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TRANSIENT RESPONSE OF A SANDWICH STRUCTURE DAMPED WITH A FIBROUS CORE MATERIAL

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ABSTRACT

This paper investigates the effect of a fibrous core material on the transient response of a sandwich structure. The core material studied is made of entangled carbon fibers cross-linked with epoxy resin. In order to understand its complex behavior, the material is characterized in shear oscillation, and the obtained shear-stress loops are described using Dahl's dynamic hysteresis model. Then, the transient response of a single-degree-of-freedom system including this material is simulated and the amplitude dependency of the response is analyzed. Sandwich beams with the fibrous core material are tested experimentally with a impact hammer and compared with classical honeycomb and foam cored sandwich beams. The entangled cross-linked fibers are shown to provide high damping resulting in a fast return to the equilibrium position. Both theoretical and experimental studies showed nonlinear damping. In the amplitude range studied, the material is more interesting at high impact amplitude.

Keywords: Vibration damping, sandwich structures, nonlinear behavior, transient response

INTRODUCTION

Aerospace and automotive structures need to be as light as possible in order to limit fuel energy consumption, while maintaining high stiffness and strength properties. Sandwich structures, composed of two facesheets separated by a light core, are widely used in such applications as they provide high stiffness-to-weight ratios. However, the use of stiff lightweight structures can lead to noise and vibration amplification. This can be detrimental to user comfort and structural durability. One way to reduce noise and vibration is to investigate new core materials with high energy dissipation properties.

Studies on the static behavior of entangled fibers indicate that energy is dissipated by friction between the fibers when they are deformed [1]. This has led to the development of a new sandwich core material in which entangled fibers are cross-linked with epoxy resin [2]. Resin cross-links ensure cohesion and stiffness of the material while fibers can provide energy dissipation. The present study investigates the effect of this material on the damping properties of sandwich structures through a transient analysis.

In this paper, the material behavior is first measured and identified with a hysteresis model. Then, the transient response of a single-degree-of-freedom system is studied numerically. The consequences of the material behavior on this simple structural response is analyzed. Finally, the transient response of a sandwich beam with entangled core material is compared experimentally with the response of classical honeycomb and foam sandwich beams.

MATERIAL CHARACTERIZATION

The material is made following the fabrication process described by Mezeix [2]. Different types of fibers can be used. Here, carbon fibers are chosen, since carbon-epoxy materials are commonly used in aerospace applications. The fibers are 7 μm in diameter, with a Young's modulus of 240 GPa and a density of 1770 kg/m^3. They are first cut to a length of 31 mm, and are then entangled in a blower room under an air flux at a pressure of 5 bar.

Epoxy resin is then sprayed on the entangled fibers with

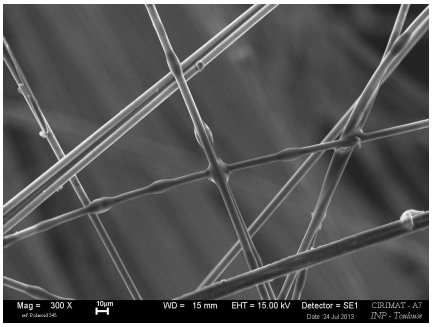


Figure 1: Scanning electron microscopy of the entangled cross-linked fibers after polymerization.

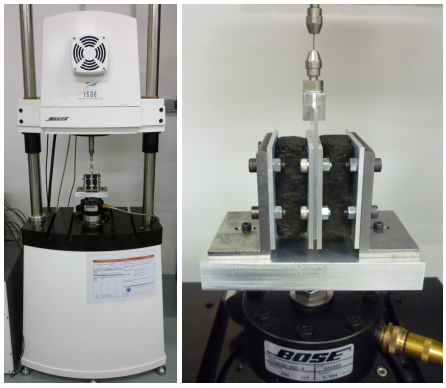


Figure 2: Experimental set-up for material characterization in shear.

a commercial paint gun at a pressure of 2 bar. The small droplets create links between the fibers at several contact points. Finally, the entangled cross-linked fibers are polymerized in a mold at 70° C during 8 hours.

The final density of the material is 180 kg/m^3 (150 kg/m^3 of carbon fibers and 30 kg/m^3 of epoxy resin). Figure 1 shows a scanning electron microscopy of the polymerized material. It can be seen that some contacts are bonded by resin while others are free to slip.

As the material is intended to be used as a core material in sandwich structures, shear is the most important mechanism to be analyzed [3]. Figure 2 shows the set-up for the shear test on a BOSE ElectroForce® 3330. Two samples of dimensions 20 mm × 40 mm × 60 mm are tested together to ensure shearing only. The samples are held by two steel brackets clamped on the bottom plate. A vertical displacement is imposed between the samples by an aluminum plate attached to the vertical motor. The resulting force is measured. From the displacement and force, the shear strain γ and the shear stress τ in the samples are deduced by assuming a constant shear through the thickness.

Measurements are made at 1 Hz, 20 Hz, 40 Hz, 60 Hz and 80 Hz, and the material behavior is found to be frequency independent in the tested frequency range. The following study is based on measurements made at 20 Hz, as they were found

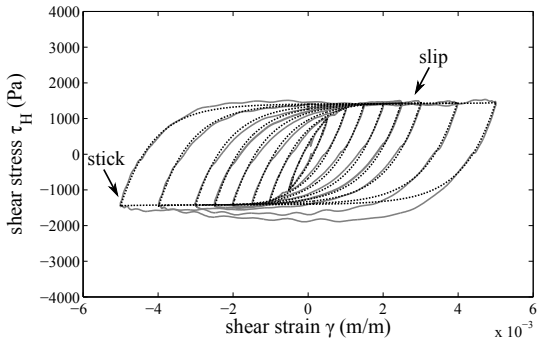


Figure 3: Shear stress-strain hysteresis loops obtained by removing the linear part of the shear stress: $\tau_{\mathrm{H}} = \tau - G_1\gamma$ with G_1 identified in Eq. (3). Loops measured at 20 Hz (grey line) and identified (black dotted line).

to be less sensitive to noise coming from the set-up.

The measured shear stress can be decomposed as a linear part of modulus G_1 and a hysteresis part defined as:

$$\tau_{\mathrm{H}} = \tau - G_1\gamma \tag{1}$$

The measured shear stress without the linear part, τ_{H}, is represented against the measured shear strain γ on Fig. 3 (grey line). The physical interpretation of the observed hysteresis is the following: after each change in the strain direction, the strain rate is null, and all unbonded contacts between fibers are blocked in a "stick" configuration, which creates an initial stiffness; then, stiffness decreases as contacts begin to slip individually, until they are all in a "slip" configuration. As for contacts cross-linked with epoxy resin, they never enter the "slip" configuration, and they are responsible for the linear behavior $G_1\gamma$ which does not appear on the figure.

The shape of the hysteresis loop, combined with the frequency independent behavior, indicates that dissipation comes from the friction between the fibers.

The hysteresis loops are described using Dahl's dynamic hysteresis model [4]:

$$\frac{\mathrm{d}\tau_{\mathrm{H}}}{\mathrm{d}\gamma} = \frac{\sigma}{\tau_{\mathrm{C}}}\left(2\tau_{\mathrm{C}} - (\tau_{\mathrm{H}} - \tau_{\mathrm{m}})\,\mathrm{sgn}(\dot{\gamma})\right) \tag{2}$$

where $\dot{\gamma}$ is the strain rate, σ and τ_{C} are constants of the model and τ_{m} is the value of the stress at the last change in the strain direction.

Figure 3 shows the identified hysteresis loops for one set of samples (black dotted line). Two sets of two samples each are tested, leading to the following parameters for the model:

$$G_1 = 6.02\cdot 10^6\ \mathrm{Pa} \quad \sigma = 1.49\cdot 10^6\ \mathrm{Pa} \quad \tau_{\mathrm{C}} = 1.39\cdot 10^3\ \mathrm{Pa} \tag{3}$$

SINGLE-DEGREE-OF-FREEDOM SYSTEM

A theoretical single-degree-of-freedom system is now simulated in order to understand the consequences of the measured material properties on the transient response of a structure.

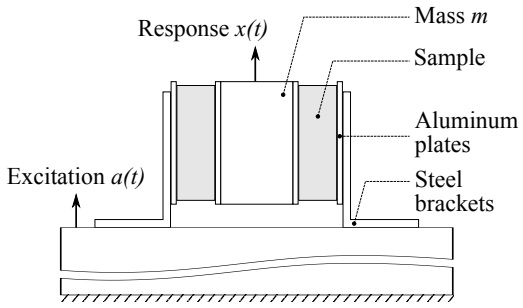


Figure 4: Principle of the studied single-degree-of-freedom system, including the entangled fiber samples in grey.

The structure studied is composed of two samples in shear configuration, as tested previously, but separated by a rigid mass. Figure 4 shows the principle of the system. The mass is taken to be $m = 1$ kg, and is assumed to move only in the vertical direction. The parameters of the material are as given in Eq. (3). A base acceleration is applied at the bottom of the structure. The shock acceleration is a half sine of duration 1.5 ms, as shown on Fig. 5(a). Transient response is computed for seven amplitudes ranging from 1 g to 25 g.

Figure 5(b) shows the simulated transient response from 0 s to 0.2 s. The response to the 25 g shock shows three decay regimes. First, at high oscillation amplitudes, fast linear decay typical of friction is observed (regime 1). Then, the decay seems to become exponential, which is more representative of viscous damping. However, the slope decreases with the oscillation amplitude, from relatively fast (regime 2) to very slow decay (regime 3). Thus, while most of the oscillation is damped before 0.1 s, the remaining oscillation is dissipated slowly.

For lower shock amplitudes, the response enters directly the "exponential" decay regimes 2 and 3, as shown on Fig. 5(c) which spans 0.5 s. The resulting decay rate is slower for those low amplitude oscillations, and the remaining oscillations when entering regime 3 represent a large part of the initial oscillation amplitude.

This simulation shows that the material behavior leads to a transient response that depends on the shock amplitude. For this simple structure and in the amplitude range studied, the entangled material leads to higher damping for higher excitation levels. The following part presents the behavior of a real structure studied experimentally in order to see if the same phenomena are encountered.

TRANSIENT RESPONSE OF SANDWICH BEAMS

The transient responses of three sandwich beams are studied experimentally. For the purpose of comparing with standard materials, the core materials of the beams are the following, along with their density ρ and linear shear modulus G:

- entangled cross-linked carbon fibers ($\rho = 180$ kg/m^3, $G_1 = 6.02$ MPa)

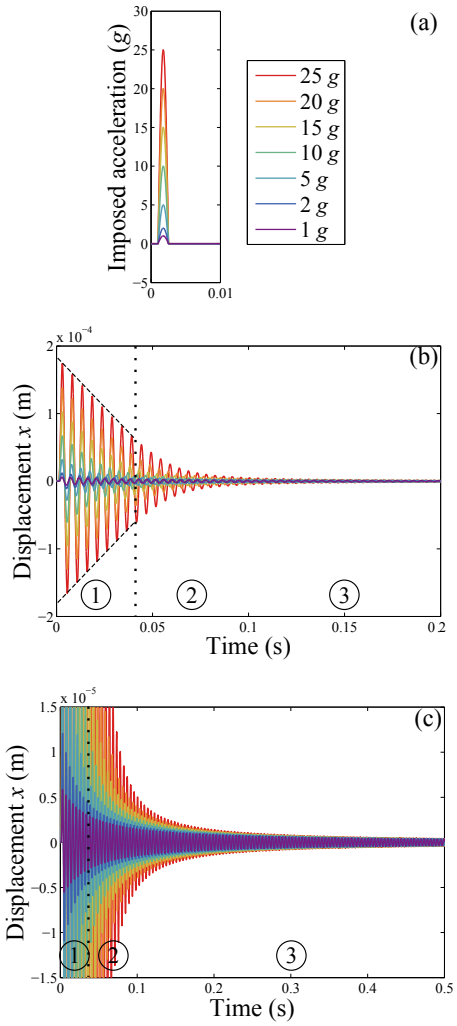


Figure 5: Simulated transient response of the single-degree-of-freedom system of Fig. 4: (a) imposed acceleration, (b) response for all amplitudes during 0.2 s and (c) zoom on the low response amplitudes during 0.5 s. Numbers indicate decay regimes: linear decay (1), and fast (2) and slow (3) "exponential" decay.

- Nomex honeycomb ($\rho = 48$ kg/m^3, $G = 44.8$ MPa)
- PMI foam ($\rho = 52$ kg/m^3, $G = 19$ MPa).

The beam length is 253 mm and the width is 40 mm. The skins are made of seven plies of prepreg carbon-epoxy fabric used in the aeronautic industry, for a total thickness of 2 mm. The core thickness is 20 mm.

The set-up is shown on Fig. 6. The sandwich beams are tested in cantilever configuration. Excitation is applied with an impact hammer close to the clamped end, and the response is measured at the free end with a laser vibrometer.

Figure 7 shows the measured impacts and transient response for two impact amplitudes of 10 N and 100 N. The durations of the impacts were 1.7 ms and 1.4 ms respectively. The response shown was obtained as the average of five successive tests.

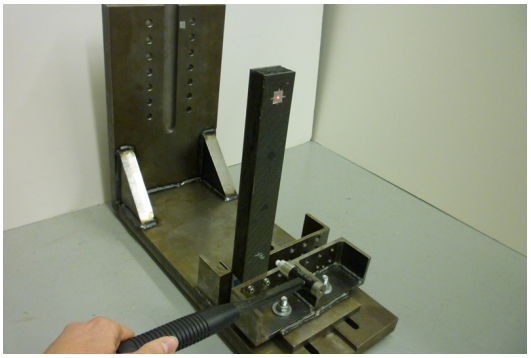


Figure 6: Experimental set-up for transient testing.

These measurements show that the entangled cross-linked fibers lead to a large improvement of damping as compared to classical core materials. While the PMI foam dissipates more than the honeycomb, the entangled cross-linked fibers are far more dissipative. The difference increases with impact amplitude, and the material is thus more interesting for high impact amplitudes.

As expected from the previous simulation, the initial slope of the response is steep, particularly at 100 N. Then, the decay rate decreases, and at low oscillation amplitude the material provides little dissipation.

While this study demonstrates very good damping properties, it should be noted that the entangled cross-linked fibers tested have a higher density and a lower stiffness than the two other core materials.

CONCLUSIONS

The effect of a fibrous material on the transient response of a structure has been studied. Material study showed a hysteretic behavior indicating dissipation coming from friction between the fibers. Dahl's dynamic hysteresis model was used to model the measured hysteresis. The simulated transient response of a single-degree-of-freedom system showed three decay regimes depending on the amplitude. The first regime, typical of friction, corresponds to the higher decay rate, and is thus the most interesting. For the amplitude range studied, the entangled material is more dissipative for higher excitation amplitudes.

The transient response of a sandwich beam with entangled core material showed high added damping as compared to two classical core materials (Nomex honeycomb and PMI foam). Moreover, as predicted by the single-degree-of-freedom simulation, the added damping was increased at higher impact amplitude.

This study shows that the entangled-cross-linked material is a good candidate for vibration damping of sandwich structures. It should be noted however that its lower stiffness and higher density than classical core materials prevents a total replacement of classical materials. Future studies should be conducted to investigate possible applications and analyze the effect of the fiber density and fiber type on damping.

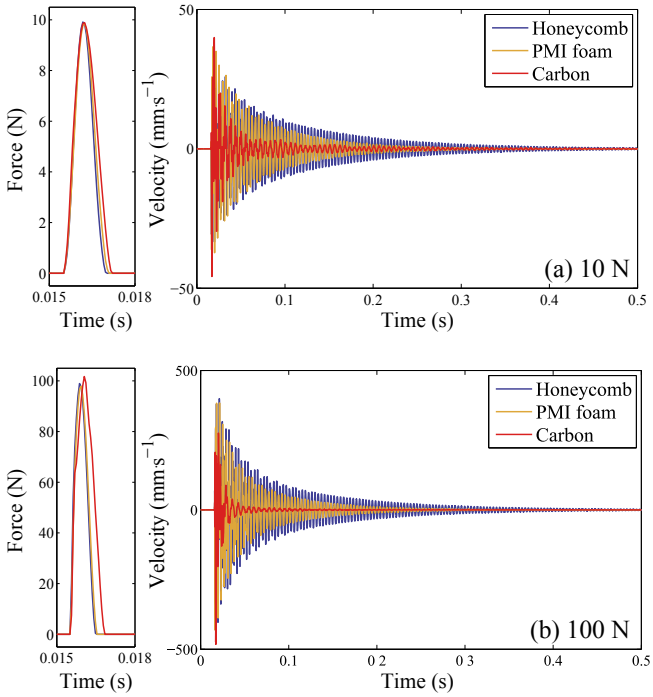


Figure 7: Transient response of sandwich beams with three different core materials to two impacts: (a) 10 N, 1.7 ms and (b) 100 N, 1.4 ms.

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