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Fatigue response of fabric reinforced polymeric composites

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FATIGUE RESPONSE OF FABRIC REINFORCED POLYMERIC COMPOSITES

by
Venkatakrishnan Natarajan

**Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
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for the degree of**

**Master of Science
in
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ABSTRACT

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Venkatakrishnan Natarajan

Fiber Reinforced Polymeric (FRP) Bridge decks have been an active area of research for the past 10 yrs. In order to better understand the long term efficiency and reliability of FRP bridge decks, and to develop design and test specifications, laboratory testing and characterization of the deck systems and the FRP material, is necessary. Majority of the FRP deck systems available to date are made of glass-reinforcing fibers in the form of fabrics, mats, rovings etc. Currently, the fatigue response of multidirectional composite is not readily available in the literature and much work needs to be done to understand the behavior of these composites under fatigue loading.

In this study three fabric based glass FRP composites used in bridge components were tested under fatigue loading. A fatigue life prediction model is proposed, with internal strain energy as damage metric, to predict the useful life of FRP composites based on the experimental results. The experimental and predicted lives at various strain levels were compared (S-N curves) and the model was found to be conservative within 10% error.

Two lightweight Glass FRP composite modular bridge decks were evaluated for structural integrity and degradation in bending rigidity under repetitive simulated wheel load (HS20-44 design truck load) to determine the applicability of the decks to bridge applications. The first deck failed due to local punching shear failure after 230,000 cycles. The second deck was reinforced in the loading area with 100 oz/yd² of fiber in the transverse direction. No damage was observed for two million cycles and there was no considerable degradation in bending rigidity.

Dedicated to:
Maatha pitha guru theyivam
(Mother, Father, Teacher and God)

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

Applications of Fiber Reinforced Polymeric (FRP) composite materials are rapidly expanding in areas dealing with load transfer systems such as aircraft structures, aircraft landing decks of naval carriers, bridge decks, pavements and others. In particular FRP composite materials have been an active area of research in repair, rehabilitation and construction of new structural systems. West Virginia bridges such as Laurel-Lick and Wickwire Run, installed in year 1997 are two of the first FRP bridge decks in the country. Following the construction of the two bridges, various FRP bridge decks have been designed and installed at various locations in the United States.

In order to apply FRP bridge decks to high volume roads, the long term efficiency and reliability of FRP materials needs to be characterized. Also acceptance test methods and design specifications for FRP bridge decks and superstructures need to be developed for quality control and quality assurance purposes. Currently researchers and designers use the AASHTO Standard Specifications and AASHTO LRFD specifications for steel bridges as a basis to evaluate FRP bridge decks. Unlike steel, FRP composites are inhomogeneous and anisotropic and FRP composites behave in a manner very similar to wood. Hence adopting the design limits as per AASHTO specifications of steel or concrete for FRP bridge decks may lead to erroneous results.

In order to develop design specifications for FRP bridge decks and superstructures, understanding the long-term behavior of FRP coupons and bridge deck components is essential. This requires laboratory testing and characterization of the composite materials under static, fatigue and dynamic loading. Fatigue behavior of FRP composites, a brittle material at coupon levels, is a complex process involving various

changes in the microstructure of its constituent materials before leading to different forms/types of failure. Past researchers [1] have shown that the damage process in FRP composites under fatigue loading is progressive, in terms of cycles of load applied to a structural component or a coupon. The failure is a combination of various damage modes, such as matrix cracking, fiber breakage, delaminations, etc. The different damage modes in FRP composites depend on various factors such as fiber architecture, fiber content, matrix properties (ductile/brittle), loading type, frequency of loading, load range, manufacturing process, environmental exposures, etc.

Due to the presence of various damage modes and extensive micro-cracking in composite materials during manufacturing and also under cyclic loading, the fatigue life prediction of composite materials is not straightforward. However, from an engineer's point of view the challenge is to choose materials and use them in such a way to avoid failures within the design life of an FRP component or structure. In order to accomplish successful design service life, it is necessary to understand the mechanisms of degradation in service and be able to predict the life of a composite under certain design conditions.

The long-term behavior and damage mechanisms of FRP composite materials have been actively researched by materials engineers/scientists during the past thirty years. Although extensive research has been pursued by researchers in the past to understand the fatigue response, FRP composite materials research has been limited primarily to unidirectional composites with Carbon or Aramid fibers used in high-end aerospace applications. The aerospace composites are manufactured with great care under highly controlled environments. However, life prediction models developed for these unidirectional composites may not be applicable to current FRP bridge deck systems because most FRP decks available to date are made of glass-reinforcing fibers in the form of mats, fabrics, rovings or combinations of these, using pultrusion, hand lay-

up, or resin transfer molding techniques. The behavior of these fabric based composites under fatigue loading is not readily available in the literature. Hence, extensive study is required to understand the fatigue behavior of fabric based FRP composite materials and to predict their useful life.

1.2 OBJECTIVE

The objectives of this study are to:

- Understand the micro-structural damage modes and the behavior of fabric based FRP composite materials subjected to fatigue loading at coupon level.
- Evaluate the fatigue response of FRP bridge deck system (FRP decks stiffened with steel stringers) with respect to stiffness degradation and joint integrity.
- Develop a fatigue life prediction model for fabric based FRP composite material systems with internal strain energy as damage metric.

1.3 SCOPE

Chapter 2 introduces various damage modes and the actual fatigue process influencing the fatigue behavior of FRP composite materials. Various fatigue life models available in the literature to predict the useful fatigue life of FRP composite materials are reviewed. A brief literature review is also presented on fatigue response of FRP bridge decks.

Chapter 3 describes the experimental program conducted on glass FRP composite coupons subjected to fatigue loading. Also, a fatigue life prediction model based on internal strain energy is introduced in Chapter 3 based on the experimental results.

Chapter 4 discusses performance evaluation of FRP composite modular bridge deck systems under fatigue loading. A comprehensive summary of results, conclusions and recommendations for future work are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Unlike homogeneous materials, Fiber Reinforced Polymeric (FRP) composites accumulate damage at various locations under fatigue loading rather than developing localized damage. Interestingly unlike metals fracture in FRPs fracture does not always occur by initiation and propagation of a single macroscopic crack at one location. Also there are good chances for manufacturing/processing defects to be already present in the material (matrix cracks, broken fiber, inadequate cure etc.,) even before the material is exposed to any loading. When subjected to fatigue loading, these defects lead to crack initialization, growth and interconnection of cracks of various origins and types leading to various mechanisms of failure. The damage accumulation in these materials is micro-structural which includes fiber/matrix debonding, matrix cracking, delamination and fiber fracture [12]. Due to occurrence of such damage modes under fatigue loading, the fatigue life prediction of composite materials is complex.

This chapter will present a review on fatigue behavior of FRP composite materials at coupon, component and system level and life predictions methodologies of coupons under subjected to fatigue loading. The literature review is performed from various sources such as journals, books, Internet sites, technical papers, reports etc. The information gathered from these resources is grouped and synthesized as:

1. Fatigue response of composites at coupon level;
2. Fatigue life prediction models for FRP composite materials (at coupon level);
3. Fatigue response of composites at system level (FRP bridge deck supported on stringers).

2.2 FATIGUE RESPONSE OF FRP COMPOSITES AT COUPON LEVEL

2.2.1 The Fatigue Process

The fatigue process in fibrous composite materials is best understood by loading unidirectional composite under tensile fatigue loading. Fatigue damage mechanism in unidirectional composites primarily depends on loading mode (e.g., tensile, compressive, bending, torsion or combinations) and on the loading direction i.e., parallel or inclined to the fiber orientation. Typically, the damage mechanism in tensile fatigue is of three stages [16] namely: 1) Fiber breakage, 2) Matrix cracking, and 3) Interfacial shear failure, as shown in Figure 2.1. This is true for compression fatigue, except that there could be buckling failure of fibers or fabrics that might be reinforcing the composite.

Figure 2.1. Fatigue damage in unidirectional composites under loading parallel to fibers.

Any discontinued or broken fiber in the material causes shear stress concentration at the fiber-matrix interface near a broken fiber Figure 2.1 [16]. The interface acts as a stress concentration zone while transferring longitudinal tensile stress, which may exceed the strength of the matrix, leading to transverse *micro-cracking* in the matrix. With continued loading the cracks propagate both parallel and perpendicular to the fiber direction. Under low strains, approximately 30 to 49% of ultimate tensile strain of matrix, a matrix crack stops at the interface. However at high strains, stresses at crack tips exceed the fracture stress leading to *interfacial shear*

failure of the fiber-matrix interface due to shear stresses induced at the crack tip which are aggravated by crack tip stress concentrations.

On further loading interlaminar shear failure and delamination dominate the damage process leading to *fiber breakage*. The sites of breakages are randomly distributed initially in the FRP material. Continued loading results in the breakage of the fibers adjacent to the previously broken fibers. The process continues until a cross-section having a stress high enough to break the remaining fibers in the material is found, leading to final failure (Figure 2.2).

Figure 2.2. Fiber breakage in unidirectional composites under loading parallel to fibers

For unidirectional composites with *Off-axis loading* angles between 0° and 90° , the tip of crack initiated in the matrix will be subjected to two displacement components, i.e., an opening normal to the fibers and a sliding parallel to the fibers as shown in Figure 2.3. [17] The effect of the two damage modes depends on the off-axis angle. For example at an off-axis angle of 90° the crack growth will occur in the opening mode only and at 0° (on-axis) the crack growth will occur in sliding mode only. Hence angles in between 0° and 90° will lead to a mixed mode crack growth parallel to the fibers. The opening mode is critical of the two modes since it increase with increasing off-axis angle.

The opening mode leads to debonding of the transverse fibers at the interface commonly known as interfacial debonding or transverse fiber debonding.

Figure 2.3. Crack growth under off-axis fatigue of unidirectional composites

In multidirectional composites the first event of failure is debonding of transverse fibers. The debonded crack then grows towards the ply interface causing stress concentration in the interfacial layers. This leads to further delamination and hence overstressing of the 0° ply; thus increasing the number of non-axial plies in a laminate and reducing the strength and stiffness of a composite since only fewer fibers are available to resist the mean applied stress in the axial direction [1].

Angled ply layers, with fibers typically at $\pm 45^\circ$ can also develop intraply damage, which causes a small reduction in strength and stiffness [2]. Also stress concentration is developed at the ends of intraply cracks, which causes delamination between the layers. Multidirectional laminates also develop edge-induced stresses as a consequence of different elastic properties of the layers [2], often giving rise to delamination between layers.

2.2.2 Fatigue Life Diagrams - S-N Curves

Unlike conventional materials (metals), the S-N curve of FRP composites does not characterize an endurance limit, i.e., the S-N curve slopes down continuously to zero as number of cycles increase, and hence there is no characteristic threshold level is noted [12]. Typically, plots of mean strain rather than stress versus log cycles to failure are commonly used to plot the S-N curves for composite materials. This is because both the matrix and the fibers are subjected to the same strain and the stresses in the two individual phases would differ depending on the individual stiffness and fiber volume fraction of the composite.

Unidirectional Composites

The simplest form of composite material is one with unidirectional fibers aligned with the test direction (on-axis loading). Since fibers carry most of the load under tensile fatigue loading and that the fibers are insensitive to fatigue loading, it is common to think the fatigue behavior of composite materials might be dependent solely on the fibers. However experimental results have shown that fatigue behavior of composite materials is determined principally by the strain in the matrix. Figure 2.4 shows the S-N curve for carbon fibers with different stiffness in the same standard epoxy resin. It can be seen that there is little improvement in the fatigue behavior for varying fiber stiffness.

The S-N curve for carbon fiber, glass fiber and aramid fiber in the same standard epoxy matrix is shown in Figure 2.5. The use of stiff fibers, such as carbon, results in low strains (1.0 - 1.8%) to failure while flexible fibers like glass lead to relatively higher strains (2.5 – 3.5 %) to failure. Hence, the curve is steep for glass fibers while it is shallow for carbon fibers as shown in Figure 2.5. The slope of the curve (Figure 2.5) is a function of bulk strain in the matrix and the nature of the matrix (brittle/ductile) [2].

Figure 2.4. Comparison of S-N curve for four different carbon fibers in same epoxy resin

Figure 2.5. Comparison of S-N curve for three different unidirectional composite materials.

A typical fatigue life diagram (Figure 2.6a) for a unidirectional composite under loading parallel to fibers is shown. In Figure 2.6a maximum strain below which no cracks or only non-propagating cracks maybe initiated in the matrix material is defined as the *fatigue limit* of the matrix [16]. This matrix material property is taken as the lower limit of the progressive matrix damage. It can be seen that as the fiber stiffness reduces, distinct progressive damage band (matrix cracking) is observed before fiber breakage.

Figure 2.6. Fatigue life diagram of unidirectional composites

The fatigue life diagram for off-axis loading is shown in Figure 2.6b [16]. It was found that for off-axis angles of more than a few degrees, the fiber breakage band would be lost, as matrix and/or interfacial cracking will become the predominant damage mechanism for strain up to fracture strain. [Ref. 16]

Multidirectional FRP Composites

In multidirectional composites the fatigue response of the laminate under tensile fatigue improves with increased amount of 0° plies. As discussed in Section 2.2.1, the presence of fibers in the transverse and off-axis angles leads to intraply damage and delamination. Figure 2.7 gives a comparison of S-N curve for varying percentage of 0°

plies for a multidirectional laminate [2]. It can be seen (figure 2.7) that the slope of the S-N curve is steeper for laminates with lesser amount of fibers in the 0° direction.

Figure 2.7. Normalized S-N curves for (0/±45) CFRP laminates with varying percentage of 0° fibers

2.2.3 Damage in Composite Materials

Assuming that the composite laminates experience both tensile and compressive loading and that the laminates include plies which have various orientations to the loading axis (0° direction), it is expected that a combination of damage modes might occur as seen in Figure 2.8. The damage process consists of two dominant stages: the first stage in which non-interacting cracks develop leading to Characteristic Damage State (CDS), wherein a stable crack pattern develops at this state of crack growth. Beyond the CDS, i.e., the second stage, the cracks of various types interact with increasing rates (at lower number of fatigue cycles) as the number of cycles increase, causing increasing localization of cracks and consequent failure.

In the first stage, matrix cracks initiate in plies if the stresses (tensile, shear etc.,) in directions perpendicular to the fibers exceed the strength of the matrix material. These

cracks generally occur in composite systems if the matrix is brittle (epoxy), but also occur in systems with ductile matrix (metal matrix composites) under fatigue loading. As discussed earlier, the inherent micro-flaws in the material grow continuously with fatigue loading and when the individual size of the flaws reaches a characteristic size, a *primary crack* is formed at the start of CDS. Primary matrix cracks are sources of subsequent damage development under cyclic loading, and also form a basis for damage development localization under tensile loading and for the development of localized buckling and growth of delamination in compressive loading.

The primary cracks in off-axis plies do not initiate monotonically throughout the fatigue life of the specimen. Instead the number of primary cracks in the off-axis plies saturate for a given cyclic load level and thus primary cracks creates a regularly spaced pattern of cracks, which are undisturbed throughout the remainder of the life of the specimen. This generic pattern of cracks is called the *Characteristic Damage State (CDS)* of the laminate.

Figure 2.8. Development of fatigue damage in composite laminates

It has been determined that the CDS is a laminate property and is defined by the properties of individual plies, their thickness and laminate stacking sequence of the plies. The CDS is independent of loading history, loading environment, cure rate, residual and moisture related stresses; but it could be dependent on three dimensionally stitched fabric based composites [30]. The CDS is the starting point for those processes, which control the strength, stiffness and life of a laminate. It is also a well-defined damage state and can be accurately described and predicted. [12]

Delamination and interlaminar debonding dominate the second stage of the damage accumulation process. The primary cracks initiate as small cracks at short distances away from the interface between the plies. The short cracks are called *secondary cracks* and are generally perpendicular to the primary cracks. [17]. Secondary cracks are caused by tensile stress along the crack axis ahead of the primary cracks. Strong interlaminar stresses, in the region where primary cracks and secondary cracks cross, initiates interlaminar cracks leading to delamination in the interior of the laminate.

On further cyclic loading, fibers fail in large scale (third stage) causing an abrupt final failure. In many cases, it has been observed that two thirds of the fiber breakage is observed in the first one third of the total number of fatigue cycles (fatigue life) of the material. However final failure occurs only when the fiber breakages are approximately aligned to the principal tensile stress. The stages of damage modes do not occupy distinct regions of total life. However they are dominant in the above-mentioned stages, matrix cracking being the dominant damage mode in the first stage, and delamination being dominant damage mode in the second stage.

2.3 FATIGUE LIFE PREDICTION MODELS IN COMPOSITE MATERIALS

Various methodologies have been proposed to predict the fatigue life of composite materials. The models are classified from the failure criteria. Basically the fatigue life prediction models can be classified into three major categories [15]

- Fatigue life models based on S-N curves (empirical theories)
- Residual strength degradation models
- Actual progressive damage models (matrix cracking, delamination, fiber breakage, etc)

All the three methodologies use individual failure criteria to determine the fatigue life of a composite specimen.

2.3.1 Fatigue Life Models Based On S-N Curves

Theories based on S-N curves do not take into account the various damage modes exhibited in composite materials under cyclic loading. They are hence empirical and require extensive experimental work. Empirical fatigue theories are used to characterize S-N curves for the material. Many empirical equations have been developed and are still being used to characterize the S-N data for polymer matrix composite materials.

Most theories based on S-N curves are limited to uniaxial cyclic loading. Attempts have been made to extend the theories based on S-N curves to the multi-axial loading case by various researchers [15]. These extensions involve the generalization of static strength criterion to the case of residual strength criterion after cyclic loading, thereby introducing the effect of cyclic loading. These models predict fatigue life of composite materials using the information from the S-N curve or Goodman type diagrams. A failure criterion is generally used to determine the fatigue life.

The following assumptions must be taken into account to predict life in composite materials based on the S-N curves [15]

- The S-N curve is described by a deterministic equation
- The static strengths are uniquely related to the fatigue lives and residual strengths at failure
- The static strength is a two parameter Weibull distribution

The general static strength criterion for unidirectional laminate or lamina is given as

$$\max. f_{\alpha} (\sigma_{ij}, S_k) \quad (2.1)$$

where, σ_{ij} and S_k are the stress component in the material direction and material constant. Including the cyclic loading the constants S_k depend on temperature, moisture content of the laminate, strain rate, frequency, stress ratio, and number of cycles and is written as

$$S_k = S_k (\sigma_{ija}, T, M, R, \omega, n) \quad (2.2)$$

Where, σ_{ija} is the maximum or minimum cyclic stress. For fatigue failure, $\sigma_{ij} = \sigma_{ija}$ and hence from above equations

$$\max. f_{\alpha} (\sigma_{ija}, S_k (\sigma_{ija}, T, M, R, \omega, n)) = 1 \quad (2.3)$$

The above equation is the generalized equation of constant amplitude fatigue loading to failure. Many theories based on this model have been developed which differ from each other in the failure criterion and the fatigue function (S_k) applied. A few of the empirical fatigue life models available in literature are discussed briefly.

Hashin – Rotem [3] theory is one of the first theories describing the fatigue damage behavior of composites materials. The theory is based on separation of different fatigue failure modes that a composite may exhibit. For the simplest case of unidirectional composites, two common failure modes are the matrix cracking and the

fiber breakage. Hashin – Rotem failure theory predicts that the failure occurs if one of the following conditions is satisfied:

$$\begin{aligned} \sigma_A &\geq \sigma_A^u \\ \left(\frac{\sigma_T}{\sigma_T^u} \right)^2 + \left(\frac{\tau}{\tau^u} \right)^2 &\geq 1 \end{aligned} \quad (2.4)$$

where,

σ_A , σ_T , τ are the maximum fatigue stresses of the material in uniaxial loading parallel, perpendicular and in shear of the principal plane respectively, and

σ_A^u , σ_T^u , τ^u are the ultimate tensile, transverse and shear stresses.

The ultimate strengths are expressed in terms of three S-N curves in the above directions obtained experimentally from testing off-axis unidirectional laminate under uniaxial loading. The theory is limited to unidirectional composites. Various theories have been proposed to adapt Hashin – Rotem theory to other damage states in multidirectional composites.

Reifsnider and Gao [13] established a fatigue criterion based on an average stress formulation of composite laminates derived from Mori-Tanaka method. The failure theory is similar to Hashin – Rotem theory, but the criteria for matrix cracking and fiber breakage are expressed in terms of the average stresses $\langle \sigma_{ij}^m \rangle$ and $\langle \sigma_{ij}^f \rangle$ in the matrix and fibers respectively. The average stresses are calculated using the Mori – Tanaka method. The theory states that failure occurs when one of the following conditions is satisfied

$$\begin{aligned} \langle \sigma_{11}^f \rangle &= X^f \\ \left(\frac{\langle \sigma_{22}^m \rangle}{X^m} \right)^2 + \left(\frac{\langle \sigma_{12}^m \rangle}{S^m} \right)^2 &= 1 \end{aligned} \quad (2.5)$$

Where,

$\langle \sigma_{11}^f \rangle$ - is the average tensile stress in the fiber.

$\langle \sigma_{22}^m \rangle$, $\langle \sigma_{12}^m \rangle$ - are the average tensile and shear stresses in the matrix respectively

X^f , X^m - are the fatigue failure functions under tensile loading for the fibers and the matrix materials respectively, and

S^m – is the fatigue failure function of the unreinforced matrix under shear loading.

These failure functions are actually the S-N curves, which has to be determined experimentally.

Fawaz – Ellyin [7] proposed a fatigue life model for multi-axial fatigue loading using a semi-log linear relationship between applied cyclic stress (S) and the number of cycles to failure (N) given by

$$\begin{aligned} S &= m \log(N) + b \\ S_r &= m_r \log(N) + b_r \end{aligned} \quad (2.6)$$

where, (m_r, b_r) are material parameters of a reference S-N line and (m, b) are the parameters of the laminate in study which are given by the following relations

$$\begin{aligned} m &= f(a_1, a_2, \theta) \cdot g(R) m_r \\ b &= f(a_1, a_2, \theta) \cdot b_r \\ a_1 &= \frac{\sigma_y}{\sigma_x} \text{ and } a_2 = \frac{\tau_{xy}}{\sigma_x} \end{aligned} \quad (2.7)$$

where,

a_1 and a_2 –biaxial ratios,

R and θ - stress ratio and the stacking angle respectively.

σ_x , σ_y , σ_{xy} – longitudinal, transverse and shear stresses in the laminate respectively.

The model predicts the parameter m and b of a S-N line, for any a, θ , R, using a reference S-N curve with parameter m_r and b_r . Although the model was effective in most cases, the accuracy depended largely on the reference S-N curve chosen.

Philippidis and Vassilopoulos [10] proposed a multiaxial fatigue failure criterion, similar to the Tsai-Wu failure criterion for static loading, given as

$$F_{ij}\sigma_i\sigma_j + F_i\sigma_i - 1 \leq 0 \quad i, j = 1, 2, 6 \quad (2.8)$$

where, F_{ij} and F_i are functions of the number of cycles N , the stress ratio R and the frequency of loading. The tensor components, F_{ij} and F_i are calculated from the fatigue failure stresses (X_t , X_c , Y_t , Y_c and S) in the longitudinal, transverse and shear (1,2,6) directions, which are obtained by the S-N curve values of the laminate in the same directions and under the same conditions.

Five S-N curves are required to determine these failure stresses. However, it can be reduced to three by assuming $X_t=X_c$ and $Y_t=Y_c$. Laminate properties are used instead of lamina properties since the S-N curve accounts for the various modes of failure in the material. Hence the criterion is applicable to any laminate and stacking sequence; however the criteria proposes that at least three S-N curves have to be determined which requires extensive experimental work.

2.3.2 Fatigue Life Theories Based On Residual Stiffness and Strength

These models propose a gradual loss of stiffness and strength in a composite material due to fatigue loading. The degradation is due to the damage accumulated in the material with number of cycles and may be time which represents creep damage. Creep damage can be of critical influence in damage especially when sustained stress levels exceed 30-40% of ultimate stress of a composite. These models maybe deterministic, predicting a single-valued stiffness property. In residual strength approach failure is assumed to occur when the applied stress equals the residual strength. In residual stiffness approach, failure is assumed to occur when the stiffness or modulus

reaches a critical value, which is determined by various failure theories. Reifsnider and O'Brien [9] assume fatigue failure occurs when the fatigue secant modulus degrades to the secant modulus at the moment of failure in a static test.

Fatigue Theories Based on Residual Strength Degradation

Currently fatigue theories are based on the residual strength as the damage metric. The residual strength models can be classified into two types, namely, the *sudden death model* and the *wear-out model*. The sudden death models propose that the residual strength as a function of number of cycles is initially constant and decreases drastically when the number of cycles to failure is being reached. This condition is suitable to describe the behavior of high-strength unidirectional composite materials subjected to high stress levels and low frequency.

The wear-out models propose that the strength degradation is more gradual and is a function of the number of cycles at low stress levels. In general the following assumptions hold good for residual strength degradation fatigue theories [15]

- The static strength is a two parameter Weibull distribution
- The residual strength σ_r after N cycles of constant-amplitude loading is related to the initial static strength, σ_e by a deterministic equation, typically given as

$$\frac{d\sigma}{dN} = -(1/\gamma)f\sigma_a^\gamma\sigma^{1-\gamma} \quad (2.9)$$

where, σ , σ_a , f and γ are instantaneous strength during fatiguing, maximum induced cyclic stress and dimensionless functions that do not depend on σ respectively

- Fatigue failure occurs when the residual strength is decreased to the maximum applied stress level. Hence, at $\sigma_r = \sigma_a$, the above equation could be modified and written as

$$\sigma_e = \sigma_a [1 + (N-1)f]^\gamma \quad (2.10)$$

where, N is Number of cycles to failure at σ_a . S and f are functions of stress ratio R and can be interpreted as the extent of flat region at high σ_a and the asymptotic slope at σ_a on a log-log plot of the S-N curve.

Assuming that σ_e is a two-parameter Weibull distribution, the probability that the initial strength is greater than σ_e is given by

$$P(\sigma_e) = \exp. [-(\sigma_e/\beta)^\alpha] \quad (2.11)$$

Where α and β are Weibull shape and scale parameter respectively.

Fatigue theories based on *Residual Strength Degradation* have the following limitations [15]:

- Non-destructive evaluations cannot find the remaining life of a laminate.
- Residual strength is not uniquely related to the state of damage and it is not a sensitive measure of damage accumulation.
- Requires extensive experimental characterization of each laminate and material system.

Fatigue theory based on stiffness degradation

The limitations of the strength degradation fatigue theories led to the choice of stiffness as the damage metric. Under cyclic loading, the elastic properties of the composite material degrade typically as shown in Figure 2.9. Hwang and Han [5, 6] introduced the concept of fatigue modulus, which is defined as the slope of applied stress and the resultant strain in at a specific cycle. The fatigue theory based on stiffness degradation is based on the following assumptions: [15]

- The life of a laminate is governed by the fatigue behavior of a critical element.
- The life of a critical element is governed by a residual strength degradation fatigue theory.

- Fatigue damage in a non-critical element or lamina in the laminate changes the magnitude of cyclic loads that the critical element is subjected to.

The stiffness of a lamina or laminate changes monotonically with cyclic loading and the change is greater than the change in residual strength as shown in Figure 2.9.

Figure 2.9: Change in stiffness under cyclic loading

In theories based on stiffness degradation, the stiffness change in the laminate is assumed to reflect accurately the load redistribution in the laminate and hence it is used as a second damage metric. For constant amplitude cyclic loading, the residual strength degradation equation for the critical element is given as

$$\frac{d\sigma}{dn} = -(1/\gamma)f\sigma_{ac}^{\gamma}\sigma^{1-\gamma} \quad (2.12)$$

where, σ , σ_{ac} , f and γ are the instantaneous strength of the critical element, the maximum applied cyclic stress and two dimensionless functions which do not depend on σ but depend on composite material properties, process etc. The maximum applied cyclic stress of the element σ_{ac} is given as a function of the maximum applied cyclic stress (σ_a) acting on the laminate, the stiffness of the critical element (E_c) and the stiffness of the laminate, i.e.,

$$\sigma_{ac} = f(\sigma_a, E_c, E_1) \quad (2.13)$$

In the above equation E_c is assumed not to degrade with cyclic loading and E_1 is a monotonically decreasing function of cycles for a given σ_a level. It can be shown that the life of the laminate (N) is given by [15]

$$N = \{1 - [c(\gamma-1)(N_c-1) + (1-c)^{1-\gamma}]^{1/(1-\gamma)}\} / c \quad (2.14)$$

where, N_c , γ , and c are respectively the life of the critical element at σ_{ac} , the reciprocal of the S-N curve for the critical element and the stiffness degradation rate (assumed constant). The above equation holds good when the stiffness degradation rate is assumed to be linear.

2.4 FATIGUE OF FIBER REINFORCED POLYMERIC BRIDGE DECKS

Better performance of Fiber Reinforced Polymeric (FRP) composite materials under harsh environments has attracted civil engineers to use the material in various highways structural applications such as bridge decks, pavements etc. FRP bridge decks have been an active area of research for the past ten years. Laurel-Lick Bridge and Wickwire Run Bridge, installed in the rural areas of West Virginia, USA in year 1997, are two of the first FRP bridge decks in the country. Following the construction of the two bridges, various FRP bridge decks have been designed and installed at various locations in the United States.

The majority of the FRP deck systems available to date are made of glass-reinforcing fibers in a polyester or vinyl ester resin matrix. Carbon or aramid fibers and epoxy resins offer superior structural performance characteristics, but are cost prohibitive for use in bridge deck systems. The typical in-service deck systems consist of two principal types: pultruded shapes that are bonded together with adhesive and honeycomb or sandwich core systems that are manufactured either using hand lay-up techniques or vacuum assisted resin transfer molding techniques. Figure 2.10 shows examples of pultruded and sandwiched core FRP bridge deck systems.

Figure 2.10. (Left) Superdeck™- Pultruded FRP deck from Creative Pultrusions, Inc. (Right) Sandwich core FRP deck system from Kansas Structural Composites, Inc. (KSCI)

In order to extend the application of FRP bridge decks to high-volume roads, durability of FRP bridge decks needs to be experimentally established. Currently researchers use the AASHTO's LRFD specification for steel bridges as a basis for the design and development of test methodology for FRP bridge decks.

2.4.1 Design Approach

In general, the design procedures for structural engineering applications assume that the material is homogeneous and isotropic. However, FRP composites are highly anisotropic. Thus conventional design methods may not be effective or efficient in exploiting the directional strength and stiffness of FRP composite systems and the application of existing design specifications to composite materials has been questioned. [23]. However until the LRFD specifications are extended to FRP composite bridge deck, researchers have been approaching the issue with simplifications and conservative assumptions.

Mertz and Kulicki [28] discussed an extension of LRFD specifications to FRP composite bridge decks. The authors discussed various provisions, such as the bulk of the specified loads and material-dependent serviceability criteria of the LRFD specifications and their application to composite bridge decks. They also proposed that FRP bridge deck design must be governed by the optional live load deflection limit state of the LRFD specifications due to the fact that glass based FRP composites, have high strength but are more flexible. In order to account for this FRP bridge decks, (eg. wood decks) must have larger allowable deflections when compared to steel and concrete decks.

Lopez-Anido et al [25] proposed a design approach based on LRFD specifications according to which, three limit states, namely: 1) service, 2) strength and 3) fatigue limit states, have to be considered for FRP bridge decks. The service limit

state checks for excessive local deflection of the deck to prevent premature failure of deck joints and the wearing surface. The strength limit state checks for the bridge components to remain in the elastic range under a HS25-44 design truck with an impact factor of 33%. Finally the fatigue limit state checks structural integrity of the deck components for a HS20-44 design truck with an impact factor of 75%.

2.4.2 Fatigue Limit State

The fatigue resistance of FRP composite decks is not well established and there are no specifications available on the required number of load cycles. Available fatigue data are typically from aerospace applications and cannot be used for the type of fiber and resin materials and fabrication processes used for FRP decks. Hence researchers have adopted the AASHTO LRFD Bridge Design Specifications for steel bridges to propose a fatigue design criteria for FRP bridge decks. [22-27]

AASHTO Standard Specification and LRFD specifications require that the number of cycles to check for fatigue to be two million cycles, and the level of fatigue load be 75% of the actual axle load of a HS20-44 design truck to evaluate fatigue and fracture in steel structures [1, 2]. In order to develop a practical qualification test and, in agreement with AASHTO Standard Specifications, two million cycles is being adopted by most researchers to evaluate the fatigue response of the FRP deck [23].

Although for 50 year life span of a bridge deck and an average daily truck traffic of 500, the number of axle load exceeds 15 million cycles. However, the actual axle loads will typically be smaller than the HS20-44 design. Since, it is not equivalent to an increase in the load range to predict a more extended fatigue life, two millions cycles to evaluate the fatigue response of FRP decks maybe inappropriate [25]

Mertz and Kulicki [28] argued that the AASHTO standard specification's shift to a lower number of cycles (two million cycles) than anticipated during the 75-year design

life of the bridge is valid only for steel bridge members and may not be valid for FRP composite materials. Hence, adopting two million cycles to evaluate FRP bridge decks may be unconservative. The authors also proposed that FRP bridge decks must be validated for actual number of cycles that the decks are expected to experience during the 75-year design life based upon the anticipated average daily truck traffic.

LRFD Specifications state that the level of fatigue load be 75% of the actual axle load of a HS20-44 design truck to evaluate fatigue and fracture of the decks. Again, this fatigue load level was developed for steel bridges based upon accumulative damage models for steel components. These damage models may not be appropriate for composite materials and hence the “load factor” of 0.75 must be reconsidered as fatigue-resistance data for composite materials. However until the LRFD specifications are extended to FRP composite bridge decks currently researchers use the load range and number of cycles specified in the specification.

Fatigue loading of FRP composite materials is accompanied by degradation in the strength and stiffness of the material due to damage accumulation. In addition to the above mentioned requirements of AASHTO's Standard and LRFD specifications, researchers also monitor the stiffness degradation and the failure strength of the decks after subjecting the FRP decks to two million cycles. The Constructed Facilities Center, West Virginia University (CFC-WVU) has proposed in the draft AASHTO specification as a qualification test for FRP deck samples as “The flexural rigidity of an FRP deck component subjected to two million cycles at a load range of 5 – 40% of the component's ultimate load shall not be less than 80% of the initial flexural rigidity of the FRP bridge deck component” [24].

2.4.3 Fatigue Response of FRP Bridge Decks

Lopez-Anido et al [23] demonstrated that, a simply supported three-point bending fatigue test simulating the wheel loads for HS20-44 design truck can be adopted to evaluate FRP bridge decks under fatigue loading in the laboratory. They tested a pultruded FRP bridge deck under flexural fatigue loading. The test span for the deck was 108". In addition to the HS20-44 loading a conservative factor (C) of 1.5 was included to account for extended service life of the bridge deck.

To simulate the wheel load of a HS-20-44 design truck, a rectangular steel plate 20"x10"x2" was used. The deck was fatigue loaded for 2 million cycles and quasi-static tests were performed every 500,000 cycles to determine the change in stiffness of the deck specimens with cyclic loading. The failure load of the deck after fatigue loading the decks for 2 million cycles was determined. They found that there was a 4% decrease in failure load and 10% increase in central deflection of the deck, after fatigue loading the deck to 2 million cycles.

Howdyshell et al [25] conducted fatigue test on two FRP bridge decks, one fabricated by pultrusion and the other fabricated by VARTM. The pultrusion deck was 36" wide and the VARTM deck was 45" wide. To accommodate for the difference in the deck widths two different fatigue load ranges were used: 2 to 50 kips for the VARTM deck and 2 to 35 kips for the pultrusion deck. The test setup for the two decks was similar. The decks were loaded by a 10" x 20" patch load at the mid span for two million cycles. Quasi-static tests were performed every 500, 000 cycles to evaluate stiffness degradation in the decks. It was observed that there was 5% loss of stiffness in the VARTM deck and 6% loss of stiffness in the pultrusion deck.

Dutta et al [22] conducted fatigue tests on four composite bridge decks, a hybrid FRP -concrete bridge deck, an FRP bridge deck fabricated by pultrusion, an FRP deck fabricated by Vacuum Assisted Resin Transfer Molding (VARTM) and, an FRP deck

fabricated by contact molding hand lay-up process in extreme temperatures (-22°F and 50°F). They also tested a concrete bridge deck for comparison purposes. The test set-up for all the decks was similar.

The decks were placed on three steel stringers resulting in two test spans. The load range applied on each span was 2 kips to 26 kips. The load was applied by two 9 x 22" patch loads at the two mid spans. The fatigue evaluation procedure consisted of applying two million cycles at room temperature, four million cycles at -22°F and another four million cycles at -122°F. Quasi-static tests were performed at 0 cycles, 2 million cycles, and 10 million cycles to monitor change in stiffness of the decks at elevated temperatures. Results from the tests indicated that there was a significant loss in stiffness in the FRP deck only at high temperature when compared with the hybrid and concrete deck. The stiffness of FRP composite bridge decks under simulated wheel loads was more susceptible to extreme temperatures than to 10 million fatigue cycles.

Kumar et al [26] conducted four-point bending fatigue and failure tests on a 30 ft long by 2 ft wide pultruded FRP bridge deck specimen. The load range was calculated based on strength and maximum deflection. A maximum load of 11 kip and a minimum load of 0.5 kip were applied for 2 million cycles at a nominal frequency of 4 Hz. Stiffness changes were monitored by periodically by performing quasi-static tests. Results from these tests indicated no loss in stiffness up to 2 million cycles. Following the fatigue testing, the test sample was tested to failure and no loss in strength was observed.

Lockwood et al [27] tested a sandwich core FRP bridge deck system under three-point bending fatigue. The load range was calculated based on a HS25-44 design truck. The maximum applied load was 19.5 kips and was applied by a 20"x10" patch load. The bridge deck was tested for only 300,000 cycles since the bridge deck was to be installed in a secondary road where traffic was not high. The stiffness degradation of the deck panels was monitored periodically. It was observed that there was a 15%

decrease in stiffness after the first 100,000 cycles of loading. On further loading there was no significant loss in stiffness.

Based on the available test methods and test data of various FRP bridge deck systems, the test methodology to evaluate the performance of FRP bridge decks under fatigue loading and to determine the fatigue life of the decks can be summarized as below:

- The FRP bridge deck has to be simply supported on two supports and a three-point flexural fatigue test has to be performed.
- The FRP deck system has to be tested under sinusoidal loading (at a rate of up to 3 cycles per second and higher frequency may lead to softening of resin under loading pads due to heat generated from fatigue cycling) up to 2 million fatigue cycles.
- The deck has to be tested for an HS20-44 design truck with an impact factor of 75%. The fatigue loading has to be applied by a patch load (10" x 20") load at the center of the each span.
- Intermediate static tests have to be conducted at every 250,000 cycles to evaluate any degradation in flexural strength and flexural rigidity of the deck to predict fatigue life.
- The reduction in flexural rigidity of FRP bridge decks subjected to two million fatigue cycles shall not be more than 20%.

CHAPTER 3

FATIGUE TESTING OF GFRP COMPOSITE COUPONS

3.1 INTRODUCTION

Structural systems made of composite materials, under fatigue loading, can be characterized by a constant degradation rate in strength with number of cycles. In the past, researchers have shown that the S-N curves (stress range vs. number of cycles) of FRP composites have no clear threshold stress level as established in metals. Various models are available in literature to predict fatigue life of composite materials using strength and/or stiffness loss as damage metric, including the remaining/residual strength after subjecting a composite to a definite number of fatigue cycles. In the present study the internal strain energy was used as damage metric to predict the fatigue life of composite materials, subjected to constant low amplitude fatigue.

The strain energy (U) of the material was taken as damage metric to quantify the fatigue damage accumulation in FRP composite materials due to the following reasons:

- Basic laws of thermodynamics have to be satisfied
- Higher sensitivity due to squaring of strain or curvature i.e.,
 - $U_{\text{bending}} = M^2/2 EI$
 - $U_{\text{axial}} = P^2/2AE$
- Easier to quantify by theory for different loading types, i.e., bending, tension, compression, shear or torsion etc.
- Accurate determination through strain (10^{-6}) or deflection (10^{-3}).
- Response is determined based on geometric and material linearity.

3.2 VARIATION OF INTERNAL STRAIN ENERGY WITH FATIGUE LOADING

Fatigue loading of FRP composites shows that strain energy is expended as externally induced work increases due to the damage accumulated in the material through matrix cracking, fiber delaminations and eventual fiber breakage. The energy expended by the material, due to the damage accumulation, is a function of the maximum applied strain, number of fatigue cycles and mechanical properties of the material.

The changes in strain energy in FRP composites under cyclic loading with number of fatigue cycles, called the *Energy curve*, consists of 3 distinct stages as shown in Figure 3.1. Stage I is identified with an initial steep loss energy, while Stages II and III are identified respectively with reference to energy loss linearly varying with number of cycles and abrupt loss of energy leading to specimen failure. The initial steep loss of energy in Stage I is attributed to matrix cracking initiated by voids and discontinuous fibers in the composite. Stage I is limited to approximately 15-20% of fatigue life.

Gradual loss in energy under increasing number of fatigue cycles in stage II signifies the propagation of fatigue mechanism. Stage II is initiated primarily by matrix cracking, interfacial crack propagation and delamination of laminates. The energy curve is linear during this stage and is characteristic of the material for a particular load or stress or strain range. Stage II is limited to approximately 70-75% of the total fatigue life of the specimen.

Stage III is characterized by very high energy loss per fatigue cycle (i.e, 15 to 20 times higher than the energy loss per cycle of Stage II) attributed to fiber failure leading to specimen failure and is limited to approximately 10% of total fatigue life of the specimen. Since, the degradation rate of Stage II is characteristic to the material for an applied strain level, the energy loss in Stage II can be used to predict the useful fatigue life of the material.

Figure.3.1. Typical energy vs. fatigue cycles (energy curve) of a (10"x1/2") GFRP composite coupon under tension-tension fatigue.

Fatigue tests were performed on Glass Fiber Reinforced Polymeric (GFRP) composite coupons and a fatigue life model was proposed based on the energy release rate i.e., energy loss per fatigue cycle, due to damage accumulation. Three GFRP materials with different fiber architecture were tested under fatigue loading. Two materials were tested under tension – tension fatigue and the third material was tested for bending fatigue.

3.3 EXPERIMENTAL PROGRAM

3.3.1 Material Description

The static and fatigue tests were conducted on three different GFRP composite plates (MAT 1, MAT 2, MAT 3) with different combinations of fabrics and glass roving (Table 3.1). All three materials under study were made of Glass/Vinyl ester and manufactured in the form of plates by pultrusion process. MAT 1 and MAT 2 were $\frac{1}{4}$ " thick plates while MAT 3 was a $\frac{1}{2}$ " thick plate. The fiber architecture and laminate sequence of GFRP plates are shown in Figure 3.2. MAT 1 and MAT 3 contained 2D fabrics while MAT 2 was made of 3D stitched fabrics.

Tension-tension fatigue tests were performed on two plates, MAT 1 and MAT 2. Bending fatigue was performed on MAT 3. A minimum of three static tests (tension and bending) were conducted prior to fatigue tests to determine the static strength and stiffness of the laminates.

Material ID	MAT 1	MAT 2	MAT 3
Fiber/Resin	Glass/Vinyl ester	Glass/Vinyl ester	Glass/Vinyl ester
Fiber direction	2 D woven fabrics	3 D stitched fabrics	2 D woven fabrics
Fiber Volume Fraction	0.3	0.4	0.3
Plate Thickness (inches)	$\frac{1}{4}$ "	$\frac{1}{4}$ "	$\frac{1}{2}$ "
Longitudinal Modulus (psi)	2.4 x 10 ⁶	3.4 x 10 ⁶	2.8 x 10 ⁶
Failure Strain (μ strains)	20000	22000	24000
Ultimate Strength (Ksi)	48	74.8	67.2
Fatigue Test	Tension - tension	Tension - tension	Bending

Table 3.1. Properties of materials used in study

MAT 1	MAT 2	MAT 3
0/45/45	CSM	CSM
36 rovings	6.5 rovings	90/45/45 (1 layer)
0/45/45	0/45/-45/90 (4 layers)	Rovings
36 rovings	6.5 rovings	90/45/45 (2 layers)
90/45/45	CSM	Rovings
0/45/45		90/45/45 (2 layers)
0/45/45		Rovings
		90/45/45 (2 layers)
		Rovings
		CSM

Figure.3.2. Fiber architecture of the three materials under study

3.3.2 Test Specimen Preparation

The test specimens used in both static and fatigue tests were cut from a single plate of each material to avoid differences in constituent materials during the manufacturing process. Tension test specimens were prepared according to ASTM D 3039. The tension test coupon configuration is shown in Figure 3.3. The rectangular coupons (10" x 1") were cut along the longitudinal direction of the plates and the edges were prepared smooth to avoid any edge defects.

Additional tab material was added to the specimens in the coupon gripping regions to reduce the stress concentration generated by clamping the coupon and to provide a wear surface between the composite and the metal wedge grips. The tab material was same as the specimen material but was grinded to a lesser thickness (1/8") and was bonded to the coupons using Plyogrip, an epoxy based adhesive. The coupons were clamped under uniform pressure at room temperature for a minimum period of 12 hours to ensure proper adhesion of the tabs to the composite surface. The tabs were 3"

long and were grinded to taper at the ends as shown in Figure 3.3 after bonding to the test specimens.

Figure 3.3. Tension test coupon configuration

The specimens for 3-point bending tests were prepared in conformance with ASTM D 790. The rectangular bending test specimens (10"x1") were cut along the longitudinal direction of the plates. The edges were prepared smooth and no further preparation was required for the bending specimens. Strain gages were installed at the center of the specimen to record strains.

3.3.3 Mechanical Testing Equipment

The static and fatigue tests were performed on three different machines. Static tension test was performed in Baldwin universal testing machine. Static 3-point bending tests were performed on a servo hydraulic Instron 8501 testing machine. A few tension fatigue tests on MAT 1 were conducted using an Instron 1331 testing machine controlled by a MTS 407 controller and the rest of the fatigue tests were performed on Instron 8501 (Figure 3.4). All these machines had their respective transducers, load cell, extensometer, and actuator LVDTs, calibrated for their respective functions as per the manufacturer's instructions.

Figure 3.4. Fatigue test setup (Instron 5000)

Strain gages supplied by Micro Measurements Inc. were installed in the center of the static test specimens and connected to a strain indicator to calibrate the gages and to monitor strain with number of cycles of load induced by the fatigue actuator. A set of standard tension test grips, which could accommodate a maximum of $\frac{1}{2}$ " thick specimens, was used for the tension tests. A special fixture designed at Constructed Facilities Center, West Virginia University, was used for the 3-point, static and fatigue, bending tests (Figure 3.4).

3.4 TEST METHODOLOGY

3.4.1 Static Testing

Static tests (tension and bending) were performed on all the three materials (MAT1, MAT2 and MAT3) under consideration. A minimum of three static tests were performed on each material to determine the material properties. Static tension tests were performed on MAT 1 and MAT 2 in a Baldwin universal testing machine. The test specimen preparation and dimension for tension tests are discussed in section 3.3.2. Strain gages were installed, at the center of the test specimen and stress-strain data

were recorded at regular intervals. The tensile stiffness, strength and the failure strain for both the materials were determined using the following equation,

$$E = \left(\frac{P}{\varepsilon} \right) \left(\frac{1}{A} \right) \quad (3.1)$$

where, $\frac{P}{\varepsilon}$ is the slope of the load – strain plot and A is the original cross-sectional area of the specimen.

The flexural properties of the composite laminates were determined by performing 3-point bending tests. The bending tests were performed in an Instron 8501 universal test machine. The coupons were prepared according to ASTM D 790. A span of 8" was used with an overhang of 1" on both ends. Strain gage was installed at the center of the test specimen to measure the strains. Central deflections of the specimens were also recorded using a LVDT built in the testing machine. The longitudinal flexural stiffness, strength and the failure strain were determined for the material using the following equations,

$$E = \left(\frac{P}{\varepsilon} \right) \left(\frac{lc}{4I} \right) \text{ from strain data, and} \quad (3.2)$$

$$E = \left(\frac{P}{\delta} \right) \left(\frac{l^3}{48I} \right) \text{ from deflection data} \quad (3.3)$$

where,

$\frac{P}{\varepsilon}$ and $\frac{P}{\delta}$ are slopes of the Load – strain plots and load – deflection plots respectively, l

is the test span, and I is the moment of inertia for the cross-section.

3.4.2 Fatigue Testing

All fatigue test specimens, in this study, were loaded through a constant amplitude sine waveform generated by the controller of the respective test machines. At high frequencies (>10 Hz) the fatigue life in composite materials is significantly affected due to adiabatic heating of the material. Hence a nominal frequency of 4 Hz was used in all tension - tension fatigue tests and a frequency of 0.5 Hz was used for the bending fatigue tests. The test frequency of 0.5 Hz was chosen for bending tests because the load levels for the material (MAT3) was very low and deflections were very high, leading to difficulty in loading at higher frequencies. Fatigue tests were performed at various strain ranges (25% to 80% of the ultimate strain) of the material. A minimum of two tests were performed for a particular strain range.

Tension – Tension Fatigue

Tension-Tension fatigue tests were performed on the GFRP laminates, MAT 1, MAT 2, at various mean strain levels and strain ranges. The test coupons used for fatigue tests are same as the tension test specimens used in static tests (Figure 3.3). The width of the test specimen was first taken as 1", and later reduced to 0.5" since at higher strains the specimens failed in the gripping area and a proper tension failure did not occur under cyclic loading. Proper tension failure i.e., failure in the gage length was observed upon reducing the specimen width by 0.5". (Refer section 3.5.1)

The fatigue tests were first performed using an Instron 1331 machine controlled by a MTS 407 controller. Strain gage was installed at the center of the coupons and connected to strain indicator to measure strain. Static test was performed on the coupons at well below the failure load to determine the load - strain data before starting the fatigue test. A sine waveform was used to apply the cyclic loading at a frequency of 4

Hz on all tension-tension fatigue tests. A minimum load of 500 lbs was chosen so that the specimen cannot be loaded under compression. Static load tests were performed at regular intervals of cyclic loading and load - strain data were recorded to study the degradation of the stiffness and the energy loss due to cyclic loading. However after a few cycles of loading the material started to delaminate and the strain gage readings were not accurate. Also due to the matrix cracking in the outer surface of the specimen it was not possible to install a strain gage properly and to get accurate strain data.

To overcome the problem of measuring strain, the tests were carried out in INSTRON 8501 universal testing machine. This testing machine was numerically controlled by a computerized data acquisition system. A built in load cell and an LVDT were used to measure respectively load and deflection (i.e., relative movement of the actuator position) during testing. Hence the deflection data were used, instead of strain data, to determine the fatigue stiffness (E_n) and the strain energy (U_n) at any cycle, using the following equations,

$$E_n = \frac{P_n l}{A \delta_n} \quad (3.4)$$

$$U_n = \frac{P_n \delta_n}{2} \quad (3.5)$$

where, ' P_n ' is the load at n cycles, ' δ_n ' is the deflection after n cycles, ' A ' is the cross-section area and ' l ' is the length of the test specimen.

The test constraints such as waveform, amplitude of the waveform, peak load, the number of cycles to load, data storage etc., were set for each test and saved to a file, called the block file, using the Wave Editor program provided by the INSTRON. The block files consisted of two blocks. Block 1 loads the specimen to the mean strain level at a constant rate using a *relative-ramp waveform*. Block 2 loads the specimen in fatigue at a set frequency and constant amplitude using a *sine waveform* (Figure 3.5).

The Wave Runner program was used to read the block file and run the tests according to the specified constraints. Two data files are stored during the test. One data file records the data for block 1 and the other data file records the data for block 2. The program records the deflection, strain (if an extensometer is used), load and the number of cycles in the data files. Under fatigue loading, the load, deflection and strain data can be recorded at the peak and trough of the sine wave or at various points in the sine wave at a default time interval according to the user's preference. The data recorded in the current study was at the peak and trough, but only the peak values were used for analysis. The interval at which the data points were collected was changed depending on the maximum applied load or load range.

Figure 3.5. Sine waveform and data measurements

The tests were terminated automatically when the specimen fails and the data file was analyzed using a spreadsheet program. The Fatigue Modulus (E_n), i.e, the slope of the load versus deflection measured at a particular fatigue load cycle, and the Strain energy (U_n) at any cycle (N) were then calculated using Equations 3.11 and 3.12 respectively, for each data point assuming the loading was in the linear range.

Bending Fatigue

Bending fatigue tests were performed on MAT 3 for various strain ranges, ranging from 30 – 80% of the failure strain. The tests were performed in Instron 8501

testing machine. A special 3-point bending fixture was used for testing. The specimens were same as the static test specimens (10"x1"). The test span was 8" with 1" overhang on both ends. A constant amplitude sine waveform was used to run the tests at a frequency of 0.5 Hz for all the tests. A minimum load of 100 lbs was used for all tests to maintain the loading. The load, deflections and number of cycles were recorded at regular interval of cycles as explained in tension-tension fatigue test methodology in previous section.

The bending stiffness (E_n) and strain energy (U_n) at any cycle n were calculated using the following equations

$$E_n = \left(\frac{P_n}{\delta_n} \right) \left(\frac{\ell^3}{48I} \right) \quad (3.6)$$

$$U_n = \frac{P_n^2 \ell^3}{96E_n I} \quad (3.7)$$

where, P_n is the applied load after n cycles, δ_n is the deflection after n cycles, and ℓ is the test span, and I is the moment of inertia for the cross-section.

3.5 RESULTS AND DISSCUSSION

3.5.1 Tension – tension fatigue tests

Tension-tension fatigue tests were performed on MAT 1 and MAT 2 coupons for various strain ranges. Tension failure was achieved in lower strain levels (25% of static ultimate strain) with larger number of cycles than at higher levels of loading (above 40% of static ultimate strain). At higher load levels, the material failed at lower number of cycles in or near the gripping area. This could be attributed to various factors such as improper bonding of the end tabs to strengthen against stress concentration, eccentricity in loading and other items. The dimensions of the coupon and the tabs, strengthening in

the gripping area, play an important role in achieving tension failure in the gage length and not near the grips.

ASTM D3039 suggests the standard dimensions of tension-tension fatigue coupons to be 10"x1", same as the coupons for the static tension tests. However, suitable thickness of the coupons specified in the ASTM is about 1/10". In the present study, all coupons were cut from 1/4" thick plates which are very high compared to the thickness of the standard coupon. Although static tests induced proper tension failure, under cyclic loading the failure was more of a bending type failure in the gage length or grip failure.

Upon reducing the width of the coupons to 1/2", with other dimensions remaining the same, a better gripping of the coupons was achieved leading to proper tension failure under cyclic loading (Figure 3.6). The size of the tabs was first chosen to be 2 1/2 " in length at first try and the ends were not tapered. Under cyclic loading the interface of the tabs failed and hence the size of the tabs was increased to 3 inches and was tapered at the end as shown in Figure 3.3

The failure process under cyclic loading was generally dominated by matrix failure, since both materials were multi-axial composites. As discussed earlier, when a weak fiber in the laminate fails, stress concentration is induced in the laminate leading to failure of the matrix around the area. On further loading the discontinuity propagated parallel and perpendicular to the fibers leading to delamination of the laminate. On most cases there were visible delaminations in the coupons even before the specimen actually failed. This led to difficulty in using strain gages to measure strains in the gage length of the specimen, since the delaminations separated the outer layers of the test specimens considerably. Hence strains measured through strain gages were not accurate. Therefore deflection, i.e., the relative position of the actuator, was used to

determine the stiffness and the remaining strain energy expended as discussed in Section 3.4.2.

Figure 3.6. Failure modes with change in width of the specimen (MAT 1)

The results of the tension-tension fatigue tests are summarized below for the two materials MAT 1 and MAT 2.

MAT 1

MAT 1 was the first material tested and difficulties were experienced with specimen dimensions and data measurements. The material consisted of 2D glass fabrics in vinyl ester matrix. First few tests were carried out in Instron 1331 testing machine and Table 3.2 provides the test data. But due to the difficulty in strain measurements, tests were only used to plot the S-N plots and no degradation of stiffness or energy could be recorded. Also the specimen dimensions were changed from 1" wide to $\frac{1}{2}$ " wide specimens, since the specimens failed in the tabs regions at high strain ranges. Both the issues were addressed in detailed in previous sections.

The rest of the specimens were tested using Instron 8501 and deflections obtained through built in LVDT were used to analyze the stiffness and strain energy degradation. The fatigue test results of MAT 1 are summarized in Table 3.2. The data from Table 3.2 were used to plot a semi-log S-N plot for MAT 1 as shown in Figure 3.6. Unlike metals, it can be seen from the S-N plot that there was no significant threshold for the material, which is common in fiber reinforced composites.

MAT 2

MAT 2 consisted of 3D stitched glass fabrics in vinyl ester matrix system. The tension-tension test methodology and data storage methods were same as the test procedure as given for MAT 1. All the specimens were 10" x ½" and all fatigue tests on MAT 2 were conducted using Instron 8501. The energy curves were plotted for all the 16 tests performed on MAT 2 at strain ranges varying from 25-70 % of the failure strain. When loaded at 25% of static ultimate strain the test specimen did not fail until one million cycles and the test was stopped after a million cycles of loading. The fatigue test results of MAT 2 are summarized in Table 3.3. The data in Table 3.3 was used to plot a semi-log S-N curve for the material as shown in Figure 3.7.

The failure in some specimens was more of a bending type of failure, instead of tensile failure due to internal bending of fibers running in the thickness direction. The fatigue performance of MAT 2 were as good as that of MAT 1 at low levels of strains. However at higher strain levels MAT 1 performed better. This could be again explained from the internal bending stresses induced by the fibers in the third direction.

Specimen No	Dimension	Load Range (lbs)	% ϵ_{ult}	Cycles to failure	Total Expended Energy (%)
1**	10" x 1 "	500-3500	25	5×10^6	NA
2		500-6500	50	4250	NA
3		500-6500	50	6500	NA
4		500-9500	75	360	NA
5	10" x 0.5 "	500-2400	40	2.5×10^5	NA
6		500-3000	50	19660	NA
7		500-3000	50	18454	NA
8		500-3600	60	3892	NA
9		500-4200	70	1582	NA
10		500-4800	80	160	NA
11*		500-2400	40	3.94×10^5	53.25%
12*		500-3000	50	66200	55.99%
13*		500-3000	50	67600	77.96%
14*		500-3600	60	10000	55.30%
15*		500-3600	60	5700	59.33%
16*		500-3600	60	4800	61.75%
17*		500-4200	70	1240	58.41%
18*		500-4200	70	2140	59.47%

* Specimens tested in Instron 5000

**Specimen did not fail (test stopped at 5 million cycles)

Frequency – 4 Hz

Table 3.2. Summary of fatigue test results for MAT 1

Specimen No	Specimen Dimension	Load Range (lbs)	% ϵ_{ult}	Cycles to failure	Total Expended Energy (%)
1*	10" x 1/4"	500 - 2250	25	1.0E+06	48.0%
2		500 - 3600	40	120000	66.0%
3		500 - 3600	40	285000	52.8%
4		500 - 3600	40	25000	61.5%
5		500 - 3600	40	27000	73.1%
6		500 - 4500	50	39265	37.0%
7		500 - 4500	50	7600	38.0%
8		500 - 4500	50	4100	63.1%
9		500 - 4500	50	5200	56.5%
10		500 - 4500	50	2800	64.0%
11		500 - 5400	60	720	64.0%
12		500 - 5400	60	919	74.0%
13		501 - 5400	60	1340	55.0%
14		500 - 5400	60	570	56.0%
15		500 - 6300	70	240	55.0%
16		500 - 6300	70	154	94.5%

* Specimen did not fail (test stopped at 1 million cycles)

Frequency – 4 Hz

Table 3.3. Summary of fatigue test results for MAT 2

Figure 3.7. S-N plot for MAT 1 and MAT 2

3.5.2 Bending fatigue tests (MAT 3)

Three-point bending fatigue tests were performed on MAT 3 at various strain ranges (30 – 80% of failure strain). The tests were performed using Instron 8501 and a special fixture was used for the 3-point bending tests. The bending fatigue test results for MAT 3 are summarized in Table 3.4. A semi-log S-N plot was plotted as shown in Figure 3.8.

Under 3-point bending fatigue it was observed that the delamination of the plies was found to be critical in determining the fatigue life of the material. The delamination initiated at the tension side of the specimen and propagated upwards towards the compression side. The effective area reduced considerably under bending due to fabric layer delamination leading to increased deflection of the test specimen.

Deflection of the specimens was very high (1.2" at 80% of ultimate loading) and the load ranges were very low (maximum of 1200 lbs). At such low loads and high deflections the loading of the test specimen was inaccurate at higher frequencies. Hence a test frequency of 0.5 Hz was used for all the bending fatigue tests on MAT 3.

At low strain ranges (30% of static ultimate strain) difficulties were experienced with loading the test specimen. The strain range was so low that the test machine was not able to load accurately even at a frequency of 0.5 Hz, as deflection of the material was very high. The energy curve of the test specimen loaded at 30% of ultimate loading is shown in Figure 3.9. It can be seen that around 5×10^5 cycles there was a big drop in energy due to delamination in specimen. The delamination of the specimen led to higher deflections and the test machine was not able to load the specimen accurately as shown in Figure 3.9.

Specimen No	% of ultimate strain	Load range (lbs)	Cycles to failure	Expend Energy (%)
1*	0.3	50-420	1.00E+06	-NA-
2	0.4	50-560	3.30E+05	38.21
3	0.5	50-700	53700	37.12
4	0.5	50-700	39400	46.16
5	0.6	50-840	9880	41.67
6	0.6	50-840	6500	35.63
7	0.7	50-980	728	45.31
8	0.7	50-980	460	44.73
9	0.8	50-1120	382	44.15
10	0.8	50-1120	326	38.34

* Specimen did not fail (test stopped at 1 million cycles)
Specimen Dimension – 10"x1/2"x1/2"
Frequency – 0.5 Hz

Table 3.4. Summary of fatigue test results for MAT 3

Figure 3.8. S-N plot for MAT 3

Figure 3.9. Energy curve of MAT 3 loaded at 30% of ultimate

3.5.3 The Energy Curve

The deflection data were recorded at regular intervals of cycles for fatigue specimens until failure. The strain energy expended by the system was calculated, using equation 3.5 and 3.7, at each data point and energy curves were plotted. Figures 3.10, 3.11 and 3.12 show the normalized energy curves for MAT 1, MAT 2 and MAT 3 respectively. The plots were normalized (N/N_f) along the x-axis to represent all specimens in a single plot.

It is important to identify the different stages of the energy curve to better predict the life of composite materials. Assuming that 10% life line as end of stage I, and 90% line as the end of stage II, the energy curves were plotted for stage II separately. The curves were then fitted linearly using regression analysis and plotted for each specimen. The point at which the linear fit is tangent to the energy curve is identified as the end of stage I. The energy of the specimens at various stages is determined from the energy curves and tabulated for all the three materials in Table 3.5

The slopes and intercepts of the fits in Figures 3.10, 3.11 and 3.12 represent the Energy Release Rates (ΔU) and the internal strain energy at the beginning of stage II. Although Stages I and III are neglected in determining the Energy Release Rate i.e. the rate of change of energy per load cycle, the energy of the specimen before fatigue loading (U_0) and energy of the specimen just before failure (U_f) are required to better predict the life. The energy expended by the specimens during stage I is tabulated in Table 3.5. A considerable amount of energy is expended during Stage I and hence to make a better prediction the total energy expended by the material from the first cycle to failure should be considered.

Figure 3.10. Normalized Energy Curves for Specimens 11 - 18, MAT 1

Figure 3.11. Normalized Energy Curves for a few specimens (MAT 2)

Figure 3.12. Normalized Energy Curves for a few specimens (MAT 3)

MAT 1						
Specimen No	U at 0 cycles	U at end of Stg I	% life at end of Stg I	% increase in U from cycle 1 to end of Stg I	U at $N/N_f = 0.9$	% increase in U from Cycle 1 to $N/N_f=0.9$
11	95.09	124.61	11.57%	31.04%	141.01	48.29%
12	137.05	199.83	22.00%	45.81%	213.02	55.43%
13	144.28	220.9	21.50%	53.11%	248.17	72.01%
14	190.48	242.35	21.00%	27.23%	278.27	46.09%
15	198.09	252.8	17.50%	27.62%	310.79	56.89%
16	220.12	286.55	22.90%	30.18%	329.79	49.82%
17	266.13	306.45	14.50%	15.15%	387.39	45.56%
18	272.73	337.68	16.80%	23.81%	414.25	51.89%
						Avg = 53.25%
MAT 2						
Specimen No	U at 0 cycles	U at end of Stg I	% life at end of Stg I	% increase in U from cycle 1 to end of Stg I	U at $N/N_f = 0.9$	% increase in U from Cycle 1 to failure
1	60.58	86.98	16.62	43.58%	94.64	56.22%
2	58.3	86.47	15.52	48.32%	95.13	63.17%
3	157.1	205.16	16.65	30.59%	240.74	53.24%
4	155.46	200.6	16	29.04%	238.42	53.36%
5	197.3	254.41	16.5	28.95%	309.62	56.93%
6	193.09	230.8	15.13	19.53%	251.86	30.44%
7	255.2	331.03	23.07	29.71%	394.18	54.46%
9	266.09	292.51	17.8	9.93%	417.34	56.84%
10	217.66	253.54	20	16.48%	337.66	55.13%
11	316	383.9	23.5	21.49%	469.30	48.51%
12	358.02	486.9	21.27	36.00%	545.87	52.47%
13	336.3	439.29	12.5	30.62%	610.39	81.50%
14	351.42	453.28	22.8	28.99%	536.11	52.56%
15	422.73	491.21	23.07	16.20%	630.39	49.12%
16	477	578.28	15.78	21.23%	889.94	86.57%
						Avg = 56.7%
MAT 3						
Specimen No	U at 0 cycles	U at end of Stg I	% life at end of Stg I	% increase in U from cycle 1 to end of Stg I	U at $N/N_f = 0.9$	% increase in U from cycle 1 to failure
2	251.02	321.11	10.73	27.90%	360.18	43.5%
3	265.05	323.89	5	22.20%	370.34	39.7%
4	214.06	261.7	23.23	22.30%	303.79	41.9%
5	206.5	255.75	23.6	23.80%	319.08	54.5%
6	169.81	206.4	4.5	21.50%	243.97	43.7%
7	150	188.5	17.12	25.70%	217.56	45.0%
8	124	154.36	23.2	24.50%	178.77	44.2%
9	108	140.24	24.25	29.90%	165.96	53.7%
10	79.49	102.18	27.06	28.50%	121.13	52.4%
						Avg = 46.5%

Table 3.5. Summary of energy at various stages for MAT1, MAT2 and MAT3

Figure 3.13, shows the variation of number of cycles to reach stage II by varying the applied strain range. The number of cycles to reach stage II decreases as the applied strain range increases. This is because stage I is dominated by matrix cracking and at higher loads, the induced stresses in the material exceed the strength of the matrix material in a shorter duration.

Figure 3.13. Variation of number cycles to reach stage II with max applied strain (normalized)

The Energy curves show that beyond the 90% life line ($N/N_f = 0.9$) there is an abrupt increase in energy (Stage III) within a short period of time leading to total failure. In most cases stage III should be ignored in accounting for additional fatigue life of a specimen because the specimen fails suddenly. As explained earlier, fiber breakage is the dominant failure mode in stage III. When the fibers start to fail the average strength of the material reduces drastically and stresses in the individual fibers increase due to

delamination of the outer fibers; hence the specimen fails immediately. Predicting fiber failure is probabilistic which depends on various reasons (manufacturing defects, voids, fiber volume fraction, matrix properties etc.). From the energy curves, it can be seen that stage III occurs only at the last 10% of the fatigue life of the specimen. Therefore, conservatively one can assume that stage III initiates somewhere around the 90% life-line.

The internal strain energy at the 90% life-line was found and tabulated in Table 3.5. Assuming that the 90% life line as the fatigue life of the specimen, the total energy expended by the specimen from the start of the fatigue test to the 90% life line was determined (Table 3.5). It was observed that there was approximately a 50% increase in the total energy expended (from 0 cycles to failure) by almost all the specimens. This was consistent with all three materials.

Hence from the above mentioned assumptions the following conclusions can be drawn:

$$\begin{aligned} U_f &= 1.5U_0 \\ N_f &= N_{90\%} \end{aligned} \tag{3.8}$$

where, U_f is the energy of the specimen just before failure, U_0 if the energy of the specimen at the just before fatigue loading, N_f is the number of cycles to failure of the specimen and $N_{90\%}$ is the number of cycles at 90% of fatigue life.

3.5.4 Energy Release Rate (ΔU)

The slope of Stage II in the energy curve, i.e., Strain energy vs. Number of cycles, gives the *Energy Release Rate* (ΔU), which can be obtained by performing a regression analysis in stage II of the energy curve. The energy release rate is found to be a constant is characteristic of a constitutive material, under similar loading conditions (strain/stress range). The energy curves (Figures 3.10-3.12) show that the energy

release rate of the material increases with increase in applied strain which is a fraction of the static ultimate strain of the material.

The energy release rate for all specimens in Tables 3.2, 3.3 & 3.4 were found from the energy curves and the mean energy release rate for a particular applied strain was calculated. The variation in energy release rates (ΔU) with normalized applied maximum strain, was plotted as shown in Figure 3.14a, 3.14b and 3.14c and the data points were fit using a power law such that

$$\Delta U = a \left(\frac{\varepsilon_{max}}{\varepsilon_{ult}} \right)^b \quad (3.9)$$

where, ε_{max} is the maximum applied strain of the material, ε_{ult} is the static ultimate strain of the material and, a , b are the fatigue coefficients. The fatigue coefficients (a , b) in Equation 3.9 were determined and tabulated in Table 3.6 for the three materials. The fatigue coefficients (a , b) are material properties and is characteristic of the material.

MAT 1, MAT 2 and MAT 3 consisted of the same type of fiber (E-glass) in same resin system (Vinyl ester). All three plates were manufactured by pultrusion process. However, the slopes of the S-N curves for the three materials show that the MAT 1 (shallow) performed better under fatigue when compared to MAT 2 and MAT 3 (steep). From Table 3.6 and the S-N curves it can be seen that the fatigue resistance is better for materials with higher value of 'b'. The values of fatigue coefficients (a , b) depends on various factors such as fiber content, laminate sequence, specimen thickness, loading condition etc.

Material	Fatigue Coefficients	
	a	b
MAT 1	6.29	13.15
MAT 2	33.1	10.11
MAT 3	1.58	11.17

Table 3.6. Fatigue coefficients (a , b) for MAT 1, MAT 2 and MAT 3

Figure 3.14a. Variation of energy release rate with percentage of ultimate strain applied for MAT 1.

Figure 3.14b. Variation of energy release rate with percentage of ultimate strain applied for MAT 2.

Figure 3.14c. Variation of energy release rate with percentage of ultimate strain applied for MAT 3.

MAT 1 Vs MAT 2

MAT 1 and MAT 2 consisted of the same matrix (vinyl ester) and same fiber (e-glass) and were of the same thickness. However, the *fatigue coefficient* (b) for MAT 1 is higher than MAT 2 which means, MAT 1 has better fatigue resistance when compared to MAT 2. The difference in the fatigue resistance can be explained as follows:

Fiber content

Since fibers carry most of the load in FRP composites it is common to think that with increased fiber volume fraction the fatigue response of the material improves. Although it is true in unidirectional composites with continuous fibers, experimental results have shown that the fatigue response in fabric based composites (woven, stitched etc.,) is actually poorer at fiber volume fractions greater than 40%.

The fiber cross-over points in the fabrics act as stress concentration sites to initiate resin cracking and interfacial debonding, resulting in poor fatigue resistance. In triaxial fabrics, the 0° strands are forced tight against the 45° strands and when the matrix cracks in the 45° strands, the main load bearing 0° strands fail sooner. This effect is not seen in unidirectional composites where good fatigue resistance is maintained at least up to fiber volume fraction of 60%. Hence, the fatigue response of laminated composites composed with woven fabrics is poor at (1) high fiber contents, and (2) high relative amounts of 45° reinforcements. The fiber volume fraction of MAT 2 was higher ($V_f = 0.4$) when compared to MAT 1 ($V_f = 0.3$) and hence MAT 1 had better fatigue resistance than MAT 2.

Fiber Architecture

The fatigue performance of FRP composites largely depends on the fiber volume fraction in the loading direction i.e., 0° strands in the case of tensile fatigue. Table 3.7 gives the breakdown of amount of fibers in different directions for the three materials (MAT 1, MAT 2, and MAT 3). Table 3.7 shows that MAT 1 had 9% more fibers when compared to MAT 2.

Unidirectional composites loaded in the transverse direction of the fiber orientation have shown poorer fatigue resistance than those tested along the fiber direction. This is because the transverse stiffness of fibers is generally 10 times lower than the longitudinal stiffness. Table 3.7 shows that MAT 1 had 4 % less fibers in the transverse direction than in MAT 2.

MAT 1 consisted of 2D woven fabrics and MAT 2 consisted of 3D stitched fabrics. The presence of fibers in the 2nd direction in MAT 1 and in 3rd direction in MAT 2 leads to stress concentration effects and hence poor fatigue resistance when compared to unidirectional composites.

Fiber Direction	MAT 1	MAT 2	MAT 3
0°	69%	60%	64%
90°	7%	11%	NA
45°	12%	11%	18%
-45°	12%	11%	18%
CSM	NA	7%	NA

Table 3.7. Breakdown of amount of fiber in different directions for MAT 1, MAT 2 and MAT 3

MAT 1 Vs MAT 3

MAT 1 and MAT 3 consisted of the same matrix (vinyl ester) and same fiber (e-glass). However, the fatigue coefficient (b) for MAT 1 is higher than MAT 3 which means, MAT 1 has better fatigue resistance when compared to MAT 3. The difference in the fatigue resistance can be explained as follows:

Loading Type

MAT 1 was tested under tensile fatigue and MAT 3 was tested under bending fatigue. As mentioned earlier the failure processes in bending fatigue was dominated by delamination due to failure of the plies in the tension side of the specimen. This leads to increased loss in the load bearing area of the material leading to specimen failure.

Specimen Thickness

Thickness of MAT 3 was higher (1/2") than MAT 1(1/4"). Comparing the values of the fatigue coefficient "b" it can be seen that with increased thickness the fatigue resistance of the material decreases. This is because with increased thickness the shear transfer capacity of most composites goes down. The fatigue resistance of FRP composites decreases with increase in thickness due to shear lag and hence, lowers the

load resistance. Also, with increase in thickness of the composite it is difficult to control the void ratio and proper curing of the laminate and hence, the fatigue resistance is poor.

3.6 FATIGUE LIFE PREDICTION USING ENERGY CURVES

The energy release rates determined from the energy curves could be used to predict fatigue life of FRP composite materials, since the fatigue coefficients a , and b are material constants and should be constant for a particular material under similar loading conditions. A prediction model based on the internal strain energy is proposed herein based on the fatigue test results of MAT1, MAT2 and MAT3.

Since the strain energy released by the material is linear in Stage II, and assuming the useful life in Stages I and III is less compared to useful life in Stage II, the strain energy (U_n) of the material at any given cycle (n) can be written as

$$U_n = U_0 + D \quad (3.10)$$

where, U_0 is the internal strain energy of the material before fatigue loading i.e., at 0 cycle and D is the function describing the damage accumulated in the material. Since the specimen is loaded linearly up to the mean strain level before starting the fatigue test, the energy of the material before fatigue loading is the energy at the mean level. Hence, the energy of the material at 0 cycles can be written as

$$\begin{aligned} U_0 &= \frac{P_{mean}^2 l}{2AE} \quad (\text{for tensile loading}) \\ U_0 &= \frac{P_{mean}^2 l^3}{96EI} \quad (\text{for 3 - po int bending}) \end{aligned} \quad (3.11)$$

where, P_{mean} is the mean load of the cyclic load (average of maximum and minimum load applied on the test specimen), E is the Young's modulus in the loading direction, l is the span, I is the moment of inertia of the cross section, and A is the cross sectional area of the specimen.

Upon fatigue loading, the damage (D) is a function of the number of fatigue cycles and the maximum applied strain ($\varepsilon_{\max}$), and can be written as

$$D = f(N, \varepsilon_{\max}) \quad (3.12)$$

Experimental results have shown that for most of the life of specimen i.e., stage II in Figure 3.1, the damage function varies linearly with number of cycles. The damage function can then be written as

$$D = (\Delta U)N \quad (3.13)$$

where, ΔU is the internal strain energy expended per cycle, referred to as the *Energy Release Rate*, for a particular loading. The energy release rate (ΔU) is constitutive of the material for a particular loading condition and is a constant, which varies only with the maximum applied strain ($\varepsilon_{\max}$). The energy release rate (ΔU) can be written as a varying function of the maximum applied strain through a power law as

$$\Delta U = a \left(\frac{\varepsilon_{\max}}{\varepsilon_{ult}} \right)^b \quad (3.14)$$

where, ' a , b ' are fatigue constants, and ε_{ult} is the static ultimate strain of the material which can be determined from experiments for the material. From equations 3.1, 3.4, and 3.5, variation of strain energy under cyclic loading can be written as

$$U_n = U_0 + \left(a \left(\frac{\varepsilon_{\max}}{\varepsilon_{ult}} \right)^b \right) N \quad (3.15)$$

If the fatigue constants " a and b " are known the fatigue life of the material under cyclic loading can be determined for a particular loading, by rearranging equation 3.6, and by writing $U_n = U_f$ and $N = N_f$ as

$$N_f = \frac{U_f - U_0}{a \left(\frac{\varepsilon_{\max}}{\varepsilon_{ult}} \right)^b} \quad (3.16)$$

where, U_f is the strain energy just before entering Stage III i.e. end of Stage II, and N_f is the fatigue life of the specimen, recognizing that additional fatigue cycles are needed before failure i.e., end of stage III which is neglected in the evaluation procedure.

Substituting Equation 3.8 in the above equation, N_f can be written as

$$N_f = \frac{1.5U_0 - U_0}{a \left(\frac{\varepsilon_{max}}{\varepsilon_{ult}} \right)^b} = \frac{0.5U_0}{a \left(\frac{\varepsilon_{max}}{\varepsilon_{ult}} \right)^b} \quad (3.17)$$

where, U_0 can be determined from equation 3.11 and the fatigue coefficients a , b for the material can be determined from experiments.

Using the above equations the fatigue life of the three materials under consideration were predicted and the S-N plots of both experimental and prediction are plotted in Figures 3.15, 3.16 and 3.17. The error was less than $\pm 10\%$ of experimental results.

Figure 3.14. Comparison of experimental and predicted S-N plot for MAT 1

Figure 3.14. Comparison of experimental and predicted S-N plots for MAT 2

Figure 3.15. Comparison of experimental and predicted S-N plot for MAT 3

3.7 CONCLUSIONS

Three FRP composite materials were tested under fatigue at various strain ranges. The S-N plots for the three materials were plotted. The variation of internal strain energy with cyclic loading (energy curve) was recorded and analyzed. It was observed that the rate of change of energy with cyclic loading (energy release rate) due to damage accumulation was a constant for a particular load /strain/ stress level and was characteristic of the constitutive material. The energy release rates varied with applied strain/stress level by a power function. A fatigue life prediction model based on the energy curve was proposed and the experimental and predicted were compared. The prediction was conservative for all the three materials and the error involved was less than 10%.

CHAPTER 4

FATIGUE TESTING OF FRP MODULAR BRIDGE DECKS

4.1 INTRODUCTION

Two lightweight Glass FRP composite modular bridge decks designed by Constructed Facilities Center and manufactured by Bedford Reinforced Plastics Inc. were evaluated under flexural fatigue. The pultruded FRP bridge decks were supported by W10x39 steel stringers and tested to evaluate structural performance under fatigue loads. The FRP decks were fatigued up to two million cycles at a frequency of 2 Hz with a load range of 2-50 kips. The decks were evaluated for structural integrity and degradation in bending rigidity under repetitive simulated wheel load to determine the applicability of the decks to bridge applications. This chapter presents the fatigue response of the FRP composite bridge decks under flexural fatigue loading.

4.2 GENERAL DETAILS ON FRP COMPOSITE BRIDGE DECK SYSTEM

The lightweight FRP composite bridge decks consisted of pultruded components as shown in Figure 4.1. The FRP bridge deck modules weigh about 15 lbs/ft². The fiber architecture consists of E-glass fibers in the form of multiaxial stitched fabrics, continuous rovings, and continuous fiber mats with fiber volume fraction of about 54%. The resin system for one deck was polyester while the other deck was made of a vinyl ester resin. The FRP decks used in this study were 136"x100"x 8" in dimension which were achieved by bonding 6 modules end to end with 4 deck joints and was supported on three steel stringers to test under fatigue loading.

In the bridge applications, the FRP bridge deck modules, with strong bending axis are placed transversely to main steel stringers/girders (perpendicular to flow of traffic) or floor beams (parallel to traffic flow). The FRP bridge deck modules are

supported on longitudinal steel stringers. The modules can be pultruded to any required length and the required size of the deck can be achieved by bonding the modules together. The pultruded components are bonded together using Plyogrip adhesive supplied by Ashland Chemicals Inc.

Figure 4.1. Cross – section details of the bridge deck module

4.3 SPECIMEN PREPARATION

4.3.1 Surface Preparation of Bridge Decks

The surface preparation for both the polyester and vinyl-ester decks was more or less same, which is described below. The top surface of the decks at joints was first sanded with 40-grit sandpaper and excess dust was removed by vacuum cleaning. The sanded area was cleaned with acetone and left undisturbed for twenty minutes before vacuuming the residue. MBRACE primer (parts A and B) was then applied over the cleaned area and allowed to cure for 24 hours.

The joints were reinforced mainly to ensure proper shear transfer between components. The reinforcement over deck joints in polyester and vinyl-ester decks was different. The polyester deck joints were reinforced with 2 layers of glass fabrics (each of 26 oz/yd²) consisting of 6" wide bottom layer and 4" wide top layer. During fatigue loading, the polyester deck failed prematurely due to lack of reinforcement in transverse directions. Hence, to overcome this type of failure, the vinyl ester deck, was provided with additional reinforcement in the transverse direction with 8 layers of 26 oz/yd² quadriaxial fabrics at location of patch loads (Figure 4.2). Section 4.3.2 explains in detail the procedure used for the application of the reinforcements. Once the joints were reinforced, polymer concrete wearing surface of about 3/8" to 1/2" thick was applied over the deck surface. The method of application of the wearing surface is discussed in Section 4.3.3

4.3.2 Procedure for Application of Reinforcement

After the surface preparation of deck surface, the deck joints were ready for reinforcement. Before laying the fabrics over joints, the fabrics were thoroughly soaked by slowly pulling them through an MBRACE saturant (parts A and B epoxy resin) bath as they were being placed onto the deck. The fabric strips were pulled through the bath until the entire length had been immersed. One end of the strip was then clamped to the

module and the strip was pulled tight and laid into position. The excess resin and air voids were squeezed out by tightly pressing over the fabrics with rollers. Finally, the fabric strips were allowed to cure for seven days.

Figure 4.2. Vinyl-Ester deck with 3'x3' reinforcements at the patch load areas

4.3.3 Procedure for Application Wearing Surface

A low modulus polysulfide epoxy overlay (Transpo T-48), supplied by Castek Inc., was applied to both the deck surfaces (polyester and vinyl-ester). It is a completely impervious overlay that will prevent any ingress of moisture, chlorides, salts, and other corrosion inducing substances. Transpo T-48 was applied on the deck surface to about ½" thick. Additional dead load of about 3-4 pounds per square feet was added to the deck, due to the application of overlay. The overlay was applied according to the technical data sheet provided by the manufacturer.

Transpo T-48 resin has two parts, T-48A resin and T-48B hardener. The two components were first mixed at 2:1 ratio for uniform curing and performance, for about

2-3 minutes, using a jiffy mixer powered by an electric drill until the blend was uniform. The epoxy was applied in two-coat (1/4") application using a Broom and Seed Method. The First coat of T-48 resin was applied using rollers at the rate of 40-50 square feet per gallon on the prepared surface. Immediately after the application of the resin a very light broadcast was applied to break any air bubbles that may have formed during the priming process. A heavy broadcast was then applied by hand after 10-15 minutes and rolled until refusal. Standard ballast (dry, dust free, with Mohr's hardness greater than 6) was used as the cover aggregate. After curing the excess aggregate was broomed off for reuse and a second layer was then applied. Thus a 1/2" thick polymer concrete was applied on the deck surface.

4.3.4 Stringer Preparation

The bridge decks were supported on three W10x39 steel stringers placed along the perpendicular to the strong bending axis of the deck. The top flanges of all stringers were sandblasted to ensure a clean and bondable surface. The stringers were placed at 68" apart (center to center). Prior to the connection of the deck and stringers, the area of the deck, to be in contact with the stringers, was sanded with 40-grit sandpaper. The excess dust was removed by vacuum cleaning, and acetone was applied and allowed twenty minutes to evaporate before vacuuming the residue. The deck was then bonded to the stringers by using PLIOGRIP -7779/300. The adhesive was allowed to cure for 48 hours before the bridge deck system was moved into the testing bay.

4.4 EXPERIMENTAL PROGRAM

4.4.1 Testing Equipment

The testing equipments comprised of a loading frame, MTS hydraulic pump and MTS 407 controller. The loading frame contained the hydraulic actuator with a built-in 50 kip load cell unit. A programmable MTS 407 controller controlled the hydraulic actuator through an MTS hydraulic pump. The MTS 407 can be programmed to move the actuator through different waveforms (sine wave, triangle wave etc.,) depending on the kind of test. For fatigue tests the controller could be programmed for different frequencies, and amplitudes. A maximum load of 50 kips could be applied by the controller.

4.4.2 Support conditions

The FRP bridge deck systems (FRP deck with steel stringers) were placed on rigid, 14" deep, steel supports to provide a firm base for fatigue testing. Elastomeric pads were placed below the supports to ensure an even contact with the floor. Steel rollers were welded to the top of these supports to simulate simply supported conditions for the deck/stringer systems. The center-to-center span between the rollers was maintained at 88" as shown in Figure 4.3

4.4.3 Loading conditions

Patch Loads (10"x 20") were applied on the system through a hydraulic jack and were monitored by a load cell. The patch load size was chosen to simulate the size of the contact area of AASHTO HS20-44 design truck wheel. Two patch loads were applied symmetrically at 34" from the center of the middle stringer at the mid-spans of the deck by 2" thick steel plates. A ¼" thick elastomeric pad was placed under the steel plates to apply uniform pressure on the deck surface. A load range of 2-50 kips was used for both the fatigue tests. Figure 4.3

Figure 4.3. Experimental setup and instrumentation for fatigue test performed on the FRP bridge deck systems

4.4.4 Instrumentation

Strain gages and dial gages were used to monitor the strain and deflection readings of the deck under fatigue loading. The dial gages were mounted at bottom surface of the deck at center of mid-span to measure the deflection. Strain gages were installed both at the top and bottom surface of the deck. At the bottom surface, strain gages were mounted at mid-span in longitudinal directions, to evaluate the strain of the deck. At the top surface, strain gages were installed at mid-span and at distances of 1 ft away from the mid-span in all four directions to evaluate local behavior of the deck (Figure 4.3).

4.4.5 Test procedure

The FRP composite bridge deck system was fatigue loaded through two patch loads (10"x20") at mid-spans between the steel stringers (Figure 4.3). The deck system was tested under sinusoidal loading at a rate of 2 cycles per second up to 2 million fatigue cycles. The frequency of the tests was chosen as 2 Hz because frequencies higher than 4 Hz may lead to softening of resin under loading pads due to heat generated from fatigue cycling. A load range of 2 – 50 kips was applied for both the decks (Figure 4.4).

Static test was conducted before starting the fatigue test, i.e. at 0 cycles. The cyclic loading was stopped and intermediate static tests were conducted at every 500,000 cycles to evaluate any degradation in flexural rigidity of the deck. The decks were loaded up to 30 kips (15 Kips on each test span) for during static tests. Strain and deflection data was recorded for each intermediate static test and the load vs. deflection and load vs. strain graphs were plotted.

Figure 4.4. Experimental test setup for the vinyl ester deck

4.4.6 Evaluation of Test Data

The flexural rigidity of a deck at every 500,000 cycles of fatigue loading is evaluated from the load vs. deflection and load vs. strain within the linear elastic limits.

Longitudinal Flexural Rigidity, EI (based on deflection)

The flexural rigidity of FRP composite deck in the longitudinal direction for a section of constant width is

$$EI = \frac{PL^3}{48\delta} \quad (\text{Neglecting shear effects}) \quad (4.1)$$

Where,

$\frac{P}{\delta}$ = Load over bending deflection (at the bottom) in the linear elastic limits (slope of load vs. deflection curve)

P = Applied load; L = Span length; δ = mid-span deflection of the bridge deck

Longitudinal Flexural Rigidity, EI (based on strain)

The flexural rigidity of FRP composite deck in the longitudinal direction for a section of constant width is

$$EI = \frac{PLd}{8\varepsilon} \quad (4.2)$$

Where,

$\frac{P}{\varepsilon}$ = Load Vs Strain ratio in the linear elastic limits (slope of load vs. strain curve)

d = Depth of the deck

ε = Strain at mid-span of the bridge deck on tension side only

4.5 RESULTS AND DISCUSSIONS

4.5.1 Stiffness Degradation in FRP Bridge Decks

Polyester deck

The polyester deck was loaded under fatigue loading at load range of 2-50 kips. Static test was performed before fatigue loading of the deck i.e., at 0 cycles. After 230,000 cycles, the deck failed under the patch load area due to punching shear.

The shear stress around the area where the patch load (tire impression of 10"x 20") was applied created a punching shear effect around its perimeter Figure 4.5. The reason for this behavior is that the vertical webs in the deck modules are spaced at a distance greater than the width of the patch load. The width of the top flange (in lightweight bridge deck module) in between the two webs was 12" and while the width of the patch load was 10". As a result, the patch load punched through the top flange by shearing the deck along its two 20" sides.

Figure 4.5. Damage due to punching shear failure around the patch load area

This type of failure mode also explains that and that there were not enough fibers, in the transverse direction of the deck to transfer the shear stresses. Since the deck failed in 230,000 cycles there was no test data recorded for the deck. Hence, the degradation in bending rigidity in the deck was not determined.

Vinyl ester deck

The mid span deflection at the bottom of the deck and strains that were recorded after every 500,000 cycles are shown in Table 4.1. The load-deflection plots and load-strain plots were plotted and the flexural rigidity of the deck was found using Equations 4.1 and 4.2. The variation of the flexural rigidity with fatigue loading are shown in Figure 4.6 . It was observed that there was only about 2% change in flexural rigidity which indicated that there is no considerable change in the flexural rigidity of the deck after fatigue loading for two million cycles.

Figure 4.6. Variation of flexural rigidity with number of cycles for the vinyl-ester deck from mid-span longitudinal deflection and strain

4.5.2 Joint Evaluation

The joint integrity between of the FRP bridge deck was evaluated based on strains measured across the joints. From Figure 4.7 and 4.8, we can observe that the difference in strain across joint 1 (i.e., between gage 2 and 6) was about 80% while the difference across joint 2 (i.e., between gage 2 and 5) was about 50%. This indicates that the joint was not efficient in transferring load from one module to another. Further the difference in strain across joint 1 and 2 varied due to eccentricity in position of patch load. Also, strain in gage 6 was about 30% less than strain in gage 5. This is attributed to poor shear transfer across the deck joints. However, the strain differences across the deck joints remained same up to 2 million cycles, which further indicates that there was no degradation in the joint under fatigue loading. This is because the deck was subjected to a low stress range, which was 25% of static ultimate strength.

Figure 4.7. Variation of strain at different locations of the deck at 15 kips load.

Figure 4.8. Location of strain gages on the top surface of the deck

0 – Cycles

P x 2	Strain Gages								Deflection
	1	2	3	4	5	6	1B	2B	
0	0	0	0	0	0	0	0	0	0
5	56	97	16	16	56	23	57	28	49
10	152	208	35	36	116	39	121	57	81
15	238	319	54	58	180	46	183	85	113
20	325	435	67	65	237	63	236	106	136
25	412	548	81	72	289	84	292	119	159
30	506	662	94	78	342	109	345	136	180

500,000 cycles

P x 2	Strain Gages								Deflection
	1	2	3	4	5	6	1B	2B	
0	Gage failed	0	0	0	0	0	0	0	0
5		105	12	10	58	19	56	35	27
10		223	25	14	115	37	109	67	55
15		311	35	15	172	54	158	94	79
20		405	46	15	228	73	206	117	100
25		476	55	14	280	92	252	136	117
30		542	65	15	337	112	295	151	132

1,000,000 cycles

P x 2	Strain Gages								Deflection
	1	2	3	4	5	6	1B	2B	
0	Gage failed	0	0	0	0	0	0	0	0
5		118	14	32	59	18	57	36	29
10		227	24	59	118	36	110	67	55
15		326	35	83	176	55	160	95	78
20		403	45	105	231	74	207	118	98
25		475	55	124	283	92	252	135	115
30		527	64	140	333	110	296	151	131

1,500,000 cycles

P x 2	Strain Gages								Deflection
	1	2	3	4	5	6	1B	2B	
0	Gage failed	0	0	0	0	0	0	0	0
5		139	13	13	67	24	60	38	28
10		264	24	21	134	42	114	70	56
15		362	33	28	198	64	165	100	76
20		465	44	33	265	85	214	125	101
25		527	53	39	323	105	260	143	122
30		613	61	63	380	128	307	160	136

2,000,000 cycles

P x 2	Strain Gages								Deflection
	1	2	3	4	5	6	1B	2B	
0	Gage failed	0	0	0	0	0	0	0	0
5		142	12	10	71	23	59	35	29
10		259	21	28	146	47	113	66	57
15		373	29	18	215	70	164	96	81
20		456	39	20	288	94	217	117	105
25		530	47	22	343	114	260	137	127
30		579	57	26	403	135	304	154	147

Table 4.1. Strain and deflection data at various locations in the deck

4.6 CONCLUSIONS

Two FRP bridge decks were tested for simulated repetitive wheel loading for 2 million cycles. The polyester deck failed in 230,000 cycles due to punching shear failure. The issue was addressed by strengthening the vinyl-ester deck with 100 oz/yd² of fibers in the transverse direction. No visible damage or cracking was observed in the strengthened deck (vinyl-ester deck) for 2 million cycles and there was no degradation in flexural rigidity of the deck with cyclic loading. Also, the deck joints were not efficient (i.e, the strain difference across the joints was about 50% - 80%) to transfer load between the modules. However, there was no change in the performance of the joints due to fatigue loading.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

5.1.1 Fatigue testing of GFRP composite materials

Upon testing three, multidirectional, glass FRP composite materials under fatigue loading at various strain levels the following conclusions were drawn:

- The loss in strain energy under fatigue loading in FRP composite materials, called the *Energy Curve*, typically consists of three stages.
- It was observed that Stage I consisted of 15-25% of life of the material. Stage II consisted of 65-75% of life of the material and, Stage III consisted of approximately 10% of life of the material.
- An initial steep energy loss occurred during Stage I and the number of cycles to reach end of Stage I decreases with increased applied strain level.
- The rate of change of energy, called the *Energy Release Rate* (ΔU), in Stage II of the energy curve was found to be a constant and characteristic of the constitutive material for a particular strain/stress/load level.
- The energy release rate (ΔU) varied with the applied strain level by a power function and the coefficients of the power fit, called the *fatigue coefficients* (a, b), can be used to predict the useful life of FRP composites under fatigue loading.
- The fatigue resistance of the materials increased with higher values of the fatigue coefficient (b).
- A 50% increase in external strain energy at the end of Stage II was observed in almost all the specimens tested.

- Stage III was characterized by an abrupt (steep) energy loss leading to failure of the test specimen. Hence the end of Stage II was assumed to be the fatigue life of the material for a conservative fatigue life prediction.
- The following factors were identified to affect the fatigue resistance of FRP composite materials:
 1. Type of fiber
 2. Higher percentage of fiber in the loading direction
 3. Lower percentage of fiber in 90° and $\pm 45^\circ$
 4. Fiber volume fraction (percent, preferably) less than 40%
 5. Lesser thickness of the laminate ($1/2''$ or less for 2-D stitched fabrics)
 6. Mode of loading

The effect of each factor on the fatigue life of multidirectional FRP composite materials is discussed in detail in chapter 3.

- A fatigue life prediction model based on the energy curve was proposed and the model was used to predict the useful fatigue life of the three FRP composite materials under consideration.
- The experimental and predicted lives at various strain levels were compared (S-N curves) and the model was found to be conservative within 10% error for all the three materials.

5.1.2 Fatigue testing of FRP modular Bridge decks

From testing the two FRP modular bridge decks under three-point bending fatigue the following conclusions were drawn:

- The 8" deep deck failed along the patch load area due to punching shear failure. The shape of the deck module was found to be critical.

- The top flange of the 8” deep deck was lacking enough fibers in the transverse direction.
- Strengthening the top flange of the 8” deep deck modules with 100 oz/yd² of glass fibers in the transverse direction avoided the punching shear failure along the patch load area.
- The shear load transfer between the 8” deep deck joints was not symmetrical.
- There was no considerable degradation in flexural rigidity of the bridge deck for two million cycles after the area under the patch load was strengthened.

5.2 RECOMMENDATIONS

In order to improve the fatigue life prediction model proposed herein based on the energy curve, additional fatigue tests need to be performed in coupon level with various laminate configurations. The individual effect of the factors (mentioned in Section 5.1.1.) on the fatigue life of FRP composite materials has to be determined. If the effect of each factor is identified separately, equation 3.17 can be written as

$$N_f = C_1 \times \frac{0.5U_0}{a \left(\frac{\varepsilon_{max}}{\varepsilon_{ult}} \right)^b} \quad (5.1)$$

where, C_1 , would be the reduction factor depending on factors such as fiber content, laminate sequence, material constituents, loading conditions, etc.

Further, the model could be expanded to structural FRP components, like FRP bridge decks by including an another reduction factor C_2 in the above equation to account for various structural factors such as shape, joints, ply drop-offs, stress concentrations, manufacturing process of the composite etc.

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