FATIGUE BEHAVIOR OF A CARBON FIBER SMC-R UNDER UNIAXIAL AND COMBINED STRESSES

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Abstract

Randomly oriented short fiber reinforced sheet molding compound composites (SMC-R) are among the most commonly used composites for automotive and many non-aerospace structural applications. There is also a growing interest in using carbon fiber SMC-R composites in structural components in both automotive and aerospace industries. The current study considers fatigue characteristics of a randomly oriented carbon fiber SMC-R under both uniaxial and biaxial stress conditions. A modified Arcan specimen was used to conduct the biaxial stress tests involving both tensile and shear stresses. Since the fatigue life data exhibited significant variation, a statistical analysis was conducted to analyze and predict the variations in the fatigue life of the material.

Background and Requirements

Sheet molding compounds with randomly oriented short fibers (SMC-R) are a low cost, lightweight composite alternative to conventional materials in many structural and semi-structural applications. They exhibit relatively high modulus-density and strength-density ratios, and a planar isotropic characteristic. The compression molding process for transforming flat SMC-R sheets to complex composite parts is now well established. The quasi-static behavior of glass fiber SMC-R is well documented in the literature [1-7]. Carbon fiber SMC-R which is being investigated in this study has significantly higher mechanical properties compared to glass fiber SMC-R and can potentially be used in more demanding applications. However, there has been limited research on the mechanical behavior of carbon fiber SMC-R, especially on their durability characteristics under fatigue loading conditions. Previous studies have focused on uniaxial fatigue behavior of glass fiber SMC-R in pure tension [1, 6 and 7] and have documented variations in fatigue life similar to the static tests. In the present study, experiments were conducted to determine the fatigue behavior of a carbon fiber SMC-R under tension, shear and combined tension/shear loading conditions. A butterfly shaped modified Arcan specimen [8], capable of inducing both uniaxial as well combined loading on the specimen, was used.

Experiment

The material used in this experimental study is a carbon fiber SMC-R supplied by A. Schulman. It contains a mix of 25 mm and 50 mm long chopped 3K-PAN carbon fibers in an epoxy matrix with a fiber weight fraction of 0.52. The SMC-R plates were compression molded using a stack of three layers to obtain final dimensions of 300 mm x 300 mm x 3.18 mm (thickness). The basic mechanical properties of the material as provided by the material supplier are listed in Table I.

Table I: Properties of carbon fiber SMC-R

Property	Value
Density	1.45 g/cm^3.
Tensile Modulus / Tensile Strength	37.92 GPa / 290 MPa
Compressive Stress (at break)	276 MPa

The fatigue tests were conducted using a butterfly shaped Arcan specimen shown in Figure 1. Its external dimensions are 75 mm x 50 mm and it contains two opposing 90° notches with 10 mm radius at its mid-length. The region between the notches is called the significant section. The specimen dimensions were selected to create a nearly uniform stress distribution across the significant section and were determined after conducting a parametric study using ABAQUS finite element software. The tests were conducted on an MTS 210 servo-hydraulic test system. The modified Arcan specimen was clamped onto a circular test fixture (Figure 2) containing two front and two back steel plates which contain bolt holes drilled at 15° intervals. The fixture was mounted on the testing machine using three pins at both fixed and moving ends of the loading arms of the MTS machine. By mounting the specimens at different loading angles (α) with respect to the loading axis (Figure 2), the loading condition on the specimen can be varied from uniaxial tension to uniaxial shear with combined tension and shear in between.

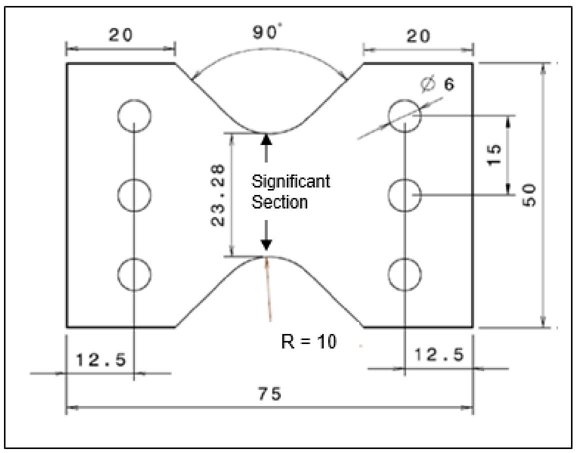


Figure 1: Arcan Specimen Dimensions.

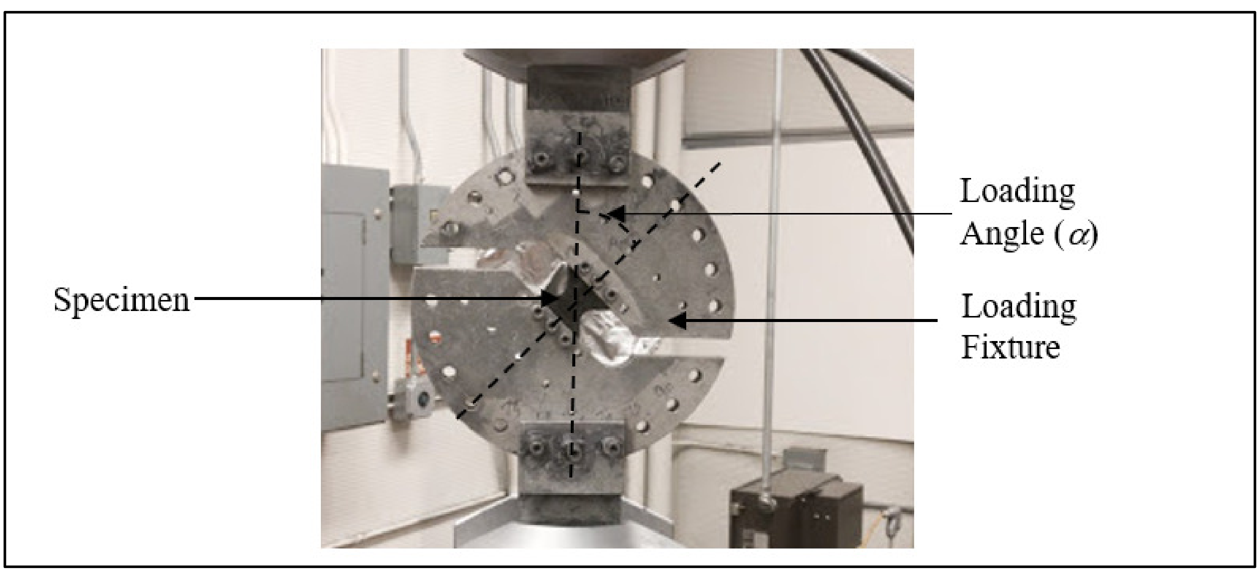


Figure 2: Arcan specimen mounted in the modified Arcan fixture.

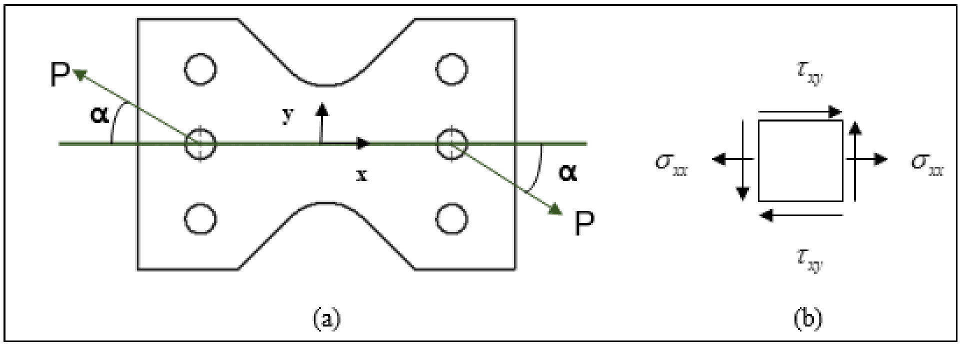


Figure 3: (a) Load acting on the specimen at an angle α. (b) Stress element at the significant section of the specimen with normal (σ_{xx}) and shear (τ_{xy}) stresses.

Figure 3 schematically shows a specimen subjected to load P at a loading angle α and a stress element in the significant section. The average nominal stresses in the significant section of the specimen are given by Equation (1). Note that for $\alpha = 0^o$, the only nominal stress in the significant section is σ_{xx} and for $\alpha = 90^o$, the only nominal stress is τ_{xy}. For $\alpha = 45^o$, both σ_{xx} and τ_{xy} are present and they are equal in magnitude.

$$\sigma_{xx} = \frac{P_x}{A} = \frac{P\cos\alpha}{A}, \ \sigma_{yy} = 0 \qquad (1)$$
$$\tau_{xy} = \frac{P_y}{A} = \frac{P\sin\alpha}{A}$$

Fatigue experiments were conducted in a load-controlled mode at 0°, 45° and 90° loading angles corresponding to uniaxial tension, equal tension and shear, and uniaxial shear. Quasi-static monotonic tests were first performed at a crosshead speed of 2 mm/min to obtain the strength of the material at these loading angles. Initially, uniaxial tensile fatigue tests were conducted at a frequency of 2 Hz and a maximum stress of 86 % of static tensile strength. These tests showed no failure up to 200,000 cycles. Further tests at this frequency were discontinued due to long experiment time. A higher frequency of 10 Hz was then used for the rest of this study. A fatigue load ratio of 0.1 was used and the fatigue life run out was set to 2 million cycles. The cyclic load and displacement data were recorded at a frequency of 100 Hz.

Fatigue Test Results

The fatigue test results are shown in a maximum cyclic stress (S) vs. fatigue life (N) plots in Figure 4. The results show significant scatter in fatigue life, which can be attributed to variation in fiber orientation and distribution in the tested specimens. Large scatter in strength data was also observed in quasi-static tests [9]. For example, with 0° loading angle, the tensile strength ranged from 198.29 MPa to 310.71 MPa. At 45° loading angle corresponding to a combination of equal tensile and shear stresses, the tensile strength ranged from 101.20 MPa to 144.66 MPa. The mean tensile strengths determined using 2-parameter Weibull statistics were 256.24 and 123.8 MPa, respectively. The mean strength values at all three loading angles are listed in Table II.

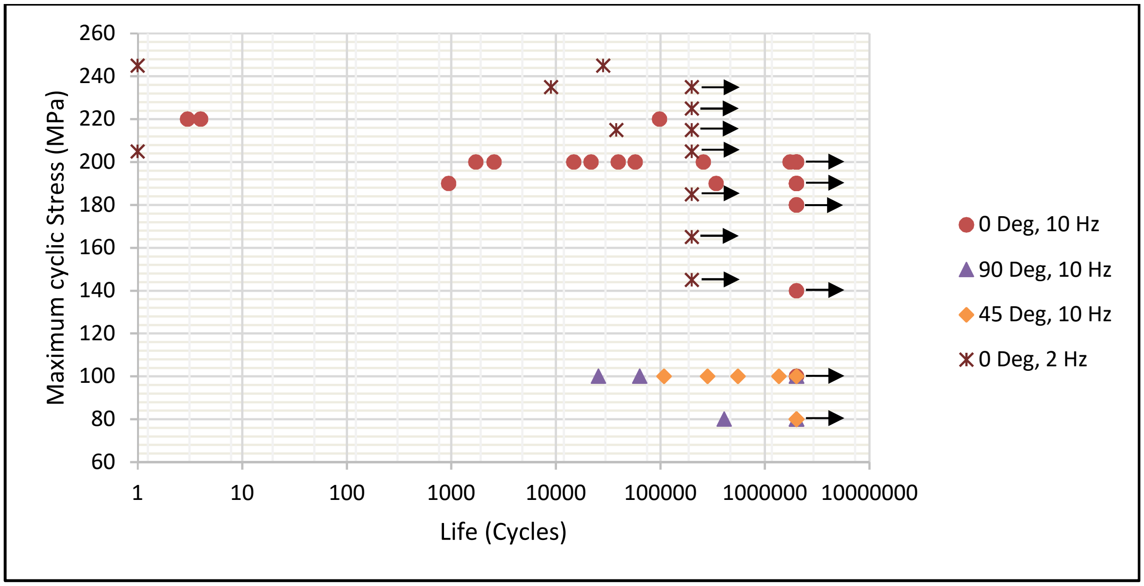


Figure 4: Fatigue Test Data of 27 Specimens at 0º, 10 Specimens at 45º and 10 specimens at 90º Loading Angles (the arrow to the right indicates run-out at 2 x10⁶ cycles).

Table II: Quasi-static strength data

Loading Angle	Stress Condition	Mean tensile stress at peak load (MPa)	Mean shear stress at peak load (MPa)
0	Tension only	256.24	0
45	Equal Tension and Shear	123.8	123.8
90	Shear only	0	149.2

The tensile fatigue tests at 0° loading angle were conducted at different maximum cyclic stress levels ranging from 100 MPa to 220 MPa. At 220 MPa, which is 86% of the mean static strength, two specimens failed in less than 5 cycles, while the third specimen failed at 97,800 cycles. Subsequent fatigue tests were conducted on 24 specimens at different maximum stress levels ranging from 100 and 200 MPa. No failure was observed in 2 million cycles below a maximum cyclic stress level of 180 MPa. At 190 and 200 MPa maximum stress levels, fatigue life ranged from 945 cycles to over 2 million cycles. There was no major difference in the variation of fatigue life for specimens taken from different plates.

Under biaxial fatigue with 45° loading angle, no failure was observed up to 2 million cycles at a maximum stress of 80 MPa which is 64.6% of the static strength. However, the fatigue life decreased sharply at 100 MPa, with failure observed at as low as 108,000 cycles. In the case of shear fatigue experiments with 90° loading angle, failure was observed at 406,600 cycles at a maximum cyclic stress of 80 MPa in one test, which is 53.6% of the static strength; none of the other specimens tested at this load level failed. At 100 MPa or 67% of static strength, failure was observed in two tests at 25,500 and 63,503 cycles, while three other specimens reached the run-out limit. Further tests at higher cyclic stresses were not conducted as the maximum stress would be quite close to the static strength of the material.

Figure 5 plots the stiffness (calculated as the ratio of the maximum load and maximum displacement) vs. fatigue cycles under uniaxial tensile fatigue load and a maximum cyclic stress

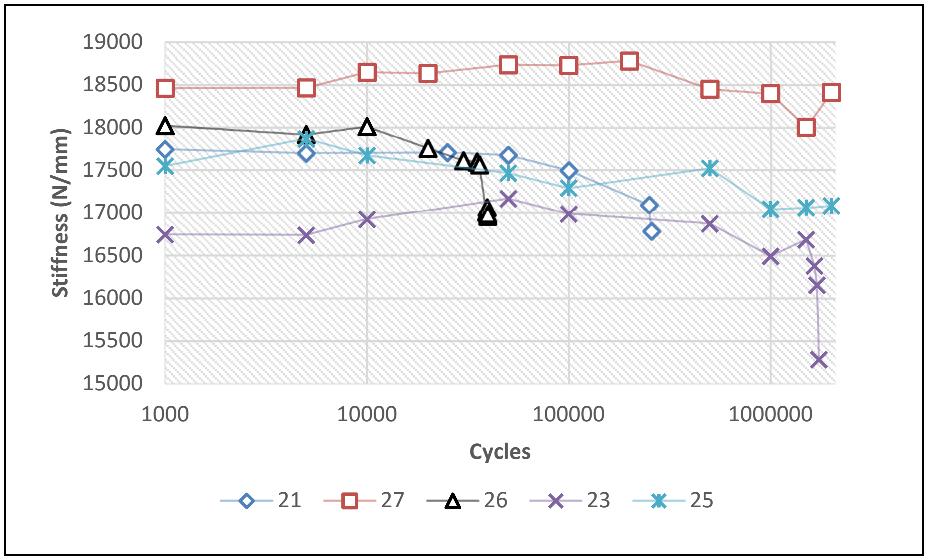


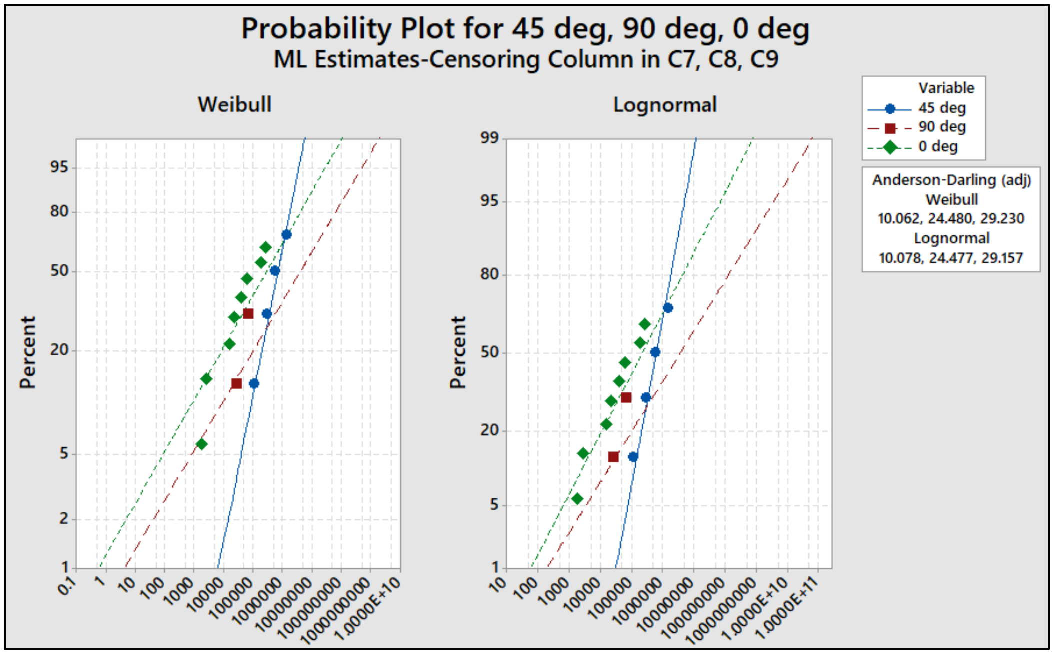
Figure 5: Stiffness variation in specimens during tensile fatigue test at 200 MPa maximum cyclic stress. The loading angle is 0º.

of 200 MPa. Here also, the variability in fatigue performance can be observed. Specimens 21, 23 and 26 which failed at 2.571 x 10^5, 1.739 x 10^6 and 39,650 cycles respectively show a sudden decrease in stiffness just prior to failure. Specimens 25 and 27 did not fail in 2 x 10^6 cycles and show a gradual decrease in stiffness over the duration of fatigue cycling.

Statistical Analysis of Fatigue Test Data

Due to the large variation in the fatigue life data at each load level, statistical analysis was conducted to predict the fatigue performance of the material. The best fit for the fatigue life values was obtained using standard maximum likelihood methods. The statistical software MINITAB (version 17.3.1) was used to fit Weibull and Lognormal curves to the experimental data and Anderson-Darling test was used to determine the best fit curve. The data was right-centered at 1 million cycles to account for the run-out. Figure 6 plots the probability distribution with Weibull and Lognormal fits for 0º, 45º and 90º data at maximum cyclic stress levels of 200 MPa, 100 MPa, and 100 MPa respectively. The y-axis represents the probability of failure in percent and the x-axis represents the cycles to failure. The Anderson-Darling test shows that the best fit is different for each case. A similar approach is performed for the other load steps as well.

Figure 7 and 8 plot the S-N curves of the material under pure tension, pure shear and combined tension and shear loading cases. These curves were obtained with a probability of failure at 10% or 90% reliability. Figure 7 shows the S-N plots with maximum cycle stress versus number of cycles and Figure 8 plots the cycles to failure as a function of maximum stress in terms of percentage of static failure stress. The S-N curve under combined tension and shear loading is close to the S-N curve under shear loading, and both are much lower than the S-N curve under pure tension. Looking at the data as a fraction of the static strength, the fatigue strength under 45º loading is similar to the tensile fatigue strength. The shear fatigue strength as a fraction of its static strength is much lower.



(a) *(b)*

Figure 6: (a) Weibull and (b) Lognormal probability plots of the fatigue life data for 45º, 90º and 0º results at 100 MPa, 100 MPa and 200 MPa respectively.

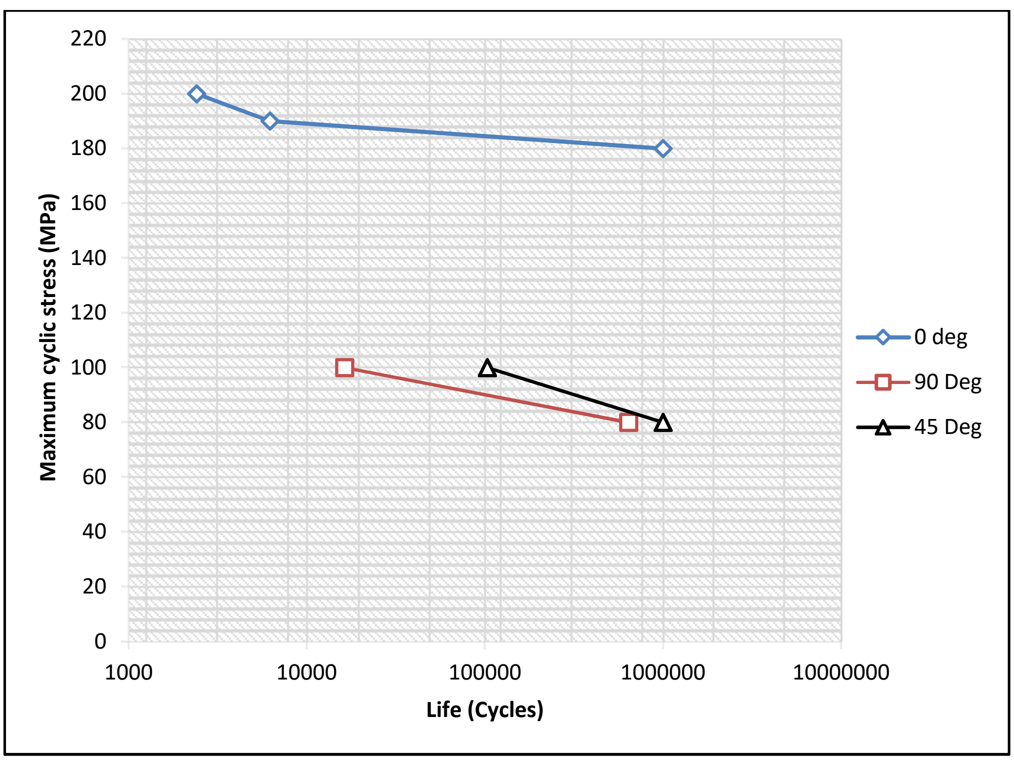


Figure 7: SN curves at 90% reliability under tension (0 deg), shear (90 deg) and combined equal tension and shear (45 deg) fatigue load

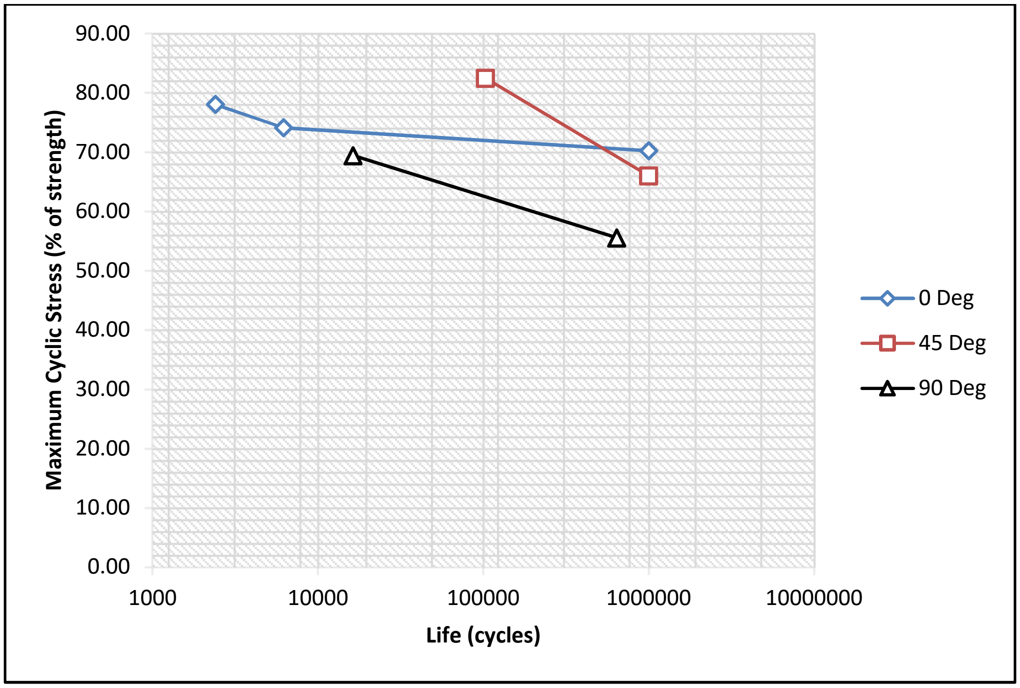


Figure 8: SN curves at 90% reliability as a fraction of static strength under tension (0 deg), shear (90 deg) and combined tension and shear (45 deg) fatigue load.

Summary and Next Steps

The fatigue behavior of a carbon fiber SMC-R was investigated under tension, shear and combined tension-shear conditions. Since a large variation in fatigue life was observed, standard maximum likelihood methods were used to plot the S-N curves at 90% reliability. The fatigue strength of the material under pure shear and combined tension and shear is much lower than the fatigue strength under pure tension. As a percentage of static strength, the fatigue strength at 1 million cycles is about 70% of its static strength in pure tension as well as combined equal tension and shear. Under pure shear loading, the fatigue strength is about 50% of the static strength. Further fatigue testing of the material under different tension-shear ratios will be the next step to obtain a detailed understanding of the material under different biaxial loading conditions.

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