Investigating Core Gaps and the Development of Subcomponent Validation Methods for Wind Turbine Blades

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National Renewable Energy Laboratory

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Investigating Core Gaps and the Development of Subcomponent Validation Methods for Wind Turbine Blades

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Core gaps are a common manufacturing defect observed in wind blade composite sandwich constructions, which occur when sheets of core material are not properly adjoined in the mold. The aim of this study was to characterize core gaps in composite sandwich constructions at the coupon scale to gain an initial understanding of the defect before developing appropriate methodologies for more complex subcomponents as part of a much broader wind blade structural validation and damage tolerance program. Long beam flexure in 4-point-bending was chosen as the most appropriate loading scenario. Beam specimens were characterized with and without 10 mm core gaps in fiberglass/balsa sandwich beams. The core gaps were characterized with two different resin systems: a Hexion epoxy and Arkema's Elium resin system (a novel, infusible thermoplastic). Results showed that the Elium beams without the core gaps had a 15% lower static strength than their epoxy counterparts. The introduction of the core gap to the epoxy beams reduced their static strength by 35%. The Elium beams, however, exhibited negligible strength reductions with the inclusion of the core gap, but did show a notable change in failure mechanism. Overall, this characterization study provided pertinent information with regards to core gaps as a manufacturing defect to allow for continued development of damage tolerance and subcomponent validation methodologies with the inclusion of manufacturing defects.

I. Background

It is well known that wind turbines have been rapidly increasing in size over recent years, with blade lengths expected to reach over 120 m in the very near future. This growth is leading to significant challenges in wind blade structural validation and certification requirements. With increased blade lengths, current validation and certification methods are becoming increasingly difficult and uneconomical. This has led to the need for the continuous development of structural validation methods which can keep pace with current blade development. Currently, blades are structurally validated by relatively basic flap and edge static and fatigue loads according to the International Electrotechnical Commission (IEC) 61400-23 standard for validation requirements of wind turbine blades [1]. Torsional loads are currently not considered to be as influential as flap and edge loads but may become a larger consideration as blade spans and chord lengths continue to increase. As blade lengths increase, it is becoming more difficult to validate blades without overloading or underloading areas of the blade. Constant-amplitude, single direction fatigue loading methods currently in use may result in a poor representation of actual operating conditions. In addition to this, fatigue loading is very much reliant on the excitation of blades' natural resonant frequencies. Of course, longer, heavier blades have lower resonant frequencies, meaning significant increases in fatigue validation times. These scenarios, compounded by increased test facility space requirements, are resulting in higher validation costs and are pushing the capacity of current test facilities.

To reduce these costs, while still ensuring accurate and reliable structural validation, researchers are beginning to adopt a building block approach commonly used in the aerospace and automotive industries (see Fig. 1). Currently the IEC 61400-23 standard only specifies requirements for coupon level characterization and full-scale testing for

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blade certification. With regards to wind turbine blades, subcomponents and full-scale components have historically been the most overlooked blocks in the pyramid. Now researchers are directing efforts toward test development for filling in the gaps to reduce costs and streamline validation procedures. This may be in the form of spar cap/shear web I-beams [2], box spars, trailing edge failure validations [3], similitude analysis [4], or spanwise sectional validation [5]. Each of these techniques come with their own benefits and drawbacks. The main difficulties are centered around recreating the complex stress states exhibited by irregular blade geometries constructed from complex composite laminates without damaging the specimen or causing unrealistic failure modes.

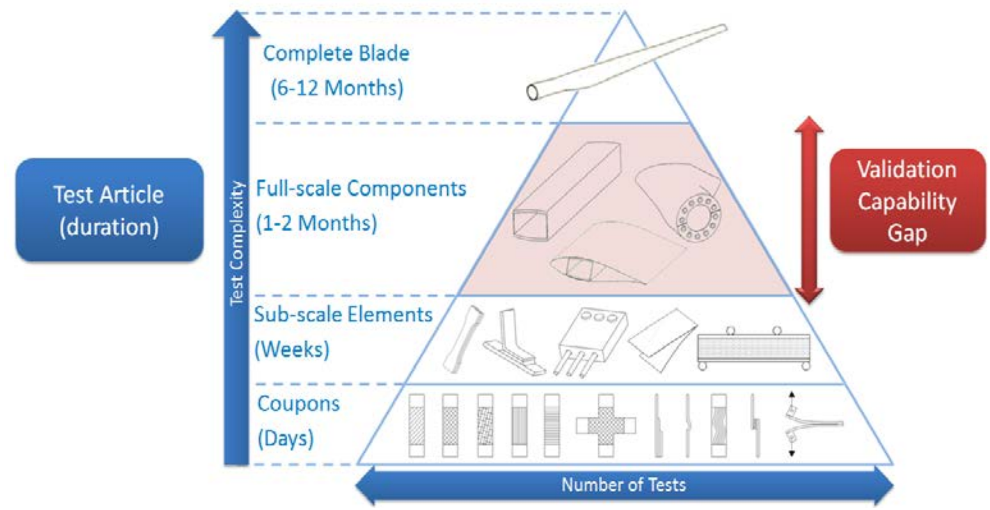

Fig. 1 Building block approach for wind turbine blades showing the current capability gap.

Another shortcoming of the IEC blade design and validation standards is the heavy reliance on a safe-life design approach (i.e., variations in manufacturing, loads and environmental factors are accounted for via design safety factors and validation load factors). Continued failures of wind turbine blades have shown that load and safety factors alone are insufficient to ensure blades can reliably operate throughout their intended design lives. Alternatively, the commercial aerospace industry began to adopt a damage-tolerant design approach over 50 years ago [6]. This philosophy assumes that damage or defects will be present within a structure during its operational life but can be accounted for or detected and repaired well before the damage spreads and causes catastrophic failures. This requires a much more detailed understanding and emphasis on fracture mechanics, understanding of manufacturing defects, structural inspection and maintenance, structural health monitoring techniques, and repair [7]. A damage tolerant design approach requires more of a concentration on the coupon, sub-scale element and full-scale component levels of the characterization pyramid to explore specific manufacturing defects, inspection and structural health monitoring techniques, and repairs before validating full-scale structures. Of course, this all comes at a cost penalty and in the wind energy industry there is not the same risk to human life as in the aerospace industry. Despite this distinction, wind blades are rapidly increasing in size, becoming more valuable assets, and expected to operate for longer. Furthermore, inspection techniques are becoming more advanced and cost effective, so certain aspects of damage tolerant design philosophies are becoming much more attractive to the wind energy industry.

Recently, effects of manufacturing defects have been a heavy focus for wind blade damage tolerance research. Many types of common manufacturing defects have been explored, such as dry adhesive bond lines, porosity, in- and out-of-plane waves [8, 9], and delaminations. Because of increased edge (lead-lag) loading in larger blades, skin (or more generally sandwich) panels are of particular interest in blade failure analyses as a result of phenomena such as panel breathing. This has led more concentrated research into the failure of composite sandwich structures utilized in wind blade leading- and trailing-edge panels [3, 10, 11]. A supposedly common manufacturing defect, which has seen little public research effort, is core gaps. Core gaps are the result of separate sheets of core material (e.g., balsa or foam) laid-up in the blade mold next to each other, but not being properly butted-up against each other, leaving a gap (see Fig. 2). This could be a result of human error or shifting of the blade materials when the vacuum is applied for resin infusion. This results in a resin rich region and distortion of the overlaying fiberglass fabrics. Core gaps can act as a damage initiation point, which can trigger delaminations with the potential to spread to more critical parts of the blade structure. Several studies have been conducted on the effects of various core joints/junctions [12, 13], but little research has been done to investigate the possibility that the joint/junction is less than perfect. A recent study by researchers at TPI Composites and Luna Innovations found significant curing strains in the resin-rich region of core gaps [14]. These curing strains were highly dependent on curing temperature and significantly affected the mechanical properties of the composite sandwich structure. Understanding and characterizing these defects is paramount to adopting damage-tolerant design philosophies with respect to wind blade manufacturing variabilities.

The research presented in this paper aims to characterize the effects of core gaps on the load-carrying capacity of composite sandwich structures for wind blades at the coupon scale in 4-point bending. Specifically, we compare the effects of core gaps on glass/balsa sandwich beams infused with epoxy and a novel, recyclable, acrylic-based thermoplastic resin system, which has gained significant traction within the wind energy industry [15]. This research is part of a much broader structural validation method development program for sub- and full-scale components to understand the procedures necessary to bridge the knowledge gap between coupon-level characterization and full-scale structural validation. Ultimately, this research is working toward developing and defining the required pathways to evolve existing wind turbine blade validation and certification practices, keeping costs low, and allowing existing test facilities to keep pace with the rapid growth of wind turbine blades. These practices aim to encompass the full range of the building block pyramid from baseline materials, to design allowables and full-scale validation for the IEC 61400-23 blade validation standard.

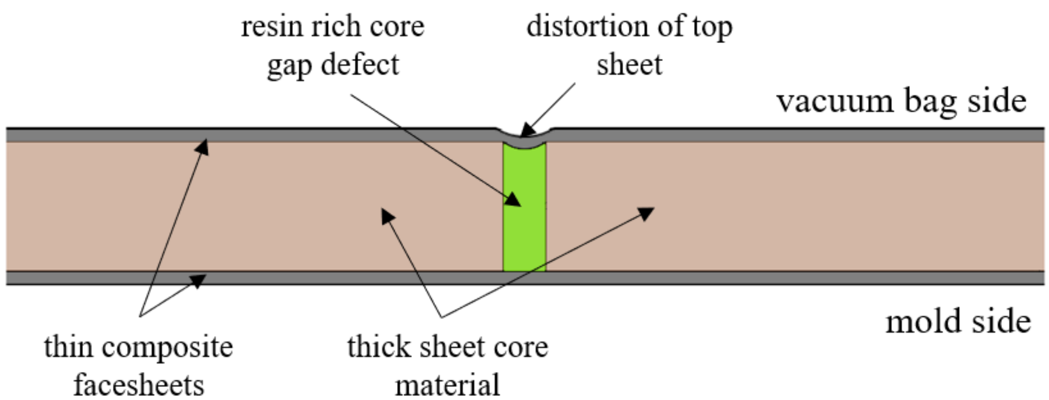

Fig. 2 A schematic of the effects of core gaps in wind blade sandwich structures.

II. Approach and Methodologies

The goal of this research was to characterize the effect of core gaps on composite sandwich panels for wind turbine blades to gain an initial understanding of the defect before developing more complex sub-component characterization methodologies. These will include larger, more detailed sub-components with more complex, multiaxial loading scenarios introduced to them. This study only concentrates on the effects of core gaps on the static strength of sandwich panels in long beam 4-point bending.

A. Specimen Manufacturing

Specimens were designed and manufactured following the ASTM D7249/7249M-18 Standard Test Method for Facesheet Properties of Sandwich Constructions by Long Beam Flexure. Also, recommendations from the DNVGL-ST-0376 Standard for Rotor Blades for Wind Turbines [16] were acknowledged for the core thickness and facesheet properties, although the long beam flexure test method is not specifically cited in the standard, despite similarities in the diagram.

The long sandwich beam samples were manufactured using vacuum assisted resin infusion molding. The fiberglass fabric used was Vectorply E-BX2400; an E-glass, 821 $g.m^2$, ±45°, biaxial fabric with a universal sizing to be compatible with both the epoxy and thermoplastic resin systems. For the core material, 25.4 mm Baltek SB100 end-grain balsa wood from 3A Composites was used. Panels were arranged with sandwich layups of [$\pm45_2$/core/$\pm45_2$]. This layup was chosen because it is widely representative of wind blade skin panels. The sandwich constructions were infused with two different resin systems to compare their damage tolerant properties. The epoxy was Hexion Epikote RIMR 135 with Hexion Epicure RIMH 1366 hardener, mixed at a ratio of 100:30 and cured at 80 °C for 5 hours. The novel, infusible, acrylic-based thermoplastic resin system was Arkema Elium 188-O with Luperox AFR40, Benzoyl peroxide initiator, mixed at a ratio of 50:1 and cured at room temperature for 3 hours. Panels were made both without core gaps for control specimens and with 10 mm core gaps. The gaps between the core sheets were controlled using

10 mm chocks of balsa core at each side of the panel and the application of spray adhesive between the balsa sheets and the mold-side layers of fiberglass fabric (see Fig. 3). Despite best efforts, the gap width still varied along the width of the panels caused by manufacturing variations of the balsa core sheets (~±0.5 mm). Once cured, panels were cut into beam specimens 610 mm long by 70 mm wide, with the core gaps centered and perpendicular to the length of the beams (see Fig. 3). The overall cured thickness of the sandwich panels was approximately 28 mm, yielding a facesheet thickness of 1.2-1.3 mm. Table 1 shows a summary of the number of specimens characterized under each condition.

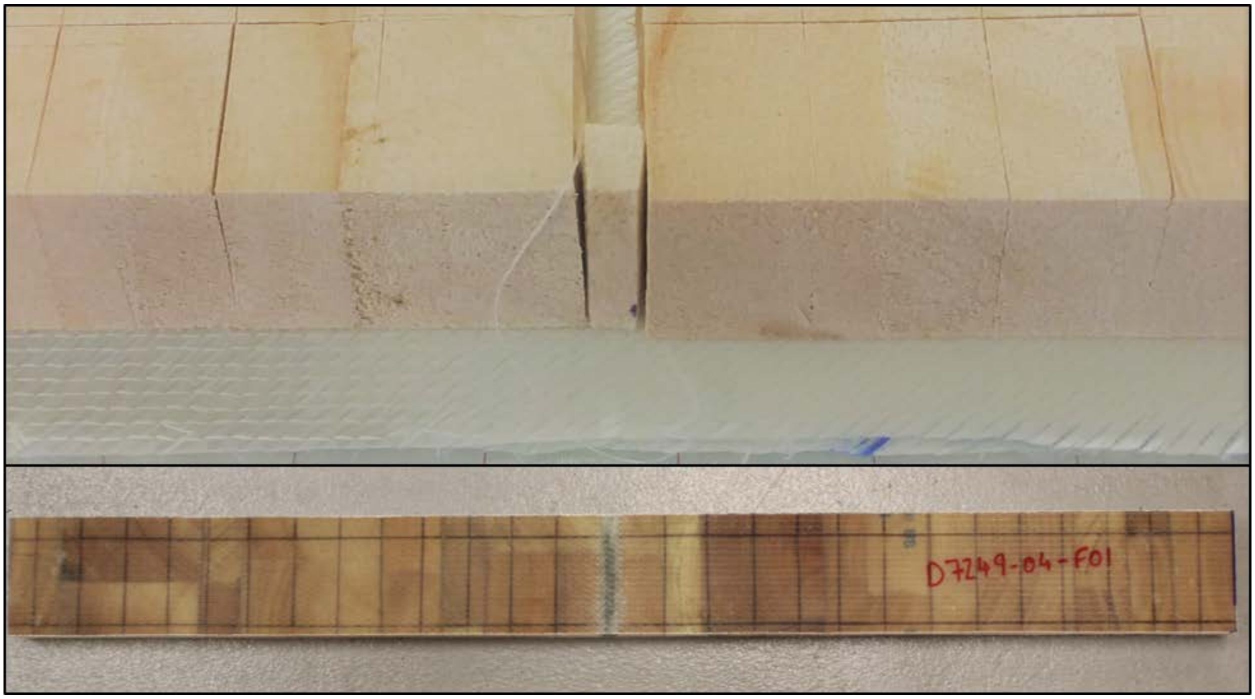

Fig. 3 Manufacturing of the long beam specimen showing the chock controlling the core gap (top) and a finished specimen (bottom).

		Core Gap	
		0 mm	10 mm
Resin System	Hexion 135/1366 epoxy	4	4
	Arkema Elium 188	4	4

Table 1 A summary of the conditions and number of specimens characterized.

B. Long Beam Flexure

Long beam flexure in static 4-point bending was the chosen characterization method for this study because it is the most representative loading scenario for wind blade skin panels at the coupon scale. Stress states experienced by skin panels are predominantly bending stresses with negligible through-thickness shear stresses. This means 4-point bending is more beneficial when compared with the more commonly used 3-point bend; there are no shear forces applied through the gage section. Also, the 4-point bending setup has a longer gage section of constant bending moment which is less influenced by the load introduction points.

Tests were conducted on an MTS 100-kN load frame with MTS FlexTest 40 and Multipurpose Elite software. Loads were applied using a long-beam flexure fixture manufactured by Wyoming Test Fixtures. The support span (S) and the loading span (L) were set at 560 mm and 100 mm, respectively, as per the ASTM D7249 standard configuration. The support and loading bars were 25 mm wide steel blocks which allowed free rotation of the specimen. In addition, 3 mm rubber pressure pads with a Shore A hardness of 60 were applied to the support and loading blocks to reduce stress concentrations and prevent localized crushing of the specimens. All specimens were loaded with the vacuum-bag-side face in compression. Figure 4 shows a schematic of the setup, including a photo of the fixture and a specimen in the load frame.

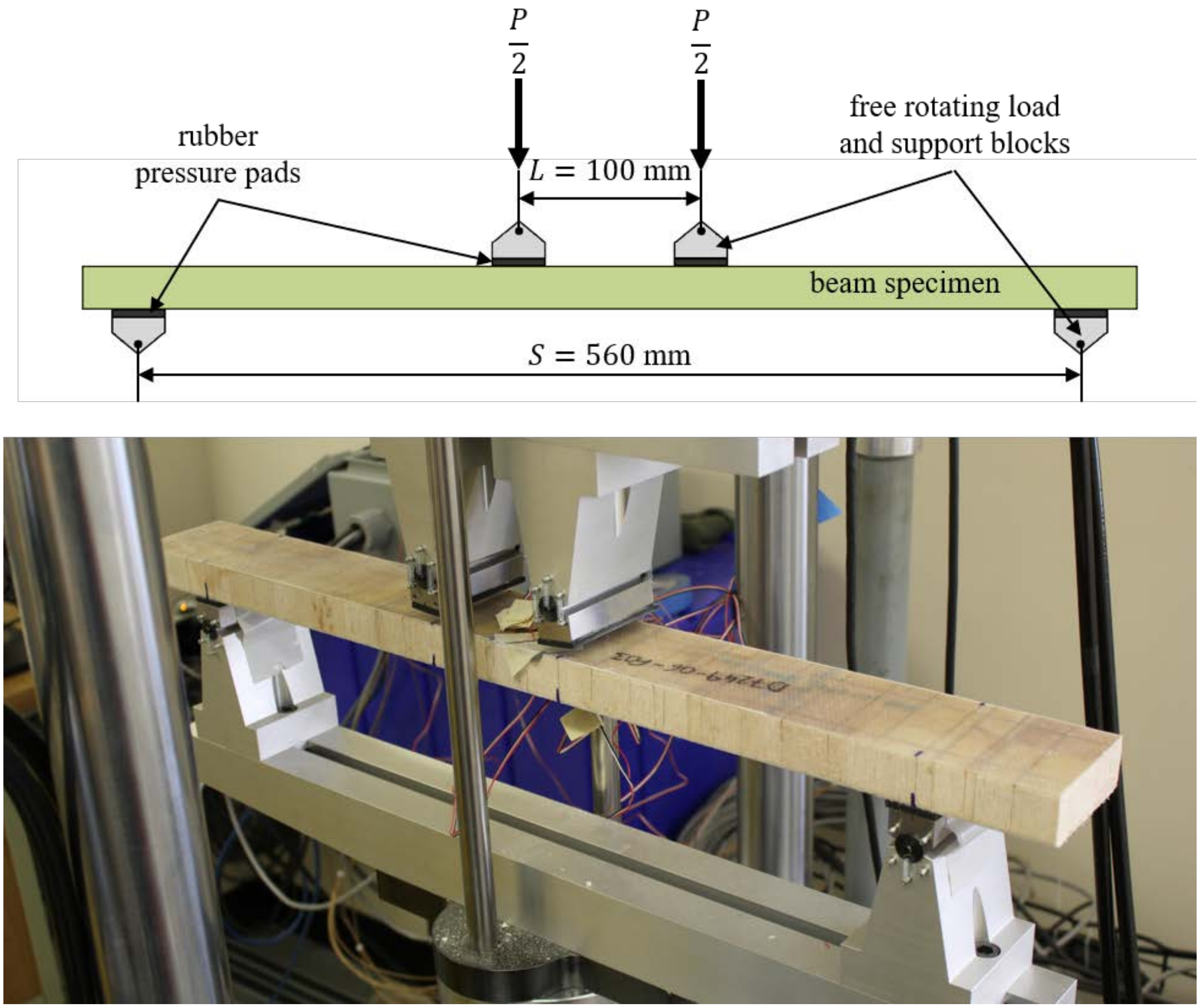

Fig. 4 A schematic of the fixture setup (top) and a photo of the long beam flexure fixture and a specimen mounted in the load frame (bottom).

Specimens were loaded to failure at a rate of 13 $mm.min^{-1}$. Load cell and crosshead displacement data were acquired for every test, and some specimens were instrumented with foil strain gage rosettes on both the tension and compression facesheets within the specimen gage sections. Any core shear failures or failures outside of the gage section were deemed unacceptable. Only pure bending failures within the gage sections were accepted.

From the load data, facesheet stresses (σ_f) and ultimate facesheet strengths ($\sigma_{f,ult}$) were calculated using Eqn. 1, derived from beam bending equations where P is the load, b is the specimen width, t is the facesheet thickness and c is the core thickness. This assumes that the stiffness of the core material is negligible when compared to the stiffness of the fiberglass composite facesheets. It also assumes that the facesheets are significantly thin in comparison to the thickness of the balsa core.

$$\sigma_f = \frac{P(S-L)}{4bt(c+t)} \tag{1}$$

III. Results and Discussion

A. Core Gap Inspection

Before the core gap specimens were mechanically loaded, they were visually inspected to gain a greater understanding of the effect of having a significant resin-rich region within a composite sandwich construction. Figure 5 shows a photo of the cross-section of one of the specimens infused with the epoxy resin system. It was originally anticipated that the core gap would cause distortion in only the top layers of the E-glass fabric, but Fig. 5 shows that both the mold-side and vacuum-bag-side plies have been distorted around the core gap. It appeared that the vacuum between the two core sheets had pulled them slightly closer together, but the gap was still measured as 10 mm. It may be that this could also be attributed to shrinkage of the epoxy through the thickness during curing and cooling. Significant degrees of porosity can also be observed, which is more concentrated towards the vacuum bag-side of the core gap. It is likely that the constrained, resin-rich region dramatically overheated because of the exothermic curing reaction when the curing heat was applied, resulting in the resin off-gassing.

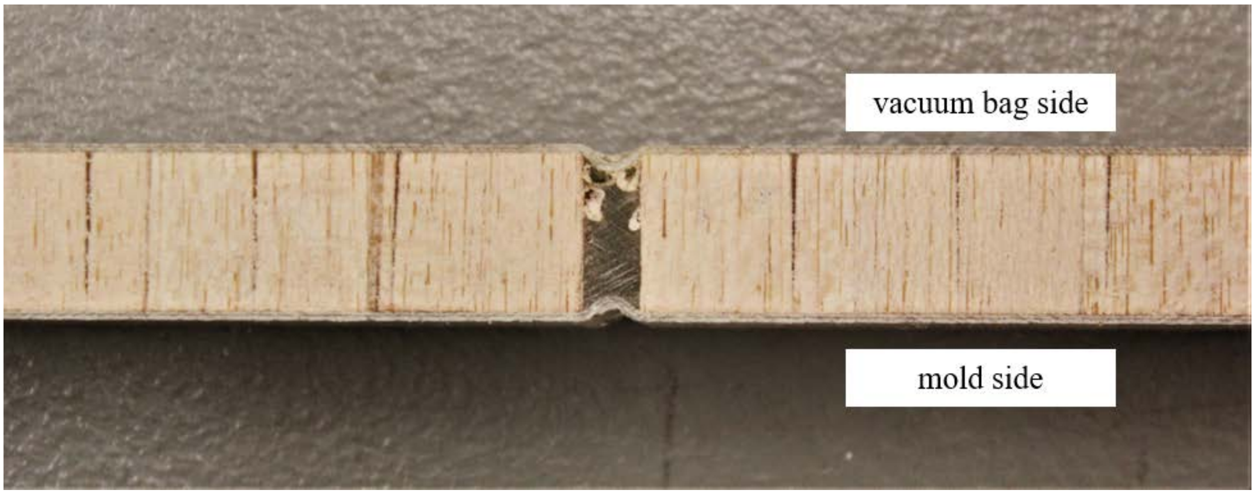

Fig. 5 Photos through the cross section of a beam specimen infused with the epoxy resin system.

The Elium thermoplastic core gap specimens exhibited similar phenomena (see Fig. 6). The core gap caused distortion of the E-glass plies, but to a much lesser degree than the epoxy specimens, especially on the mold-side of the specimens. Most interestingly, the Elium resin appears to have expanded out of the core gap in localized areas along the length of the gap, despite the pressure being applied by the vacuum bag. The Elium resin system is fairly volatile and can actually boil under vacuum at room temperature in resin-rich regions. The exothermic curing reaction will have exacerbated this, which could have displaced some of the resin in the core gap and forced it up between the balsa sheets and E-glass plies. There is also a lot of porosity within the core gap. In comparison to the epoxy, the air pockets within the Elium are smaller but greater in quantity. They also appeared to be much better distributed in the gap and did not rise to the bag-side facesheet in the same way as in the epoxy.

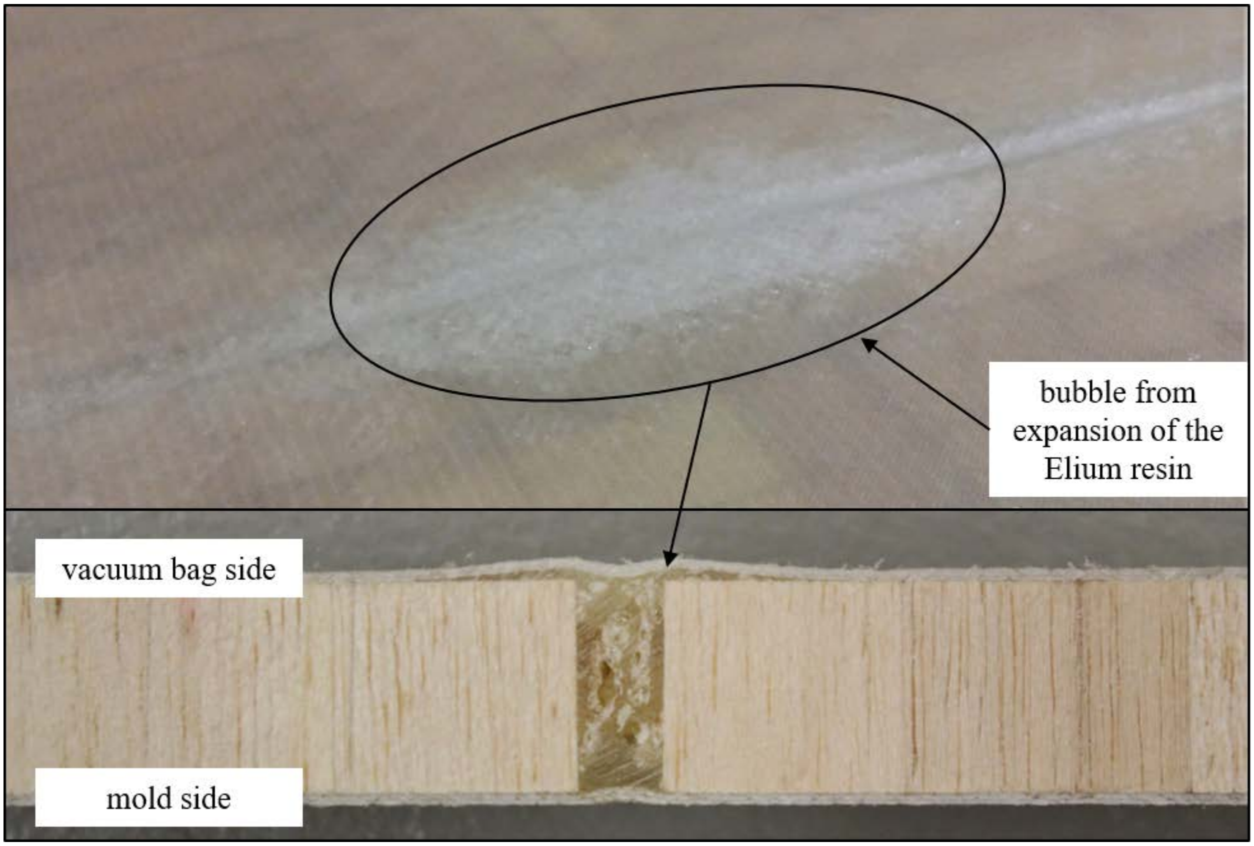

Fig 6. Photos of the view of the core gap on the vacuum-bag-side surface of the full sandwich panel showing the resin expansion (top) and through the cross section of a beam specimen (bottom) infused with the Elium thermoplastic resin system.

B. Mechanical Characterization

Ultimate facesheet strengths were calculated for all specimens, using Eq. 1. For the specimens with core gaps, the distortions in the fiberglass plies were ignored and facesheet strength was based on the uniform thickness of the beams. The average ultimate strength results are shown in Fig. 7, with the error bars indicating standard deviation of all specimens characterized under each condition. Comparison of $\sigma_{f,ult}$ for the epoxy and Elium beams with no core gap yielded significant differences. On average, the Elium beams were approximately 15% weaker than the epoxy beams. This was unexpected because the Elium resin system has been described as having stiffness and strength properties similar to more common epoxy resin systems [17]. Also, the biaxial fabric used in this study was specifically recommended by Arkema to be compatible with the Elium resin system.

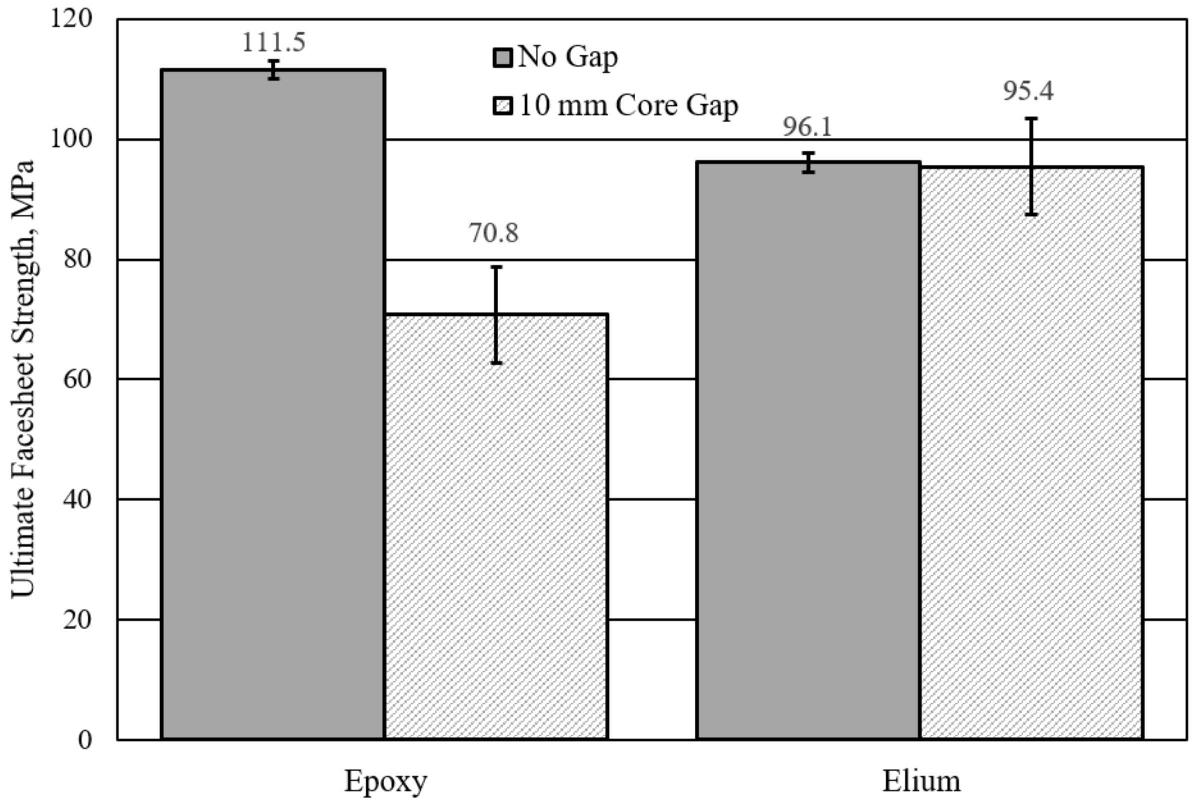

Fig. 7 Average ultimate facesheet strengths of the specimens characterized under each condition with error bars indicating standard deviation.

Representative stress-strain curves from specimens characterized under each condition are shown in Fig. 8. Strains were taken from the longitudinal gages on the strain gage rosettes bonded to the tension and compression facesheets. Both the epoxy and Elium specimens exhibited highly non-linear behavior, as is typical with ±45° biaxial E-glass composite laminates [18], despite the inclusion of the balsa core material. Both the epoxy and Elium control specimens displayed similar stiffnesses, but the Elium reached peak stress several thousand με earlier than the epoxy specimens. Inspection on the failed specimens revealed noticeable irreversible necking of the tension-side composite facesheets within the gage sections, despite the constraint of the balsa core (see Fig. 9). In comparison to the epoxy specimens, the Elium specimens did not shown any visual signs of cracking, only permanent curvature in the specimens.

Comparisons of the $\sigma_{f,ult}$ of the sandwich beams with the 10 mm core gaps introduced revealed some unexpected results (see Fig. 7). The epoxy specimens showed an average $\sigma_{f,ult}$ of 70.8 MPa, a reduction in strength of approximately 35% compared to the epoxy control specimens. Also, the standard deviation was large compared to the control specimens, caused by the increased variability of the discontinuities introduced by the core gap. The Elium specimens, however, exhibited little to no reduction in strength at all, despite the core gap, expansion of the resin within the core gap, porosity, and distortion of the facesheets. There was increased variability indicated by the significantly greater standard deviation when compared with the control specimens. In fact, some of the specimens with the core gap failed at higher facesheet stresses than any of the control specimens. Additionally, the epoxy core gap specimens were approximately 25% weaker on average than the Elium core gap specimens. Further investigation of the failure mechanisms was required to understand this phenomenon.

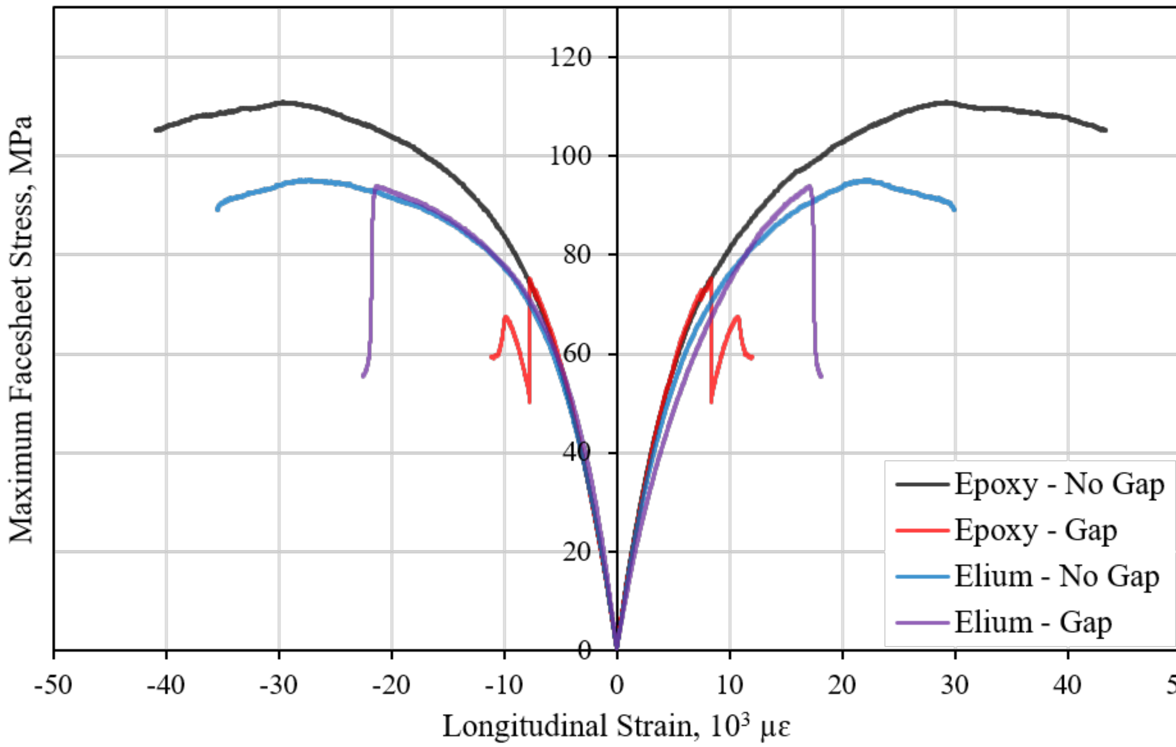

Fig 8. Facesheet sheet stress vs. strain taken from the longitudinal strain gages mounted on both the tension and compression facesheets (note that strain has been linearly interpolated after the strain gages failed during each test).

On observation of Fig. 8, the stress-strain curves of the epoxy and Elium core gap specimens followed the same trends as their control counterparts. The strain gage rosettes on the core gap specimens were specifically placed 25 mm away from the core gap because flat bonding surfaces were required. This explains why the stiffnesses were similar when comparing the core gap specimens to the controls. The core gap specimens failed prematurely and more dramatically, indicated by the more sudden drops in facesheet stress, which suggest a significant change in failure mechanism when compared to the control specimens.

Inspection of the failed core gap specimens revealed comparable damage mechanisms between the epoxy and the Elium (see Fig. 10). Both the epoxy and Elium specimens failed through local buckling of the vacuum-bag-side facesheets in compression. This also resulted in delaminations emanating away from the core gap. The epoxy specimens exhibited delaminations on both the compression and tension facesheets, and the resin-rich gap had completely separated from the balsa core on one side. Comparatively, the Elium specimen only displayed damage in one localized area, and the rest of the sandwich construction appeared in-tact. The Elium specimens showed a significant degree of permanent curvature, whereas the epoxy specimens still appeared to be perfectly flat away from the core gap region. This is attributed to the Elium specimens failing much closer to their typical failure stresses and the tension facesheets accumulating damage before failure at the core gap. After close inspection of the Elium core gap specimens' failure strength and damage mechanisms, it appears that the expansion and overflow of the resin in the core gap into the top sheet may have helped them retain their strength. The thin layer of compliant resin between the balsa and the top sheet could have reduced the stress concentrations caused by the "wave" in the fiberglass plies and allowed stresses to shear-lag back into the balsa core more smoothly. The resulting increased thickness (although only ~1 mm) will have also aided in reducing stresses in the fiber "wave" around the core gap. Finite element analysis will be required to fully understand and quantify this phenomenon. One final contributing factor to the differences in strength reduction could have been the locations of the porosity within the core gaps. Generally, the porosity in the epoxy core gaps was more concentrated at the top of the gap and around the fiber "wave". This will have contributed to the reduction in strength when compared with the Elium specimens, as a result of the reduced cross-sectional area bonding the fiberglass plies to the resin-rich core gap.

Although only static loading was explored in this study, the recorded strength reductions and observed damage mechanisms indicate that resin-rich core gaps in composite sandwich constructions for wind turbine blades will be a significant detriment to fatigue strength. This is a much bigger concern for wind blade laminates and structures with manufacturing defects. The delaminations like those observed in this study have the potential to propagate into more critical structural elements, such as shear webs, spar caps and the bonds between them through fatigue loading over the 20-year operational life of a wind turbine blade.

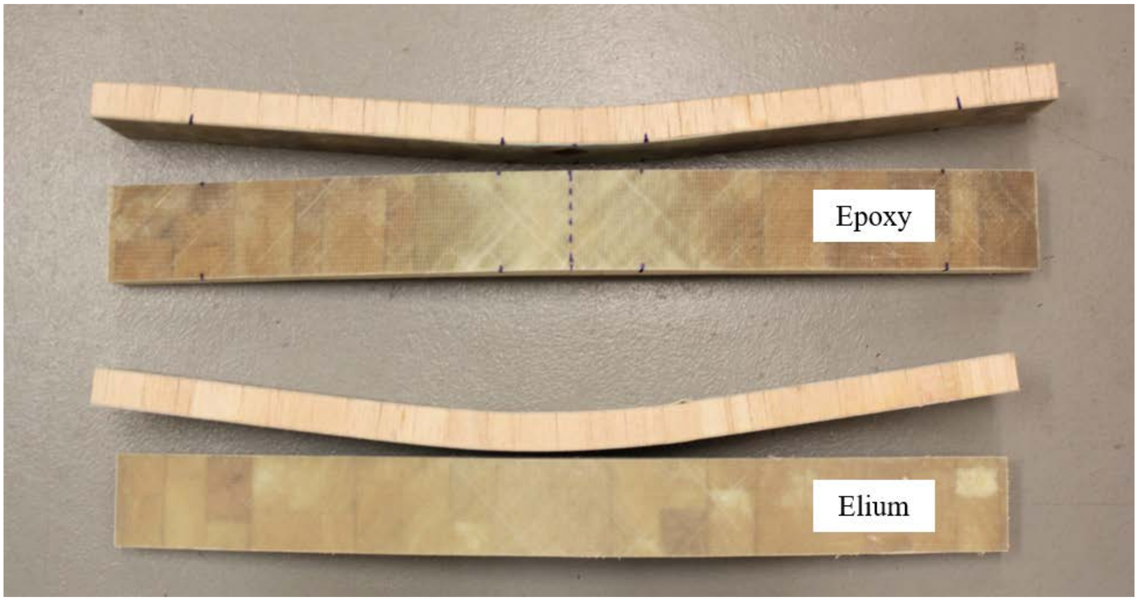

Fig 9. A comparison of failure modes between the epoxy (top) and Elium (bottom) control specimens, showing distributed damage, necking, and permanent curvature.

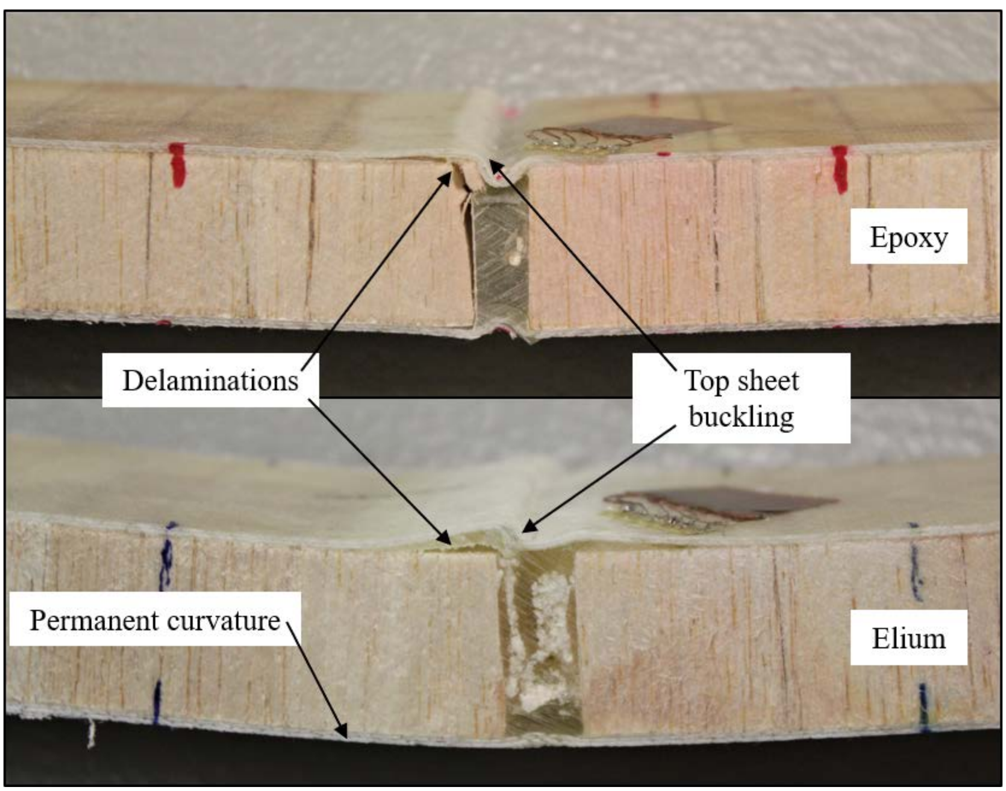

Fig. 10 A comparison of failure modes between the epoxy (top) and Elium (bottom) specimens with 10 mm core gaps.

IV. Conclusions and Continuous Research

The research presented in this paper has characterized the effect of core gaps in composite sandwich panels for wind blade structures through static 4-point bending. Two different resin systems were compared to evaluate their damage-tolerant properties: a Hexion epoxy and Arkema's Elium—a novel, infusible thermoplastic system. Results showed that the Elium beams without core gaps were 15% weaker than the epoxy beams. The introduction of a 10 mm core gap to the epoxy beams reduced epoxy beams' failure strengths by 35% on average. Unexpectedly, the Elium beams exhibited little to no strength reduction with the inclusion of the 10 mm core gaps. Inspections of failed specimens revealed significant changes in damage mechanisms with the core gaps for both resin systems: from slow, progressive tensile failures to abrupt, localized compressive buckling and delaminations. The observed damage mechanisms indicate that this particular manufacturing defect could potentially have a significant impact under fatigue loading scenarios at the structural level. Overall, we conclude that the inclusion of core gaps in wind blade composite sandwich structures can have a profound impact on their strength and damage-tolerance, which is also matrix material dependent.

The next immediate steps in this research will be focused on characterizing fatigue strengths of composite sandwich constructions with core gaps at the coupon-scale and developing the appropriate finite element and progressive damage modeling techniques to accurately describe the results observed in this study and further characterization efforts. We will then continue to develop subcomponent structural validation techniques for larger wind blade skin panels which can accurately recreate the stress and strain states of full-scale wind blades.

As previously stated, this study is part of a much broader wind blade damage-tolerance and structural validation methodology development program. Continued research is aimed at investigating all aspects of structural characterization and validation, including coupon-scale, to subcomponents, full-scale components and complete blades. Our objective is to continuously improve state-of-the-art validation methods that will inform the development of the IEC 61400-23 standard to address needs to validate and certify long blades as subcomponents and full-scale components rather than to solely rely on coupon-level characterization and the testing of complete blades. This research will also include damage-tolerant design and validation philosophies, as well as development of the appropriate finite element modeling techniques required for accurate validation methodologies.

Acknowledgments

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