IN-PLANE FATIGUE CHARACTERIZATION OF CORE JOINTS IN SANDWICH COMPOSITE STRUCTURES

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IN-PLANE FATIGUE CHARACTERIZATION OF CORE JOINTS IN SANDWICH COMPOSITE STRUCTURES

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In practice, adjacent preform sandwich cores are joined with a simple butt joint without special precautions. When molded, this gap is filled with resin and creates a resin rich area. Stress risers will be amplified under cyclic load, and consequently, the serviceability of the structure will be affected. Designers and researchers are aware of this problem; however, quantifying this effect and its intensity and consequence on the service life of the structures has not yet been developed. Despite pervious findings, limited experimental data backed by a comprehensive root cause failure analysis is available for sandwich under axial static, fatigue and post-fatigue. If such a comprehensive experimental characterization is conducted, specifically understanding the nature of the damage, intensity, and residual strength, then a valid multi-scale damage model could be generated to predict the material state and fatigue life of similar composite structures with/without core joints under in-plane static and fatigue load.
This research study characterized the effect of scarf and butt core joints in foam core sandwich structures under in-plane static and fatigue loads (R=0.1 and R= -1). Post-Fatigue tensile tests were also performed to predict the residual strength of such structures. Nondestructive Evaluation Techniques were used to locate the stress concentrations and damage creation. A logical blend of experimental and analytical prediction of the service life of composite sandwich structures is carried out. The testing protocol and the S-N curves provided in this work could be reproducible and extrapolated to any kind of core material. This research study will benefit composite engineers and joint designers in both academia and industry to better apprehend the influence of core joints and its consequence on the functionality of sandwich structures.
This dissertation is dedicated to my lovely mother Mary, proud father Professor A. Sheriff, beautiful pregnant wife Jasmine, coming so soon, son Ishmael, beloved sisters, supportive brothers and friends, for all of their support and love.
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CHAPTER 1

INTRODUCTION

1.1 Introduction and Problem Statement

New infrastructure and products are designed, fabricated and created every day. Sandwich composite structures have a high stiffness and strength to low density. Typically sandwich composite structures can have the same mechanical properties or even better in some ways, yet are lighter and more cost effective. Core joints exist in large sandwich composite, structures and special attention with regards to the effect of core joints on the fatigue performance of such structure is of interest to many composite engineers. The choice of the joint is very important and determines the longevity, stiffness and strength of the structures. When loaded in-plane, mismatched Poisson’s ratio between the joint and the core generates out-of-plane stresses (interlaminar) at the core joint/facesheet interface, creating a stress-riser at this location that will eventually affect the performance and fatigue life of the structure. This research is aimed at providing knowledge of the strength of sandwich composite structures that experience static and/or cyclic loads. The types of mechanical testing will include pure tension and compression static tests, tension-compression and tension-tension fatigue tests.
1.2 Research Objectives

The following objectives were set for this research:

- Characterize and investigate the effect of scarf and butt core joint designs in foam core sandwich structures under axial static, tension-compression ($R=-1$) and tension-tension ($R=0.1$) fatigue tests.
- Quantify the reduction in fatigue life due to the core joints and justify the increase in residual strength and stiffness of the scarf joint relative to plain foam and butt joint samples.
- Find out which joint is reliable when used for applications not only in civil infrastructure applications but also for use in construction and maintenance of offshore platforms, polar and marine terminal infrastructure.
- Finding the mechanical behavior of the GFRP laminate composites under different tests.
- Determine the best and most appropriate modeling to describe the fatigue life prediction of composite sandwich with core joints.

Some of the questions to be addressed are:

- What mechanical properties of the sandwich composite samples are affected by using different joint?
- To what extent are the foam core and facesheet laminates affected by the joint?
- What will happen to the microstructure of components of the sandwich composite structure with different joints?
- What is the mechanism of failure of these joint designs and how do they fail?
• What joint and foam core are strong and stiff when loaded in-plane?
• Which degradation analysis method is most appropriate for these structures?
• What is the best-fit model to describe the behavior of sandwich composite structures with and without core joint under various loads?

This research will conclude with answers to the following questions:
• Using the Digital Image Correlation (DIC), do the joints act as stress risers affecting the long-term performance of composite sandwich structures?
• Does the density of the foam (core) have an effect on static and fatigue tests results?
• What is the failure mechanism of sandwich composite core-joints under axial static and fatigue loading (plain/core joints)?
• Which core joint is the most reliable in static and fatigue regime?
• What are the compressive strength, stiffness and in-plane tensile properties of the GFRP laminates?
• What will happen to the microstructure of the damaged samples and what are the internal damage/defects?

1.3 Research Significance

Failure of composite sandwich structures with core joints under axial in-plane load and some certain conditions are complex phenomena. The resin line creating the joint between two cores is known as stress-riser during loading which affects the performance of the composite sandwich structures. To date, no research investigated the core joints under in-plane axial fatigue in sandwich composite structures and no work has
been published in this area. There is no ASTM test method and no fixture exists to test composite laminate under tension-compression fatigue. This research is aimed to provide innovative core joints techniques in sandwich composite structures with high strength, durability and less stress concentrations.

1.4 Dissertation Structure

This dissertation is comprised of six chapters. Chapter 1 provides an introduction and points out the problem statement, research objectives, and research significance. Introduction and background to sandwich composite structures and laminate, ±45° double bias fabrics and reasons for joining structures are described in Chapter 2. Chapter 2 also discusses the relative literature review in terms of fatigue of core junctions, materials used and potential ways to join two cores. The experimental methodologies, materials selection, panel manufacturing and samples preparation, instrumentation, analysis methods and non-destructive evaluation testing are presented in Chapter 3. Characterization and discussion of the results of static and fatigue tests for sandwich composite samples and GFRP facesheet laminate and damage mechanism are outlined in Chapter 4. Chapter 5 deals with post-fatigue residual, fatigue life predictions, and residual strength. Chapter 6 lists the observations and conclusions of this dissertation.
CHAPTER 2

COMPOSITE SANDWICH STRUCTURES AND JOINTS

2.1 Introduction and Background

Composite materials (composites) are materials, which are made by combining at least two chemically and physically different constituents. When combined, the individual properties of each constituent give composite materials specific and unique characteristics [3]. Usually, composites are lighter and stronger than their individual substitutes. The structure of composite materials is unique and consists of two parts: matrix and reinforcement. The matrix is usually made from different types of resin. Resin ensures plasticity and binds the reinforcement. The role of the matrix is to spread and effectively transfer loads and protect the reinforcement from damaging elements or agents. The reinforcement is made from different materials. Its main function is to increase mechanical properties of composite materials such as strength, stiffness and thermal expansion [4]. Composites are different from other alloys because their constituents remain separate and distinct in the finished material.

Composites are widely used in naval, aeronautic, transportation, and other industries, which rely on strong, resilient, and reliable materials. There are several important factors which affect the main properties of composites. These factors include
the type of materials used as well as the internal alignment and structural patterns of those materials within the final composite structure.

2.2 Sandwich Composite Structures

Sandwich composite structures are composite materials made from a thick and light-weight core material enclosed by two thin and stiff facesheets. The core material is usually made from lightweight polymer foams (Polyvinyl-Chloride, Polystyrene, Polyurethane, Polyester and Acrylic foams), balsa wood or honeycomb cores. Its main function is to separate the two facesheets and ensure a higher bending stiffness. Facesheets are produced from firm and thin materials such as Aluminum, Titanium, Steel Alloys, or Fiber Reinforced Polymer Composites. Their main function is to maintain in-plane and bending loads. The varying properties of individual constituents ensure a high bending stiffness-to-weight ratio. This ratio is one of the most important properties of sandwich composite structures [5].

Due to their mechanical and psychical properties, sandwich composites are widely used in various industries. Low weight and high stiffness make these composites a material of choice for producing outer shells of aircrafts, ships, train coaches, buses, trucks, etc. Sandwich composites are also widely used in bridge constructions and reconstruction and for manufacturing wind turbine blades. Sandwich composites are very cost-effective materials. For example, sandwich structures reduce the overall weight of vehicles, which consequently reduces their fuel-consumption. Additionally, the combination of GFRP and foam in sandwich composites has allowed manufacturers to increase the size of wind turbine blades which make individual turbines more efficient.
than ever before. On the other hand, sandwich composite structures are subject to moisture and different environmental considerations. For sandwich cores, the ideal strength and stiffness even under extensive heat must be able to tolerate significant fluctuations in moisture before breakage. There are a variety of ways the structures can fail during loading, including environmental conditions such as variable temperature and fire-induced damages [6-11].

2.3 Literature Review

The task of this section is to carefully observe recent achievements found in a series of comparative studies regarding the strength of sandwich beams and the fatigue of core junctions. The flexural fatigue behavior and failure of composite sandwich beams with core joints have been discussed extensively in the literature [12-17]. While there has been substantial work directed to improve the core junctions, in-depth characterizations of the core joint to predict the residual strength and fatigue life in sandwich structures are still limited. Couple of studies examined the composite sandwich structures with core joints due to in-plane loads [18, 19]. They investigated the effects of butt joints between different core densities with Aluminum and GFRP facesheets. They found that the failure mode was initiated in the softer core near the joint followed by facesheet failure, this in turn lead to shorter fatigue life. They also addressed the critical need to better understand the stress/strain state at the core junctions. Material properties are also compared for suitability under various conditions for various purposes. In lieu of optimization information, recent articles finally reveal the best way that cores are conventionally joined, and the best way they can be joined under certain situations.
Homogeneous cores reduce localized junction stress, while transfer the stress to the surrounding stressors, thereby ultimately increasing the vulnerability of the whole structure [20-23]. Bozhevolnaya and Thomsen used different core junctions to analyze the various fatigue properties, including strength and elasticity to name a few. The team placed measuring tools at various points across the structure to initiate both sudden fractures and displacement shut limits after having applied the requisite weight to the structures. By use of multiple applications of the student’s t-distributions two conclusions quickly became apparent. The first is that sandwich beams loaded using the conventional butt junctions displayed the lowest levels of sustained pressure endurance [18, 19]. Conversely, the reinforced butt junctions were incredibly strong by comparison. The structural grading of the cores allow for the most ideal configuration [20, 21]. The statistical processes used were relevant and properly applied. The correct conclusion was drawn in the article, with all mathematic processes truly sound.

While many combinations of geometries and materials are possible, the sandwich structures do have some known structural weaknesses, like those associated with local transversal loadings [21]. Bozhevolnaya et al consider many of the other types of possible riggings for these structures, with sub-structures including, “cores of higher stiffness, edge and corner stiffeners, backing plates, through-the-thickness and partly potted inserts”. However, early data examines core joints in sandwich structures and suggests methods for improvement in the future. Implementation of the peel-stopper concept could improve bending stiffness rates by around 10%, roughly speaking [20]. Similarly, data shows that critical loads for spline junctions rather than butt junctions can produce improvements of four times the tension of traditional loadings. With the failures of static
loadings so effectively offset, the honeycomb foam composite styles, with peel-stopper and spline shaped technologies, can be the most effective in the future at offlaying tensile, axial, and compressive forces [24].

2.4 Laminate Composites

Laminate composites are composites with layers that are stacked one on top of the other. Each stacked layer is placed at a different angle (0°, 45° or 90°) to its adjacent layers. The uniqueness of the layering process enhances mechanical and thermal properties of the finished material and makes laminate composites strong and stiff. The most commonly used type of laminate composites is fiber-reinforced polymer (FRP) composites.

Fiber-reinforced polymer (FRP) or fiber-reinforced plastic consists of a polymer matrix and fibers. The matrix is usually made from resin (Epoxy, Phenol Formaldehyde, Vinylester and Polyester Thermosetting Plastic). The reinforcement fibers are usually made from carbon, glass, aramid or other materials. Glass fibers are the most commonly used type of FRP. Glass-Fiber Reinforced Polymer (GFRP) is made from FRP matrix that is reinforced with glass fibers. The glass component is usually made from calcium-alumina borosilicate. The molten glass is poured into platinum alloy bushing that has many small holes. The production process ensures that the fibers have versatile properties which can vary according to need [25]. GFRP shows a very high resistance to heat. These materials can perform in temperatures as high as 375°C or even higher. However, the increase in temperature proportionately decreases the quality and strength of GFRP.
There are several different types of GFRPs. The S-type GFRP has superior strength properties, but it is relatively expensive to produce. This is why many manufacturers choose to use the cheaper E-type. E-type glass composites have high tensile strength and good stiffness properties. These materials are also very resistant to moisture, electricity and fire which makes them excellent insulators. E-glass composites are mostly used in shipbuilding, aviation, automobile, plastic, and many other industries.

2.5 ±45° Double Bias Laminates

Double bias fabrics are materials with fibers that are oriented in ±45°. The ±45° fibers produce high strains under bending loads and nonlinearity behavior under static loads [26, 27]. These fibers resist the maximum strain under static and fatigue loads and introduce more strength and stiffness loss prior to failure in fatigue [28]. A commercially available double bias fabric material E-BXM 1708 consists of three plies: +45°, -45° and chopped mat (random glass fibers) stitched together in the 0° direction to produce triaxial fabrics. While the orientation of plies in the biaxial fabric increases stiffness, the chopped mat simplifies resin soaking during the infusion process and increases stiffness and strength [28].

The fatigue failure of 45 off-axis laminate composites (loaded at 45 to the fibers) is dominated by a combined transverse stress and in-plane shear stress (parallel to the fibers) [29]. Matrix failure in laminate composites is considered as the fundamental failure mechanism [28, 29]. ±45° laminates with a urethane resin showed higher strains and less fatigue strength versus those with epoxy. The viscoelastic shear property of the resin in ±45° laminates is important under tension and compression loadings. Cracks in
±45° laminates open under transverse tension status and grow parallel to the fibers which leads to delamination [28].

Double bias fabrics are particularly important for the wind turbine industry. These materials are heavily used in wind turbine blade structures to build up the thickness of the root and resist buckling and torsion in both shells and webs. Double bias fabrics are also built into the spar cap along with carbon hybrid blades in order to resist splitting and provide further stabilization [26, 27, 30]. Carbon fiber reinforced plastics (CFRP) cost 10 times as much as glass fiber reinforced plastics (GFRP); therefore, most wind turbine rotor blade industries use fiberglass [31].

The majority of studies that investigated various properties of double bias fabrics focused on unidirectional fabric laminates stacked at ±45° rather than on commercial biaxial fabrics [28]. There is little research that has studied ±45° double bias laminates compared with multidirectional and unidirectional laminates [28, 29]. Reviews of relevant research, the SNL/MSU/DOE Fatigue Database for Wind Turbine Blade developed by Mandell et al. provided significant data with different materials and test methods for unidirectional, multidirectional and triaxial composite laminates but not enough for ±45° biaxial under reversed loading (tensile-compression fatigue, R=-1). Other studies focused on tension-tension axial fatigue, but no focus was given to double bias ±45° laminate composites under tensile-compression fatigue [32, 33].

2.6 Reasons For Joining Structures

Ideally, joints should not be used when designing a majority of structures especially when designing static structures. Joints can add additional weight and/or
weaken the structural integrity. Regardless of their limitations (additional weight, local weakening of structural integrity), joints are very often used in practice either as preferred or necessary components. Apart from connecting different structures and materials together, using joints also has many other advantages.

Dynamic structures are very specific. Their design needs to allow movement of parts without compromising the ability of the whole structure to withstand loads which are generated and/or imposed on its assembly. The most obvious way, which helps achieve the movement of parts in dynamic structures, is by using joints or joining.

It is interesting to note that static structures, especially ones produced on a large scale, may also require joining. Even though static structures do not move, every increase in their size also increases the size of their individual components. As the manufacturing process limits the size and the shape complexity of these components, joints are used to overcome these limitations and connect different parts together.

Joints are also used as a way of increasing damage tolerance levers of materials and ensuring better structural integrity. In certain instances, the service load may produce internal damage (e.g. crack), which compromises the overall integrity of structures. In order to address this issue, the design of structures needs to consider two things. Firstly, a structure can be made from materials which can withstand service loads without any damage. Secondly, the design can also consider using crack-arresting elements, which increase resistance. These elements are almost exclusively designed as joints.

Using joining in manufacturing has different advantages. One of the most important benefits of using joining is its ability to enhance structural efficiency and functionality. By increasing structural efficiency designers can achieve adequate
structural integrity (e.g., impact strength or toughness, creep strength, static strength, fatigue strength and/or life, etc.) at the lowest weight of structural components [34].
CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Materials Selection, Panel Manufacturing and Samples Preparation

H100 and H200 PVC foam (Divinycell® Inc.) were used as core materials. Vinylester resin (DERAKANE 610 C-200 by Ashland Inc.) reinforced with knitted E-glass fabric (E-BXM1708 by VectorPly Corporation) was used to manufacture the composite sandwich panels. This specific resin is commonly used in infrastructure applications and provides superior corrosion and durability. Organic peroxide Catalyst (1.25%) by Cadox® LLC was mixed with the resin prior to infusion. The stacking design of the sandwich panel consists of [3-plies /core /3-plies] where each ply is constructed of [+45/-45/Mat; 882gr/m²] and mat placed against the core. Sandwich panels were fabricated by the Vacuum Assisted Resin Transfer molding process (VARTM). Table 4-1 shows the material properties of the face sheets, foam cores, and resin.
Table 3-1 Face Sheet Laminates, Core, and Resin Properties [35].

<table>
<thead>
<tr>
<th>Face Sheet Laminate</th>
<th>Foam Core H100</th>
<th>Foam Core H200</th>
<th>Resin (core-to-core joint)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressive Modulus [MPa]</td>
<td>Compressive Modulus [MPa]</td>
<td>Tensile Modulus [MPa]</td>
</tr>
<tr>
<td>$E_1$ [MPa]</td>
<td>14123</td>
<td>134</td>
<td>310</td>
</tr>
<tr>
<td></td>
<td>Tensile Modulus [MPa]</td>
<td>Tensile Modulus [MPa]</td>
<td>Flexural Strength [MPa]</td>
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<tr>
<td>$E_2$ [MPa]</td>
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<td>129</td>
<td>250</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
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<td>0.4</td>
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</tr>
<tr>
<td>$G_{12}$ [MPa]</td>
<td>9912</td>
<td>34</td>
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</tr>
<tr>
<td>Thickness [mm]</td>
<td>2.1±0.1</td>
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<td>25.4</td>
</tr>
</tbody>
</table>

The face sheet laminates had a fiber volume fraction of 52%. The core joint thicknesses (core-to-core joints) were controlled by using a peripheral confined closed molding frame. All panels were then infused and post-cured for 6 hours at 60°C. Panels were cut into dog-bone shape using water jet technique. Epoxy tabs (G10 material) with 76 mm long, 102 mm wide and 12.5 mm thick were bonded to the ends of the specimens using urethane adhesive (Lord adhesive 7150A/B High Strength Urethane, LORD corporation). The two end tabbed sections were placed in a mounting tab fixture and drilled using an upright drill press (Figure 4-1).
All specimens were perfectly machined flat on both ends and shimmed using two wedges on both ends prior to testing. A novel steel-mounting fixture initially designed and used in this experimental work (Figure 4-1c). The dog-bone shaped specimens were 305 mm long, 102 mm wide and 29.6 mm thick (Figure 4-1). The scarf joint is an efficient structural joint commonly used in laminated wood/timber structural members. The scarf joint design included in this study has a diagonal line (through the thickness) forming a 30° angle with the longitudinal axis. Figure 4-2 shows the areal weight due to the resin uptake for all plain/joint configurations.
3.1.1 Vacuum Assisted Resin Transfer Molding Process

Sandwich composite panels were fabricated by the Vacuum Assisted Resin Transfer Molding Process (VARTM). VARTM is a process facilitated by the pressure difference caused by a vacuum. The advantage of this technology is the cheaper manufacturing cost and any complicated shape can be easily fabricated. The process is a variation of resin transfer molding which uses a vacuum bag lining the molding tool. The set includes a peel ply to ensure a smooth composite surface and an infusion mesh to direct the flow of the resin. The vacuum bag also contains the E-Glass fabric and the H100/H200 PVC foam cores (Figure 4-3).
The bag is sealed and tested for air leaks, which may cause defects on the composite. Air leaks need to be avoided as to not compromise the quality of the composite formed. Once the bag is proven to be air tight, injection of the Epoxy Vinylester resin through a tubing ensues (Figure 4-4).
The resin flows due to pressure difference created by the vacuum. Once the fabric is fully covered, the injection of the resin is stopped and the vacuum bag is sealed. The face sheet laminates has a fiber volume fraction of 52%. The core-to-core joints were squeezed together to create precise butt and scarf joints.

3.2 Instrumentation and Analysis Methods

All sandwich composite specimens were strain gauged back-to-back and adjacent to the core-to-core junction. Bonded strain gages were centrally mounted to the laminate samples in a [0/90] orientation and continuous load-strain data to failure were recording. The measured strain indicated herein is the average strain on both sides of the specimen.

3.2.1 Mechanical Testing Methods

Initial static tensile test was performed on 11 different dog-bone shaped composite sandwich samples. All dog bone sandwich specimens were strain gauged back-to-back and adjacent to the core-to-core junction. The measured strain indicated herein is the average strain on both sides of the specimen. All static tests were initially conducted at 23°C and 50% RH using a servo-hydraulic Testing Machine (MTS Model 312.41/132) with 2.5 mm/min constant head displacement rate. Figure 4-5 shows the test setup and apparatus used.
Tension-compression (R=-1) and tension-tension (R=0.1) fatigue tests with constant load amplitudes and different frequencies were performed on a total of 62 samples. Due to the thermal softening effect of the foam, Burman and Zenkert [36] found that the variation in temperature of 5°C to 10°C could affect the Divinycell foam fatigue life. To mitigate this effect, two fans were used on both sides of the specimen during cycling. The load range spanned from 20% to 40% of the average ultimate static tensile load. Table 4-2 lists the fatigue test matrix for H100 and H200 specimens and the number of specimens for each fatigue regime.
Table 3-2 Fatigue test matrix and number of specimens.

<table>
<thead>
<tr>
<th>Butt/scarf Joints and Plain samples</th>
<th>Target Number of Cycles</th>
<th>Load Frequency (Hz)</th>
<th>Max Load (kN)</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H200</td>
<td>H100</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Tension-Compression (R=-1)</strong></td>
<td>1K</td>
<td>1</td>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>23</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10K</td>
<td>2</td>
<td>18</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>100K</td>
<td>3</td>
<td>14</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>1M</td>
<td>4</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td><strong>Tension-Tension (R=0.1)</strong></td>
<td>1K</td>
<td>1</td>
<td>31</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>10K</td>
<td>2</td>
<td>27</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>100K</td>
<td>3</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>1M</td>
<td>4</td>
<td>18</td>
<td>4</td>
</tr>
</tbody>
</table>

Note: 1K=1,000 cycles, 100K=100,000 cycles and 1M=1,000,000 cycles

Continuous displacement readings were taken during cycling. Increased in displacement (stiffness reduction) was recorded with the number of cycles during the fatigue test. Final number of cycles was recorded for every tested specimen at the point of failure. Failure protocol entailed to a 30% reduction in stiffness or facesheet fracture.

### 3.3 Non-Destructive Evaluation Testing

Post-fatigue non-destructive evaluation (NDE) testing was used to assess and detect the delamination and crack propagations in the core and facesheets. To map out the damage propagation in the factsheets, an Ultrasonic Phased Array Inspection was employed after each target cycles (1K, 10K, 100K and 1M cycles). Inspection with a RollerFORM scan method was performed at 3.5 MHz with 64 elements, pulsed 8 at a time with a 44mm apparatus. The 3.5L64-IPW1 Phased Array Linear probe by Olympus America Inc. was used for this purpose. Digital Image Correlation (DIC) was also employed to examine the displacements and strain distributions at the reduced section,
specifically at the core-to-core junctions. A high-speed camera detecting local deformations along with ISTRA software version 4.3.1 [37] was used to record the data. Scanning Electron Microscope (SEM) was also used to detect the damage and cracks at the cross sectional area of the dog bone (inward side of the butt and scarf joints).

3.3.1 Digital Image Correlation (DIC)

Digital image correlation (DIC) is a non-contact technique used to conduct 2D to 3D measurements. Basically, DIC is the use of any form of optical device to capture images during a deformation and processing via software the images to determine the extent of deformation experienced by the material, but not the existing damage. The technology, DIC, works by the comparison of the photographs or frames taken at different stages in the deformation process. The pixel-by pixel comparison worked out through the use of software using pre-programmed cross-correlation which measures the lag between two similar functions. This is comparable to the convolution of two functions. The set-up for DIC consists of a computer with the necessary DIC software connected to cameras (optical device), a good light source, and the test specimen as shown in Figure 4-6.
Figure 3-6 Digital Image Correlation testing setup.

The optical device to be used is controlled by the application. The technology could be used for various applications such as the measurement of deformation in construction and other engineering works particularly for materials testing. Determining the mechanical properties of a material, to modeling the deformation of materials. Aside from the vast applications, an emphasis on the non-contact nature of the technology should also be given since it does not destroy the material subjected to testing. The technology is also less costly as compared to other optical non-destructive testing methods since the materials are readily available [37].

### 3.3.2 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) is the use of microscopes with a focused set of electrons. These electrons react with the surface of the material producing signals that give information on the surface. The signals produced are classified as either secondary electrons, back-scattered electrons, photons of characteristic x-rays, light,
absorbed current, and transmitted electrons. Surface properties such as topography, composition, and dimensions can be gathered through this technique (Figure 4-7).

There are various conditions for the SEM operation which varying levels of vacuum conditions and temperature ranges. Sample preparation is a vital step in this process since improper sample preparation may lead to bad results. Scanning Electron Microscope in Figure 4-8 (HRSEM-Hitachi S-4800) was also used to detect the damage and cracks at the cross sectional area of the dog bone (inward side of the butt and scarf joints).
3.3.3 Ultrasonic Phased Array Inspection

The equipments in Figure 4-9 were used to detect flaws, delaminations and crack propagations as well. Inspection of each sample is an encoded one-line scan of expected defect location as seen in Figure 4-10. A-Scan window in Figure 4-11 shows the amplitude of reflectors (indications). B-Scan shows intense reflectors along the entire scan, indicating the porosity of the resin layer. C-Scan shows top view of the samples. S-Scan window shows the side view with respect to data cursor location or Virtual Probe Aperture (VPA).
Figure 3-9 From left to right: OmniScan MX2 32:128PA Phased Array Unit, RollerFORM Scanner Phased Array Wheel Probe, Dual Linear Array (DLA) probe and OmniPC software for offline analysis.

Figure 3-10 Scanning methods with RollerFORM (left) and Dual Linear Array (DLA) probe (right).

Figure 3-11 Olympus-OmniPC-4.3R2 software shows A, C and S scan windows.
CHAPTER 4

IN-PLANE AXIAL LOAD-EXPERIMENTATION METHODOLOGY

4.1 Executive Summary

In this chapter, a novel testing methodology was used to characterize the influence of core junction in lightweight sandwich structures under axial load. Most designers are unaware of this influence. Quantifying this influence and its criticality on the life of the structure is still a challenging task. Scarf and butt core joints in foam core sandwich composites were subjected to axial static and fatigue loads (R= 0.1 and R= -1). The outcome of this chapter will not only target sandwich composite structures, but also provide a novel testing methodology of composite laminates subjected to tension-compression fatigue loading.

4.2 Introduction

Composite sandwich structures are currently being employed in a variety of structural applications where high strength/stiffness to weight ratio is critical. Applications include space structures, bridge decks, boats, transportation, and wind turbine blades. Core joints exist in most of these large structures and special attention with regards to the effect of core joint on the fatigue performance of sandwich structure is
of primary interest to design engineers. When loaded in-plane, mismatched Poisson’s ratio between the joint and the core generates out-of-plane stresses at the core joint/facesheet interface (Figure 5-1).

Consequently, stress risers at this location will eventually form and affect the fatigue life of the structure. Most structural designers are aware of this problem; however, quantifying this effect and its consequence on the service life and reliability of the structures is not fully developed.
4.3 Results and Discussion

4.3.1 Static Tensile Tests—Sandwich Composite Samples

All sandwich samples exhibited inclined cracks in the facesheets followed by foam separation in the core. These diagonal cracks were parallel to the fibers’ directions across the anticipated maximum principal stresses and formed an angle of approximately 45° relative to the horizontal axis of the samples. Subsequent horizontal cracks through-the-thickness in the core occurred at the reduced section of the dog-bone sample (Figure 5-2).

Figure 4-2 Failure modes of scarf (a) and butt (b) joints after tension tests (H200 foam core).

Figures 5-3 and 5-4 show significant ductility and plastic deformation at constant load up to skin fracture in the butt joint and plain samples.
Figure 4-3 Peak facing stress and tensile load vs. strain for H200 sandwich composite samples under tension test.
Failure modes of the butt joint samples under tensile tests were more prolonged than the scarf joint samples; this was mainly due to the horizontal crack in the foam followed by the core joint separation (Figure 5-2). The scarf joint failure occurred more sudden than the other core joint samples. This is related to the coupling of the two facesheets provided by the inclined joint and most likely due to friction of the core with the scarf resin line. The axial strain capacity of the butt joints and plain samples revealed a very large strain, 10% versus 5% strain for the scarf joints. This large strain is due to the redundancy in load distribution between the core/joint and the facesheets. Table 5-1 compiles the tensile mechanical properties of all tested sandwich samples. Figure 5-5 summarizes the result in bar charts of all specimens under tension test with respect to the peak facing stress.
Table 4-1 Average tensile mechanical properties.

<table>
<thead>
<tr>
<th>Core Type</th>
<th>Samples</th>
<th>Modulus of elasticity E (GPa)</th>
<th>Maximum Stress $\sigma_{\text{Max}}$ (MPa)</th>
<th>Failure Strain $\varepsilon_{\text{Max}}$ (%)</th>
<th>Ultimate Tensile Strength (UTS) (KN)</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>H200 Foam</td>
<td>Butt Joints</td>
<td>8.9</td>
<td>260</td>
<td>10</td>
<td>56</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Scarf Joints</td>
<td>11.2</td>
<td>260</td>
<td>5</td>
<td>56</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Baseline Plain (no core joint)</td>
<td>8.8</td>
<td>270</td>
<td>10</td>
<td>56</td>
<td>4</td>
</tr>
<tr>
<td>H100 Foam [3]</td>
<td>Butt Joints</td>
<td>8.2</td>
<td>250</td>
<td>6</td>
<td>59</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Scarf Joints</td>
<td>11</td>
<td>242</td>
<td>5</td>
<td>53</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Baseline Plain (no core joint)</td>
<td>7.6</td>
<td>230</td>
<td>8</td>
<td>51</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 4-5 Average maximum stress and axial modulus for H200 and H100 sandwich samples in comparison with results in reference.

The facesheets are the major in-plane load carrying components in sandwich panels under axial load, and hence, the peak facing stress refers to the ultimate load divided by the cross-sectional area of the facesheets at mid-section of the dog-bone specimen. This stress refers to the average maximum stress in Figure 5-5. It is also apparent from Figure 5-5 that the scarf joint provided a higher axial stiffness and efficiently engaging both factsheets in resisting the tensile load. Comparing all tested
samples, the core made of H200 foam core demonstrated a 7% increase in axial stiffness with respect to the H100 foam core. The H200 scarf joints exhibited additional 21.4% in axial stiffness than the H200 plain samples, and 20.5% more than the H200 butt joints. With respect to the H100 scarf joint, the H200 scarf joints showed a 7% increase in strength and negligible change in axial stiffness. The H200 butt joints displayed a slight increase (approximately 8%) in strength in comparison to the H100 butt joints. The H200 foam core (no core joint) displayed 14% and 15% increase in axial stiffness and strength, respectively, than the H100 foam core samples.

4.3.2 Static Compression Tests-Sandwich Composite Samples

Compression static test was applied on 6 different dog-bone shaped composite sandwich samples at 23°C and 50% RH using MTS Model 312.41/132 with 2.5 mm/min constant head displacement rate (Figure 5-6). To understand the compressive behavior under fatigue testing, Digital Image Correlation (DIC) was used to characterize the critical parameters of the specimens under axial compressive load (Figure 5-7).

The tension spots shown in butt joints sample facesheet acting as a stress concentration due to the strain increase in x direction (horizontal axis). Unlike the scarf joint samples, which have the elastic nature under compression load leading to more 10% strain in y directions. Figure 5-8 illustrates the peak facing stress and compressive load vs. strain for compression test.
Figure 4-6 Butt and scarf core joints samples under compression test.
Figure 4-7 Engineering strains in facesheets, x and y directions of for butt and scarf joint samples under compression test (front view). Red spots show high stress concentration.

Figure 4-8 Peak facing stress and compressive load vs. strain for compression test.
4.3.3 Fatigue Tests

Figure 4-9 shows the Digital Image Correlation (DIC) result during tension-compression fatigue test (±23 KN at 0.5 Hz). For the strains in the y direction, the scarf joint shows a high stress concentration at the midsection of the scarf line, indicating some combined axial load and bending moment on the inclined joint. A free body diagram that justifies this behavior is provided later in Chapter 6.

Whereas for the butt joint; the maximum strains are shown as red and blue fringe patterns located far away from the butt joint line (Figure 4-9a). This strain distribution clearly explains the high ultimate strain values previously listed in Table 4-1 for the butt joint and plain samples. One can notice that the displacement and the state of strain in the x direction for the butt joint are more uniform than the scarf joint samples (Figure 4-9b). For the scarf joint, the strains in the x direction are localized on top and bottom of the skewed joint line (Figure 4-9b).
A closer examination at the location of the strain field (y-direction, scarf joint) revealed a crack initiation during the cycling event. Figure 5-16 exhibits this crack in the scarf resin line due to the high strain concentration and combined axial and bending effects on the scarf line. No cracks in the butt joint resin line were noticed using DIC technique.

Figure 4-10 a) DIC image showing incipient crack at the scarf joint line (side view) b) Crack in joint and foam during cycling (±23 kN tension-compression fatigue at 0.5 Hz).

Table 4-2 shows typical failure modes of the butt joint, scarf joint, and plain samples. This Table lists the damage patterns in the facesheets at mid-section (dog-bone location).

**Table 4-2 Typical facesheets damage patterns (H200 core, R=-1).**

<table>
<thead>
<tr>
<th>Target Number of Cycles</th>
<th>Damage Pattern (Reduced Sections)</th>
<th>Load Amplitude, kN</th>
<th>Frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plain Sample</td>
<td>Scarf Joint</td>
<td>Butt Joint</td>
</tr>
<tr>
<td>1K</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>1K</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>10K</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>100K</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>1M</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Unlike the butt joints and plain samples where skin fracture was the dominant failure criteria, the scarf joint samples experienced the 30% drop in stiffness failure criteria. Micro-cracks propagated in the core (away from the joints) with a length of approximately 4 to 6 mm (approximately halfway of the fatigue life for all samples). The plain and butt joint samples failed by delamination at the edge of the dog-bone and then propagated to the center of the facesheet up to fracture (Table 5-4). As anticipated, cracks propagated along the fiber directions and oriented ±45° with respect to the horizontal axis.

Similar load frequencies were applied for the tension-tension fatigue test regime (Table 5-5). Fatigue life of H200 samples under tension-tension test (R=0.1) was higher than tension-compression test (R=-1). Visual inspection of the facesheets and joints revealed that the butt joint samples were more damaged than the scarf joint samples (Tables 5-4 and 5-5).

<table>
<thead>
<tr>
<th>Target Number of Cycles</th>
<th>Damage Pattern (Reduced Sections)</th>
<th>Load Amplitude, kN</th>
<th>Frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Butt Joint</td>
<td>Scarf Joint</td>
<td></td>
</tr>
<tr>
<td>1K</td>
<td><img src="image1.png" alt="Image" /></td>
<td>+31</td>
<td>1</td>
</tr>
<tr>
<td>10K</td>
<td><img src="image2.png" alt="Image" /></td>
<td>+27</td>
<td>2</td>
</tr>
<tr>
<td>100K</td>
<td><img src="image3.png" alt="Image" /></td>
<td>+22</td>
<td>3</td>
</tr>
<tr>
<td>1M</td>
<td><img src="image4.png" alt="Image" /></td>
<td>+18</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4-3 Typical facesheets damage patterns (H200 core, R=0.1).
CHAPTER 5

RESIDUAL STRENGTH, FATIGUE LIFE PREDICTIONS AND DAMAGE MECHANISM

5.1 Executive Summary

The motivation of this chapter is to address this knowledge gap and quantify the effect of different joint configurations under axial static and fatigue load. Under cyclic axial load, differential movement (through-the-thickness) between the foam and core joint was more significant than anticipated. Non-destructive evaluation techniques were used to locate the damage and assess the failure mechanisms. The root-cause-failure analysis showed that cracks were initiated in the facesheets for the butt-joint, and in the core for the scarf-joint samples, respectively. Consequently, at 80% residual strength, the butt-joint reduced the predicted fatigue life by 42% and 32% at low and high cycle fatigue, respectively. Residual tensile tests revealed the sizeable damage induced by the traditional butt-joint design. This chapter confirmed that despite the facesheets’ primary in-plane load carrying mechanisms, core junction will substantially influence the axial fatigue life of the structure.
5.2 Post-Fatigue Residual

Post-fatigue residual static tensile tests (H200 samples) were performed after each target number of cycles (1K, 10K, 100K and 1M). A replicate of 5 samples were used per configuration. The facesheet are the primary load resisting components under axial in-plane load, and hence, they were used to assess the fatigue life of the samples. Figure 6-1 shows the average peak facing stress of the specimens before and after cycling.

Figure 5-1 Pre- and Post-Fatigue tensile strengths and average fatigue life cycles of H200 butt joint, scarf joint, and plain samples at different target number of cycles.

The average fatigue life of the plain foam core samples (no core joint) did exceed all other samples with core joints, hence, stress concentrations exist in core junctions irrespective of their geometry and configuration. What is also interesting is that the tensile residual strengths of the scarf and plain samples increased with respect to the number of cycles, whereas the butt joint samples revealed a constant value (100 MPa) regardless of the number of cycles. This clearly indicates that the localized stress concentration at the core junction amplified the damage in the facesheets at low and high
cycle fatigue. The reduction in the peak facing strength was significant and ranged from 30% to 4% for the scarf joint samples, and 39% to 27% for the plain samples, after 1K and 1M cycles, respectively (Figure 6-1, Post-Fatigue RS bar charts).

5.3 Fatigue Life Predictions

In order to predict the fatigue life, the experimental results were compiled into S-N curves with respect to the ultimate static loads using the following Weibull Curve Fitting Model [38]:

\[
\sigma_s(N) = \sigma_{th} + (\sigma_{ss} - \sigma_{th})e^{-\log\left(\frac{N}{a}\right)^b}
\]  

(6.1)

Where \( N \) is the number of cycles to failure, \( \sigma_{ss} \) is the static failure strength of the facesheets, \( \sigma_{th} \) is the fatigue threshold (endurance limit) relative to the number of cycle \( N \) achieved by each sample. The curve fitting parameters (a and b) were optimized using MATLAB [39] to minimize the error between the model and the test results. Figure 6-2 shows the experimental and curve fitting trend lines with respect to the peak facing stress (facesheet).
Figure 5-2 Fatigue S-N curve–linear trend lines with respect to static tensile strength for H200/H100 at R=-1 and R=0.1.

Worth mentioning that for the H100 foam, the difference at low and high cycle fatigue was more pronounced between the scarf and butt joint (Figure 6-2a), whereas for the denser foam (H200) this difference was negligible (Figure 6-2b). This behavior is explained in-depth in the damage mechanism section (Section 6.4). The H200 scarf joints exhibited additional fatigue-life than the butt joints (H100 and H200 core) under tension-tension fatigue test (Figure 6-2c). Figure 6-2d shows a slight difference in fatigue life between the H200 and H100 scarf joints. This result was anticipated due to the coupling effect of the two facesheets provided by the inclined scarf joint design, which consequently minimized the effect of the core’s density.
Figure 6-3 shows the percentage increase in fatigue strengths ($\sigma_s$) of the scarf joint samples (H100 and H200 core) compared to other configurations at high cycle fatigue ($N = 1 \times 10^6$ cycles).

![Figure 5-3 Increase of average fatigue strengths of scarf joint samples with H100 and H200 foam cores at high cycle fatigue ($1 \times 10^6$ cycles).](image)

Figure 5-3 Increase of average fatigue strengths of scarf joint samples with H100 and H200 foam cores at high cycle fatigue ($1 \times 10^6$ cycles).

Figure 6-3 validates the data presented using the Weibull Curve Fitting Model and confirms the effectiveness of the scarf joint at high cycle fatigue with reference to the butt joint, 15% to 30% increase for the H200 and H100, respectively. Negligible effect was observed between the plain H200 core and scarf joint.

### 5.4 Residual Strength

A linear model of residual strength prediction suggested by Kassapoglou [40] was used to get the best fit to the experimental data. Residual strength curves in Figure 6-4 were generated by fitting the experimental data into the following equation:
\[
\frac{\sigma_r}{\sigma_{sf}} = 1 - \left(1 - \frac{\sigma}{\sigma_{sf}}\right) \frac{n}{N-1}
\]  \quad (6.2)

Where \(\sigma_r\) presents the residual strength, \(\sigma_{sf}\) is the static strength, \(\sigma\) is the cyclic stress, \(n\) is the applied cycle and \(N\) is the number of cycle at failure.

Figure 5-4 H200 residual strength by the linear model (tension-compression fatigue test).

Figure 6-4 shows the rapid strength reduction in the butt joint samples as compared to the scarf joint and plain core samples. This rapid reduction in the residual strength was combined with short fatigue life. It is clearly shown from Figure 6-4 that the core with no joint (labeled as plain samples) possessed higher residual strength and fatigue life than samples with core joints, and this correlates well with the post-fatigue residual strength presented in Figure 6-1.

Figure 6-5 shows the rate of increase in displacement with increasing number of cycles is directly proportional to possible displacement remaining. The increase in
displacement is related to the decrease in stiffness and corresponding to the achieved number of cycles.

Figure 5-5 H200 displacements as function of number of cycles under load control fatigue (R=-1 and R=0.1) with exponential fit.

For the first stage, the maximum displacement $D_{\text{max}}$ is equal to the maximum displacement in the first cycle $D_{0\text{max}}$, where $N=1$ and $N/N_f=1$ at the 30% stiffness reduction. It is known from the stress strain curves that the scarf joint samples show the higher stiffness than the butt joint and the plain samples. Consequently, the scarf joint samples (at R=0.1 and R=-1) showed less decrease in stiffness. The butt and scarf joints (R=0.1) in Figure 6-5 showed more progressive reduction in stiffness in the first stages followed by abrupt increase in displacement and failure without reaching out to the failure protocol (30% stiffness reduction). This explains the progressive damaged laminate in the samples under tension-tension loads (Tables 5-4 and 5-5).
Equation (6-3) below is exponential fit to present data in Figure 6-5 and predict the stiffness reduction as a function of number of cycles:

\[
\frac{D_{0\text{max}}}{D_{\text{max}}} = e^{-b\left(\frac{N}{N_f}\right)}
\]  \hspace{1cm} (6.3)

Where \(D_{\text{max}}\) is the maximum displacement, \(D_{0\text{max}}\) is the initial displacement, \(N_f\) is the failure cycles, \(N\) is number of cycles and \(b\) is the material parameter.

5.5 Damage Mechanism

The failure mechanisms and root-cause failure analyses of each joint design are presented in this section. When a composite sandwich panel is subjected to in-plane loads, the differential expansion and contraction (through-the-thickness) between the foam core possessing a high Poisson’s ratio and the core joint with a lower Poisson’s ratio creates internal forces acting on the core joint (Figure 6-6).

Figure 5-6 Exaggerated deflection modes showing free body diagram of facesheets and joints a) butt joint and b) scarf joint.
This performance is due to the mismatch in Poisson’s ratio, which was previously highlighted by the higher average strain to failure (33% higher, Table 5-1) in the plain foam (H100) samples with respect to the butt joint samples. These internal axial/shear forces and internal bending moments will reverse signs under cyclic loading and will initiate the damage in the facesheets and the core joint.

Under in-plane compression load, the butt joint is subjected to axial tensile force perpendicular to the facesheet (Figure 6-6). This tensile force generated inter-laminar cracks and delamination in the thin resin line between the plies. Whereas for the scarf joint, inclined axial force, shear, and bending moments were generated. This combined effect tends to minimize and counteract the separation of the facesheet from the core joint under applied compression force, which proved to extend the fatigue life of the structure (Figure 6-4).

The SEM images in Figure 6-7a, clearly reveals the presence of such cracks (perpendicular to the lateral movement) in the butt joint samples.
This large delamination and separation of the horizontal joint from the facesheets is believed to have significantly affected the axial stiffness, strength, fatigue life/strength and caused less residual strength for the post-fatigued samples (Figure 6-1). On the other hand, the skewed ends in the scarf joints minimized the effect of Poisson’s ratio and improved the axial stiffness and fatigue life. The combined internal forces shown in Figure 6-6 created a plastic hinge zone in the vicinity of the core rather than in the facesheets.

Using the ultrasonic phased array evaluation techniques, additional examination of the delamination of the facesheet in the butt joint design is shown in Figure 6-8. The C-scan result shown in Figure 6-9 reveals that the crack propagated along the sample
length for low cycle fatigue and then propagated across the length (along the width) for high cycle fatigue (100K and 1M cycles).

Figure 5-8 Scanning method of Phased Array Linear probe (3.5L64-IPW1) with RollerFORM (a) and Dual Linear Array (DLA) probe (b).

Figure 5-9 C-Scan and Ultrasonic Phased Array Inspection along the facesheet for butt joint samples, blue dots represent damage; (a) Untested sample; (b) side view showing delamination using Ultrasonic Phased Array Inspection; (c) after 1,000 cycles; (d) after 10,000 cycles; (e) after 100,000 cycles; (f) after 1x10^6 cycles.
CHAPTER 6

CONCLUSIONS

This study presented a comprehensive experimental characterization and failure mechanisms of plain, scarf, and butt core-to-core joints under in-plane axial static, fatigue (R=−1 and R=0.1, constant load amplitude), and post-fatigue load. Two types of sandwich core materials (H100 and H200) were designed and fabricated using a Knitted biaxial E-glass reinforced Vinylester resin. Fatigue failure protocol constituted two thresholds, 30% stiffness reduction, and facesheet (skin) fracture. The outcome of this study will not only produce a technical knowledge base to properly design and quantify the effect of the core joints, but will also provide a novel testing methodology for composite laminates subjected to tension-compression fatigue using the developed dog-bone sandwich and test fixture configurations. Results are summarized in the following:

• Comparing the core materials with no core joint, under static tensile test, the H200 displayed an increase in axial stiffness and strength of 14% and 15%, respectively, more than the H100 foam core material.

• The scarf joint design presented a high axial stiffness and engaged both factsheets in resisting the static tensile load. The scarf core joint design with H200 foam showed an increase in axial stiffness by 21% more than the butt joint and plain core samples.
• This was justified with the DIC technique, where the ultimate axial strains for the butt joint and plain foam core samples reached 10% versus 5% strain for the scarf joint samples.

• Under cyclic load, core joints acted as stress risers and significantly affected the fatigue life of the sandwich structure. The mismatch in Poisson’s ratio between the foam and the horizontal butt joint caused axial tensile forces perpendicular to the facesheets, leading to delamination and reduction in stiffness. Instead, the skewed ends in the scarf joint minimized this effect and improved the stiffness and fatigue life. This was related to the combined internal forces that created a plastic hinge zone in the vicinity of the core rather than in the facesheets. Post-Fatigue SEM techniques located these preferred damage sites.

• Samples under tension-tension fatigue presented higher fatigue life than samples under cyclic tension-compression test. Post-fatigue Acoustic Emission (AE) revealed that the damage propagated along the sample length for low cycle fatigue and then propagated along the width for high cycle fatigue (R=-1, 1×10^5 and 1×10^6 cycles).

• The Post-fatigue tensile residual strengths of the scarf and foam samples (no core joint) increased with the number of cycles to failure (from 1×10^3 to 1×10^6 cycles), whereas the butt joint samples revealed a constant value (100 MPa) regardless of the number of cycles. This clearly indicates the initial sizeable damage that occurred in the butt joint samples.

• The developed S-N curves demonstrated that the average fatigue life of the plain foam core samples (no core joint) did exceed all other samples with core joints. The Weibull Curve Fitting Model confirmed the effectiveness of the scarf joint at high cycle
fatigue with reference to the butt joint, 15% to 30% increase for the H200 and H100, respectively. The residual strength using the linear prediction model showed that at 80% residual strength, the butt core joint could reduce the fatigue life by 43% at low cycle fatigue, and 32% at high cycle fatigue. This correlated well with the post-fatigue tensile residual strength results.

- The difference between the scarf and butt joint designs at low and high cycle fatigue was more pronounced for the H100 foam than the denser foam (H200).
REFERENCES


[37] ISTRA software by Dantec Dynamics, a Nova Instruments Company.

