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Mixed Mode Fracture Testing of Foam Core Sandwich using the DCB-UBM Test Method

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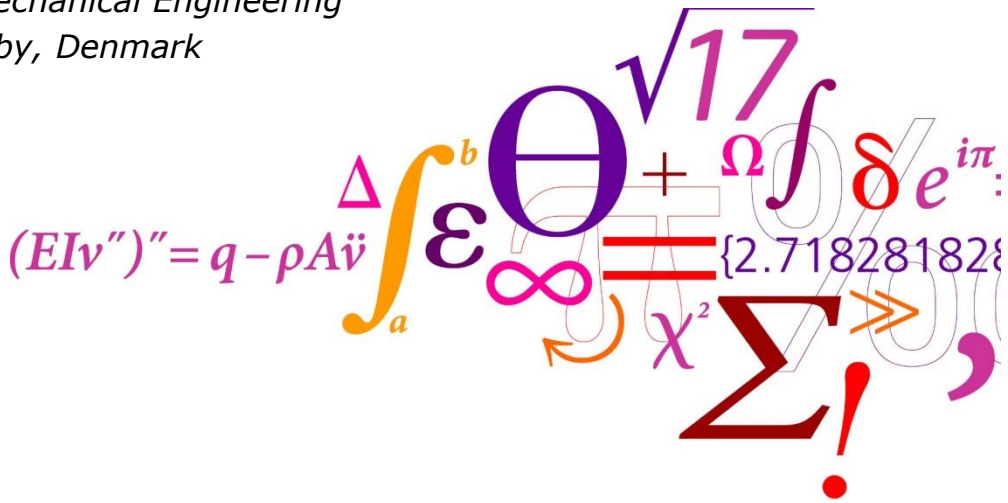

DTU Mechanical Engineering
Department of Mechanical Engineering

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- Sandwich DCB-UBM specimen
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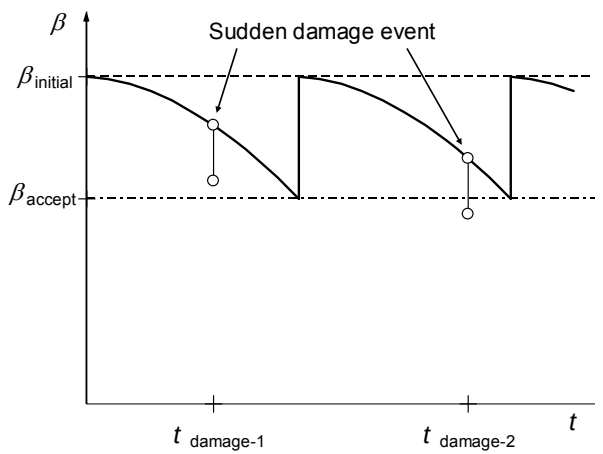
- Conclusions

Background and Motivation

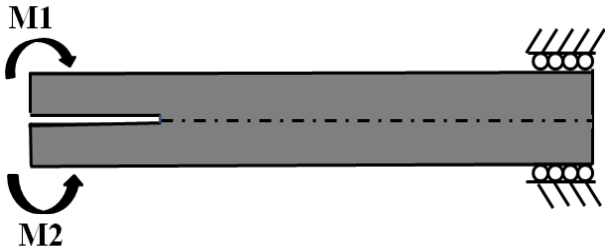
- Sandwich composites are today used over a broad range of industry applications
- Today structures are increasingly optimized to give minimum weight and max. perf.
- Pushes the utilizations of construction materials closer to their performance limits
- Built-in reserve margins may be significantly reduced
- 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** using **fracture mechanics** are therefore an increasingly important task
  - Fracture toughness
  - da/dN diagrams
  - Etc.



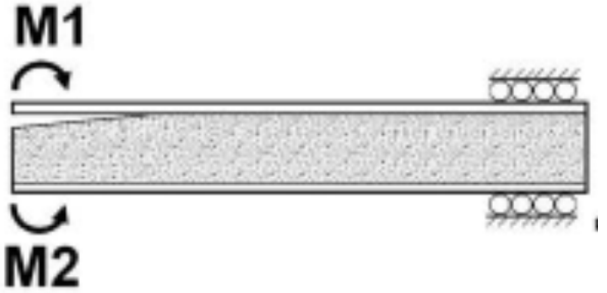
Fracture Toughness - Sandwich DCB-UBM specimen

Sandwich Double Cantilever Beam with Uneven Bending Moments (DCB-UBM) specimen

- Pure moments applied at the crack flanks
- No transverse forces
- G-controlled by nature
- Stable crack growth
  - Possible to develop large process zones



- 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



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

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

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

Sandwich DCB-UBM specimen reinforced with steel doublers

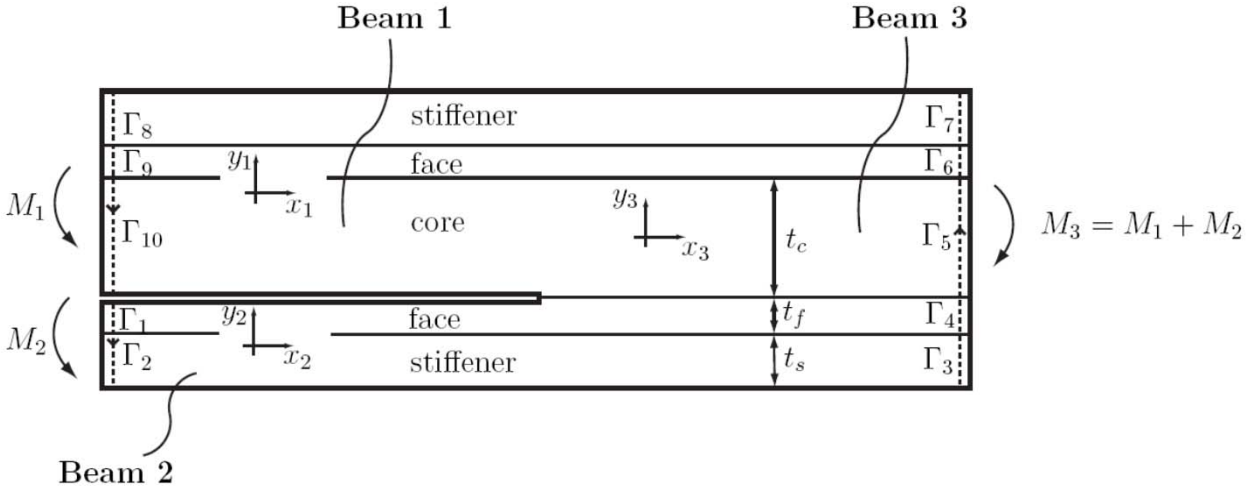
- Avoid excessive rotations with thin sandwich face sheets
- Steel reinforcement layers (doublers), but avoid yielding/damage in doublers
- Energy Release Rate (ERR) via J-integral calculation with doubler layers: *(Lundsgaard et al, 2007)*
- *On-going work to derive closed-form expressions for ERR and mode-mixity for a general penta/n layer configuration*

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

$$A_b = \sum_{k=1}^{n} \bar{E}_k (y_k - y_{k-1})$$

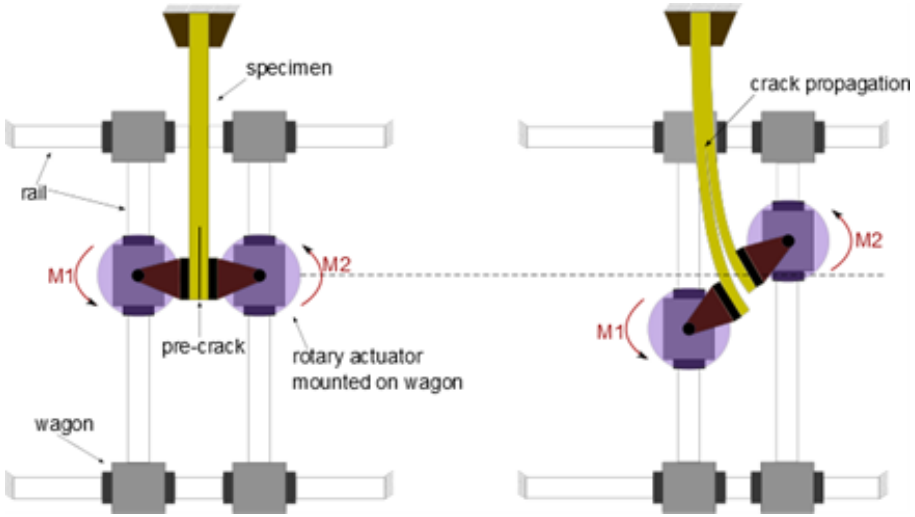
$$B_b = \frac{1}{2} \sum_{k=1}^{n} \bar{E}_k ({y_k}^2 - {y_{k-1}}^2)$$

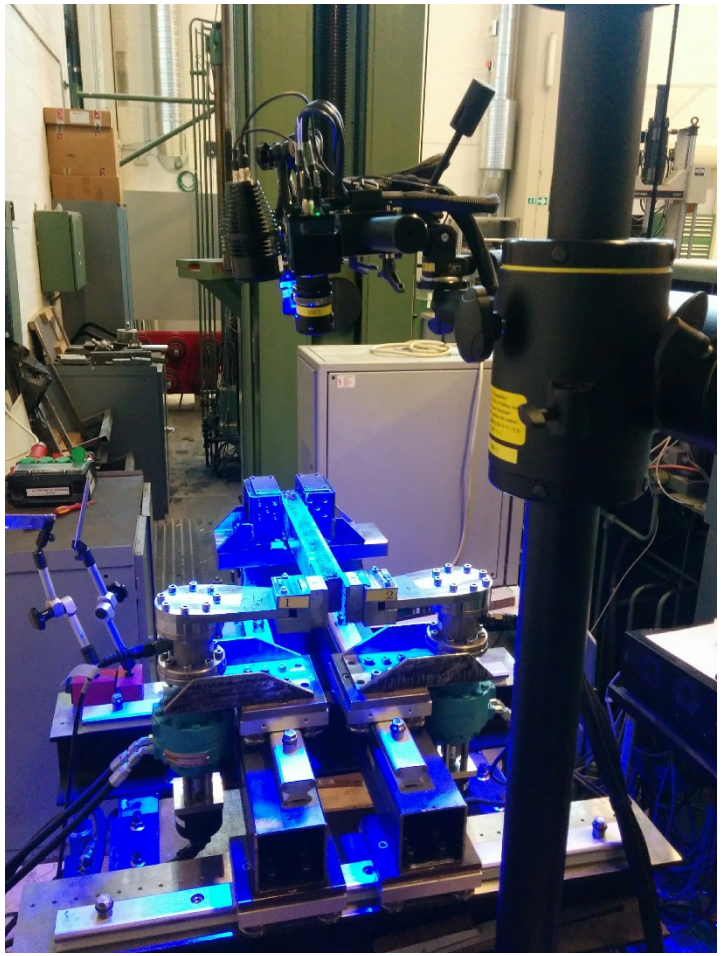
$$D_b = \frac{1}{3} \sum_{k=1}^{n} \bar{E}_k ({y_k}^3 - {y_{k-1}}^3)$$



Sandwich DCB-UBM specimen
Novel compact fatigue rated rig

- *Novel* 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

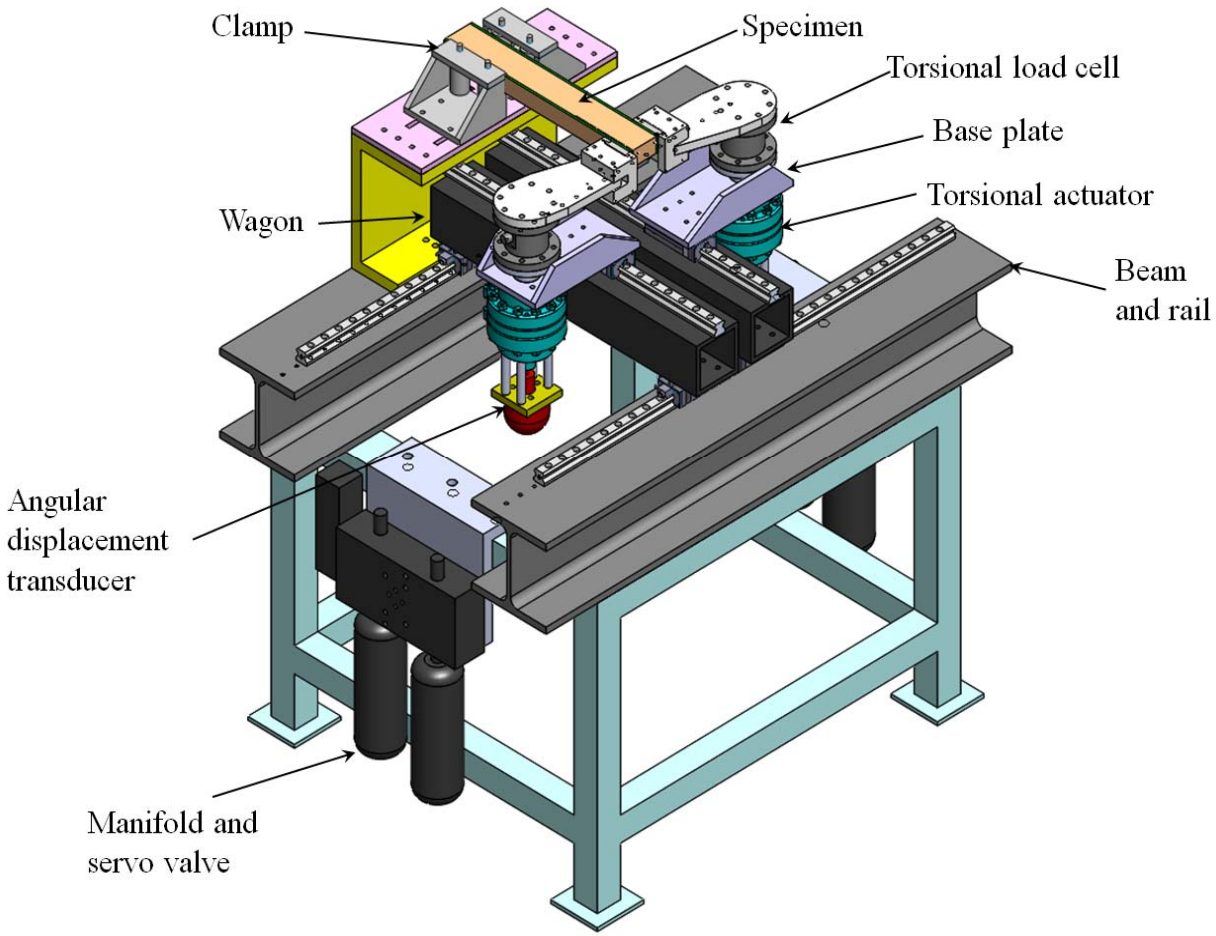




Sandwich DCB-UBM specimen
Novel compact fatigue rated rig

Specifications:

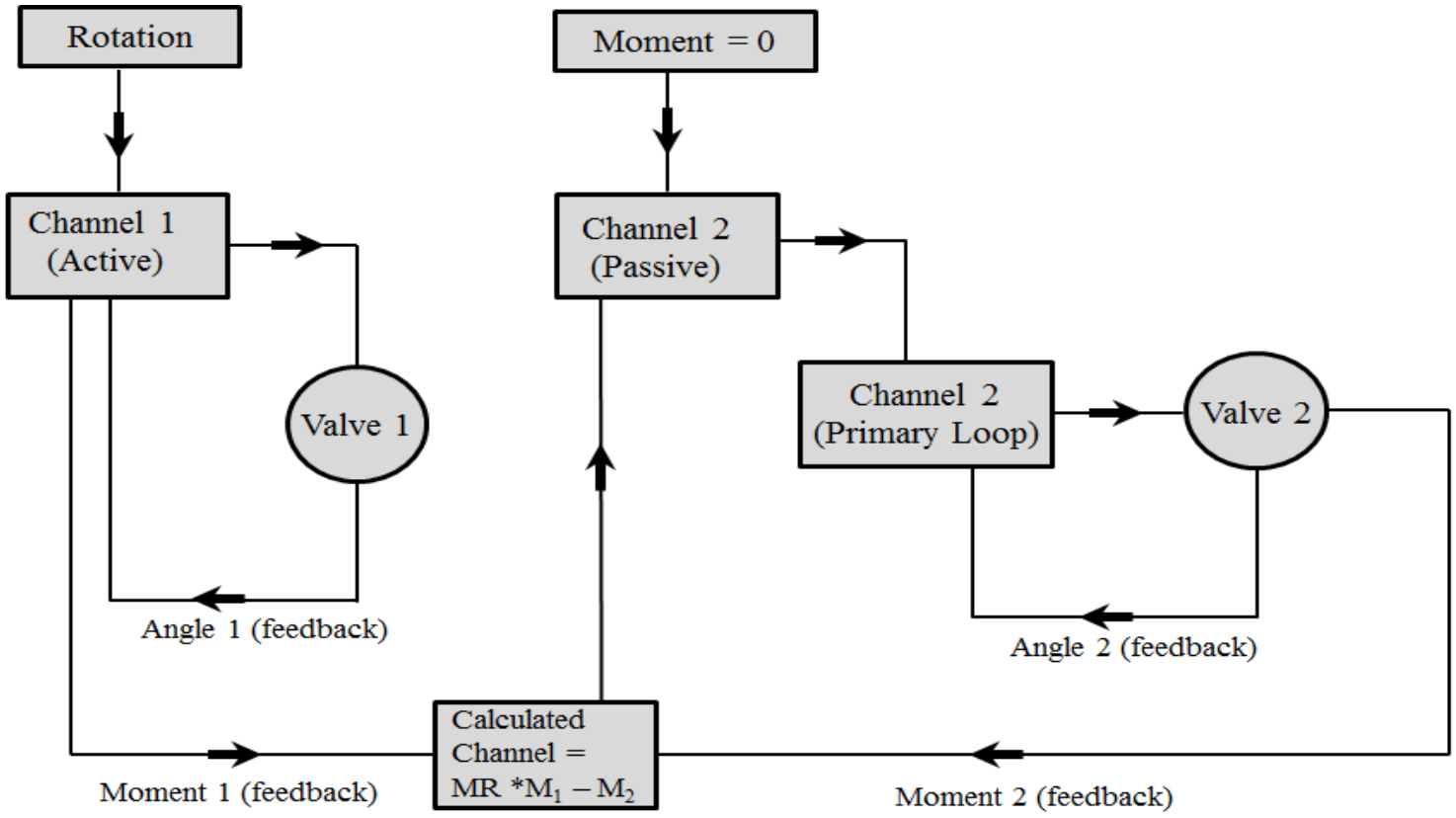
- Low friction roller wagon/rail system
  - Two torsional actuators (700 Nm)
  - Two 10 [L/min] servo-valves
  - Two 565 [Nm] torsional load cells
- Bi-axial servo-hydraulic controller (MTS FlexTest SE)
- Conditional control (CASCADE)
  - Rotation controlled tests



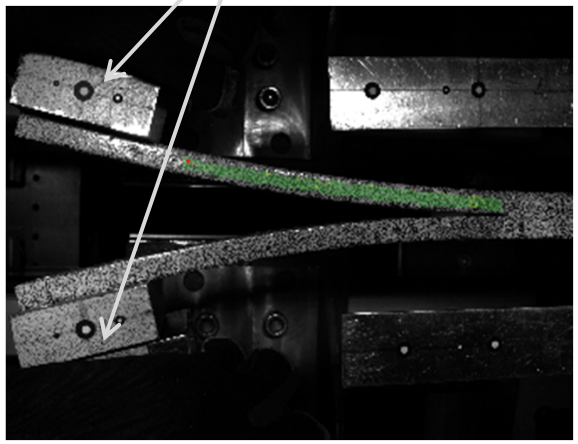
Sandwich DCB-UBM specimen

New compact fatigue rated rig

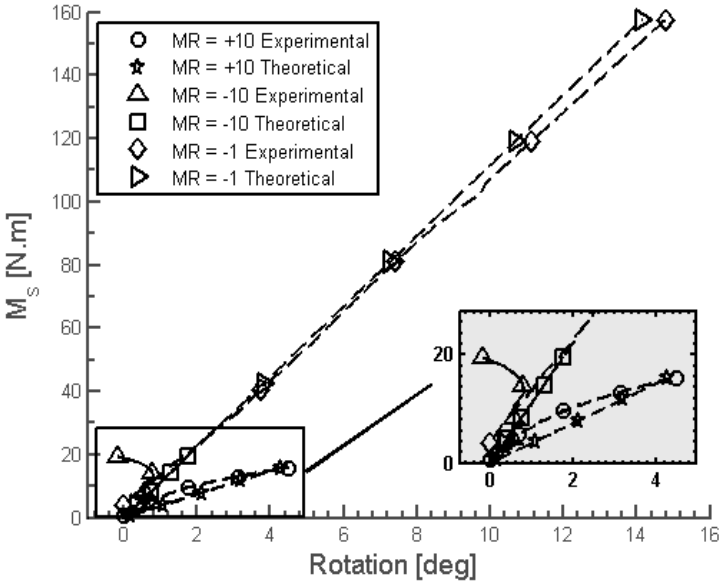
- Bi-axial conditional control loop (CASCADE control)

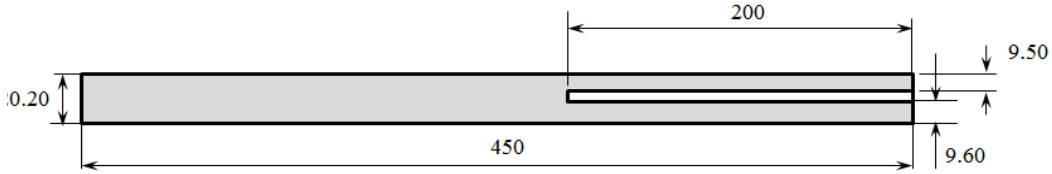


Sandwich DCB-UBM specimen
Friction Study



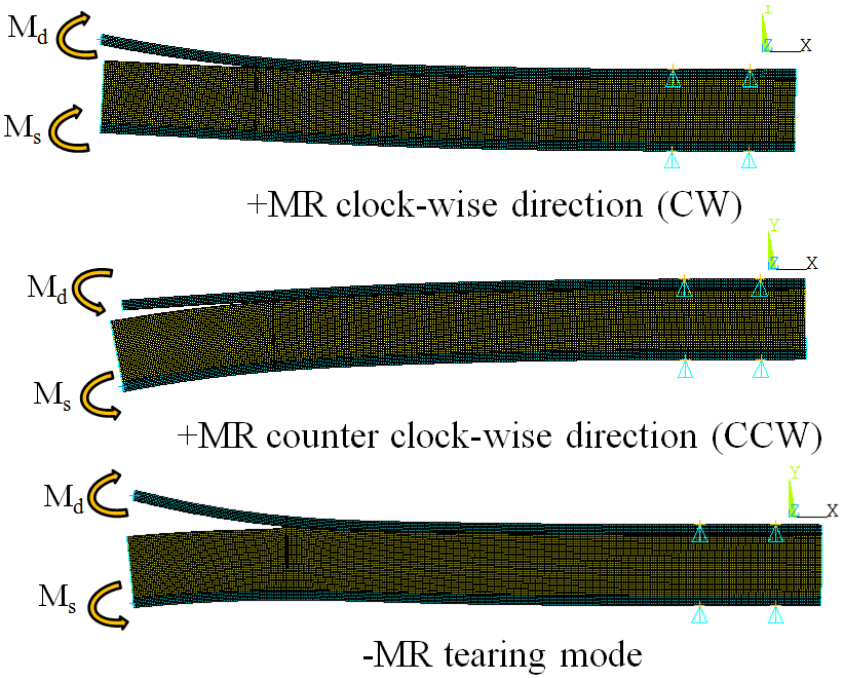
- Friction study performed using a calibraton specimen
- Calibration performed under MR =10, -10, -1 (*prominment cases*)
- ARAMIS 12M DIC system used for tracking of rotation & to check for yielding in the calibration specimen

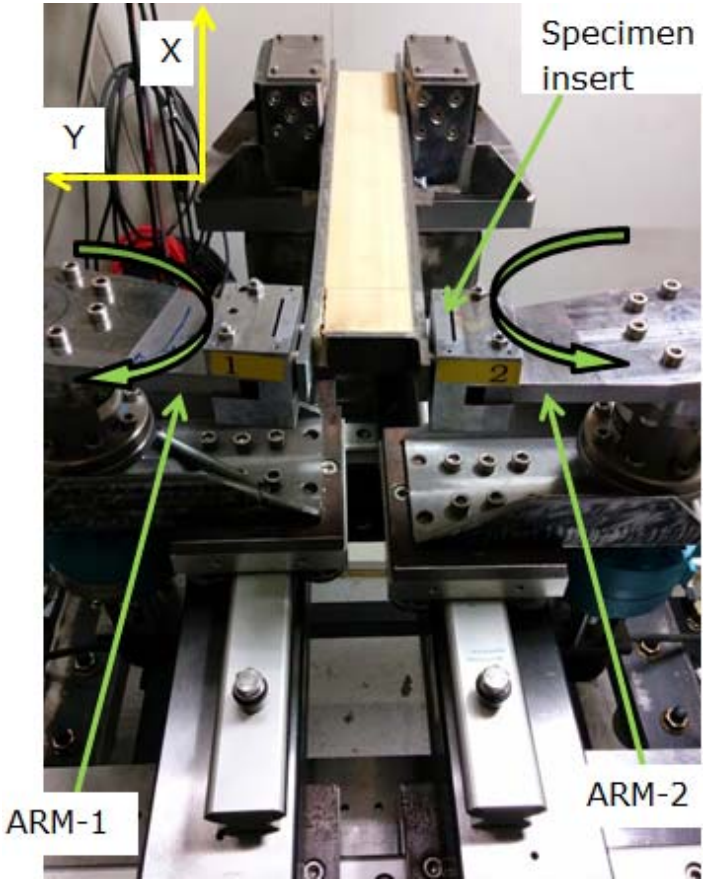




Mixed-mode screening of H45 sandwich specimens

- Moment Ratio – sign convention, MR = Md/Ms

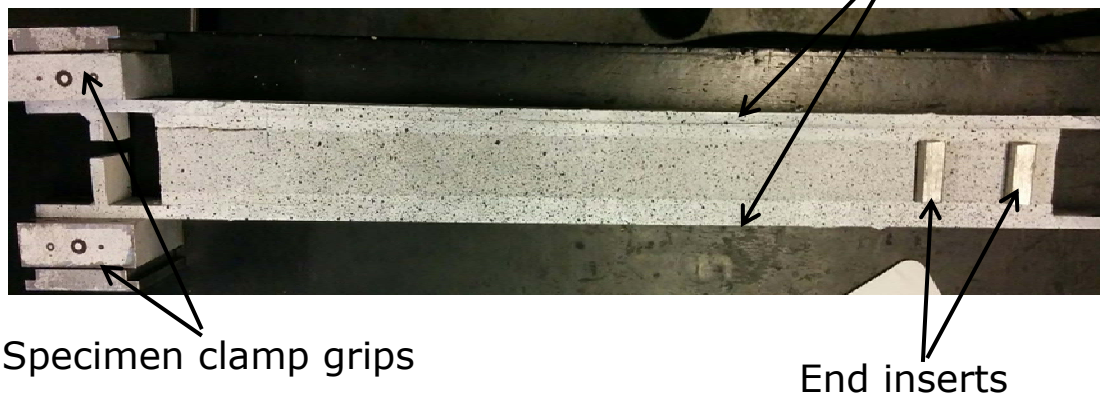


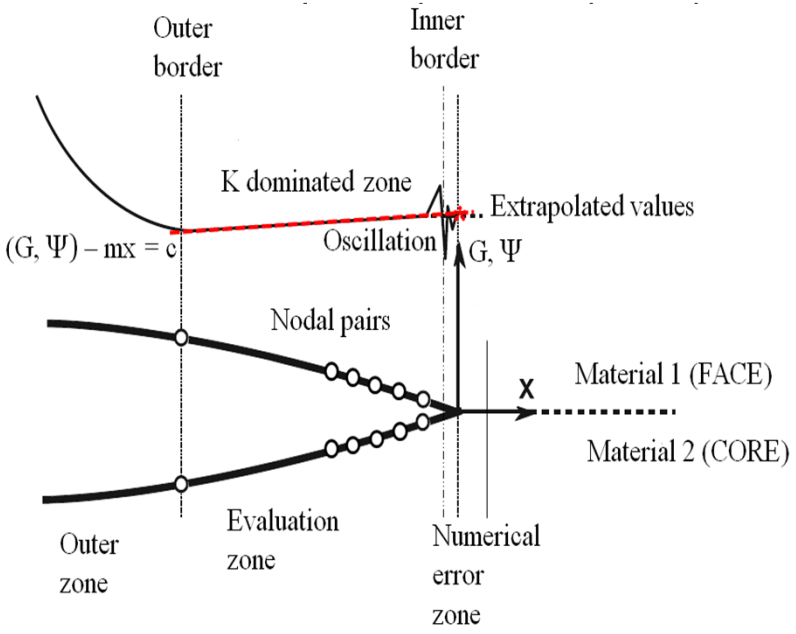


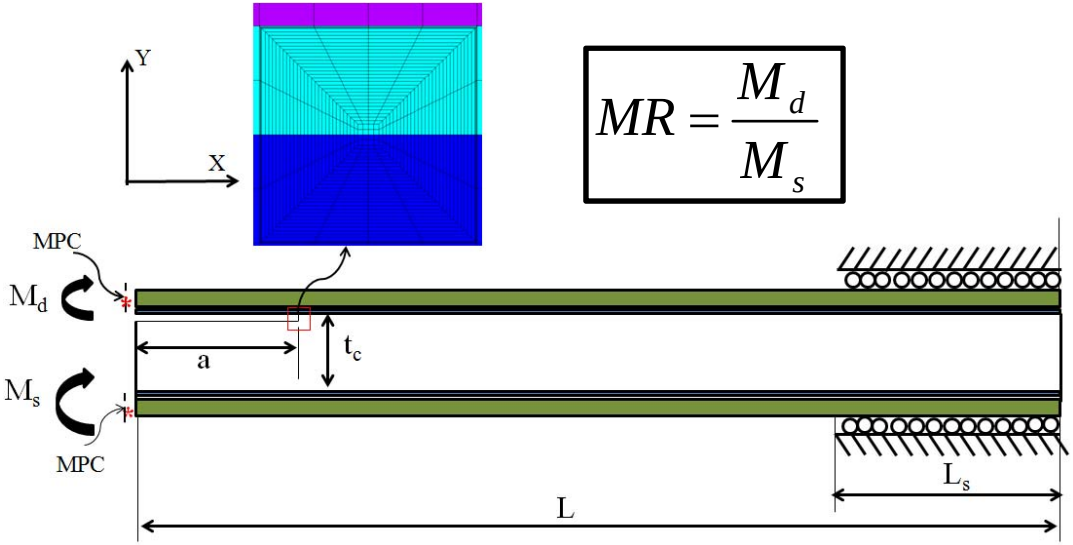
Mixed-mode screening of H45 sandwich specimens

- Face-sheet thickness t_f = 5.7 [mm], core-thickness t_c = 30 [mm]
  Beam lengh, L = 450 [mm]

- Sizing of doubler (in LEFM regime)
  - HS Steel σ_y= 750 [MPa]
  - J = 1500 [J/m^2] , t_{steel} = 6 [mm]





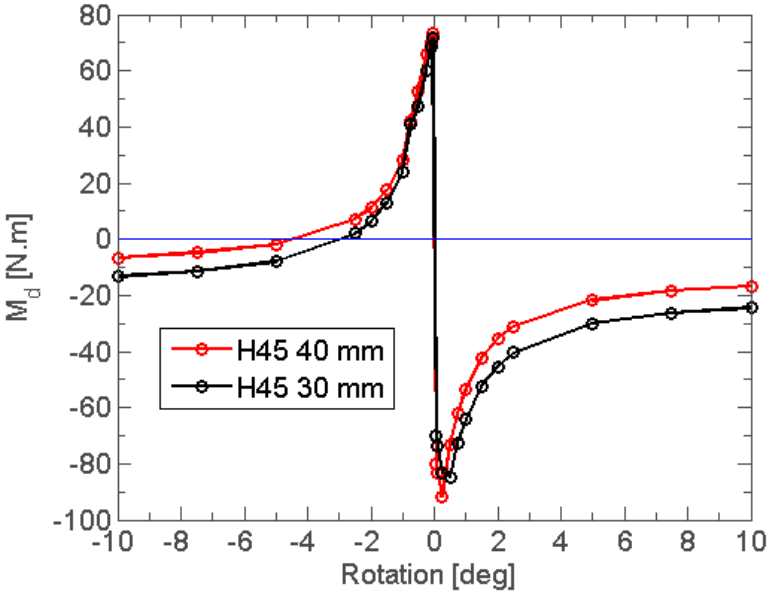


$$MR = \frac{M_d}{M_s}$$

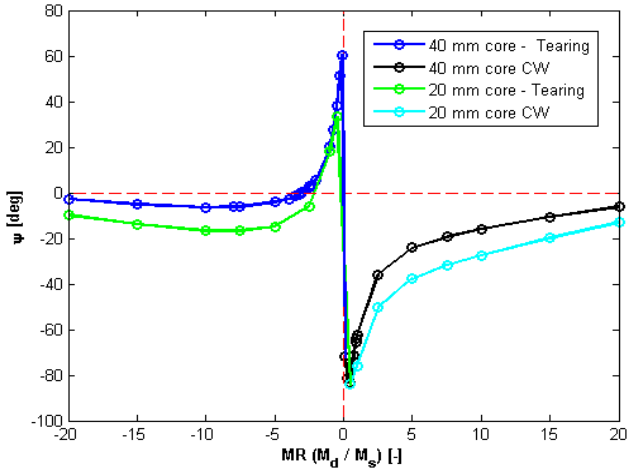
Mixed-mode screening of H45 sandwich specimens

Phase angle vs. moment ratio map - CSDE

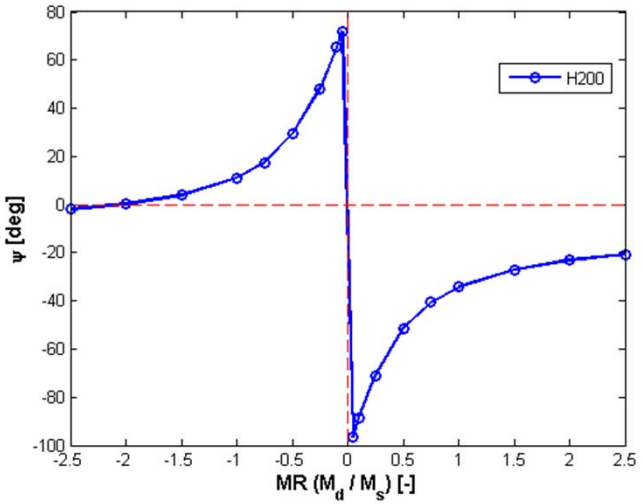
- Mode-mixity map made for different core types, **H200**, **H45**, **Nomex honeycomb**



Specimen dimension: (450 mm x 30 mm)



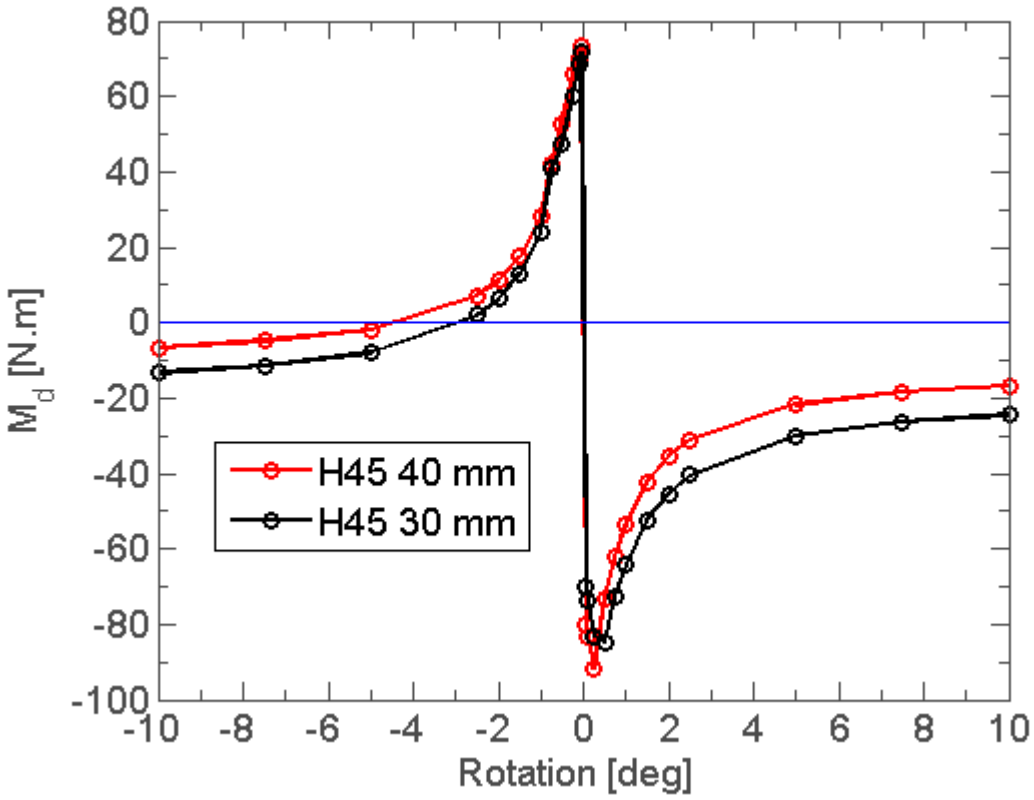
Nomex Honeycomb core



H200 foam – 40 mm

Mixed-mode screening of H45 sandwich specimens

Mode-mixity phase angle vs. moment ratio map: MR Selection



MR	Ψ [deg]
-10	-13.3
-7.5	-11.6
-5.0	-7.9
-2.5	1.98
1.0	-64.1
-1	20.2
1.5	-52.5
2.0	-45.4
5.0	-29.9
7.5	-26.4
10	-24.6

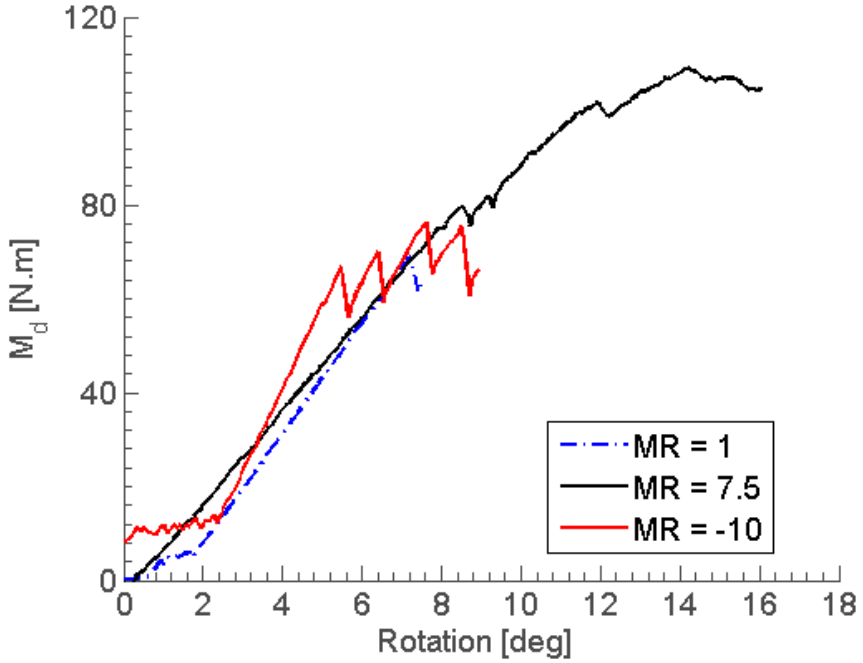
Specimen dimension: (420 mm x 30 mm)

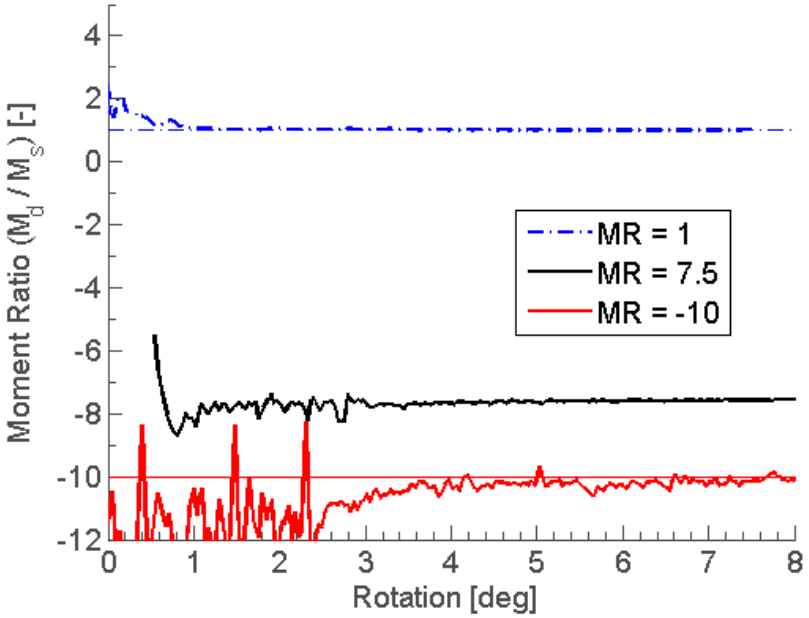
Thickness of core for test = 30 [mm]

Mixed-mode screening of H45 sandwich specimens

Moment and MR vs Rotation

- **M_d vs θ_d** and **MR vs θ_d**



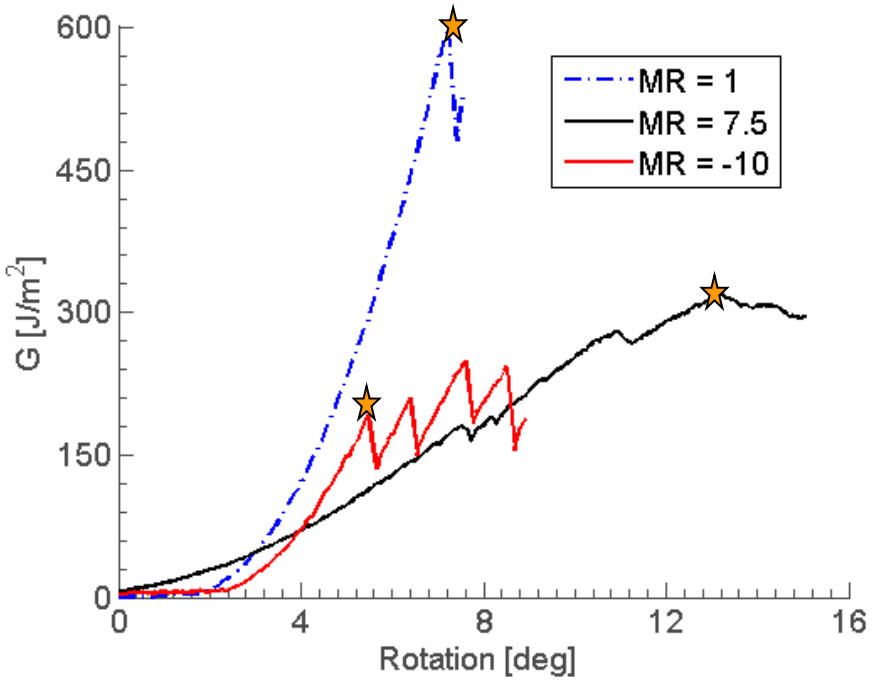


Controller compensates for the crack propagation and adjusts substrate arm based on input MR

Mixed-mode screening of H45 sandwich specimens

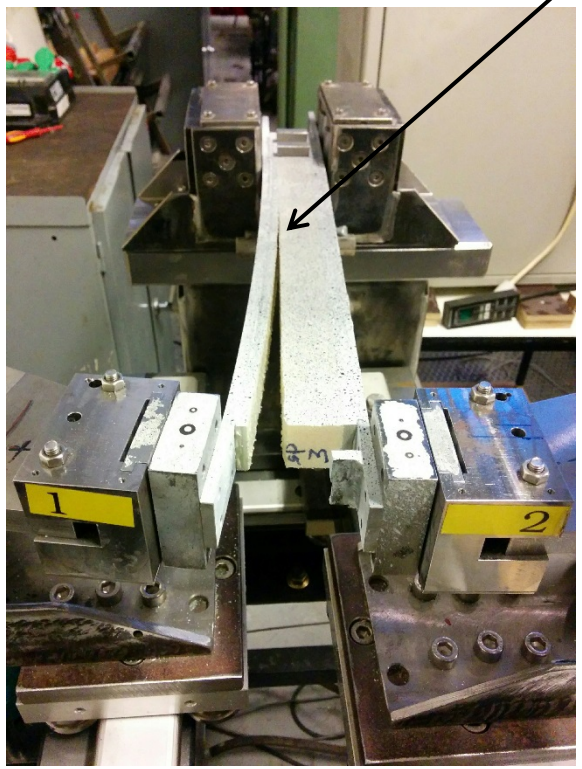
ERR vs Rotation

- ERR vs θ_d



Interface crack

MR = 7.5, ψ = -26.4°



MR = 1.0, ψ = -64.1 , $\Gamma_{J\text{-analyt}}$ = 589.7 [J/m²]

MR = 7.5, ψ = -26.4 , $\Gamma_{J\text{-analyt}}$ = 315.5 [J/m²]

MR = -10, ψ = -13.3, $\Gamma_{J\text{-analyt}}$ = 248.2 [J/m²]

Conclusions, On-going and Future Work

- A new novel DCB-UBM test rig was presented for measurement of toughness properties for PVC foam cored sandwich specimens
- Comparison of fracture toughness data from literature showed small deviations
- Re-usability of same specimen for various mode-mixities
- **On-going work**: Fracture toughness data reduction based on sudden departure from the G vs Rotation plot (slope > 5%)
- **On-going work**: Derivation of closed-form expressions for a general specimen configuration with doublers
- **On-going work**: Measurement of fracture toughness properties in aircraft honeycomb sandwich specimens (with Airbus)
- **Future work**: Expansion to fatigue testing!

THANK YOU FOR YOUR ATTENTION!

ACKNOWLEDGMENT

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