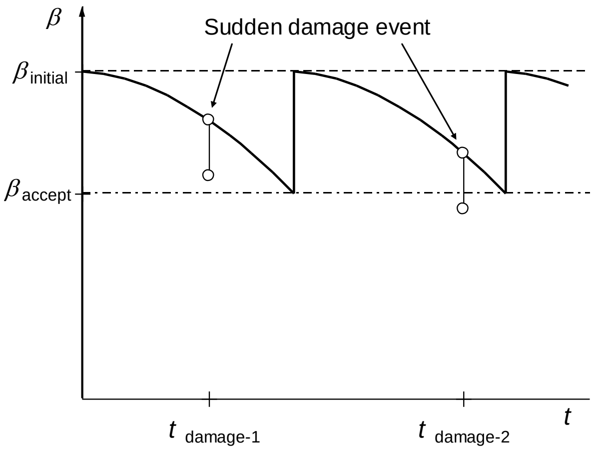
Contents

- Background and motivation
- Modified TSD specimen
- Sandwich MMB specimen
  - Basic principles
  - Static and fatigue testing
  - G-control
- Sandwich DCB-UBM specimen
  - The existing DCB-UBM rig
  - New closed form expressions for the DCB-UBM specimen with asymmetric face sheets
  - New rig (work in progress!!)
- Concluding recommendations
- <u>If time</u>: Structural applications of mixed mode fracture data

Background and motivation

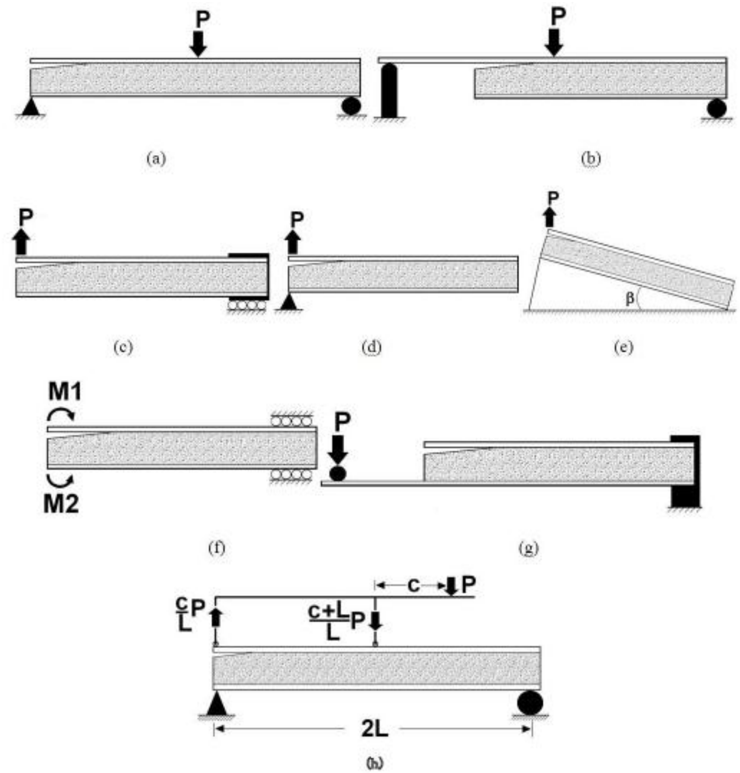
Background and motivation

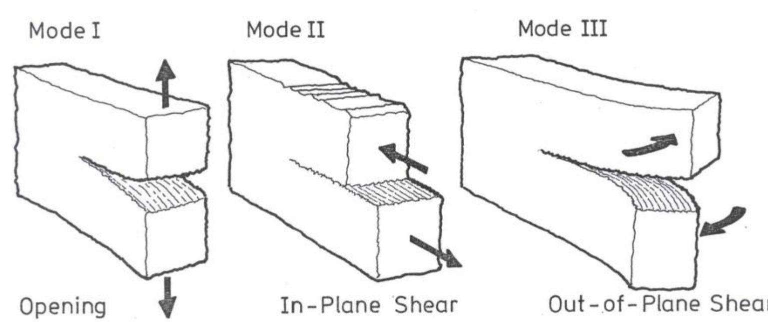
- Today structures are increasingly optimized to give minimum weight
- Pushes the utilizations of construction materials closer to their performance limits
- Built-in reserve margins may be significantly reduced
- Reduced allowance to continue performing adequately in the presence of *degradation* and *damage*
- Struc. reliability index vs. life time →
- Emphasizes the need for adequate *fracture mechanical tools* for damage assessment
- Key issue: Measurements of **fracture properties** are therefore an increasingly important task
  - Fracture toughness
  - da/dN diagrams



Background and motivation

- Large number of sandwich fracture specimens available in literature
- Most aim at measuring the fracture toughness for either *global* mode I or II
- For modeling of structural crack propagation, *mixed mode fracture* input is <u>generally</u> needed (static/fatigue)
- Only few monolithic/sandwich specimens have the possibility for <u>varying</u> the mode-mixity directly:
  - MMB (only negative mode-mixities) [Reeder and Crews (1990)]
  - DCB-UBM (very tall test frame) [Sørensen et al. (2006)]
  - TSD (limited mode-mixity var.) [Li and Carlsson (1999)]
- *<u>Simple</u> test methods are needed for standard implementation for mixed mode fracture characterization!*

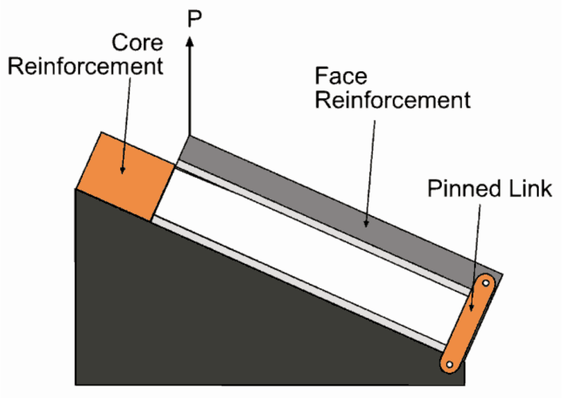




Background and motivaton
New sandwich mixed mode specimens (DTU)

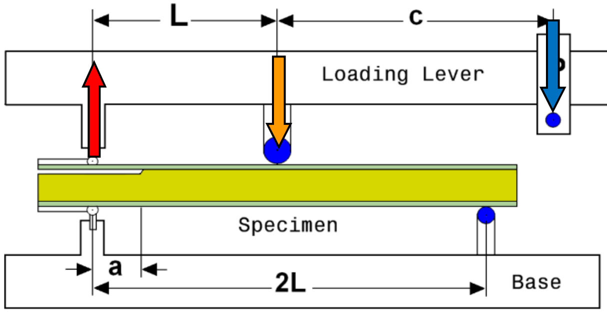
Modified TSD specimen

1. Berggreen, C. and Carlsson, L. A., "A Modified TSD Specimen for Fracture Toughness Characterization – Fracture Mechanics Analysis and Design", *Journal of Composite Materials*, 44(15):1893-1912, 2010.
2. Berggreen, C., Quispitupa, A., Costache, A. and Carlsson, L.A., "Face/core Mixed Mode Debond Fracture Toughness Characterization Using the Modified TSD Test Method", *Journal of Composite Materials*, in press, 2013.



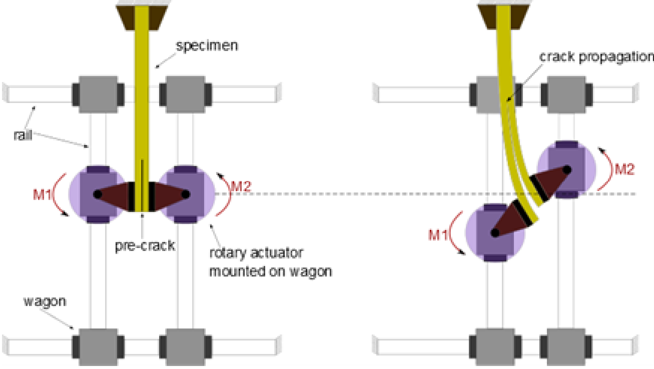
Sandwich MMB specimen

1. Quispitupa, A., Berggreen, C. and Carlsson, L. A., "On the Analysis of a Mixed Mode Bending Sandwich Specimen for Debond Fracture Characterization", *Engineering Fracture Mechanics*, 76(4):594–613, 2009.
2. Quispitupa, A., Berggreen, C. and Carlsson, L. A., "Design Analysis of the Mixed Mode Bending Sandwich Specimen", *Journal of Sandwich Structures and Materials*, 12(2):253-272, 2010.
3. Quispitupa, A., Berggreen, C. and Carlsson, L. A., "Face/Core Interface Fracture Characterization of Mixed Mode Bending Sandwich Specimens", *Fatigue & Fracture of Engineering Materials and Structures*, 34(11):839-853, 2011.
4. Manca, M., Quispitupa, A., Berggreen, C. and Carlsson, L.A., "Face/core Debond Fatigue Crack Growth Characterization Using the Sandwich Mixed Mode Bending Specimen", *Composites Part A*, 43:2120–2127, 2012.



Sandwich DCB-UBM

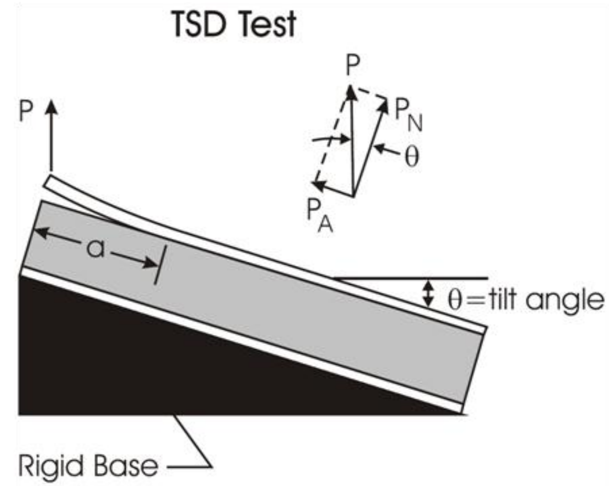
1. Lundsgaard-Larsen, C., Sørensen, B. F., Berggreen, C. and Østergaard, R. C., "A modified DCB sandwich specimen for measuring mixed mode cohesive laws", *Engineering Fracture Mechanics*, 75(8):2514-2530, 2008.
2. Kardomateas, G.A., Berggreen, C. and Carlsson, L.A., "Energy Release Rate and Mode Mixity of a Face/Core Debond in a Sandwich Beam", *AIAA Journal*, 51(4):885-892, 2013.

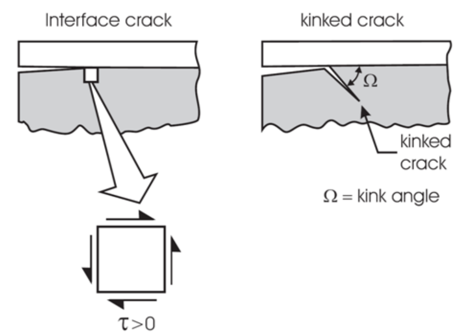


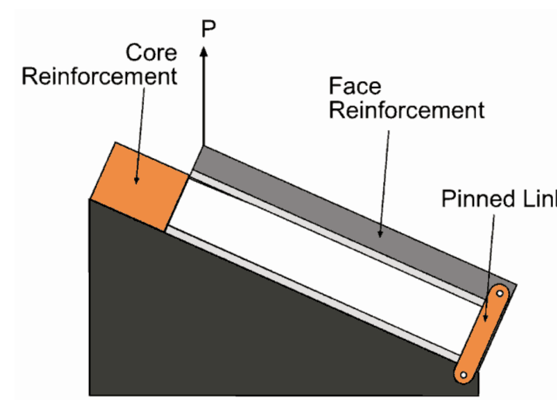
Modified TSD specimen

Modified TSD specimen

- First presented by Li and Carlsson (1999) for debond testing (SCB is a special case at zero tilt!)
- The tilt angle results in:
  - Both normal and axial forces exist
  - Mitigate positive shear at crack tip due to interface to promote interface prop.
  - Counter tendency for kinking
- However, FE analyses have shown that the mode-mixity variation is very limited for practical face thicknesses and tilt angles
- Limited face stiffness → limited shear deformation is transferred to crack tip
- **<u>Solution:</u>** From parametric analysis → stiffening of the face sheet → increasing the mode-mixity variability!!
- **<u>Proof of concept:</u>** *Application of the modified TSD-specimen for characterization of two sandwich interface types.*







Modified TSD specimen

Driving mechanisms:

- For *shorter* crack lengths or *stiff* crack flanks, transverse shear loading at the crack tip <u>cannot</u> be neglected!

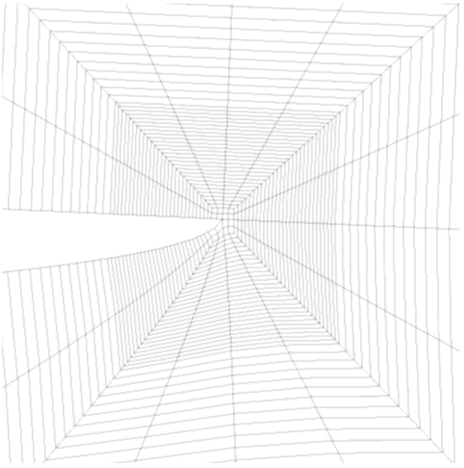
- Analyzed for a general case by Ferrie et al. (1999) and Li et al. (2004)

- Transverse shear loading will
  - Introduce crack root rotations
  - Consequently alter mode-mixity
  - Add to the energy release rate

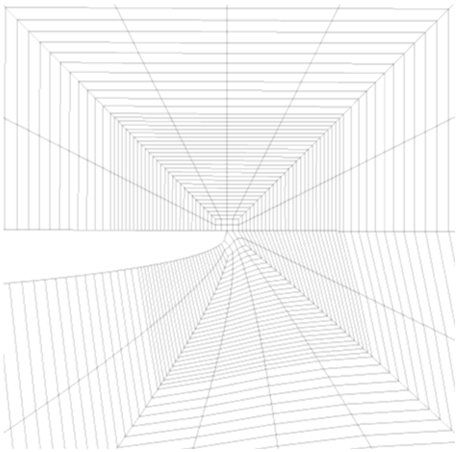
➢ Thus, by *stiffening* the face sheet the transv. shear deformation can be increased/varied

➢ More/less transverse shear (tilt) will be able to alter the mode-mixity

➢ Sensitivity wrt. practical tilt angle has been investigated →



Low transverse/in-plane shear

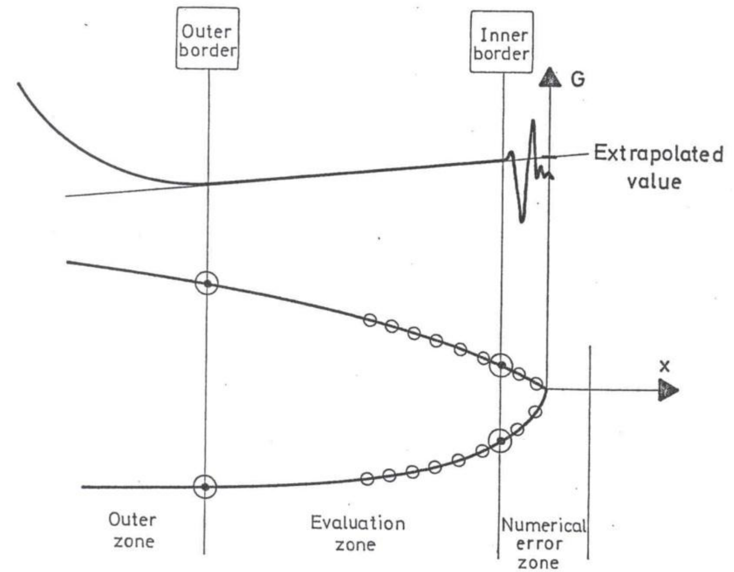


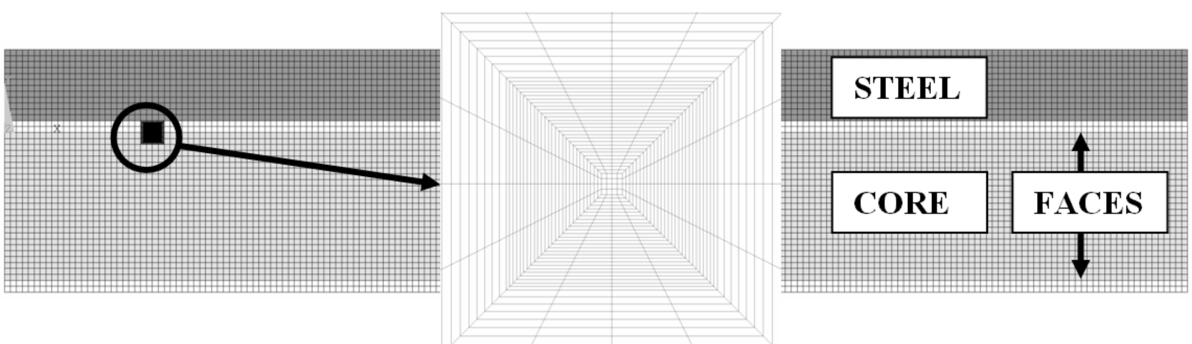
High transverse/in-plane shear

Modified TSD specimen

FE based fracture mechanics analysis

- ANSYS + additional fracture routines
- Linear (4 noded) and parabolic (8 noded) isoparametric plane elements are applied
- Highly densified mesh near crack tip
- Geometrically linear analyses are performed
- Linear Elastic Fracture Mechanics is assumed valid
- The Crack Surface Displacement Extrapolation (CSDE) method is used to determine energy release rate and mode-mixity
  - ERR: J-integral calculation
  - Mode-mixity: Extrapolation of relative crack flank displacements

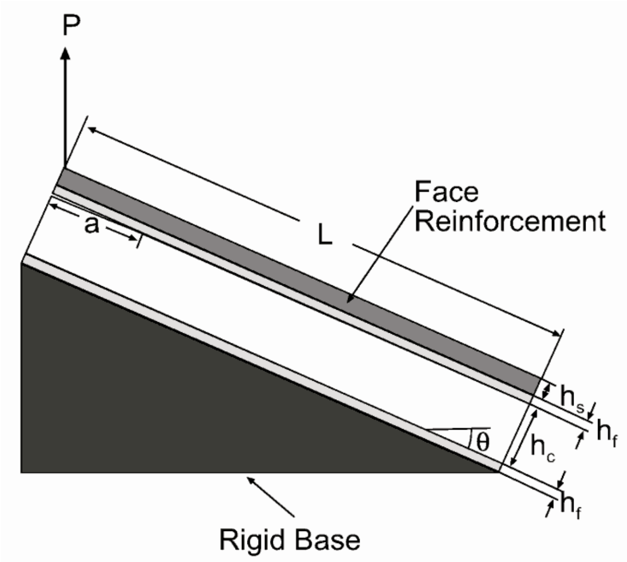


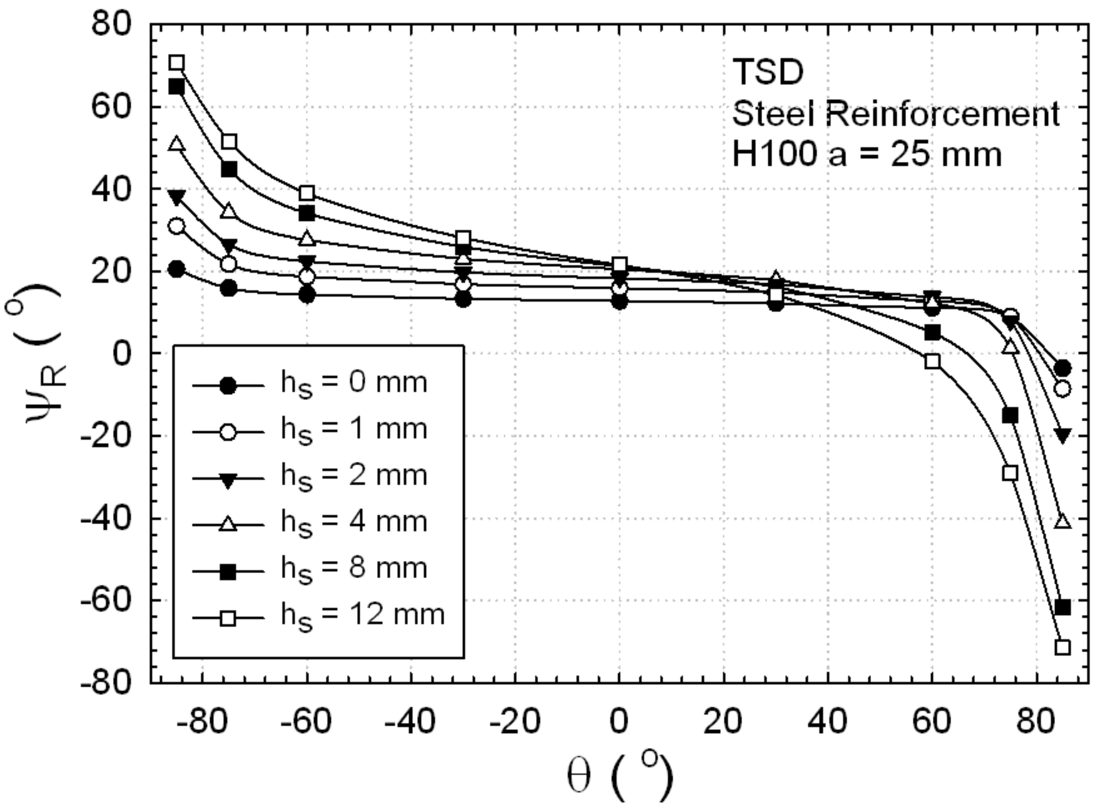


Modified TSD specimen

Performance overview

- Variation of phase angle for increasing steel reinforcement thickness





Modified TSD specimen
Test setup

- H45/H100 core, E-glass/polyester face sheets [0/45/90/-45]
- Initial pre-crack was sharpened prior to testing by cyclic pre-cracking

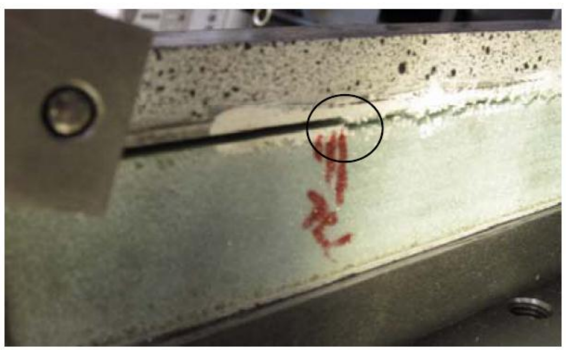
- Adjustable TSD-rig inserted in a 20 kN servo-hydraulic Instron 8511 testing machine
- Quasi-static loading of 2 mm/min were applied (displ. control)

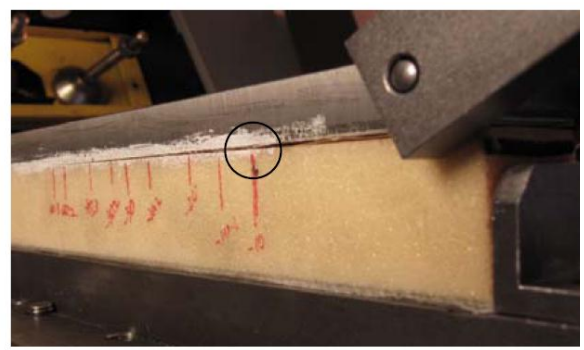
Modified TSD specimen
Pre-cracking

- Performed at 0º of tilt angle (as a SCB-specimen)
- Sinusoidal loading (5 Hz frequency)
- Load ratio: R= 0.1
- P_{max} vary from 10%-50% from the estimated propagation load
- Use of white liquid and magnifying glasses (10xx) to facilitate crack tip localization

H45

Pre-crack in the core





H100

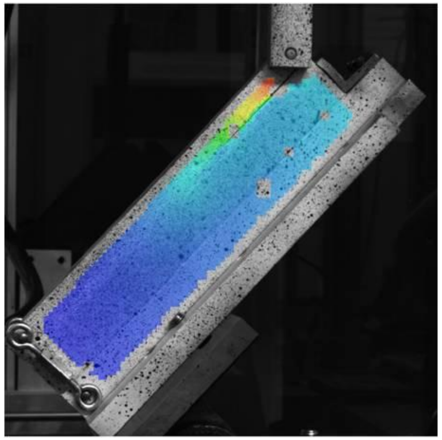
Pre-crack in the interface

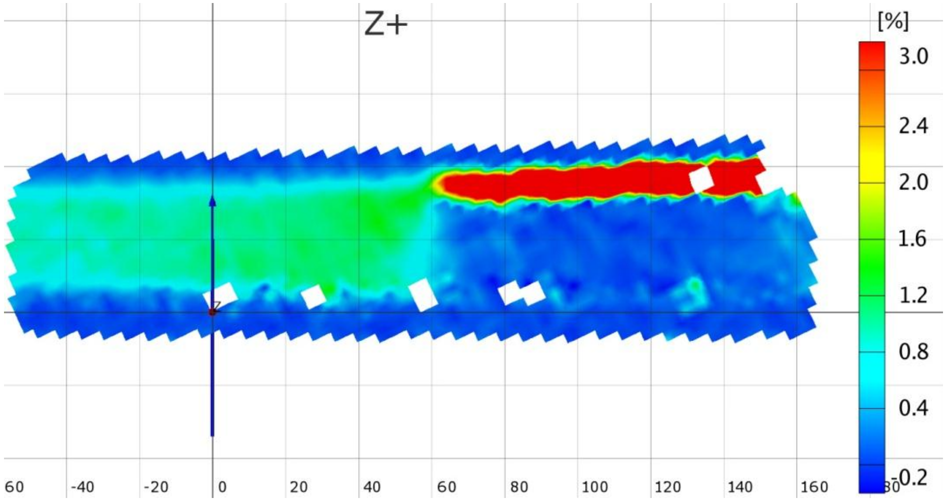
Carried out consistently for ALL specimens!!

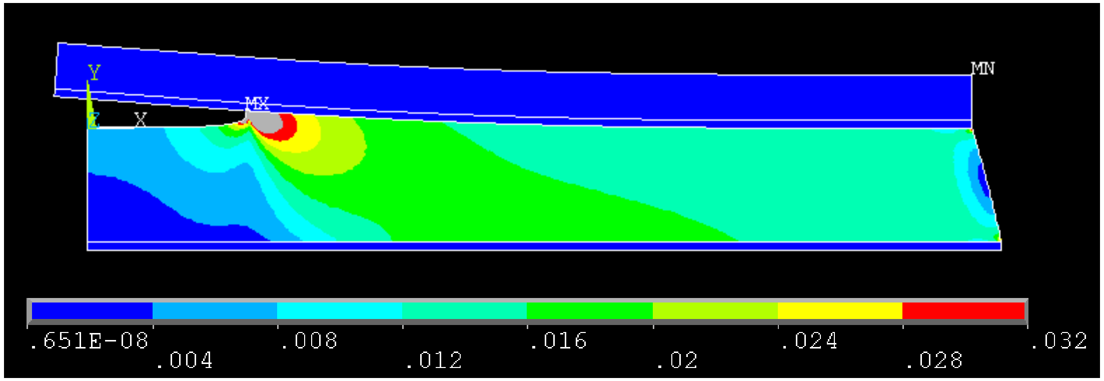
Modified TSD specimen

DIC measurements and FEA comparison

- Major strain in a H45 specimen with a tilt angle of 65º
- Fair agreement!

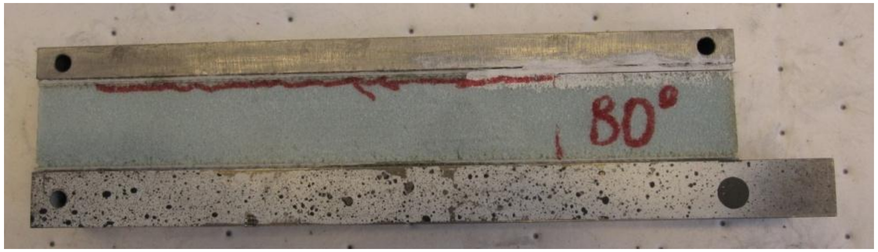


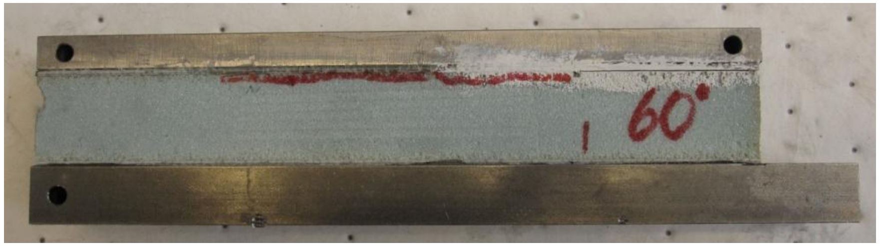


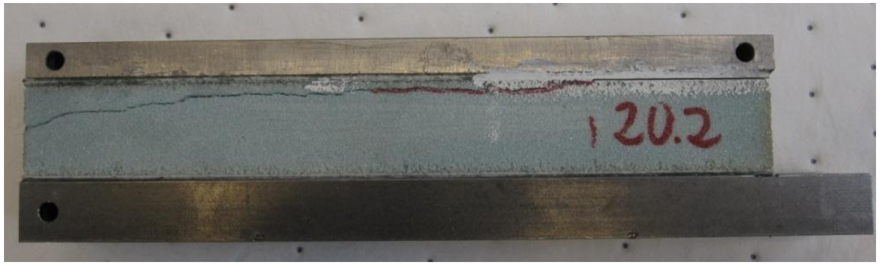


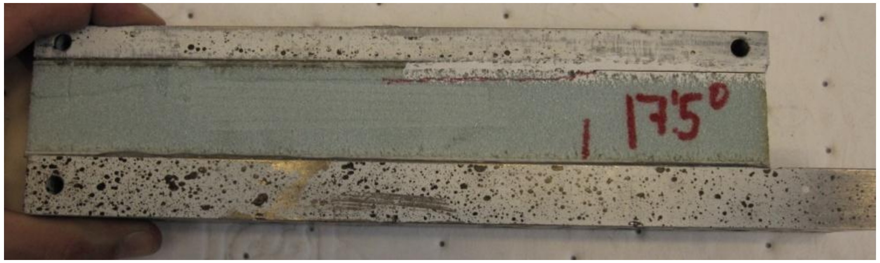
Modified TSD specimen
Fracture paths (I)

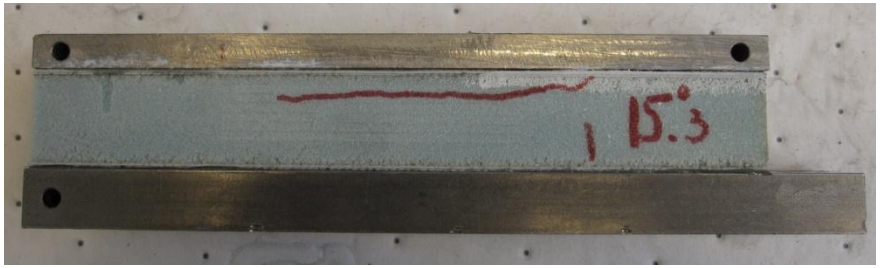
- H45

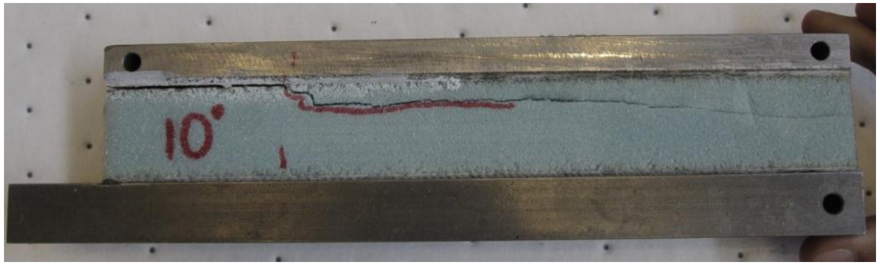






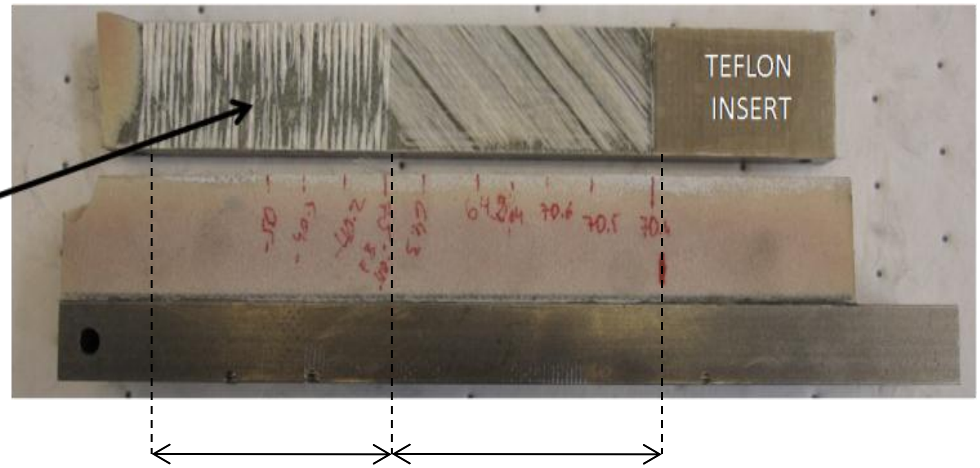




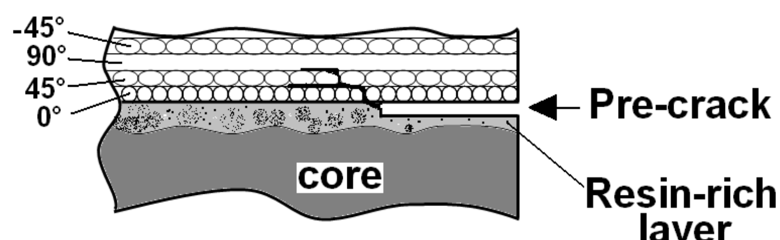


Modified TSD specimen
Fracture paths (II)

- Typical H100 specimen tested at varying tilt angles
- Progressive kinking into face sheet



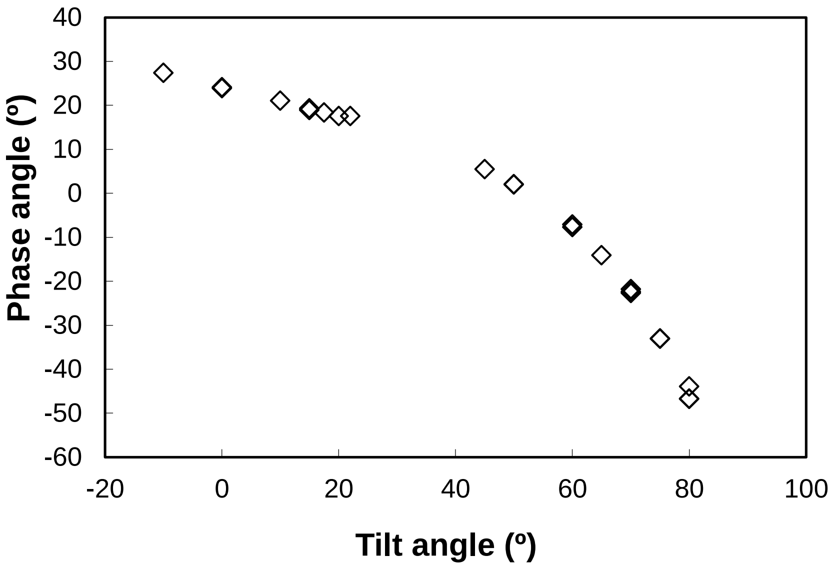
-60º < θ < -40º   -70º < θ < -64º

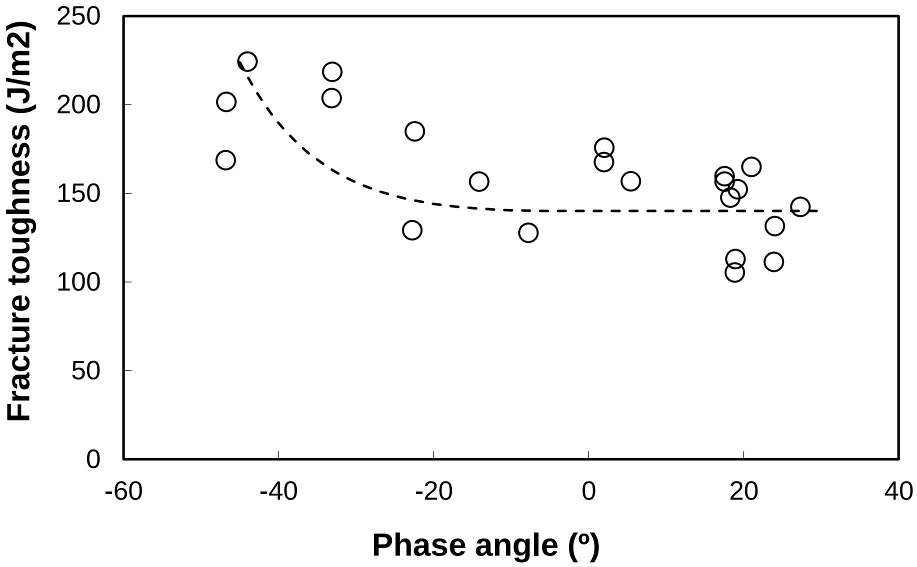


Modified TSD specimen
Fracture toughness measurements

H45 (reduced formulation):

- Phase angles achieved between approx. -50° to 30°
- Measured at different crack lengths
- Increasing tendency for mode II domination

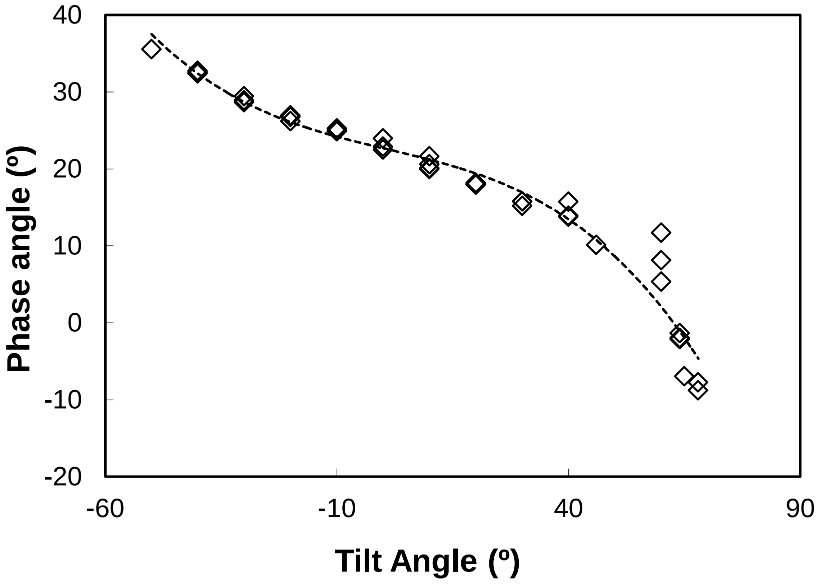


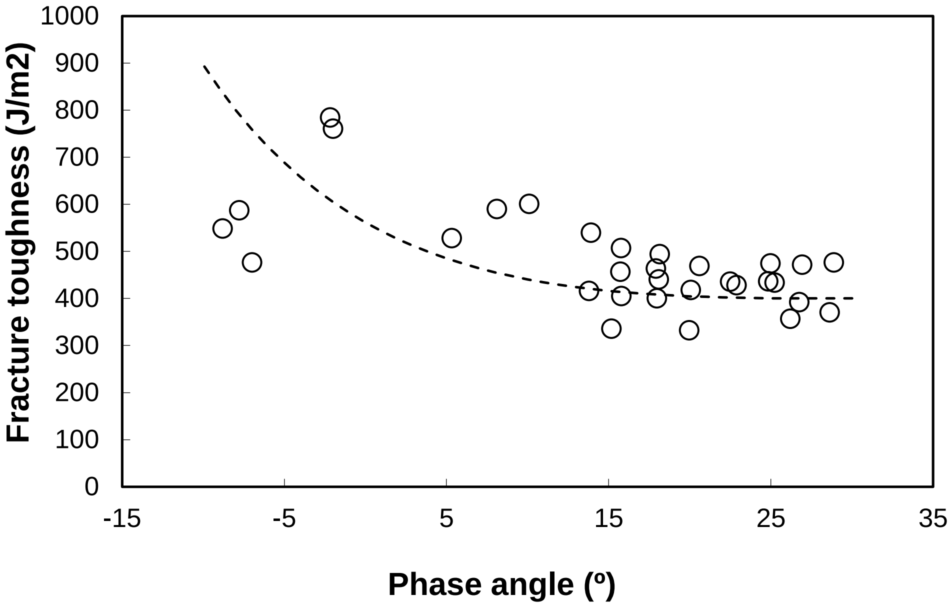


Modified TSD specimen

Fracture toughness measurements (II)

- H100 (reduced formulation)
- Phase angles achieved between approx. -10° to 35°
- Again measured at different crack lengths
- Scattered fibre bridging present in all measurements – toughness values should be taken with reservation (LEFM validity compromised)
- However, still increasing tendency for mode II dominance





Modified TSD specimen
Conclusions

- The performance of the modified TSD specimen was presented

- Two interface types were investigated experimentally
- Specimen fracture paths:
  - H45: Located just below the resin rich layer
  - H100: In the interface or face sheet with scattered fibre bridging
- Toughness values for H45 and H100 specimens were achieved over a wide range of mode-mixities
- Increasing tendency for mode-II dominance

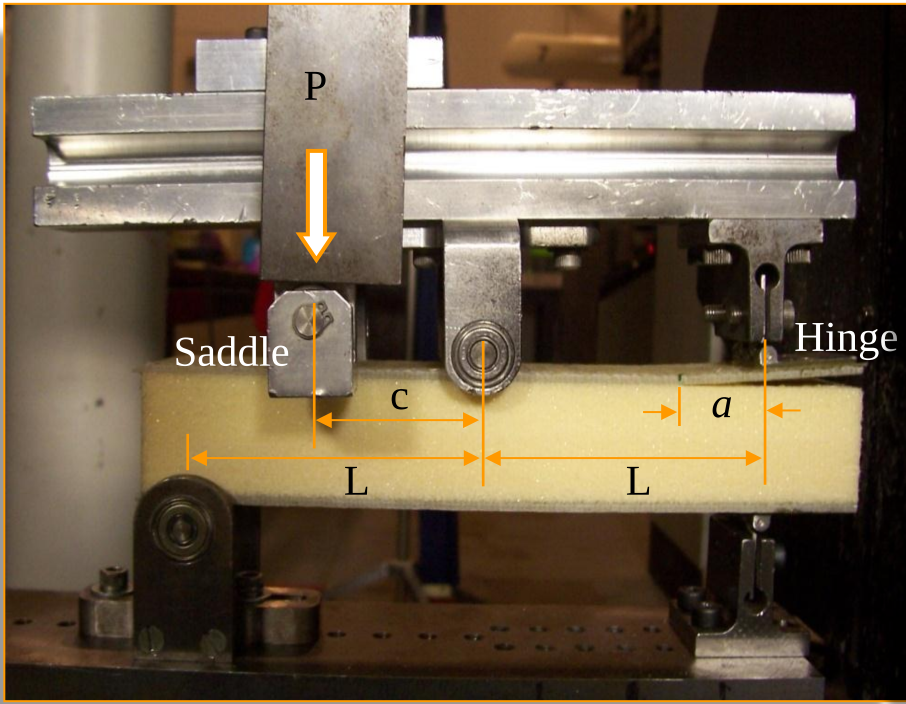
- **The modified TSD specimen and test was identified as a *simple, viable* and *promising* method to achieve mixed mode fracture toughness measurements**

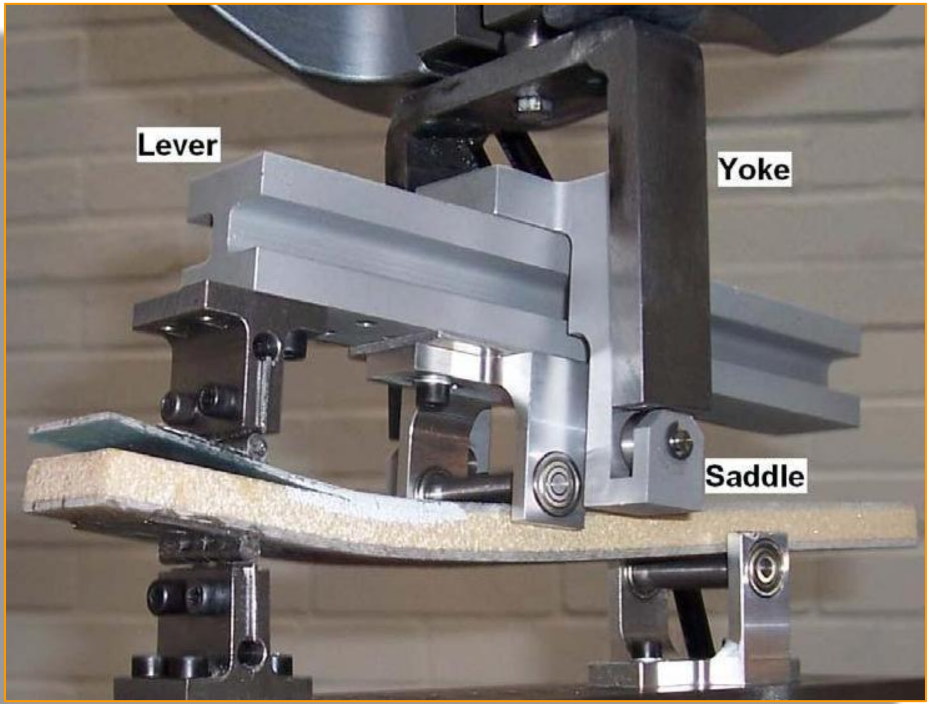
Modified TSD specimen
Future work

- Testing of other sandwich material configurations, eg. Honeycomb cores!
- Experimental benchmarking against fixed or variable mode-mixity specimens (DCB, CSB, MMB etc.)
- **Development of an analytical kinematic model for the TSD specimen (influence of transverse shear!!)**
- **Derive closed-form solutions for determination of ERR and mode-mixity**
  - An absolute necessity for standard implementation!!
  - Funding needed for such a project!
- Development of a *G-controlled fatigue testing methodology*, based on either an analytical or empirical model

Sandwich MMB specimen

Sandwich MMB specimen

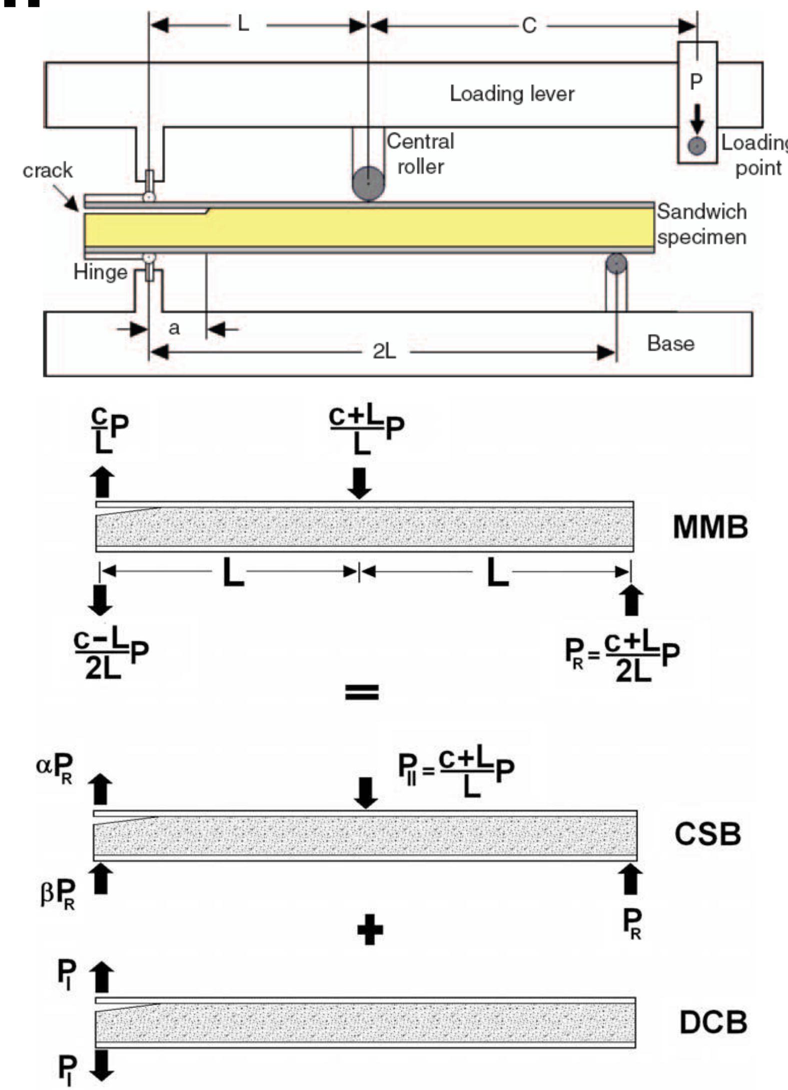




The mixed mode ratio at the crack tip is controlled by the lever arm distance and it’s **constant** during the test

Sandwich MMB specimen

- The MMB rig is relatively simple and has proven successful for delamination crack growth.
- Already an ASTM-standard for mixed mode delamination characterization of laminates.
- Superposition of a CSB and DCB specimens.
- Promotes constant mode-mixity at the crack tip for a growing crack. Good for fatigue testing!
- Various combinations of mode-mixity (mode II/mode I) can be achieved by changing the loading application point, ***c***.



MMB = CSB + DCB

Sandwich MMB specimen
Kinematics and ERR

- Kinematics of the MMB sandwich specimens

$$\delta_{MMB} = \frac{c}{L}\delta_{DCB\_upper} + \frac{c-L}{2L}\delta_{DCB\_lower} + \left(\frac{c+L}{L}\right)\delta_{CSB}$$

- Compliance

$$C_{MMB} = \left[\frac{c}{L}C_{DCB\_upper} + \frac{c-L}{2L}C_{DCB\_lower}\right]\left(\frac{c}{L} - \alpha\frac{c+L}{2L}\right) + \left(\frac{c+L}{L}\right)^2 C_{CSB}$$

- Energy release rate

$$G_{MMB} = \frac{P^2}{2b}\frac{d}{da}\left(\left[\frac{c}{L}C_{DCB\_upper} + \frac{c-L}{2L}C_{DCB\_lower}\right]\left(\frac{c}{L} - \alpha\frac{c+L}{2L}\right) + \left(\frac{c+L}{L}\right)^2 C_{CSB}\right)$$

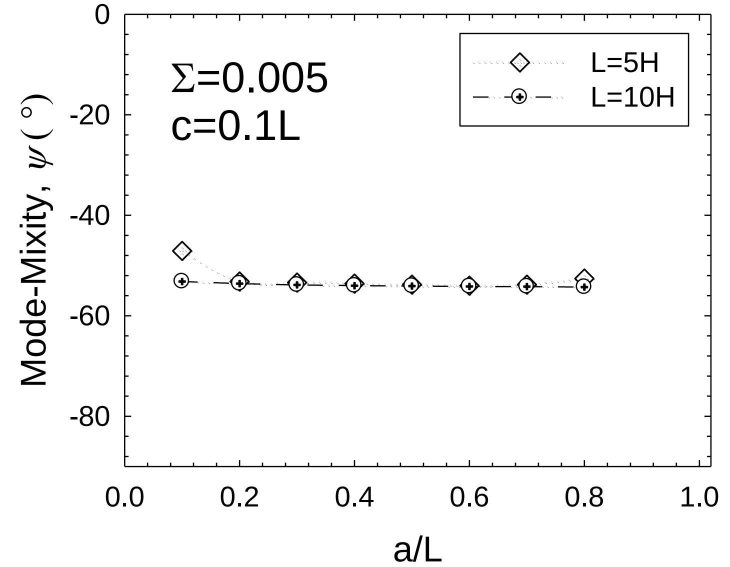
Equations were derived from a superposition analysis using beam theory including core shear deformation and elastic foundation analysis.

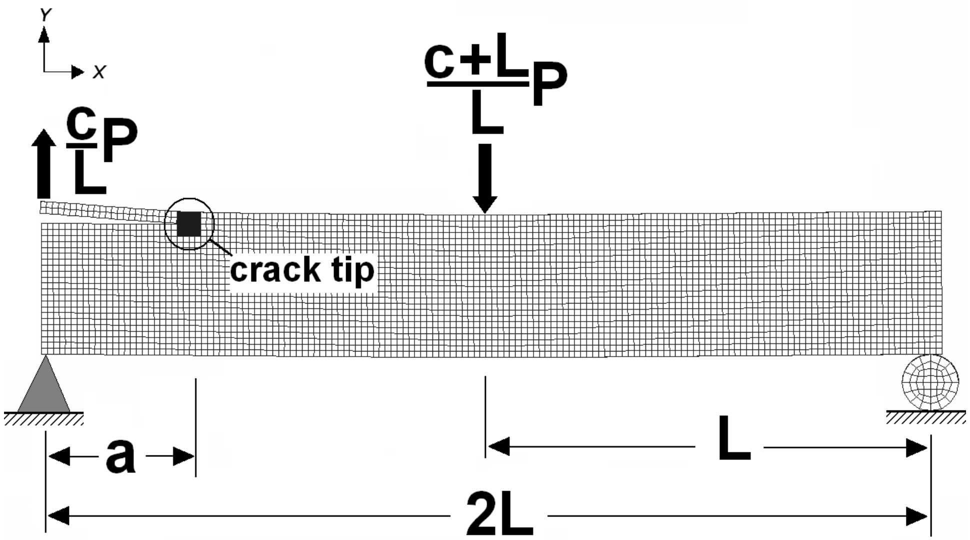
Sandwich MMB specimen
Mode-mixity

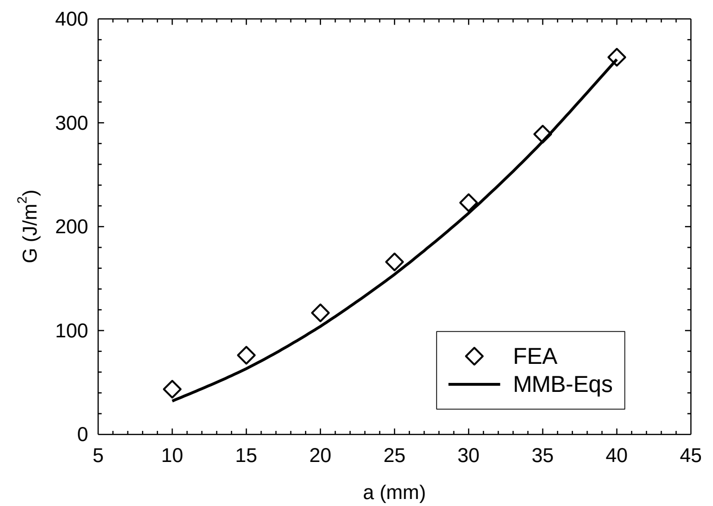
- Determined by FEA $$\psi = \tan^{-1}\left(\frac{\delta_x}{\delta_y}\right) - \varepsilon \ln\left(\frac{x}{h}\right) + \tan^{-1}(2\varepsilon)$$

- The CSDE-method is applied to calculate the mode-mixity phase angle (ψ) (and ERR (G)).

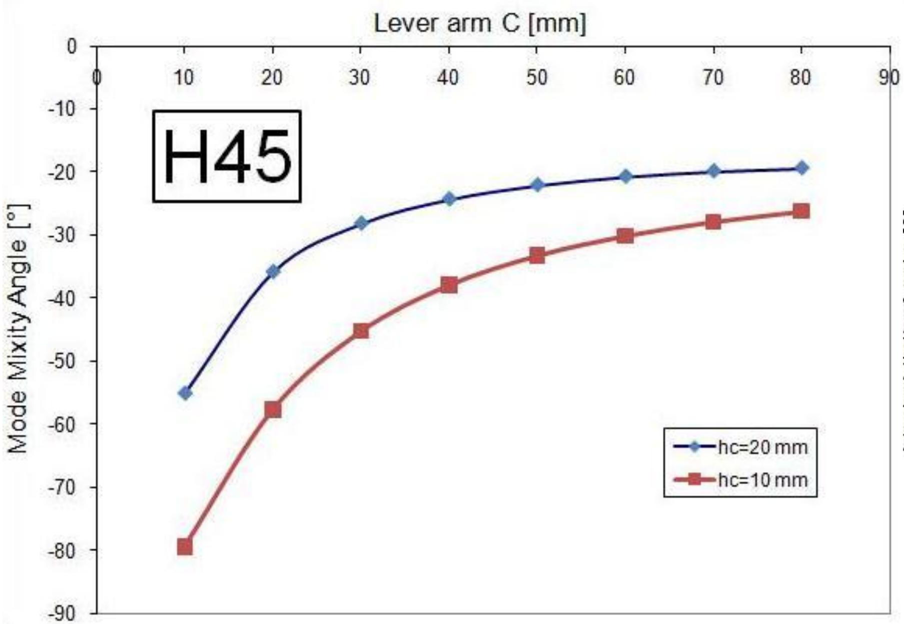
- MMB loading produces constant mode mixity for *(a/L) ≥ 0.2*

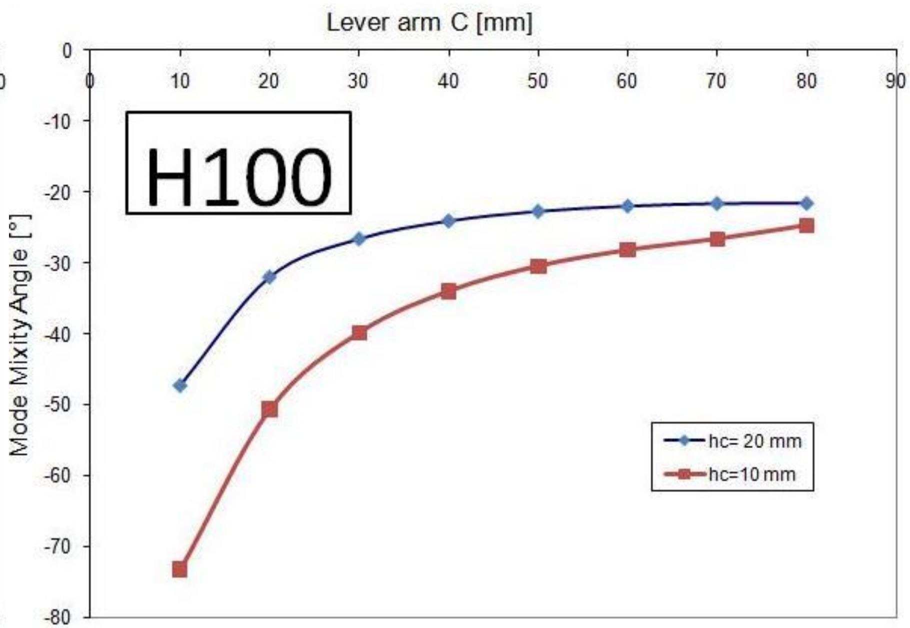






Sandwich MMB specimen
Mode-mixity



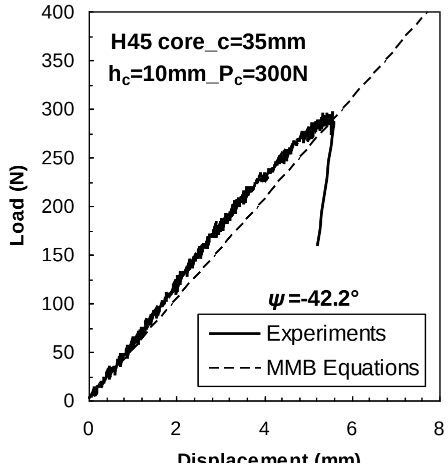


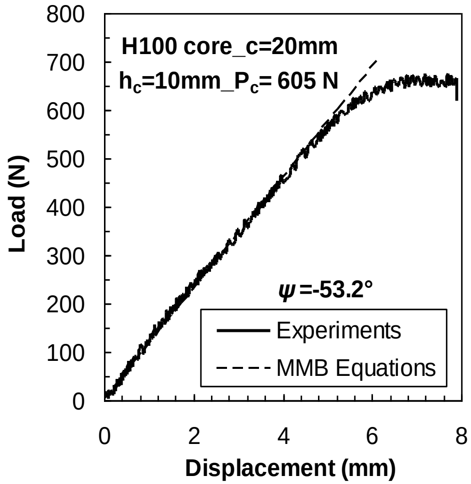
Large c → mixed mode with dominant mode I.

Small c → mixed mode with dominant mode II.

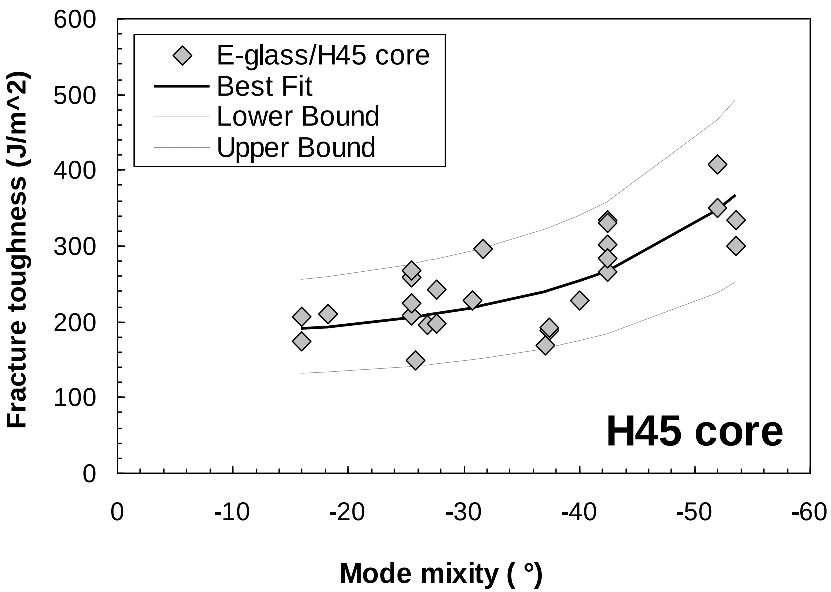
Sandwich MMB specimen
Static fracture toughness characterization

- Examples of fracture toughness measurements





Generated using the sandwich MMB specimen!



Fracture toughness results for sandwich specimens with H45 core

Sandwich MMB specimen

Crack length analysis

Compliance:

$$C_{MMB} = \left[\frac{c}{L} C_{DCB\_upper} + \frac{c-L}{2L} C_{DCB\_lower} \right] \left(\frac{c}{L} - \alpha \frac{c+L}{2L} \right) + \left(\frac{c+L}{L} \right)^2 C_{CSB}$$

Energy release rate:

$$G_{MMB} = \frac{P^2}{2b^2} \left(\begin{array}{l} \frac{c}{L} \left(\frac{c}{L} - \alpha \frac{c+L}{2L} \right) \frac{12}{E_f h_f^3} \left[a^2 + 2a\eta^{1/4} + \eta^{1/2} \right] + \\ \frac{c-L}{2L} \left(\frac{c}{L} - \alpha \frac{c+L}{2L} \right) \left[\frac{1}{h_c G_{xz}} + \frac{a^2}{\left(D - \frac{B^2}{A} \right)} \right] + \left(\frac{c+L}{L} \right)^2 \left(\frac{a^2}{8} \left[\frac{1}{\mathrm{D}_{\mathrm{debonded}}} - \frac{1}{\mathrm{D}_{\mathrm{intact}}} \right] \right) \end{array} \right)$$

The crack length can be obtained from the equation:

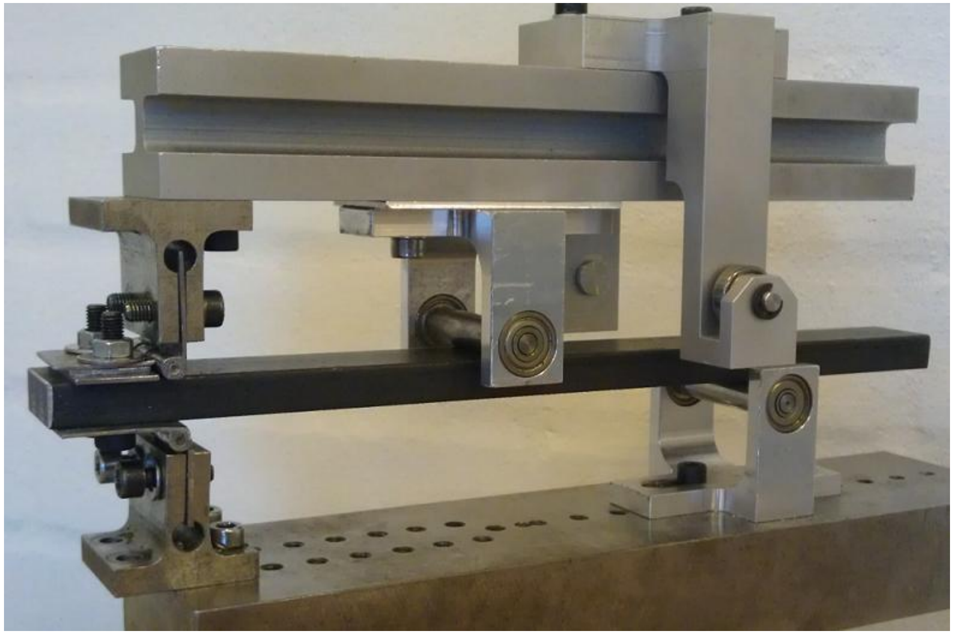
$$C_{MMB\_analytical} = C_{MMB\_\mathrm{experimental}}$$

where the compliance is experimentally determined from the LVDT and load cell signals, during the test.

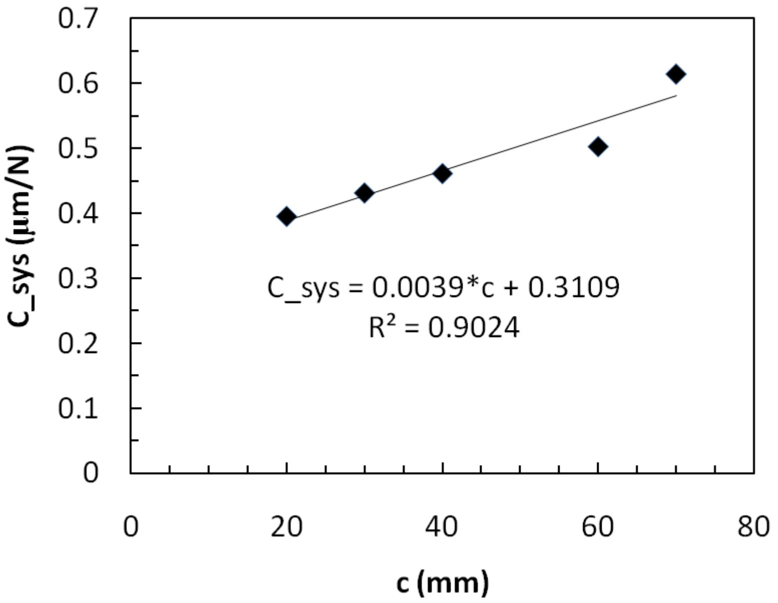
How can this be carried out during a test?

Sandwich MMB specimen
Compliance calibration

Especially connections and loading points in the MMB test-rig may cause friction and additional compliance unaccounted for in the FE-model. -> *compliance calibration is necessary!*



Steel beam in the test-rig



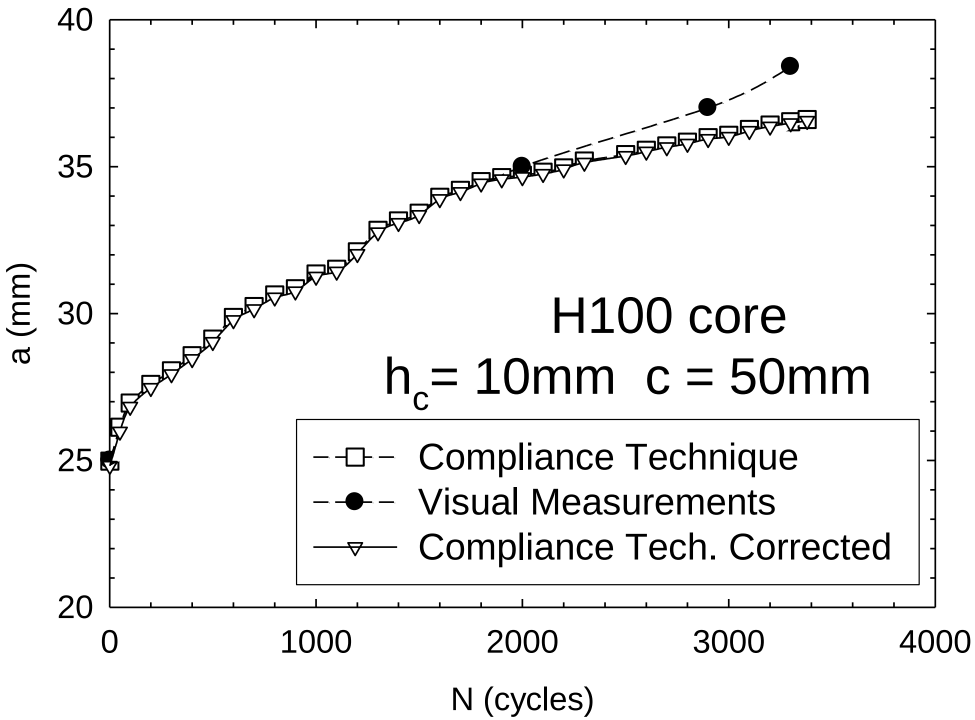
Compliance of the test-rig vs. lever arm

Sandwich MMB specimen
Example of crack length calculation

$$C_{MMB} = \left[\frac{c}{L} C_{DCB\_upper} + \frac{c-L}{2L} C_{DCB\_lower} \right] \left(\frac{c}{L} - \alpha \frac{c+L}{2L} \right) + \left(\frac{c+L}{L} \right)^2 C_{CSB}$$

$$C_{sys} = C_{measured} - C_{steel}$$

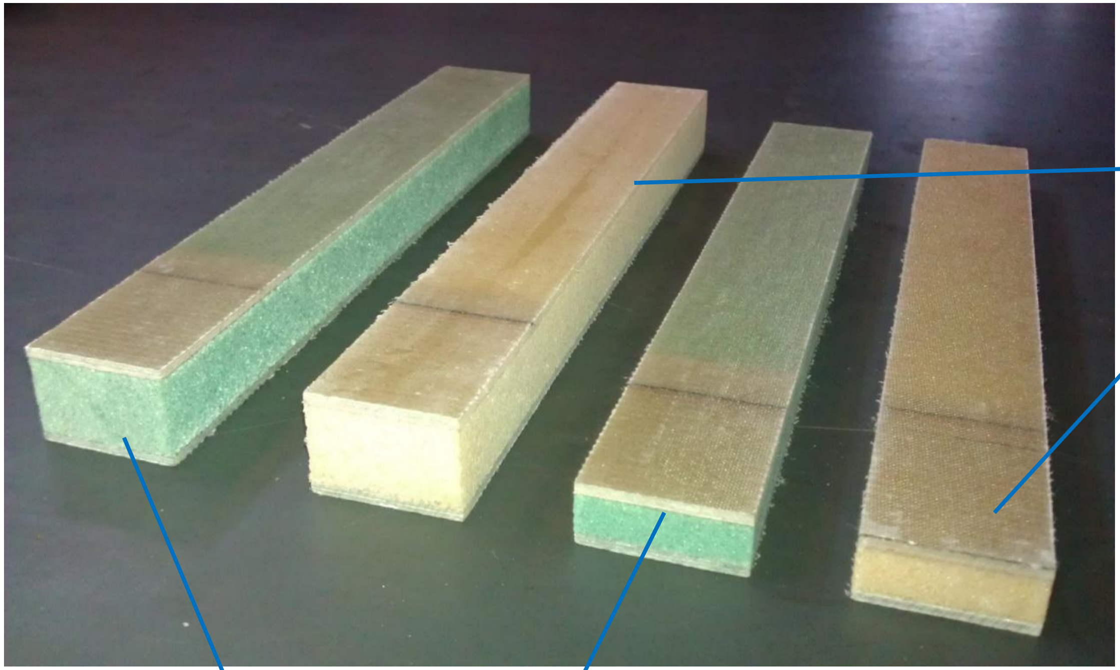
= equal => back-out crack length



- Visual inspections can be difficult and inconvinient
- May lead to uncertainty in the measurements
- *For this case: The effect of the fixture compliance was negligible*

Sandwich MMB specimen

Fatigue characterization: Specimens



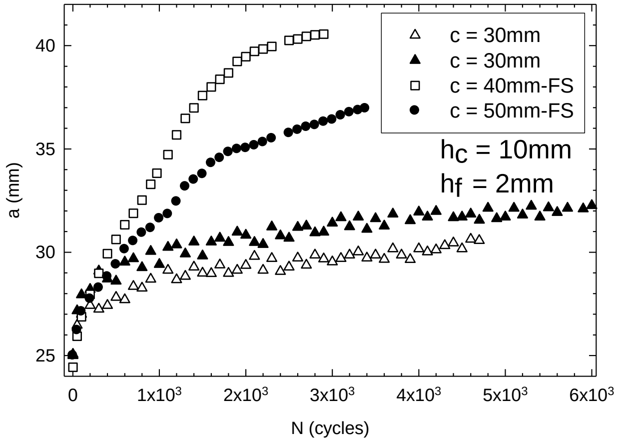
E-glass/polyester + H100:
Width=35 mm
Specimen length = 250 mm
Core thickness= 10 and 20 mm
Face thickness= 2 mm

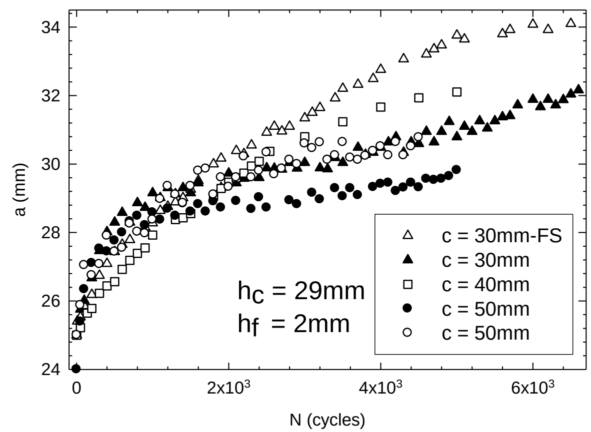
E-glass/polyester + H45: Width=35 mm
Specimen length=250 mm
Core thickness= 10 and 20 mm
Face thickness= 2 mm

Sandwich MMB specimen

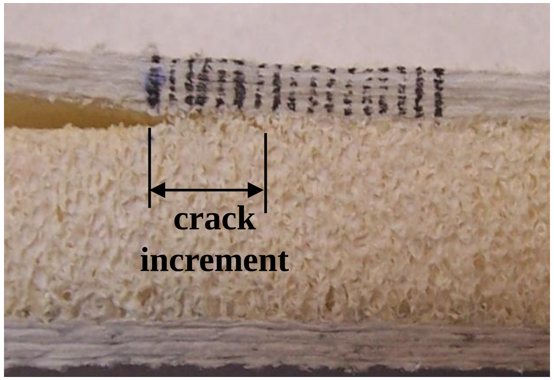
Crack growth results under displacement control mode

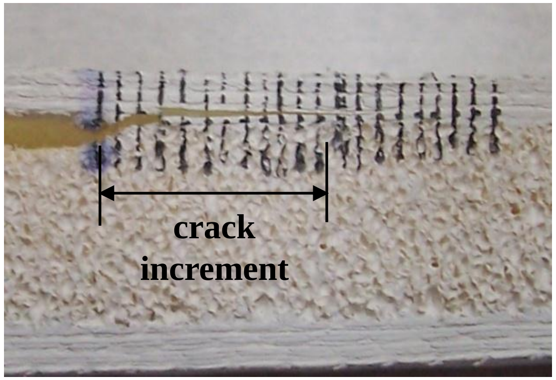
- Compliance based crack length measurements (***a*** vs. ***N***) for a sandwich specimen with H100 core





- Crack paths under fatigue testing





Sandwich MMB specimen

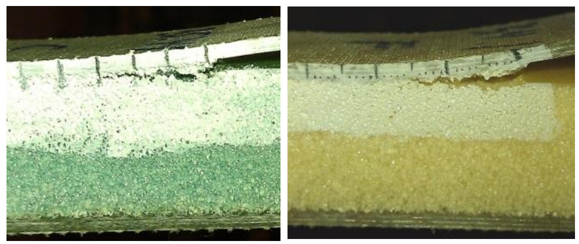
Crack growth results under displacement control mode (cont.)

- Several c values were used in order to have different loading conditions and mode mixities at the crack tip

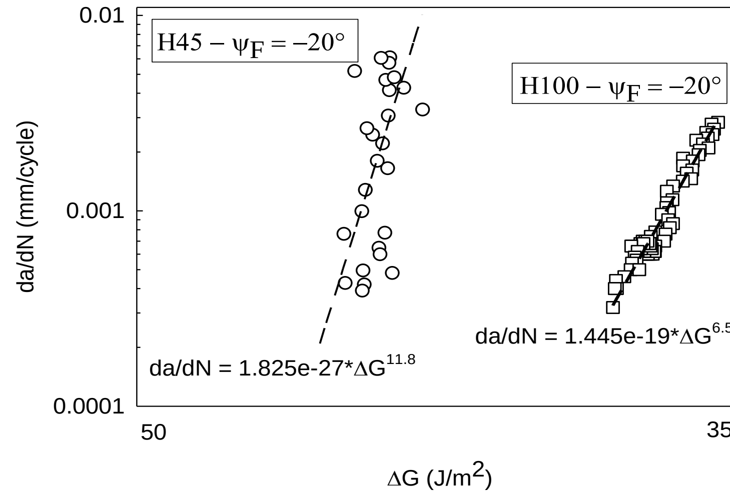
Modified Paris Law to characterize fatigue crack growth rates

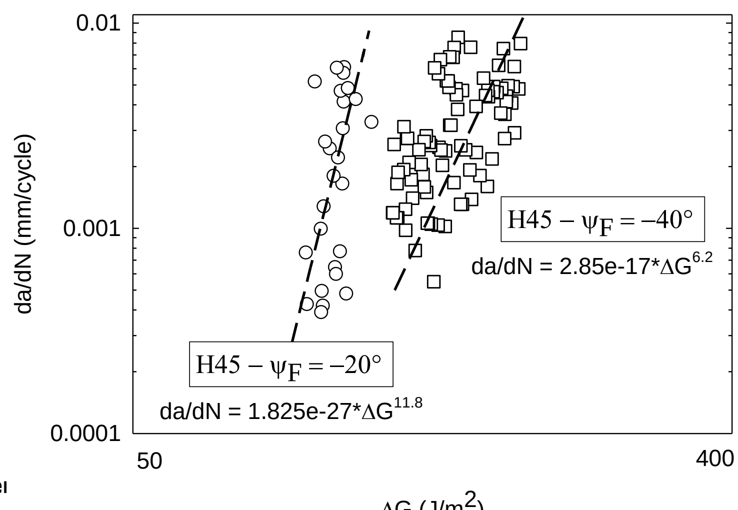
$$\frac{da}{dN} = C\left(\Delta G_{MMB}\right)^m$$

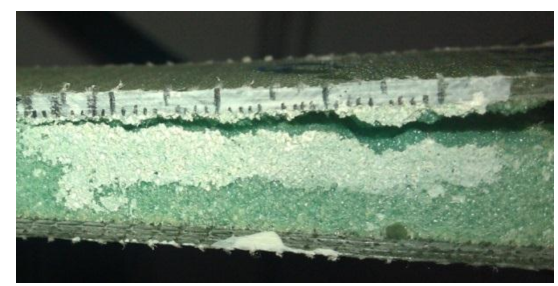
$$\Delta G_{MMB} = \frac{\left(P_{\max}^2 - P_{\min}^2\right)}{2b}\left(\frac{dC_{MMB}}{da}\right)$$



H45 and H100 at phase angle -20°





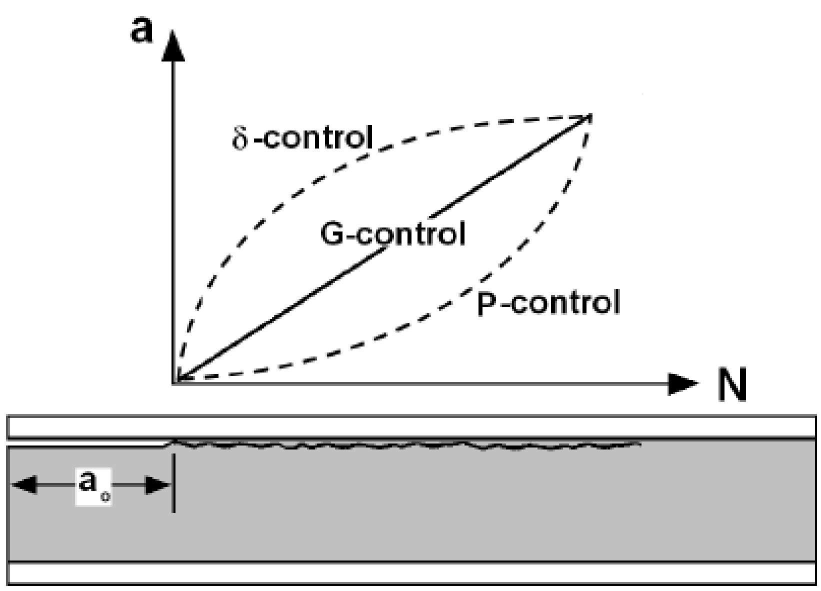


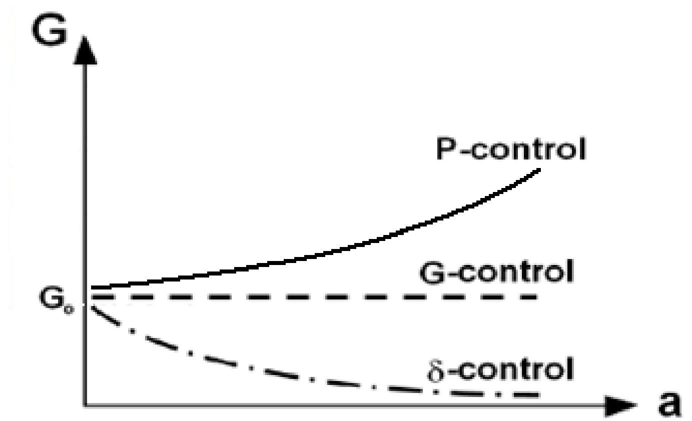
Scattered results at -40 ° - rough crack surfaces.

Sandwich MMB specimen

Fatigue characterization:
Loading control

- MMB: Small loads – large displacements – **DISPL. CONTROL chosen!**

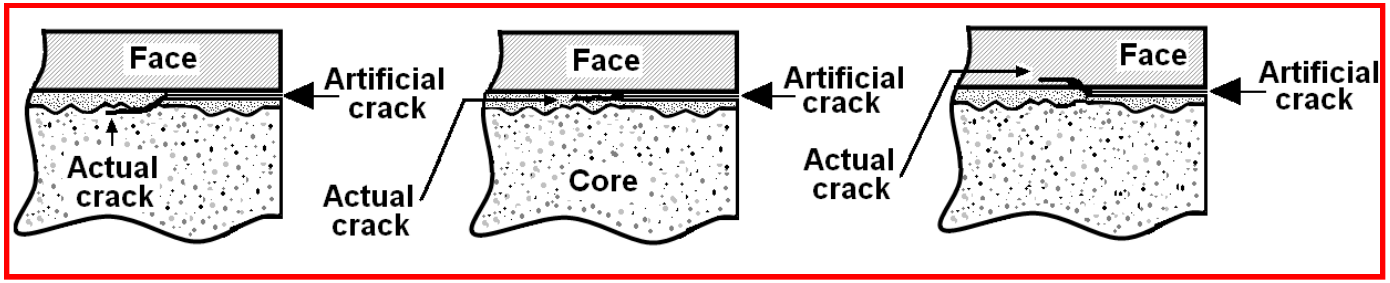




<u>NOTE:</u>
Cumbersome data reduction, when G is varying throughout the test!!
Possible crack path history effects??

Sandwich MMB specimen

Fatigue characterization:
History effects



- Kinking behavior will depend on both mode-mixity AND energy release rate level
- **Thus, we want to control both mode-mixity and energy release rate**

G-controlled testing!!

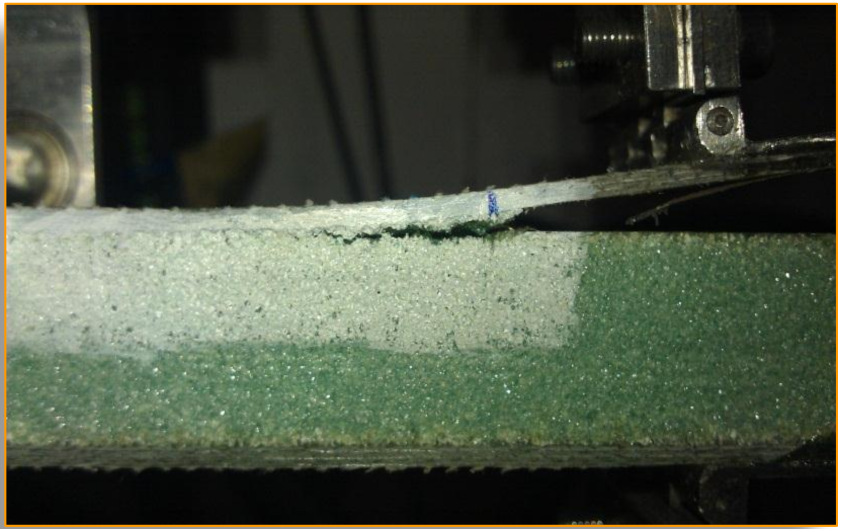
- Stable mode-mixity at the crack tip by using the MMB specimen
- Constant crack growth rate
- Possibility to use the same specimen for several fatigue tests

Sandwich MMB specimen
General principle of the *G*-control methodology

- Control mode:

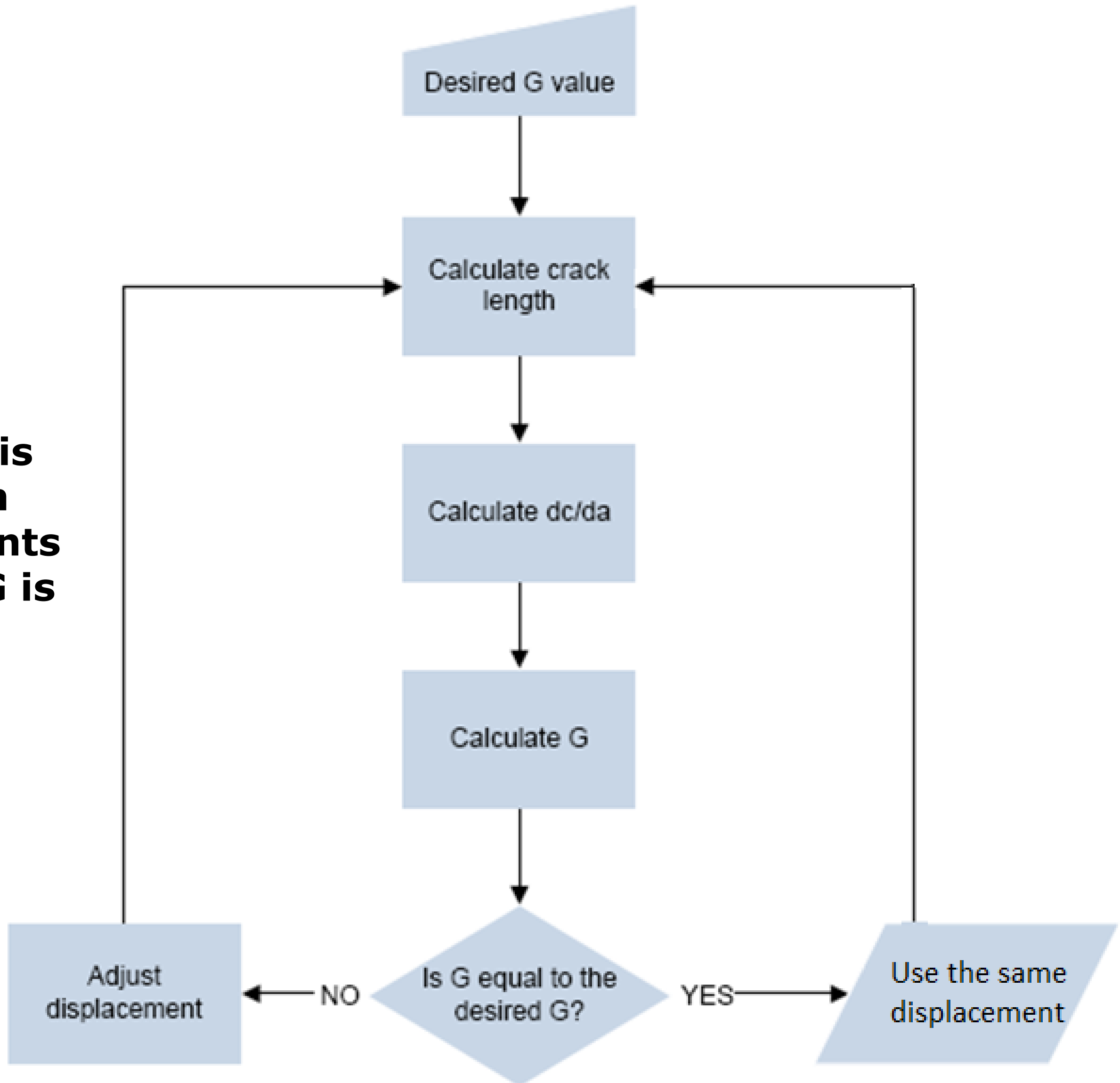
  - The test is run under **displacement control mode**, and online adjusted every X cycles

  - The displacement is adjusted in order to achieve the desired *G* level.



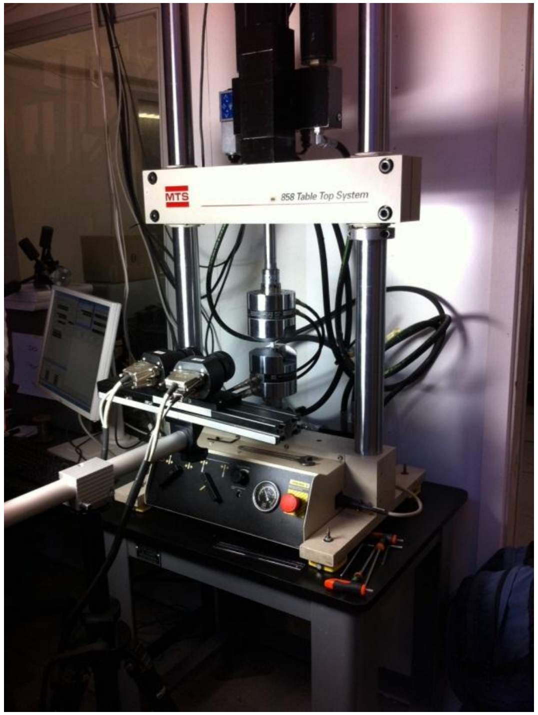
Sandwich MMB specimen
General principle of the *G*-control methodology

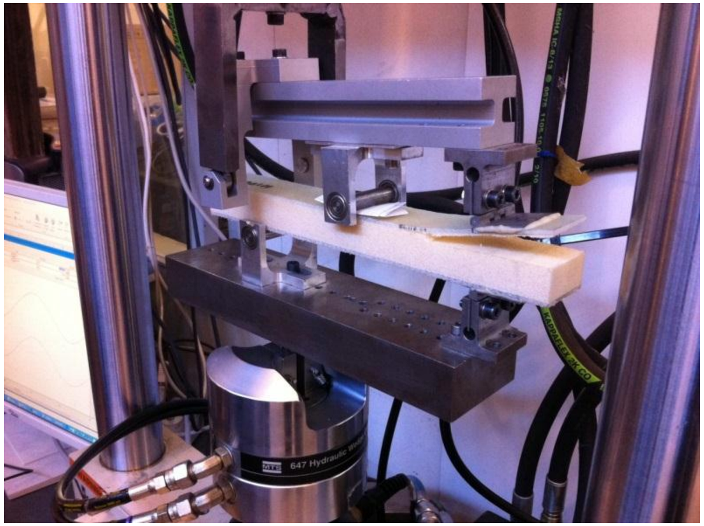
Displacement is increased with small increments until desired G is reached



Sandwich MMB specimen
Experimental setup

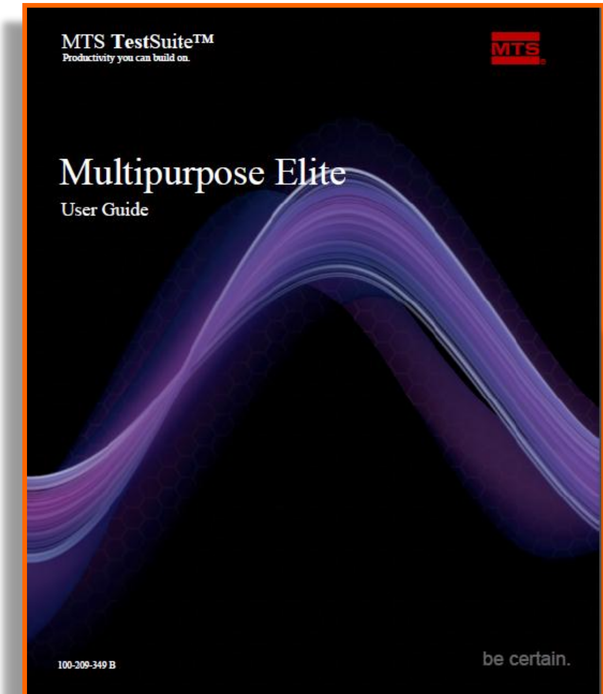
- **MTS 858 Table Top machine**
  - Model 242 10 kN servo-hydraulic actuator
  - 10 kN load cell
  - 647.02A hydraulic grips
  - FlexTest 60 controller
    - 1 of 6 stations installed
    - 1 of 8 axis of control
    - Running software version 5.1
    - Basic TestWare
    - MPT
    - Test Suite



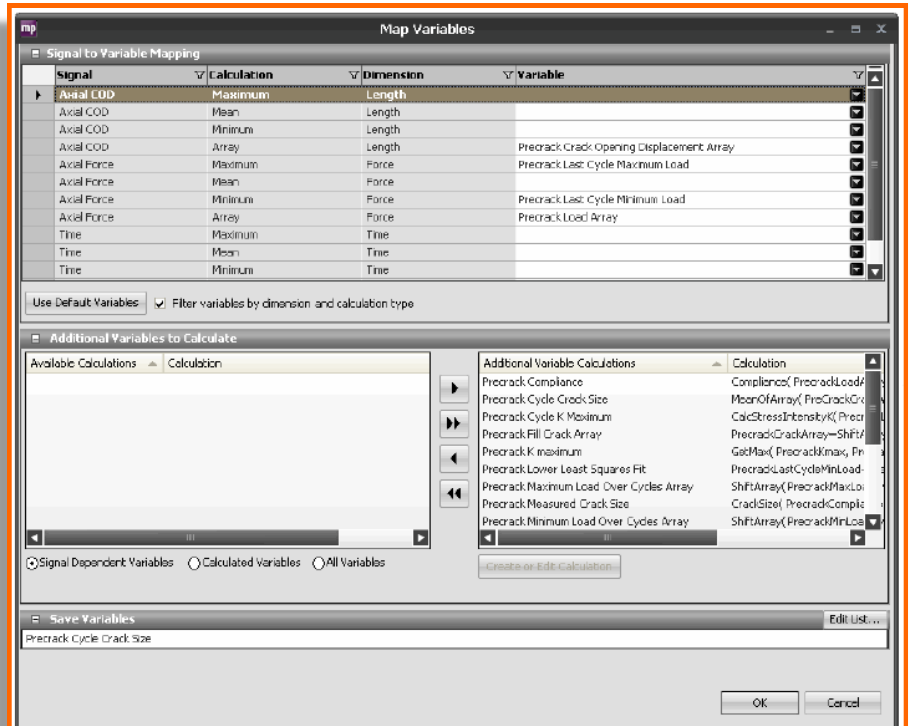


Sandwich MMB specimen

Implementation of the G-control code in MTS Test Suite



MTS TestSuite Multipurpose Elite is extremely flexible and allows accurate programming of complex tests. Any type of variable can be stored and used for calculations in the Calculations Editor.

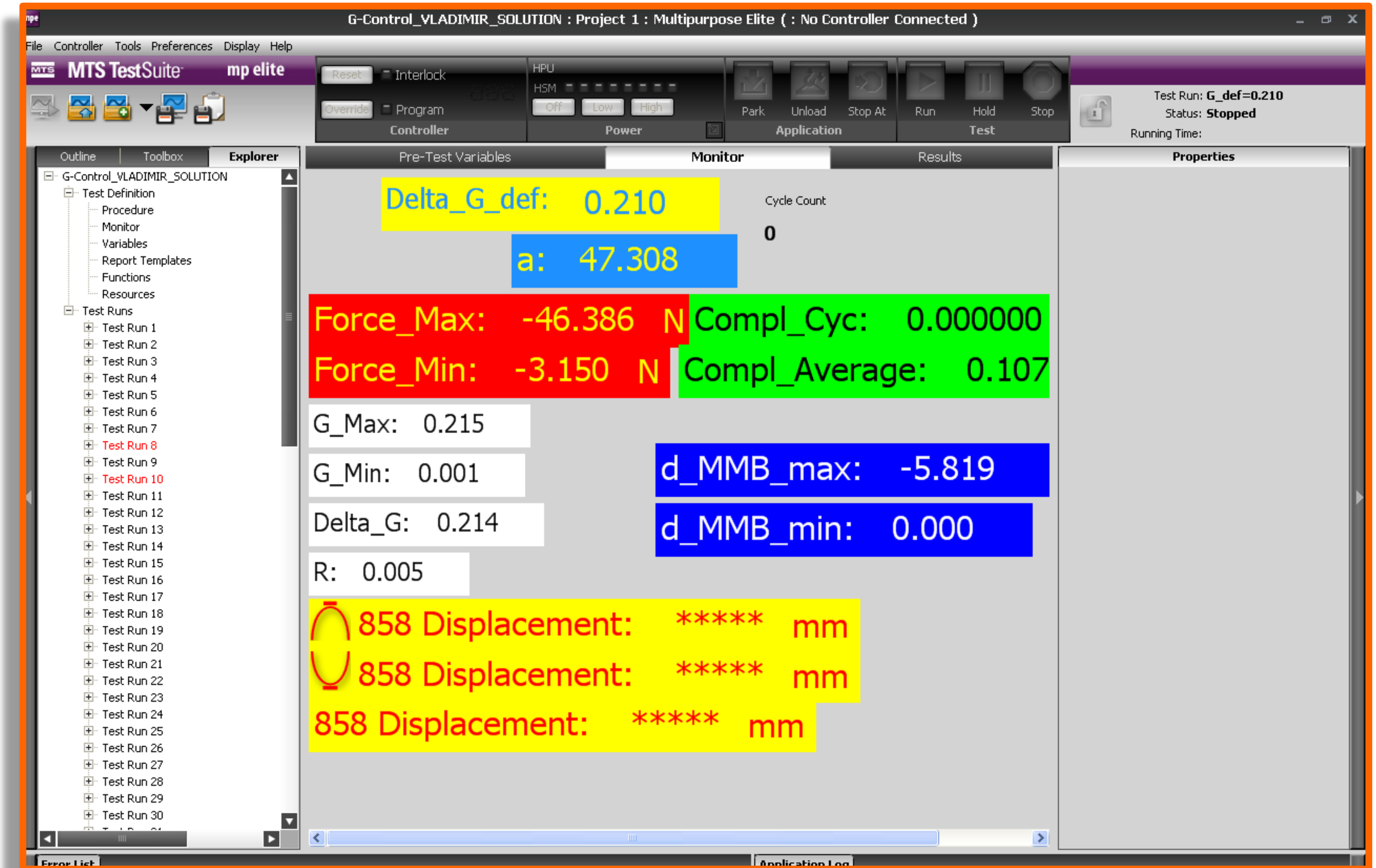


Application version 2.1 (platform version 3.0.0.1119) was used for our tests.

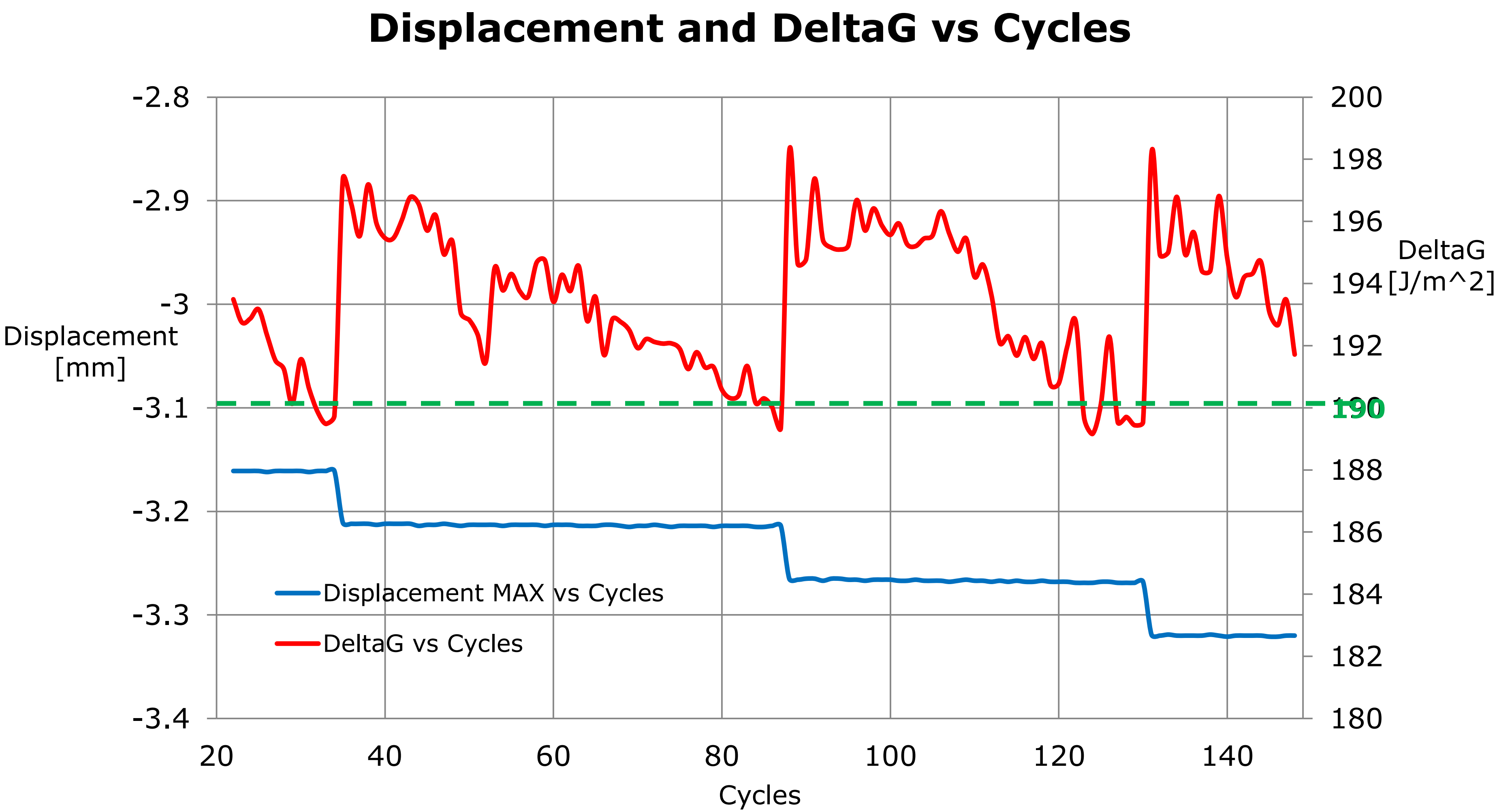
Sandwich MMB specimen

Implementation of G-control code in MTS Test Suite

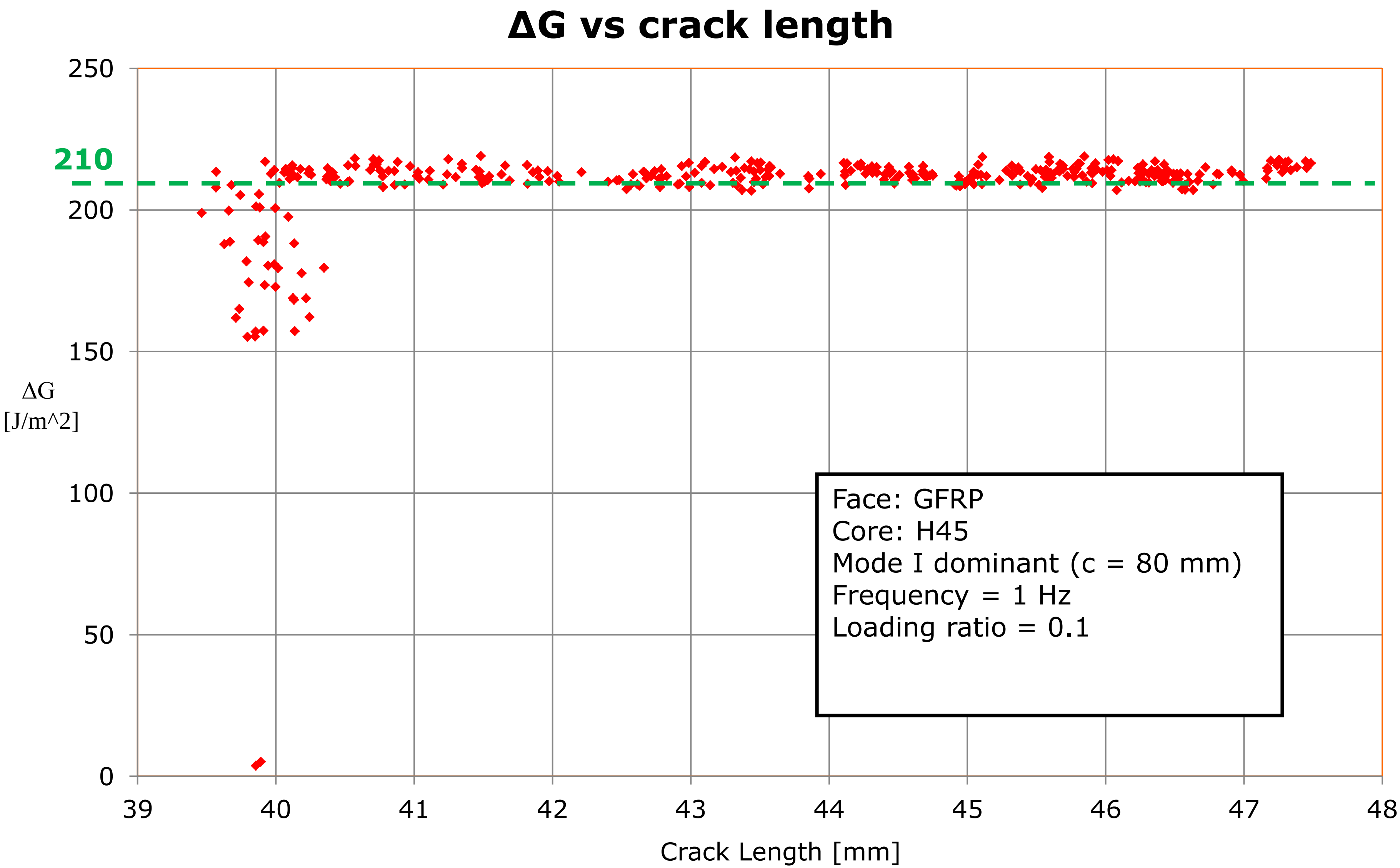
Screen shot of MTS Test Suite Monitor during a test. All the critical parameters are updated in real time.



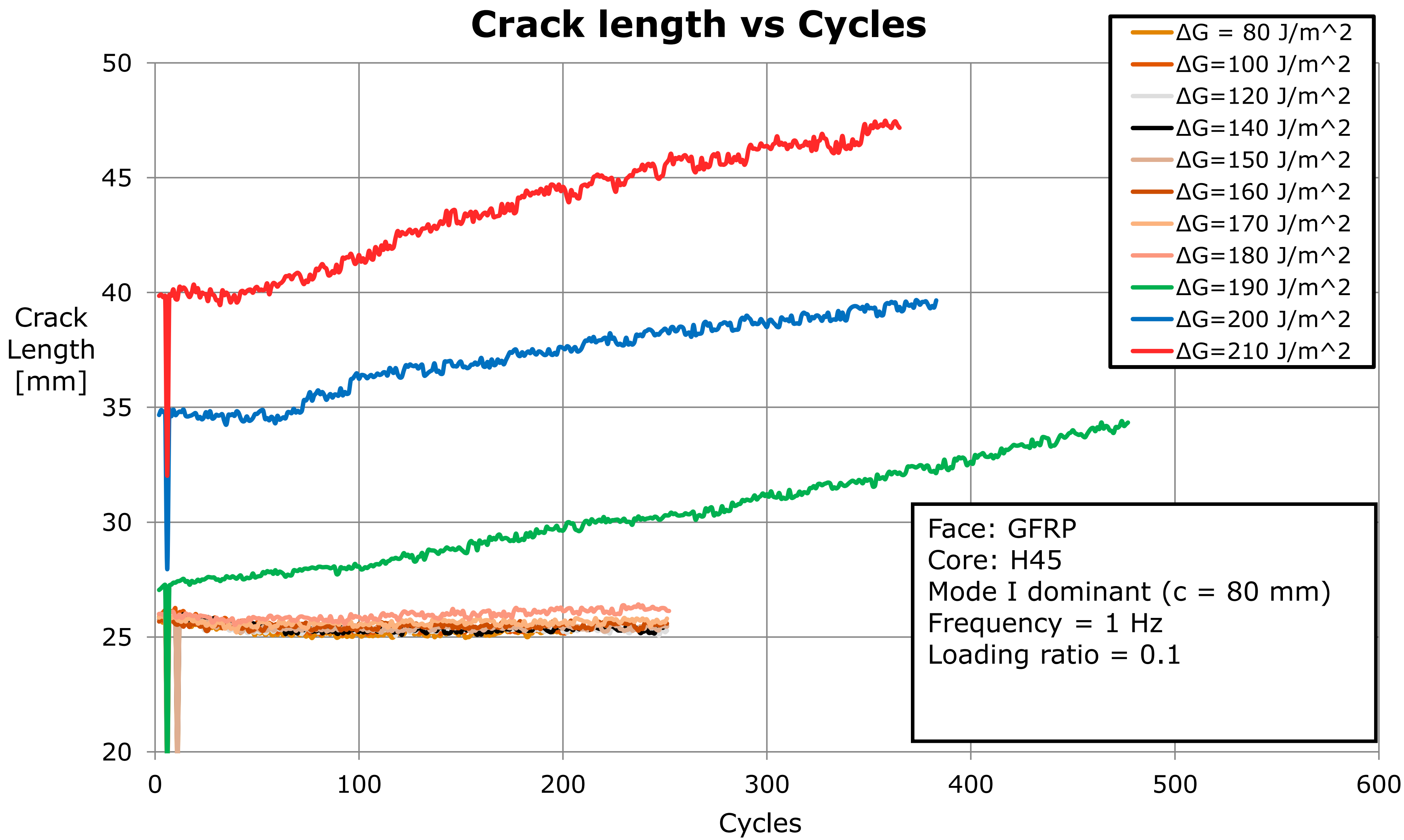
Sandwich MMB specimen
Results from G-controlled tests



Sandwich MMB specimen
Results from G-controlled tests



Sandwich MMB specimen
Results from experimental tests



Sandwich MMB specimen
Conclusions

- A new fatigue characterization method of sandwich face/core interface based on the sandwich MMB specimen was presented
- A compliance based crack length measurement technique was demonstrated
- A series consisting of GFRP/polyester and H45/H100 specimens were tested
- A G-control approach and test method proves valuable for advanced fatigue characterization

- **The sandwich MMB test seems to be a good candidate for fracture toughness as well as fatigue characterization!**

Sandwich MMB specimen
On-going and Future work

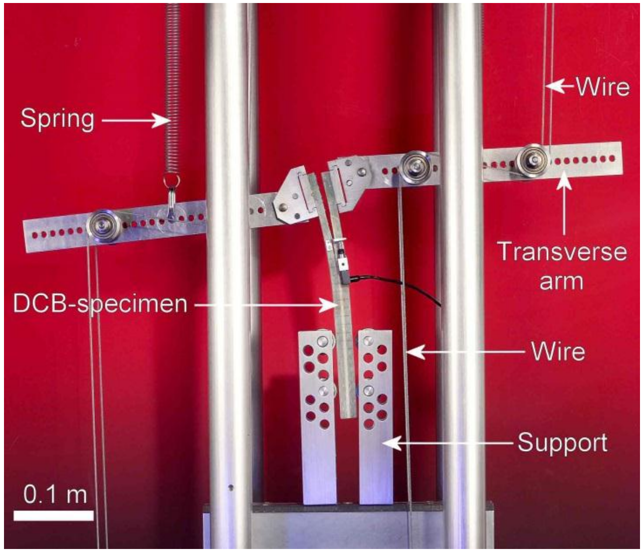
- Testing of other sandwich material configurations, eg. Honeycomb cores!
- Comparison of fatigue charactarization results from other mixed mode specimens, mod-TSD and DCB-UBM. (**on-going**)
- Possible standalization, ASTM, ISO, etc.
  - **A necessity is an analytical closed form solution for the mode-mixity!!**
  - **The transverse shear problem is a key milestone in achieving this**
  - Funding is needed for such a project!

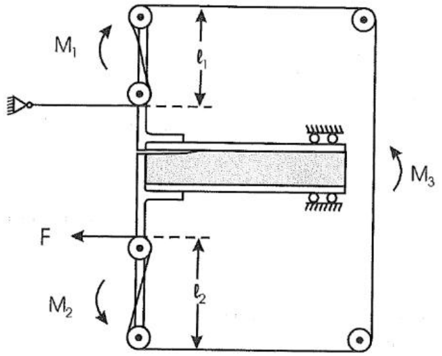
Sandwich DCB-UBM specimen

Sandwich DCB-UBM specimen

- The traditional DCB-UBM test method was presented by Sørensen et al. (2006) for laminates
- Pure moments load the crack flanks
- No transverse forces!
- G-controlled by nature!

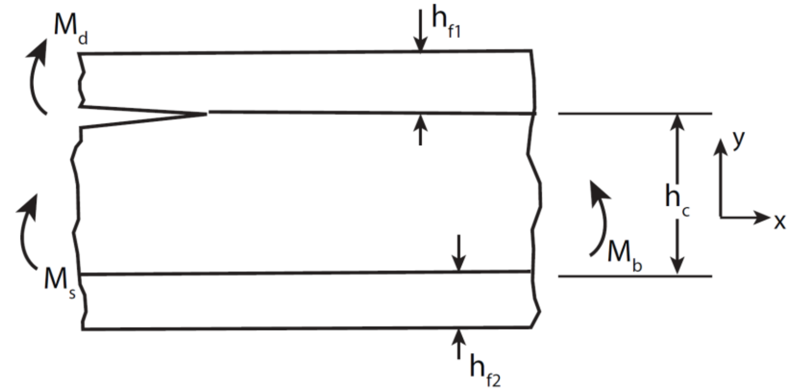
- Recently extended for sandwich testing
- Complete analytical foundation recently published
  - Kinematic relations for a general asymmetric sandwich with moments (and in-plane forces)
  - Closed form solutions for ERR and mode-mixity (!!)





Kardomateas, G.A., Berggreen, C. and Carlsson, L.A., "Energy Release Rate and Mode Mixity of a Face/Core Debond in a Sandwich Beam", *AIAA Journal*, 51(4):885-892, 2013.

Sandwich DCB-UBM specimen
Closed form solutions



Energy release rate:

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

$$P^* = C_2 M_b \qquad (4a)$$

$$M_d^* = M_d - C_3 M_b \qquad (4b)$$

$$M_s^* = P^*\left(e_s + \frac{h_c}{2} + \frac{h_{f1}}{2}\right) - M_d^* \qquad (4c)$$

Mode-mixity:

$$\psi = \tan^{-1}\left[\frac{\lambda \sin\omega - \cos(\omega+\gamma)}{\lambda\cos\omega + \sin(\omega+\gamma)}\right] \qquad (13a)$$

$$\lambda = -\frac{P^*}{M_d^*}\sqrt{\frac{a_1}{a_2}} \qquad (13b)$$

$$K h_{f1}^{i\varepsilon} = |K| e^{i\psi} \qquad (14)$$

$$K = K_1 + iK_2 \qquad (9)$$

Table 2 H100 core (130 MPa) sandwich

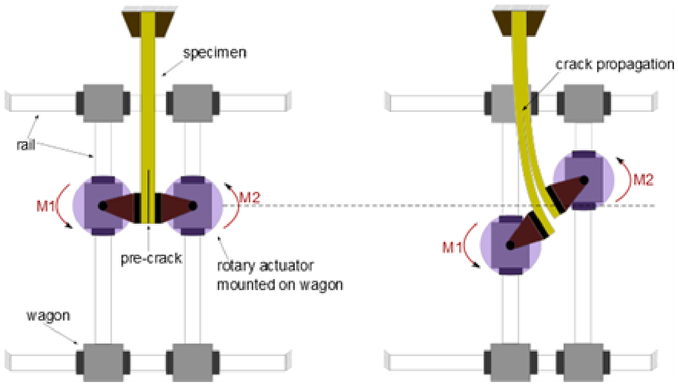
M_d, N · mm	75.6	129.6	196.1	118.6	71.1
M_s, N · mm	−604.8	−518.4	−196.1	474.4	568.8
G_{anal} [Eq. (22)], N/mm	0.4239	0.4350	0.4140	0.3613	0.3727
G_{FEA}, N/mm	0.4076	0.4214	0.4107	0.3553	0.3626
ψ_{FEA}, deg	52.6	35.6	1.11	−68.5	−85.4
ω [Eq. (31c) with ψ_{FEA}], deg	74.09	73.66	73.34	73.74	73.54

- ω is achieved from FEA
- ω depend only on face/core stiffnesses and thicknesses
- ω only need to be mapped one time for a large range of face/core combinations

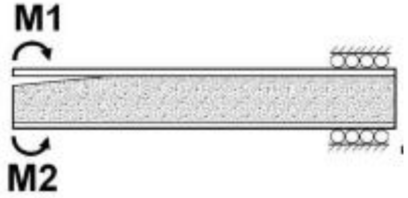
Seems attractive for standard implementation!

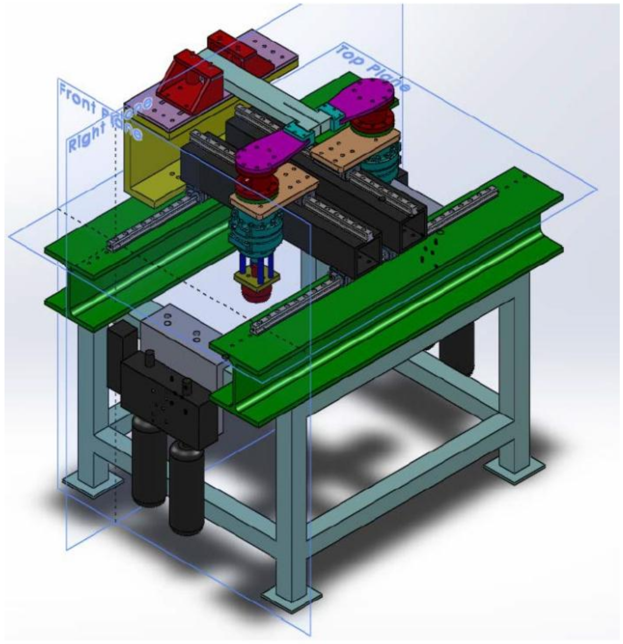
Sandwich DCB-UBM specimen
New compact fatigue rated rig!!

- The traditional DCB-UBM test rig requires a quite tall rig/machine in order to minimize wire misalignment
- Only specific moment ratios possible
- Not good for fatigue testing due to long wires



- A new bi-axial servo-hydraulic operated stand-alone rig is under development/construction at DTU!
- Consists of two torsional actuators and load cells in a special x-y fixture
- Able to apply any moment combination
- Fatigue rated at theoretically any frequency (there are physical limitations though)





Concluding recommendations

- There is a general need to extend present sandwich fracture characterization into mixed mode through new standards

- Three generic mixed/controlled mode sandwich fracture specimens have been presented as promising candidates

- <u>However</u>:
  - More testing with a broader range of material classes is needed, eg. with honeycombes, wider range of foams etc.

  - Both fracture toughness and fatigue characterization

  - **The transverse shear problem <u>must</u> be addressed in order to move towards standards for a simple specimen/rig (eg. mod-TSD and sandwich MMB)**

Acknowledgements

The financial support of the Danish Council for Independent Research Technology and Production Sciences (Grant 10082020), is gratefully acknowledged.

Also, financial support from the office of Naval Research (USA), Grant N00014-07-10373, and the interest and encouragement of the Grant Monitor, Dr. Y.D.S. Rajapakse, are both gratefully acknowledged.

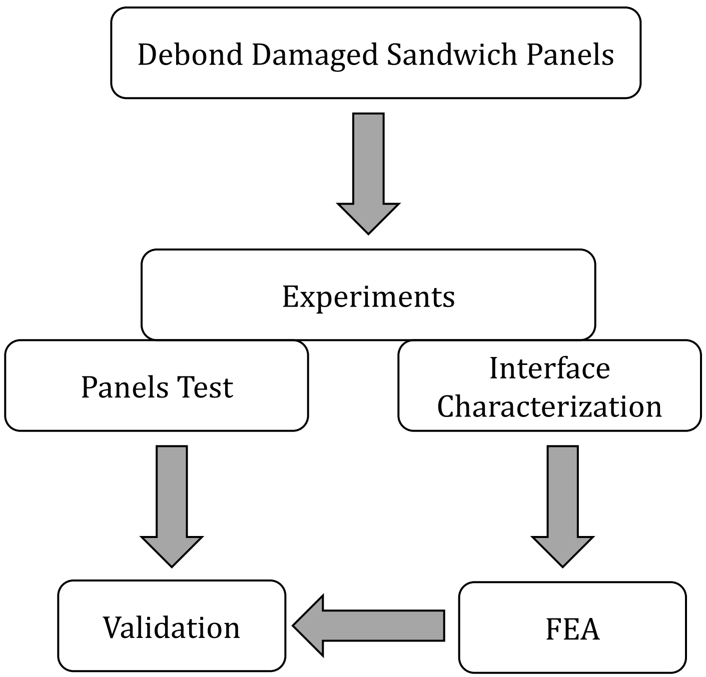
DTU

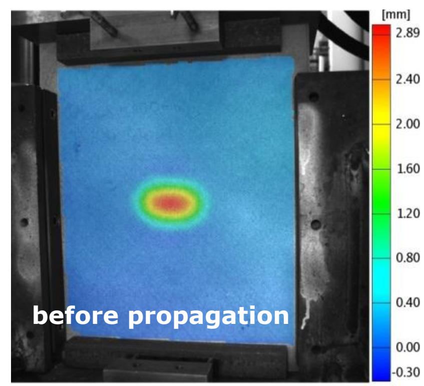
THANK YOU FOR YOUR ATTENTION!

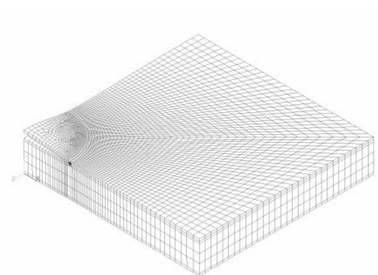
Extras

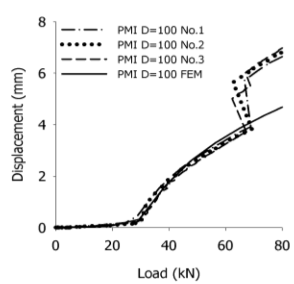
Structural applications of mixed mode fracture data

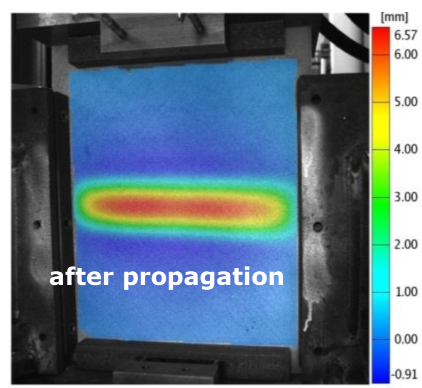
SANTIGUE
Failure of Uniformly Compressed Debond Damaged Sandwich Panels

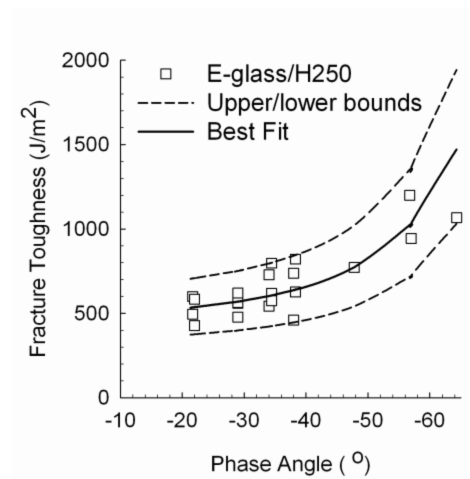






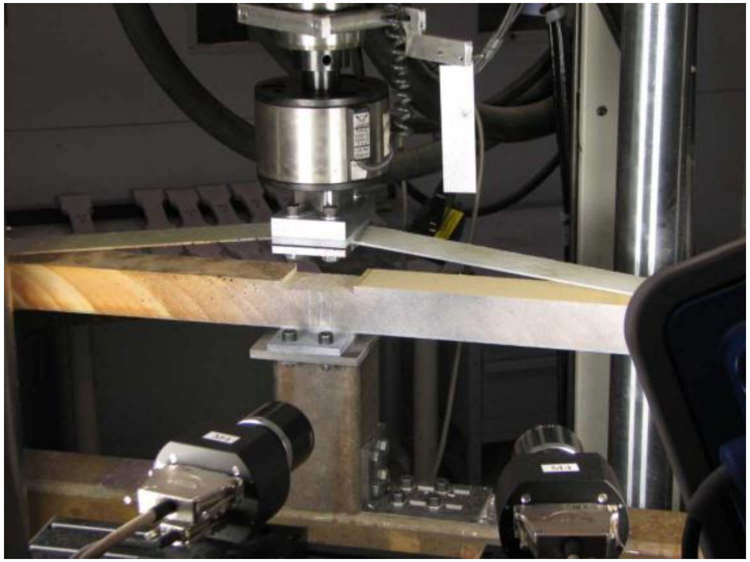


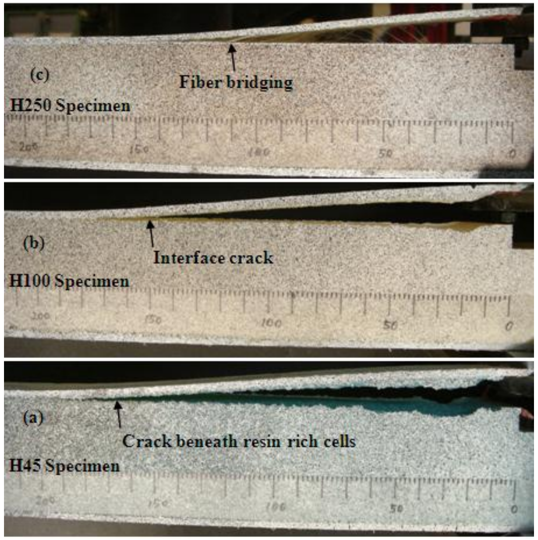


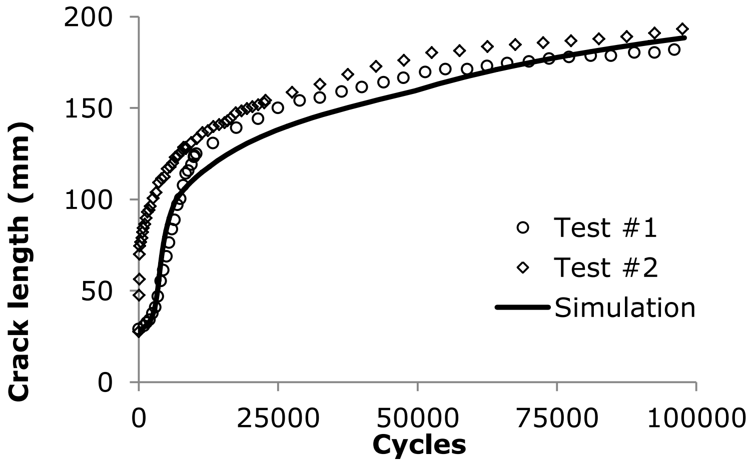


SANTIGUE
Interface Fatigue Crack Growth in Sandwich Structures

- Fatigue tests were performed on cracked sandwich X-joints
- Fatigue response of the face/core interface was characterized using the MMB test rig
- A FE-based Cycle Jump Method was applied
- Up to 99% save in computation time can be achieved using the cycle jump method with good accuracy



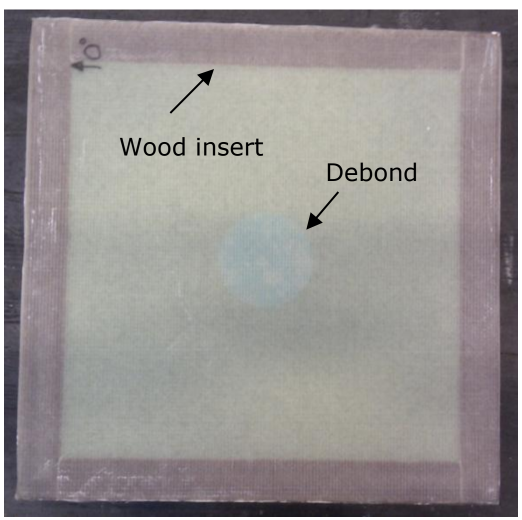


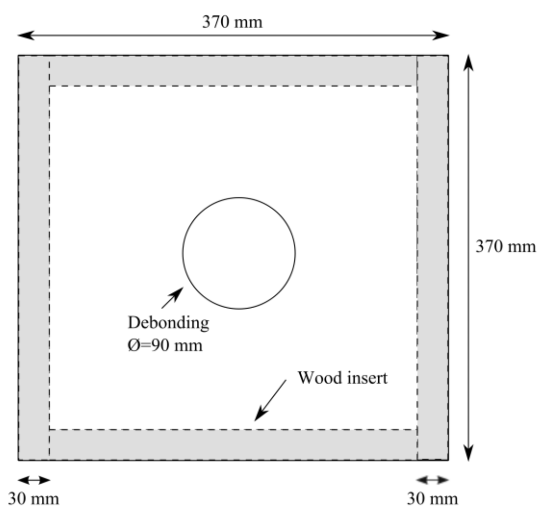


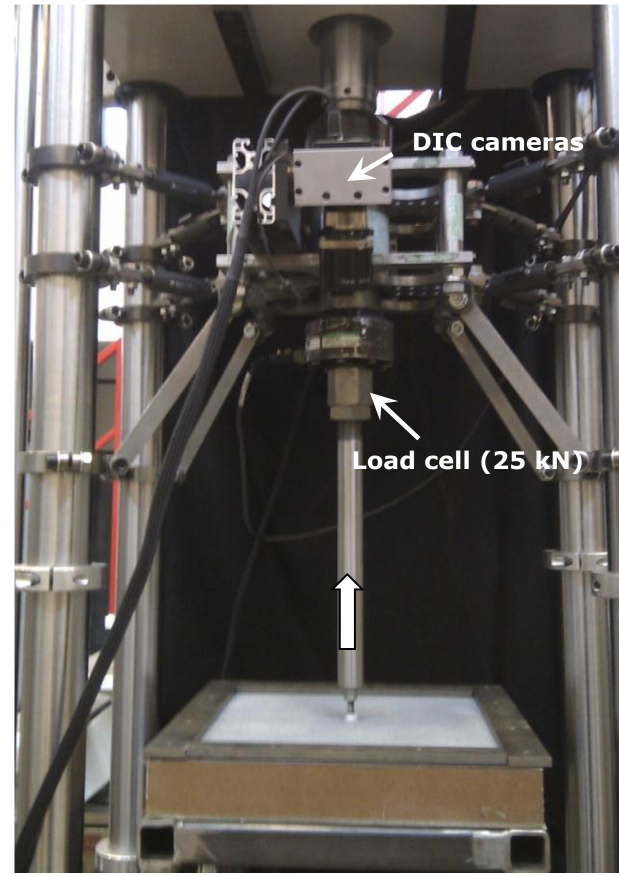
SANTOL

Debonded panel specimens and test setup

- Five sandwich panels with a circular Ø90mm debond at the center were manufactured
- Three layers of Devold AMT DBLT 850 g/m^2 quadri-axial glass fibre mats of a total thickness of 2 mm for face sheets
- H45 Divinycell PVC foam of 50 mm thickness
- Resin infusion process with polyester resin



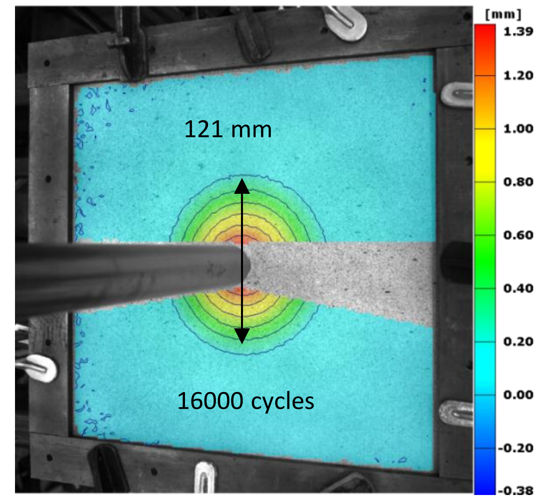


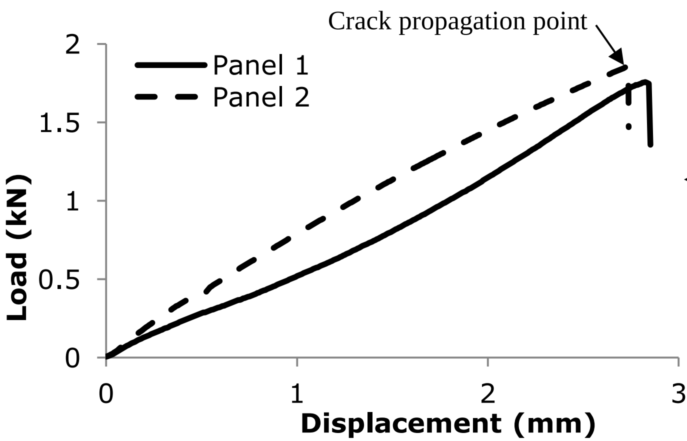


Test setup

SANTOL
Static and fatigue tests

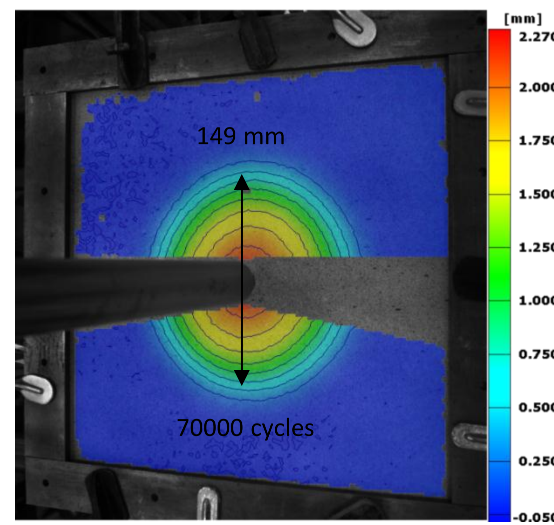
- Static tests were conducted initially
- Load controlled fatigue tests were performed after
- 80% of the static crack propagation load was applied as maximum fatigue load
- Loading ratio *R=0.1*
- Loading frequency of 2 Hz
- Debond growth was monitored using DIC technique





Static tests

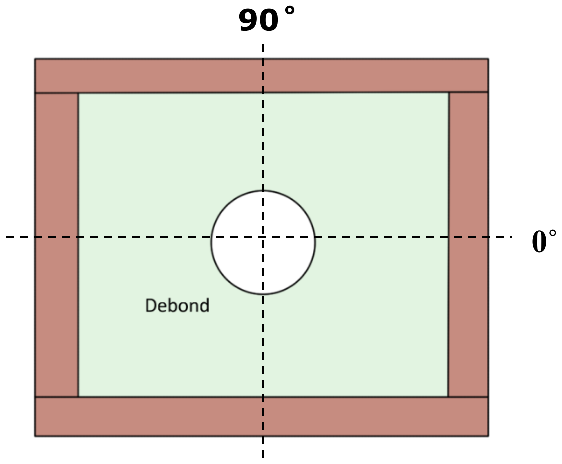
Fatigue tests

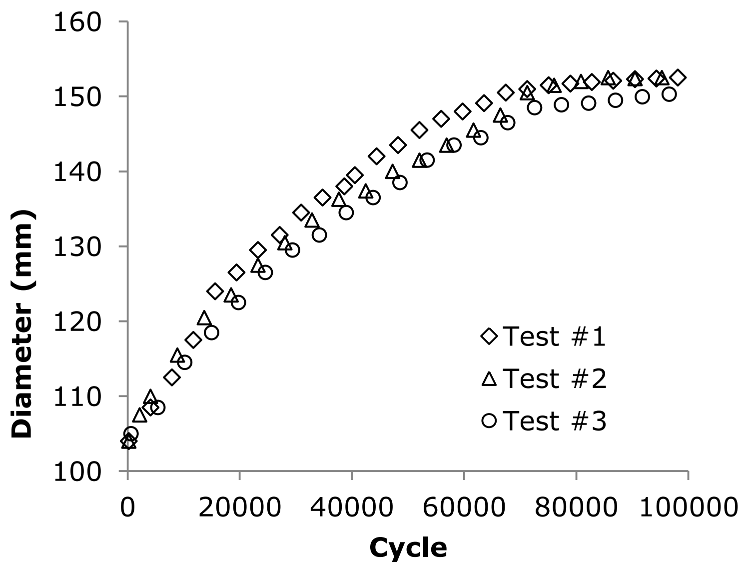


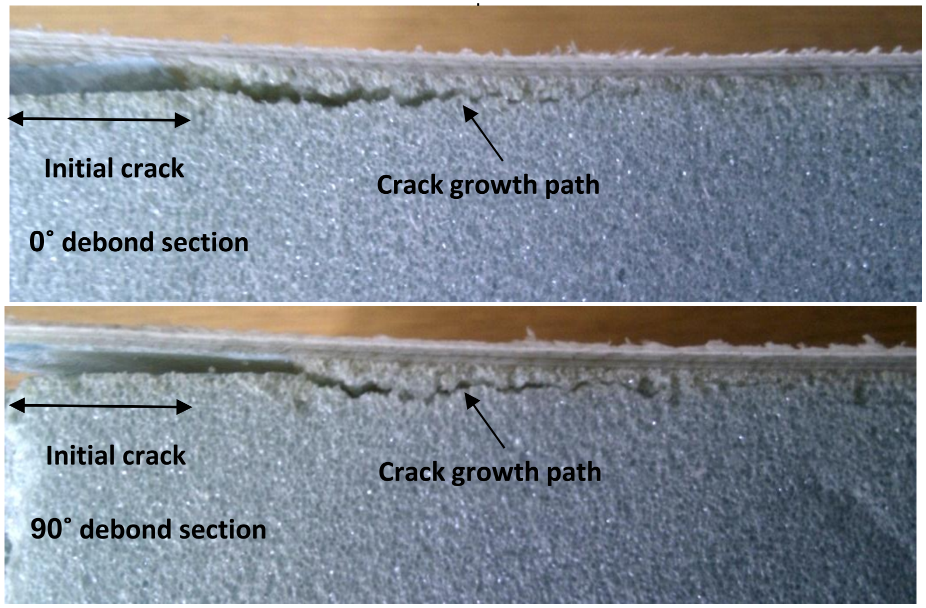
58

SANTOL
Static and fatigue tests

- Debonds remained circular for all specimens
- Debond diameter vs. cycles
- Fair repetition between samples
- Typical low density PVC foam crack growth paths just below the face/core interface

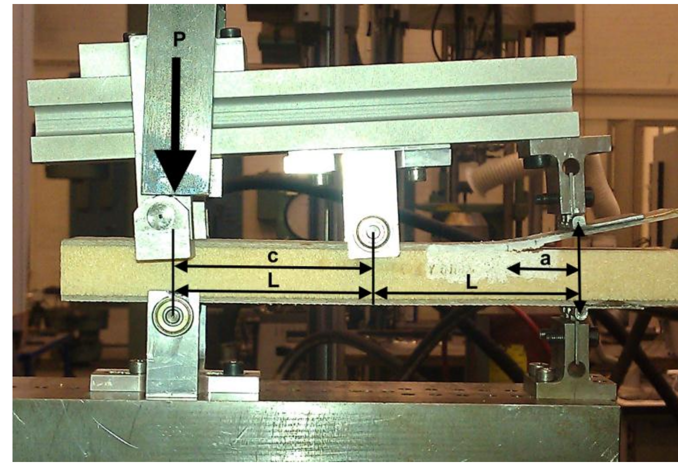


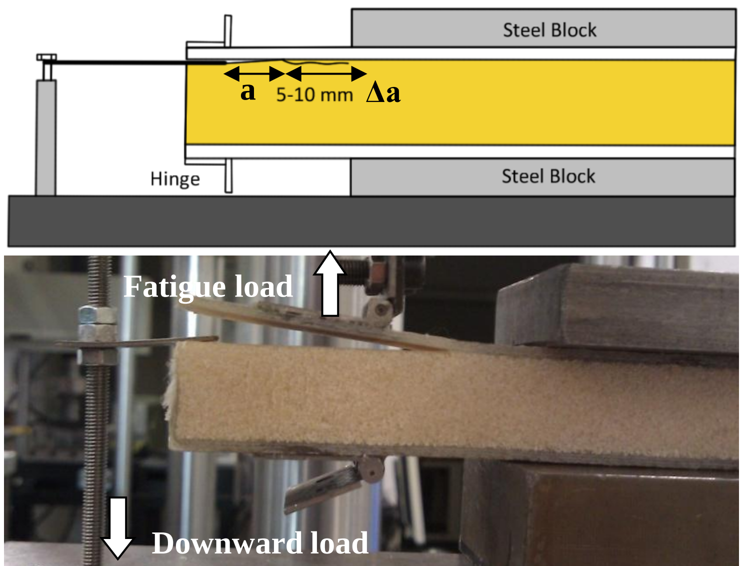




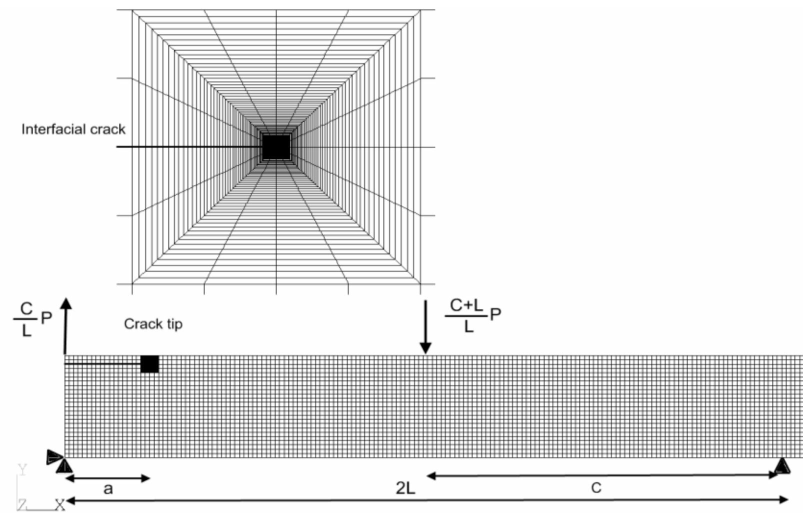
SANTOL
Face/core interface characterization

- Sandwich Mixed Mode Bending (MMB) tests were conducted
- Finite element model of the MMB specimen was developed
- Lever arm distance *c* was determined by FEA to achieve target phase angle
- Pre-cracking was performed





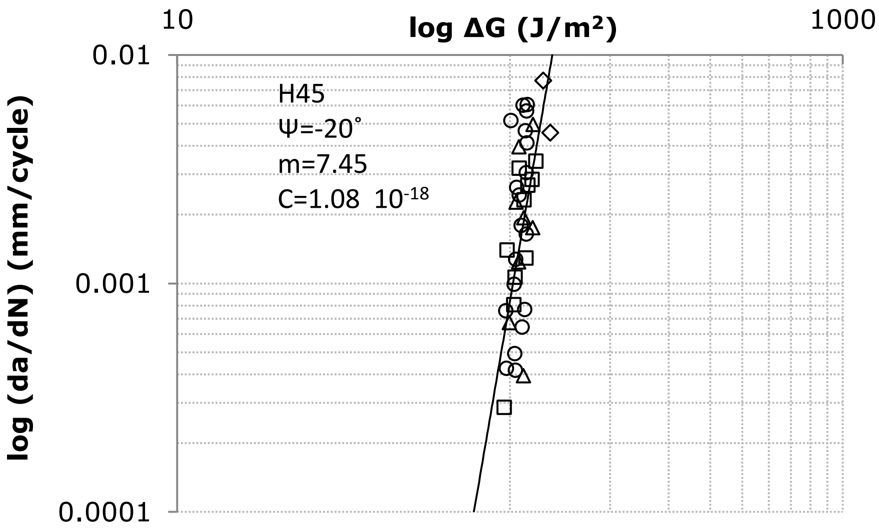
0



SANTOL
Face/core interface characterization

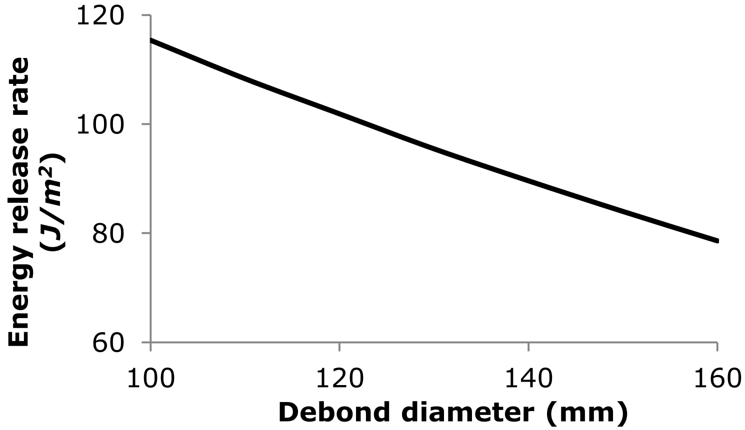
- Fatigue tests only carried out for target phase angle
- da/dN curves as function of ΔG
- Modified Paris Law!
- Similar crack propagation paths as seen for panel specimens
- Fair linearity

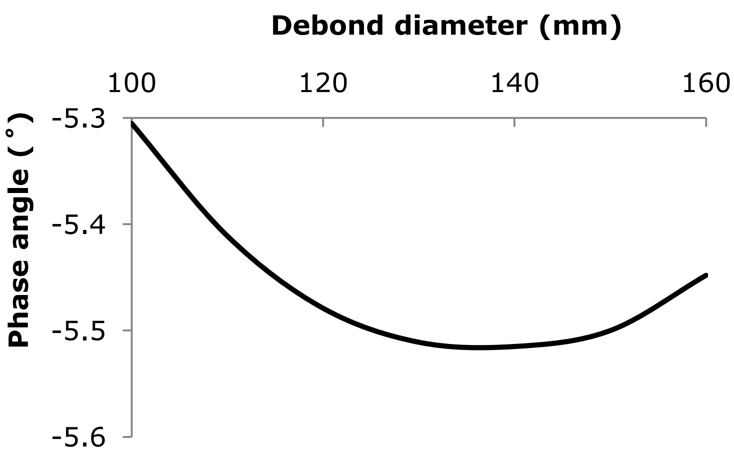
$$\frac{da}{aN} = C\Delta G^m$$

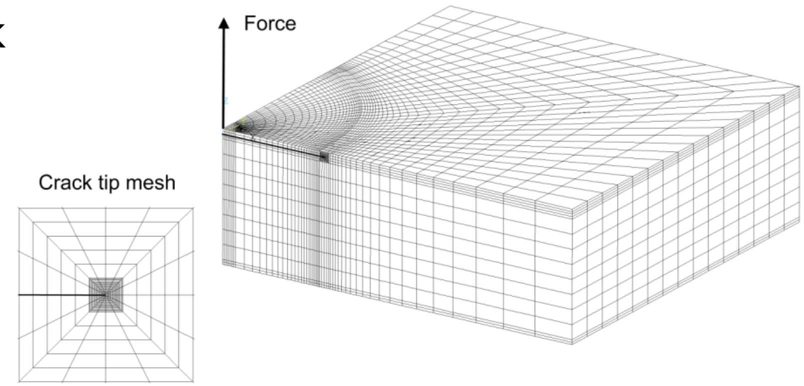


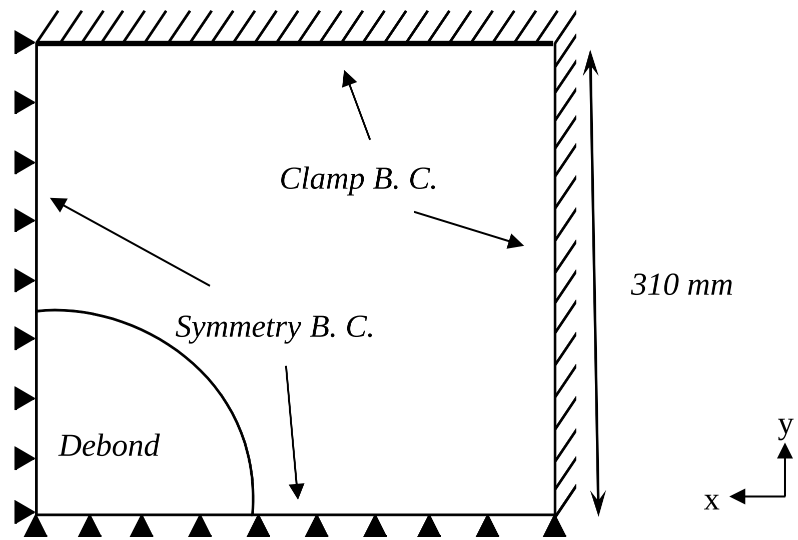
SANTOL
Finite element modeling of the tested panels

- Quarter finite element model of the panels was generated with high density crack elements







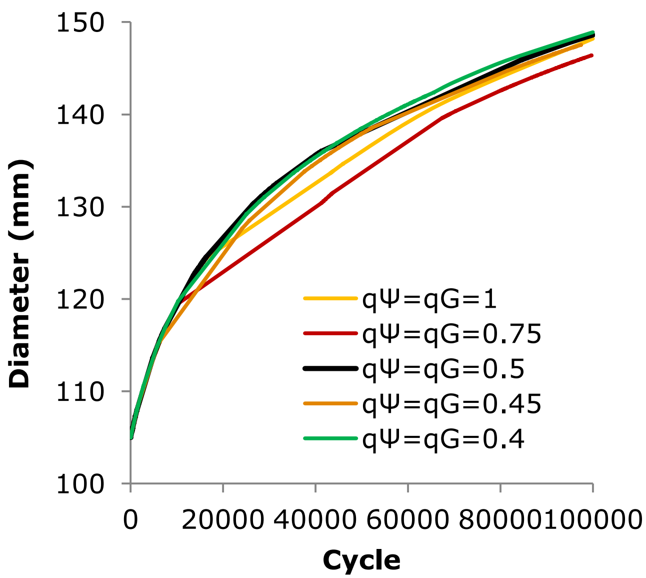


6
2

SANTOL

Finite element modeling of the tested panels

- The fatigue crack growth finite element routine based on the *Cycle Jump* method used for the simulations
- 100.000 cycles were simulated
- Sensitivity analysis to find the most optimal set of control parameters was performed



Control parameter $q_G = q_\Psi$	Simulation of debonded sandwich panels	
	Number of simulated cycles	Saved simulation cycles (%)
0.4	7121	92.879
0.45	6087	93.913
0. 5	5896	94.104
0.75	5051	94.949
1	3778	96.222

Larger control parameters → Less simulation time
Less accuracy

Finite element modeling of the tested panels

- Comparison of the fatigue simulation with experiments show fair accuracy
- The maximum deviation of approximately 7 mm occurs around 70.000 cycles
- Utilizing the cycle jump technique with a fair accuracy up to 94% computation time can be saved