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Experiment and modeling of uniaxial tension fatigue performances for filled natural rubbers

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ABSTRACT

A tension fatigue model of filled natural rubbers is investigated to study the contributions of two key factors, namely, the damage parameter and the specimen geometry used in the fatigue experiment. The uniaxial tension fatigue experiments were carried out for three filled natural rubber specimens with different geometry: a dumbbell simple tension specimen (STS), a dumbbell cylindrical specimen (DCS), and a hollow cylindrical specimen (HCS). The commonly used damage parameters for fatigue life prediction are discussed. The fatigue life prediction models are formulated using the measured tension fatigue life of the STS together with different damage parameters. The effectiveness of the models is established in terms of a correlation coefficient characterizing the error between the measured and predicted fatigue lives. It is concluded that all the damage parameters considered in the study can effectively estimate the tension fatigue life with correlation coefficients exceeding 0.9. The fatigue life model formulated for the STS was also found to be appropriate for predicting the fatigue life of specimens with different geometry (DCS and HCS) suggesting that the relationship between the tension fatigue life and the damage parameters is independent of the specimen geometry. One may thus conduct tension fatigue tests with STS alone in order to model the tension fatigue life of rubbers with alternate geometry.

1. Introduction

Owing to their superior ability to withstand large strains without permanent deformations, rubbers are widely used in many engineering applications, such as engine powertrain mounts, suspension bushes, exhausting isolators, seals and so on [1]. Rubber components are usually subjected to substantial static and dynamic loads, and often fail due to nucleation and growth of defects or cracks. Prevention of such mechanical fatigue failures necessitates thorough understanding of the deformation mechanisms of the rubber materials during cyclic loading, so as to predict the fatigue life of rubber components more accurately.

The long-term durability of rubber components is strongly dependent on a number of material and geometry-related factors in a relatively complex manner. Mars and Fatemi [2] and Mars [3] have presented a comprehensive review about factors affecting the fatigue life of rubbers, together with the key issues that need special attention for designs of elastomeric structures. These included factors related to mechanical loading and its history, environment, rubber formulation effects, and dissipative aspects of the constitutive response of rubbers. Among the various factors influencing the fatigue behavior of rubber, the factor related to mechanical loading history has been most widely investigated in many reported studies [4–14].

Uniaxial fatigue [4–10] continues of significant importance especially during the initial design stages that involve selection of the rubber compound for optimal fatigue resistance [4–10], although multi-axial fatigue [11–14] occurs more frequently in rubber components during service. Characterization of fatigue loading experienced locally by the material firstly requires determination of the damage parameters. Reported studies, however, have employed widely different damage parameters for prediction of fatigue life of rubbers under uniaxial loads [4–10], although reasons for choosing a particular damage parameter are seldom

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explained. Since the nonlinearity and finite deformation characteristics of rubber materials, several kinds of strain measures can be used as damage parameters, such as Green–Lagrange strain, Almansi–Euler strain, engineering strain, logarithmic strain and the stretch ratio. While Kim et al. [10] suggested that the Green–Lagrange strain is more appropriate to be used as a damage parameter for estimating fatigue life of rubbers, other studies have used alternate strain measures as damage parameters [4–9]. Only limited information could be found in the literature on relative merits or limitations of different damage parameters for charactering the fatigue behaviors of rubbers, even under uniaxial loading.

Owing to the highly nonlinear properties of rubbers, the measurements with simple test specimens under constant-amplitude uniaxial loads are vital for fundamental understanding of multi-axial fatigue mechanisms. The data obtained from uniaxial fatigue experiments are also essential for developing reliable fatigue life prediction models. Furthermore, the effects of specimen geometry on the fatigue properties also need to be investigated.

This study is aimed at analysis of different damage parameters used in uniaxial fatigue of rubbers by investigating the fatigue life estimation models using different damage parameters based on measured fatigue life data. Furthermore, the specimen geometry effects are investigated considering three types of specimens of varying geometry in the fatigue experiments in order to establish the specimen geometry-independency of the fatigue life prediction. The material and configurations of the three specimens are initially described together with the measurement methods, the criterion of crack nucleation fatigue life and the test loads. The three specimens used for the uniaxial fatigue tests included the dumbbell simple tension specimen (STS) (ASTM: D4482-11), the dumbbell cylindrical specimen (DCS) [10,11], and the hollow cylindrical specimen (HCS) [15].

The different damage parameters are subsequently described, and classified as strain-based and energy-based damage parameters. The strain-based parameters considered in the study include the peak of the maximum (1st) principal strain (Green–Lagrange strain, Almansi–Euler strain, engineering strain, logarithmic strain and stretch ratio), and peak of the octahedral shear strain. The energy-based damage parameters employ two different strain energy density peaks derived from the stress–strain data during loading and unloading.

The fatigue life prediction models are formulated using different damage parameters and measured tension fatigue life data for the STS specimen, while the effectiveness of the models is characterized by a correlation coefficient relating the predicted fatigue life with the measured data. The relative performance of the fatigue life models employing different damage parameters is subsequently assessed. The specimen geometry-dependence of the prediction model is finally evaluated using the test data acquired for the other two specimens (DCS and HCS), and applicability of the fatigue life prediction models for rubbers of different geometry is highlighted.

2. Experiment design

2.1. Rubber materials and specimens

Fatigue life experiments were designed to investigate the tension fatigue of a particular type of filled natural rubber. Three rubber specimens of different geometry, molded from a filled natural rubber (NR) compound, were considered for the experiments, including a dumbbell simple tension specimen (STS), a dumbbell cylindrical specimen (DCS), and a hollow cylindrical specimen (HCS). Fig. 1 illustrates the geometric configurations of the selected specimens. The STS specimen was compression molded and cured at 150 °C for 7 min. The DCS and the HCS specimens were transfer molded, and cured at 150 °C for 10 and 8 min, respectively. The constituents and mechanical properties of the specimens are listed in Tables 1 and 2, respectively.

The STS specimen was designed in accordance with the ASTM standard (ASTM: D4482-11), while the DCS and HCS specimens were designed as described in [10,11,15]. The STS could be used for measurements of fatigue life only in the tension direction; while the fatigue experiments on DCS and the HCS specimens could be performed under tension and compression, either independently or simultaneously. The fatigue life tests with the STS, however, can be performed in a more efficient and cost-effective way compared to those with DCS and HCS specimens, since relatively fewer samples of DCS and HCS could be tested simultaneously with most of the available test machines.

2.2. Fatigue measurement methods for rubber materials

Owing to the visco-elastic behavior of the rubber materials, considerable accumulation of ratcheting strain (cyclic creep) may occur under load (stress) controlled fatigue tests, which is known to be detrimental to the fatigue life [16]. The ratcheting strain effect could be circumvented through displacement (strain) controlled fatigue tests, where the mean stress relaxation tends to saturate in relatively short duration. The loading could thus be retained near the same steady level during the fatigue test [16]. The fatigue tests in this study were thus conducted under controlled sinusoidal displacement at a frequency of 5 Hz.

Fatigue tests on the STS specimens were performed with the EKT-2102-DF Demattia test machine [5] (Machine A), while those for the DCS and HCS specimens were carried out on a MOOG durability test machine (Machine B) and a Bose EFL3500 test machine (Machine C), respectively. Machine A could perform fatigue tests with twenty samples simultaneously under identical displacement, as shown in Fig. 2(a). The test machine B, however, could employ only 3 samples of the DCS specimen simultaneously using the specially designed clamp, as shown in Fig. 2(b), while a single sample of the HCS specimen could be tested on machine C at a time, as shown in Fig. 2(c). The fatigue experiments with the DCS and HCS specimens are thus deemed inefficient and costly. All the tests were conducted at the laboratory temperature (≈23 °C), and a fan was used to cool the samples in order to minimize the contributions due to possible thermal load. A loading cycle counter was used to record the number of load cycles. The cycle counter, however, continued to operate even after the total fracture of a sample. A video recorder was thus also used to determine the instant complete fracture of a sample and thus the number of load cycles to failure.

2.3. Criterion of nucleation fatigue life of rubber materials

The total fatigue life of a specimen is the summation of the crack nucleation life and the crack growth life. The fatigue analysis approaches for the two stages, however, differ. The approach for predicting crack nucleation life is based on the continuum mechanics, while the crack growth life is predicted from the fracture mechanics. In this study, the method of crack nucleation fatigue life prediction is used, which requires the use of a criterion to identify the occurrence of crack nucleation. While the length of the crack is determined arbitrarily [17], it strongly depends on the specimen geometry and size. The occurrence of crack nucleation, however, is always related to a significant decrease in the sample stiffness.

The measured data obtained with different samples of a rubber specimen under a given loading condition generally reveal somewhat consistent trends, although substantial variations in the data