PROBABILISTIC FATIGUE LIFE MODELLING OF FRP COMPOSITES

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Abstract

Fiber reinforced polymer (FRP) composites have been used in industries such as aerospace, marine transportation, and wind energy for several decades prior to attracting widespread attention for applications in civil engineering. While limited data is available on the long term fatigue performance of FRP materials for construction projects, it is worthwhile to review the extensive work done in other engineering disciplines and consider the lessons learned. In particular, the probabilistic nature of the fatigue life of composite materials under cyclic stresses has been captured by various models presented in literature; although the contextual parameters may differ, their use may extend to other applications. In this work, the Sendeckyj wear-out model based on the strength-life-equal-rank assumption is applied to fatigue data from a variety of material types and configurations intended for building projects. The results presented show that the model is versatile and can be calibrated to describe the probabilistic nature of both the static and fatigue response of FRP composite materials for various applications.

1. INTRODUCTION

Fiber reinforced polymer (FRP) composite materials are growing in popularity for a wide range of applications as a result of their unique properties which include light weight, versatility, high strength, and corrosion resistance. Whereas FRP composites have been used for many decades in industries such as aerospace, marine and automobile manufacturing, and wind turbines, their extension to civil engineering applications, particularly construction projects, has by comparison been more recent. As a result, data on long-term field performance, including damage accumulation due to cyclic loading, is lacking.

A relatively small number of research studies have focused on the fatigue life of FRP composites for civil engineering structures [1-9]. Conversely, the fatigue characteristics and failure mechanisms of FRP composites have been well-documented by researchers in mechanical engineering and other disciplines, and a variety of probabilistic and phenomenological models have been developed to explain their behavior [10-20]. While there are generally significant differences in the magnitude of deformations involved, the expected number of loading cycles over the service life of the component, the environment in which the materials are used, and the manufacturing processes employed, there are nevertheless several lessons to be gained from a review of this work and some of the general findings are transferable and provide a basis for further study.

The fatigue behavior of FRP materials depends on many parameters, including the fiber and resin types, as well as the configuration and geometry of the test specimens [21]. Unlike metals and other homogeneous materials, fatigue failures in FRP are generally the result of damage accumulation rather than damage propagation in a single mode [22]. The predominant mechanisms leading to failure depend on the range of applied strain, dividing typical FRP fatigue life curves into three distinct stages (Figure 1) [12]. At high strain ranges, failure is dominated by fiber breakage and interfacial debonding resulting in a nearly horizontal band representing the non-progressive nature of random fiber ruptures. The second stage can generally be described by a power law function, where damage accumulation is dominated by progressive matrix cracking and interfacial shear failures. Finally, in the third stage, the slope tends to flatten out at low strain levels as the fatigue limit is approached; for low stiffness composites, such as glass FRP (GFRP), the strain limit is usually much less than the strain capacity of the composite and is therefore ignored for most practical applications.

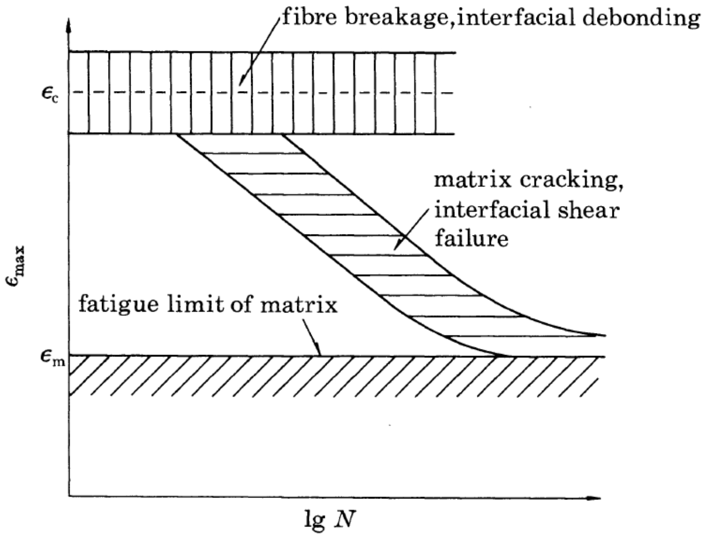

Figure 1: Fatigue life diagram for unidirectional composites [12]

The stochastic nature of fatigue in FRP composites has been widely observed [13, 16]. The scatter in fatigue life can exceed an order of magnitude for a given set of parametric values; this may be partially attributed to the high anisotropy of the material, density of defects, and distribution and alignment of fibers [11], as well as competing damage and failure mechanisms [19], and large variation in strength of individual fibers [20, 23].

2. MODELLING APPROACH

Fatigue life models for composite materials are often empirical in nature; the difficulty in developing rational models is linked to the various complex fatigue damage mechanisms, and the limited applicability of the fatigue and fracture mechanics concepts developed for metals [24]. It has also been argued that macroscopic phenomenological damage models are more practical than microscopic physical models since they require less data, are easier to measure, and the interaction of different damage types can often be neglected [25].

Chou & Croman [26] introduced a strength-life-equal-rank (SLER) assumption to relate the fatigue lives and static strengths of composites assuming that both followed 2-parameter Weibull distributions. SLER assumes that the static strengths are uniquely related to the fatigue lives and residual strengths of fatigue specimens at runout; i.e. the specimen with the highest static strength is also assumed to have the longest fatigue life and/or the highest residual strength following a fatigue test. This assumption is both simple and intuitive, although it is worth noting that it cannot be proven experimentally and may not necessarily be valid if competing failure modes are observed during fatigue tests.

Sendeckyj [27] used the SLER assumption to develop a method for fitting probabilistic fatigue life models to experimental data for composite materials. This method simultaneously determines the fatigue model parameters and the Weibull distribution parameters by converting fatigue data to equivalent static strength values using the maximum likelihood estimate method. The procedure is optimized by maximizing the Weibull shape parameter for the equivalent static strength data. The equivalent static strength of specimens tested under fatigue loading according to the so-called wear-out model is presented in Equation 1. The probability that a sample's static strength is higher than the equivalent static strength is given by Equation 2.

$$\sigma_e = \sigma_a [\left(\frac{\sigma_r}{\sigma_a}\right)^{1/S} + (n-1)C]^S \tag{1}$$

$$P(\sigma_e) = \exp[-(\frac{\sigma_e}{\beta})^{\alpha}] \tag{2}$$

Where, σ_e, σ_a, and σ_r are the equivalent static strength, applied stress level, and residual strength of the fatigue specimens, respectively, n is the number of applied cycles, C and S are model calibration coefficients, $P(\sigma_e)$ is the probability that the static strength is greater than the equivalent static strength, and α and β are Weibull distribution parameters.

For fatigue failure, the residual strength is equal to the applied stress level and the number of applied cycles is equal to the fatigue life, N. Equation 1 can therefore be simplified to give Equation 3:

$$\sigma_e = \sigma_a [1 - C + CN]^S \tag{3}$$

For $C = 1$, Equation 3 reduces to the classical power law fatigue failure criterion, whereas $C < 1$ results in an S-N curve that flattens out at low cycles on a log-log plot. Values of $C > 1$ result in a curve which steepens at low cycles.

The applied stress range corresponding to a specified fatigue life and probability of failure is given by Equations 4 and 5:

$$\sigma_a = \beta \left(\{-\ln[P(N)]\}^{\frac{1}{\alpha}}\right) [(N-A)C]^{-S} \tag{4}$$

$$A = -\frac{1-C}{C} \tag{5}$$

Where, $P(N)$ is the probability of survival after N cycles, and A is a model parameter.

3. ANALYSIS

The Sendeckyj model was used by [8] to analyse the fatigue life of GFRP reinforcing bars under axial tension and in beams, and by [9] for the fatigue behavior of GFRP-reinforced concrete slabs with CFRP post-tensioned tendons. A comparison with other fatigue models is discussed elsewhere [28]. The applicability of this approach to other research works with various material properties, configurations, and damage conditions is explored in this section.

3.1 GFRP reinforcing bars

Experimental fatigue testing of GFRP reinforcing bars were conducted by [8, 9]. The bars had a nominal diameter of 16 mm and the surface had a sand-coating layer to improve bond with concrete. The average tensile strength and modulus of elasticity were 784 MPa and 55.9 GPa, respectively. The bars were tested under cyclic loading in three configurations: axial tension-tension cycles using a novel anchor system and modified bar profile to control the location of the fatigue failure; beam-hinge specimens to investigate the effect of surrounding concrete on the fatigue performance; and as reinforcement in large concrete slabs with a length of 5 m and post-tensioned with CFRP tendons.

The results showed that the concrete had an adverse effect on the fatigue response, and that the fatigue behavior was also influenced by the stress ratio. An "effective" stress range was proposed to account for these effects as given by Equation 6:

$$\sigma_{eff} = K_{te}\sigma_n(1 + R) \tag{6}$$

Where, σ_{eff} and σ_n are the effective and nominal stress ranges, respectively, K_{te} is a factor to account for the abrasion at the FRP-concrete interface, and R is the stress ratio between the minimum and maximum stress values.

The static and fatigue data from the three test setups were used to calibrate the Sendeckyj model (Figure 2a). The failure band limits shown in Figure 2 correspond to 5% and 95% probabilities of failure. The approach was found to describe the data set well, including both static and fatigue results, while capturing the non-deterministic nature of fatigue behavior. A horizontal band is observed in the low-cycle fatigue region, while a steeper slope characterizes the intermediate-cycle fatigue range.

3.2 CFRP reinforcing bars

Few researchers have studied the fatigue life of FRP reinforcing bars in detail. Bare 9.4 mm diameter CFRP bars were tested by [4], while tests on 7.8 mm diameter CFRP bars in concrete were reported by [3]. The reported results and corresponding calibrated Sendeckyj models are shown in Figure 2b. It is worth noting that while [3] reported a lower fatigue life for bars in concrete, the bare bar results were not provided. Therefore, the factor K_{te} presented in Equation 6 was taken as unity for both studies; however, the applied stress ranges were multiplied by the factor $(1 + R)$ to account for the effect of the stress ratio.

It can be observed from Figure 2b that the slope and scatter of the S-N curves varied between the two different CFRP bars; nevertheless, the Sendeckyj model was able to capture the experimental results satisfactorily. It can also be observed that, unlike the GFRP bars in Figure 2a, there is no horizontal band in the low cycle region; hence, fatigue life data for CFRP composites are more likely to be well-described by a classical power law function.

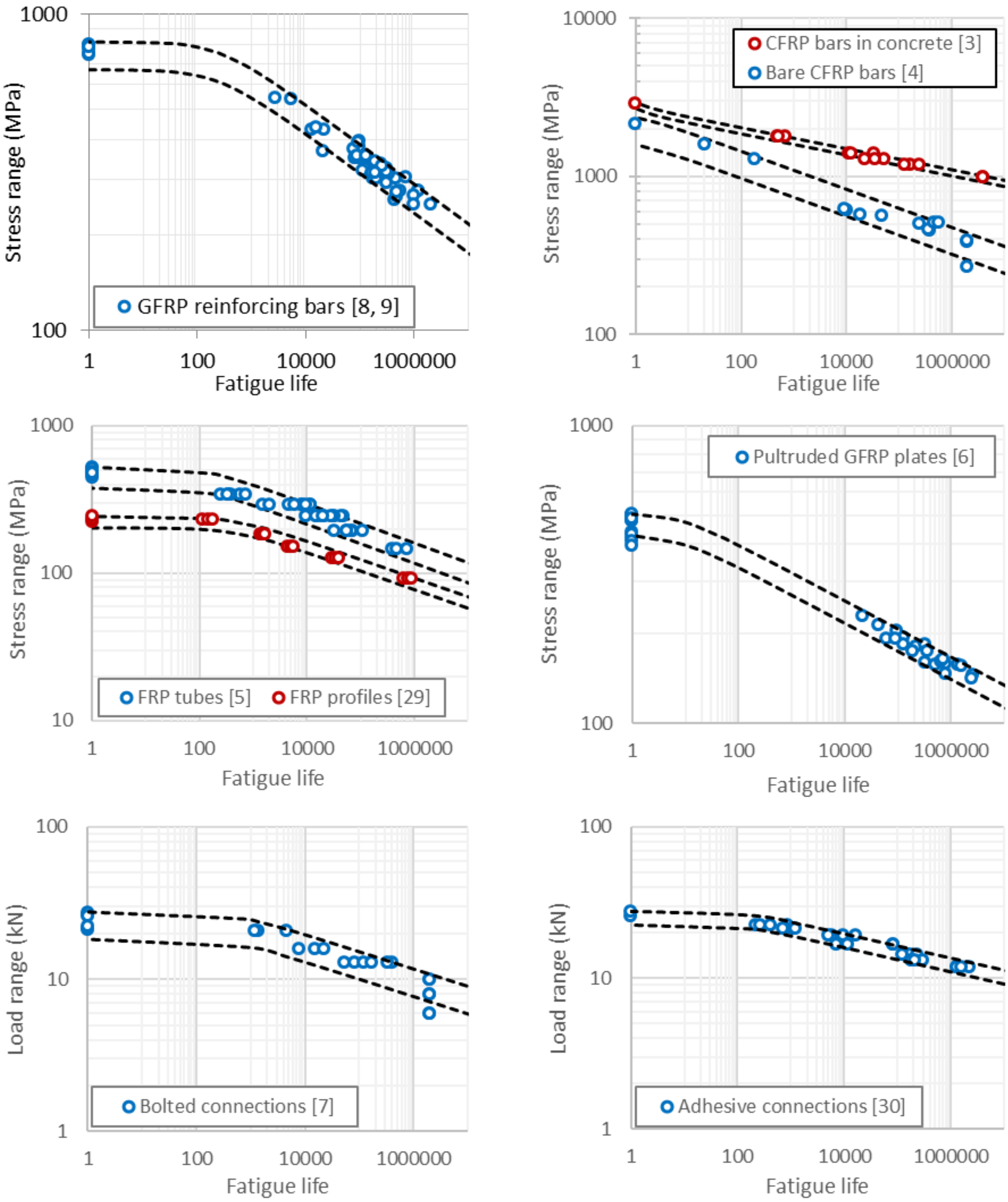

Figure 2: From top: calibrated models for a) GFRP reinforcing bars, b) CFRP reinforcing bars, c) GFRP coupons, d) pultruded GFRP plates, e) bolted connections, and f) adhesive connections

3.3 FRP coupons

Unlike FRP reinforcing bars, which have unidirectional fibers and are produced through pultrusion, many FRP applications make use of composites with different fiber orientations and manufacturing processes. [5] conducted a large number of fatigue tests on coupons cut from GFRP tubes with a thickness of 5.7 mm produced using a continuous filament winding process. The stacking sequence of different layers in the tube were [-87° / +10° / -87° / +10° / -87° / +10° / -87° / +10° / -87°]. The manufacturer reported properties include a tensile strength in the longitudinal direction of 402 MPa and an elastic modulus of 23.1 GPa.

The coupons were cut in various orientations; only the coupons in the direction parallel to the fibers are shown here (Figure 2c). Similarly, specimens tested under compression-compression cycles, or combined tension-compression are not included; while the Sendeckyj model can be used for such cases, the (1 + R) modifier does not seem applicable.

Also shown are the fatigue results from FRP coupons cut from pultruded structural profiles [29]. The profiles had a nominal thickness of 8.0 mm and an average tensile strength of 233 MPa. The calibrated models and experimental results in Figure 2c show a similar trend to that of the pultruded GFRP bars in Figure 2a. A shallow band is observed in the low-cycle region followed by a steeper slope in the intermediate-life region.

3.4 FRP plates and connections

Fatigue testing has also been conducted on GFRP pultruded plates [6], bolted connections [7], and adhesively bonded connections [30]. The applicability of the Sendeckyj approach for these cases is demonstrated in Figure 2d, e, and f. It can be observed that while the slope and scatter of the results vary in each case, as well as the length of the horizontal low-cycle fatigue band, the experimental results are well-captured in each case.

3.5 Summary

The normalized predictions as a ratio of the ultimate static strength corresponding to a 50% probability of failure are presented in Figure 3. Conversely to the GFRP samples, the CFRP bars did not show a change in slope in the low-cycle region.

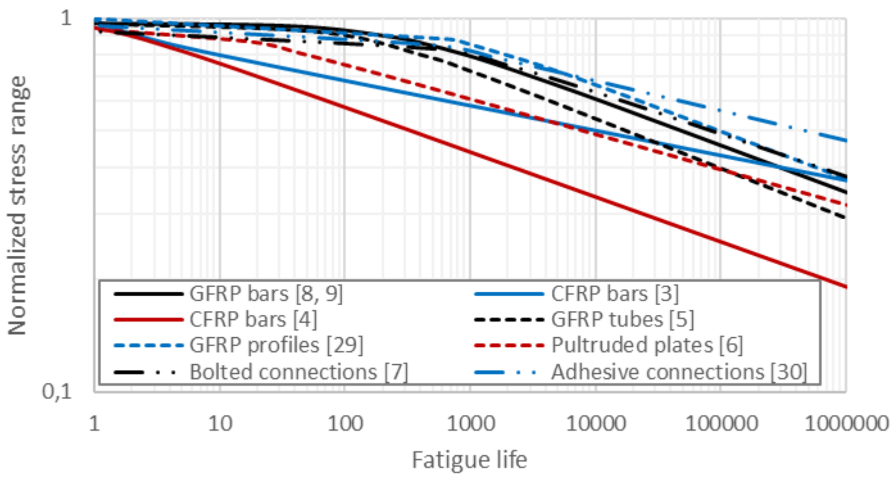

Figure 3: Summary of normalized fatigue results

The ratio of predicted fatigue life for a given stress range corresponding to a 5% reliability, P5, to a 95% reliability, P95, is approximately constant within the linear sloped region of each S-N curve, and may be considered as an indication of the scatter in the experimental results. As seen in Table 1, this ratio varied from approximately 4.0 to 42 for the studies considered in this work. The highest variability in results was observed in the bolted connections, whereas the lowest variability was observed in CFRP bars tested in concrete. Of course, it is important to note that many factors influence fatigue behavior, and no attempt is made here to draw general conclusions from this comparison.

Table 1 also shows the normalized stress range providing a 95% reliability for fatigue lives of 1 million and 10 million cycles. From a design perspective, this gives an indication of allowable stress ranges depending on the estimated number of load cycles applied throughout the expected service life. For 10 million cycles, the critical stress range varies from 11-34% of the ultimate static strength for the materials and configurations considered.

Table 1: Summary of fatigue life data

Source	Specimen type	P5/P95	P95 for 1 million cycles	P95 for 10 million cycles
[8, 9]	GFRP reinforcing bars	5.3	0.30	0.22
[3]	CFRP reinforcing bars	4.0	0.35	0.30
[4]	CFRP reinforcing bars	25.6	0.15	0.11
[35]	GFRP coupons	10.3	0.24	0.18
[36]	GFRP coupons	4.1	0.33	0.25
[6]	Pultruded GFRP plates	6.1	0.28	0.23
[7]	Bolted connections	42	0.29	0.22
[37]	Adhesive connections	14	0.41	0.34

4. CONCLUSIONS

The Sendeckyj model was used to fit experimental fatigue data for FRP composites with a range of material properties and configurations. The approach was able to satisfactorily capture the scatter of the experimental results under both static and fatigue loading.

The critical stress range for the FRP materials considered in this study for a fatigue life of 10 million cycles ranged from 11 to 34% of the ultimate static strength.

Many factors affect fatigue behavior, and no attempt is made here to draw general conclusions from the limited available data. Nevertheless, the proposed probabilistic approach is versatile and can be used to estimate fatigue lives of FRP components if sufficient experimental data is available for calibration.

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