Composites Part B 91 (2016) 306–314

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Multiscale modeling of vibration damping response of shape memory polymer fibers

Soodabeh Sharafi [a], Guoqiang Li [a, b, *]

[a] Department of Mechanical & Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
[b] Department of Mechanical Engineering, Southern University, Baton Rouge, LA 70813, USA

ARTICLE INFO

Article history:
Received 11 July 2015
Received in revised form
16 September 2015
Accepted 26 December 2015
Available online 3 February 2016

Keywords:
A. Polymer (textile) fibre
A. Smart materials
B. Vibration
C. Analytical modelling

ABSTRACT

Health of a structure under vibration loads is highly related to the damping characteristics of the system. This work explores an engineered smart Shape Memory Polymer Fiber (SMPF) system that is capable of adjusting its damping capabilities based on applied load frequency and temperatures. A SMPF based structure with smart vibration/damping capability is of interest to many industries including aerospace, automotive and biomedical sectors. SMPFs enable structure engineers to incorporate smart functionality into their design through programming or training of SMPFs. While SMPF structural applications in the case of static loadings have been studied, the application of SMPFs in mitigating vibration responses of a structure has not been fully addressed in the research arena. The vibration damping response of a SMPF material system is studied with a goal to design damping response of smart structures that can mitigate severe vibrations. In this work vibration damping response of a SMPF bundle is experimentally studied through Dynamic Mechanical Analyzer (DMA) machine, and a numerical model is developed to correlate the loss/storage moduli to the damping/stiffness characteristics of the SMPF system. The model is then applied to study forced vibration responses of SMPFs. DMA data are utilized to verify the performance of the proposed model. The presented experimental data and the numerical model provide insight into vibration damping application of SMPFs in smart structures.

1. Introduction

Shape memory polymers are classified as smart materials that are able to respond to the external stimuli sources such as heat, sound, light, etc. [1–7]. Most recently, Li and co-workers have developed several Shape Memory Polymer Fiber (SMPF) reinforced polymer matrix composite (PMC) systems with capabilities for crack self-healing [8–14]. Most of the up to date studies concern quasi-static response of shape memory polymers including shape memory polymer fibers and artificial muscles [15–37]. However, there is currently a lack of modeling technique to addresses vibration analysis of SMPFs.

Vibration analysis enables designers to study stability of the structure when oscillation occurs. Unwanted noises or dissipative vibration mechanisms, resulted from lack of meticulous design of components, may lead to premature failure of structural components. Prognosis techniques and damping of severe oscillating loads become a cardinal point in the structural design. For the past decades, the inception of new technologies such as space exploration programs have provided an increasing need for lightweight materials with high damping capabilities and tolerance to the harsh environments.

The nature of damping lies in the microscopic response of a material when vibration is initiated. Damping property of polymers is strongly temperature dependent, especially around the glass transition temperature where polymers hit the highest level of damping [38]. Elevated damping capability is related to the excessive viscoelastic motion of polymer chains in this temperature. In fact, these giant molecules transform from low temperature solid-like state to high temperature liquid-like state. During this reversible transition, the long range molecular reordering results in dissipation of the energy of vibration [39]. Crandall discussed the nature of some important damping mechanisms to clarify their dependency on the amplitude and frequency of a cyclic motion [40].

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* Corresponding author. Department of Mechanical & Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA. Tel.: +1 225 578 5302; fax: +1 225 578 5924.
E-mail address: lguoqi1@lsu.edu (G. Li).

http://dx.doi.org/10.1016/j.compositesb.2015.12.046
1359-8368/

As compared to conventional non-shape memory polymers, SMPs experience about two-orders of change in stiffness in the glass transition region, signifying exceptional molecular viscoelastic motion, and thus potentially superior damping properties. It is expected that if the SMP fibers are used in fiber reinforced polymer composites, the damping properties of the composites can also be enhanced. The damping properties of fiber reinforced polymer composites have been a topic of intensive research in the recent years [41–48]. However, before the wide application of SMP fibers in polymer composite for vibration damping, understanding of the damping behavior and effect of materials parameters on the damping performance of SMP fibers, particularly through mathematical modeling, is highly desired.

The modeling techniques are an essential part of the vibration analysis in order to minimize the experimental *trial-and-error* efforts for optimizing damping capability of a structure. Four distinct categories of modeling techniques are introduced by Treviso et al., including linear viscoelastic, complex modulus, strain energy methods and dissipative coordinate methods [41]. In linear viscoelastic models, material is modeled through application of spring elements, the representation of elastic segment, and the dashpot elements, the representation of inelastic or dissipative part. Nowick et al. have elaborated the application of this methodology to predict dynamic response of inelastic solids; however, the nature of energy dissipation in this type of modeling remains unanswered [49]. Complex modulus methodologies are the second category of these modeling techniques. However, their cumbersome computations hinder their applications. Crandall has elaborated some examples to illustrate application of the proposed mathematical formulations [40]. In another study, Bagley and Torvik have suggested that damping mechanism results from a frequency dependent modulus, which is a fractional power of frequency. Also, Caughey et al. applied Raid's non-linear model to describe hysteric damping mechanism. The proposed model suggests a mathematical procedure to include nonlinearity of dynamic response. However, discrepancy between the proposed model and the exact solution below the resonance frequency is merely negligible [50]. The biggest drawback, for these types of modeling as mentioned above, is the complexity associated with the definition of viscoelastic behavior [51].

The third category of modeling is based on an exchange of strain energy for vibration analysis. Johnson et al. have used the notation of change in the strain energy density to measure the existence of deformation mechanism related to loading and unloading condition. The strain energy methods suffers from lack of direct methodologies to relate material parameters to the experimental results; this paucity has overshadowed their applications [52].

The fourth and last category encompasses modeling techniques, which are based on the evolution of internal variables; these methodologies are not easily supported by the experimental results. In this category, the notable Golla-Huges-McTavish (GHM) method is formulated through application of the second-order matrix to solve the equation of motion. The material properties are substituted to mass, stiffness and damping matrices. The so-called “auxiliary coordinate” has been introduced to incorporate the internal dissipation mechanism [40,53]. Lack of accuracy in the introduced curve fitting parameters obfuscates their unlimited applications. However, to compensate for the limited applications of the proposed model, McTavish et al. have suggested a new approach to modify these curve fitting parameters [54]. There are few other methodologies that are in close relation to the GHM method such as augmenting thermodynamic fields (ATF) and anelastic displacement field (ADF) [55,56]. ATF is a coupled equation of motion demanding the adaptability of the thermodynamic field at each element. ADF is proposed to simplify the ATF methodology by considering the evolution of “displacement field” introduced to solve the higher order equation of motion. Despite their sophisticated methodology, correlation to the experimental results is hardly reachable.

As a new member of the smart materials family, there are few studies concerning the application of shape memory polymer fibers, SMPFs, either independently or as a reinforcing element to augment dynamic material property of a composite system. Therefore, in this work we aim at exploring the possibility of design and development of smart SMPF systems to control the energy dissipation and suggest the optimum range of damping properties, which can be programmed at different temperatures. Also we propose a novel numerical methodology to correlate dynamic mechanical analysis (DMA) results to the stiffness and damping coefficient of the Single Degree of Freedom (SDOF) equation of motion. Both experimental tests and numerical modeling analysis are incorporated to fully understand the vibration damping response of SMPFs. DMA test is utilized to study the complex viscoelastic behavior of SMPFs; frequency sweep tests are carried out to obtain the storage and loss moduli of SMPF bundles at various temperatures. A phenomenological SDOF model is then developed based on the DMA test results to calibrate the two proposed relations. It is shown that the proposed modeling procedure can favorably capture the forced vibration response of the SMPF system at different temperatures. These proposed relations are meant for relating the micro structural properties of polymer chains to the macroscopic vibration/damping response.

This work is organized as follows, first the theory behind the forced vibration analysis is briefly discussed and then the SDOF model is described. After that, the experimental setup and test results are presented; furthermore, multiscale model and its numerical implementation procedure are elaborated in two sections. Finally, the results and discussions are presented.

2. Single degree of freedom (SDOF) model for SMPF system

The proposed SDOF model for SMPF system is discussed in this section and the performance of the developed model is examined in Section 6 where the reported experimental data, which concern with forced vibration of a typical SMPF sample under sinusoidal forces, together with the model performance are shown. It is assumed that the vibration response of the SMPF sample is described through a SDOF model. The steady state SDOF equation of motion reads:

$$m\ddot{x} + c\dot{x} + kx = F_0 e^{i\omega t} \tag{1}$$

where m is the mass of a vibrating fiber, c is the coefficient of damping, k is the stiffness of a typical SMPF sample, and F_0 is the amplitude of the applied force.

Steady state response of the linear system to the harmonic force could be expressed through definition of a transfer function H (t) and a corresponding phase angle which is well-established in the literature and is given by Ref. [57]:

$$x(t) = \frac{F_o}{k} H(\omega) e^{i(\omega t - \phi)} \tag{2}$$

where ω is the frequency, $H(\omega)$ is called transfer function or magnification factor, and ϕ is the phase lag.

$$\phi = tan^{-1}\left(\frac{2\zeta r}{1 - r^2}\right) \tag{3}$$