HIGH-FIDELITY MULTIAXIAL TESTING OF COMPOSITE SUBSTRUCTURES

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Abstract

This paper outlines a facility and general methodology for high-fidelity experimental characterization of complex composite substructures subjected to complex multiaxial loading conditions. The load response and failure behaviour of 'grid-scored' sandwich panels used in wind turbine blades have been investigated. A full-scale structural experimental and numerical characterization of a composite wind turbine blade has been conducted. The development of a full-scale numerical model is detailed, and the necessary experimental set-up is described. Further, the numerical and experimental results obtained are compared, and an idealised set of boundary conditions for a chosen blade substructure is presented. From this, the development of a test rig suitable for representing the established loading and boundary conditions is presented, and selected experimental results are discussed. Moreover, simple failure criteria for the prediction of the onset of failure of the grid-score sandwich core have been proposed based on the experimental findings. Finally, a generic methodology for high-fidelity testing of composite substructures subjected to realistic multiaxial loading conditions has been proposed.

1. Introduction and motivation

It is well established that especially 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. Moreover, 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. This makes the prediction of initiation and propagation of failure inaccurate and in some cases completely off. Full scale structural testing would be a more consistent approach to obtain valid experimental data with respect to load response and failure initiation and progressive collapse behaviour of complex composite structures. However, the costs associated with full scale structural testing are often prohibitive, and in addition the shear amount of data and the complexity associated with conducting and controlling the actual testing to realize the desired loads and failure behaviour makes full scale testing less attractive.

Accordingly, it is becoming increasingly clear that there is a need for the development of high-fidelity mechanical testing methodologies that enables realization of realistic loading conditions on substructures/components that can be handled and instrumented conveniently using state of the art full field imaging and sensor techniques. This will enable the conduction of data rich testing that will include quantitative monitoring and assessment of the multiaxial load response, failure initiation and progression in complex composite substructures. This in turn can be used to inform and improve computational models with an aim to improve their predictive capabilities.

The aim of the research presented is to outline a general methodology enabling the conduction of data rich experimental testing on composite substructures. The background for the research presented is the testing and validation of composite wind turbine blades, where a particular and unexpected local substructure failure mode was encountered on a large number of wind turbines in operation. These failures that occurred as resin grid cracks and progressive face sheet core debonding in grid-scored sandwich panels in the blade aero foils were not predicted by the design analyses, and they could not be explained by simple coupon like tensile, compression and shear tests conducted on sandwich samples either cut from the blade laminates or manufactured to replicate the blade laminate configurations. Figure 1 illustrates the experimental testing on the coupon, substructure and full scale levels.

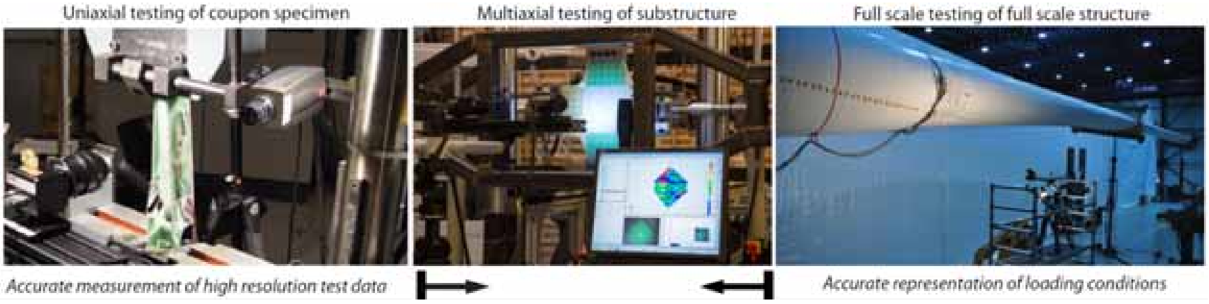

Figure 1. Testing and on different length scales: left, coupon specimen; middle, high-fidelity multiaxial substructure test; right, full scale blade test.

The work presented provides a summary of recently published research [1, 2]. For full details reference is made to these publications.

2. Experimental substructure testing methodology

The focus has been to facilitate high-fidelity experimental substructure testing of grid-scored foam cored sandwich panels for wind turbine blades. Thus, a full scale structural experimental and numerical characterization of a composite wind turbine blade has been conducted. The numerical and experimental results obtained were compared in order to validate the numerical model. Further an idealized set of boundary conditions for a chosen blade substructure was established depending on the global induced loading conditions.

As shown Figure 2, three loading components were found sufficient for representing the local loading conditions realistically:

- Tension/compression forces (P_L) that occur in the longitudinal direction of the blade due to the global blade bending deformation mode.
- Constrained contraction/expansion leading to tension/compression forces (P_T) in the transverse direction occurs due to Poisson’s ratio effects and due to the closed-box cross section design.
- Bending moments (M) in the chordwise direction that occur due to ovalisation of the cross section with increasing levels of P_L.

Further, the local loading conditions were generalised into a tension-tension-bending and compression-compression-bending multiaxial loading case, respectively. From this, a test rig suitable for representing the established loading and boundary conditions was developed together with a multiaxial specimen suitable for characterizing the failure behaviour, see Figure 3.

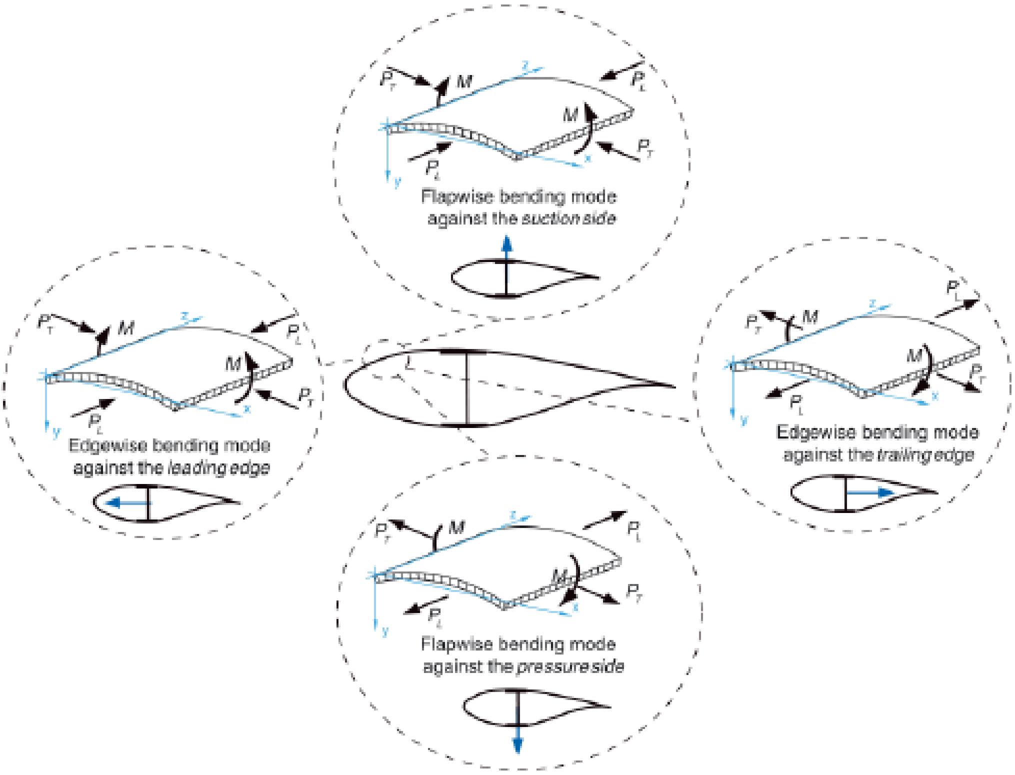

Figure 2. Local loading conditions derived from the full scale numerical modelling.

The substructure test rig was designed with free visual access to the front and back sides of the test specimen enabling measurement of the surface displacement and strain fields using digital image correlation (DIC), as well as measurement of the surface temperatures using an IR camera (IR thermography). For the present tests, the surface strains were measured using both strain gauges and DIC. The gauge zone for the strain measurements (strain gauges and DIC) is shown in Figure 3, where the specimen geometry and layout has been being designed such that failure during testing occurred within gauge zone area.

3. Summary of experimental results

The detailed experimental results indicated that the tension–tension–bending load case lead to damage initiation in the longitudinal resin grid. For the compression–compression–bending load case, face sheet delamination/debonding and subsequent wrinkling were observed as a result of onset of cracking in the transverse resin scores in the core.

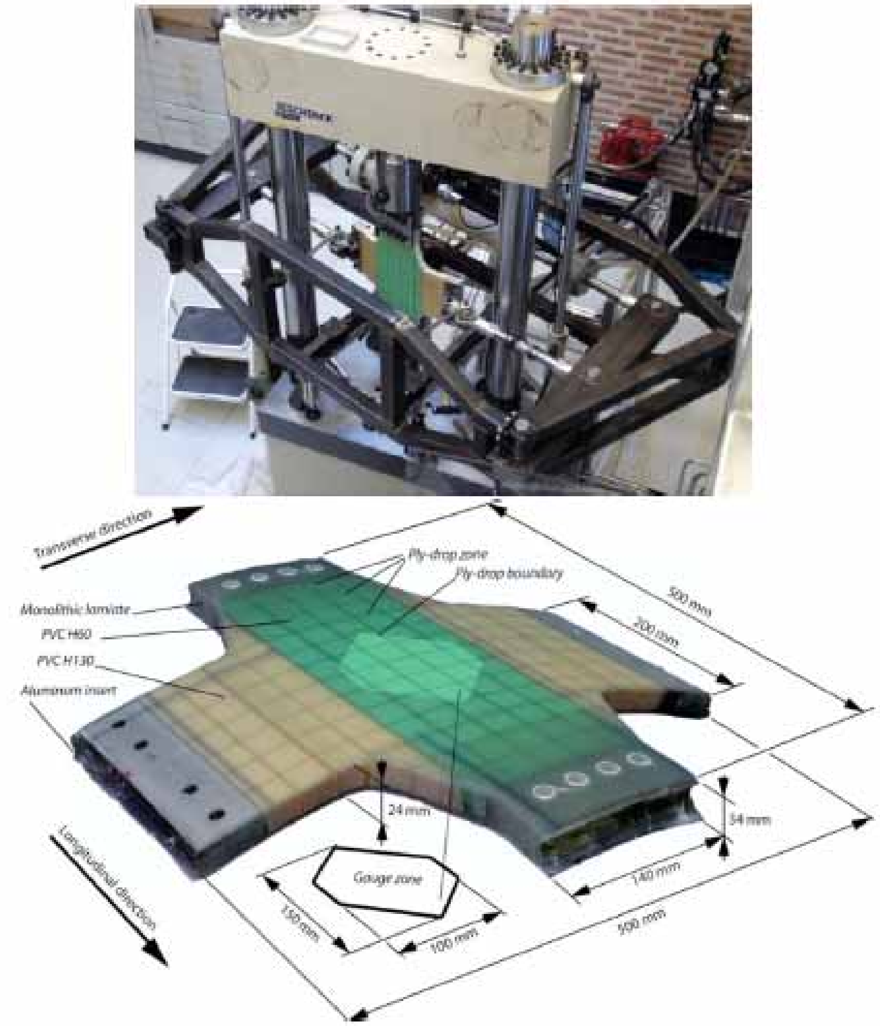

Figure 3. High-fidelity substructure test rig and layout of multiaxial foam cored and grid-scored composite sandwich test specimens.

The progressive series of failure phenomena were triggered by a significant transverse bending moment occurring due to blade cross section ovalisation. This indicates that special awareness of this load component in combination with biaxial compression is recommended when using grid-scored sandwich configurations in the aerofoils of wind turbine blades.

The tests conducted have provided a detailed overview of the failure behaviour of the particular foam cored grid-scored sandwich structure under realistic loading conditions and how the different constituents influence this behavior. The multiaxial load cases revealed critical combinations of the load components, P_L, P_T, and M, which caused failure to initiate in the resin grid. Figures 4 and 5 show the resin cracks induced in the multiaxial tension and compression case, respectively.

The most severe case was the multiaxial compression case where the crack in the transverse (y-direction in Figure 5) resin bridges triggered a subsequent wrinkling phenomenon of the front face sheet, which resulted in a complete loss of the load carrying capacity.

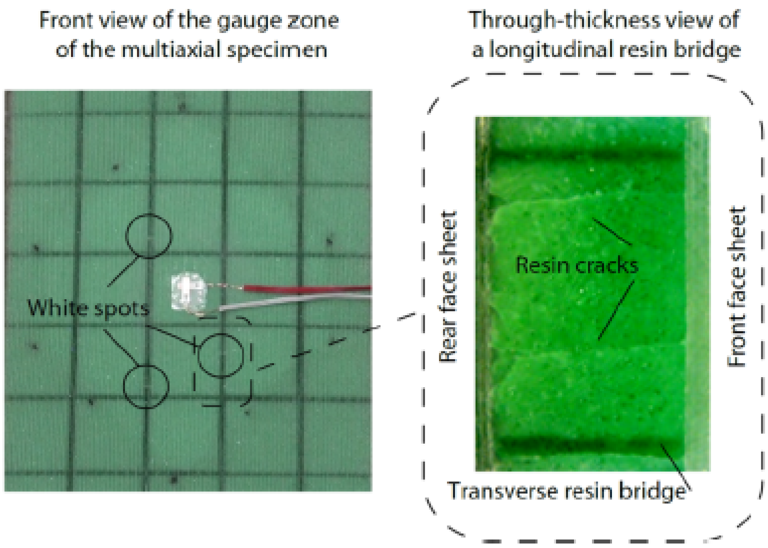

Figure 4. Post mortem images showing through-thickness (z direction) cracks in the longitudinal resin bridge when subjected to the multi-axial tension load case.

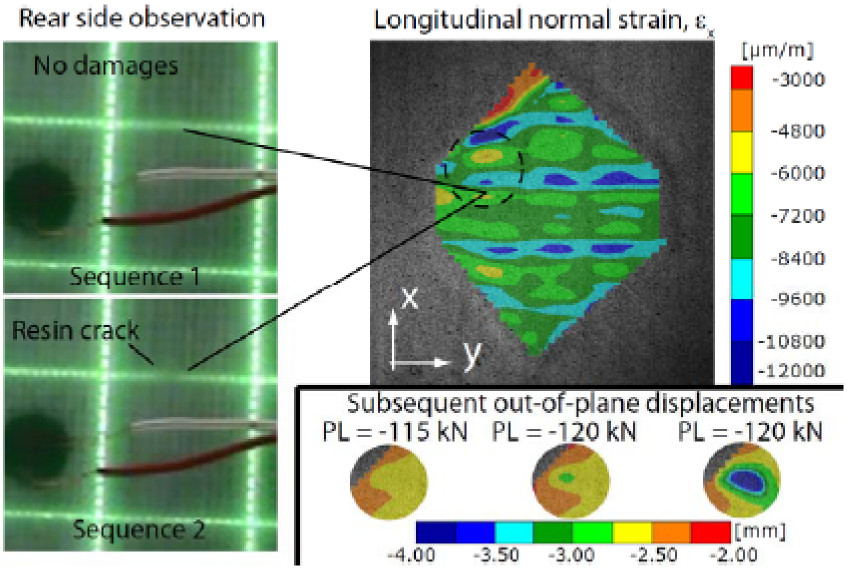

Figure 5. Failure event recorded by DIC on the front side of the specimen and video recording from the rear side at PL=-110 kN for the biaxial compression load case. The subsequent out-of-plane face sheet displacement fields within the circular area are shown at 3 different stages.

4. Criteria for prediction of grid-score failure under multi-axial loading

The experimental evidence together with validated FE-model predictions has been used to propose two failure criteria for the onset of fracture in the resin grid in the sandwich substructure. The first criterion relies on a fracture mechanics approach, where the resin bridge is considered as a brittle layer between two tough substrates (‘tunneling crack’). A conservative form of the criterion is suggested, which computes the steady state value of the energy release rate. Thus, 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, $\overline{E} = E/(1-\nu^2)$:

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

The main reason for adopting a fracture mechanics approach was the observed fracture behaviour of the resin grid, which appeared as white spots (see Figure 4) through the transparent glass fibre face sheets. A CT-scan of the resin and the adjacent core material, shown in Figure 6, further revealed a very rough and notched surface of the resin bridge where e.g. edge cracks occur from the scored foam cells.

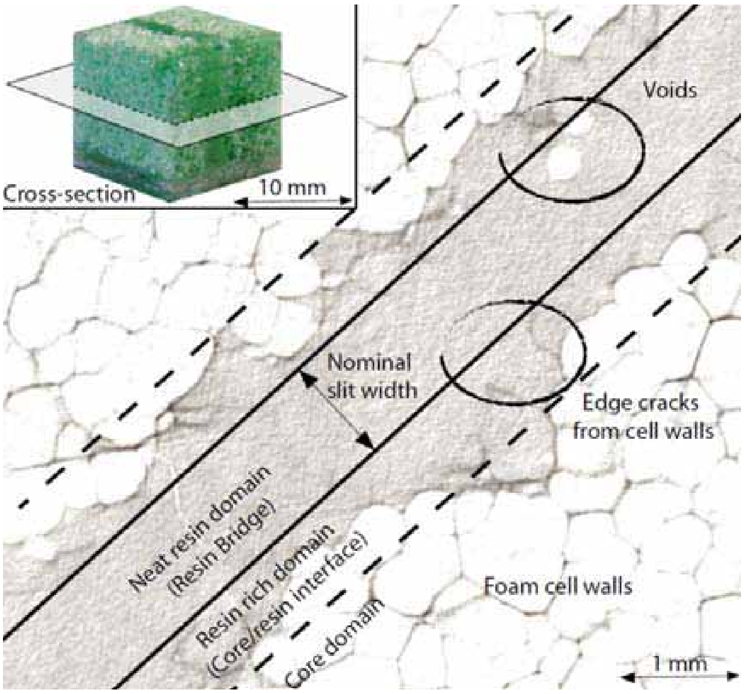

Figure 6. CT-scan of the resin grid infused in cross-linked PVC H60 foam.

The disadvantage of the proposed ‘tunneling crack’ criterion is that it is very computationally expensive, since it requires a 3D solid element model of the sandwich structure. Furthermore it requires estimates of the effective resin grid width, *h,* which in some cases can be three times higher than the nominal (as shown in Figure 6). Therefore the tunneling crack criterion is mostly useful for identifying the parameters governing the ‘resin grid’ failure phenomenon rather than serving as a practical tool for failure prediction. To accommodate for this a point strain criterion was proposed as an alternative:

$$\frac{\varepsilon_p}{\varepsilon_{ult,t}} \geq 1 \qquad (2)$$

The criterion relies on an ultimate strain ($\varepsilon_{ult,t}$) input derived from a uniaxial tension test of the sandwich structure, and the computed principal strain (ε_p) of the resin bridge. Thus, the influence on the fracture strength of the resin-core interface and chosen resin system is implicitly taken into account. The comparison of the two criteria with the obtained experimental data revealed a satisfactory correlation, and thus the general conclusion was that the ‘maximum principal strain criterion’ would be most useful for engineering design purposes due to its simplicity.

5. Road map for high-fidelity substructure testing

The work conducted has provided a suggested road map, see Figure 7, for developing high-fidelity experimental substructure tests, which in more generic terms will be applicable to similar developments of substructure tests.

Step 1 involves the numerical analysis of the full scale structure, with the option of doing full scale testing as well to validate the overall predictions. For many large composite structures necessitate the adoption of geometrical nonlinearity in the FE model is necessary to achieve accurate predictions.

Step 2 involves the analysis and interpretation of the load vs. deformation behaviour and the establishment of suitable substructure loading conditions. An idealized model can show if it is beneficial to achieve more detailed stress/strain predictions.

The established loading conditions facilitate the development and realization of the high-fidelity test rig in Step 3. The basic assumption for the test rig is that it facilitates the realization of substructure loading conditions that are representative of the in situ loading conditions on the full-scale structural level.

This is validated in Step 4 where the results obtained from a detailed FE model of the specimen are compared with the validated full scale predictions. Further, the comparison allows a fine tuning of the desired loading conditions provided these are realizable within the limitations of the test rig. Finally, the procedures in Step 4 allow the detailed experimental characterization of the chosen substructure.

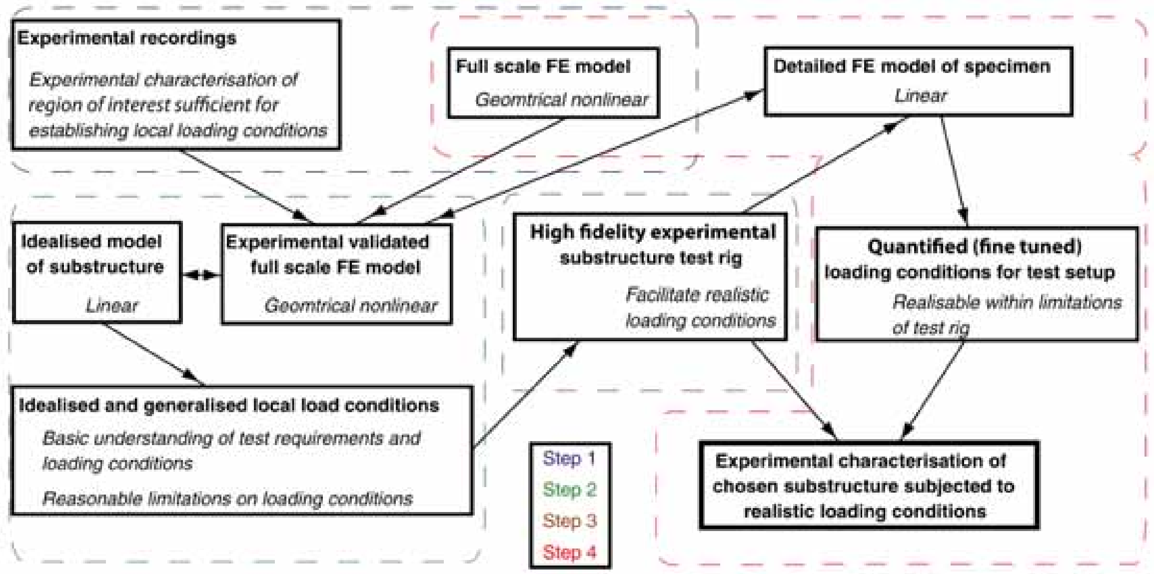

Figure 7. Generic road map for high-fidelity substructure testing.

6. Summary and conclusions

Based on combined numerical and experimental characterization of the full-scale load response of a particular wind turbine blade configuration and subsequent substructure test development, the research presented illustrates how full-scale tests can be translated into more detailed subcomponent tests without significantly compromising the in situ loading state. This is particularly useful when the objective is to observe and understand the failure initiation and progression under realistic (multi-axial) loading scenarios, as well as in situations where test to failure of the full-scale structure is not possible to the same extent.

The design and commissioning of a high-fidelity rig, for the testing of a composite sandwich substructure, has enabled the investigation of the damage and failure phenomena occurring when the considered composite sandwich substructure was subjected to loading conditions derived from the full-scale numerical modelling. For the particular grid-scored sandwich substructure investigated, which represents a part of the aerodynamic outer shell of a wind turbine blade, it has been found that the tension–tension–bending load case leads to damage initiation in the resin grid. For the compression–compression–bending load case, face sheet delamination and subsequent wrinkling were observed, as a result of onset of cracking in the transverse resin slits in the core. The progressive series of failure phenomena were triggered by a significant transverse bending moment occurring due to cross section ovalisation. This 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.

Based on the research presented, a generic methodology for high-fidelity testing of composite substructures subjected to realistic multiaxial loading conditions has been proposed. The steps of this methodology are outlined in Figure 7.

Fur full details of the research conducted and the results obtained, reference is given to [1,2].

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