Abstract Book

1st International Symposium on Multi-Scale Experimental Mechanics (ISMEM-1)

October 5, 2016
Niels Bohr Auditorium, DTU Risø Campus, Roskilde, Denmark

Foreword

There is a rapidly growing need for experimental data to consolidate our knowledge and deepening our understanding of the mechanical behavior of structures and materials. The underlying issues include the rapid introduction of new and innovative structures and materials in all areas of our society, the fact that the data which forms the basis for existing codes and standards is gradually becoming obsolete as well as the changes in the natural loads which our existing infrastructure is subjected to and its gradual aging and deterioration.

Furthermore, it is increasingly being realized that performance of structures may be understood as the performance of a set of interrelated sub-systems each representing the structure at different scales, ranging from full scale (e.g. the entire structure regarded as an assembly of structural elements), over the meso-scale (e.g. element and cross sectional properties) and material (coupon)- scale to the micro-scale (e.g. material structure, inhomogeneities and their interfaces).

Designed to meet the current challenges of the field, the newly formed *Villum **C**enter for **A**dvanced **S**tructural and **Ma**terial **T**esting* (CASMaT) is a strategic initiative at DTU to strengthen experimental research in mechanics of structures and materials. The Center is organized to ensure combination, coordination and alignment of equipment and expertise at DTU across a range of application areas (including but not limited to civil, mechanical and wind Engineering) *and* length scales including full and large scale, sub-structure and component scale and the material and micro scale.

The Center strengthens the testing facilities at all scales but more importantly – through its modular and multi-scale lay-out – it supports ongoing research efforts to improve our understanding of the multi-scale nature of structures and materials.

Within the framework of the Center a series of yearly Symposia on Multi-Scale Experimental Mechanics is now launched creating a forum for experimentalists, researchers and end-users of research results for presentation and discussion of the latest results in experimental mechanics across length scales.

While parts of the Center are still under construction and development, other parts are up and running – and have been for some time. The program of this year’s Symposium reflects the wide range of activities already supported by the Center and the Center’s international profile is emphasized by two distinguished invited speakers. I sincerely hope that you will enjoy the event!

Henrik Stang
Center Leader, Villum Center for Advanced Structural and Material Testing

Technical program

Morning

08:30-09:00	Coffee and rolls	
09:00-09:10	Welcome	Henrik Stang
09:10-09:50	**Invited lecture: Understanding the materials – manufacturing – structural performance hierarchy for composite materials and structures**	**Professor D.S. Cairns** **Montana State University**
09:50-10:05	Fiber Bragg Grating: a promising technology for wind turbine blade strain detection	Federico Belloni
10:05-10:20	Modal and static response of small wind turbine blades	Vladimir Fedorov
10:20-10:35	Initiation of and challenges associated to full scale concrete bridge testing and related monitoring	Philip Skov Halding
10:35-11:00	Coffee Break	
11:00-11:15	Scanning Laser Doppler vibrometry	Marie Brøns
11:15-11:30	Sub-structural testing of a wind turbine blade section with localized X-stiffener reinforcements	Maurizio Sala
11:30-11:45	Low temperature testing of debonded PVC foam cored sandwich composites for naval vessels	Arash Farshidi
11:45-12:00	Sub-structural testing of large composite structures – a hybrid simulation approach	Jacob Paamand Waldbjørn
12:00-12:15	H-TRIS testing of foam cored sandwich panels for ship superstructures	Vasileios Karatzas
12:15-12:30	Determination of mechanical properties of glass-epoxy composites and sandwich structures at elevated temperatures	Mohsen Rezaei
12:30-13:30	Lunch	

Technical program

Afternoon

13:30-14:10	**Invited Lecture: Multi-scale CT for Imaging and testing of composites**	**Dr. Gregor Borstnar** **University of Southampton**
14:10-14:25	X-ray tomography in DTU Wind Energy	Søren Fæster
14:25-14:40	Approach for investigations of progressive fatigue damage in 3D in fibre composites using X-ray tomography	Lars Pilgaard Mikkelsen
14:40-14:55	Multi-scale testing of fiber reinforced concrete under corrosion deterioration	Victor Marcos Meson
14:55-15:20	Coffee break	
15:20-15:35	Single fibre tensile testing	Justine Beauson
15:35:15:50	Mixed mode fracture testing of foam core sandwich using the DCB-UBM test method	Christian Berggreen
15:50-16:05	Determination of face/core fracture toughness in aircraft honeycomb sandwich composites using the SCB test method	Francesco Attanasio
16:05-16:15	Closure and practical information	Henrik Stang
16:25-17:30	Departure with bus to guided tour to selected CASMaT facilitiet at Risø Campus	
18:00	Departure with bus to restaurant 'Rådhuskælderen'	
18:30-21:00	Dinner in Roskilde at restaurant 'Rådhuskælderen'	

Understanding the materials – manufacturing – structural performance hierarchy for composite materials and structures

Douglas S. Cairns[1]

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Dr. Douglas S. Cairns is the Lylse A. Wood Distinguished Professor at Montana State University. He has over 38 years' experience in the design, analysis, manufacturing, and testing of composite materials and structures. PhD from MIT Aeronautics and Astronautics, scale, MSME and BSME University of Wyoming.

Abstract

Composite materials are enabling for a variety of structural applications. Their specific mechanical properties (properties normalized by material density) far exceed traditional engineering materials used for primary structures. They are the materials used in all new aircraft structures and are finding widespread use in industrial applications such as wind turbine blades, energy efficient transportation systems, and consumer products. This enhanced performance does not come without difficulties and a price. Compared to homogeneous, isotropic materials, composite materials for structural applications exhibit directional mechanical performance, and are difficult to form into complex shapes. A typical development cycle for a new aircraft made from composite materials is shown in Figure 1. The typical time scale for Figure 1 is several years, and can cost over $350 Million US. Aerospace companies recognize that this is not sustainable. From a recent email to the author from Dr. John Tracy, Chief Technology Officer of the Boeing Corporation:

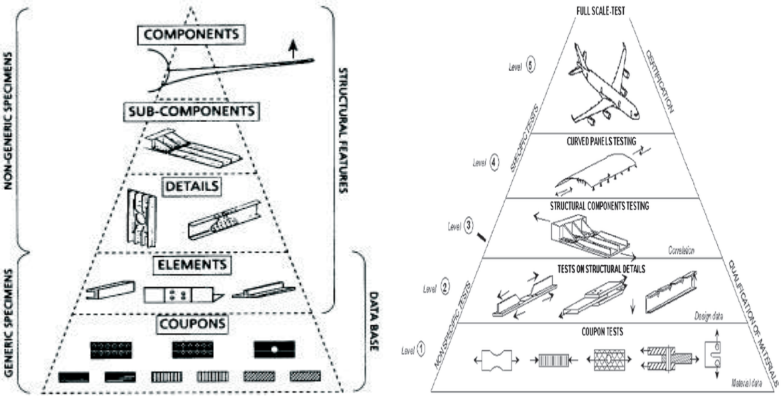
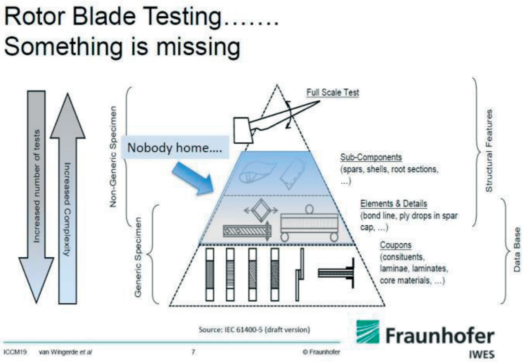


Figure 1: Building Block Approach, coupons through full scale structures

"For us, it's about focusing our efforts where the payoff will be the greatest. Introducing a new material for the fuselage with so little lead time (several years is little lead time for us considering how long it takes to qualify the materials, make sure it can be scaled up, do all the sub element testing, etc) is very hard. What we really need is to have the composites community help figure out how we can qualify a material and get it production ready much faster than it is possible to do today." Obviously, industrial applications cannot afford the time and cost of aerospace. In the case of wind turbine blades, some work is done at lower scales, but then applied to the full scale without intermediate testing. This is shown in Figure 2.


Rotor Blade Testing…….
Something is missing

Source: IEC 61400-5 (draft version)

ICCM19 van Wingerde *et al* 7 © Fraunhofer

Fraunhofer IWES

Figure 2: Wind turbine materials and structural testing – coupons, then full blade

In this seminar, the author will compare and contrast how the *DTU Villum Center for Advanced Structural and Material Testing* can streamline the process for aerospace and fill in levels for applications such as wind turbines. He will discuss how augmenting the intermediate steps with analysis to understand the scale up processes can also optimize the multi-scale hierarchy. In particular, how data translate from lower levels (coupons) through higher levels (full scale) will be discussed with examples.

Fiber Bragg Grating: a promising technology for wind turbine blade strain detection

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Federico Belloni MSc in Mechanical Engineering, Development Engineer, structural design and full scale testing of wind turbine blades and sub-components, fatigue resonance testing, fatigue damage evaluation, structural optimization, strain measurements, fiber Bragg grating.

Abstract

Fiber Bragg Grating (FBG) technology has been applied in the past four decades to several fields, including underwater acoustic sensing, strain monitoring, chemical/biomedical sensors and temperature sensing [1]. FBG sensors are crystallographic planes artificially introduced into an optical fiber, which reflect a specific wave length of the light spectrum travelling through the fiber [2]. Every sensor appears in the spectrum as an output power peak, shown in Figure 1 a), which shifts sideways when the sensor is subject to strain. The shift of the reflected wave is proportional to the measured strain. Since a FBG fiber line can usually accommodate several sensors, in order to avoid interference between neighbouring ones, the wavelength bandwidth associated to every FBG is a parameter to be defined as the inverse function of the amount of measurement points in the fiber line. In the presented work, FBG technology was deployed for strain monitoring along the blade trailing edge in the longitudinal and transversal directions during a full scale test campaign of a SSP 34 m blade, as shown in Figure 2. A test configuration presenting 10 sensors per line and a

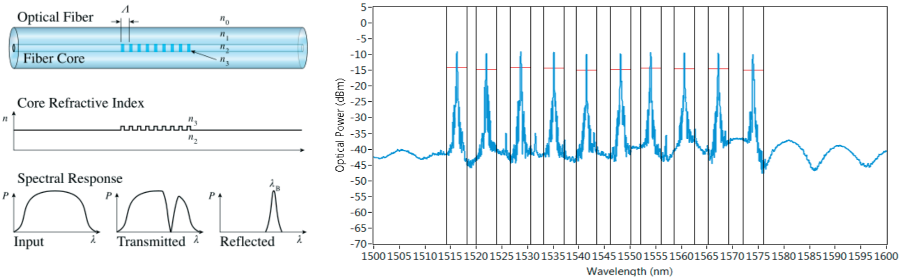

Figure 1: a) FBG working principle and b) Output power spectrum of a 10 FBG sensor fiber line.

measurable strain range equal to ±2400 μm/m was adopted, as displayed in the output power spectrum in Figure 1 b). FBG measurements were successfully verified against electrical resistance strain gauge measurements and used to validate a blade numerical model analysing trailing edge deformation under quasi-static loading [3]. The experimental results showed that FBG measurements are sensitive to the material where the sensors are applied. Due to the very short gauge length, a FBG installed on the sandwich material instead of the composite laminate can present a higher level of noise in the measurement. Additionally, strain data can be lost if the expected strain level is exceeded and the wavelength peak is shifting outside of its pre-defined bandwidth. In respect to electrical resistance strain gauges, the main advantages of the FBG sensors are related to the simpler and cleaner installation and alignment of the fiber lines, the absence of electrical power at the sensing point and the possibility to deploy them for both surface and embedded strain measurements.

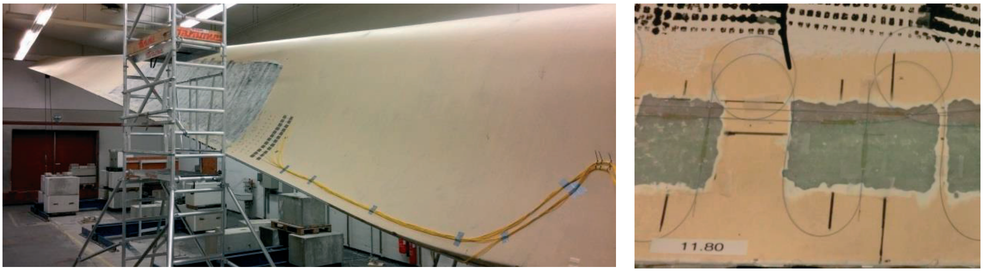

Figure 2: a) Installation of 160 FBG sensors for longitudinal and transversal surface strain measurement on a SSP 34m blade during full scale quasi-static test to failure. b) Detail of FBG sensors along the trailing edge.

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[1] Kersey AD, “A review of recent developments in fiber optic sensor technology,” *Optical Fiber Technology,* vol. 2, p. 291–317, 1996.

[2] Hill K, Meltz G, “Fiber Bragg grating technology fundamentals and overview,” *Journal of Lightwave Technology,* vol. 15, p. 1263–1276, 1997.

[3] Haselbach PH, Eder MA and Belloni F, “A comprehensive investigation of trailing edge damage in a wind turbine rotor blade,” *Wind Energy,* vol. 17, pp. 657-669, 2015.

Modal and static response of small wind turbine blades

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Vladimir Fedorov PhD, researcher within the field of composite structures, primarily related to wind turbine blades. Experience in testing of composite structures from 50 mm test coupons and up to 15 m long blades using advanced loading and measurements techniques, e.g. DIC.

Peter Berring M.Sc, Senior Development Engineer within the field of: Numerical modelling and simulations of wind turbine blades. Experimental testing of composite structures and wind turbine blades at varies length scales.

Abstract

A small 1 meter long wind turbine blade is tested dynamically and statically for the reasons of validating numerical models of the blade structure. The blade is manufactured with a foam core as internal structure that constitutes the aerodynamical shape of the blade, a thin film of polymer material to ensure smooth outer surface and carbon-fibre spars with fibres biased to the blade pitch axis in order to introduce bend-twist coupling. The blade is designed and manufactured by Politecnico di Milano as a part of INNWIND.EU project for use on a scaled down model of a 10MW DTU reference horizontal axis wind turbine. The blade is depicted in Fig. 1.

Figure 3: Blade with carbon-fibre spars where fibers are biased to the blade pitch axis to introduce bend-twist coupling.

First, the blade was tested dynamically using a laser scanning vibrometer available at DTU MEK (funded by VILLUM) to measure its eigen-frequencies and to visualize eigen-modes. The results are found to be in good correlation both with the results of numerical modal analysis performed at Politecnico di Milano and presently by the authors with e.g. the first bending mode frequency being at 21 Hz and the fourth at 182 Hz, see Fig. 2.

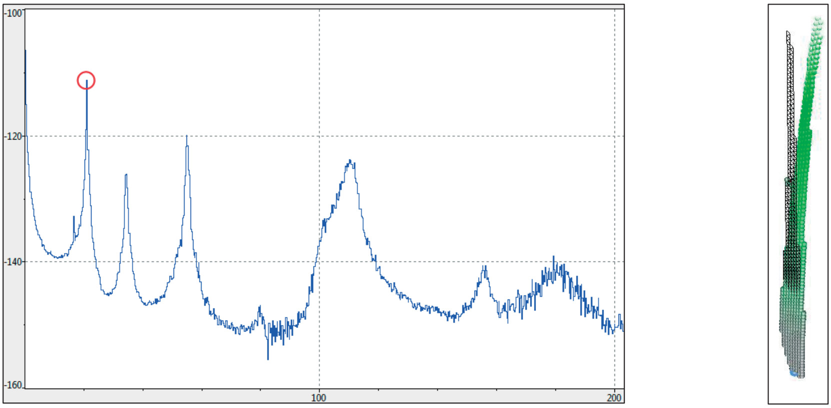

Figure 2: Measured spectrum of the blade, left, and first bending mode shape, right (marked with red circle on the left figure).

Next, the blade was loaded statically in two load cases, bending and torsion to measure coupled response of the blade structure, bending deformations and twist angles. It was done using the newly obtained DIC system ARAMIS available at DTU Wind Energy (funded by VILLUM). This work is still in its final stage and the measurement results are expected to be available after post-processing and used for validation of FE models of the blade and verification of the amount of coupling in the blade due to biasing of the fibres in the blade spars.

Initiation of and challenges associated to full-scale concrete bridge testing and related monitoring

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Philip S. Halding, M.Sc., Ph.D. Post Doc. at department of Civil Engineering at the Technical University of Denmark. His research regards holistic structural testing of concrete bridges as well as related sub-component testing combined with monitoring methods.

Jacob W. Schmidt, M.Sc, Ph.D. Associate professor at department of Civil Engineering at the Technical University of Denmark. His research regards assessment of existing structures, monitoring and testing of full scale bridges as well as FRP strengthening methods.

Abstract

In June 2016 a project regarding full-scale load-testing of concrete bridges was initiated. The project runs for four years, and is a collaboration between DTU, COWI, and the Danish Road Directorate. The overall project scope is to develop test methods and related state-of-the-art monitoring which can be used in a standardized way to test the capacity of existing (one span) full-scale concrete bridges. This method combined with applied theory is hypothesized to provide an efficient tool to evaluate the bridge class and potentially provide a more exact way to evaluate the full scale structural response of the tested bridge. Even though the project was initiated in June 2016, already four bridges have been tested in September 2016: Three were tested to verify the novel test rig and loading procedures, and one bridge was monitored using different types of

monitoring equipment. The loading configuration and monitoring equipment is shown in Figure 1. A unique combination loading was applied in two tempi: 1) Initially, steel weights were applied onto the loading frames (force controlled loading), and 2) jacks between the loading beams and the loading frames apply an additional semi deformation controlled load. This two-step approach ensured controlled, high magnitude loading of the bridge as well as a load configuration as it is applied in theoretical evaluations according to given standards. In addition, this test setup enabled the possibility to reveal the initiation of inelastic regime.

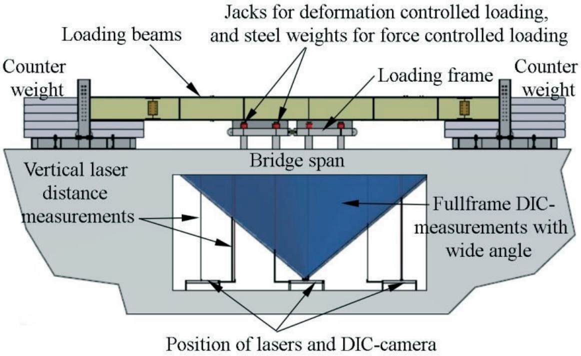

Figure 1: Test-setup of tested bridge in September 2016

The monitoring equipment used in this initial test was: Laser distance meters (vertical deflections in several locations), wide angle DIC-camera (checking for cracks underneath the bridge), and LVDT's to verify the laser readings. The forces and displacements of the individual jacks were also measured as well as the displacement of one of the loading beams. This, first step, monitoring on site, was performed in a way which could support the decision-taking regarding future monitoring equipment purchases. One of the future main scopes related to the full-scale testing is to allow real time monitoring of the full-scale bridge response. Such a method could enable a more exact control of the stop criterions and the possibility to have experts following the test directly on a shared interface while they are located externally. Also the subsequent time spent on data analysis will be reduced when the method is more developed. Additionally, it would be desirable if the test procedure is based on remote access monitoring, meaning that all monitoring equipment is running without too much personnel interference when calibration has been conducted.

The testing scheme of the bridge was conducted within only one day. This was one of the most critical points, since the road above and below will have to be closed during a test which is very expensive and troublesome for the road users.

It was concluded that the test rig worked as desired enabling an axle pressure of approximately 95 tonnes (highest axle load for a class 500 vehicle is 23.7 tonnes). The test rig enabled fast and controlled loading and the measurement equipment provided the desired values. However more data analysis has to be done to get a more detailed overview of the obtained results. Based on this testing, the next step can be taken, where monitoring and sampling of data acquisition will be more optimized and wireless. In addition, the DIC results were at a quality level which opens the opportunity of adding more cameras in combination with more advanced laser measurements.

Scanning laser Doppler vibrometry

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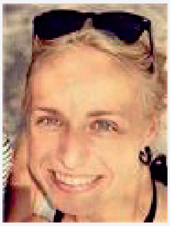


Marie Brøns, MSc student. Current theoretical and experimental MSc thesis work on modified Timoshenko beam theories. User of the scanning laser facility at MEK, DTU.

Jon Juel Thomsen, assoc. prof., dr.techn. Longtime teaching & research in theoretical and experimental vibration analysis. Responsible for the scanning laser facility at MEK, DTU.

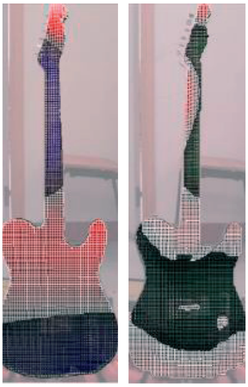
Abstract

With a *Scanning Laser Doppler Vibrometer* (SLDV) a vibrating surface is automatically scanned over predefined grid points, and data processed for displaying vibration properties like mode shapes, natural frequencies, damping ratios, and operational deflection shapes. Our SLDV – a PSV-500H from Polytec Inc. – was acquired and put to operation in October 2014, paid by a sub-donation of DKK 1,5 mill. of the total VILLUM CASMaT grant. Opening possibilities of measuring complicated vibration shapes of almost any object – contactless, mostly automatically, and with only a single transducer – this costly equipment had been top priority on our wish list for many years.

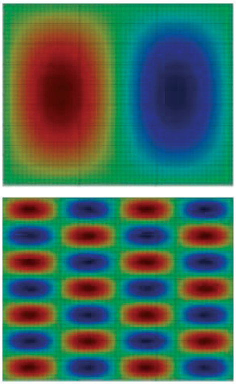
The equipment is installed in suitably protected environments in a lockable small room in the larger lab.-building 414/041 at DTU Lyngby Campus, just next to our Brüel & Kjær PULSE open space lab. for more traditional vibration analysis (using accelerometers or other single-point transducers). In the talk we provide a brief account of what can be done with the equipment, and some examples of recent and planned usage. Some main features of the equipment are listed below.

- Measures *velocity*, *1D*/out-of-plane (optionally 3D), non-contact, full-field, stationary and transient
- Range: Velocity 0.001-10 m/s; Deformation > 0.1 mm; Frequency 0-100 kHz; Distance 0.12-100 m
- Measurement objects: > 1 mm (smaller with an optional microscope front); Generally 3D / curved, with a diffusively reflecting surface (i.e. *not* glossy black or like a window or mirror)
- 3D object geometry definition by (ordinary) distance laser sensor
- Easy scan grid definition / re-definition, typically takes a few seconds
- Spatial scan rate up to 50 points/s; full scans take from seconds to hours, typically unsupervised
- Built-in signal generator for driving object exciters (shaker, piezo discs, loudspeaker,..) using, e.g., swept sine, burst/stationary random, or impulse signals
- Easy export to common commercial modal analysis program (we use ME'Scope)
- Well suited for standard shaker testing; handles input e.g. from force transducers or other reference signals to calculate frequency response and coherence functions
- Available for use by CASMaT associates that already holds some expertise in standard experimental vibration testing. A lab. technician will get a new user started by demoing a simple standard measurement. Beyond that the user will generally need to bring in or acquire his/her own expertise.

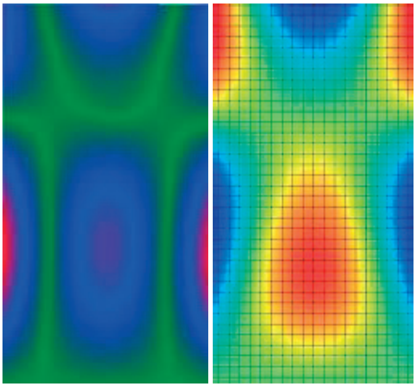
The PSV-500H scanning laser vibrometer [Polytex Inc.], and an example test object [Joensen 2015]



Guitar body & neck mode shapes @193/1038 Hz [Joensen 2015]



Thin plate mode shapes @608/10114 Hz. [Joensen 2015]



Clamped plate mode shapes, measured (left) and theoretically predicted (right) [Støme 2016]

Sub-structural testing of a wind turbine blade section with localized X-stiffener reinforcements

Maurizio Sala[1], Jacob P. Waldbjørn[1]

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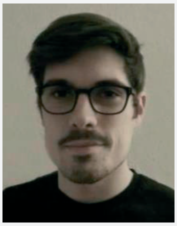

Maurizio Sala Master of Science in mechanical engineering with the thesis: "Investigating benefits of wind turbine blade retrofit reinforcements". Research assistant at DTU Mechanical Engineering, working with composite structures and structural testing.

Jacob P. Waldbjørn is working as a postdoctoral fellow within advanced sub-structural scale testing through a hybrid simulation approach. The technique is applied for structural assessment of different retrofitted reinforcement methods for wind turbine blades.

Abstract

Sub-structural test of the inner 15m root section of an SSP34m wind turbine blade is conducted through a specifically designed test rig. The work is carried out within the EUDP funded "LEX-Project"[1]. The overall scope of this project is to develop, prepare for market and demonstrate an applicable method for regaining operational life of installed wind turbine blades with structural defects based on Bladena's patented technology, the X-Stiffener. DTU Mechanical Engineering is responsible for the sub-component and sub-structure testing.

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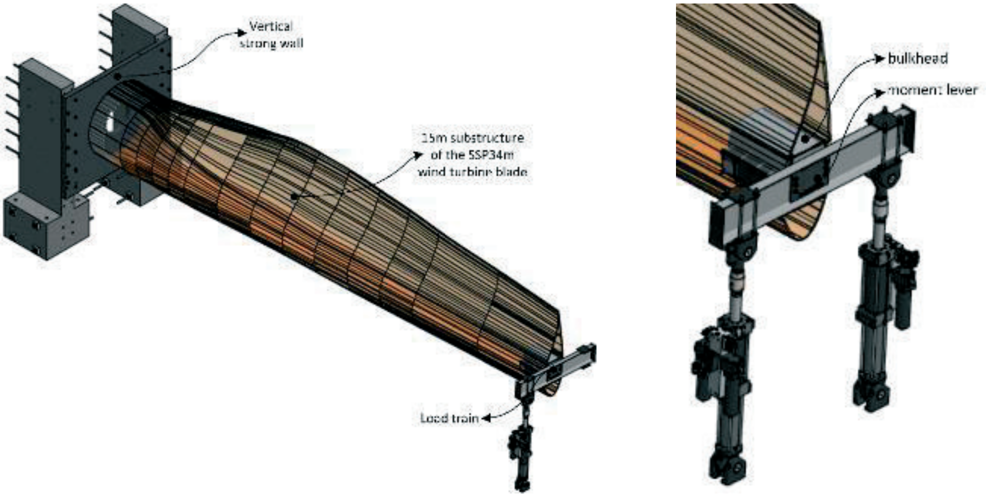
[1] The project is supported by the Danish Energy Agency EUDP program "Development and Demonstration" EUDP project file number 64013-0115. The title of the project is: "Torsional stiffening of wind turbine blades – Mitigating leading edge damages", also called "LEX Project".

The test rig consists of two main parts: the load train and the clamping support. The load train is designed capable of applying a discrete load at the free end of the wind turbine blade sub-structure comprising two degrees of freedom: translation in the edgewise direction and torsion. The load is introduced using one and two actuators configuration. The load is transferred to the free end of the wind turbine blade through a bulkhead installed in the load carrying box girder.



(a) (b)

Figure 1: Sub-structural test set-up: (a) shows the one actuator loading configuration, and also the clamping support, (b) shows the two actuators loading configuration with focus on the bulkhead and the moment leaver.

Wire potentiometers are implemented to quantify the cross-sectional shear distortion of the load carrying box girder. The relative change of distance in the two diagonals is measured at a number of locations along the blade. In order to evaluate the structural response of the aerodynamic skin a number of strain gauges are applied on the surface of the blade. Moreover, digital image correlation measurements are used at the max chord section with the purpose of acquiring a detailed picture of the structural response of the aerodynamic surface.

Thanks to the new equipment obtained through the Villum fund, it is possible to simultaneously control the two new 250 kN MTS dynamic structural actuators, by means of a MTS FlexTest 100 control system. Integrated to the system is a MTS FlexDac 20, capable of acquiring data from all the strain gauges and from the wire potentiometers installed along the blade sub-structure.

The results of the sub-structural test are used to validate the effectiveness of the torsional stiffener device.

Further testing is planned using the newly developed test rig, including applications with a hybrid simulation approach. There is an option for mounting a third structural actuator acting horizontally, allowing flapwise loading and more complex and complete loading scenarios.

Low temperature testing of debonded PVC foam cored sandwich composites for naval vessels

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Arash Farshidi working as a PhD student in an industrial partnership between AIRBUS and DTU on a project with title of “Disbond Damages in Aircraft Honeycomb Sandwich Structures”. He worked on an ONR project on “low temperature debond characterization” as Research Assistant.

Marcello Manca former PhD student and Research Assistant at the Mechanical Engineering Department, Technical University of Denmark (DTU). His PhD project title is: “Fracture Characterization of Sandwich face/core Interface”.

Abstract

Sandwich structures are considered as key enablers for future and present lightweight structural applications in naval ships because of their superior stiffness/weight and strength/weight ratios compared with traditional metallic as well as monolithic structures made from composite materials. Failure often occurs as a consequence of either manufacturing flaws or in-service loads experienced by the structure, such as general overload and impact events, eg. hull bottom slamming, which exacerbate the importance of fatigue loading. Naval vessels are expected to operate in a variety of climatic conditions, including arctic regions. Therefore, the ability for the Navy to operate safely in arctic polar regions under the presence of ice, high-light the need for further research aimed at the influence of low temperature operational conditions on debond fracture growth in sandwich composites.

Mixed-mode I/II fracture characterization and measurements of low temperature (i.e. -20°C) fracture properties for typical naval type sandwich material configurations has been carried out in a state-of-the-art climatic chamber facility using mixed-mode bending (MMB) specimens (see Figure 1). The test methodology is utilized to measure mixed-mode fracture toughness as well as crack speed (da/dN) vs. cyclic energy release rate, and comparing ambient and low temperature fracture face/core behaviour in Navy type sandwich composites.

Figure 1: Sandwich MMB test setup inside climatic chamber

Quasi-static and fatigue tests were carried out at -20°C as well as room temperature, 23°C. For each temperature two set of tests with different mode-mixities were carried out. Eight specimens have been tested using the MMB fixture in displacement control mode inside the climatic chamber to achieve the critical propagation load, Pc, and fracture toughness, Gc, based on MMB formulation in [1]. Fatigue tests have been carried out on eight more specimens using the G-control test methodology [2] to characterize crack growth based on the modified Paris-Erdogan relation. Static test results showed that the debond fracture toughness substantially decreases at low temperature. However, stiffness properties showed to be independent of temperature. Fatigue tests revealed that debond growth rate increases at low temperature.The intensity of fracture toughness degradation and increment of debond growth rate depend on mode-mixity.

ACKNOWLEDGEMENTS

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[2] M. Manca, C. Berggreen and L. A. Carlsson, G-control fatigue testing for cyclic crack propagation in composite structures, *Engng Frac. Mech*., 149, 2015, 375-386.

Sub-structural testing of large composite structures – a hybrid simulation approach

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Jacob P. Waldbjørn is working as a postdoctoral fellow within advanced substructural scale testing through a hybrid simulation approach. The technique is applied for structural assessment of different retrofitted reinforcement methods for wind turbine blades

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Abstract

Structural assessment through Hybrid Simulation (HS) is a cost effective substructural technique where the behaviour of the emulated structure is revealed by combining the advantages of numerical modelling with those of experimental testing. The coupling governed through the interface between the experimental and numerical substructure – referred to here as the shared boundary – is achieved by maintaining the compatibility and equilibrium at the interface. During the test, a predefined external load is applied the numerical substructure and the corresponding load computed. Through a communication platform, the displacement at the shared boundary is induced on the experimental substructure through an e.g. Proportional Integral Derivative (PID) regulated servo-hydraulic actuator – referred to here as the transfer system. The forces required to deform the experimental substructure – referred to here as the reaction force – are fed back to the numerical substructure to reveal the response of the emulated structure. The experimental and numerical substructure, communication platform and transfer system combines to form the HS approach.

Structural assessment through HS originated in the late 1960s and has to date expanded upon numerous branches including Civil and Mechanical Engineering – referred to here as conventional HS. Common to conventional HS is that the shared boundary is defined by a discrete point operated within a few Degrees-Of-Freedom (dofs). This configuration has become a mature and reliable approach however; it imposes some limitations in the effort of spreading the HS technique within other application areas among those: large composite structures. Therefor a new generation of HS is presented capable of handling a shared boundary covering a continuous edge or plane – referred to here as single component HS. An illustration of the basic principle is outlined in figure 1.

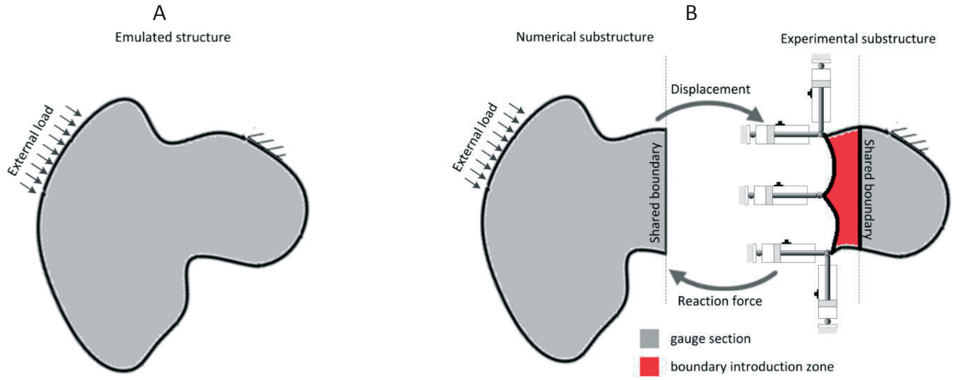

Figure 1: principle of single component HS for structural assessment: a) emulated structure and b) partitioning

The scope of this research is to introduce a single component HS architecture and strategy facilitating single component HS. Here an open source communication platform named OpenFresco is introduced which enables the coupling between the numerical and experimental substructure. The numerical substructure is typically handled through a commercial FE-platform, which facilitates a User Defined Element function among those: Abaqus, Ansys, LS-Dana, Simulink, etc. A direct communication protocol between OpenFresco and the transfer system is established through the FlexTest100 (FT100) using a MTS Computer Simulation Interface software (CSI). Furthermore, external measurements through e.g. DIC can be included, which enables real-time spatial tracking capabilities of the shared boundary. By knowing the actual deformation of the shared boundary an adjustment of the transfer system is feasible, compensating for slack and deformations in the load train. Finally, a case study for a single component HS strategy on an SSP 34 m wind turbine blade is presented. Here an 8 m root section of the blade is identified as a representative substructure, capable of physically replicating the structural phenomena of interest. Furthermore, a boundary introduction zone of 6 m is added to erase the distortion induced by the load train at the shared boundary. A fatigue rated multi-axial test setup is designed to accommodate the inner 14 m root section of the wind turbine blade.

H-TRIS testing of foam cored sandwich panels for ship superstructures

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Mohsen Rezaei, Research scientist at DTU, research interests include fracture mechanics, structural analysis, testing of composites and degradation of adhesive joints at aggressive conditions.

Abstract

Composites are increasingly being implemented in a variety of industrial applications in which metallic materials were considered as the sole viable solution. This is attributed to the outstanding physical, thermal, chemical and mechanical properties that composite materials exhibit. Possibly the major disadvantage of the majority of composite materials is poor performance at elevated temperatures. When composites are heated to moderate temperature they soften, creep and distort which in turn can result in buckling and failure of load-bearing composite structures [1].

The behaviour of composite and sandwich structures at elevated temperature has been an area of significant interest with researchers performing experiments under combined thermomechanical loading focusing on the prediction of the ultimate failure and the mechanisms that govern it However in most cases the effects of delamination and debonding have not been addressed.

In this work medium sized sandwich panels were tested under combined thermal and mechanical loading. For the conduction of the experiments a special, custom testing rig has been designed and constructed. The experiments were performed employing a burner whose position and intensity could account for different Heat flux scenarios, in combination with a custom hydraulic compression testing rig which was developed to operate at high temperatures. The setup resembles the H-TRIS (**H**eat-**T**ransfer **R**ate **I**nducing **S**ystem) developed by Maluk et al. Constant compressive loading of different magnitudes were applied for each test series (i.e. 70%, 60%, 40%, 20%, 10% of the ultimate load of the specimens at room temperature) while simultaneously one face of the specimens was exposed at a constant heat flux (3.6 kW/m^2).

Emphasis has been given in associating the developed temperature at the composite face exposed to the burner and the interface between that face and the core of the sandwich panels to the specimen’s response and its ultimate load bearing capacity.

To this end, apart from the imposed force and the axial displacement of the actuator, a digital image correlation (DIC) system was stationed at the unexposed side of the specimen in order to investigate the out of plane deflection of the specimens during testing. The DIC system could not be used on the exposed heated side as the spray speckle pattern required for the DIC measurements, being flammable, could jeopardize the integrity of the measured data and interfere with the conduction of the experiment. Regarding the thermal loading, 5 thermocouples were placed at different positions along the thickness to measure the temperature distribution during testing. Additionally, a camera was placed focusing on the exposed face of the specimens in order to correlate the findings of the DIC measurements at the unexposed side with the evolution of damage in the exposed side.

The experimental results revealed that the failure mode was caused by the debonding of the skin to the core which is preceded by local delamination of the skin. Additional testing is required however to allow the connection of these mid-scale test series to larger scales and to further validate the noted dependency between the load bearing load and the developed temperature.

Despite the fact that the conducted mid-scale experiments do not allow for the measurement of the fracture properties of the interface, significant insight has been gained on the evolution of damage, the failure mechanisms and the governing parameters for the load bearing capacity of sandwich structures subjected to combined thermomechanical loading.

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Determination of mechanical properties of glass-epoxy composites and sandwich structures at elevated temperatures

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Vasileios Karatzas is a postdoc at DTU whose research interests include fracture mechanics, structural analysis and testing of composite, sandwich and marine structures, and the implementation of composites in marine applications.

Abstract

Composite materials are widely used in in different structures due to their outstanding material properties. In the service condition, composite and sandwich structures are needed to endure elevated temperatures, this topic has been an area of many researches [1]. In this study mechanical properties of E-glass / epoxy composites and foam cored sandwich structures measured by performing 5 series of experiments inside of the environmental chamber followed by the relevant ASTM standards. The Environmental chamber can maintain temperatures from -60 ^{o}C to +180 ^{o}C. Tests for characterization of the mechanical properties were performed in different temperatures starting from room temperature and proceeding to elevated temperatures. In this study curve fitting function has been extracted based on tanh equation model and applied to all of

the test results. Tensile elastic modules of the tensile specimens were measured using one extensometer capable of working at maximum 180 °C. To measure the compressive modulus of the specimens and control the bending ratio, two strain gauges suitable for working at high temperatures were installed on both sides of the specimen. The IITRI test fixture was used for this test. V-notched rail shear method was used to measure the shear properties of the composite specimens. To investigate the strain distribution and shear modulus in the test specimens, the DIC measurement technique is employed. The software used for processing is Aramis from GOM. The system uses two 12 megapixel digital cameras to determine the movement in the specimen by processing the deformation of the pattern. In the traditional method, two strain gauges were needed to be installed on each specimen which was more time consuming and always had the risk of deboning the strain gauges from the surface of specimen at higher temperatures. Using DIC system the strain distribution is recorded during the test, two virtual Extensometer introduced and centred between the notch tips in the gauge section of the specimen (see Fig. 1). Core compressive and shear properties of the sandwich structure are defined using flatwise compression and four-point bending test of the sandwich specimens. Deflection of the sandwich panels in both tests were measured using Aramis system.

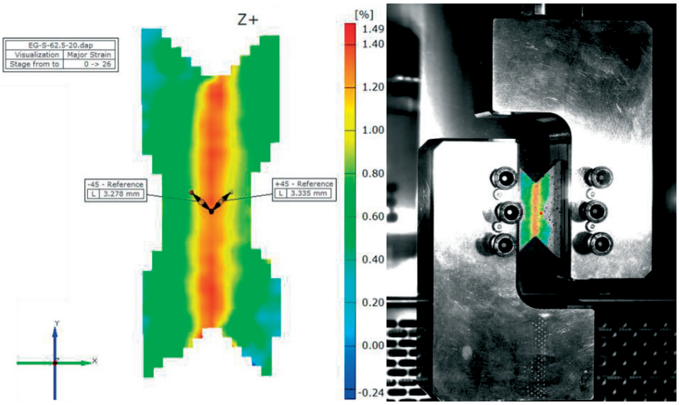

Figure 1: Strain distribution and virtual extensometers presented at +45° and -45° orientations using DIC

The experimental results revealed general reduction for both modulus and strength of the materials at elevated temperatures. Tensile test showed less elastic modulus and ultimate strength reduction comparing other tests. The reduction of strength and elastic modulus were greater in case of compression and shear tests, both had similar trend in reductions and they showed dramatic decrease after 75 °C which is above the matrix glass temperature transient. Curve fitting function applied to the test results showed good agreement with the tanh equation.

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Multi-scale CT for imaging and testing of composites

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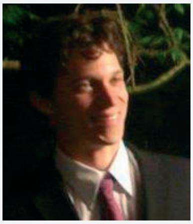

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Abstract

X-Ray Computed Tomography (CT) is a largely non-destructive 3D imaging technique that allows 3D analysis of internal structures within objects. It has been widely applied in the materials science and engineering community, from research and development to quality control and failure analysis of components. The CT technique enables identification of damage initiation and progression, non-destructively, and at several length-scales. It is broadly regarded that composite damage is progressive up to final failure, and the CT technique lends itself towards time-resolved experiments that can be targeted towards identifying the initiation and progression fracture mechanisms (from individual fibre breaks, to interlaminar cracking, to macroscopic failure). High resolution CT also lends itself well to broader materials science, where the relationship between macroscopic properties and the microstructure is often sought [1]. On the other end of the spectrum, larger components can be monitored between manufacturing steps to aid with improving processing methods and for quality control. It is clear that one specific tool will be unable to tackle this variety of applications and length-scales. Therefore, multiple types of CT techniques exist, including high flux synchrotron sources and arbitrary X-Ray path methods [2], each with their own limitations and advantages. On this basis, it is essential to understand and

consider the chosen CT method, the specimen composition and geometry, and most importantly, the ultimate goal what the experiment is aiming to achieve.

The purpose of the presented work is to introduce a number of case studies of previous CT experiments, addressing the types of rigs used for *in situ* micro-mechanical tests, relevant design considerations for synchrotron beamlines, and limitations of various CT methods. Figure 1 shows some examples of various applications of CT, with three distinct source/detector arrangements used. Figure 1(a) shows results from an *in situ* Mode I crack propagation experiment within a particle-toughened interlayer in a Carbon Fibre Reinforced Polymer (CFRP) captured using high resolution synchrotron CT. Figure 1(b) shows a micro-focus CT scan, used to identify void content, morphology and location within a Glass Fibre Reinforced Polymer (GFRP) coupon. Finally, Figure 1(c) illustrates a multi-material specimen, containing GFRP, CFRP and metal inserts, requiring the use of a line detector to reduce the effect of scattered X-Rays (arising from the use of high energy to penetrate metallic inserts) on the reconstructed CT slices. It is clear that the CT method is versatile, but numerous challenges remain, such as: data storage, automated segmentation, formalized metrology standards, and many more.

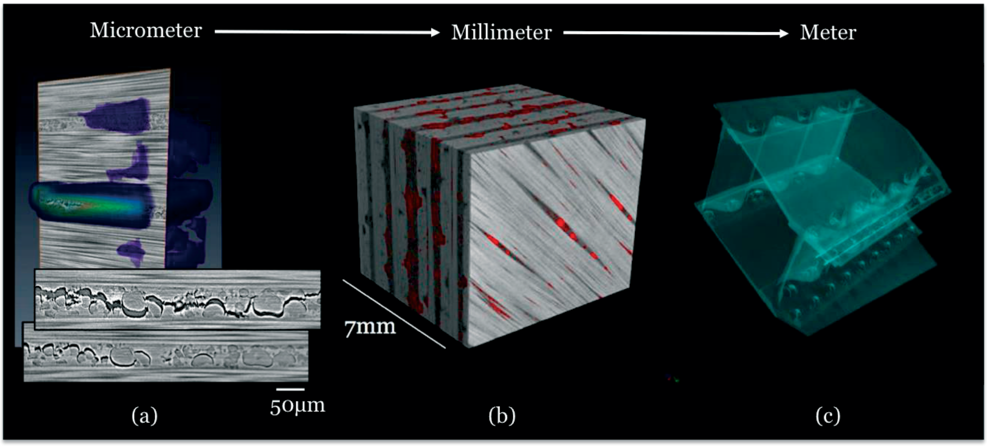

Figure 1: CT images of composite specimens showing results from (a) an *in situ* crack propagation experiment capturing tensile opening strains at the crack tip in CFRP, (b) void characterisation in a GFRP specimen, and (c) a multi-material wing structure scanned using a line detector array *(Images courtesy of μ-VIS X-Ray Imaging Centre)*

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X-ray tomography in DTU Wind Energy

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Søren Fæster. Cand. Scient in Physics. Senior scientist in DTU Wind Energy. Responsible for six electron microscopes and one X-ray tomography equipment at DTU Risø Campus. Søren is in his present position focusing on characterizing drive train components in wind turbines with the ambition of improving the service lifetime of wind turbines.

X-ray computed tomography (CT) is a non-destructive technique that provides 3D images of the internal structures of materials. The technique is ideal for characterizing materials, observing fracture and for in-situ investigations of the micro-structural evolution during heating, cooling, oxidation, tension, compression etc. X-ray tomography offers non-destructive views into deeply buried microstructures that cannot be observed with 2D imaging techniques such as optical microscopy, SEM and TEM.

In-situ deformation

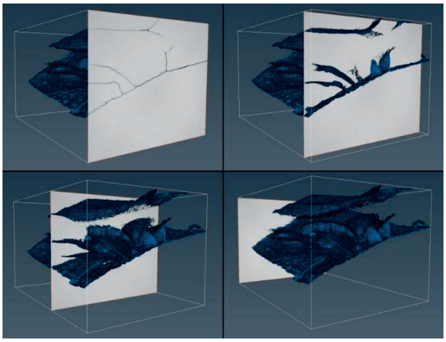
The tomography equipment at DTU Wind Energy, a Zeiss Xradia 520, is equipped with a set of different objectives, which enables reconstructions in 3D with different resolutions from tens of micrometers down to less than 1 micrometer. The instrument is thus very versatile and capable of studying a wide range of materials and scientific / technical problems. By combining 3D X-ray tomography with mechanical loading, unique information of the three dimensional damage evolution can be obtained.

In-situ observations of the evolution of microscale failure mechanisms is extremely valuable for fibre composite materials, which can fail by a number of complicated interacting failure mechanisms and in-situ observations in 3D makes it possible to establish better micromechanical models in the future.

Diffraction Contrast Tomography (DCT)

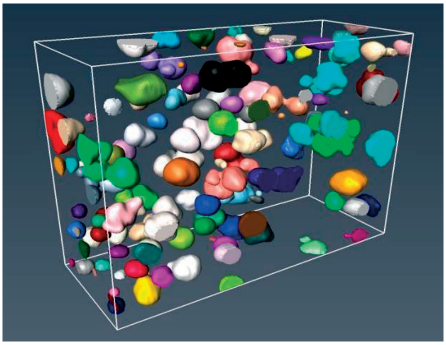
Xnovotech A/S is a spin-out company from DTU that have modified the DCT technique so it can be used not only at synchrotrons but also on laboratory X-ray equipment. The technique is based on measurements of the crystal lattice in bulk material and makes it possible to obtain grain maps in 3D non-destructively. In dynamic experiments the evolution of grain structures can be studied directly during deformation or annealing.

DTU Wind Energy is working closely together with Xnovotech in order to further develop the labDCT technique. At present we are working on utilizing the technique to measure residual stresses in bulk material.



3D representation of the crack network in a rail. The images show 4 sections at different locations through the reconstructed volume. The reconstructed voxel size is 7.3 µm/voxel.

LabDCT reconstruction of the grain structure in a cylindrical Fe sample with a diameter of 1 mm.



Segmentation of graphite nodules in a reconstruction of spherical graphite cast iron (SG iron). Statistics can be obtained on individual nodules. (4 µm/voxel)

Specifications:

- Source target: tungsten
- Tube voltage: 30 - 160kV
- Power: 10W
- Magnification: 0.4X, 4X, 20X and 40X
- Sample size: 1 – 100 mm
- Voxel size: 0.3 – 55 µm
- Spatial resolution: 0.7 µm

Capabilities:

- Absorption, phase and diffraction contrast
- In-situ deformation < 5kN
- Temp.: -20˚C to +160 ˚C

Instrument specifications.

Approach for investigations of progressive fatigue damage in 3D in fibre composites using X-ray tomography

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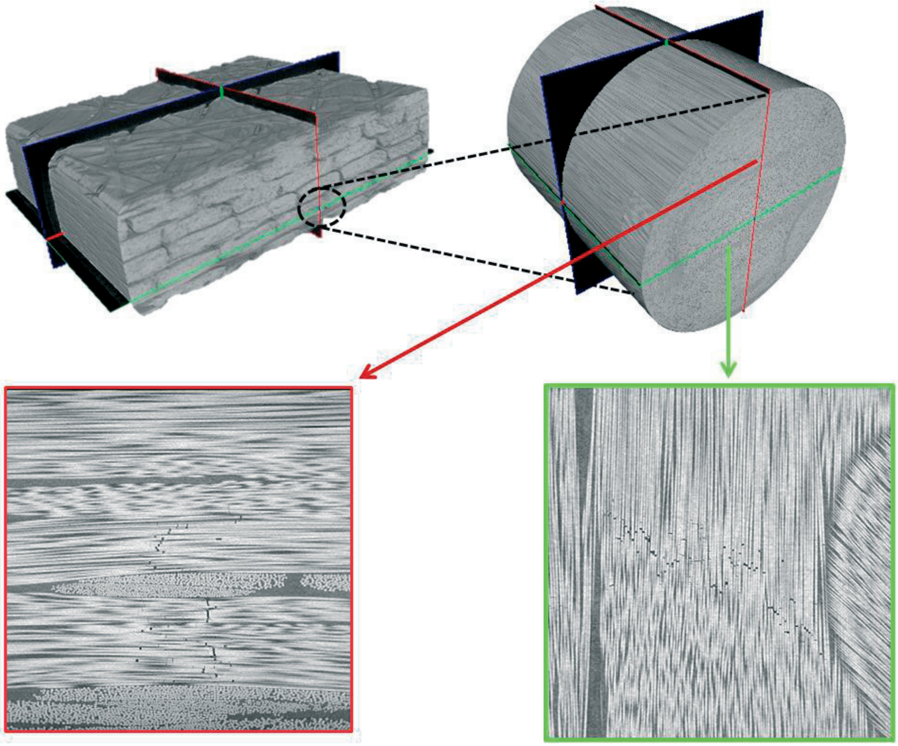
Lars P. Mikkelsen, M.Sc., M.E., PhD in Solid Mechanics, Associate Professor and team leader for Modelling in Composite and Material Mechanics. Research in fatigue and compression behaviour of composite materials and x-ray tomography based characterisation.

Kristine M. Jespersen, M.Sc., M.E., in Solid Mechanics. PhD student in the field of fatigue damage evaluation in composite materials with focus on the load carrying laminates in wind turbine blades using ex-situ x-ray tomography and in-situ transverse crack detection.

Abstract

Understanding fatigue damage initiation and evolution in the load carrying laminates inside wind turbine blade plays a key factor designing longer and lighter turbine blades. Thereby, it is possible to lower the Cost of Energy for the wind energy based electricity production either by simply building larger wind turbines or by upgrading existing turbines for lower wind classes' . In the presented work, a Zeiss Xradia Versa 520 scanner has been used in connection with ex-situ fatigue testing with the purpose of identifying fibre failure during the fatigue loading. The load carrying laminates is typically based on stacking of a number of non-crimp fabrics in where the load carrying fibres are oriented in the axial direction of the wind turbine blade. In order to ease the handling of the fabric during the dry fabric layup and ensure a good alignment of the final laminates, approximately 10% of the fibres are oriented in secondary directions. Thereby, the non-crimp fabric is given some shear stiffness.

The figures below show the results from a scanning of a fatigue damaged material. The width of the full scanned cross section is 15 mm, while the size of the zoomed scan is approximately 2.5 mm. The small black points visible in the two lower slices taken from the zoomed scan indicate fibre failure. From the red slice, the fibre failure is seen to be located in regions with the backing bundles are located. The backing bundles in the red slice are pointing out of the figure plan. In the green slice, it can be seen that the fibre failure in the load carrying fibres, are following the 45 degree orientation of the backing bundles where the 45 degree backing bundle can be seen at the left side of the green slice figure. In addition, to the scan case shown here, an ex-situ study of the fibre progression [1] has been performed [1]. An ex-situ study where it has been important to design a good gripping strategy inside the scanning machine. Doing this, it has been possible to scan the same region multiple times. Thereby, a progressive fatigue damage evolution has been observed.



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Multi-scale testing of fibre reinforced concrete under corrosion deterioration

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Victor Marcos-Meson (MSc). Industrial PhD employed at COWI and DTU, studying the impact of fibre corrosion on the fracture mechanics of cracked steel fibre reinforced concrete exposed to chlorides and carbonation through a multiscale approach (m – µm).

Alexander Michel (PhD, MSc, MSc). Post-doctoral fellow at DTU Byg with focus on multi-physics and multi-scale deterioration modelling in reinforced concrete, corrosion fatigue of steel, and multi-scale experimental testing of cementitious materials.

Abstract

Steel fibre reinforced concrete (SFRC) is increasingly being used in the civil engineering industry, among others, for the construction of prefabricated segmental linings for bored tunnels. However, the long-term effect of exposure to chlorides and carbon dioxide on cracked SFRC is in focus and under discussion. So far, experimental results do not provide a clear understanding of the long-term deterioration of carbon-steel fibres bridging cracks and the impact of fibre corrosion on the residual-tensile strength of cracked SFRC. Published research focuses on the performance at the macroscale level, and there is limited information on the mechanisms responsible for the degradation of steel fibres bridging cracks in concrete. A doctoral project has been initiated, in order to investigate the impact of carbonation and chloride exposure on cracked SFRC. The investigation involves a multiscale approach: the changes on the mechanical behaviour of SFRC on the macroscale, i.e. residual tensile strength, are to be explained through a microscale

investigation, comprising electrochemical and mechanical testing on single fibres. X-ray computed tomography is of particular interest, as it offers a wide range of possibilities: supporting the identification of micro-cracking at the fibre-matrix interface, visualization of corrosion products and characterization of corrosion pits [1], [2].

The first application of this technique to concrete research was presented in 1996 by Bentz et al., on the characterization of sulphate-attack damage on mortar using X-ray tomography [3]. Later on, Landis et al. used high resolution X-ray microtomography to investigate compression-induced damage on mortar and concrete [4], [5]. The first published investigations on X-ray tomography applied to corrosion monitoring of steel embedded in concrete were published in 2007, Beck et al. proposed the method to evaluate corrosion on a steel rod embedded in chloride contaminated mortar [1], [6], [7]. The technique has been since then utilized in various studies to characterize corrosion damage of reinforcing steel in concrete, firstly reported by Michel et al. in 2011 [8], [9].

There is limited research on the mechanical damage at the steel-matrix interface of SFRC [10], and despite corrosion damage at the microscale has been investigated using X-ray tomography [10], [11], there is still need for detailed understanding about the damage mechanisms involved during fibre pull-out and the role of the fibre-matrix interface as protection of steel fibres against corrosion. The doctoral project presented aims at describing the damage at the fibre-matrix interface arising during the fibre pull-out, as well as the healing and corrosion mechanisms involved during the service life of cracked SFRC subject to aggressive exposures.

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Single fibre tensile testing

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Justine Beauson. MSc. Mechanical Engineering, Development engineer. Field of expertise: Composite microstructure characterization, Fibre properties characterization: morphology, physical and mechanical properties. Key research area: Composite recycling and Aging of fibres.

Abstract

The mechanical properties of single fibres are crucial parameters to know for the design and modelling of composites. The determination of single fibre strength and stiffness is generally obtained with a single fibre tensile test. Due to the scatter in strength properties of brittle fibres, such as glass fibres, a minimum of 30 tests is usually required to obtain a good statistical representation.

The most common procedure for single fibre test is described by the standard ASTM C1557-03. In this procedure, the fibres are glued on individual cardboard tabs with a central window matching the wanted gauge length for the test. The card tabs are then manually placed in the testing machine and when the card tab is gripped, a section of the tab is cut away, leaving the specimen free to be loaded for the test. This procedure requires precision in the preparation of the card tabs

and is time demanding due to the manual placement of the card tab in the testing machine for each test.

These challenges are overcome by the FAVIMAT+ from Textechno, which was acquired by DTU Wind Energy. The single fibres do not need to be mounted on card tabs; instead they are placed in a magazine. A magazine contains 25 spaces, where fibres with small clamps on their extremity can be suspended. The magazine is placed in a storage compartment next to the single fibre testing area. In order to test the fibres, a robot picks up each fibre and places it in the testing area, test after test. Given a preparation time of 30 min for 25 glass fibres and a testing speed of 5mm/min, the time required to perform 50 single glass fibres tensile test is approximately 2 hours.

Another important challenge of mechanical characterization of single fibres is the determination of fibre cross sectional area in order to calculate fibre stiffness. In the procedure described by the standard ASTM C1557-03, two methods are generally used. The cross sectional area can be calculated for each fibres based on an average fibre diameter obtained with optical microscopy measurements. A single value for the fibres cross sectional area can be calculated for all fibres using a fibre diameter provided by the manufacturer. These methods consider that the fibres have a uniform circular cross section along the gauge length.

The FAVIMAT+ uses a more precise method to determine the fibres cross sectional area. The method based on vibroscopy measures the fibres linear density. This method considers the whole gauge length where the fibres will be tensile tested. During the vibroscopy test, the fibre gripped in between the two sets of clamps is excited to its resonance oscillation f under a gauge length L and a known tension F. The linear density T is then derived using Equation 1.

$$T = \frac{F}{4\, L^2 f^2} \qquad \text{Eq.1}$$

The linear density T is then used in Equation 2 together with the fibre density ρ to determine the cross sectional area A.

$$A = \frac{T}{\rho} \qquad \text{Eq.2}$$

FAVIMAT+ originally meant for textile fibres was successfully used for brittle fibres, such as glass and carbon fibres. Machine parameters, such as pressure in the clamps and clamp closing speed, were adapted to brittle fibres. Material parameter such as the presence of sizing on glass fibres was taken into account in the preparation of the test. The restricted amount of handling needed to prepare the magazine was particularly beneficial for testing recycled glass fibres, which are extremely brittle.

Mixed Mode fracture testing of foam core sandwich using the DCB-UBM test method

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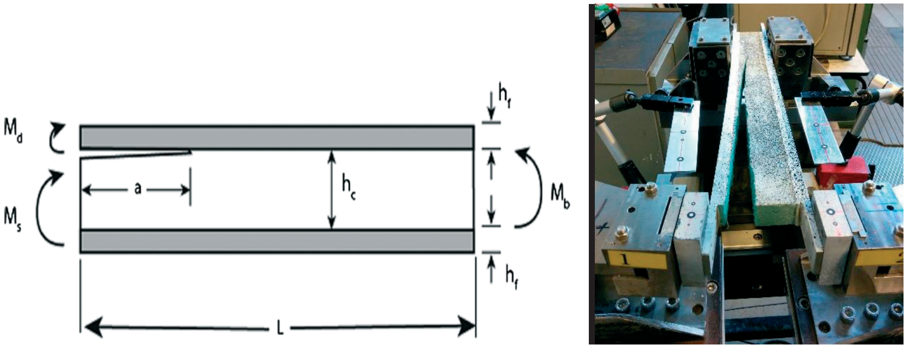
Abstract

Face/core debonds in sandwich structures cause loss of integrity of sandwich structures. The debond problem in sandwich composites is inherently mixed mode and has not been widely studied. A suitable fracture mechanics approach coupled with experimental validation is paramount to determine the fracture resistance of the face/core interface. In this paper, a novel test-rig exploiting the double cantilever beam with uneven bending moments (DCB-UBM) concept [1] is used to determine the fracture toughness of PVC foam core sandwich composites. The DCB-UBM test (Figure 1a) enables fracture testing over a large range of mode-mixities as expressed by a phase angle (ψ) which is a measure of the amount of shear loading at the crack tip. A desired phase angle may be achieved by changing the moment-ratio (MR = M_d/M_s).

Analysis of the energy-release rate (G) of the sandwich DCB-UBM specimen has been presented based on the edge couples (M_s and M_d) assuming Linear Elastic Fracture Mechanics (LEFM) to be

valid [2, 3]. A closed form expression has also been derived to obtain phase angle in terms of a scalar quantity ω. The phase angle was also determined using the crack surface displacement extrapolation (CSDE) mode-mixity method with the aid of a finite element model [4]. The model has been verified using new high-resolution DIC systems available through the CASMAT center.



(a) (b)

Figure 1: a) Principle of DCB-UBM test. b) H45 core sandwich specimen in DCB-UBM test rig

Testing of PVC H45 foam cored sandwich specimens has been performed using the DCB-UBM test method to determine the fracture toughness under mixed mode (I/II) conditions. Testing was conducted on sandwich specimens with 3 mm thick glass fiber face sheets and a 40 mm thick H45 foam core (Figure. 1b). The tests were carried out by applying edge rotation couples to the rotating clamps of the test rig at an angular velocity of 10 deg/min while measuring the resulting moment in each arm. To accommodate testing of sandwich specimens with thin face sheets, the facesheets of the DCB-UBM specimens were reinforced with high strength steel layers (“doublers”) on both sides of the specimen. These doublers prevent large rotations and limit the displacements and rotations to allow linear beam analysis to be valid.

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Determination of face/core fracture toughness in aircraft honeycomb sandwich composites using the SCB test method

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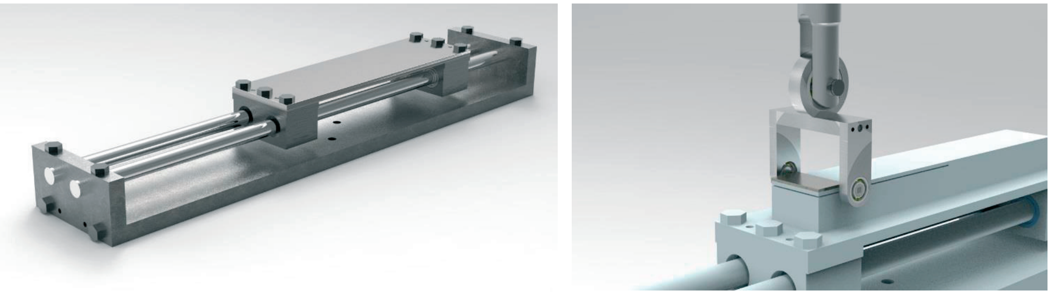
Abstract

The development of a *Single Cantilever Beam* (SCB) test-rig is conducted through a design task which is carried out within an EASA research project. The construction of the SCB rig will be used to contribute to the standardization of the Single Cantilever Beam (SCB) Test Method to determine the face-core interface fracture toughness in aircraft honeycomb sandwich composites. Although well-established fracture toughness test methods are available for composite materials, the same cannot be said for sandwich composites. Considerably less attention has been given to fracture mechanics based test methods for sandwich composites until recently. A majority of the efforts have been focused on developing a mode I (opening mode) test method. The main tasks performed in order to contribute to the standardization of the SCB test method are the design and development of a suitable SCB test rig (enabling DTU to participate in a Round Robin test in

cooperation with other six research units), performing disbonding studies in three stages (baseline, sliding and doubler layer) and subsequent data reduction and analysis.

Thanks to the new equipment obtained through the Villum fund, it is possible to use the Digital Image Correlation technique (DIC) to precisely measure the strains over the facesheet of the sandwich specimens. This allows to assess the damage of the surface and measure the energy dissipated into the yielding of the facesheet.

The test rig consists of two main parts: the load train and the specimens' support. The load train is that part of the device which by the means of a pulling rod and a hinge mechanism, transfer the load from the actuator to the disbonded beam of the test specimen. The specimen support is the assembly fixture to which the specimen is bonded. It consists of a translatable table mechanism which can be locked into its position if the horizontal movement needs to be prevented and a rigid bottom that is locked onto the test machine's bench.



(a) **(b)**

Figure 1: SCB test rig: (a) Specimens' support. (b) Load train detailed.

Results have shown how DTU SCB test rig and the agreed test routine can be considered as a reliable tool to use to assess the fracture toughness in aircraft honeycomb sandwich composites. The data reduction shows how all the laboratories' tests results converge towards a mean value which differs slightly from DTU's test results. This confirms the robustness of the test methodology and the rig's design. However, this research has also brought to the attention of the committee some shortcomings of the SCB test method which involve, among the others the need of development of a more reliable method of detecting the crack growth during testing and necessity of a bonding procedure of the specimens which does not rely on glue.