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Theoretic and Experimental Fatigue Analysis of Off-axis Unidirectional Rubbery Composites Using Nonlinear Life Prediction Model

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Abstract

The aim of this article is analyzing the fatigue behavior of off-axis unidirectional rubbery composites under uniaxial tension-tension cyclic loading based on developed damage-entropy model. The main advantage of the damage-entropy model is that it accounts the viscoelastic property and temperature increase during the fatigue loading conditions. The off-axis rubbery composites lay-ups exhibit a nonlinear stress-strain response similar to the rubber matrix. Hence, the Newton-Raphson method is employed to capture the nonlinear behavior of rubbery composites in this study. The failure criterion in the damage-entropy model is based on the fracture fatigue entropy value. To characterize the longitudinal, transverse, and in-plane shear behavior of rubbery composites, static and fatigue experimental tests on different lay-ups are conducted. Moreover, the damage energy, the energy dissipation due to viscoelastic behavior and the heat transfer to the environment during the fatigue loading will be calculated. Furthermore, the experimental results of $[45]_4$ lay-up are utilized to validate the developed damage-entropy model. Finally, the experimental and modeling results of hysteresis energy, temperature change, and fatigue life of steel-cord rubber composite $[45]_4$ lay-up for different stress levels subjected to stress ratio 0.1 and 1 Hz frequency, are compared. The comparison between the analytical results and experiments indicates the capabilities of the present model.

Keywords

Fatigue life, Rubbery composites, Developed damage-entropy model, Fracture fatigue entropy, Temperature evolution.

1. Introduction

The unique properties of rubber, including its softness, elasticity, resistance to cutting, high friction coefficient, and low gas permeability, make it an invaluable material for creating elastic structures such as hoses, belts, washers, and vibration insulation. Furthermore, rubber is a fundamental component of pneumatic tires [1]. Through the operational lifespan of rubbers, their components are exposed to static loads and fatigue. An effective approach to enhance their mechanical properties involves the integration of fibers into the rubber structure, thereby producing composite materials [2,3].

Nowadays, fatigue in composites is recognized as a definite phenomenon. With the increasing use of composites in various industries, it is essential to consider the deterioration of mechanical properties due to cyclic loading [4,5]. Multiple fatigue measurement models have been proposed by various researchers over the years. These include classic models like fatigue-life models and models for residual mechanical properties (such as stiffness and strength), as well as progressive damage models characterized by a gradual, cycle-by-cycle nature. The progressive damage models integrate classic fatigue criteria, fatigue life models, and residual mechanical properties models [6].

In recent years, a novel method has emerged for examining the fatigue behavior of composite materials. This method utilizes the concept of entropy production and has demonstrated considerable potential for advancement [7]. The concept of "Fatigue Failure Entropy (FFE)" was introduced by Naderi and colleagues in 2009. It quantifies the consistent amount of entropy generated in material under fatigue load, from the point of loading on the specimen to the moment of failure. Importantly, this measure is independent of load situation, load frequency, load magnitude, and other environmental conditions [8].

Rubbery materials undergo a considerable temperature rise due to their viscoelastic properties during the fatigue process. Previous studies have revealed that there is currently no model available that considers both the viscoelastic property and the temperature increase in steel cord rubber composites (SCRC) during the fatigue process. The aim of this research is to analyze the fatigue behavior of off-axis unidirectional SCRC structures using the damage-entropy model. Due to the non-linear stress-strain mechanical behavior of SCRC, it is important to develop an entropy-damage model that accounts for this mechanical property of SCRC materials.

2. Methodology

In the present study, we present an analysis of the fatigue behavior exhibited by unidirectional off-axis SCRC under tensile fatigue loading. This analysis takes into account the nonlinear stress-strain mechanical characteristics of SCRC materials, employing the developed entropy-damage model.

The stress-strain behavior of SCRC exhibits nonlinear changes due to the rubber matrix present in them. The article utilizes the Newton-Raphson method to accurately analyze the nonlinear fatigue behavior of SCRC materials.

Damage-entropy model expresses that:

$$\dot{W}_{ve} + \dot{E}_d = \rho C\dot{T} + \dot{E}_{diss} \quad (1)$$

in which, $\dot{W}_{ve}$ and $\dot{E}_d$ are the dissipated energy because of the viscoelastic nature of the matrix and damage energy, respectively. Also, ρ, C, T, and $\dot{E}_{diss}$ define the density, specific heat capacity, temperature, and dissipated heat, respectively.

The failure criterion in the damage- entropy model is determined by comparing the FFE value obtained using the model with experimental data. Parameters for failure growth in the longitudinal, transverse, and in-plane shear directions are calculated using CDM to measure the energy resulting from failure growth during the fatigue process.

$$\dot{E}_d = Y_i \dot{D}_i \quad (2)$$

where E_d, Y, and D are damage energy, the conjugated force, and the damage variable, respectively.

Additionally, the dynamic damping behavior of the SCRC structure, caused by the viscoelastic properties of rubber materials, is analyzed using DMTA to determine the energy lost due to viscoelastic behavior.

$$W_{ve} = \int_0^{t_c} [\varepsilon_0 \sigma_0 \omega \sin(\omega t) \cos(\omega t + \delta)] dt = \pi \varepsilon_0^2 E_2 \quad (3)$$

where $\varepsilon_0, \sigma_0, E_2, \omega, \delta$ and t_c are strain amplitude, stress amplitude, loss moduli, frequency, phase lag, and time duration per cycle, respectively.

Heat exchange from the sample to the environment is calculated through conduction, displacement, and radiation mechanisms.

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3. Results & discussion

The damage- entropy model developed for unidirectional off-axis SCRC structures is validated using experimental results from $[45]_4$ lay-up. Finally, experimental results and modeling of hysteresis energy, temperature changes, and fatigue life are presented in the following for $[45]_4$ unidirectional off-axis SCRC at different stress levels and 0.1 stress ratio under 1 Hz frequency.

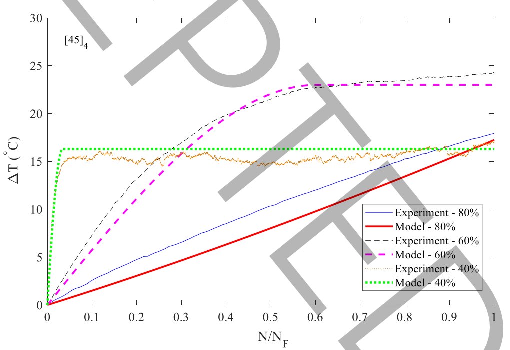

Fig. 1. Temperature variation of $[45]_4$ according experimental results and model simulation

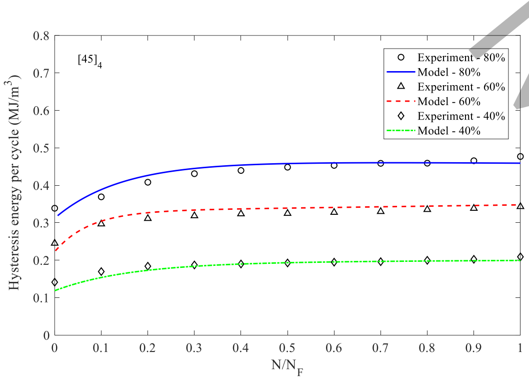

Fig. 2. Hysteresis energy variation of $[45]_4$ according experiments and model simulation

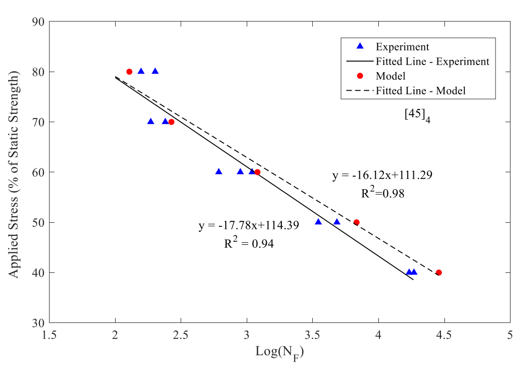

Fig. 3. Comparison of fatigue life of $[45]_4$ lay-up according experiments and model

4. Conclusion

In this article, fatigue behavior of off-axis unidirectional $[45]_4$ lay-up by using damage-entropy model was predicted. The comparison of hysteresis energy changes in composites with an epoxy matrix and SCRC shows that the wasted energy of SCRC is significantly higher than that of composites with an epoxy matrix. This is because the viscosity of the rubber matrix in the SCRC structure is higher than that of the epoxy matrix. The diagram of hysteresis energy changes indicates two stages of rapid growth followed by an increase with a constant slope until final failure. Additionally, the fatigue life of laminated $[45]_4$ unidirectional off-axis SCRC was predicted using the entropy-damage model and compared with experimental test results. The results showed that the entropy-damage model's predictions were in acceptable agreement with the experimental results.

5. References:

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