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FATIGUE DAMAGE AND COMPRESSIVE RESIDUAL STRENGTH OF A WOVEN PMC SUBJECTED TO CYCLIC HYGROTHERMAL CONDITIONING

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ABSTRACT

An experimental investigation was conducted to characterize the elevated temperature, fully reversed fatigue response of a hygrothermally conditioned carbon fiber reinforced epoxy composite. The material is a 5 harness satin weave in a high temperature epoxy matrix: AS4/PR500. Elastic modulus and residual compressive strength were recorded as a function of fatigue cycle. Unconditioned material is compared to material exposed to 12 khrs of hygrothermal cycle (HC) mission conditioning. Simulating the usage of a gas turbine propulsor component, the HC mission consisted of a 90 minute hold at 121 °C followed by a 22.5hr soak at 30 °C with 85 % nominal relative humidity. Specimens were then machined into a dogbone geometry that was developed and verified for fully reversed fatigue and static compression testing without anti-buckling supports. Fully reversed fatigue data revealed a deterministic stress-life response. The 12 khrs HC conditioned material experienced an 11 % strength degradation when compared to baseline data prior to mechanical fatigue loading. Residual compressive strength measurements were made at specified compressive modulus degradation levels. When correlated with compressive modulus, these strength data showed a clear degradation due to the HC conditioning. Work is underway to characterize material conditioned to 30 khrs.

KEYWORDS

Fatigue damage, hygrothermal conditioning, compressive properties, composites, residual strength.

INTRODUCTION

By improving their economy and quality, advances in fully automated composite fabrication techniques have led to wider use of 2-D and 3-D woven polymer matrix composite (PMC) materials in aerospace applications. However, predicting long term fatigue damage progression and durability of PMC materials under prototypical environments remains a challenge. Here, elevated temperatures, ambient moisture levels, and their combined synergistic effects can lead to enhanced degradation rates [1]. These issues are of particular concern for cases where the potential applications are primary/load bearing structures. Compensating for the lack of accurate predictive methods in the area of fatigue durability has resulted in over-conservative designs that often mitigate the advantages of using PMCs in primary components.

To address these issues, an experimental investigation was made of the fatigue damage progression and damage tolerance of a 5-harness satin carbon fiber reinforced epoxy composite, AS4/PR500, subjected to fully reversed cyclic loading. Two datasets were created and examined. The first is the baseline data for the material behavior without environmental conditioning, i.e., 0 hrs. The second dataset consisted of material that underwent 12,000 hrs (12k hrs) of hygrothermal cycle (HC) conditioning. The elevated temperature fatigue behavior and damage progression was tracked through the measurement of the real-time tensile and compressive modulus. One unique feature of the work was to quantify the severity of fatigue damage via residual compressive strength measurements made at various degrees of *actual* compressive modulus degradation. Specifically, samples were subjected to residual compressive strength tests at approximately 0, 2.5, 5, and 7.5 % reductions of their initial compressive modulus. These data illustrate a relationship between fatigue damage progression as measured by the material's effective modulus and the material's damage tolerance while avoiding all assumptions with respect to the percentage of cyclic life. This detailed examination was completed on material from both datasets and then the data trends were compared.

MATERIAL AND EXPERIMENTAL DETAILS

All material was fabricated by a resin transfer molding (RTM) process at Dow U.T. (USA) from a single batch of resin and fiber mat into thick laminates (16 ply, 6.1 mm) with panel dimensions of 63.5 x 63.5 cm. Test coupons were machined using a diamond wheel grinding process. The HC conditioning, illustrated in Fig 1, was a nominal 85/30 (85 % relative humidity at 30 °C) exposure combined with a daily "mission cycle" consisting of a 90 minute exposure at 121 °C in a forced air convection oven. The cycle was selected as representative of a static component in the propulsor region of a gas turbine engine. The 12 khr conditioning was conducted on the material in large panel form prior to cutting the test coupons to avoid edge effects influencing the mechanical properties. The weight gain, shown in Fig. 2, was monitored using a traveler panel with a width to thickness ratio of 25 to 1. Note that the 90 min cycle at 121 °C was sufficient to prevent the material from reaching a moisture equilibrium state, even after 12k hrs. After conditioning and machining of the coupons, all material was vacuum dried for 48 hrs at 105 °C and stored in a dessicator until immediately prior to testing. Mechanical testing was performed on a computer controlled servohydraulic test frame. A radiant mini-furnace was used for specimen heating and strains were measured using edge-mounted extensometers with a 12.7 mm gage length. All mechanical testing was performed at 121 °C in a laboratory air environment.

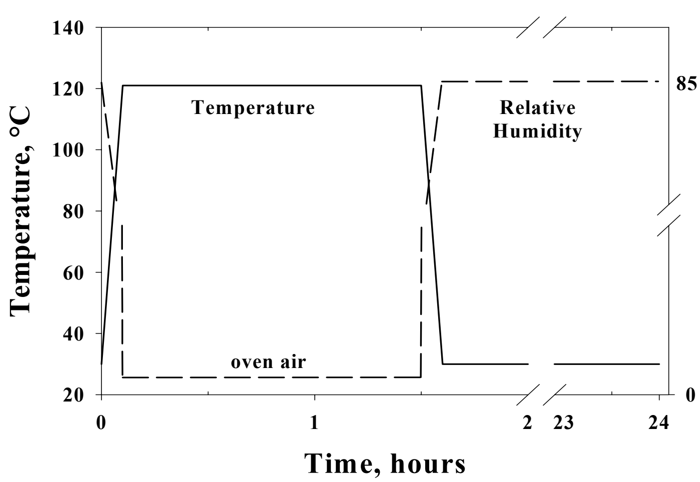

Fig. 1-Hygrothermal Cycle (HC)

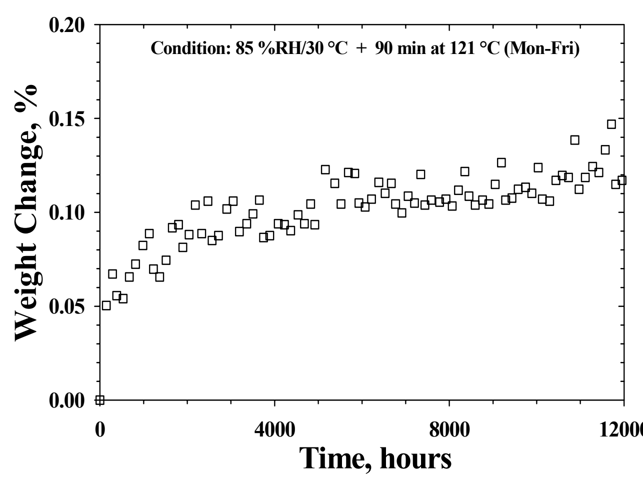

Fig. 2-Weight gain during HC conditioning.

All fatigue tests were conducted under fully reversed loading conditions. Fully reversed fatigue testing of composites is relatively uncommon due to buckling instability issues. Anti-buckling guides may be used, but problems like frictional ware and thermal influences at elevated temperatures are also formidable [2]. The current research used thick laminates with a refined dogbone specimen design (Fig. 3) and an experimental setup that served to significantly reduce specimen instabilities. The design viability was verified by comparing the compressive strength results to those obtained using the standardized Celanese fixture (ASTM Standard D 3410). Ultimate strength results showed good agreement [3]. The specimen stability and experimental set-up were further evaluated by examining the compressive behavior while monitoring the strains on opposite faces of the sample. Deviation of these two measurements is a good indicator of the most likely state of bending. This result is shown in Fig. 4 along with the extensometer strain measurement. The results indicate minimal bending until immediately prior to failure. Further, the maximum fatigue strain ranges examined do not exceed ±0.7 % which are well within the regime absent of significant bending.

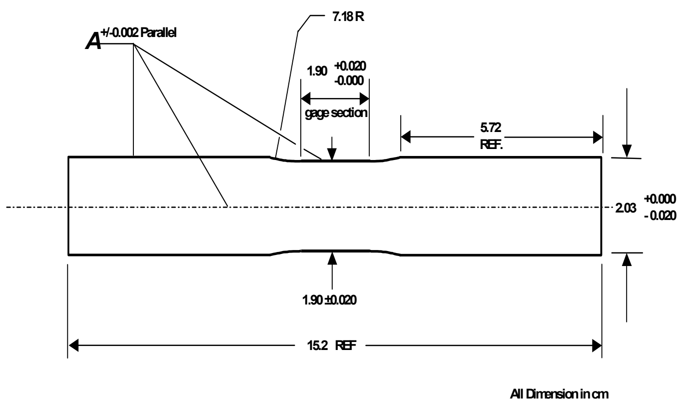

Fig. 3-Dogbone specimen geometry.

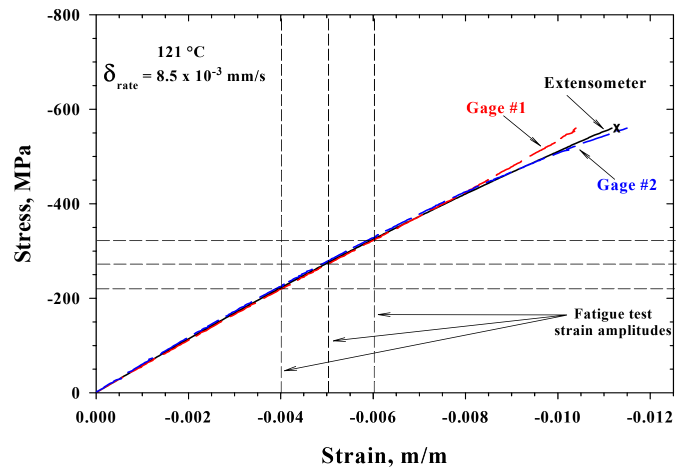

Fig. 4-Static tests indicating a lack of bending at strain ranges consistent with fatigue testing.

The fully reversed fatigue tests were conducted in load-control (R_σ = -1) with load levels selected to yield a specific initial strain range (±0.4, ±0.5 and ±0.6 %). This is consistent with the fact that the design criteria for the intended application is a limiting strain. Samples were subjected to a saw tooth waveform at a frequency of 2 Hz either until complete fracture or until a predetermined reduction in modulus. In the later case, cyclic fatigue was suspended and a residual compressive strength test was performed. All static residual strength tests were conducted at 121 °C with a controlled displacement rate of 8.5 x 10^{-3} mm/s.

FATIGUE LIFE AND MODULUS DEGRADATION RESULTS

The fatigue strength as a function of the number of cycles to complete failure is presented in Figs. 5 and 6. Figure 5 does this in terms of the initial applied cyclic strain range and Fig. 6 does this in terms of the applied cyclic stress range. Data are shown at the ±0.4, ±0.5 and ±0.6 %, strain range, in addition to a datum at ±0.3 % where failure did not occur and the test was terminated at approximately 6 million cycles. The data indicate that HC conditioning does not have a strong influence on the axial fatigue life though some deficit in life may be suggested at the lower load ranges. There appears to be some measure of increased scatter at the longer life/lower strain or stress ranges, as might be expected. One should note that the appearance of the data does not correspond with the 3-regime format generally observed in the results of PMC axial fatigue [4]. The first high stress/high scatter regime, traditionally associated with the probabilistic failure of the fiber, is not present in these results. Due to the fully-reversed loading conditions all of the samples ultimately failed in compression. Compressive loads drive the phenomenon of buckling induced delamination growth which control the compressive strength of the composite [5]. Note that there were clear distinctions between the 0 and 12k hrs samples regarding the failure morphologies and appearance of these buckled delaminations. This will be highlighted later.

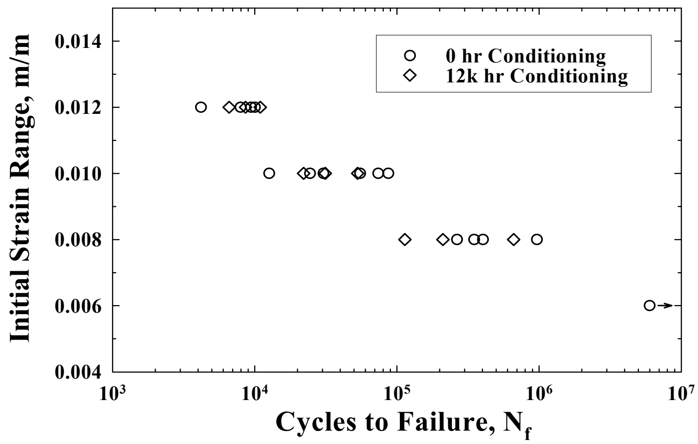

Fig. 5-Fatigue life plot based on initial strain range.

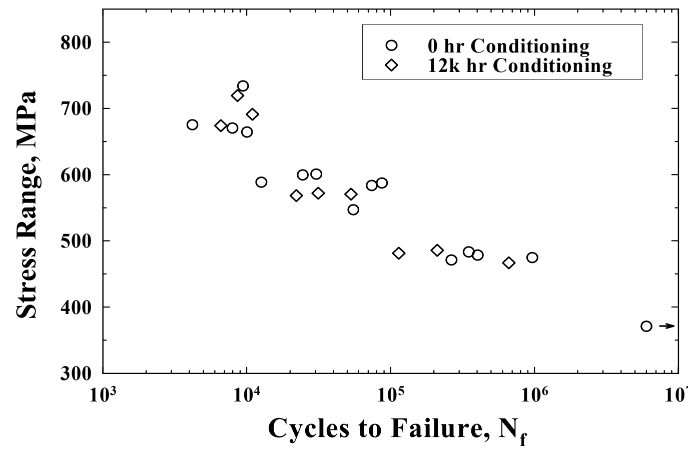

Fig. 6- Fatigue life plot based on stress range.

During fatigue tests, the elastic modulus (E) was checked periodically to determine its degradation or residual value. This was done in both tension and compression. Representative residual compressive modulus data plotted against fatigue cycle are shown in Fig. 7. Results for the 0 hr and 12k hr material are compared for the ±0.4% strain range. The modulus values are normalized with respect to the material's initial modulus (E_o) at the beginning of the fatigue test. The last cycle plotted for each of the two curves represents the point of complete specimen fracture. As illustrated, both the 0 and 12k hrs HC conditioned materials tended to maintain their initial modulus values over the first several thousand cycles. In general, the modulus of the HC conditioned material tended to degrade earlier. A number of samples experienced a slight "stiffening" trend prior to the measurable degradation, as illustrated by the 0 hr data. This may be a result of the woven fabric "locking-up" with the accumulation of deformation.

All observed trends in the modulus response were consistent between tension and compression with the difference being that the compression modulus measurements were generally 2 to 5 % lower for any given sample. In the range of approximately 50,000 cycles and up, the material begins to experience a gradual degradation of modulus that is relatively regular. At the ±0.4 % strain level, the material consistently experienced a minimum of 15 % loss in modulus prior to complete fracture. The following discussion of residual strength and modulus relationships focuses on the ±0.4 % initial strain range fatigue data.

RESIDUAL STRENGTH/MODULUS RELATIONSHIPS

There are several ways to view the material's response to the accumulation of the cyclic hygrothermal and mechanical fatigue damage and its ability to tolerate that damage under an ultimate compressive event. Using the 0 and 12k hr HC conditioned material results for the initial strain range of ± 0.4 %, three different permutations of the residual property fatigue data are presented in Figs.8-10. Fig. 8 shows the residual compressive modulus for each specimen as a function of its total number of fatigue cycles. As expected, the residual compressive modulus decreased in magnitude for specimens with a greater accumulation of fatigue cycles. While this trend is consistent with Fig. 7, the degree of degradation is masked in Fig. 8 by significant sample-to-sample modulus variation. Prior to fatigue cycling the compressive modulus of unconditioned material varied 7.6 % from 53.6 to 57.7 GPa and the HC conditioned material varied 5.8 % from 54.4 to 57.6 GPa. This is common to RTM fabricated woven composites, where variations in local fiber orientation and degree of waviness lead to local variations in properties. The average initial compressive modulus of all the samples were 55.4 GPa and 55.6 GPa for the 0 hr and the 12k hr data sets, respectively. This suggests that the degradation associated with the 12k hrs of HC conditioning had little to no influence on this "effective" property. Subsequent fatigue cycling does not cause any observable difference in the rate of compressive modulus degradation between the two data sets.

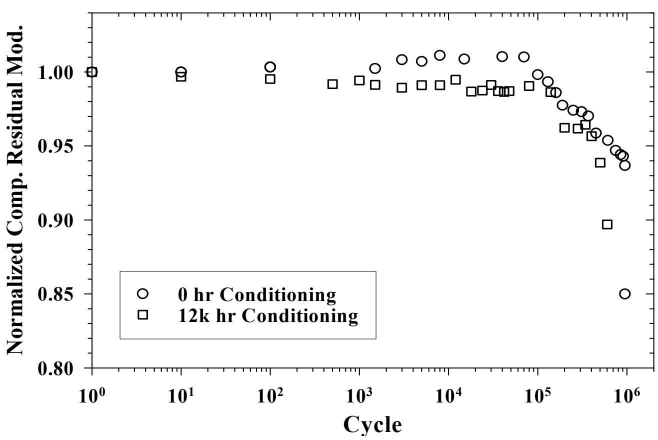

Fig. 7-Representative compressive residual modulus (normalized) during fatigue at the ±0.4 % range.

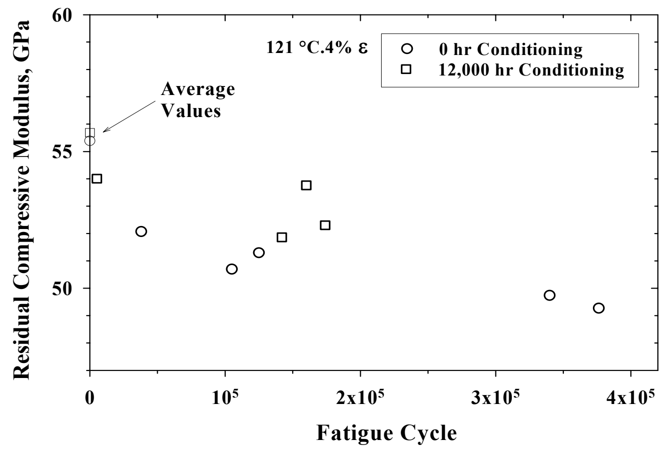

Fig. 8-Modulus values at cycle where fatigue test was suspended prior to residual strength.

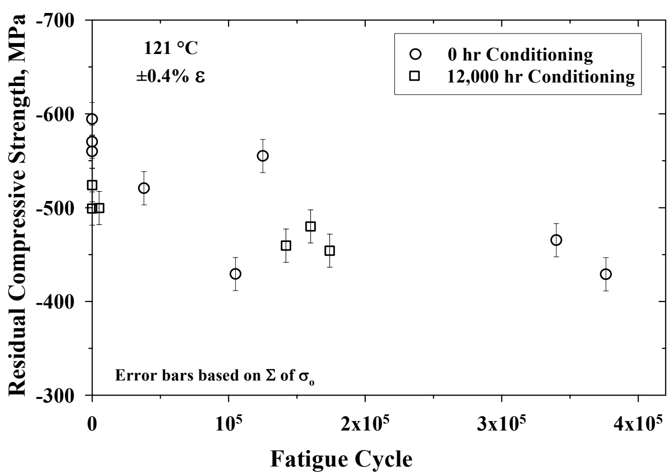

Fig. 9-Residual strength as a function of fatigue cycles.

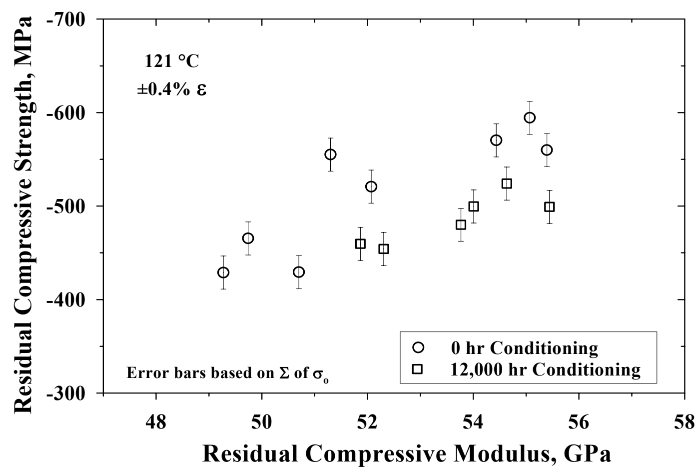

Fig. 10-Residual strength/modulus relationship.

Figure 9 illustrates the residual compressive strength as a function of fatigue cycles. Again, as expected this property reveals a degrading trend with cumulative fatigue cycling. The trends are relatively linear in cycles suggesting more regular "deterministic" response when the damage tolerance is examined as a function of residual compressive strength, as opposed to tensile. It is more common to examine the residual tensile strength properties of composites, and this, in response to tension-tension fatigue. In such cases, modest degrees of fatigue damage are difficult to assess due to the dominating effect of the fiber and its probabilistic failure characteristics [6]. In contrast, residual compressive strength is more likely controlled by the unstable growth of a critically sized buckling induced delamination [5].

Unlike the residual compressive modulus, the residual compressive strength reveals an 11 % on average knock-down due to HC conditioning alone. Damage associated with the HC conditioning may have a greater influence on the extreme values of a defect population (size, spacing) effecting strength, while having an indistinguishable influence on the average distribution of flaw characteristics effecting modulus. Indeed Lacy, McDowell, Willice and Talreja [7] show that different damage distributions may exhibit identical stiffness properties while having markedly different rates of damage evolution and tolerance to damage. The residual compressive strength of the 0 hr and 12k hr datasets are intermingled with the accumulation of mechanical fatigue. This is in spite of clear differences in the observed failure morphologies for the two datasets. Upon static failure, the 0 hr samples generally revealed clean transverse fractures, with only modest ply delamination at the most aggressive states of fatigue damage. In contrast, the 12k hr HC conditioned material revealed extensive delamination, both at the ply and bundle interfaces. This strongly indicates that the damage induced by the HC missions was most degrading to the fiber/matrix interface.

Fig. 10 takes the final step of comparing the compressive residual strengths with the corresponding residual compressive modulus values. Presentation of the fatigue data in this manner is believed to be relatively unique; empirically it infers a proportional relationship between residual strength and modulus. First, it can be stated that each of the datasets independently suggests a consistent relationship between these two properties. Furthermore the 0 hr data are layered above the 12 khr data with the similar proportionality. While the 0 hr and 12 khr material may exhibit similar compressive modulus response, the residual compressive strength of the 0 hr material tends to be greater. This relationship will be further examined with additional conditioning times ranging to 30k hours of the HC exposure.

CONCLUSIONS

In conclusion, an experimental investigation was conducted to examine the fatigue damage progression and damage tolerance of a high temperature graphite/epoxy PMC under fully reversed axial loading conditions with and without hygrothermal cycle conditioning. The specimen geometry performed well at elevated temperature without anti-buckling guides for fully–reversed fatigue and compressive strength testing. A deterministic relationship was found between the applied stress range and the number of cycles to failure; the resulting stress-life data in Fig. 6 maybe used to make design life predictions. Prior to mechanical fatigue loading, the 12 khr material experienced an 11 % strength degradation relative to the 0 hr material. No distinction was found between 0hr and 12 khr material when examining the residual compression modulus and residual compression strength as a function of fatigue cycle. Designers may find that the correlation of residual compressive strength and modulus in Fig. 10, give a clearer representation of compressive strength degradation due to HC conditioning. Evaluation of 30 khrs conditioned material is in progress to verify this trend.

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