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Test Methods for Assessing Bimaterial Interfaces in Wind Turbine Blades

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Indo-Danish Workshop on

Future Composites Technologies for

Wind Turbine Blades

Indian Institute of Technology Delhi, India

8-9 October 2012

Indo–Danish Workshop
On

Future Composites Technologies for Wind Turbine Blades

8-9 October 2012

ABSTRACTS

Jointly Organized by

Indian Institute of Technology Delhi, India

Technical University of Denmark, Denmark

Overview and Objectives

The workshop focuses on the scientific and technical aspects of composite materials, experimental test methods, and computational models for developing future wind blade technologies. The analysis and prediction models can help wind industry for developing future blade designs and experimental research studies can demonstrate the interrelations between materials and microstructures, processing, and mechanical properties.

Industry - Academic partnerships has the potential of feeding the engines of innovations. The two-day workshop will familiarize participants with the latest developments on the material and structural level in the wind energy section and in addition facilitate interaction between Indian and Denmark scientists working in the area. In this workshop, an effort has been made to strengthen the existing and establishing new collaborations with the industry. The main objective is to brainstorm ideas from the challenges and the problems faced by the industries. Our mission is to establish a "circle of information" between Universities and Industries for mutually beneficial relationship.

The workshop is jointly organized by Department of Applied Mechanics, IIT Delhi and Section of Composites and Materials Mechanics, Department of Wind Energy, Technical University of Denmark with a financial support provided by Danish Agency for Science Technology and Innovation, Copenhagen, Ministry of New & Renewable Energy (MNRE), New Delhi, Dassault Systems (SIMULIA), USA and PYRODYNAMICS, Bangalore. The workshop takes place at the *Senate Room, 1st Floor, Main Administrative Building, Indian Institute of Technology, New Delhi campus* (for more details refer workshop webpage http://indodanish.iitd.ac.in/).

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Applied Mechanics Department,
Indian Institute of Technology- Delhi, India

0905 - 0935   INAUGURAL ADDRESS   : **Prof. S.N. Singh**
Deputy Director (Operations)
Indian Institute of Technology Delhi, India

Prof. Suhail Ahmad
Head of Department,
Applied Mechanics Department, IIT Delhi, India

Dr. D. P. Agrawal
Chairman, Union Public Service Commission,
New Delhi, India

0935 - 0950   **Mr. Dilip Nigam,** Director, Ministry of New & Renewable Energy,
New Delhi, India

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1620 - 1645	**Prof. Naresh Bhatnagar**, Mechanical Engineering *Department*, IIT Delhi, India
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" Leveraging Best Practices in Design, Simulation, and Manufacturing for Composite Wind Turbine Blades – Part I"

1400 - 1425   **Dr. Mahesh Kailasam**, Dassault Systems (SIMULIA), USA

" Leveraging Best Practices in Design, Simulation, and Manufacturing for Composite Wind Turbine Blades – Part II"

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        How to collaborate near in future?

1600 - 1630   **High Tea**

1630-1645   *********************** Closing Session************************

ABSTRACTS
(As per Sessions)

Session I:

Inaugural Talks

Wind power development in India

Dilip Nigam

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The Wind Power Programme of the Ministry aims to catalyze commercialization of both grid interactive and off-grid wind power. The programme includes wind power generation; survey and assessment of wind resources; Research & Development; demonstration and field-testing of various wind power generating devices. India now ranks 5th in the world after China, USA, Germany, and Spain with a wind power installed capacity of over 18,000 MW.

Potential

Available wind data from field measurements carried out so indicate that strong wind regimes are available mainly in southern and western parts of the country, particularly in the States of Tamil Nadu, Karnataka, Andhra Pradesh, Kerala, Maharashtra, Gujarat, Madhya Pradesh and Rajasthan. The results from a study indicate that the country has a wind power potential of over 49,000 MW with 2% land availability in potential areas for setting up wind farms @10 ha/MW.

Wind Resource Assessment

The Wind Resource Assessment Programme which is being coordinated by the Centre for Wind Energy Technology (C-WET), Chennai has so far covered 31 States and Union Territories involving establishment of over 1100 wind monitoring and wind mapping stations. Out of the total stations established so far, 233 stations have found to have Wind power density in excess of 200 W/m2 at 50 m height. Eight volumes of 'Wind Energy Resource Survey in India' have so far been published covering wind data for around 250 sites in 15 States/UTs.

Achievements

A total capacity of 18000 MW has been established up to September 2012, mainly in Tamil Nadu, Gujarat, Maharashtra, Andhra Pradesh, Karnataka and Rajasthan. Wind electric generators of unit sizes between 225 kW and 2.50 MW have been deployed across the country. During 2011-12, a capacity of 3,200 MW was added. First time in the country, the wind power installations in a year has crossed the figure of 3,000 MW. With introduction of Renewable Purchase Obligations (RPOs) and Renewable Energy Certificates (RECs), wind power has good demand in coming years.

Manufacturing Base

Wind Electric Generators are being manufactured in the country by 16 manufacturers, through (i) joint ventures under licensed production (ii) subsidiaries of foreign companies, under licensed production and (iii) Indian companies with their own technology. An indigenization level up to 70% has been achieved.

Wind turbines upto capacities of 2.50 MW are being manufactured in the country. Modern technologies like permanent magnet based turbines are available in the country.

Fiscal and Promotional Incentives

An attractive package of fiscal and financial incentives is available which includes concessions such as concessional custom duty on certain items, excise duty exemption, sales tax exemption, income tax exemption for 10 years on the profit, etc. In addition, most states are offering preferential tariffs for electricity generated from wind power projects. In order to attract independent power producers, foreign direct investment, NGOs, trusts etc, a generation based incentive (GBI) scheme was introduced to provide Rs. 0.50 per unit of electricity generated from wind power projects which do not avail accelerated depreciation benefit. The GBI scheme was upto 11th Plan, which is likely to be continued in 12th Plan.

Centre for Wind Energy Technology

A Centre for Wind Energy Technology (C-WET), Chennai has been established in Tamil Nadu as an autonomous institution under the administrative control of the Ministry. The Centre serves as the technical focal point for wind power development and supports the growing wind power sector in the country. C-WET's main activities include research and development to achieve and maintain reliable and cost-effective technology; wind resource assessment; preparation of standards, testing and certification of wind power systems; information dissemination; human resource development; and offer various consultancy services to customers.

European Wind Energy - Development Trends and Implications for Wind Turbine Blade Design and Materials Selection

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The most pronounced trends in wind energy in North Europe are (i) the up-scaling, i.e., the development of yet larger wind turbines and (ii) off-shore placement of wind turbines in large wind turbine parks. The two development trends are partly coupled: Some cost associated with off-shore wind turbine parks (e.g. the costs for the making of foundations and the costs for renting of large floating cranes for on-site assemblage of wind turbines) are not significantly higher for a larger wind turbine than for a smaller wind turbine. However, the development trends have important implications for future requirement for mechanical design and materials for future wind turbine rotor blades. Some of them will be addressed in the presentation.

Simple scaling laws reveal that up-scaling is not a linear process. For instance, consider a linear scaling of all dimensions of a given wind turbine blade geometry, i.e. a proportionally scaling of length, thickness and width. Then, the aerodynamic forces would scale linearly with the area swept by the rotor blades, i.e., proportional to the square of the blade length, whereas the gravitational forces would scale linear with the cube of the blade length. Therefore, the design against weight becomes more and more important with increasing wind turbine size. Indeed weight saving of the rotor blades are of great importance since that would lower the forces transferred onto the hub, drive train, tower and foundation, enabling further weight savings in those components too. Thus, *weight saving* is the most important challenge associated with up-scaling. Another issue associated with up-scaling is manufacturing defects. Obviously, a high manufacturing reproducibility and high quality control standard are desirable. However, it will not become possible to manufacture large blades without manufacturing defects. Since a large wind turbine rotor blade represents a high value for the manufacturer (e.g. in materials), parts that contain manufacturing defects will not be rejected unless the defects are very severe. Instead, blades will be repaired. But blade repairs are non-standard and time consuming (costly). An alternative to repair of all blades with defects is to use *damage tolerant materials and structural designs*. Damage tolerance implies that the first mode of damage does not lead to imminent failure but results in detectable changes that allows the damage to be detected well before it reaches a critical state (unstable failure).

Offshore installation leads to several challenges. It is difficult and costly to access off-shore wind turbines. Personnel for manual inspection should in most cases be flow to the wind turbine by helicopter. Thus, an important challenge is to *minimize the need for manual inspection*. Furthermore, in order to reduce the number of blades being repaired, it is of great importance to evaluate whether a blade need to be repaired on the basis of physically based criteria, preferable in the form of general approaches that can be used for modeling of a rotor blade with a given damage type. Thus, another challenge is to develop r*eliable modeling tools for damage assessment and repair.*

The presentation will outline a few ideas for future research tasks associated with the above mentioned challenges.

Finally, it should be noted that the up-scaling changes the relative competition between various failure modes. Failure criteria that are expressed in terms of strain are invariant to up-scaling. However, for failure modes for which the failure criterion involves a length scale, such as tunneling cracking of constraint layers or delamination of laminates and adhesive joints.

Keywords: *wind turbine blade, failure modes, composite materials, damage tolerance, and structural health monitoring*

Session II:

Materials and Manufacturing

Future Perspectives and Challenges of Thermoplastic Wind Blades

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Polymer composites are gaining several industrial applications in today's scenario. Among them wind industry is one, which consumes lots of material in developing turbine rotor blades. Current trend points to a growing importance of the onshore and offshore wind mill farms in the world's energy segment. The industry growth over the last decade has been spectacular. It is the time to maintain market growths exponentially by upgrading the current technologies in terms of new and innovative blade designs, new materials, and automated processing system aiming cost-effectiveness to customers.

Wind industry is continuously trying to replace the current material system (i.e. thermosets) with a new material system like thermoplastics mainly to get added advantages in terms of sustainability like recyclability and potential benefits like joining methods such as resistance welding and repair methods. Since the blade lengths are increased to 61.5m long, the weight and cost saving has become a significant role on industry growth. The best option is thermoplastic composites, which can be stronger enough for the same weight than thermosets permitting light weight structures. This can be achieved only by replacing the existing material system by introducing new materials such as thermoplastic polymers or green materials such as bio-based polymers and natural fibre reinforcements.
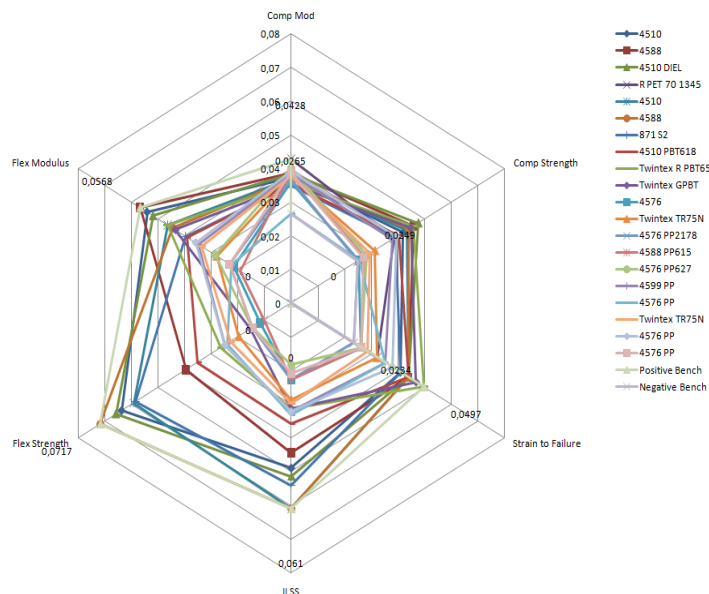
Fig. 1 – Normalized mechanical properties for various glass reinforced thermoplastic laminates

The use of thermoplastics in wind turbine rotor blades is in its early stages. The basic material properties are investigated by several researchers and continuously trying to improve the interface properties between the glass fibres and various thermoplastic polymers in order to achieve comparable properties with thermoset composites. This needs a thorough investigation and proper understanding of

basic material properties, manufacturing processes, and structural performance of final composite products such as static and fatigue performances under various stimulated loading conditions.

The current research study derives the pros and cons of various thermoplastic material systems and challenges ahead to wind industry in developing a large scale turbine rotor blade. Assessment is mainly based on mechanical tests and characterization (See Fig. 1), and challenges associated with different thermoplastic material systems are mainly derived from processing and quality of chosen materials like commingled, prepreg, and reactive based polymer systems. The main focus areas needed to resolve first are mainly highlighted as challenges to - mould designers, material specialists, blade designers, and polymer/chemical experts. This study also helps industrial designers and manufacturers to focus on thermoplastic or green materials instead of existing thermoset blade materials for the benefit of recyclability.

Keywords: *commingled yarns, prepregs, APA6 resins, process parameters, turbine blades*

Natural Fiber Reinforced Bio-Composites: Opportunities and Challenges

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Due to their inherent superior properties, synthetic fiber reinforced polymer composites have been incorporated in wide range of applications such as construction, aerospace and automobile industries. These composites are non bio-degradable in nature and therefore are a major threat to ecological system. The synthetic fibers such as glass and carbon involve several health hazards. Light to lighter weight requirements and strict environmental rules and regulations have led to the development of natural fiber reinforced bio-composites. Light weight characteristic of natural fiber polymer composites has encouraged their use in automobile industry because weight has a direct impact on the fuel economy of the vehicles.

Nowadays, researchers and technologists are focusing on increasing the production and utilization of renewable energy especially the wind energy generation. The material of wind blades used in wind turbine should have low weight, very high stiffness and strength, resistance to fatigue induced damage as well as environment loading. Natural fiber reinforced composites which are light in weight, have comparable mechanical properties and are environment loving can be engineered according to the requirement and attempts have been noted in exploring their feasibility as a wind turbine blade material. Xu et al. worked and presented a report focusing on the development of using bamboo composite materials for producing windmill turbine blades and compared the performance between bamboo turbine blades and glass fiber reinforced turbine blades with sustainable perspective. It was concluded that bamboo fulfilled the requirements of constructing a turbine blade with high performance associated with sustainable development.
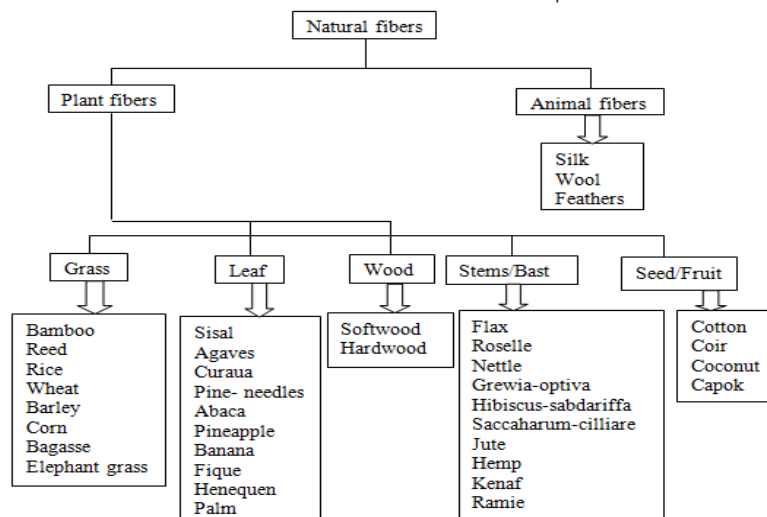

Figure 1 Classification of plant fibers.

Bio-based composites are developed by using natural fibers with biodegradable or petroleum based non-biodegradable polymer matrix. When natural fibers are reinforced with non-biodegradable polymer matrix, it is known as partially biodegradable composite. When the polymer composite is fabricated by reinforcing natural fibers with bio-degradable polymer, it is known as fully biodegradable or green composite. There are various renewable material based polymers which are fully biodegradable like poly lactic acid (PLA), cellulose esters, poly hydroxyl butyrates (PHB) and starch based plastics. Hybrid bio-composites are developed by reinforcing polymer matrix which may be petroleum based (thermoset / thermoplastic) or bio-polymer or combination of both with combination of natural fibers. Most commonly used natural fibers are plant fibers which are obtained from different parts of the trees. The classification of plant fibers is given in figure 1. Some of the animal fibers and mineral fibers have also been used. These natural fibers provide a viable and abundantly available substitute to expensive and non-renewable synthetic fibers such as glass.

Generally, natural fiber reinforced polymer composites are fabricated using the same processing techniques as used for conventional synthetic fiber reinforced polymer matrix composites. These processes are broadly classified as open mold process and closed mold processes. Hand lay up, spray – up, filament winding and autoclave method fall under open mold processes. The compression molding, injection molding and transfer molding are closed mold processes. For randomly oriented short fiber composites, extrusion and injection molding technique is preferred and for laminated bio-composites, compression molding through film stacking technique is generally employed. The characterization is an essential and important step in conceptualization and development of novel materials in order to judge their specific applications. The characterization includes various aspects such as evaluation of mechanical, thermal and physical properties, effect of different environments on properties of material, tribological and machining behaviour.

The environment friendly materials such as bio-composites are materials for future which provide viable and sustainable solution to issues and challenges associated with conventional materials. The major focus of the talk would be on the opportunities and challenges in context of the conceptualization and characterization of natural fiber reinforced polymer composites.

Keywords: *natural fiber, bio-composites, characterization, applications.*

Manufacturing Techniques for Wind Turbine Blades
- Present State of the Vacuum Infusion Process

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Modern wind turbines face a range of challenges because the increasing competition and focus on cost of energy is driving for larger and more efficient installations. Novel concepts for modular blades, divided into sections, are being developed to overcome the logistics of transporting 70+ meter blades. Transmission System Operators (TSO's) are demanding both increased stability and flexibility in production, requiring wind farms to be operated like conventional power plants. These challenges are derived from the wind turbines success, since the increased penetration of wind power in the electricity grid makes them a substantial contributor instead of a marginal power producer.

As material scientists the aim is to increase knowledge of behaviour in the materials and to continuously refine manufacturing techniques to achieve higher homogeneity in material quality. More reliable structures can achieve tighter tolerances, lower safety factors, longer service intervals and less down time, all of which helps reduce the cost of energy, and allows for a safer investment.
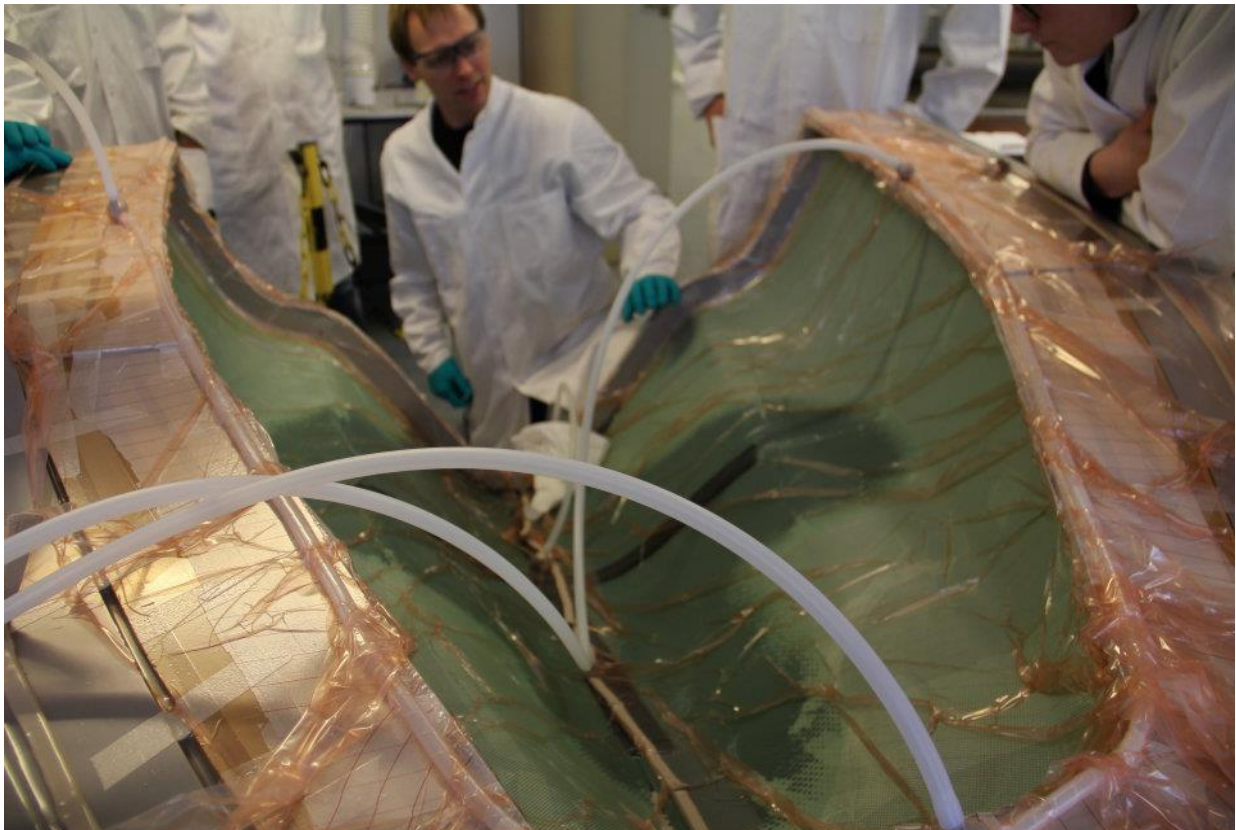
DTU Wind Energy technician performing vacuum infusion on car body shell for student course.

Requirements for higher material quality and greater consistency have led to the implementation of new manufacturing techniques in the wind turbine industry. The hand lay-up and vacuum bagging techniques have mostly been abandoned in favour of vacuum infusion. This process also has the added benefit of reducing exposure of the workforce to potentially hazardous chemicals.

Processing via vacuum infusion involves a single sided mould and a flexible tooling consisting of a polymer film. Sealant round the edges of the mould encloses a volume between the mould and tooling film, where the reinforcements are placed. Using low pressure the reinforcement is consolidated. The low pressure under the flexible tooling offers a pressure difference which can be used to drive a matrix material into the enclosed volume. The matrix constituent of wind turbine blade composites is generally a slow curing thermosetting epoxy or unsaturated polyester. With experience and modelling, an appropriate flow pattern can be achieved by adding flow media and channels under the flexible tooling.

No apparent limitation has been reached regarding the size of components that can be realized using this technique, however achieving consistent results with large and complex structures requires vast experience and a highly skilled workforce. Process control is largely dependent on visual observation, where the greatest risk remains leaks in the sealant or the flexible tooling; however the material quality depends on a wide variety of other factors.

Residual pressure difference can be of concern and not easily modelled in vacuum infusion of large structure. The low pressure suction side and the atmospheric pressure inlet side constitute the boundary conditions of the pressure distribution that is the driving force of the vacuum infusion. As the resin flow front permeates the reinforcement material, the pressure distribution from inlet to outlet changes. When the resin flow front reaches the outlet and the infusion is completed, both inlet and outlet are closed to allow the pressure under the flexible tooling to equalise. Due to the viscosity of the matrix material and the flow resistance in the reinforcement material, a residual pressure difference will remain under the flexible tooling from inlet to outlet. This pressure difference equals the pressure available to consolidate the reinforcement and therefore relates directly to the obtained volume fraction between the constituent materials.

Another important factor in process control is the degree of cure. Polymerisation of thermosetting resins is an exothermic reaction where the cross linking polymers release heat to the surroundings. Since both glass fibre and typical polymers have very poor heat conducting properties, excessive heat build-up is a problem for thicker laminates commonly found in the root section of the blades. Furthermore the rate of polymerisation is heat dependent which makes the problem synergistically linked. Slow curing resins are typically used to prevent high temperatures developed during cure, breaking down the polymers, but to achieve a higher productivity external heating must be applied in the thinner sections. This leaves the problem of determining the actual state of cure in the different sections, and quantifying the process to reach an understanding of whether it can be optimised. Several issues like polymer properties and residual stress is linked to these cure kinetics where the state of present work involves embedding sensors in laminates and neat resin samples to describe the development of mechanical properties in the resin during cure.

Dynamic Response of Composite Plates with Fillers

R Velmurugan and G Balaganesan

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Indian Institute of Technology, Madras, India

Composites have wide applications in aerospace industries due to their light weight and high strength. High damping composite materials that are useful in aerospace structure have to exhibit, high impact strength, stiffness, toughness, vibration and damping characteristics. The behavior of composite materials when subjected to projectile impact is complex, and involves several damage mechanisms. The impact on composite materials by fast moving projectiles induces large vibrations and failure of the material. If the damping characteristic of the composites is improved, it is possible to reduce the vibration of the material, which in turn reduces the damage. One way of improving the damping characteristics is by incorporating high damping nano fillers into the polymer matrix. The addition of nano fillers such as ceramic particles, nano tubes, nano fibres and whiskers etc will improve the matrix properties of the fibre reinforced polymer composites. High surface contact area of such nano fillers in the matrix provides good damping.

The laminates are prepared by hand lay-up and compression molding method. The laminates of different thickness values of 610gsm glass woven roving mats (WRM) with epoxy resin and nano clay, are prepared. Clay dispersion is varied from 1% to 5%. Laminated composites with nano fillers are subjected to projectile impact at different velocities. A piston type gas gun set up is employed to impact the composite laminates. Spherical nose cylindrical projectile of diameter 9.5 mm and mass 7.6 g is used for the study. The vibration responses of natural frequency and damping factor are obtained and are studied for laminates with all edges clamped boundary conditions. Impulse hammer technique is used to find natural frequency and damping factor of pre and post impacted laminates. Results show considerable improvement in natural frequency and damping factor due to nano clay addition. It is also seen that the nano clay controls the delamination of the laminates.

Quasi static deflection tests and dynamic tests are carried out to find the energy absorption of the laminates. The energy absorption analysis is carried out for the composites laminates subjected to projectile impact velocity below and above the ballistic limit. At the impact velocity below the ballistic limit, the energy is absorbed due to deflection of the laminate, failure due to delamination and matrix crack. The strain energy stored in deflection is then dissipated in the form of vibration. The values for the above energies are obtained and it is observed that the presence clay in matrix enhances the energy absorption in vibration and decreases the energy absorption in delamination and matrix crack which is due to decrease in damage area in delamination.

The impact velocities of the bullets are increased to predict the ballistic limits of the laminates with and without clay. The incident energy is absorbed completely by the target before reaching the ballistic limit. The energy absorbed by the laminates above the ballistic velocity is due to failure of fibers, deformation of secondary fibers, delamination and matrix crack in delaminated area. A detail delamination study of the laminates is carried out and it is observed that nano fillers completely change the mode of deformation of the plates.

Keywords: *nano fillers, delamination, composite plates*

Session III:

Blade Design and Development

Material Selection and Design Aspects of Small Wind Turbine Blades

Lars P. Mikkelsen[1], F. Bottoli[2], and L. Pignatti[3], T. L. Andersen[1], and B. Madsen[1]

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[3] Composites Engineering, Imperial College, London, UK

Based on a case study on wind turbine blades for a wind turbine car, the possibility of using bio-based materials alone or as a hybrid with conventional carbon fiber reinforced epoxy was investigated. The wind turbine cars was build as a part of a competition between universities competing on making a wind turbine car running as fast as possible heading directivity against the wind. The wind turbine car from Technical University of Denmark, see figure 1a, was able to drive 75% of the wind speed and thereby in 2011 breaking the world record.

Figure 1: Wind turbine car and the blade geometry

The mechanical performance of blades based on pure carbon fiber reinforced epoxy, pure flax fiber reinforced epoxy and a mix thereof was investigated. In order to obtain the mechanical properties of the laminate, a test program was followed testing the different lamina in tension and shear. The stiffness and ultimate strength of the different plies from these test was used in finite element simulation performed in the commercial finite element code Abaqus. Based on a fixed blade geometry determined from a CFD-study from where the loads also were extracted, the mechanical performance of the optimal fiber layups was compared. The objective for the optimizations procedure was a minimization of the twist angle of the blade keeping the weight, the transverse deflection, the laminate thickness and the failure and buckling performance inside certain limits. The optimization was performed as a

parametric study in the finite element model based on a selection of the available plies used in a 0, 45 or 90 degree layup. The material layup was decided only to be changed in four sections of the plate. The optimized layup obtained for the hybrid blade can be seen in figure 2.
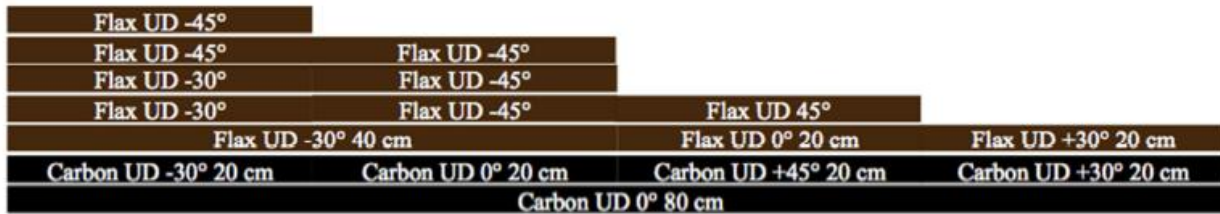
Figure 2: The resulting material ply selections in the axial and thickness direction used in the optimized carbon/flax hybrid blade layup.

It was found that the optimized hybrid blade with a dominating amount of flax fibers perform almost as good as the pure carbon blade while the pure flax did not perform as well. As it can be seen in figure 3, the twisting angle variation along the axial direction of the blade was improved significant both for the new carbon based and hybrid blade compared with the first version of a pure carbon blade manufactured in 2009 where the material layup at that time was based on qualified engineering judgments. The production energy of flax fibers is only 17% of that of glass fibers and 1.3% of that of carbon fibers. Based on this, it can be calculated that the material layup shown in figure 2 require 40% less energy than the corresponding purely carbon fiber composite based blade. The weight of the manufactured blades, see figure 1b, was 260g, 310g and 520g for the carbon, flax/carbon hybrid and the flax fiber based blade, respectively.
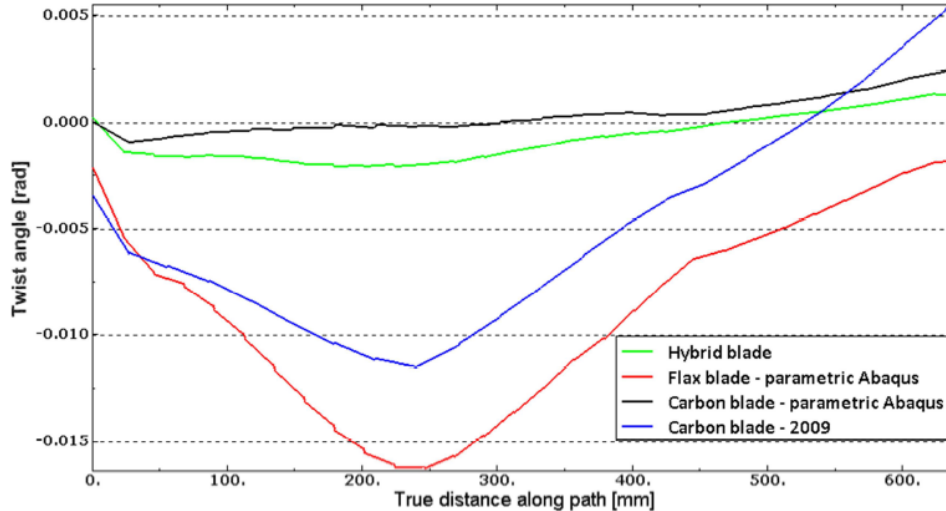
Figure 3: Comparison of the twisting angle variation along the axial direction of the blade for the optimized hybrid, flax and carbon blade compared with a regarding material layup non-optimized carbon blade manufactured in 2009.

Keywords: *optimized fiber layups, bio-based fiber reinforced composites, small wind turbine blades.*

CSIR-NAL's Experience in Development of Wind Turbine Blades

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Blade design and engineering is one of the most complicated and important aspects of wind turbine technology. Today, engineers are trying to design blades that extract as much energy from the wind as possible throughout a range of wind speeds. The wind turbine blade design is based on the theories of aerodynamics. Development of wind turbine blades at CSIR-NAL specific to Indian conditions is an excellent example of high end Aerospace Technologies finding use in societal applications. Specifically, the core competences in aerodynamics, structural design and advanced composite technologies have been effectively utilized.

CSIR-NAL has been working in the area of wind turbine development and related technologies for over a decade now. In-house expertise and skills have been used during each stage of wind turbine blade development. This included usage of Eppler's code for designing airfoil profiles suitable for Indian conditions of low wind speeds and dusty environment, GH-Bladed for the design (stacking of the airfoils and chord distribution) and aero-elastic analysis of the rotor blade, IMPRANs code (an indigenous code of CSIR-NAL) and ANSYS-Fluent for the detailed CFD analysis of the rotating blade and NASTRAN /ANSYS for a detailed composite design of the internal features of the blade.

CSIR-NAL embarked on the prestigious NMITLI program around 2004 to develop an India specific, low cost, 500 kW, horizontal axis wind turbine. The blades, about 22m in length were fabricated and tested before integrating with the indigenous wind turbine platform. Know-how in the field of GFRP as well as CFRP was used in the development of the blade as well as an innovative tip brake. The turbine has been installed at Kethanur, Tamil Nadu and limited field trials are being carried out since 2009 to assess the energy generation capabilities.

This talk dwells on the various issues involved in the design, development and testing of wind turbine blades using advanced aerospace technologies.

Keywords: *airfoil profiles, issues, testing of turbine blades*

Some Challenges in Wind Turbine Blade Design

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In recent years, there is increasing focus on Wind Energy as a Renewable Energy source. Though Wind Turbines have been in operation for the past many decades, there is now a gradual shift toward longer blade lengths. There are two main reasons for this: (a) offshore turbines and (b) turbines for low-wind regions. Long blades, which are usually fibre-reinforced composite structures, need new design paradigms.

Using a simple scaling model, the blade mass is expected to scale up as the cube of its length; however, exponents varying from 2.2 to 2.8 have been reported. Blade mass contributes to gravity loads, which are directly impact edgewise fatigue loads. Traditionally, blade structure was generally optimized for the laminate part of the structure. As the blade length increases, there are now attempts to optimize the sandwich structure also and use them for load transfer.

Another approach to reduce blade mass is to incorporate alternative fibres (high-performance glass fibres, carbon fibres, etc.) in the structure. Various attempts have been made to either replace only a portion of the structure or to optimize the entire structure for these alternative fibres. One of the challenges with using carbon fibre is its relatively high cost.

Further, these long blades pose a challenge in transportation. Though various strategies have been evolved to stretch the transportation envelope, it is likely that jointed blades would soon become inevitable.

An important parameter in long blades is the manufacturing cost component in the total blade cost. This is driven not only by bigger infrastructure requirements but higher processing times – lay-up, curing, finishing, etc. One key focus here is the lay-up process, where increased automation is being looked into.

Other challenges include (a) remote monitoring, particularly for offshore blades and (b) blade testing.

Keywords: *wind turbine, blade structure design, longer blades*

Dynamics of Rotating Cantilever Composite Panels

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The dynamic characteristics of rotating flexible bodies, such as turbine blades are significantly different from those of stationary bodies as the coriolis force and centrifugal force come into effect in addition to gravity loads. Such rotating turbine (gas or wind) blades may be modeled as cantilever beam / plate / shell panel. A rigid frame "**A**" may be attached to the rotating panel to define its geometry. The displacement, velocity and acceleration components of the rotating panel may be defined in the local coordinate system (**A**) as:

$$\vec{u} = u_1 \hat{i} + u_2 \hat{j} + u_3 \hat{k}; \qquad \dot{\vec{u}} = \dot{u}_1 \hat{i} + \dot{u}_2 \hat{j} + \dot{u}_3 \hat{k}; \qquad \ddot{\vec{u}} = \ddot{u}_1 \hat{i} + \ddot{u}_2 \hat{j} + \ddot{u}_3 \hat{k} \qquad (1)$$

Now, the panel (frame **A**) rotates at an angular velocity of ($\vec{\omega} = \omega_2 \hat{j} + \omega_3 \hat{k}$) with respect to the ground (**Fig 1**). The global displaced position ($^G\vec{r}$), velocity ($^G\vec{V}_p$) and acceleration ($^G\vec{a}_p$) of the any point P (x, y, z) may be written as

$$^G\vec{r} = \vec{r}_0 + \vec{r}; \qquad \vec{r} = (x+u_1)\hat{i} + (y+u_2)\hat{j} + (z+u_3)\hat{k} \qquad (2)$$

$$^G\vec{V}_p = \vec{V}_0 + \dot{u}_1 \hat{i} + \dot{u}_2 \hat{j} + \dot{u}_3 \hat{k} + \vec{\omega} \times \vec{r} \qquad (3)$$

$$^G\vec{a}_p = \vec{a}_0 + \ddot{u}_1 \hat{i} + \ddot{u}_2 \hat{j} + \ddot{u}_3 \hat{k} + 2\vec{\omega} \times (\dot{u}_1 \hat{i} + \dot{u}_2 \hat{j} + \dot{u}_3 \hat{k}) + \dot{\vec{\omega}} \times \vec{r} + \vec{\omega} \times (\vec{\omega} \times \vec{r}) \qquad (4)$$

Here, the acceleration component $2\vec{\omega} \times (\dot{u}_1 \hat{i} + \dot{u}_2 \hat{j} + \dot{u}_3 \hat{k})$ is the coriolis force and its effects on the rotating cantilever plate are studied by Sreenivasamurthy and Ramamurti (1981) and Ramamurthy and Kielb (1984). The component $\vec{\omega} \times (\vec{\omega} \times \vec{r})$ is the centrifugal force, causes in-plane stretching of the panel. This centrifugal force increases bending stiffness of the rotating blade and changes its mode shapes. The bending frequencies increase faster than the torsion modes and loci veering and loci crossing occur.

Fiber reinforced laminated composites are often used to manufacture turbine blades to reduce weight and increase stiffness, strength and fatigue life. Hence, the dynamic characteristics of rotating cantilever composite panels have received considerable attention of the researchers in recent years. The classical plate theory in combination with two stretch variables were employed to investigate the vibration frequencies of rotating cantilever composite plates (Yoo *et al.* 2002, Yoo and Kim 2002) using assumed space mode analytical approach. The influences of coriolis and centrifugal force on the bending and torsional frequencies of pre-twisted blades were reported by Ramamurthy and Kielb (1984) and Sinha and Turner (2011) based on analytical investigations.

(a) Rotating plate (b) Pre-twisted rotating panels
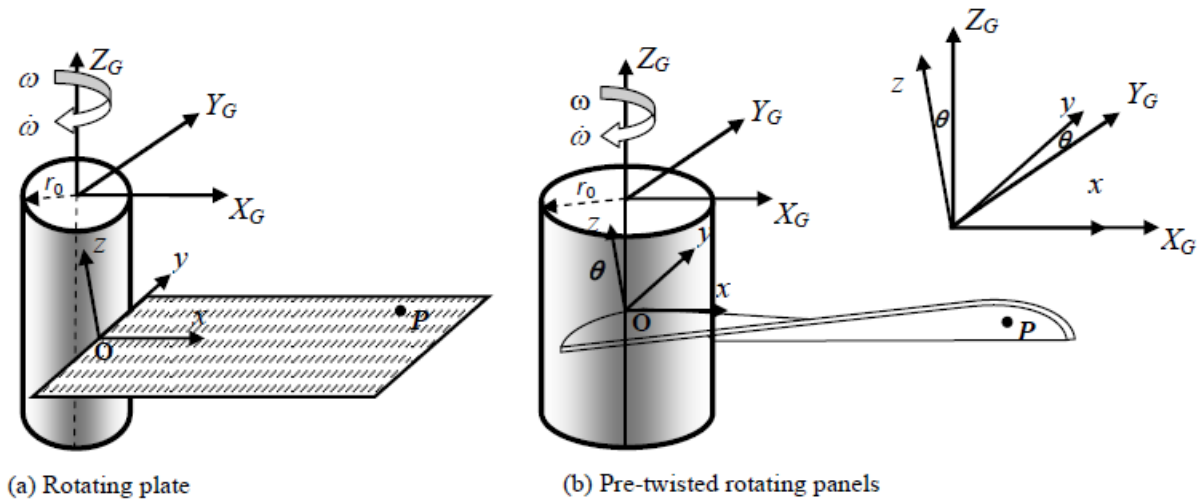
Figure 1. Coordinate system of rotating plates and curved panels

The vibration characteristics of rotating cantilever plates were investigated by Jinyang and Jiazhen (2005) using the finite element method and the accuracy of the assumed mode for the analysis of dynamically stiffened plate was examined. Finite element method was employed to examine the vibration frequencies of thick composite plates (Hashemi *et al*. 2009) and pre-twisted shell type rotating composite blades (Kee and Kim 2004). Farhadi and Hosseini-Hashemi (2011) studied the aeroelastic behavior of composite plates rotating normal to its plane.

In the present work, the dynamic characteristics of rotating composite panels are investigated using a sixteen-noded degenerated isoparametric finite element (Singha et al. 2006) with five degrees of freedom per node (u, v, w, α and β). The nonlinear equations of motion are derived considering both the coriolis force and centrifugal acceleration. The effects of angular velocity, setting angle, twist angle, aspect ratio and curvature on the vibration frequencies and mode shapes of cantilever thick composite panels are studied.

Keywords: *rotating cantilever panel, coriolis force, centrifugal force, loci veering, loci crossing, mode shape variation*

Variational Asymptotic Method (VAM): A New Methodology of Smart Slender Structural Analysis

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The research in smart structure is inherently multi-physical, where two or more physical fields combine to perform and give the desired outcome. For example, piezoelectric based smart structures are electromechanical systems, where electrical and mechanical fields get coupled. A major challenge in modeling an electromechanical system is to capture this coupling effect, so that depending on the input, be it electrical or mechanical, the output can be quantified theoretically and be used for effective control of the structure. Coupling may arise because of the topology of the structure also; for example, a pre-twisted beam-like structure shows extension-twist coupling, a pre-curved beam-like structure shows extension-bending coupling etc. Capturing these classical as well as non-classical effects in a multi-physical set up is the biggest challenge for a modeler. The evolution and availability of 3D multi-physical FEM software such as COMSOL, ABAQUS etc. have eased the situation to a large extent, but 3D analysis comes at a very large cost, mostly due to large computational time even on the high performance hardware capabilities of the day. As a viable alternative, conventional dimensionally reduced structural models (like those for beams, plates and shells) lead to a compromise on accuracy requirements while vastly improving the computational efficiency.

For example, many engineering smart structural components, like helicopter rotor blades, wind turbine blades, even micro cantilevers in AFM instruments etc can be analyzed using beam models if one dimension (strictly speaking, the wavelength of deformation) is much larger than the other two dimensions of the structure. Different researchers have proposed various smart beam models to take advantage of this geometrical feature. These models try to capture the behavior associated with the two smaller dimensions, which are eliminated in the final 1D beam analysis. Roughly speaking, most of the studies in the literature can be classified as engineering models which are based on "a priori" kinematic or stress-based assumptions and asymptotic models which are derived by asymptotic expansions of the three dimensional quantities (such as displacements and/or stresses) in terms of the small parameters such as h/l, with h as the characteristic dimension of the cross section and l as the wave length of axial deformation.

Engineering smart beam models begin with (*a priori*) assuming some kind of distribution of the 3D variables (3D here refers to the dependence on three spatial coordinates, apart from time in a dynamics problem) through the cross-section in terms of 1D variables (which depend on only one spatial coordinate, $1\,x$) defined along the axial dimension of the beam. These models $x1$, $x2$, $x3$ dominate the smart beam literature. These models use assumptions mainly based on engineering intuition and have clear physical meaning. The numerical implementation of these models can be developed straightforwardly from a variational statement. However, most of the *a priori* kinematic assumptions which are natural extensions derived from the models of beam made of homogeneous, isotropic

material cannot be easily extended or justified for heterogeneous structures made with anisotropic materials. Things get further complicated if the structure is having some pre-twist or pre-curvature. Moreover there is no rational way for the analysts to determine the loss of accuracy and what kind of refinement (i.e. single equivalently homogenized layer versus layer-wise, first-order versus higher order) should be undertaken to increase the accuracy while allowing a reasonable computational cost.

Instead of relying on *a priori* kinematic assumptions, asymptotic methods can reduce the original 3D problem into a sequence of 1D beam models by taking advantage of the small parameter h/l. The conventional practice is to apply a formal asymptotic expansion directly to the system of governing differential equations of the 3D problem and successively solve the 1D field equations from the leading order to higher orders. Although these models are mathematically elegant and seemingly rigorous, it is hard to consistently identify and drop terms in various equations constituting the set of governing equations, boundary and initial conditions. Moreover, it is very difficult, if not impossible, to implement these theories numerically. This becomes even more severely intractable for a complex problem like smart composite beam analysis with electromechanical as well as structural couplings due to geometry and anisotropy apart from initial curvature and twist. The Variational Asymptotic Method (VAM) was introduced primarily to remedy the aforementioned shortcomings of asymptotic methods. Where, asymptotic analysis was applied directly to the 3D electro-mechanical energy functional to decouple a whole smart beam problem into a 2D cross-sectional minimization problem and a 1D beam problem. This method has merits of both the variational methods (viz. systematic and easily implemented numerically) and asymptotic methods (viz. without *a priori* kinematic assumptions). VAM can be effectively applied to derive a fully coupled model for an electromechanical slender structure, with low frequency of vibration and geometric non-linearity, like generally seen in large wind turbine composite blades.

Keywords: *variational asymptotic method, slender structures, PZT*

Session IV:

Damage Mechanics and Delamination

Probabilistic Design Methodology for Composites under Impact

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Probabilistic structural mechanics for composites is an evolving and expanding field. There is a wide spectrum of application of risk and reliability assessment to composite systems. The reduction in structural failure probabilities and the benefits of such reduction in terms of increased system reliability or reduced system risk should be considered within the context of the system as a whole. A composite structural system can be ranked according to their required level of reliability. Higher ranked structure can be designed to higher reliability level or inspected and maintained at more frequent intervals to achieve higher reliability.

Probabilistic analysis is the basis of a realistic design mainly because it provides the facility to quantify the inherent uncertainties in the design input and the associated risk involved. It also quantifies the sensitivities associated with the design variables. Hence, it is inevitable to extend the probabilistic design approach to the composite blades of windmills. These blades are vulnerable to impact apart from other aerodynamic loads. Composites, in general, have more intrinsic variables than metals due to their heterogeneity. They are also subjected to sources of variation in manufacturing. The conventional factor of safety concept does not account for the random nature of design parameters like material properties, environmental loads, geometry, and boundary conditions etc. Deterministic inputs produce the design of unknown reliability or unknown risk. Reliability at par with the performance and cost with ever increasing importance on warranties, quantified reliability is an essential feature. Applications of conventional procedures do not provide appropriate design with cost/weight reduction and optimum inspection intervals for maintenance as a part of health monitoring. Statistical characterization of the random variables is required to be carefully determined. The concept of safety is rationalized through probabilistic approach. Designs are now growing more critical and competitive. Hence, there is a need to quantitatively asses and optimize reliability leading to minimization of risk.

The salient features of probabilistic analysis and design of composites comprise the identification of expected potential failure modes of the component under anticipated loading conditions. Design probability of failure is established or adopted as per the code. The critical response is obtained using stochastic finite element method. Random design variable contributing to stress and strength are statistically defined. Probability of failure is then obtained at predetermined critical location.

Response under impact essentially accounts for the most severe damage initiation possibly occurring at the worst possible location in the composite plate while it is subjected to the highest loads conceivable. In fact, the probability of occurrence of such a scenario is due to large uncertainties arising in the system. Hence, a probabilistic approach is a realistic solution that considers the stochastic variability and distribution of characteristic data of materials. It is needed to account for the uncertainties in composite design, manufacturing and loading conditions. In the present study a beam under impact

cannot be guaranteed as absolutely safe because of the unpredictability of the loads, uncertainties in the material properties, the use of simplified assumptions in the analysis (which include limitations of the numerical methods used), and human factors (errors and omissions). Nevertheless, the probability of failure is usually required to be within a specified acceptable range for the analysis, design and optimization of a component.

The relevant loads and resistance parameters, essentially random in nature, Xi and the functional relationship between the response variable Z (e.g., elastic properties, strength, impactor velocity, stress at a point, deflection etc.) and the random variables (X_1, X_2, X_3………X_N) are described as,

$$Z(x) = Z(X_1, X_2, X_3………X_N) \tag{1}$$

A limit state function/ performance function is hence defined as

$$g(x) = Z(x) - Z(0) \tag{2}$$

where Z(0) is a limiting /permissible value of Z, an implicit or explicit function of random variables such that g(x) = 0 is a boundary between the failure region [g(x) < 0] and safe region [g(x) > 0] .The probability of failure (Pf) is an integral by the joint probability distribution in which f(X_1,X_2 . . . X_N) is the joint probability density functions for the random variables X_1,X_2 . . . X_N, and the integration is performed over the failure region X where g(x)< 0.

$$P_f = \iiint f(X_1, X_2, X_3 ………… X_N) dX_1 dX_2 dX_3 .. dX_N \tag{3}$$

This integral is presently computed by the standard Monte Carlo procedure. Depending upon the number of random variables involved and the level of Pf (usually very small), this integration is performed repeatedly using reliability code to accurately model the response variables' stochastic characteristics. Although the method is inherently simple, the large numbers of output sets are generated to build an accurate cumulative distribution function of the output variables. It makes it computationally expensive. Furthermore, the need for a large nonlinear finite element analysis makes the computation prohibitive. For the present problem following steps are adopted to carry out the probabilistic analysis.

(1) A set of input random variables (of composite beam and load) are identified, and the corresponding probabilistic distributions are obtained. For a given set of random variables, a deterministic finite element analysis is carried out using ABAQUS interfacing with reliability code. The response results at failure locations are collected.
(2) The above process is repeated a number of times to generate a table of response variable values that correspond to the perturbed set of values of the selected input random variables (elastic and strength properties and velocity of impactor).
(3) The Gaussian Response Surface Method (GRSM) then uses the data, generated above, to compute the cumulative distribution function (CDF) and corresponding sensitivities of the response.

In addition to the CDF of the response, the GRSM technique provides additional information regarding the sensitivity of the response to the random variables. The magnitude of the sensitivity factor provides a way to rank the random variables that have the major influence on the uncertainty of the response variable. By controlling the scatter in the more significant variables, the reliability can be improved. In

a Monte Carlo simulation, a random value is selected for each of the variables, based on the range of estimates. The model is adopted based on this random value. The result of the model is recorded and the process is repeated. A typical Monte Carlo simulation calculates the model hundreds for thousands of times, each time using different randomly-selected values. When the simulation is complete, a large number of results from the model are obtained. These results are used to describe the likelihood or probability of reaching various results in the model. In the present study stresses in an individual lamina are fundamental to control the failure initiation in the laminate. The strength of each individual lamina is assessed separately by considering the stresses acting on it. The initial failure of a lamina (first ply failure) is governed by exceeding the maximum limit prescribed by a failure criterion adopted.

The damage of composite plates subjected to impact of foreign objects occurs due to matrix cracking, fiber breakage and de-lamination between plies. The damage considerably degrades the strength of the composite. Computational finite element model with cohesive property is employed to simulate and predict the failure behavior under drop-weight impact. The contact and dynamic forces are idealized to act in an incremental fashion. A 3-D explicit dynamic finite element analysis is performed to determine the contact force and displacement between the impactor and the target. Puck and Shurmann and Hashin 3D failure models are used to predict the failure of a lamina. The uncertainties associated with the properties of composite material, loading condition and assessment of critical stresses affect the failure limit state to a greater extent. The limit state function for the composite plate under impact is derived from Puck and Shurmann as well as Hashin 3D failure models. If the stresses in the lamina are such that the limit state function ($g(x)>0$), Gaussian response surface method (GRSM) is used to predict the probability of failure (P_f). The probabilistic analysis takes into consideration the effect of scatter in elastic and strength properties of composite plate, and velocity of impactor. It is found that the probability of failure is influenced more by de-lamination than the failure due to matrix cracking. It is because the inter-laminar stresses influence the de-lamination considerably. Probability of failure due to matrix cracking of first two ply causes the overall failure. It is mainly because the contact stresses in that case are predominant. The probabilistic analysis and reliability prediction of the system is carried out using the GRSM and validity of method is established using Monte Carlo simulation (MCS) procedure. GRSM saves the computational time considerably. The final component design is obtained after optimization as per the sensitivity behavior of random variable achieving target reliability.

Keywords: *reliability design, optimization, probability, composites*

Progressive failure of laminated composites using continuum damage mechanics

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The structural components made up of composites are increasingly being used in fuselage, drop tanks, radomes, wing skins, wind turbine blades and alike. These components are subjected to different loading environment during their service life which may lead to nucleation/growth/development of microscopic defects such as matrix cracks, fibre breakage, fibre matrix debonding and inter-layer delamination. The growth of these defects not only affects strength but stiffness properties. The residual load carrying capability of the composite structure from the onset of material failure or initiation of damage to final failure can be quite significant. Accurate prediction of damage initiation and progression is important for optimal, reliable and safe designs. Continuum damage mechanics (CDM) is a phenomenological approach that represents the macroscopic effects of microscopic defects by introducing an internal state variable (damage variable). Damage variables are introduced in the constitutive law for the phenomenological treatment of the state of defects and its implications on the degradation of the stiffness properties which enables to predict the progressive damage and failure load. The damage evolution model is based on a generalized macroscopic continuum theory within the framework of irreversible thermodynamics. In the present work, progressive damage/failure analysis including geometric nonlinearity is carried out using finite element method based on the first order shear deformation theory. The nonlinear governing equations are solved using Newton-Raphson iterative technique coupled with the adaptive displacement control method to efficiently trace the equilibrium path. The finite element analysis using classical continuum damage models is prone to deformation/strain localization and exhibits strong spurious mesh sensitivity. To overcome the problem of mesh dependency, nonlocal continuum damage models for fibre reinforced laminated composite panels is explored. In the nonlocal model, growth of damage at a point is no longer governed by the local strain/damage driving force, but also depends on the weighted average of these parameters in a finite neighborhood of that point.

Using Clausius–Duhem inequality and principle of maximum dissipation, evolution equations for damage parameters $\dot{D}_i$ and $\dot{\beta}$ are given as:

$$\dot{D}_i = \lambda \frac{\partial g}{\partial Y_i} \quad , \quad \text{and} \quad \dot{\beta} = \lambda \frac{\partial g}{\partial \gamma} \quad \text{with} \quad \lambda = \left(\frac{\partial g}{\partial Y_i} \middle/ \frac{\partial \gamma}{\partial \beta} \right) \dot{Y}_i \tag{1}$$

where g is a convex damage function of thermodynamic damage driving force (Y_i) and damage hardening variable γ. $\dot{D}_i$, $\dot{\beta}$, $\dot{Y}_i$ are the time derivates of damage, overall damage parameter and damage driving force, respectively. The performance of nonlocal approaches based on strain, damage driving force and damage parameter to overcome the spurious mesh sensitivity is compared. Considering geometric nonlinearity (GNL) and damage evolution, the static response characteristics,

progressive damage and final failure load of laminated composite panels subjected to different loading and boundary conditions are investigated

Typical results for laminated all edges simply supported cylindrical panel (length (a) = 2 m, radius to length ratio (r/a) = 2.0, circumferential span angle (ϕ)= 0.4 rad.) under uniaxial loading along curved edges are given in Table 1. Failure loads corresponding to failure point ($D_i = D_c \approx 1$ or convergence failure ($D_i = D_c < 1$)) obtained using three different nonlocal models for various discretizations are compared. It can be observed from the table that the convergence trend obtained from all the three models based on nonlocal strain, nonlocal damage deriving force and nonlocal damage variables are qualitatively similar.

Table 1: Failure load (in MN/m) of four-layered cross-ply $(0^0/90^0)_S$ laminated SSSS cylindrical panel (a = 2 m , r/a = 2.0, ϕ = 0.4 rad.) under uniaxial loading.

Model	Mesh	Local					Nonlocal				
		F.L. (MN/m)	w_0/h at F.L.	D_{1max}	D_{2max}	D_{3max}	F.L. (MN/m)	w_0/h at F.L.	D_{1max}	D_{2max}	D_{3max}
Nonlocal Damage Variables	5x5	2.830	1.701	0.005	0.914	0.001	2.909	1.994	0.005	0.989	0.001
	10x10	2.949	1.814	0.005	0.997	0.003	2.979	2.036	0.005	0.997	0.003
	20x20	2.956	1.778	0.004	0.830	0.002	2.986	1.986	0.005	0.953	0.002
Nonlocal Strains	5x5	2.830	1.701	0.005	0.914	0.001	2.929	2.016	0.007	0.958	0.001
	10x10	2.949	1.814	0.005	0.997	0.003	2.999	2.062	0.008	0.958	0.002
	20x20	2.956	1.778	0.004	0.830	0.002	3.000	2.014	0.007	0.957	0.001
Nonlocal damage driving forces	5x5	2.830	1.701	0.005	0.914	0.001	2.921	1.977	0.005	0.974	0.001
	10x10	2.949	1.814	0.005	0.997	0.003	2.990	2.021	0.005	0.981	0.003
	20x20	2.956	1.778	0.004	0.830	0.002	2.990	1.985	0.005	0.979	0.002

Keywords: *continuum damage mechanics, progressive failure, layered composites*

Machining of FRP Composites – Past and Present Research Endeavors

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Fiber reinforced polymer (FRP) composites are widely used in various applications, due to their high specific strength and high specific stiffness. Most of the FRP products are made to near-net-shape; however, postproduction removal of excess material by means of machining is often carried out to meet dimensional requirements and assembly needs. Machining of FRP products is difficult due to their material discontinuity, inhomogenity and anisotropic nature. Also various damage mechanisms such as fiber pullout, fiber fragmentation, delamination, matrix burning, matrix cracking and subsurface damage lead to poor cut surface quality. Compared to the machining of metals, studies on machining of composites are few and limited in number. Also, because of their inhomogeneous and anisotropic nature as also the various possible damage mechanisms, the process of material removal is different from that of machining single-phase material. With the advent of newer class of materials and in particular further reinforcement of matrix by nano-particles, the challenges to the secondary process of machining in terms of new process parameter selection, tool selection in order to minimize damage to a machined FRP composite product is fast building up. This brief lecture will bring about the importance of machining in the application of advance composites and its need to further investigate plethora of problems faced by industry everyday.
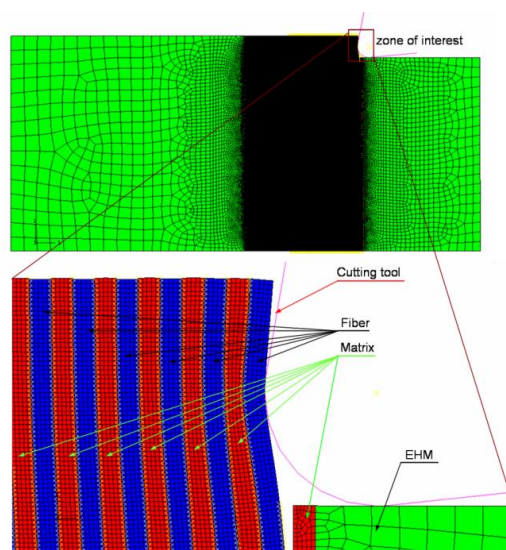
Keywords: *machining, composites, damage, FEA*

Advanced Composite Materials For Multiple Damage Resistant Applications

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Composite materials are increasingly being sought for fabricating engineering components and structures which are prone to multiple damages, caused by impact, fatigue, corrosion, erosion, lightning strikes, heat and explosion etc. The high specific strength of fiber reinforced composites and their ability to resist various types of damages makes them preferred material over traditional metals and metallic alloys. For example, wind turbine blades experience a wide range of wind loads such as, tension, compression, shear, torsion, twisting and so on, which may cause delamination, debonding, fatigue damages in the blades. Near coastal areas, the issue of erosion of the blades due to wind laden with sand particles and corrosion due to saline atmosphere have become a major issue of concern. Over the past two decades, the sizes of the turbine blades have exceeded 20-30 meters. This has made them prone to lightning strikes with associated damages caused by heat and fire. Considering these issues, there is no known light metallic alloy which can address these multiple damages.
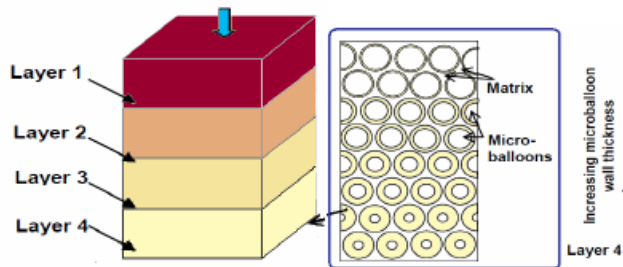

Figure 1 Schematic depiction of the layered composite structure

In this paper, we propose novel designs of advanced composites which can mitigate multiple damages by virtue of the layered and functional structures. The basic principle behind the design is to create a layered structure with various functionalities in each structure. Figure 1 is a schematic diagram of such a layered composite. The inner layer (layer 4) is made of a highly elastomeric polymeric system comprising a graded structure with hollow microspheres embedded in a rubbery matrix. This acts as a high load absorbing medium and imparts sufficient compressive and fatigue strength. The next layer (layer 3) comprises high strength fiber reinforcements according to specific applications. A high strain energy flexible fiber (rubberized glass fiber) has been designed and developed for use in layer 3. This imparts high toughness and elastomeric properties to the component such that damages due to bending and torsional loads are mitigated. Layer 2 comprises polyurethane resin with glass fiber reinforcements to enhance impact toughness while retaining elastomeric properties. The outermost layer (layer 1) comprises phenolic resin and woven glass fabrics which will provide protection against erosion, corrosion and fire. Resistance to heat and fire induced damages will be enhanced by adding various fire retardant fillers including fine ceramic powders.

The layered composite panels have been tested for various mechanical and environmental properties. Various fiber loadings in the range of 50 to 65% have been used to prepare these composite panels, The tensile strength, flexural strength and Izod impact strength of these panels have been evaluated. They show appreciably high values for deployment in engineering structures. With increased fiber loadings, the tensile strength, the flexural strength and the impact strength show a maximum increase of upto 39%., 45% and 108%, respectively. The tests for hydrothermal degradation revealed upto 92% to 96% retention of strength after 24 hours of boiling / heat aging treatments. The rate of strength loss was as low as 0.33% and as high as 4% per hour. Work is in progress to optimize the properties of various layers for improving multiple damage resistant behaviours of these polymer based composites for various civil and strategic applications.

Keywords: *composites, layered structure, damage resistant*

Session V:

Testing and Characterization

Challenges Testing Composite Materials for Wind Turbine Blades

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The main components in the wind turbine are the rotor blades taking the kinetic energy out of the wind. The rotor hub on which the blades are mounted connects the rotor into the transmission system through the main shaft to the gearbox, which synchronizes the rotation to the generator and power converter. An alternative to the gearbox configuration is the multi-pole direct-drive generator which obviates the gearbox. The transmission system and generator is placed in a nacelle on top of the tower. A yaw bearing system makes it possible for the nacelle to rotate. For wind turbines in the MW range the top head mass carried by the tower is in the range from 100 tons to more than 500 tons.

The objective of this presentation is to evaluate the challenges in the wind turbine rotor blade design and to discuss requirements and challenges testing composite materials used in wind turbine blades. The basis is a broad understanding of how the materials used in the structures respond on different length scales.

The majority of blades are produced from polymer composite materials reinforced with mainly glass fibres and to some extend carbon fibres and carbon fibres in hybrid combination with glass fibres. Especially for smaller blades biobased fibre materials made from hemp, flax or other celluloses based fibres are potential candidate materials. Also wood and bamboo are being used.

The matrix resins are mainly thermoset polymers such as epoxy, polyester, and vinylester. Resins such as polyurethane and thermoplastic polymers are introduced but still not widely used and the sustainability are enhanced by introducing biobased resins in the components.

Early blade production was hand lay up of the laminate giving both large variations in laminate quality and giving serious working environment problems with handling of both epoxy and polyester. Modern manufacturing methods are dry layup of the laminates and structures followed of a vacuum infusion of the resin (VARTM).

The carrying beams, the spar caps, are predominantly made from unidirectional laminates tapered off with plydrops from the root end to the tip. Also at the leading edge and at the trailing edge UD laminates are used in the reinforcement. The UD laminates contributes approximately 50% of the weight of the blade. Hence these UD materials are in focus in the optimization.

The aerodynamic shells and the webs in the blade are made from sandwich materials with composite skin layers in ±45° or 0/±45° laminate lay-up separated with cores made from balsa wood and polyvinyl chloride (PVC). Other materials to be used as core materials are foams or honeycomb

structures polyethylene terephthalate (PET), styrene acrylonitrile (SAN), polyurethane (PU), Polystyrene (PS), polyetherimide (PEI), polymethacrylimide (PMI) and polypropylene (PP).

Most of the larger blades are produced in two halves, the upper and lower part, and are joined using adhesive bonding. Adhesives are epoxy, vinylester, polyurethans (PUR), methyl methacrylate (MMA) among others. Other production concepts are fully integrated injection moulding (invented by Siemens Wind Power, the IntegralBlade® technology) and mould cast smaller blades. Micro blades can be cut from wood or cast as pure polymers.

The blades end in a root section with integrated threaded bushings and other fastener solutions and the blades are bolted via a pitch bearing to the rotor hub.

In review papers by Brøndsted el al. 2005, Hayman et al 2008, and Brøndsted et al. 2008 the main challenges for the composite materials used for wind turbine blades are described. The technology has improved through the years. Blade materials has developed to be a specialized topic for the material suppliers, and the challenge in developing the correct matching qualities have been in focus and improved materials are introduced to the market. Combining this with optimized design, knowledge of the load and environments impact on the material quality, the degradation of properties etc. the expected life-time of a wind turbine is now expectedly predicted to be 25 or even 30 years compared to the design life time of 20 years only a decade ago.

The main design requirements for a wind turbine blade is optimization of stiffness, optimization against fatigue (Life time 20-30 Years => >100.000.000 load cycles), optimization of compression strength and optimization of weight.

These requirements are optimised by ensuring a consistent quality of fibres, sizings, and resins, which are the basic constituents in a composite and are the basis for the performances of the composites. The properties are very dependent of consistency between fibre surface treatments (named sizings), resin quality and manufacturing parameters. Hence research disciplines such as basic materials properties, fibers, sizing, resins, laminate and sandwich architectures, processing, microstructure characterisation (microscopy), modelling (micromechanical and materials modelling) and mechanical characterization give a substantial basis for high quality performance in the application. The long term behaviour and the endurance are controlled by damage detection, non-destructive evaluation and structural health monitoring, and damage mechanics are used for evaluating the reliability of the blade components.

The increasing demands for both fibres and resins generate and develop markets for new suppliers and require additional quality assurance for the raw materials deliverables. It is an important requirement to ensure uniformity in the manufacturing processes and hereby maintain a high product quality. This is done by close control of process parameters and by a post manufacturing quality control and inspection of the new blades.

Keywords: w*ind turbine blade, test methods, polymers, composites, fibre reinforcements*

Test Methods for Assessing Bimaterial Interfaces in Wind Turbine Blades

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The mechanical properties of bimaterial interfaces play a big role at various length scales in wind turbine blades. On the sub-structural level, bimaterial interfaces are present within laminates, at sandwich core/skin interfaces and adhesive bond lines. On the micro scale, the fibre/matrix interfaces is believed to control the micro scale damage evolution potentially leading to macro scale failure of the composite material.

Despite its obvious importance, the characterization of the mechanical properties of interfaces is not a well established and standardized. This is partly due to the complicated and unusual behavior that some composite interfaces exhibit and partly due to the difficulty of performing good mechanical experiment on the microscale.

The relevant properties to be used in models on the sub-structural scale can be determined from "coupon" test specimens. The properties to be determined are mixed mode fracture energy (in case of brittle, small scale fracture process zone), expressed as a function of a mode mixity parameter or mixed mode cohesive laws (in case of a large-scale fracture process zone, e.g. in the form of large-scale bridging due to cross-over bridging). Determination of mixed mode cohesive laws from experiments is a relatively new field. Cohesive law determination puts more demands to fracture mechanics testing than linear elastic fracture mechanics (LEFM) does. For instance, cohesive law determination requires the use of test configurations that gives stable cracking - otherwise the entire cohesive laws cannot be determined. One of the proposed approach for mixed mode cohesive law determination is based on the path-independent J integral. This approach requires the use of specimens for which the J integral, evaluated along the external boundaries, can be obtained from the applied loads. The authors prefers the use of DCB (double cantilever beam) specimens loaded with uneven bending moments (DCB-UBM), since, for this configuration, an equation for the J integral evaluated along the external boundaries can be determined closed analytical form, independent of details of the cohesive zone (including the crack length).

Determination of interface properties on the microscale is even more challenging. Some testing methods that are relative easy to perform under optical microscopy, such as the single fibre fragmentation test, relies on a relative simple model and only allows the determination of a "interfacial shear stress". A more advanced model, that can separate effects on interfacial friction, crack tip fracture energy and residual stresses, is available for the single fibre pull-out tests. Yet, other testing methods, such as experiments performed in a scanning electron microscope offers more detailed and qualitatively very accurate measurements of the fracture and deformation process. However, these methods required much more sophisticated testing equipment and usually also requires a numerical model in order to extract the relevant interfacial properties.

In this presentation, various test methods will be reviewed. Their advantages, limitations and disadvantages will be discusses. Examples of measurements will be given and the accuracy of approached will be discussed.

Keywords: *wind turbine blade, mixed mode cracking, cohesive laws, composite materials, adhesive joints*

Performance Testing of Wind Turbines – A View from Wind Industry

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Performance testing of wind turbines includes testing of aspects such as structural loads, power performance, vibrations, noise, and power quality. Performance testing is required to verify the theoretical models of the wind turbines and there by validating its performance. Structural loads testing fundamentally cover testing of blade loads, drive train loads, and tower loads in compliance with IEC-specification. Power performance testing validates the theoretical power curve against the measured power curve based on IEC-standard. Noise is measured as per the IEC standard, but there are no models to validate it against. The other aspects such as vibrations and power quality have their own standards of testing.

The loads testing is an important area in turbine testing to verify the load levels as well as the life of the mechanical components. Different turbine manufacturers have their own way of verifying the loads, and there is no standard guideline for this. But everyone almost follow the IEC-61400-13 specification. This specification is made by a committee of experienced professional members representing various manufacturers and accredited institutes. According to the specification, a loads measurement campaign is completed when the capture matrix mentioned in IEC-61400-13-is full. The capture matrix covers both the wind speed and the turbulence ranges. However, the specification is now getting transformed into a standard soon.

In verifying the structural loads, it is required to have a model representing the wind turbine to compare the measurements. The wind turbine models commonly used in the industry are based on Flex4/Flex5 models, which are fundamentally based on blade element momentum (BEM) theory. HAWK (developed at Risø) is one such an example. Inputs such as – wind speed, air density, inflow angle, wind shear, turbulence intensity are used to simulate the loads on the blades, tower and drive train, and thereby estimating the other component loads such as – pitch loads, yaw loads, etc. The loads simulated via these tools are verified in the field by placing strain gauges on the specified locations of the turbine components and thereby measuring appropriately. While placing the strain gauges on the components, several challenges must be taken into account, such as – stress distribution, stress concentration factors, surface curvature, etc. Once the strain gauges are placed on the components, then proper calibration methods should be adopted in order to ensure the right quality of measurements are made. Apart from these measurements, the inputs required for the simulations should also be measured. All these measurements should be synchronized in order to avoid any measurement inaccuracies. A recommended sampling frequency for the loads measurements is 20 Hz. The uncertainties can be estimated independently and approximately 5% to 10% of deviations between the simulated and measured loads are accepted. In order to certify the loads on wind turbines, the measurements should be accredited by instituted such as Risø, DEWI and GL-GH, etc. And the certification is typically performed by certification bodies such as GL-GH, DNV, etc.
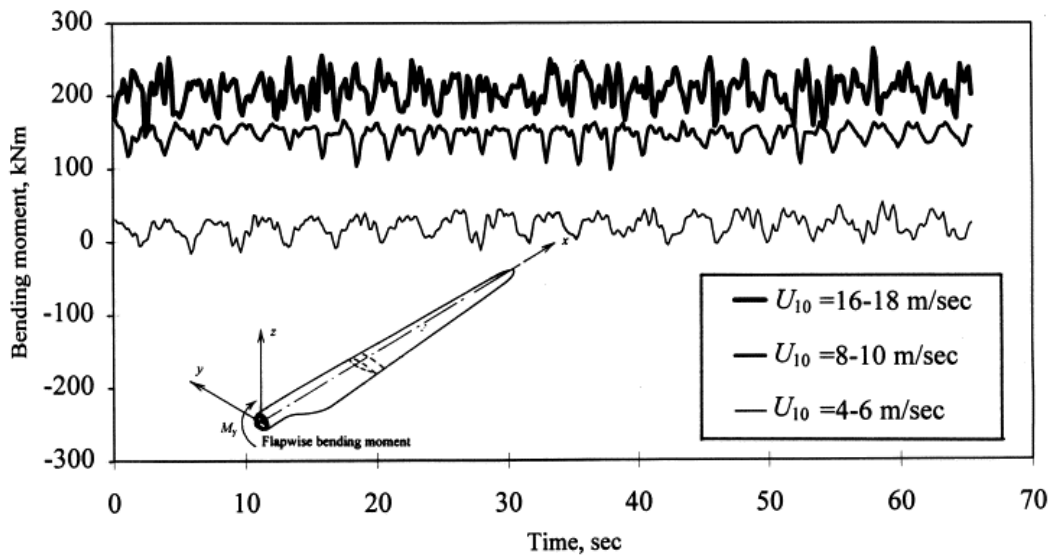
Figure: 1. Wind turbine blade flap-wise loads at different wind speeds

The other important area of testing the wind turbine is power performance. In order to ensure the customers (as well as themselves), the manufacturer needs to verify the power measured by the wind turbine. Typically the power curve is dictated by the aerodynamics of the wind turbine. It is also directly connected to the structural loads. Using the airfoil of the blades and the turbine operational parameters such as – wind speed, pitch angle, RPM, air density, tip speed, and etc., the theoretical power generated by the turbine is estimated. It is also required to verify the power co-efficient (Cp) of the turbine as a part of power performance. Based on the wind speed distribution, the Annual Energy Production (AEP) is estimated.

The wind turbine noise is measured based on the IEC-61400-115 standard. However, the noise levels accepted in various countries is different. So, it is important to measure the noise and ensure design of the turbine is tuned according to those needs.

There is no standard for vibration testing in the area of wind turbine testing. However, vibration testing is mainly performed to verify the component designs. There is a lot of scope in the structural dynamics area of the wind turbines.

The power quality testing aims at verifying the quality of the measured power. The harmonics and flicker levels need to be tested in order to comply with the individual country legislations.

Keywords: *wind turbine testing, loads, power performance*

Application of Digital Image Correlation for Full Field 3D Profile Measurements

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Composite materials need no introduction neither their benefits need to be reemphasized. Dedicate continuous research efforts have resulted in many application oriented designer composites. Some of these include fabrication of large windmill blades, high strength light weight propellers, and blast resistant composite armors among many. Also with ever increasing complexity in designing components and structures, difficulty associated with measuring their dynamic response is increasing. Traditional techniques like strain gauges, clip gauges, and photoelasticity suffers from problems like:

- Limited range of measurable strain.

- Only one data point per gauge.

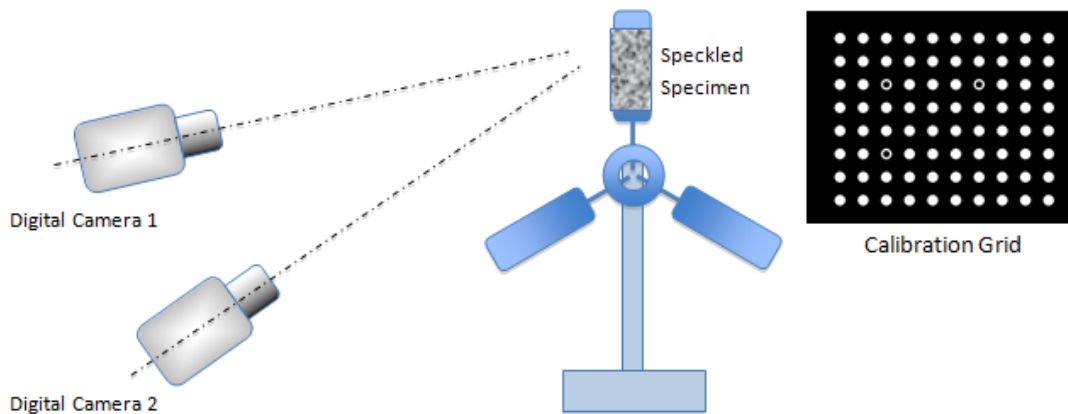- Required optical characteristics of the specimen.

Figure 1. A simplified schematic of 3D DIC experimental arrangement, along with a picture of a camera calibration grid.

In the light of above shortcomings many researchers nowadays are using a vision based, non-contacting technique known as Digital Image Correlation (DIC). This technique employs the image subset matching algorithms, where the portions of undeformed image are mapped in the deformed image. After multiple iterations a complete full field displacement profile is obtained. For inplane measurement only one camera is sufficient (2D DIC) while for out of plane measurements (3D DIC) two or more cameras running in a synchronized manner are employed. A simplified schematic can be seen in Fig. 1. Here a random speckle pattern is painted over a area of interest and during the experiment a pre-calibrated synchronized camera system is used to acquire the series of transitional

images. These images are later post processed using suitable DIC algorithms to obtain full-field deformation / displacement profile which can also be turned into a full-field strain data. With the advancements in high speed imaging it is now possible to apply these concepts in the dynamic testing also. Recently researchers have employed 3D DIC on a plated subjected to the explosive loading. Information like full field displacement, strain, strain rate distribution, dynamic yield strength was obtained. Full field transient plate displacements from one of these tests are given below.
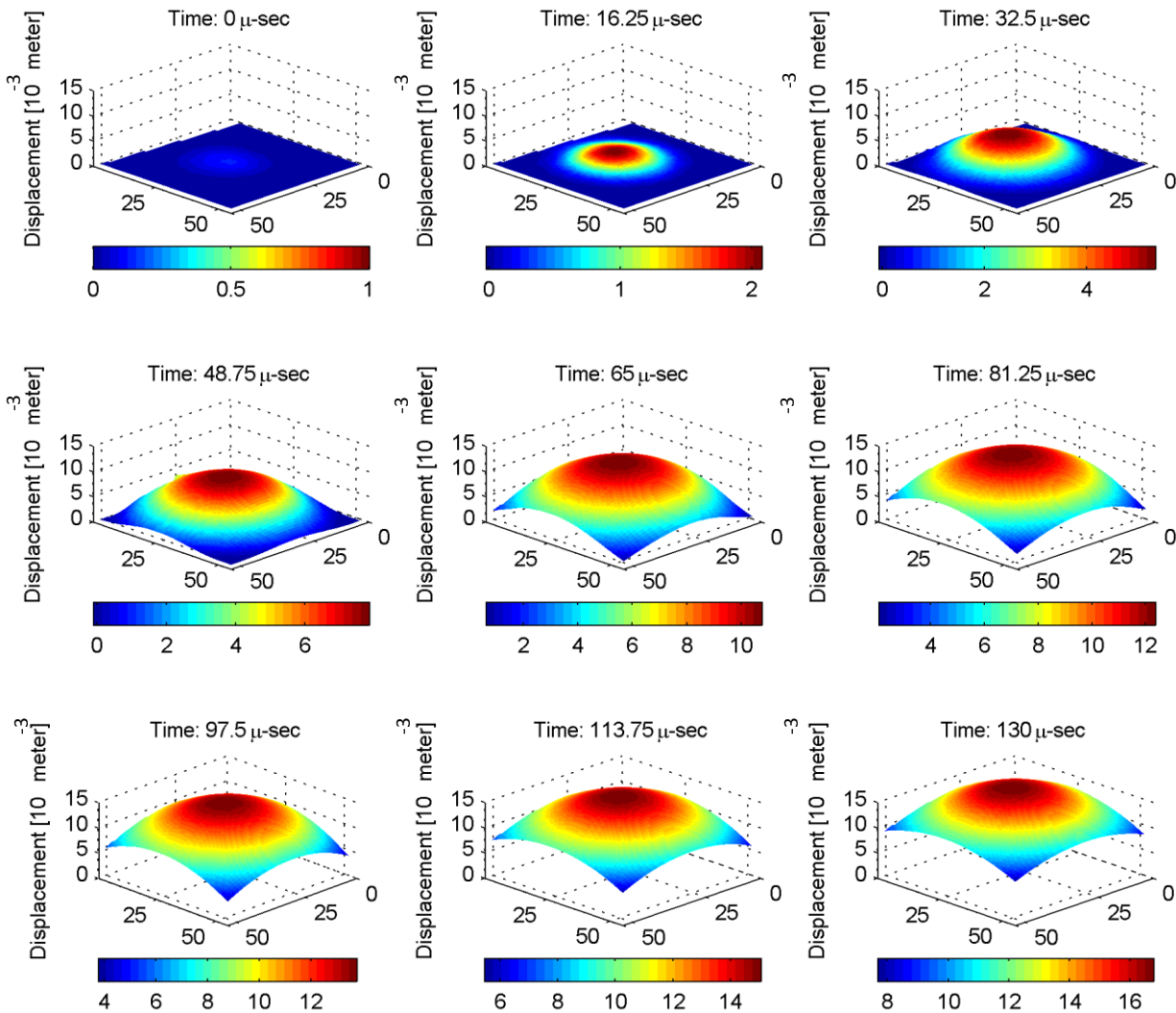

Figure 2. Full field transient sheet displacement profile of shallow (7.6mm) buried test, representing the out of plane deformation in the initial part of the impact

Taken together, the previous research work confirms that DIC is a robust and accurate measurement tool. It provides investigators with the ability to study wide range of applications.

Keywords: *digital image correlation, 2D DIC, 3D DIC, blast loading*
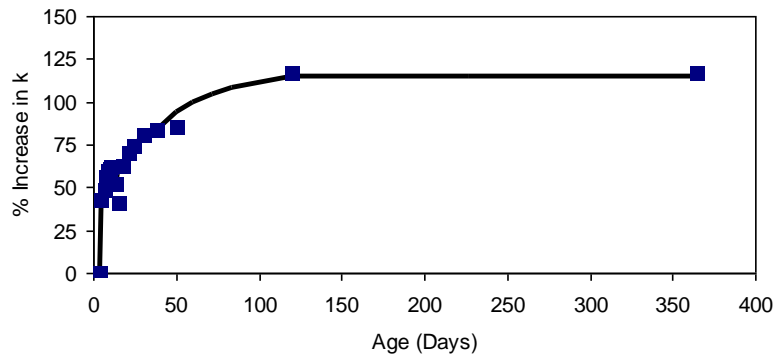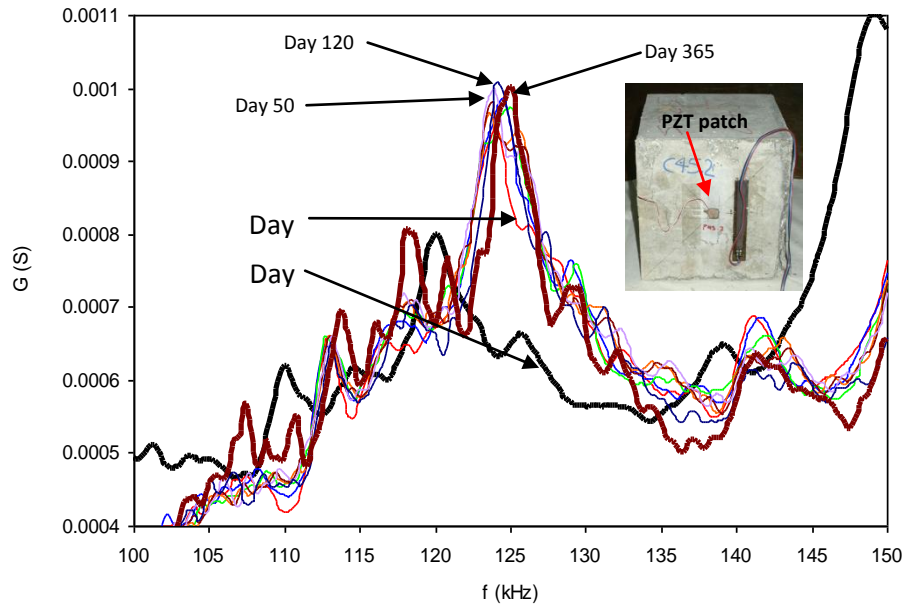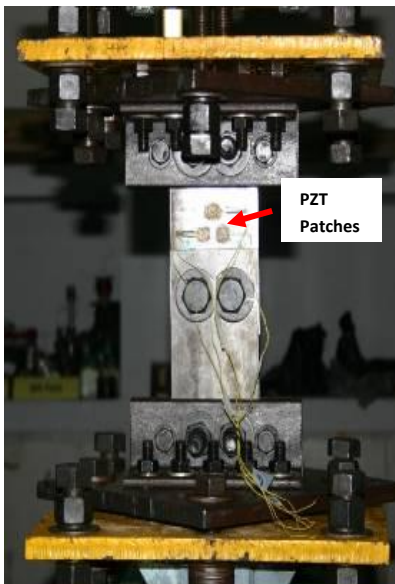
Session VI:

Structural Health Monitoring/NDT

New Developments in Structural Health Monitoring Using Piezo-Transducers

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This paper presents a mechanical impedance based paradigm for structural health monitoring (SHM) and non-destructive evaluation (NDE) using surface-bonded and embedded piezoelectric-ceramic (PZT) patches. The PZT patch identifies the structural system as a combination of elementary structural elements, any variation of which provides an indication of damage as well as quantification of damage. The approach is illustrated through experimental studies involving concrete and steel structures. The variation in the identified equivalent stiffness is found to correlate well with the loss of the actual stiffness of the structure on account of damage. Further, the impedance based approach is seamlessly integrated with global vibration technique to carry out an improved SHM using the same set of the PZT patches as well as the hardware.

Hybrid NDT and Health Monitoring Strategy For Composite Structures

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Fiber reinforced composites are being hailed as engineering materials of the 21st century due to a host of advantages over known metallic alloys, such as, high specific strength, high stiffness, flexibility of design, modular construction, good fatigue and impact strength, low susceptibility to environmental damages and so on. They are fast gaining acceptance for designing critical engineering and structural components, such as, bridge decks, aircraft landing platforms, storage tanks for liquids, wind turbine blades, car body shells and panels, primary load bearing structures of aircrafts, such as, Boeing 787 and Airbus 380 etc. In spite of their advantages, some of the challenges in using composite materials lie in the difficulty in understanding and detecting the damage modes and their interactions. Composites, unlike metals, do not give early warnings for failure. By their very construction, fiber reinforced composites are multilayer structures with distinct layers of fibers of various configurations, such as, weaves, knits, uni-directional tapes etc., impregnated in resin. Such structures are able to impart high stiffness and toughness by virtue of the very high stiffness of the fiber which act as crack inhibitors. The damages that develop in-service in fiber reinforced composites are cracks, disbonds, voids, delaminations, porosity, inclusions, erosion, fiber breakage, micro-cracks in the matrix, kissing bonds, environmental ingress, fiber and ply misalignment, etc.

Non-destructive testing (NDT) of composites and health monitoring of composite structures are critical steps for ensuring long term usage and prevention of catastrophic failures. As already discussed, fiber reinforced composites are characterized by heterogeneity of constituent phases and anisotropy. It is not easy to establish a NDT protocol for rapid estimation of damages in such structures. A variety of NDT techniques have been explored for detecting different categories of damage. They can be classified as acoustic, thermographic, electromagnetic, optical and radiographic techniques. Acoustic techniques rely on propagation and detection of acoustic or ultrasonic elastic waves through the bulk or surface layers of the structure. The detection of damages is based on a change in time domain signals due to reflection and refraction of the elastic wave at the flaw boundary. The thermographic techniques are based on detection of infrared signals from a structure and correlation of the thermal states with these signals. If a structure has voids caused by delaminations the thermal transport through the flaw will be poor and will cause a change in the thermal state around the flaw which will be detected by pulsed or lock-in infrared thermography. Electromagnetic NDT, such as, microwave NDT or ground penetrating radars, is a class of technique very similar to the acoustic NDT. A directed beam of electromagnetic waves is made to interact with the damages in the structure where some part of the energy is transmitted and the remaining is reflected back. The reflected energy creates a resulting signal measured in volts and can map the location and size of the flaw as an image. Optical NDT techniques, such as, electronic speckle pattern interferometry (ESPI), digital shearography, holography etc. essentially records the amplitude and phase of coherent, monochromatic beam of light reflected from the test sample before and after it has been stressed under some mechanical, thermal or vibrational loading. The resulting interference pattern can be used to generate whole field mapping of

deformations undergone by the test sample. The surface and sub-surface flaws can be detected as distortions in an otherwise uniform pattern of fringes. Radiographic NDT deploys beams of ionizing radiation, such as, X-rays and neutrons, onto the test sample. Portions of the test sample having damages have different radiation absorption properties and can be delineated in an image formed by the beam transmitted through the specimen. Advanced techniques, such as, computed tomography enable three-dimensional reconstruction of the flaw geometry. Among these classes of NDT techniques, the acoustic / ultrasonic class of NDT is by far the most widely accepted industrial technique which is affordable and amenable to on-site deployment.

In this paper, we show the application of an advanced non-contact ultrasonic NDT technique based on pulsed laser induced elastic wave generation and CW laser based interferometric detection of surface displacements for detection of sub-surface and surface flaws. Both bulk waves and surface acoustic waves are generated relatively easily by laser induced ultrasonics. Due to the perfectly non-contact nature of NDT, interrogation of arbitrarily shaped three dimensional composite structures is easy. While NDT is an offline technique for damage diagnosis, more advanced concept of early prognosis of incipient damages in the structure are also envisaged for structural health monitoring (SHM). We discuss two techniques of SHM, based on, piezo wafer active sensors and fiber Bragg grating sensors which are embedded or bonded to the test structure for on-line monitoring of damage growth in a structure in-service. While the former generates acoustic/ultrasonic signal, the latter is an optical technique for detection of damages. Application of a hybrid NDT/SHM strategy is discussed as the new trend of research in various civil and aerospace industries for inspection of composite components and evolving an effective repair/replacement strategy.

Keywords: *composites, NDT, SHM, ultrasonics, piezo wafers, fiber bragg gratings*

Wind Turbines – An Enabling Application for Structural Health Monitoring?

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Wind power is an ancient technology that has been used by human civilisation for many thousands of years. However, the modern industry traces its' history to the Worlds first oil crisis in the 1970s. Initially, government supported schemes in Europe made Germany, Denmark, and Spain the top countries for installed capacity; but by 2012 the major nations are China, USA, and Germany. 2009 was the first year where most new capacity for wind energy was installed in Asia, and this dynamic region continues to be the most active (India installed over 3GW of new capacity in 2011, a level of activity only exceed by China and the USA.) All figures are from the GWEC, the Global Wind Energy Council, website www.gwec.net

While the actions of the OPEC nations forty years ago were the impetus for the start of our modern drive to exploit wind power, the factors pushing us in this direction have not diminished. On the contrary, it can be easily proven that the worlds need for more wind energy is greater now than it has ever been. The technological developments in wind power generation encourage those in the Industry to agree that the targets set by politicians are challenging, but achievable. And finally, a "natural" energy source with no fuel (and therefore no waste products) has much to offer society. This combination of geopolitical, technological, and societal perspectives support an industry that has quickly become a proven technology area and is now poised at a period of massive potential growth.

Across Europe and the World, huge wind farm developments have been planned. The towers, turbines and blades themselves are all becoming larger (to catch more wind) as modern materials permit more ambitious designs to become reality. The locations of these new farms are increasingly remote (offshore), and this in turn promotes the strong interest in Structural Health Monitoring (SHM) technology within the industry.

Wind energy can be an important industry for establishing SHM as an applied technology. The industry is growing rapidly and is under pressure to adopt remote sensing. The prospect for the extensive use of sensor technology is apparent. And a further important factor in identifying the wind energy sector as the best prospect for adoption of monitoring technology lies in the pioneering culture that exists within this young industry, in contrast to that which exists in more traditional areas of structural engineering. All stages in the rapid development of the wind turbine structure design have required new approaches to solve challenging engineering problems. This is a sector that encourages the rapid integration of new ideas and approaches. A far more conservative point of view exists among civil sector engineers due to the greater emphasis on minimising risks, generally tighter constraints on budgets, and a huge reserve of good engineering practice and already established material and design information.

At this Workshop the author will argue that the direction for Wind Energy in the next ten to twenty years supports the adoption of SHM technologies more strongly than other more established markets for "smart structures", and describe the current activities at the Technical University of Denmark in this area.

The following statements are offered:-

- Developments in the wind energy industry demand new approaches
- Challenges exist for the effective structural performance of larger blades
- Opportunity exists for SHM and other "smart" solutions to speak to these challenges
- Modular monitoring systems are envisaged to harness the synergy required to cover all significant damage types
- Implementation strategy will be critical in any successful adoption of SHM systems
- Structural Health Monitoring is a form of Information Technology
- Management and Organisation of the developments are as much an issue as any technical challenges

Keywords: *wind energy industry, structural health monitoring*

Offshore Wind Energy – Indian Perspective

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There has been an exponential growth in the installed wind energy capacity in the world during 1996-2011 and stands at 238 GW as per an estimate of Global Wind Energy Council (GWEC). 41 GW of wind power has been added in 2011 alone which is an increase of 21%. China is at number one position with 62 GW whereas India has 5th position with wind energy capacity of about 17.5 GW. However, contribution of offshore installed wind capacity is presently only 3.9 GW (1.6% of total installed wind energy capacity).

Wind farms on land have a number of limitations viz. lower wind potential, availability of land, Visual and Noise impact etc. Potential energy produced from the wind is directly proportional to the cube of the wind speed and increase of wind speed of only a few kilometers per hour can produce a significantly larger amount of electricity. Technological advancements in offshore construction of wind turbines have encouraged many countries to commercially harness the offshore wind energy. However, there are many challenges in deploying wind turbine generator (WTG) in the offshore environment, such as assessment of wind potential in offshore regions, water depth, hydrodynamic loading due to waves and current, foundation design, transportation, installation, evacuation, etc.

According to India Wind Energy outlook 2011, India plans to increase wind energy capacity to 65 GW by 2020 and 160 GW by 2030. Presently in India, there is no contribution of wind energy from offshore. However, India has tremendous potential of wind energy as we have got a long coast line. According to its Perspective Plan 2030, ONGC intends 30% of its revenue from non E&P business. ONGC has taken the first step by developing a 51 MW onshore wind farm at Bhuj, in state of Gujarat in line with its policy of sustainable development with a key focus on Environment Management. ONGC also intends to generate offshore wind energy for its captive use and commercial application.

Developing renewable energy will help India increase its energy security, reduce adverse impacts on the local environment, lower its carbon intensity and contribute to a more balanced regional development. A long coastline and relatively low construction costs could make India a favoured destination for offshore wind power. As this technology is in its nascent stage in India, there is a need for taking initiatives in offshore wind power generation.

Keywords: *offshore wind energy, indian perspective*

Session VII:

Computation Tools and Modeling Techniques

Finite Element Modeling of Low Velocity Impact of Composites

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Composite structures in service are subjected to low velocity impact and experience damage such as matrix cracking, fiber breakage, delamination etc. Typical examples of impact are debris from ground hitting an air-craft structure such as wing or a tool being dropped on a composite component.

Low velocity impact simulations were performed on unidirectional E-glass/epoxy composite specimens manufactured by the hand lay up of E-glass fibers in epoxy resin in 0^0 direction with a fiber volume fraction of 60%. An instrumented drop weight tower was used to strike the 175 mm^2 glass epoxy composite sheet of different thicknesses. The impactor tup was of 12.7 mm diameter and had a weight of 1.4 kg. Impact loads, displacement of the impactor and energy of impact were measured. High speed cameras were used to measure the impact phenomenon and Digital Image Correlation (DIC) was used to measure displacements and strains at 1.5 mm away from the region of impact.
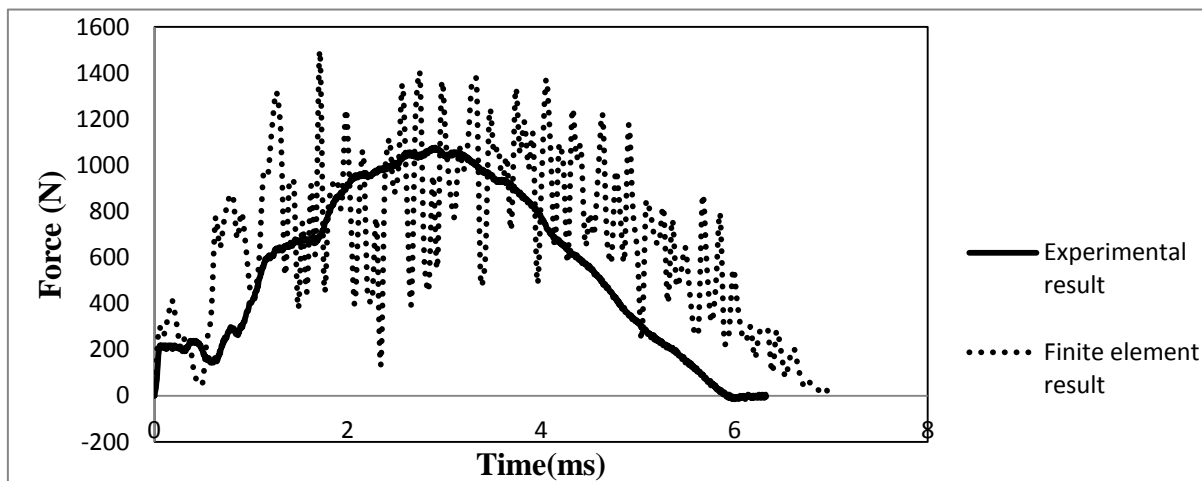

Figure1: Plot of contact force with respect to time for impact of a unidirectional E-glass/epoxy composite of 4mm thickness subject to an impacting velocity of 2m/s.

For modeling damage in low velocity impact simulations, elastic properties, fracture energy values of unidirectional Glass/Epoxy composite specimens are required. Some of the elastic properties were determined from tension and Iosipescu shear tests. Inter-laminar fracture energies were determined experimentally by Double Cantilever Beam (DCB) test for mode I and End Notch Flexure (ENF) test for mode II. Intra-laminar fracture properties of transverse and longitudinal failure in tension were

obtained by performing three point beam bending tests. For transverse tension failure, a notch was introduced in the direction parallel to the direction of fibers and for longitudinal tension failure, notch was introduced perpendicular to the direction of fibers.

Impact simulations were performed on E-glass/epoxy composites of different thickness to compare its behavior with the experimental results. Composite panels were simply supported at the ends and the impact was done normally using a rigid impactor of hemispherical shape. Numerical simulations were done using ABAQUS/Explicit FE code with a user subroutine to quantify the extent of damage in the composite during impact. 3-D brick elements with full integration were used as reduced integration gave very high artificial energy. Hashin's failure criteria for fiber tension and matrix failure were implemented in a subroutine to predict damage initiation in various modes. Evolution equations for various damage variables were also provided in the subroutine to determine the extent of damage and elastic modulus of the plies was degraded. When the value of the damage variable reached a critical value in an element, it was deleted. The critical value depended on the fracture energy of the ply in the particular failure mode. To make the calculations mesh insensitive characteristic length of each element was calculated and used in determining the displacement at which damge reached the critical value. Fracture energy values used in modeling inter-laminar and intra-laminar damages were taken from literature. Cohesive based surface behavior was used for modeling delamination.

Major mode of failure observed in simulations was matrix failure due to impact. Contact force plot with respect to time in the simulations showed a lot of fluctuations (Fig. 1) although the results matched closely with experiments once high frequencies were removed from the simulation results. The oscillatory behavior of the contact force has been reported by others as due to dynamic coupling between the specimen and the support. Delaminations were observed at the laminate interfaces in simulations.

Keywords: *Low velocity impact, Finite Element, Digital Image Correlation*

Leveraging Best Practices in Design, Simulation, and Manufacturing for Composite Wind Turbine Blades - Part I & Part II

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A breakdown of the cost of wind energy shows that wind turbine equipment costs continue to contribute between 40-60% of the cost of a wind farm over its lifetime, with composite wind turbine blades forming a significant part of the cost of a wind turbine. In addition, any needed repairs, replacement, or other scheduled maintenance of the composite blades can have a further negative impact on the cost of wind energy. Composite blade developers and manufacturers have responded to these challenges with attempts to develop larger, more efficient, and more reliable wind turbine blades, but much more needs to be done and done faster. This presentation will explore solutions to improve composite wind turbine blade performance and reliability in a more efficient (faster) and cost-effective manner.

The latest advances in computer-based composite design, simulation, and manufacturing methods have already proven to be of significant value to the aerospace industry and can likewise provide significant value to composite wind turbine blade developers and manufacturers. However, adoption of these latest methods continues to be slow and scattered in the wind turbine industry. In this presentation we will explore several of these technologies and demonstrate the value that they can bring to the wind turbine industry. Some of the topics that will be covered include:

- Fiber simulations and producibility assessments to eliminate costly redesigns or reengineering
- Use of advanced simulation techniques like XFEM and Cohesive Methods for more accurate life assessment of composite blades
- Smoothed Particle Hydrodynamics (SPH) for impact assessments on composite blades, for example from hail
- Composites fatigue simulations for faster evaluation and certification of composite blades
- Optimization techniques to improve reliability and performance of composite blades
- Planning and automation of composite blade manufacturing for improved quality, throughput, and flexibility
- Use of data and pattern recognition technologies and rules to reduce manufacturing errors and improve composite blade quality

In addition, the presentation will highlight the benefits of using an integrated and collaborative platform for the design, simulation, and manufacturing techniques mentioned above – a "3DExperience Platform" for composite blade development. The presentation will conclude with ideas and topics for further improvement and research such as condition-based maintenance of composite blades that can provide additional benefits to the wind turbine industry.

Keywords: *design aspects, turbine Blades, XFEM, SPH*

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