TESTING AND ANALYSIS OF ADVANCED COMPOSITE MATERIALS AND STRUCTURES IN WIND TURBINE APPLICATIONS

P.L. Hansen, S. Giannis, and R.H. Martin
MERL Ltd.
Wilbury Way, Hitchin, Hertfordshire, SG4 0TW, UK
Web: merl-ltd.co.uk
phansen@merl-ltd.co.uk, sgiannis@merl-ltd.co.uk

SUMMARY

The increasing demand to reduce the cost of energy generated from the wind, drives wind turbine designs towards larger blades. These large structures experience high cycle fatigue and can contain defects from manufacture or be subject to damage events so it is desirable that they possess a high degree of damage tolerance to prevent costly failures and to minimise forced maintenance. This paper describes the damage tolerance characterisation of a critical area of a composite material wind turbine blade.

Keywords: Wind Turbine Blades, Fracture, Testing, Damage Tolerance, High cycle Fatigue

INTRODUCTION

There is an increasing demand to boost electricity generation from renewable sources, mainly due to factors such as climate change, fuel resource depletion and energy security. The wind energy industry plays a key role in this increasing *green* energy generation, and it is currently the fastest growing sector in the general power generation industry. Therefore a considerable amount of the *green* electricity will be generated from onshore and offshore wind energy fields.

The demand for increased energy generation from wind fields at a lower cost per energy unit raises the demand for larger more efficient turbine blades. This can be achieved by using advanced, high performance, polymeric composites. However, designing against failure with composites can be complex, since not all failure mechanisms are well understood. A way forward would be to follow a damage tolerant design approach [1]. In such an approach, a main fibre reinforced composite structural part (*e.g.* wind turbine blade spar) could continue to perform with 'damage' or 'defects' present throughout the remainder of its life. Such damage could have resulted either from deviations in the manufacturing process or mechanical handling, impact damage from handling tools and systems, *etc.* or in-service damage.

Horizontal Axis Wind Turbine (or HAWTs) have the main rotor shaft and generator at the top of a tower. Turbine blades are designed for high stiffness to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount. Because turbulence leads to fatigue failures and reliability is important, most HAWTs are upwind machines. HAWT wind turbines are usually three-bladed, counterbalanced and pointed into the wind by computer-controlled yaw motors.

The design of blades are generally company confidential but are usually constructed in one of two basic forms:

- a spar, taking the main bending loads and two aerodynamic shell moulds or
- two longitudinal stiffened shells and a central shear web

Many materials are used in blade construction of wind turbines, including composites, steel and wood. However, as blades become larger, high performance composite materials are used in hybrid constructions of carbon-epoxy and glass-epoxy. Wood can also be present in composite blades, acting as either laminates, or the core, and bonded to carbon or glass skins using epoxy adhesives.

Currently there are limited damage tolerance methodologies established for wind turbine blade spars and other similar polymeric composite structures. Significant efforts towards establishing such techniques were made through a UK Government Technology Strategy Board (TSB) part funded collaborative project entitled MSI-SPAR. The project involved selected partners from the supply chain for wind turbine blades and selected results from this project are presented.

The MSI-SPAR project aimed to investigate the damage tolerance of large composite spars including turbine blade spars and yacht spars, with the aim to deliver improvements in structural durability, design and quality control. This included the use of Finite Element Modeling (FEM), mechanical testing and Structural Health Monitoring (SHM) as well as the development and application of non-destructive technologies for structural polymer-matrix composites. The project also aimed to develop novel RapidScan[1] ultrasonic equipment and effect-of-defects fracture mechanics testing methodologies integrated with SHM methods. The results were delivered as updated non-destructive testing hardware and life assessment methodologies. For the marine industry these are being encompassed in a Maritime and Coastguard Agency (MCA) applications guidance document as part of the Large Yacht code (LY2) [2].

EFFECTS OF DEFECTS AND DAMAGE TOLERANCE

A polymeric composite structure's ability to continue to perform with damage present throughout the remainder of its life is defined as its damage tolerance. Composite structures such as wind turbine blades are typically exposed to a variety of events during their life which can include 'normal' in-service loading, the service environment and events that cause damage initiation and structural degradation. Defects that can be considered as "damage" can also occur through manufacture or handling before the structure is installed in service.

The location and/or severity of manufacturing defects and in-service damage can be difficult to anticipate and detect. Some manufacturing flaws may not be detectable until the structure is exposed to the service environment (*e.g.* weak bonds may not be detectable until the joint is loaded in service). The complex loading that a structure may

[1] Developed by NDT Solutions, Chesterfield, UK – Part of the Sonatest Group

see in service and the design of the structure can result in load cases that are not predicted during the design phase for the structure.

To construct a damage tolerance assessment for composite structures, the following threats are typically defined for each structure:

- damage (or defects) from manufacturing processes
- damage from assembly and handling
- damage from in-service operation

The next stage is to define the modes of damage for each threat (*e.g.* porosity, delamination, puncture, core crush, *etc.*).

As part of the MSI-SPAR project the threats and damage modes were catalogued for the different designs of wind turbine spars. Of highest importance for the wind energy industry is manufacturing defects followed by in-service threats. This is because the in-service threats are well understood and managed and the larger wind turbine blades that are placed offshore have very little human contact. Critical areas were identified and the different threats noted along with potential damage mode. An assessment was then performed on the importance of the threat discussed. Some of the critical areas include:

- Spar caps and shear webs
- Shear web to cap joints
- Blade-shell connections
- Structural spar elements including corner voids
- Leading and trailing edge joints on spars
- Scarf joints
- Shell to shell and shell to spar bonding
- Root stud connections

Several parts of the spars were selected for study within the MSI-SPAR project. This paper covers an assessment of a corner void in the main load bearing spar.

ELEMENT TESTING OF A SPAR CORNER

In the course of the MSI-SPAR project scaled down wind turbine blade spars were manufactured containing simulated defects at pre-defined areas. FEM was used to translate global loading of the turbine blade spar into local loading around the defects and investigate the damage tolerance of the structure through local FEM and laboratory testing. In the case presented in this paper a high porosity region at the corner of the spar was identified as a potential risk for affecting the performance of the structure.

A corner part was cut from the scaled down wind turbine spars for subsequent element testing if this region. The element comprises of biaxial glass and unidirectional carbon reinforced layers, co-cured to give a hybrid structure, as shown in Figure 1. The element also simulates a porosity region (manufacturing defect) in the corner of the section.

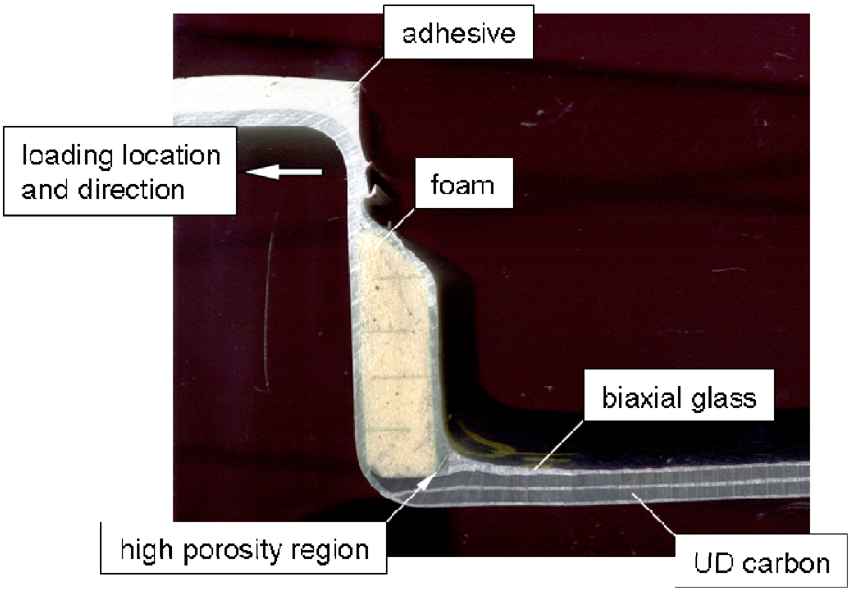

Figure 1 Picture of the corner parts cut from the wind turbine blade spars containing a high porosity region

The force *vs.* displacement response of the loaded part is shown in Figure 2. Loading was applied under displacement controlled mode, in several loading-unloading steps in order to identify the locus and type of failure easier.

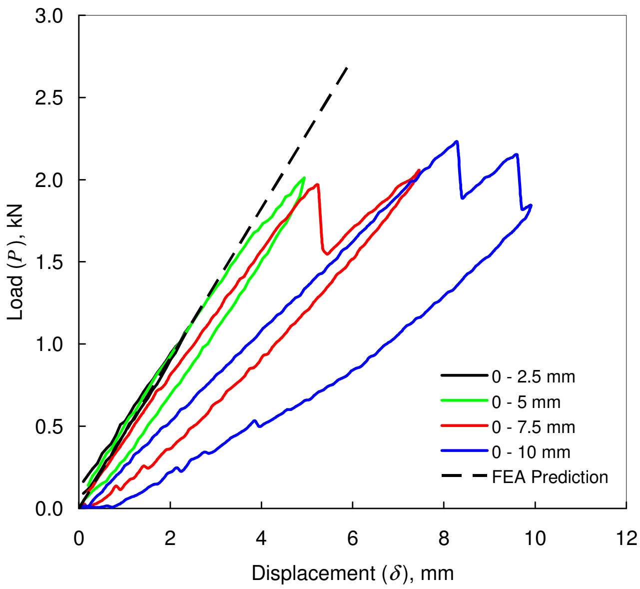

Figure 2 Experimental loading/unloading curves of the corner part of the wind turbine blade and comparison to the finite element model results

During the first step (up to 2.5 mm) there was no damage indication in the composite specimen. In the second step (up to 5 mm) some acoustic emission activity indicated the initiation of damage. That could also be seen from a small change in the slope of the load-displacement curve at around 1.7 kN. During the third step (up to 7.5 mm displacement) and at a load level of 1.97 kN the foam failed, very close to the interface with the glass fibre reinforced epoxy layers. Finally, in the fourth step (up to 10 mm) a crack, in the form of delamination, initiated and propagated at the corner of the sample, where the high porosity region was located. The failure locus for the third and fourth step are presented in Figure 3.

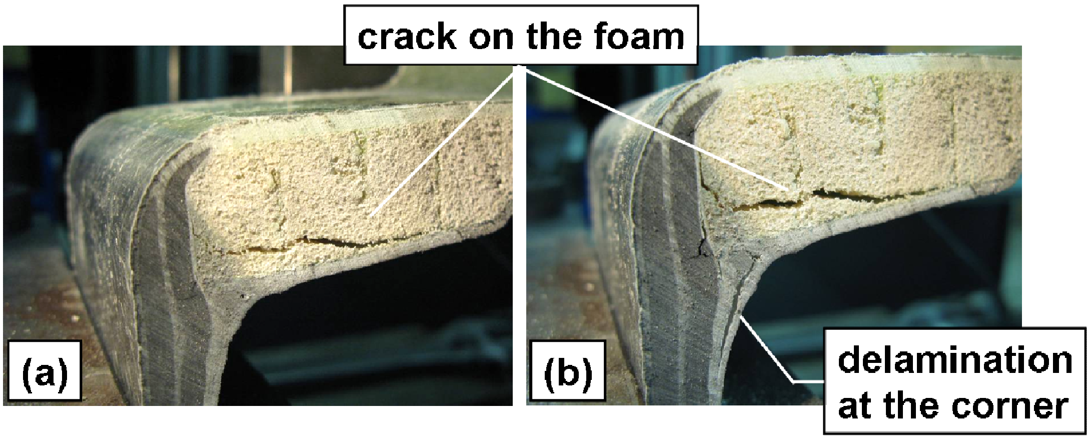

Figure 3 Photographs of the failure of the corner part under loading (a) during the 0 to 7.5mm loading step and (b) the 0 to 10 mm loading step

MATERIALS TESTING

Selected materials commonly used for the construction of wind turbine blade spars were tested to evaluate their fracture/delamination behaviour. These were typical unidirectional (UD) carbon/epoxy and biaxial E-glass/epoxy composites as well as co-cured carbon/E-glass reinforced epoxy systems. Details on these experimental results are given in [3]. The experimental procedures and results for the materials used in prototype wind turbine blade spar are presented here.

A carbon fibre reinforced epoxy composite system (WE91-2/HEC Fibre B UD prepreg) and an E-glass fibre reinforced epoxy (WE90-1/E-glass biaxial prepreg) were tested. WE91-2 and WE90-1 are conventional epoxy systems with low viscosity that allows them to easily wet relatively heavy fabrics and produce prepregs with large areal weight. Both carbon and E-glass prepregs had areal weights of 600 g/m^2.

Double cantilever beam (DCB) specimens were manufactured with a nominal thickness of 10 mm for the carbon/epoxy and 16 mm for the E-glass/epoxy material. A layer of Tygavac RF242 release film, with a thickness of 15 μm, was incorporated at the middle, through the thickness, of the specimens to produce an initial delamination 50 mm in length. The lay-up of the carbon/epoxy system was $[0_9//0_9]$, where // denotes the insert layer. The E-glass biaxial prepreg was cut to produce a laminate with lay-up $[(0/90/90/0)_7//0/90/90/0)_7]$ and the initial delamination on a (0°/0°) interface. All materials and specimens were manufactured and supplied by Gurit Ltd.

Fracture toughness was evaluated under Mode I (peeling) loading using the DCB specimen and following the principles of ISO 15024 international standard. All tests were carried out on a universal testing machine (Lloyd Instruments) using a load cell with maximum capacity of 5 kN. The measured fracture toughness, was 230±23 J/m^2 for the carbon/epoxy system and 386±18 J/m^2 for the E-glass/epoxy system.

The fatigue delamination propagation curves were also established for these two materials. Currently there is no International Standard defining the methodology for measuring the fatigue delamination propagation in polymer matrix composites. However, protocols are being used at various organisations for performing such tests following the principles of ASTM D6115 Standard on Mode I delamination growth onset. The testing procedure to obtain the delamination propagation data involves fatigue testing of DCB type specimens under displacement controlled mode at an initial high value of $G_{I\max}$, which can be up to 80% of the G_{Ic} of the material. As a result, delamination initiates and propagates rapidly at a decreasing rate, as the delamination grows, until it reaches threshold conditions when the delamination growth will effectively cease.

The fatigue tests were performed on a multi-station servo-hydraulic test facility developed by MERL. The testing facility allows for up to six test pieces to be cycled simultaneously. Each station is monitored using a dedicated 1 kN load cell, giving measurements of the load applied to each specimen. The outputs from each load cell are monitored with a computer using software developed at MERL Ltd. At specified cycle intervals the maximum, minimum load and displacement data are captured and the compliance at that point is calculated and stored together with the number of cycles. A plot of compliance versus elapsed cycles is displayed in real time on the screen so that the test can be stopped at the appropriate level of delamination growth or compliance change.

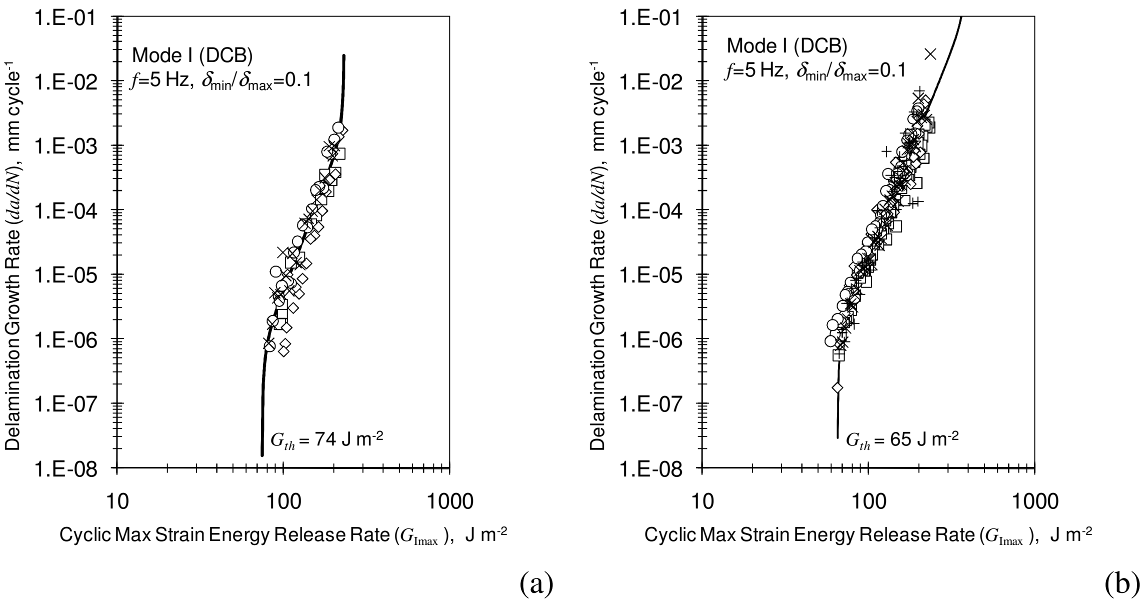

Figure 4 Plot of the delamination growth rate, da/dN, *vs.* the maximum cyclic strain energy release rate, $G_{\mathrm{I}max}$ for (a) carbon/epoxy and (b) E-glass/epoxy composites

The DCB specimens were cycled with a displacement ratio of 0.1 and at a frequency of 5 Hz. All tests were conducted at ambient laboratory conditions (22±2 °C and 55±5% RH). Up to six specimens were tested for each material system. The experimental results are presented in Figure 4 in the form of delamination growth rate, da/dN, *vs.* the maximum cyclic strain energy release rate, $G_{\mathrm{Im}ax}$. Threshold $G_{\mathrm{Im}ax}$ were evaluated at 74 J/m^2 and 65 J/m^2 for the carbon and E-glass reinforced composite materials, respectively.

FINITE ELEMENT MODELLING AND PREDICTIONS

To investigate the damage tolerance of the corner part under the application of the specific loading, a finite element model was built in Abaqus®. The geometry of the model can be seen in Figure 5. The boundary conditions and loading were chosen to represent the element tested. Materials were modelled as linear elastic with properties as shown in Table 1. The stiffness of the model under the applied loading was compared to the experimental results and a very good correlation was found (Figure 2).

Table 1 Material properties

Material	Young's Moduli [GPa]		Poisson's Ratio	Shear Modulus [GPa]
	E_{11} / E_{xx}	E_{22} / E_{yy}	ν_{12} / ν_{xy}	G_{12} / G_{xy}
UD Carbon	120	7.9	0.34	4.2
Biaxial Glass	13	13	0.092	5.95
Foam	0.094		0.49	
Adhesive	2.7		0.30	

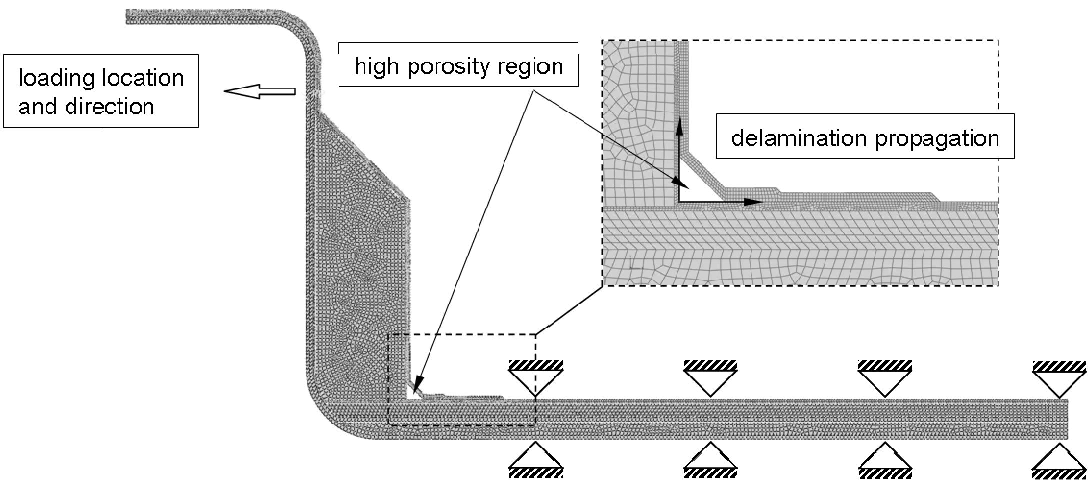

Figure 5 Finite element model of the corner part of the wind turbine blade spar

It was then assumed that damage due to manufacturing was present at the high porosity region in the form of an initial delamination (5 mm in length) running along the interface of the biaxial glass/epoxy layers. Using an energy balance approach the critical strain energy release rate was then calculated at the delamination tip, as a function of the delamination length, through the following relation:

$$G_c = -\frac{dU}{dA} = -\frac{1}{b}\frac{dU}{da} \tag{1}$$

where, U is the elastic strain energy, A is the area of the delamination, b is the width of the specimen and a is the delamination length. The numerical predictions of the strain energy release rate are presented in Figure 6(a) as a function of the delamination length, for various applied displacements. The predicted values of the strain energy release rate are compared to the experimentally G_{Ic} obtained of the biaxial glass/epoxy. For low applied displacements the strain energy release rate at the delamination tip is very low compared to the G_{Ic} of the material and therefore the existing delamination will not propagate. It is only after 4 mm of applied displacement that the strain energy release rate at the delamination tip will exceed the critical value of the material for initiation of propagation and delamination will grow. However, based on the numerical predictions the delamination will only grow for 5 mm under a constant applied displacement of 4 mm and it will then arrest.

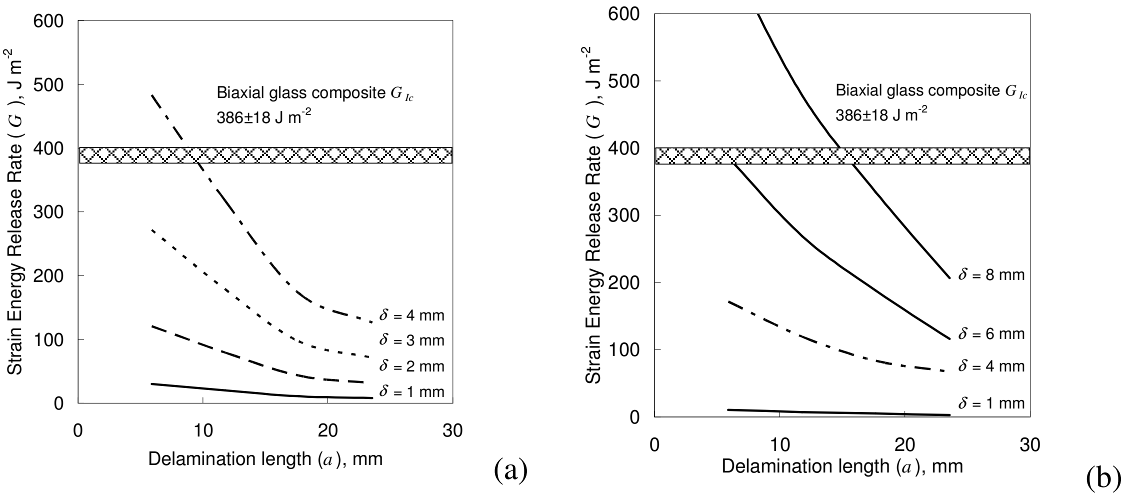

Figure 6 Numerical predictions of the strain energy release rate (G) at the delamination tip as a function of the delamination length for (a) corner part and (b) corner part with cracked foam.

During the experiments it was found that the delamination will not propagate for the above loading conditions and it will be the foam that will initially fail (at 1.97 kN load), due to high shear stresses. It is therefore important to examine what will be the effect of the foam failure at the considered delamination behaviour. To simulate the foam failure as this was observed in the tests, a crack running along one of the sides of the foam was introduced and the strain energy release rate was recalculated at the delamination tip. The numerical results are given in Figure 6(b). It can be seen that for a corner part where the foam has been dis-bonded, the applied displacement has to increase just above 6 mm in order to have delamination propagation between the biaxial glass layers in the vicinity of the high porosity region. This correlates well to the experimental findings where delamination in the biaxial glass layers propagated unstably for a load of 2.23 kN and displacement of 8.2 mm. The numerical analysis also predicts that delamination will arrest after it has propagated for approximately further 6.5 mm, for an initial delamination length of 5 mm.

CONCLUSIONS

Critical areas and causes of damage within a wind turbine spar have been identified and one case of a manufacturing defect is presented. Using a global-local approach the spar was modelled and a high porosity region in the corner of the load bearing spar was assessed for damage tolerance. Numerical predictions revealed that a corner part of a wind turbine blade spar containing a defected region (high porosity and void content) had a large degree of damage tolerance and only when failure first occurs somewhere else in the component, delamination would grow from this defect. This correlates with the mechanical testing where the failure only occurred in the laminate once the adjacent foam had failed.

ACKNOWLEDGEMENTS

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