

Fatigue Behavior of Neat and Short Glass Fiber Reinforced Polymers under Two-Step Loadings and Periodic Overloads

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ABSTRACT

An experimental study was conducted to evaluate the variable amplitude fatigue behavior of a neat polymer (polypropylene impact co-polymer) and a polymer composite made of polybutylene terephthalate (PBT) with 30 wt% short glass fibers. Fatigue tests were conducted on un-notched and notched specimens at room temperatures. Plate-type specimens were prepared in the transverse direction with respect to the injection mold flow direction and a circular hole was drilled in the center of notched specimens. Two-step loadings (high-low and low-high) tests at two damage ratio of 0.2 and 0.5 at stress ratios of $R = 0.1$ and -1 were conducted to investigate load sequence effects and prediction accuracy of the linear damage rule. Different behaviors were observed for unreinforced and short glass fiber reinforced polymers under the two-step loading tests. Periodic overload tests were also conducted to evaluate the effect of overloads during cyclic loading on fatigue life and this effect was found to be less pronounced for polymeric materials, as compared to metallic materials.

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INTRODUCTION

Applications of polymeric materials including neat and short glass fiber reinforced polymer composites are increasing rapidly in the automotive industry. Reduction of vehicle weight which increases fuel efficiency, reduction of manufacturing cost due to their rapid production rate, design flexibility due to ease of manufacturing in complex geometries, and high chemical resistance are some of the advantages. Most of the applications of polymeric materials in the automotive industry are in components which are exposed to cyclic loading. As a result, fatigue failure is one of the most common types of failure and must be taken into consideration in the design of components made of polymers.

The majority of these components are subjected to complex variable amplitude load histories. Experimental evaluation of the behavior of the component under these load histories is costly and time consuming, therefore, an accurate life prediction method is required. This includes a reliable damage quantification parameter, a robust cumulative damage rule, along with constant amplitude material fatigue data. In addition, understanding of cumulative damage mechanisms is crucial since it provides the important physical bases for modeling the cumulative damage process.

Two-step cyclic loading tests, including low-high (LH) and high-low (HL) tests are usually utilized to investigate the load sequence effect on fatigue behavior and to evaluate the cumulative damage of the

material. Service load histories typically contain overloads, therefore, understanding the response of material to overloads which can occur at any time during fatigue life is also important. A shortening of fatigue life and reduction in long life fatigue strength due to overloads, particularly if the overloads are periodic, usually occurs.

Variable amplitude fatigue behavior of metallic materials has been studied extensively during the last decades [1, 2], including cumulative fatigue damage mechanisms, damage quantifying parameters, and cumulative damage rules. Although several linear and non-linear cumulative damage models have been developed to account for different phenomenological factors such as load dependence, load sequence and interaction effects, overload effects, small amplitude cycles below fatigue limit, and mean stress, the Palmgren-Miner or Linear Damage Rule (LDR) [3] is still dominantly used in design, in spite of its shortcomings [2].

Variable amplitude fatigue behavior of polymeric materials has been studied far less, as compared to metallic materials, and almost all the studies are related to continuous fiber reinforced polymer composites. Due to the complex interaction and growth of different damage mechanisms such as debonding, matrix failure, delamination, and fiber fracture, in addition to the influence of temperature, frequency, and moisture on the fatigue behavior of polymer composites [4, 5], their cumulative fatigue damage mechanism are more complicated than for metallic materials. A nonlinear behavior has been reported for

damage accumulation of different polymer composites and the assessment of fatigue life with the Palmgren-Miner linear damage rule has been reported to result in inaccurate predictions for block and spectrum loading conditions in most of the studies [6]. Moreover, for two-stage loading condition, a low-high loading sequence has been reported to be more damaging than a high-low loading sequence, while the reverse situation has been typically reported for metallic materials [6].

Due to these discrepancies in the fatigue damage process of metallic materials and polymer composites, a variety of cumulative fatigue damage rules have been developed for composite materials. These models are mainly based on the residual strength and residual stiffness and were reviewed extensively by Post et al [7]. They reported that the Palmgren-Miner rule was non-conservative for most cases and the models based on simple residual strength law, such as the one proposed by Broutman and Sahu [8] gave more accurate predictions.

Despite the widespread occurrence of variable amplitude loading in engineering applications of neat polymer components, to the authors' best knowledge, no investigation on the variable amplitude fatigue behavior of them can be found in the literature. Also, studies regarding the variable amplitude fatigue behavior of short fiber reinforced polymer composites (SFRPCs) are very few.

Zago et al [9] investigated cumulative fatigue damage of short fiber reinforced co-polyamide composites reinforced with 30% and 50% by weight (%wt) short glass fibers. Smooth specimens were used with their axis in 0°, 45°, and 90° with respect to the mold flow direction for experimental studies and subjected to two-stage low-high and high-low loadings, two-stage block loading, and blocks of variable amplitude random load histories. Rainflow cycle counting method was used to replace the variable amplitude load histories with blocks of constant amplitude load for damage analysis. According to experimental results under mentioned loading conditions, the generalized Palmgren-Miner rule in the following form was suggested as the fatigue damage accumulation model:

$$\sum \left(\frac{n_i}{N_i} \right)^b = 1 \quad (1)$$

where n_i and N_i are the number of applied cycles and the number of cycles to failure, respectively, at i^{th} stress level, and b is a material constant. The exponent b was found to vary in a narrow range of 0.9 to 0.95 for different fiber orientations and the average of 0.92 was suggested for all conditions. The proximity of constant b value to one shows that experimental results almost followed LDR.

Zago and Springer [10] used equation (1) for fatigue life prediction of a plate type specimen with a central hole and a gear shift link component made of short glass fiber reinforced co-polyamide under different types of variable amplitude load histories. Commercial softwares were utilized to determine the fiber orientation and stress distribution in the gear shift link component. For life prediction under variable amplitude random load histories, Rainflow method was used

for cycle counting and modified Goodman model was used for the mean stress correction. Reasonable agreement between experimental results and predicted fatigue lives by the model were observed.

Hoppel et al [11] investigated fatigue damage accumulation during two-stage high-low and low-high loadings of short glass fiber reinforced (10% by volume) styrene-maleic anhydride. Specimens were tested in tension-tension fatigue in the longitudinally oriented fibers with respect to the loading axis. Stress or R ratio (ratio of the minimum stress to the maximum stress) was 0.1 for both high and low loads at different damage ratios (ratio of applied cycles to cycles to failure in constant amplitude loading condition) for the first step of loading. LDR was employed to analyze the experimental results which over-predicted low-high test results, while the predictions of LDR for high-low test results were accurate. Scanning electron microscopy (SEM) of fractured surfaces indicated extensive matrix crazing in high-low tests, compared with low-high tests. For high-low loading condition, during high stress level, significant plastic deformation occurred in the matrix which induced compressive residual stresses at the fiber/matrix interface. This resulted in increase of clamping force, therefore, the composite showed more resistance to the subsequent low stress. For low-high loading condition, at the low stress level, cracking occurred in the matrix with no plastic deformation and crack propagated by the subsequent high stress which resulted in shorter fatigue life. The degree of plastic deformation and cracking in the first stage of loading affected the fatigue behavior of the second stage.

Sonsino and Moosbrugger [12] studied variable amplitude fatigue behavior of 35 wt% short glass fiber reinforced polyamide-6.6 composite. Notched specimens and a fuel rail component were tested under blocks of Gaussian random load sequences with $R = -1$ and $R = 0$ at room temperature, as well as at 130 °C. Fatigue life predictions were non-conservative for $R = 0$ but conservative for $R = -1$ using LDR. Non-conservative calculated life under a positive mean stress was attributed to the influence of cyclic creep which was not considered by the linear damage rule. According to notched specimen test results, recommendations about allowable damage sums were also provided. With damage sum of 0.5, all results for $R = -1$ condition and with damage sum of 0.1 all results for $R = 0$ condition were on the conservative side. Hartmann et al. [13] also studied variable amplitude fatigue behavior of 50 wt% short fiber reinforced polyamide-6.6 composite under the same loading conditions in [12]. Total damage sum of 0.1 using LDR was suggested for all the conditions to ensure conservative fatigue lives predictions.

Dreißig et al. [14] conducted pulsating Gaussian variable amplitude load testing on un-notched specimens of 35 wt% short glass fiber polyamide-6.6 machined in 0°, 30°, and 90° directions with respect to the mold flow direction. Linear damage sum were obtained to be 0.2 for 0° and 30° direction tests and 0.35 for 90° direction tests.

Generalized Palmgren-Miner rule mentioned earlier as Eq. (1) was used. The fitting parameter, b , was considered to be constant or to be load dependent. These models in addition to another nonlinear damage accumulation model with three fitting parameters were fitted to experimental data. The nonlinear cumulative damage models calculated the fatigue life well, however, they require the use of fitting parameters from experimental data.

The aim of this study was to investigate the variable amplitude fatigue behavior of one neat thermoplastic and one short glass fiber reinforced thermoplastic composite under two-step high-low and low-high load sequences as well as periodic overload histories using un-notched and notched specimens. The experimental results are compared with LDR predictions and used to investigate cumulative damage mechanisms, load sequence effects, and to evaluate appropriate cumulative damage models for each material.

EXPERIMENTAL PROGRAM

The materials used in this study were an injection molded impact polypropylene copolymer, here designated as PP, with a melting point of about 170 °C and glass transition temperature of 4 °C, and an injection molded short glass fiber reinforced polybutylene terephthalate containing 30 wt% short glass fibers (designated as PBT) with a melting point of 220 °C and the glass transition temperature of 60 °C.

Rectangular plaques with a thickness of 3.8 mm and dimensions of 100 × 200 mm were injection molded. Rectangular strips were cut in 90° (transverse) directions with respect to the mold flow direction from the middle of plaques to prevent end effects. The specimens were machined from the strips with the geometry shown in Figure 1. A 2 mm diameter hole was drilled at the center of notched specimens. The theoretical elastic stress concentration factor based on net cross section area was 2.5. Although both materials have been known not to be prone to absorbing significant moisture, they were dried and preserved in a desiccator before testing.

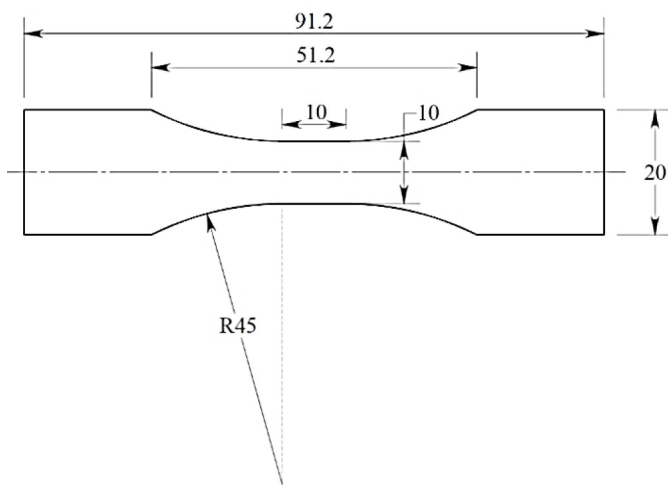


Figure 1. Specimen geometry used for fatigue tests. For notched fatigue tests, a 2 mm diameter central hole was drilled in the middle of the gage section (all dimensions shown are in mm).

Load-controlled fatigue tests were performed using a servo-hydraulic testing machine which was controlled by a digital controller. A pair of 5 kN pneumatic grips were used to grip the specimens. A strain-gaged specimen was used to check the alignment of the load train, prior to testing.

The signals used for two-step high-low (HL) and low-high (LH) loading and periodic overload (POL) tests are shown in Figure 2. For two-step loading tests, specific number of cycles were applied in the first stage and test continued in the second stage up to failure of specimens. Both loading stages had the same R ratio. For periodic overload tests, each block of loading contained certain amount of cycles with low amplitude, followed by one cycle of overload with the same R ratio of low amplitude cycles to be 0.1 for all the tests. Most of two-step loading tests were conducted under $R = 0.1$ condition. Limited number of tests without mean stress (i.e. $R = -1$) for two-step low-high loading of notched specimens were conducted to investigate the mean stress effect. At least two repeat tests were conducted for each condition. The frequency of variable amplitude fatigue test at each specific loading condition was the same as that of constant amplitude fatigue test. Failure was defined as fracture of specimen for both un-notched and notched samples.

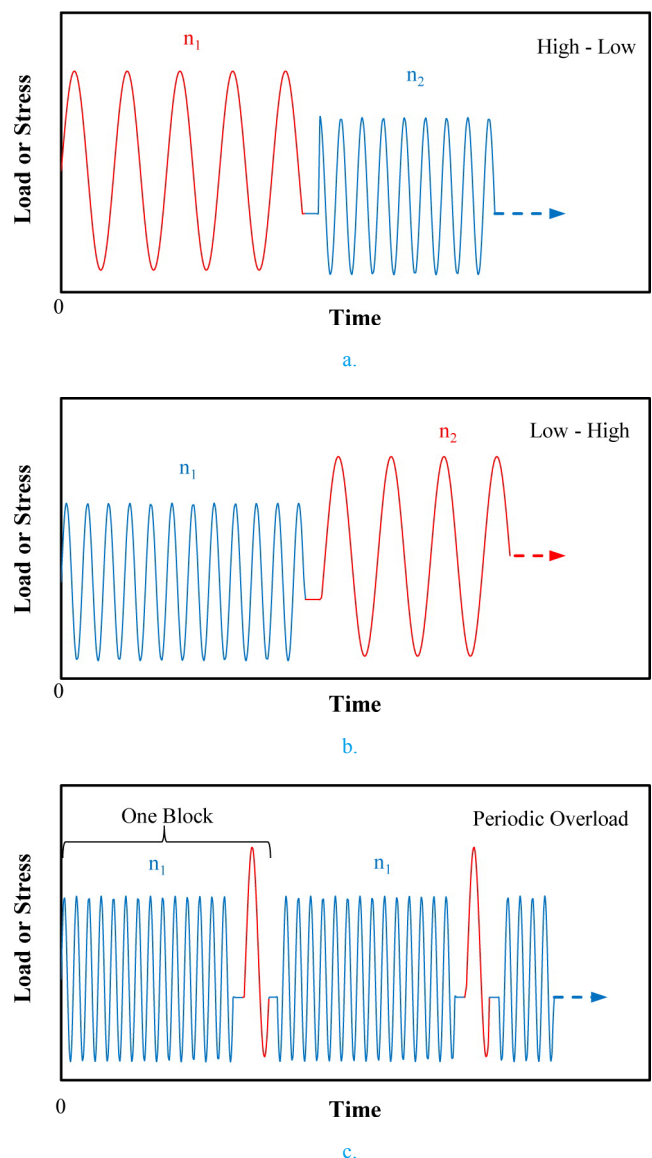


Figure 2. Load histories used, including (a) two-step HL loading, (b) two-step LH loading, and (c) periodic overloads.