An integrated approach to data-rich testing and modelling of composite structures and sub-structures (for maritime applications)

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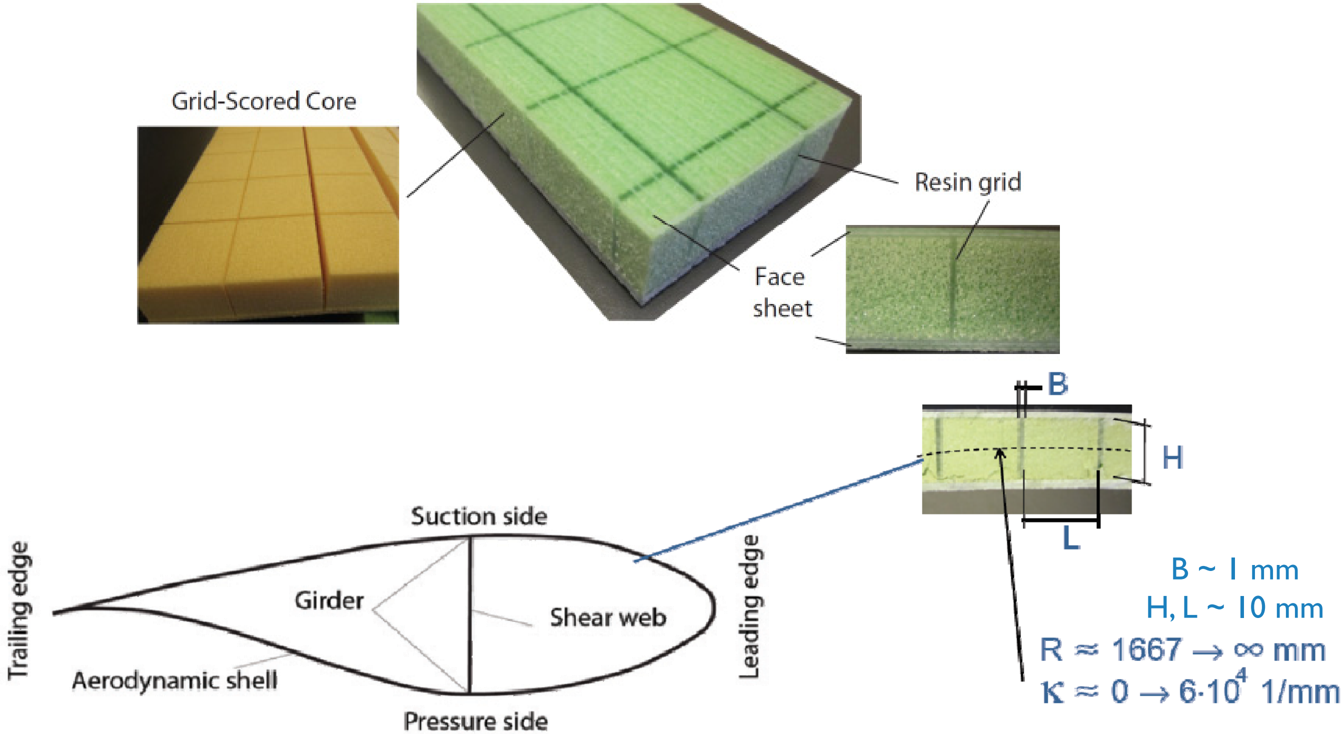
Outline

- Background and motivation
- Objectives
- High fidelity (smart) testing demonstrator – wind turbine blade substructure
- Experimental substructure testing methodology
- Grid-score failure under multi-axial loading – experimental results and predictive models
- Generic road-map for high-fidelity composite substructure testing
- Conclusions

Background & motivation

- Background problem: load response and failure behaviour of 'grid-scored' sandwich panels used in wind turbine blades (very similar to boat hull structures wrt. materials, manufacturing and load environment).



- In service occurrence of large face sheet/core debonds near root end section
- No explanation of causes from design analyses or simple coupon tests.

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- Failure data based on simple (uniaxial) coupon tests renders information of limited value with respect to understanding and explaining the in-situ material failure behaviour experienced in complex full scale composite structures subjected to multiaxial loading conditions.
- Computational predictions of the load response and failure behaviour of complex large scale composite structures are typically based on input in the form of experimental data obtained from simple/conventional coupon tests.

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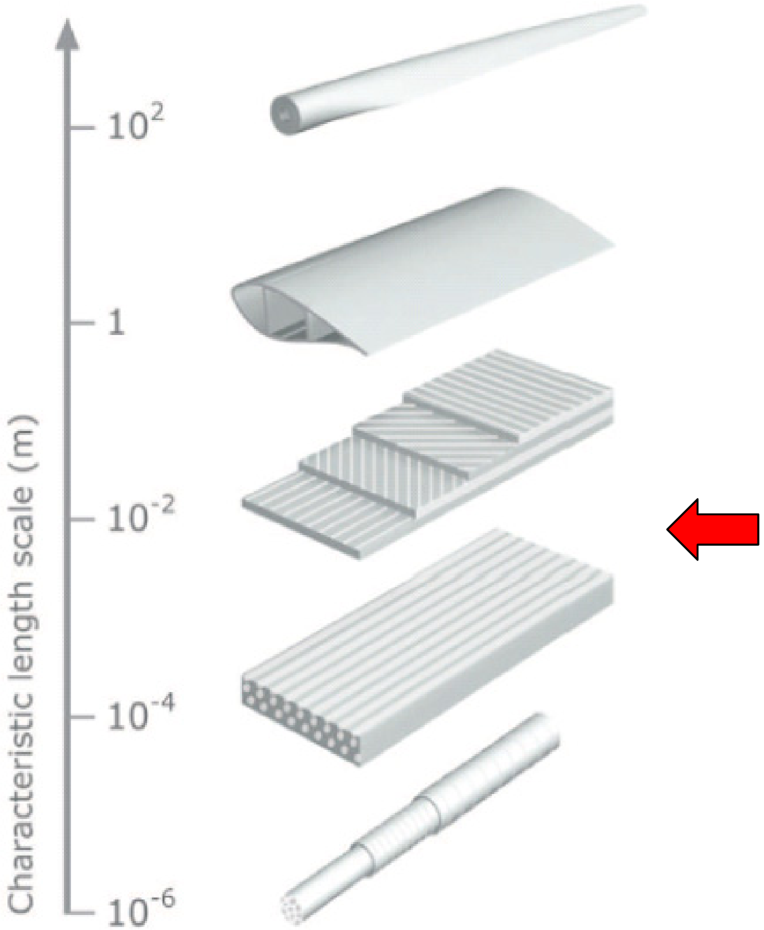
- Prediction of initiation and propagation of failure often very inaccurate and in some cases completely off.
- Full scale structural testing would be a more consistent approach.
- Costs associated with full scale structural testing are often/typically prohibitive.
- Amount of data and the complexity associated with conducting and controlling the actual testing to realise the desired loads and failure behaviour makes full scale testing less attractive.

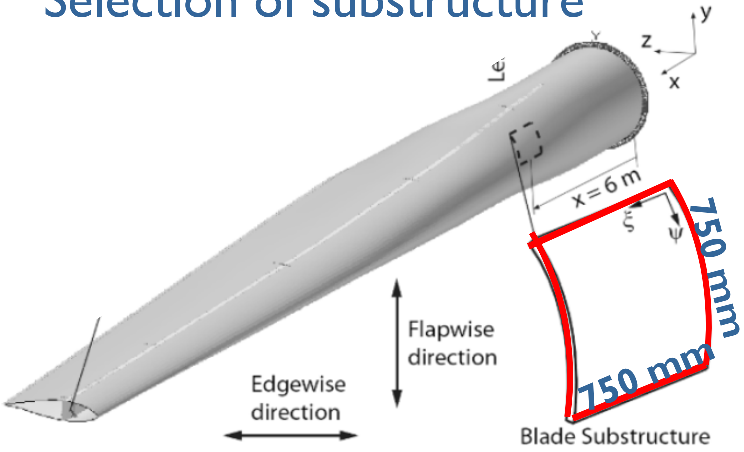
Objectives

- Outlining of a facility and general methodology for high-fidelity mechanical testing integrated with computational modelling that enables realization of realistic loading conditions on substructures/ components instrumented using state of the art full field imaging and sensor techniques.
- Will enable the conduction of data rich testing that will include quantitative monitoring and assessment of the multiaxial load response, failure initiation and progression.
- **Improved prediction of failure and performance envelopes.**
- Data can/will in turn be used to inform and improve computational models with an aim to improve their predictive capabilities wrt. load response and failure.

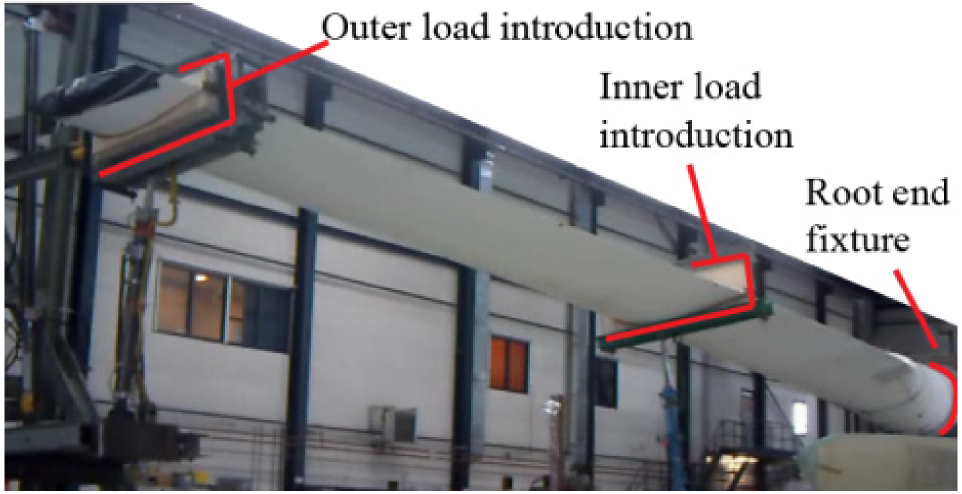


High fidelity (smart) testing demonstrator – wind turbine blade substructure

Selection of substructure



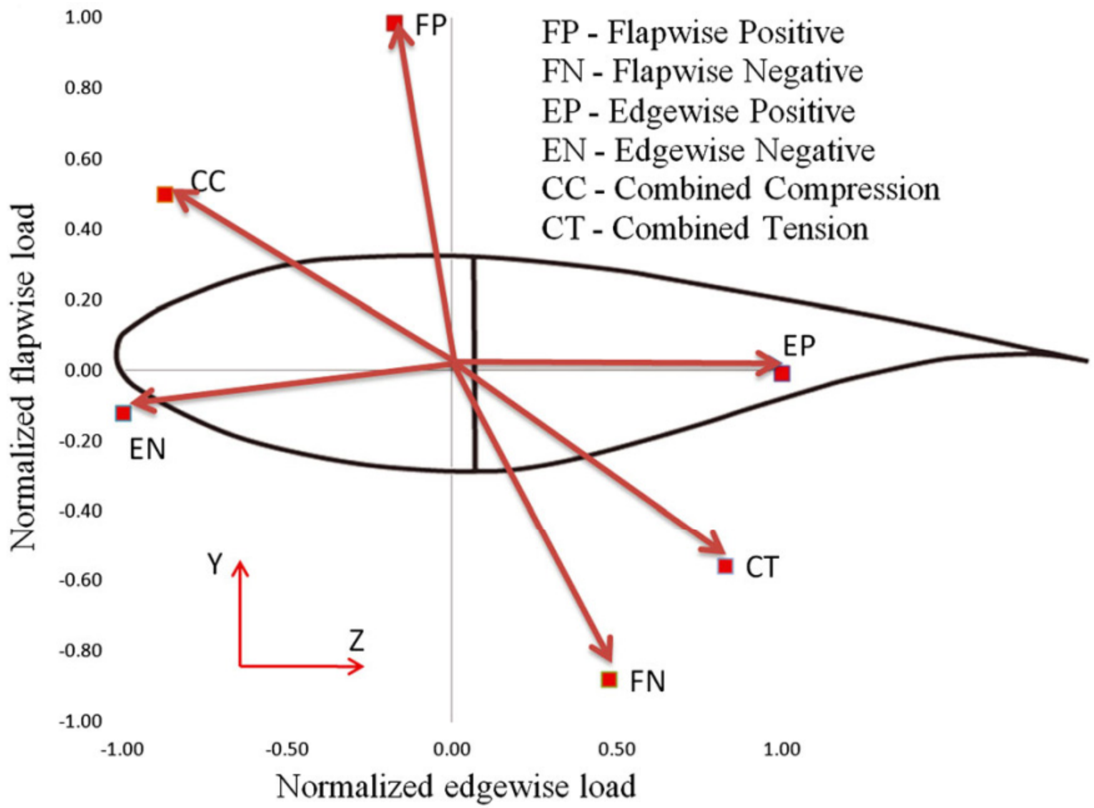
Full scale blade test setup



Monitoring

Measurements provided detailed recording of the local loading/displacement conditions experienced by substructure

Definition og load and displacement boundary conditions



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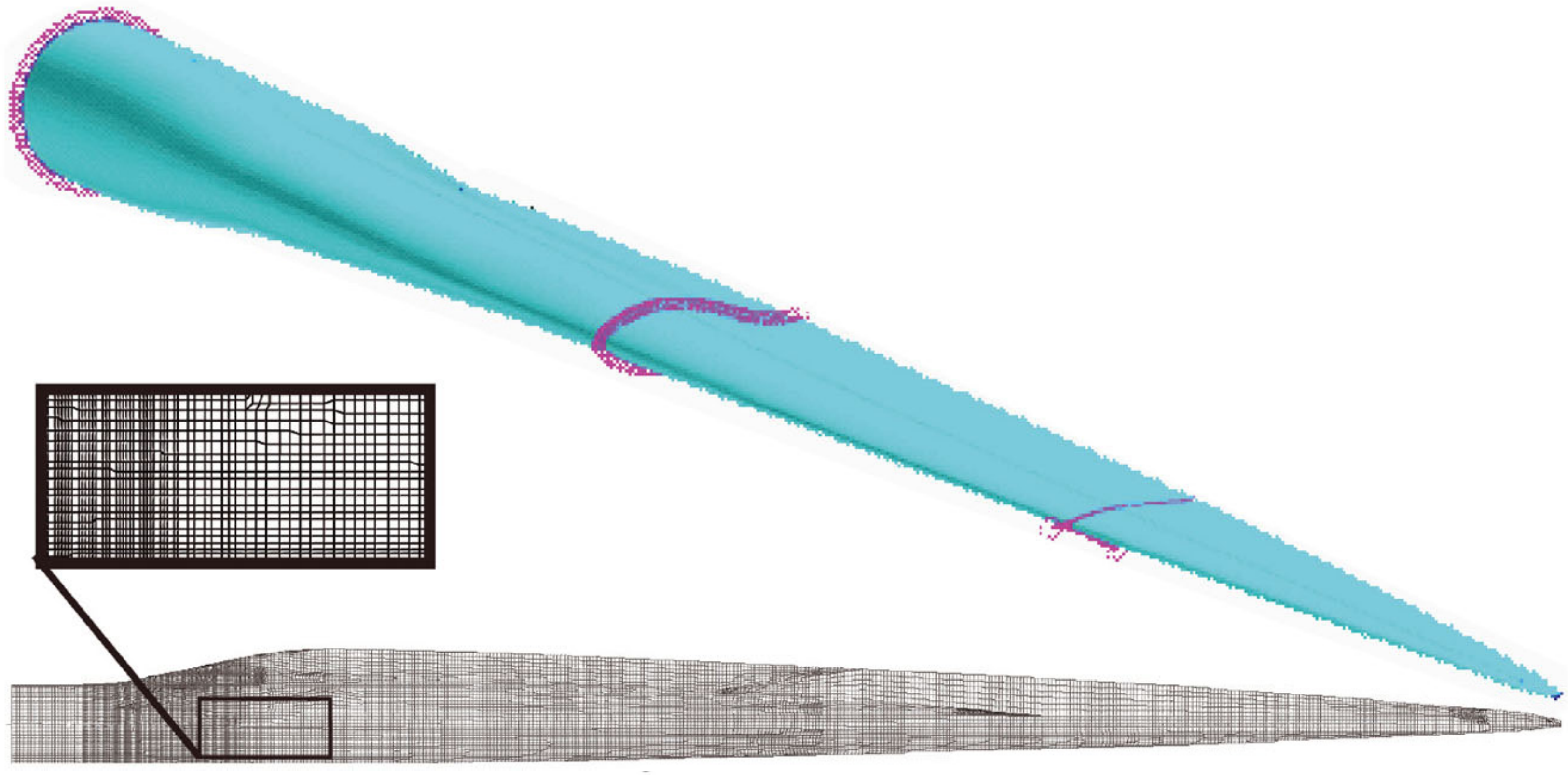
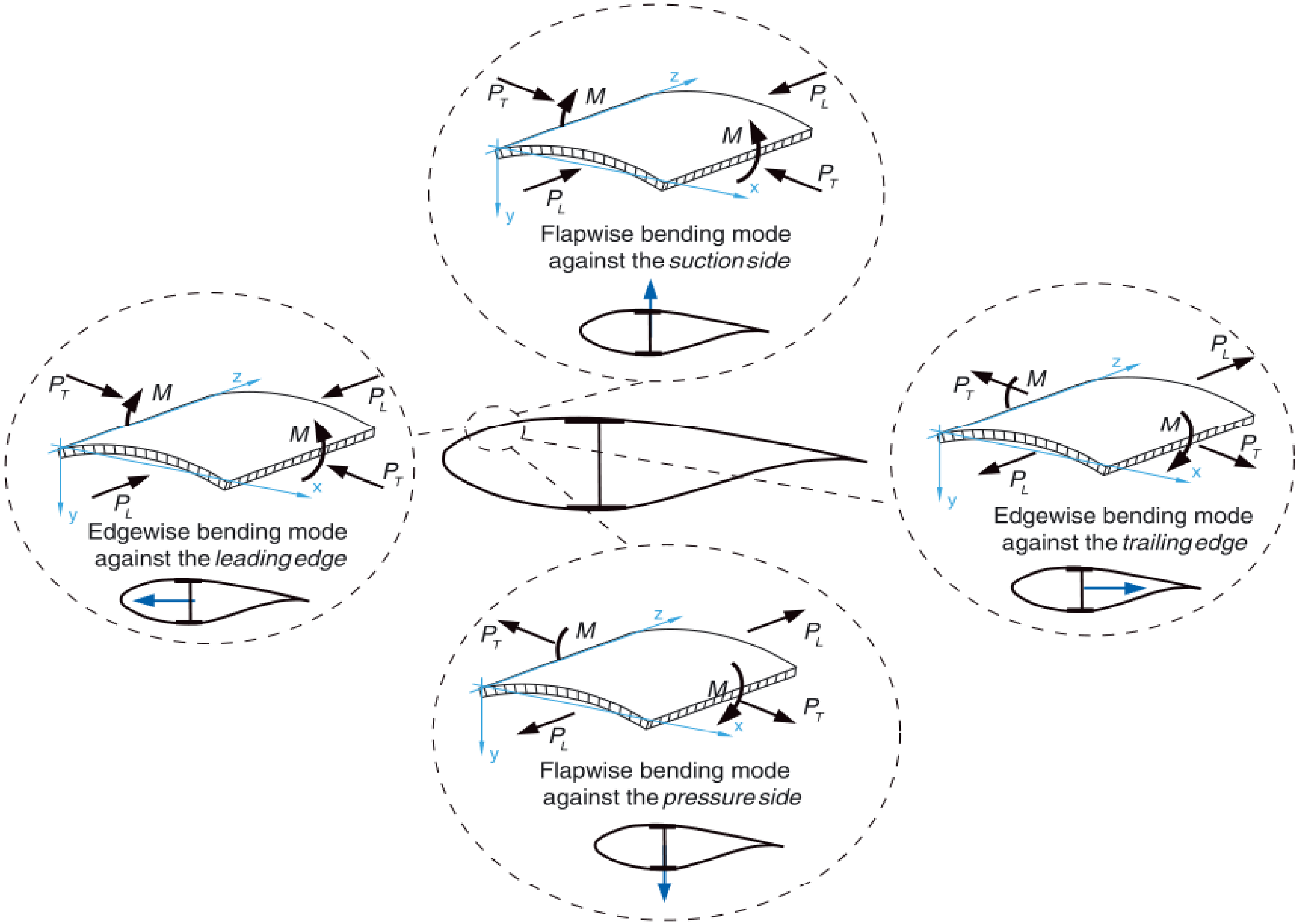
Definition og load and displacement boundary conditions

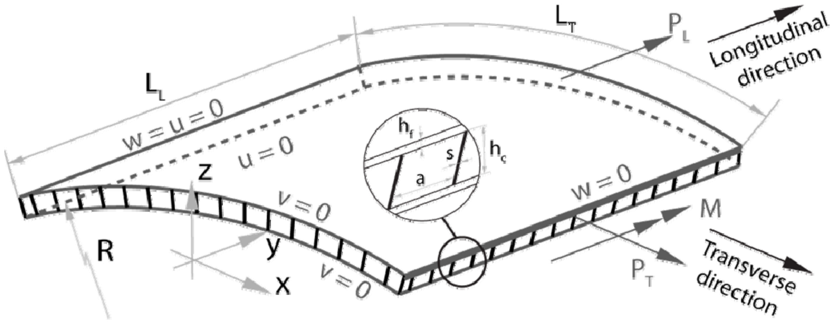


Geometrically nonlinear FE analysis (solid shell elements)

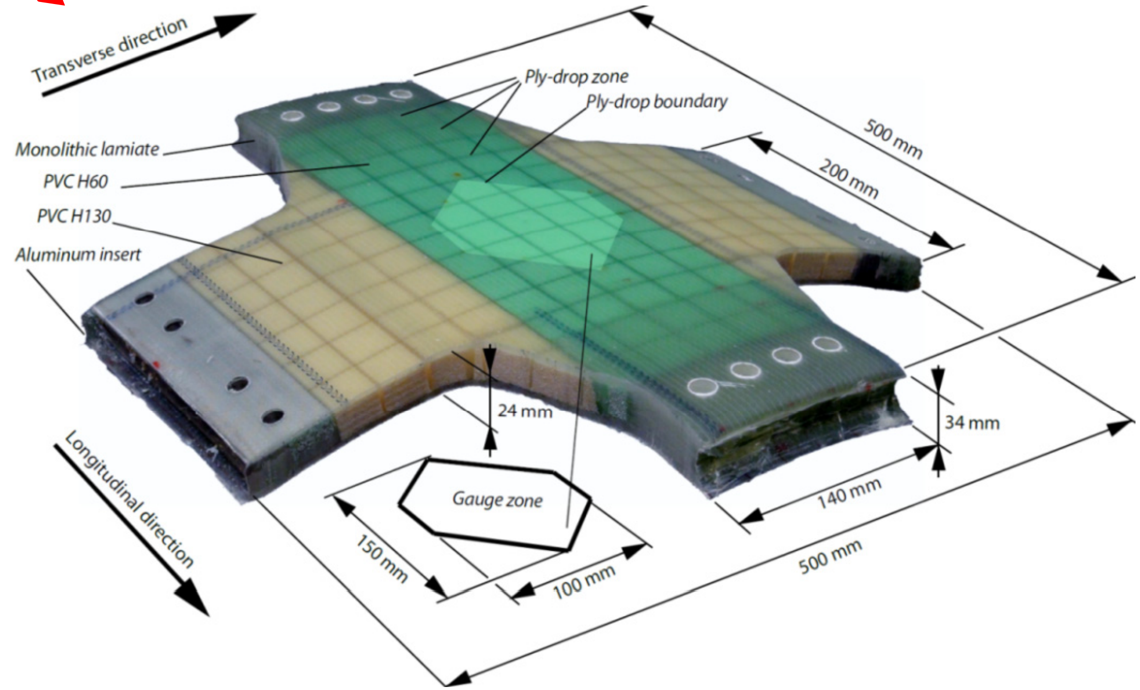


Flapwise bending mode against the *suction side*
Edgewise bending mode against the *leading edge*
Edgewise bending mode against the *trailing edge*
Flapwise bending mode against the *pressure side*

Full scale results are translated into local loading conditions



Substructure test specimen



Experimental substructure testing methodology

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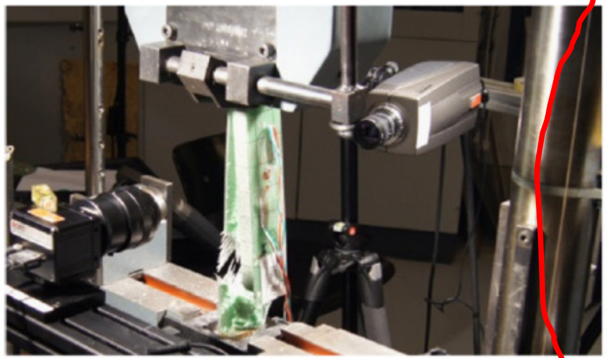
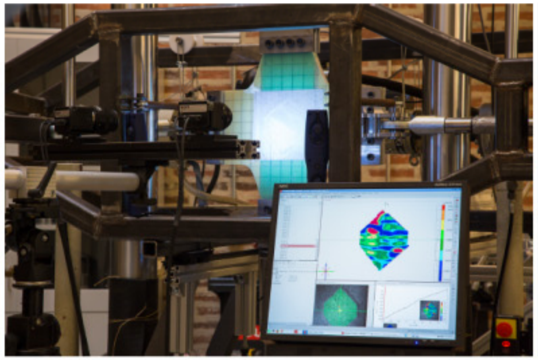
Uniaxial testing of coupon specimen



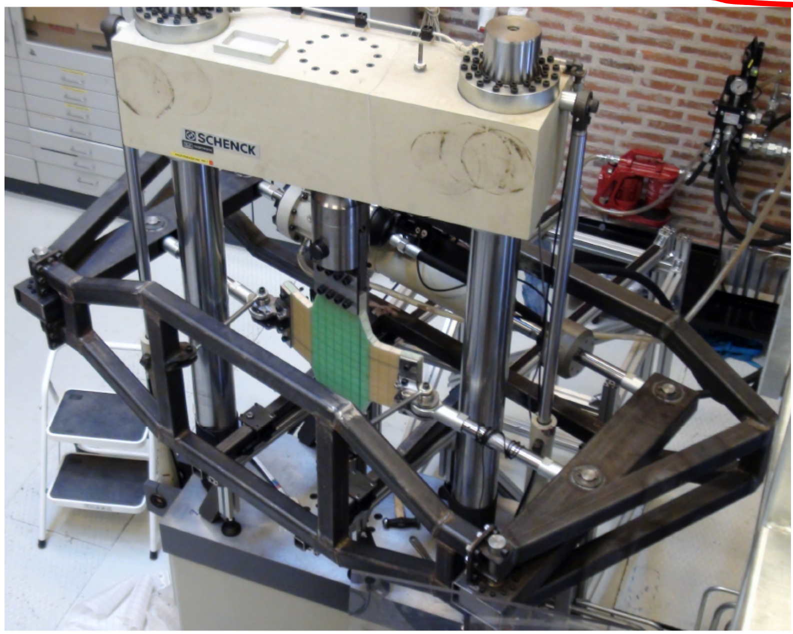
Accurate measurement of high resolution test data

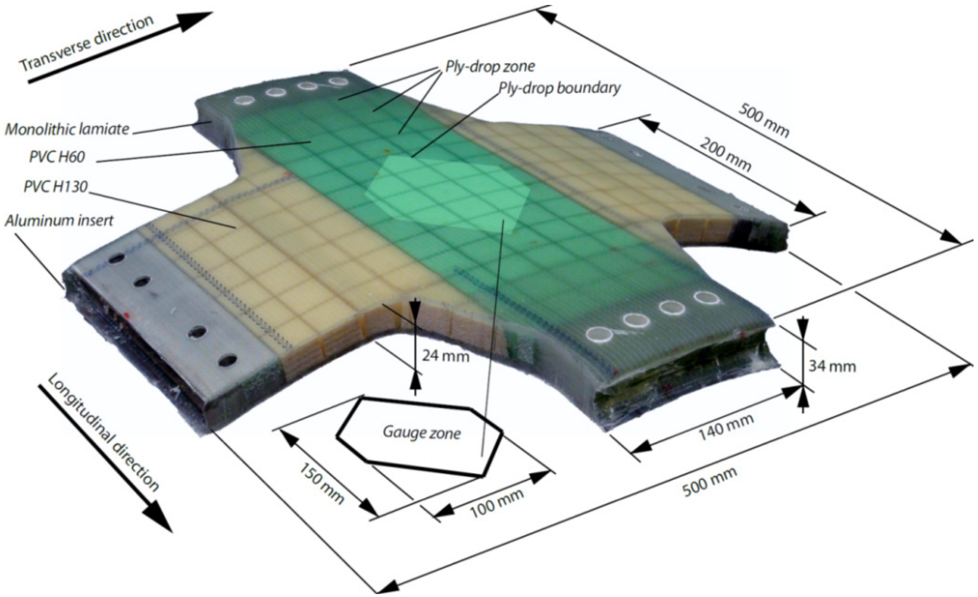
Multiaxial testing of substructure



Full scale testing of full scale structure

Accurate representation of loading conditions

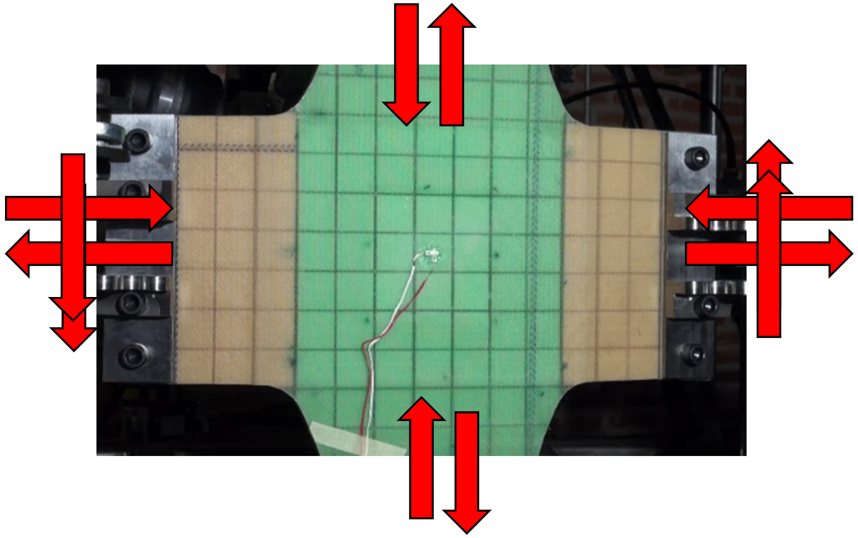


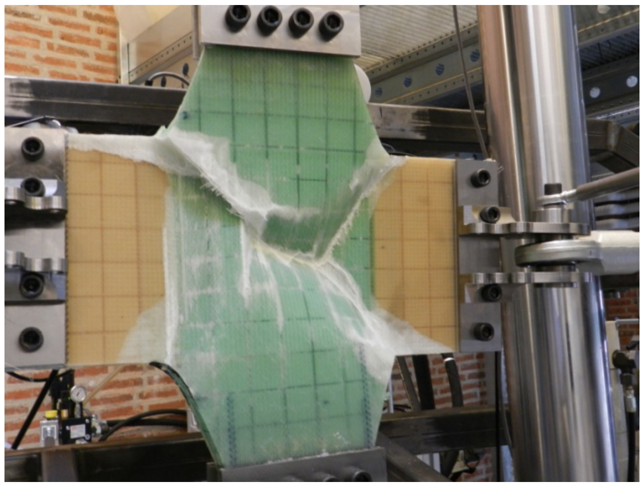


Biaxial compression loading - cyclic fatigue

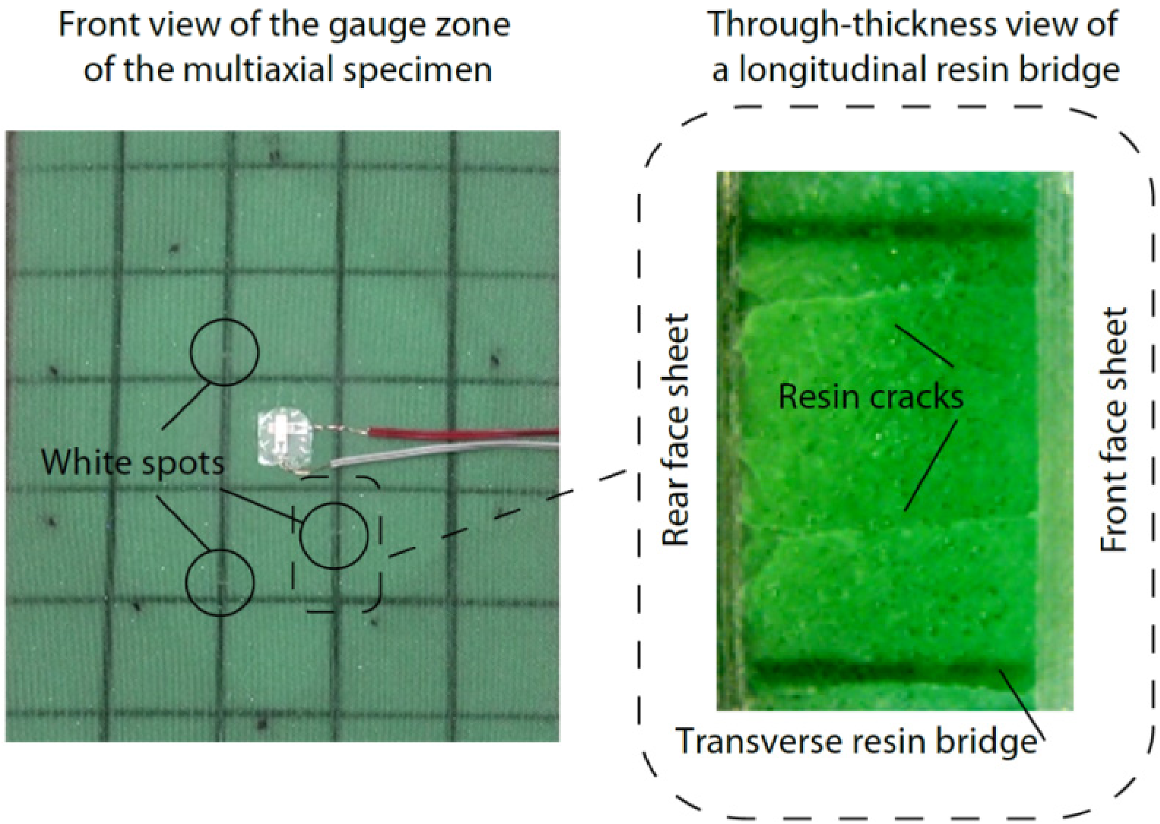
Grid-score failure under multi-axial loading – experimental results and predictive models

- Failure phenomena triggered by a significant transverse bending moment occurring due to blade cross section ovalization.
- Detailed overview of the failure behaviour under realistic loading conditions and how the different constituents influence this behavior.
- Critical combinations of the load components, P_L, P_T, and M, that caused failure to initiate in the resin grid.
- Biaxial compression generally observed to be most critical – transverse resin bridges triggered ***wrinkling*** of the front face sheet (resulted in a complete loss of load carrying capacity).

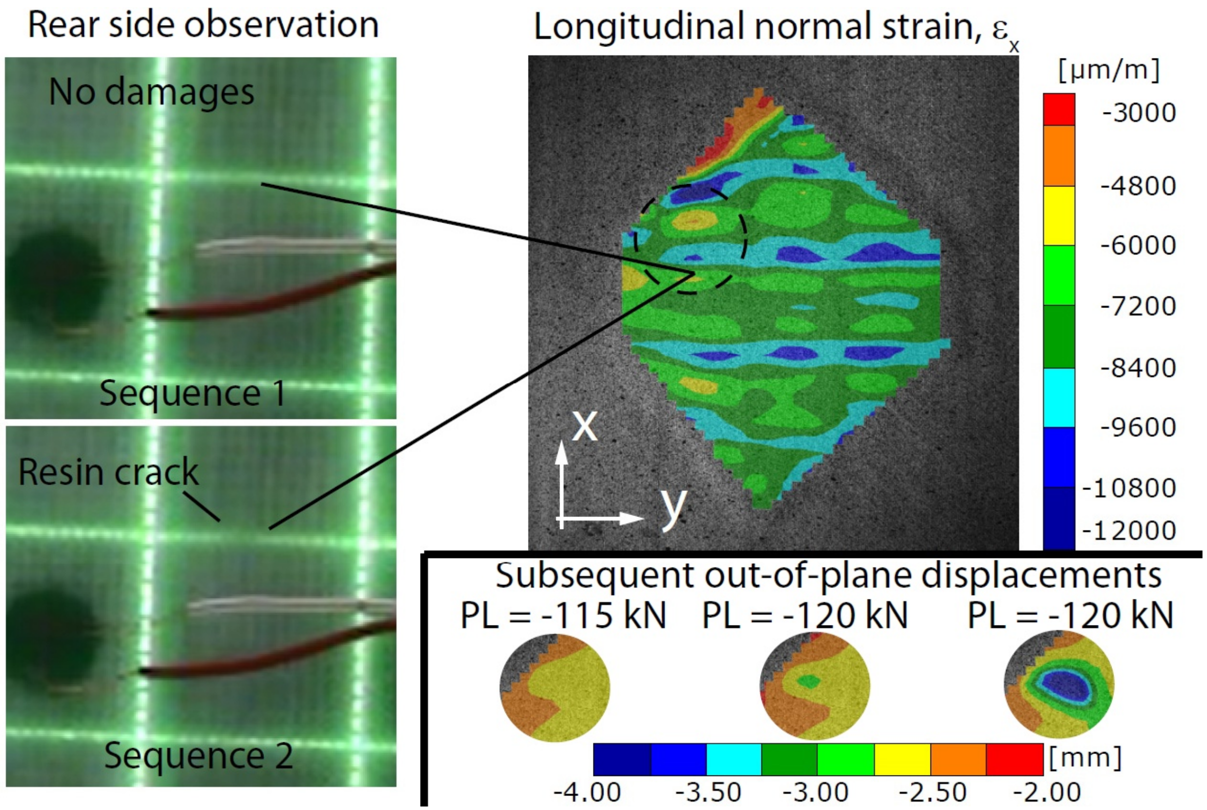


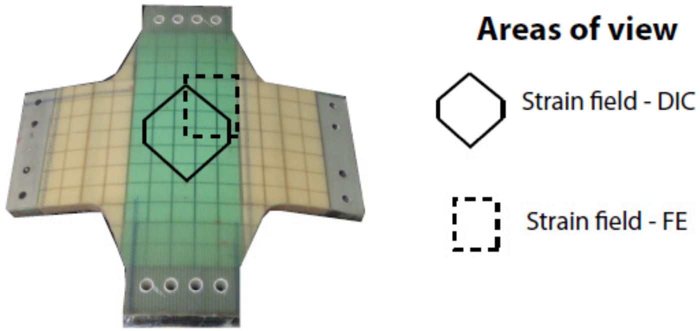


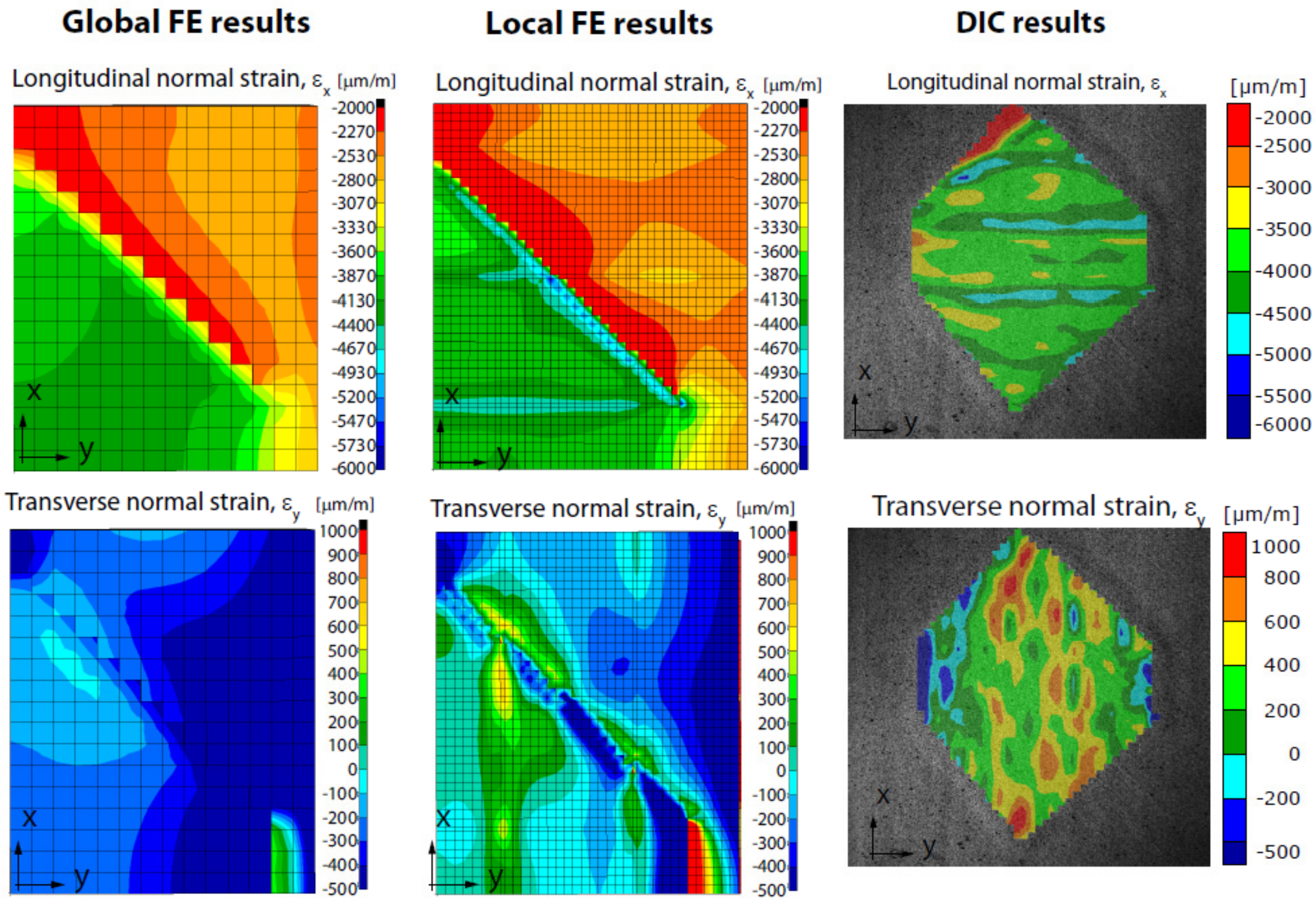
Post mortem images showing through-thickness (z direction) cracks in the longitudinal resin bridge when subjected to the ***multi-axial tension load case***.



Failure event recorded by DIC on the front side of the specimen and video recording from the rear side at P_L=-110 kN for the ***biaxial compression load case***.
Out-of-plane face sheet displacement fields within the circular area are shown at 3 different stages.







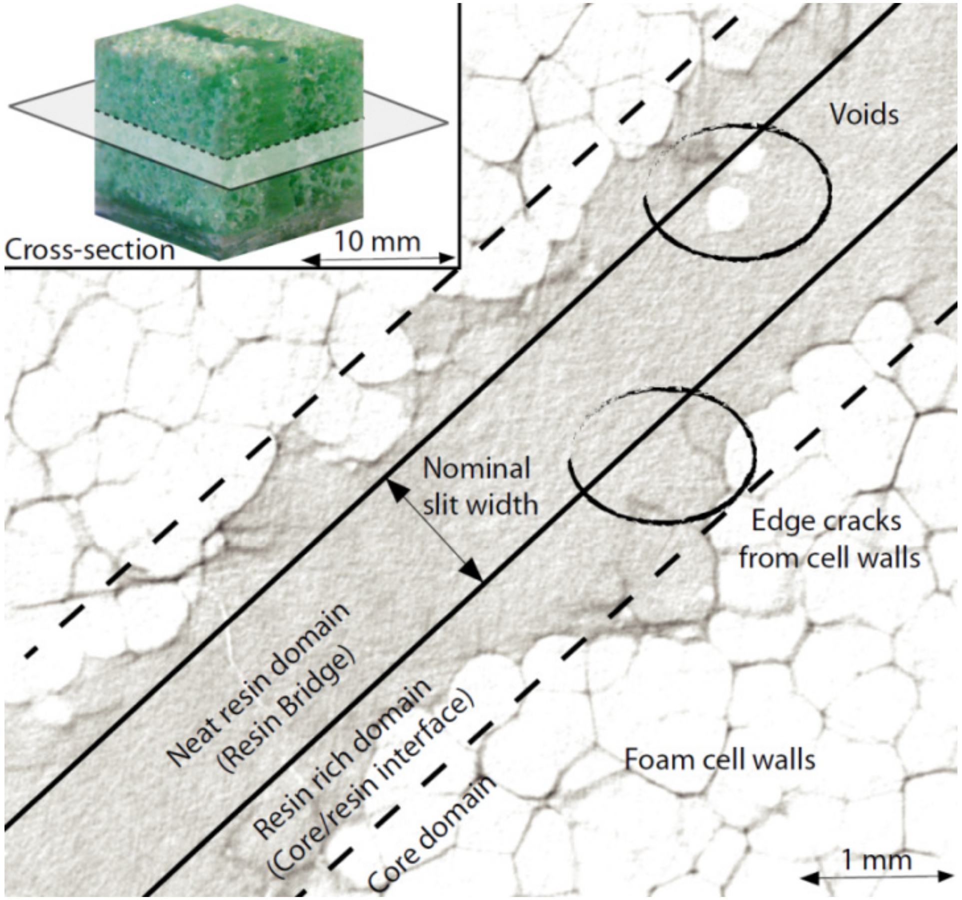
Global and local FE model predictions vs. DIC measurements for the ***multiaxial compression case*** at P_L =-60 kN.

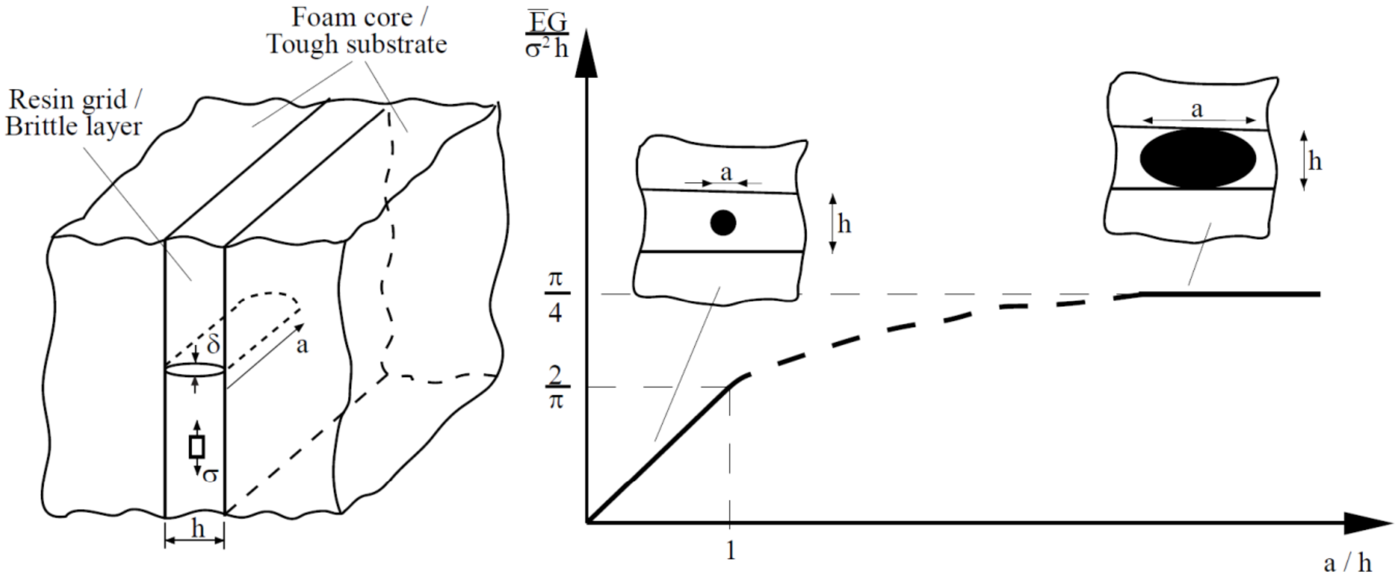
- Experimental evidence & validated FE-model used to propose 2 failure criteria for the onset of fracture in the resin grid in the sandwich substructure.
- ***Criterion #1:***
  - Fracture mechanics approach, where the resin bridge is considered as a brittle layer between two tough substrates ('tunnelling crack' in constrained layer).
  - A conservative form of the criterion is suggested, which computes the steady state value of the energy release rate.
  - The criterion is governed by the maximum principal stress in the resin, σ_p, the width, *h*, of the resin bridge, the critical energy release rate, Γ_r, of the resin, and the stiffness of the resin $\overline{E} = E/(1-\nu^2)$:

$$\frac{\pi \sigma_p^2 h}{4 \Gamma_r \overline{E}} \geq 1$$

  - Justification for adopting a fracture mechanics approach is the observed fracture behaviour of the resin grid (white spots visible through the transparent glass fibre face sheets).

- CT-scan of resin and the adjacent core material: very rough and notched surface of the resin bridge where e.g. edge cracks occur from the scored foam cells





- ‘Tunnelling crack’ criterion is computationally expensive - requires a 3D solid element model of the sandwich structure.
- Requires estimates of the effective resin grid width, *h*, which in some cases can be three times higher than the nominal width.
- ‘Tunnelling crack’ criterion may be mostly useful for identifying the parameters governing the ‘resin grid’ failure phenomenon rather than serving as a practical tool for failure prediction.

- Criterion #2:
  - To accommodate 'issues' with 'tunnelling crack' criterion a 'point strain' criterion was proposed as a simple alternative:

$$\frac{\varepsilon_p}{\varepsilon_{ult,t}} \geq 1$$

  - Ultimate strain ($\varepsilon_{ult,t}$) input derived from uniaxial tension test of the sandwich structure, and the computed principal strain (ε_p) in the resin bridge (FE model / shell or 'solid').
  - Influence on the fracture strength of the resin-core interface and resin system is implicitly taken into account.

- Comparison of the two 'failure criteria' with the obtained experimental data revealed a reasonable correlation – prediction ~ ±10% of mean experimental value
- 'Maximum principal strain criterion' would be most useful for engineering design purposes due to its simplicity.

Failure indices computed by the TUNNELING CRACK CRITERION together with the (local – 3D solid) FE model predictions

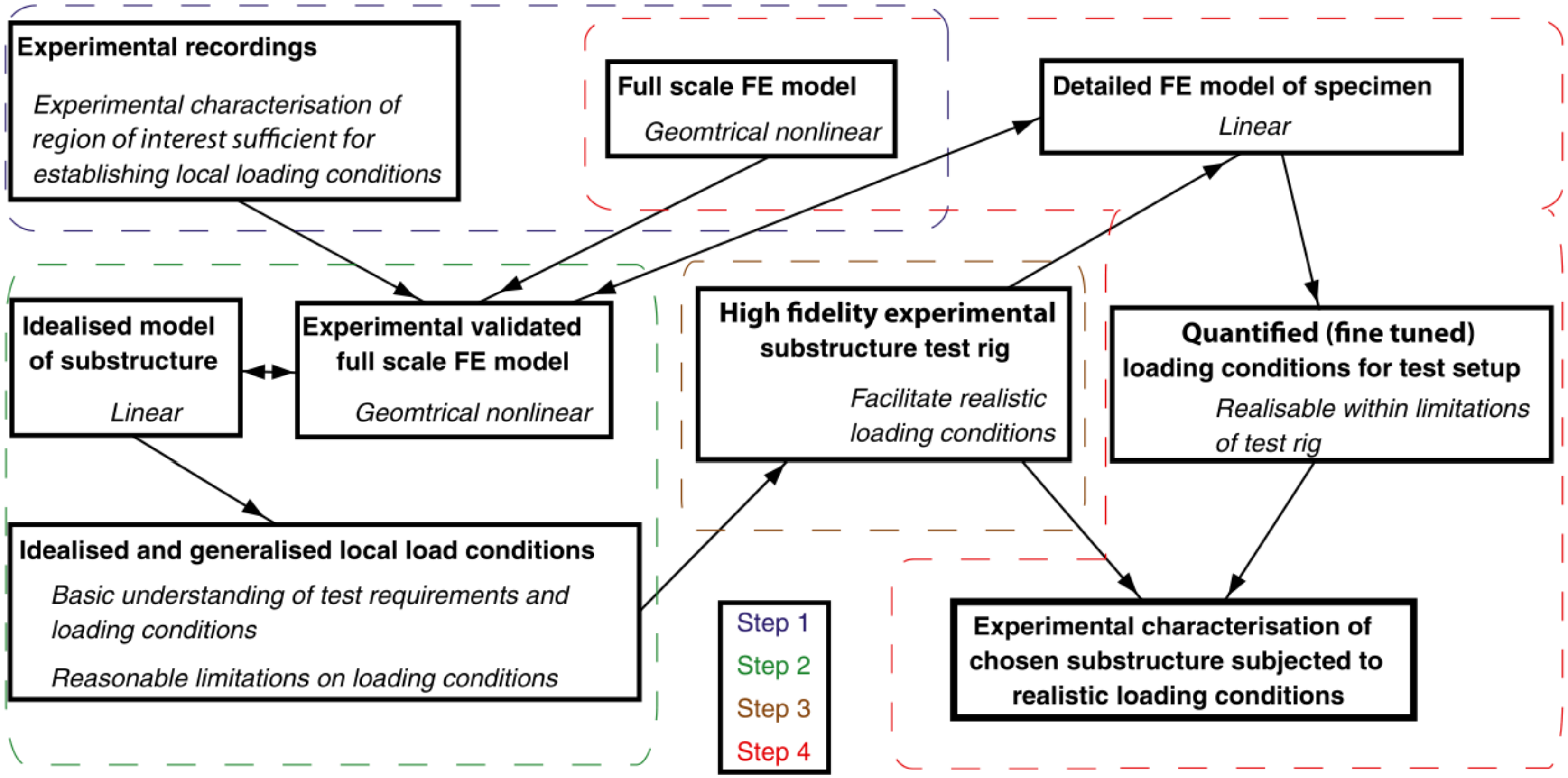
Test configuration	Failure load	Principal stress	Material and geometrical parameters	Failure index
Multiaxial tension	P_L=90 kN	21.0 MPa	Γ_r=0.3N/mm, h=3mm, E=3.0GPa	1.1
Multiaxial compression	P_L=-110 kN	21.2 MPa	Γ_r=0.3N/mm, h=3mm, E=3.0GPa	1.1

Failure indices based on resin-grid PRINCIPAL STRAINS at failure calculated from FE 3D solid and FE shell models predictions

Test configuration	Failure load	Failure strain [mm/m]		Failure index
		FE Solid model	FE Shell model	Shell model
Multiaxial tension	P_L=90 kN	6360	6660	0.8
Multiaxial compression	P_L=-110 kN	6430	7710	0.9

$\varepsilon_{ult,t}$= 8443 mm/m - Divinicell H-grade H60, epoxy grid score

Generic road-map for high-fidelity composite substructure testing



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Conclusions

- Combined numerical and experimental characterisation of the full-scale load response (of a particular wind turbine blade configuration) and subsequent substructure test development was conducted.
- Demonstration of how full-scale tests can be translated into more detailed subcomponent tests without significantly compromising the in situ loading state.
- Particularly useful for observing and understanding failure initiation and progression on substructure/component under realistic (multi-axial) loading scenarios.
- Useful where test to failure of the full-scale structure is not possible.
- Particular composite wind turbine blade substructure:
  - Progressive failure phenomena were triggered by a significant transverse bending moment occurring due to cross section ovalization.
  - Indicates that special awareness of this load component in combination with biaxial compression is recommended when using grid-scored sandwich configurations in the aerodynamic shell of wind turbine blades.
- A generic methodology for high-fidelity testing of composite substructures subjected to realistic multiaxial loading conditions has been proposed.

More information - recently published papers:

- Laustsen, S., Lund, E., Kühlmeier, L. and Thomsen, O.T. (2014), 'Development of a high-fidelity experimental substructure test rig for grid-scored sandwich panels in wind turbine blades'. *Strain - An International Journal for experimental Mechanics, Vol. 50, pp. 111-131. DOI: 10.1111/str.12072*
- Laustsen, S., Lund, E., Kühlmeier, L. and Thomsen, O.T. (2014), 'Failure behaviour of grid-scored foam cored composite sandwich panels for wind turbine blades subjected to realistic multiaxial loading conditions'. *Journal of Sandwich Structures and Materials, Vol. 15(5), pp. 481-510. DOI:* 10.1177/1099636214541367

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Questions?