VISCOELASTIC SELF-HEATING IN COMPOSITE MATERIALS

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ABSTRACT

Fatigue testing of polymer matrix composite materials requires a long and expensive testing campaign to generate traditional S-N curves for design. The focus of current research is to develop methods for accelerating the process of generating useful fatigue design data. A promising accelerated fatigue testing method makes use of infrared thermography to measure heat emission during fatigue tests. Multiple researchers have associated such heat generation with multiple material behaviors such as damage growth, irreversible deformation, the viscoelastic nature of the matrix material, and other potentially unknown types of material behavior. The goal of this presentation is to model heat emission associated with the viscoelastic nature of the matrix.

1 INTRODUCTION

Heat-based accelerated fatigue testing was initially developed for accelerating the fatigue testing of metallic alloys such as steels. A summary of these methods is presented, followed by current research aiming at applying them to composite materials. Risitano [1] and Luong [2] published methodologies for inferring the fatigue endurance limit and the fatigue life of steel alloys. They noted that the surface temperature of steels exhibited a three-stage evolution through their fatigue life, Figure 1.

1. Phase 1: rapid rise in surface temperature relative to the initial temperature. This phase is brief compared to the number of cycles to failure;
2. Phase 2: Surface temperature stabilization at a temperature higher than initial temperature;
3. Phase 3: Rapid increase in surface temperature at an accelerating rate prior to specimen failure.

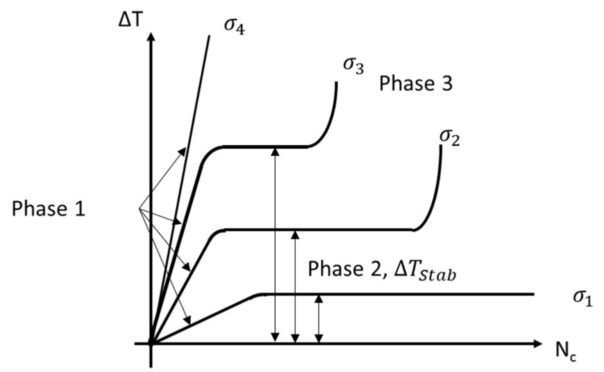

Figure 1 – Temperature evolution during fatigue tests (Adapted from [1])

Risitano [1] and Luong [2] used the stabilized surface temperature increase (Phase 2) as a metric for summarizing the results of a fatigue test. Upon plotting the stabilized surface temperature as a function of the applied stress amplitude they noted a bilinear relation, Figure 2. The intersection was found to correlate strongly with the fatigue endurance limit of steels. In the context of the heat-based methodology, the fatigue endurance limit corresponds to a change in heat dissipation mechanisms.

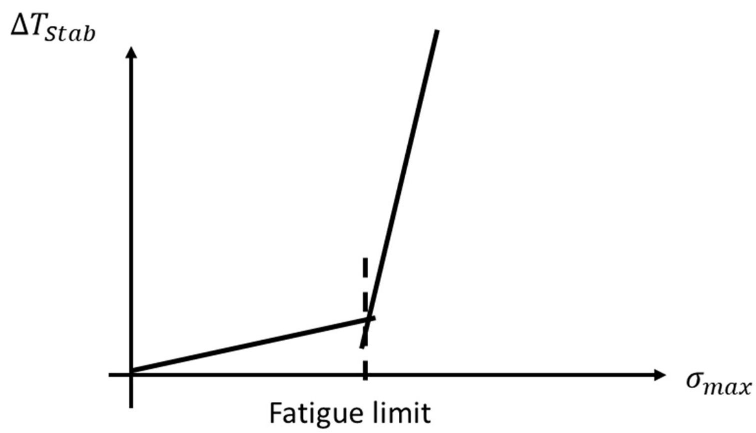

Figure 2 – Graphical inferrance of fatigue limit (Adapted from [1,2])

Below the fatigue endurance limit, heat generation is associated with energy dissipation due to internal friction [3, 4]. At stress levels above the fatigue endurance limit, heat generation is associated with energy dissipation due to microplastic deformation [3, 4].

Other researchers have proposed metrics for inferring the fatigue life of test specimens based on infrared thermography. Fargione [5] proposed the concept of a limiting energy value, representative of the total energy generated from heat dissipation associated with micro-plastic deformation. Assuming a constant testing frequency for each test specimen, the limiting energy was assumed constant for each applied stress level. S-N curves were inferred from surface temperature measurements.

Naderi [6] proposed the concept of a limiting entropy value, referred to as the Fracture Fatigue Entropy (FFE). The FFE was inferred from thermographic measurements for multiple types of loading (tension-compression, bending, and torsion fatigue) and for multiple testing frequencies. The author found that the FFE stayed constant for multiple types of loading and testing frequencies. The FFE represents the cumulative entropy generation of the material during fatigue loading. The main source of entropy generation was attributed to cyclic plastic deformation.

Multiple researchers have adapted heat-based techniques for inferring fatigue properties of composite materials. Examples can be found in references [7-11]. Notably, Huang [8, 9] proposed that the main source of heat generation during fatigue at loads below the fatigue limit was internal friction, i.e. non-damaging mechanisms.

This paper presents on-going work pertaining to in heat generation during fatigue tests at loads below the inferred fatigue limit, using viscoelastic material models.

2 VISCOELASTIC MODELLING

Viscoelastic materials exhibit a combination of viscous and elastic behaviors when subjected to loading. Viscoelastic materials creep when subjected to suddenly applied constant stresses, and relax when subjected to a suddenly applied constant strain. The most general form of the constitutive law relating stresses and strains in linear viscoelastic materials is given by:

$$\sigma(t) = \int_0^t E(t-\tau)\frac{d\epsilon}{d\tau}d\tau \qquad (1)$$

where E is the relaxation function. Multiple models may be used for modelling the relaxation function, such as the Maxwell model, the Standard Linear Solid (Zener) model, the Burger model, and the Generalized Maxwell model. In this work, the Generalized Maxwell model is used for modelling the viscoelastic behavior of the matrix. The relaxation function of a Generalized Maxwell model is given by:

$$E(t) = E_\infty + \sum_{i=1}^{N} E_i \exp\left(-\frac{t}{\tau_i}\right), \qquad \tau_i = \frac{\eta_i}{E_i} \qquad (2)$$

In terms of physical interpretation, the coefficients are most easily understood by using an arrangement of elastic springs and viscous dashpots, Figure 3. Constants E_i are representative of the spring constants in each Maxwell branch of the model, and constants τ_i are the exponential time constants associated with each Maxwell branch of the model. The constant E_∞ is representative of the relaxation at infinite time.

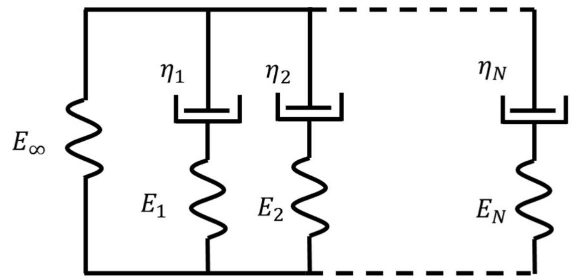

Figure 3. Generalized Maxwell Model (Adapted from [14])

Upon cyclic loading, a phase shift between stress and strain is observed due to the viscous component of the deformation. Under cyclical deformation given by:

$$\epsilon(t) = \epsilon_0 \exp(i\omega t) \tag{3}$$

it may be shown that the stress response is given by [14, 15]:

$$\sigma(t) = E^*(i\omega)\, \epsilon_0 \exp(i\omega t) = |E^*(i\omega)|\, \epsilon_0 e^{i(\omega t + \delta)} \tag{4}$$

where *E*(iω)* is the complex modulus of the material, which is a function of the applied frequency. The complex modulus, its magnitude, and the phase shift between stress and strain are given by [14, 15]:

$$E^*(i\omega) = E'(\omega) + i\, E''(\omega) \tag{5}$$

$$|E^*| = \sqrt{(E')^2 + (E'')^2} \tag{6}$$

$$\tan(\delta) = \frac{E''}{E'} \tag{7}$$

where *E′* and *E′′* are the storage and loss moduli, respectively. The storage modulus is indicative of the material's ability to store energy elastically, while the loss modulus is indicative of the material's viscous dissipation. The storage and loss moduli can be calculated from the relaxation function according to [15]:

$$E'(\omega) = E_\infty + \omega \int_0^\infty \tilde{E}(\eta) \sin \omega\eta \, d\eta \tag{8}$$

$$E''(\omega) = \omega \int_0^\infty \tilde{E}(\eta) \cos \omega\eta \, d\eta \tag{9}$$

where E_∞ is the relaxation modulus at infinite time, $\tilde{E}(\eta)$ is the transient component of the relaxation function, and ω is the loading frequency. For the Generalized Maxwell Model, the storage and loss modulus can be calculated according using the relaxation function parameters [16]:

$$E'(\omega) = E_\infty + \sum_{i=1}^{N} E_i \left[\frac{(\tau_i \omega)^2}{1 + (\omega \tau_i)^2}\right] \tag{10}$$

$$E''(\omega) = \sum_{i=1}^{N} E_i \left[\frac{\tau_i \omega}{1 + (\omega \tau_i)^2}\right] \tag{11}$$

An hysteresis appears when plotting the stress-strain curve for one cycle of loading of viscoelastic material. The area between the loading and unloading portion of the curve represents energy dissipated per unit volume [12]. The amount of dissipated energy per cycle is given by:

$$\Delta w_{cyclic} = \pi \epsilon_a \sigma_a \sin(\delta) \tag{12}$$

where σ_a is the stress amplitude, ϵ_a is the strain amplitude, and δ is the phase shift between stress and strain.

Cyclic energy dissipation values of composite materials can be found in [7-9]. The reported ranges of energy dissipation at fatigue loads below their respective fatigue limits are listed in Table 1.

Table 1. Reported ranges of energy dissipation

Reference	Material system	Cyclic Energy Dissipation (J/m^3/cycle)
[7]	[0/±θ] carbon / thermosetting polyimide	0 to 50,000
[8]	[+45/-45]$_8$ carbon / HexPly M79 matrix	0 to 40,000
		(Reported as 0 to 200,000 J/m^3/s at 5 Hz)
[9]	[0]$_8$ carbon / HexPly M79 matrix	0 to 4,000
	[(0/90)$_2$/0/(90/0)$_2$] carbon / HexPly M79 matrix	0 to 4,000

Montesano [7] measured hysteresis loops experimentally during fatigue tests and found a very strong correlation between the stabilized surface temperature and the hysteresis loop area. Huang [8, 9] inferred cyclic energy dissipation from heat transfer simulations using finite-element analysis. It is noted that the order of magnitude of energy dissipation is similar in both cases.

3 FUTURE WORK

The subject of current work is the viscoelastic modelling of composite materials. The aim is to inform on the contribution of viscoelastic energy dissipation of the matrix material on the overall self-heating phenomena observed during fatigue loading of composite materials.

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