R-RATIO EFFECTS ON GLASS-REINFORCED POLYMER COMPOSITE LIFE AND REMAINING STRENGTH

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Keywords: *Composite, R-ratio, fatigue, remaining strength, vinyl-ester, GRP*

Abstract

This paper describes recent work that is aimed at understanding and modeling the effect of R-ratio (ratio of minimum applied stress to maximum applied stress) on the fatigue life and remaining strength of glass-reinforced polymer composite materials, and which is part of a larger effort to develop predictive, reliability-based models utilizing the Load and Resistance Factor Design (LRFD) approach.

Experimental fatigue and remaining strength testing were performed at R-ratios of R=0.1, R=-1, and R=10 on materials manufactured using two closely related resin systems. As expected, the experimental results show that the damage accumulation and failure modes are qualitatively different for different R-ratios. However, an empirically based remaining strength model that was acceptable for R=0.1 is shown to be unacceptable for R=-1 and R=10.

A future paper will more closely investigate the damage accumulation modes present at different R-ratios in the hopes of developing a more mechanistic and generally applicable model.

1 Introduction

E-glass/vinyl-ester composites are increasingly being used in naval and civil applications in which they may be subjected to spectrum cyclic stresses of randomly varying magnitude and sign. It is important to understand how such loading affects the remaining strength of the composite, and to be able to predict the remaining strength (and lifetime) as a function of the loading.

Load and Resistance Factor Design (LRFD) [1] is one method of life prediction for composite materials. In this method, the loads and material properties (such as strengths) are taken to be stochastic in nature.

Therefore, in order to implement the LRFD approach, the statistical attributes of the material properties on which the model depends must be known, and this knowledge requires fairly extensive testing for characterization of the material as pertains to a variety of loading and environmental conditions, such as the effects of R-ratio, loading frequency and order, temperature, moisture, chemical and UV exposure, etc.

Towards this end the authors are part of an on-going program [2,3,4] with a goal of developing a material database, which when combined with a suitable and robust life-prediction methodology, will enable a more complete and accurate approach to reliability-based design and life prediction of composite materials.

Empirical Goodman diagrams detailing the effect of R-ratio on the spectrum fatigue life of fiberglass composites for use in wind turbines has been extensively investigated [5,6]; these studies have primarily used Goodman diagrams to analyze data for fiberglass/polyester composites involving tensile-tensile, tensile-compressive, and compressive-compressive loading. The authors then use these Goodman diagrams to predict failure in coupons tested using load spectra that are commonly used in the wind turbine industry and which are primarily tensile in nature.

The work presented in this paper will establish partial Goodman diagrams for materials typically used by the US Navy and will focus on constant-amplitude fatigue loading of nearly-quasi-isotropic, E-glass/vinyl-ester laminates commonly used in naval applications; the knowledge gained in this and follow-on studies will be of help in ongoing studies [2] investigating spectrum loading of these laminates, as well as longer-term efforts to combine knowledge of all of the loading and environmental effects mentioned above into a general composite life prediction tool.

2 Material/Test Methods

The materials examined in this study were 10-ply nearly-isotropic E-glass/vinyl-ester composites with a schedule of $[0/45/90/-45/0]_s$. Two material data sets were examined. The fiber reinforcement for both was Vetrotex 324 woven-roving fabric (note the schedule orientations refer to the warp direction of the fabric). The polymer matrices were Ashland Derakane 510A, a fire-resistant brominated vinyl-ester epoxy; and Derakane 8084, a similar resin with added toughening agents. The straight-sided specimens, which were 152 mm long and 25.4 mm wide, were cut from an 890x890mm panel manufactured using the VARTM (vacuum-assisted resin transfer molding) process. Prior to testing, the edges of the samples were surface ground to ensure consistent widths and parallelism.

The fatigue behavior of both materials were first characterized by developing S-N curves for three different R-ratios (R=0.1, R=-1, and R=10.) The remaining strength testing reported in this paper pertains only to the 510A composite, as the testing is in progress for the 8084-based material and will follow the same method. From each of the S-N curves from the 510A-based composite material, two stress levels were chosen for investigation into the remaining strength analysis. At each of these stress levels, remaining strength tests were performed by cycling the specimen through one of four specific percentages of the mean lifetime predicted by the S-N curve (10 samples at each lifetime percentage). The specimens were then monotonically loaded until failure and the breaking strength was recorded. All quasi-static remaining strength tests were performed at a loading rate of 667 N/sec. It is important to note that the testing of the composite with Derakane 510A matrix was performed at 10 Hz, while the toughened 8084 composite material was tested at 5 Hz. This difference lead to significantly different rates and degrees of viscoelastic heating, and therefore should be kept in mind when the data sets are compared directly.

3 Modeling

Many approaches have been developed to model and predict fatigue life and remaining strength. Some of the more important of these models are described in [7]. Recent efforts at Virginia Tech have used the remaining strength model first proposed by Case and Reifsnider [8]. This model is a nonlinear damage accumulation model that employs one curve-fitting parameter to fit empirical residual strength data.

This model has been successfully used in the past to model constant-amplitude fatigue life at R=0.1 (tension-tension loading.) However, current research efforts by the authors and their colleagues have begun looking at developing predictive, reliability-based models of GFRP (glass fiber reinforced polymer) composite remaining strength for spectrum (i.e. variable amplitude) loading. This paper details a portion of this work, in which the effect of the R-ratio on the constant-amplitude fatigue behavior and remaining strength is investigated in the hopes that the knowledge gained will help extend the model to variable-amplitude loading.

The model assumes a two-parameter Weibull distribution for material properties, such as the initial strength of the material, given by Eq. 1, below:

$$P_f = 1 - \exp\left[-\frac{\sigma_{init}}{\beta} \right]^{\alpha} \qquad (1)$$

where α and β are the Weibull shape and location parameters, respectively.

The Case & Reifsnider remaining strength prediction model [5] is shown in Eq. 2,

$$Fr(n) = 1 - \left[\int \left\{ \frac{(1 - Fa(n))^{1/j}}{N(Fa)} \right\} dn \right]^{j} \qquad (2)$$

where n is the number of cycles, Fr is the normalized remaining strength (normalized by the median initial strength), Fa is the normalized applied stress, N is the number of cycles to failure at a given load Fa, and j is a curve fitting parameter. For constant amplitude loading, Eq. 2 reduces to Eq. 3:

$$Fr(n) = 1 - (1 - Fa(n)) \left(\frac{n}{N(Fa)} \right)^{j} \qquad (3)$$

Failure is considered to occur when the applied stress is equal to or greater than the residual strength. That is, the material fails when

$$Fr(n) \le Fa(n) \qquad (4)$$

The purpose of this study is to determine if the model is capable of adequately modeling remaining strength history for R-ratios other than R-0.1, specifically R=-1 and R=10.

4 Results

The S-N curves for the three different R-ratios tested show not only quantitative differences in the lifetimes predicted for a given applied load, but also show qualitative differences in the nature of the curves. This is especially true for the untoughened (Derakane 510A) material. At R=0.1 (tension-tension), the data fall on a single power-law curve of the form

$$\log(N) = A\log(\sigma) + B \tag{3}$$

where N is the lifetime in cycles, and σ is the applied stress.

For the untoughened Derakane 510A composite at R=10 (compression-compression), the data are not well fit by a single power law curve, and seem to instead lie on two curves of significantly different slope (see Fig. 1). That is, the slope for lifetimes above approximately 10,000 cycles is substantially shallower than that below 10,000 cycles.

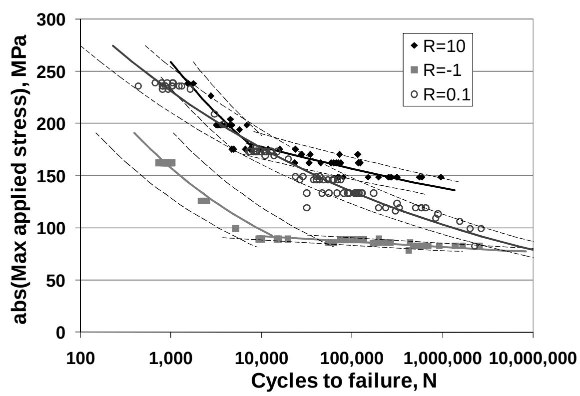

Fig. 1. S-N curve for E-glass/510A composites for three R-ratios with 95% confidence intervals.

Furthermore, for this same material at R=-1 (fully-reversed), this bi-linear nature of the data is more pronounced. The slope of the S-N curve above approximately 10,000 cycles is extremely shallow, leading to large scatter in the data in this portion of the curve. It is thought that the bi-linear nature of the R=-1 curve, and to a lesser extent the R=10 curve, is suggestive of a change in the dominant damage mode when changing from high applied stress to low applied stress. Another phenomenon that may be tied to the mode of damage accumulation and failure is that of temperature rise caused by viscoelastic heating of the specimens, since the nature of the specimen surface temperature time history is largely dependent on the applied loading (as well as the frequency, which, as mentioned above, was 10 Hz for this material).

The toughened Derakane 8084 composite material did not exhibit the same pronounced bi-linear S-N curves as the Derakane 510A material. For each of the three R-ratios examined, the S-N data were reasonably fit using a single power law equation of the form of equation 3. The data with 95% confidence intervals are shown in Fig. 2. The S-N curve fitting parameters, A and B, from Eq. 3 are summarized in Table 1.

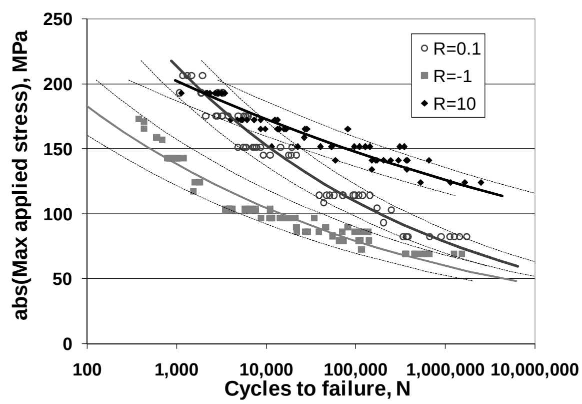

Fig. 2. S-N curve for E-glass/8084 composites for three R-ratios with 95% confidence intervals.

The S-N data shown in Figs. 1 and 2 can alternatively be displayed in Goodman diagrams similar to those constructed in [5] and [6] (see Figs. 3 and 4.)

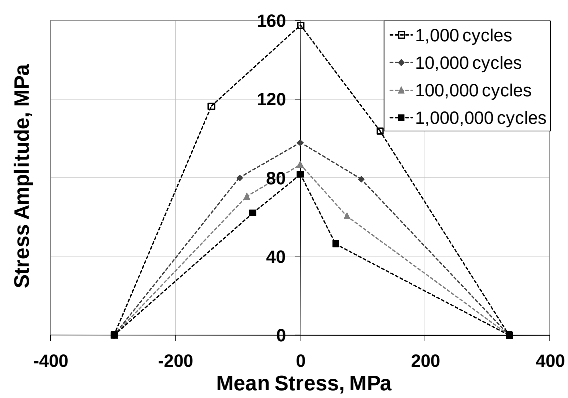

Fig. 3. Goodman diagram for E-glass/510A composites for three R-ratios with 95% confidence intervals.

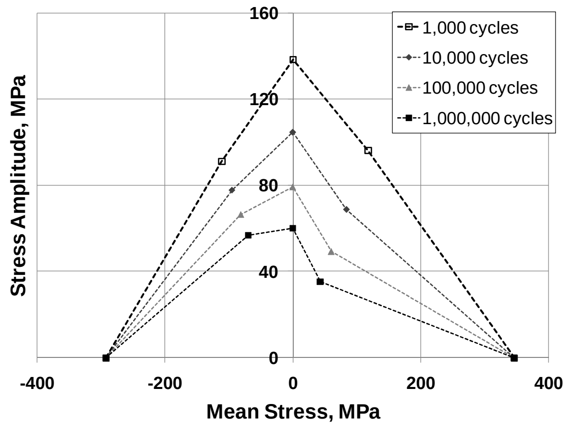

Fig. 4. Goodman diagram for E-glass/8084 composites for three R-ratios with 95% confidence intervals.

Table 1. S-N curve parameters *A* and *B* from Eq. 3.

	<10,000 cycles		Material system
R-ratio	**A**	**B**	
0.1	-8.57	41.8	**E-glass / 510A**
-1	-4.83/-38.5*	24.0/162.7*	
10	-5.52/-18.3*	28.3/84.8*	
0.1	-6.88	33.9	**E-glass / 8084**
-1	-8.27	38.6	
10	-14.6	68.2	

**Two values given for bi-linear curves*

Examples of the remaining strength data for the E-glass/510A material are shown in Figs. 5, 6, and 7. It can be seen that the remaining strength trends throughout the sample life are different for each R-ratio. For R=0.1, the remaining strength generally falls off at a relatively constant rate during the majority of the life. At R=-1, the remaining strength seems to degrade mostly in the latter half of the life. And for R=10, the samples generally experience "sudden death", in which very little loss in strength is observed throughout most of the life until the very end of the life, at which point the strength degrades very rapidly. It is by fitting the model to this data (using a least-squares regression analysis) that the parameter *j* is determined for each loading case.

The model described in section 3, which successfully models the remaining strength behavior for R=0.1 (that is, it is able to fairly well fit the experimental cumulative distribution functions, Fig. 8, of the remaining strength distributions), has been shown to be inadequate to describe the remaining strength behavior for compression-compression loadings (R=10) and for fully-reversed loading (R=-1). For these R-ratios the experimental data are not well fit by the model-predicted CDF for the 510A-based material. It is unclear whether the on-going remaining strength testing on the E-glass/8084 material will reveal similar trends.

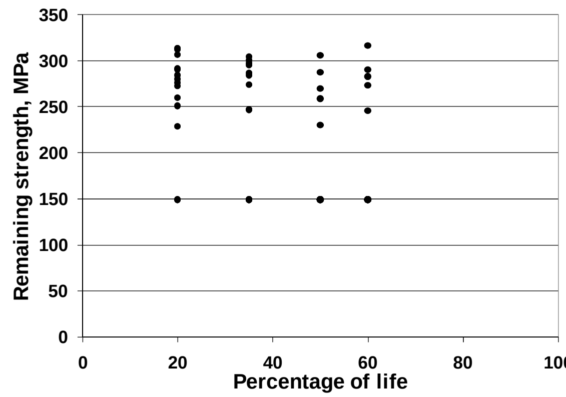

Fig. 5. Remaining strength for E-glass/510A composites at R=10 and a cyclic load of 50% of the ultimate compression strength (UCS).

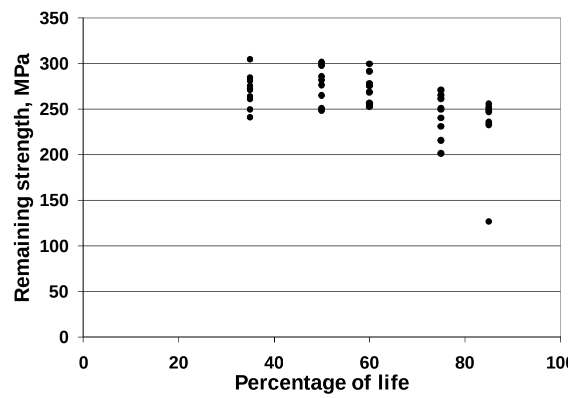

Fig. 6. Remaining strength for E-glass/510A composites at R=-1 and a cyclic load of 30% of the ultimate compression strength (UCS).

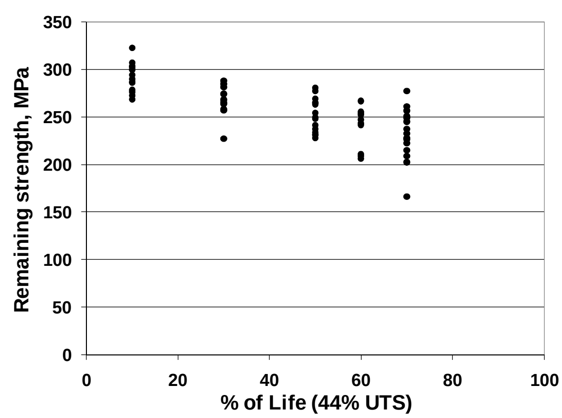

Fig. 7. Remaining strength for E-glass/510A composites at R=-1 and a cyclic load of 30% of the ultimate compression strength (UCS).

It is thought that the shallow slopes of portions of the S-N curves cause numerical issues for the model for the 510A material, in which the high-cycle portion of the R=-1 S-N curve is extremely shallow. It can be said, therefore, that the model is unable to describe the varying damage modes of the various R-ratios. This is not surprising, given that the model relies on curve-fitting and is not based fundamentally on a micromechanics model that is able to account for varying damage accumulation modes.

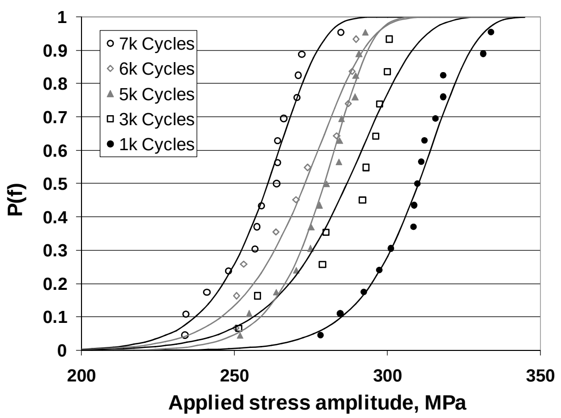

Fig. 8. Experimental cumulative distribution functions (CDF) for remaining strength, at a tension-tension loading level of 44% of the ultimate tensile strength.

5 Future work

The remaining strength testing is ongoing for the E-glass/8084 material. When this is complete, a further assessment of the current remaining strength model will be made based on those results. However, the model's inability to fit the E-glass/510A data at R=10 and R=-1 suggests the necessity of a refined or altogether new model.

This new model may take the form of another curve-fitting model. Or it may be one based to some extent on mechanics on the micro or macro scale. While it is unlikely that a model will be developed that is solely micro-mechanics based, nevertheless an improved understanding of the damage mechanisms present in composite materials may very well facilitate an improved remaining strength model that may handle a wider range of loading conditions.

Upcoming work at Virginia Tech will investigate these issues through various destructive and non-destructive damage assessment techniques. Non-destructive methods include video monitoring, in which video of a back-lit sample is recorded and numerically evaluated to arrive at an estimate of damage area, as well as edge replication, in which acetate tape is used to replicate the edge of a damaged sample for later microscopy and crack counting. Destructive methods include microscopy of ground sample segments cut from testing coupons at various damage states. It is hoped that some or all of these methods, alone or together, will provide insight into the damage mechanisms and damage progression paths for various loading conditions.

6 Conclusions

The differing damage mechanisms present in E-glass/vinyl ester composite materials under different loading conditions leads to qualitative and quantitative differences in the fatigue life curves, as well as the remaining strength behavior.

The remaining strength model used in previous work at R=0.1 is unable to capture the behavior of E-glass/510A vinyl-ester composites under compression-compression fatigue (R=10) or fully reversed fatigue (R=-1). Future work will focus on identifying the varying damage and failure modes seen in fatigue as a function of R-ratio and loading level. Also, an improved model will be sought which will incorporate this knowledge to predict the remaining strength and lifetime at various R-ratios.

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