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Diagnosis of the Fabrication Process of a Sandwich Structure with Fiber Network Core by Vibration Testing

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The aim of this paper is the fabrication and vibration testing of a sandwich structure including a new core material known as fibre network sandwich material. As fabrication norms for such a material do not exist as such, so the primary goal is to reproduce successfully fibre network sandwich specimens. Enhanced vibration testing diagnoses the quality of the fabrication process. These sandwich materials possess high damping values, making them suitable for vibro-acoustic applications where structural strength is of secondary importance e.g., internal panelling of a helicopter.

Introduction

The vibration characteristics of sandwich materials have drawn much attention recently. The dynamic parameters of a structure i.e. natural frequency, damping and mode shapes are determined with the help of vibration testing which provides the basis for rapid inexpensive dynamic characterization of composite structures [1]. D.J Ewins gave a detailed overview of the vibration based methods [2]. A wide amount of literature is present related to vibration testing of composite sandwich structures [3-7]. The equations that explain the dynamic behavior of sandwich beams are described extensively in the literature and notably in the references [8,9].

The importance of material damping in the design process has increased in recent years as the control of noise and vibration in high precision, high performance structures and machines has become more of a concern. At the same time, composites sandwich researchers have focused more attention on damping as a design variable [10,11]. One way of increasing damping in sandwich materials is by putting a viscoelastic layer as core between the two laminates [12,13]. Jueng and Aref reported that sandwich structures with combined honeycomb-foam cores have higher damping than those with individual honeycomb or solid viscoelastic cores [14].

These advancements have led to the need for developing materials possessing better damping characteristics. New materials like fiber network materials can be used as potential dampers and sound absorbers in specific applications like the inner paneling of a helicopter, where structural strength is not the primary requirement. Fiber network materials are made from natural materials (wool, cotton etc) as well as artificial ones (carbon, steel, glass etc) and are quickly becoming of widespread use as sound absorbers [15]. Bonded metal fibers network materials offer advantages for use as heat exchanger [16] or insulation [17]. These materials possess low relative density, high porosity and are cost-effective. Sandwich structures normally consist of two thin skins separated by a thick core. Traditional core materials are usually honeycomb, foam or balsa. Recently, a novel type of sandwich has been developed with bonded metallic fibers as core material [18-20]. This material presents attractive combination of properties like high specific stiffness, good damping capacity and energy absorption. Fiber network materials with carbon fibers have also been studied for using as core material [21]. Entangled cross-linked carbon fibers present many advantages as core materials i.e.,

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open porosity, multifunctional material or the possibility to reeve electric or control cables on core material. In addition, L. Mezeix et al. studied the mechanical behavior of fiber network materials in compression [22]. Mechanical testing has also been carried out on specimens made of wood fibers [23], glass fibers [24] and various matted fibers [25]. Although few works can be found in the scientific literature devoted to the mechanical testing of sandwich fiber network materials, and in fact no scientific literature can be found related to the vibration testing of sandwich fiber network materials or even simple fiber network materials.

Therefore, the main motivation of this work is to develop a process in order to fabricate sandwich fiber network specimens. Whereas, vibration testing is used to diagnose the quality of the fabrication process and to verify the potential damping capabilities of these sandwich specimens.

Fabrication Process

The core of the sandwich test specimens used in this article consists of carbon fibers that are made of a yarn of standard carbon filaments. For the cross-linking of carbon fibers epoxy resin is used. The skin materials are made of unidirectional pre-impregnated plies of type T700/M21. The upper and lower skins consist of four plies each with a lay-up of [0/90/90/0]. For the test specimens used in this article, approximately 900 g of fibers of 10mm length are cut manually. The carbon fibers are then treated in a solution of dichloromethane for 24 hours and are then cleaned for 2 hours in methanol. These uncoated carbons are then separated by a blow of compressed air. The mixture of resin and hardener is then sprayed on the separated carbon fibers by a spray paint gun. The fibers vaporized by the resin are then placed in the mold between the two skins of unidirectional composites. In order to polymerize the fiber network sandwich specimens, the mold is then heated in an autoclave up to 180°C for two hours. The dimensions of the vibration test specimens are 480x50x11 mm. The thickness of the fiber network core is 10 mm and that of each skin is 0.5 mm.

The fiber density of the fiber network core is chosen to be 150 kg/m³. First a small mold (510x65x11 mm) is used to fabricate a single vibration test specimen with a fiber core density of 150 kg/m³. Then a larger mold (510x250x11 mm) is used to produce four vibration test specimens at one time. In the first instance, four identical specimens are produced, in view to have the same composition as that of the single specimen fabricated from small mold. These four specimens shall be referred to as heavy specimens in this article. In the next step, four lighter specimens are fabricated having 20 g less resin than the heavier ones, keeping the same fiber core density of 150 kg/m³. The composition of these three types of test specimens is listed in Table 1.

Table 1. Composition of fiber network sandwich specimens for vibration tests fabricated from the small and large mold having 150 kg/m³ fiber density

Density	Small Mold	Large Mold	
	150 kg/m ³	150 kg/m ³ (Light)	150 kg/m ³ (Heavy)
Weight of Fibers	39 g	39 g	39 g
Weight of Resin & Hardener	43 g	18 g	43 g
Weight of Skin (Upper + Lower)	38 g	38 g	38 g
Total Weight of Specimen	120 g	95 g	120 g

Vibration Testing

The experimental equipment used to obtain the vibration test results discussed in this paper is shown in Figure 1. The experimental set-up is that of a free-free beam excited at its center, based on Oberst method [26]. The Oberst method states that a free-free beam excited at its center has the same dynamical behavior as that of a half length cantilever beam. The test specimen is placed at its center on a B&K force sensor (type 8200) which is then assembled on a shaker supplied by Prodera having a maximum force of 100 N. A fixation system is used to place the test specimens on the force sensor. The fixation is glued to the test specimens with a HBM X60 rapid adhesive. The response displacements are measured with the help of a non-contact and high precision Laser Vibrometer

OFV-505 provided by Polytec. The shaker, force sensor and the laser vibrometer are manipulated with the help of a data acquisition system supplied by LMS Test Lab.

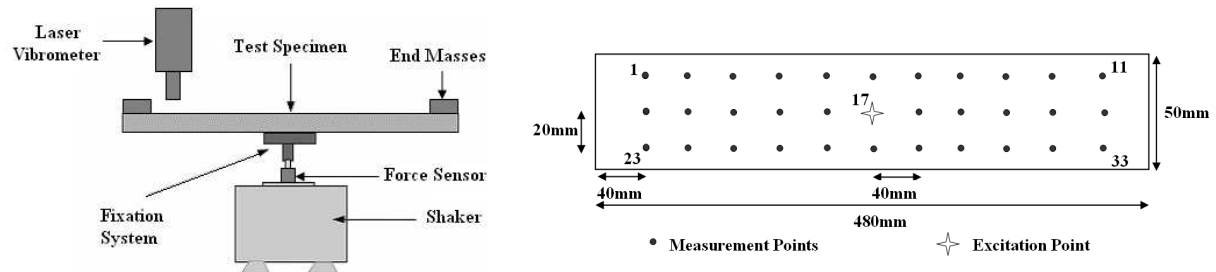


Figure 1. Experimental set-up for vibration testing **Figure 2.** Vibration test specimen specifying the location of the excitation and the measurement points

The center of the test specimens is excited at Point 17 as shown in Figure 2. Burst random excitation is used which is a broadband type excitation signal (0-2650 Hz). The signal is averaged 10 times for each measurement point. Hanning windows are used for both the output and the input signals. The linearity is checked and a high frequency resolution ($\Delta f = 0.25\text{Hz}$) for precise modal parameter estimation is used. Response is measured at 33 points that are symmetrically spaced in three rows along the length of the beam. The modal parameters are extracted by a frequency domain parameter estimation method (Polymax) integrated in the data acquisition system.

Results and Discussion

The aim of the vibration testing is to diagnose the variability of the fabrication process and to extract the global modal parameters i.e., natural frequencies and damping ratios. The modal parameters for the first four bending modes are studied. Firstly, vibration tests are carried out on the vibration test specimen fabricated from the small mold and then on the four light and heavy specimens fabricated from the large mold. The modal parameters extracted from 33 high quality frequency response functions with the help of Polymax algorithm integrated in the LMS data acquisition system, are presented in Table 2. The difference in weight between each of the four heavy and light specimens is due to the fact that with the currently available fabrication technology it is difficult to spray the resin equally on the fibers. This difference in weight is also evident in the natural frequencies of these specimens (Table 2). The heavy specimen 5 and light specimen 6 have comparatively high natural frequencies due to them being relatively heavier in weight than the rest.

Keeping in view the difficulty level of the fabrication process, a major aim of this work is to successfully reproduce multiple sandwich fiber network specimens having the same characteristics. For this reason, the intent is to reproduce four vibration test specimens identical to Specimen 1 (150 kg/m^3 fiber core density and 43 g of epoxy resin) in a large mold. The comparison of the modal parameters of Specimen 1 with those of the heavy specimens (Specimen 2-5) show that large sandwich specimens with fiber network core can be reproduced with a relative efficiency. The natural frequency of the first mode for Specimen 1 is 225 Hz (Table 2), where as for the heavy specimens (Specimens 2-5) the average natural frequency for the first mode is 211 Hz with a standard deviation of 18 Hz. The main reason for this dispersion is the uneven spray of resin on the fibers. So vibration tests have been used here as a diagnostic tool in order to verify the quality of the fabrication process.

On the other hand, the light specimens (Specimens 6-9) possess better damping characteristics because lesser amount of resin increases the friction between the carbon fibers in the

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sandwich core (weakening the cross-linking between the fibers), which leads to higher values of damping ratios (Table 2).

Table 2. Modal parameters comparison for the light and heavy vibration test specimens fabricated from the small and large mold (150 kg/m³ fiber core density)

Type of Specimen	Specimen No	Specimen Weight (g)	Damped Natural Frequencies (Hz)				Damping Ratios (%)			
			1st Mode	2nd Mode	3rd Mode	4th Mode	1st Mode	2nd Mode	3rd Mode	4th Mode
Heavy (Small Mold)	1	120.0	225	622	1064	1536	0.331	0.386	1.17	1.24
	2	124.1	222	652	1069	1550	0.331	0.386	0.622	1.235
Heavy (Large Mold)	3	116.0	189	506	947	1493	0.464	0.697	1.204	1.263
	4	118.6	202	562	981	1428	0.556	0.641	1.033	1.124
	5	126.4	230	632	1107	1673	0.691	0.792	1.351	1.126
Light (Large Mold)	6	98.0	160	349	701	1217	2.75	3.29	2.65	1.59
	7	93.0	140	295	636	1160	3.31	2.18	3.98	1.25
	8	94.7	145	311	680	1179	3.63	2.98	2.53	0.93
	9	94.5	144	320	681	1171	3.62	2.59	2.28	1.10

The vibration tests results show that the heavy specimens (Specimens 1-5) being more dense are less dissipative in nature thus possessing lower damping characteristics whereas, the light specimens (Specimens 6-9) having higher damping values. This observation can be further explained by studying the comparison of the sum of frequency response functions (FRF) for Specimen 2 (Heavy) and Specimen 7 (Light) in Figure 3. The sum of the frequency response functions can be compared for all the vibration test specimens in this article, as same number of measurement points (33) have been chosen for all the specimens i.e. symmetry has been respected. The resonance peaks for the first four bending modes for each specimen are also highlighted in Figure 3.

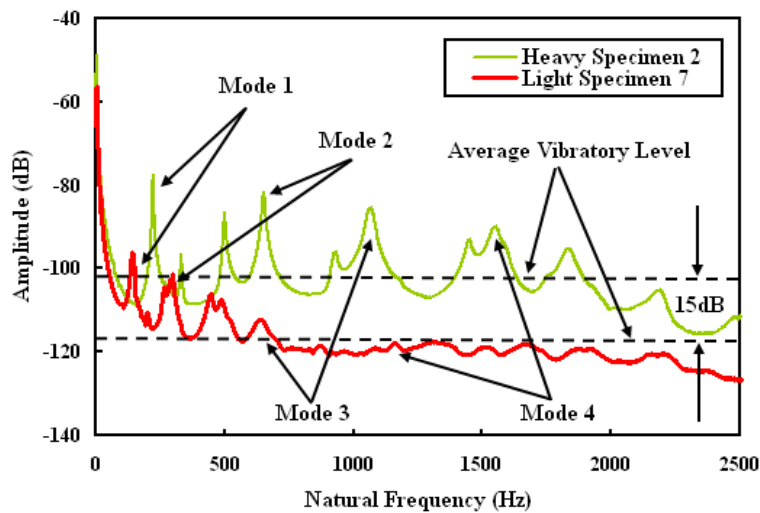


Figure 3 Comparison of the Sum of Frequency Response Function (FRF) for a light (Specimen 3) and a heavy specimen (Specimen 7) having 150 kg/m³ fiber core density.

It can be seen in Figure 3, that the resonance peaks of the heavy specimen are more pointed and possess higher amplitude than the light specimen. The resonance peaks of the light specimens are

comparatively rounded specially after 800Hz. An interesting global approach is developed next in order to compare the average vibratory level of the specimens. The average vibratory level is calculated by taking the average of the amplitude (in dB) of the sum of the frequency response function for each specimen. The average vibratory level (AVL) is also compared for the two types of specimens, and it can be seen that the light specimens possess on average a 15 dB lower amplitude than the heavy ones.

From Figure 3, it can be inferred that the difference in the natural frequencies between the heavy and light specimens signifies a loss in rigidity, whereas the change in vibratory level signifies a reduction in the amplitude of vibration. The percentage change in frequency and the change in vibrational level between the four heavy and four light vibration test specimens (150kg/m^3 fiber core density) for the first four bending modes are calculated with the help of Equations (1) and (2) and the resulting values are laid out in Table 3.

$$\text{Change in frequency } (\Delta f) = \frac{f_H(k) - f_L(k)}{f_H(k)} \quad (1)$$

where $f_H(k)$ is the average frequency for the four heavy specimens (Specimens 2-5) for the k_{th} mode and likewise $f_L(k)$ is the average frequency for the four light specimens (Specimens 6-9) for the k_{th} mode

$$\text{Change in vibratory level } (\Delta a) = a_H(k) - a_L(k) \quad (2)$$

where $a_H(k)$ is the average amplitude in dB for the four heavy specimens for the k_{th} mode and $a_L(k)$ is the average amplitude in dB for the four light specimens for the k_{th} mode

Table 3. Change in frequency and vibrational level for the light and heavy vibration test specimens for the first four modes

	Mode 1	Mode 2	Mode 3	Mode 4
% Change in frequency (Δf)	30,1%	45,7%	34,3%	23,1%
Change in Vibratory Level (Δa)	10.1 dB	13.7 dB	17.9 dB	17 dB

Conclusion

The aim of this article is to fabricate a sandwich material that possesses high damping characteristics for specific applications like the inner paneling of a helicopter cabin. For this reason, a new type of sandwich material having fiber network material as core and unidirectional carbon pre-impregnated plies as skins is fabricated. The advantage of the vibration testing is to diagnose the variability of the fabrication process and to verify experimentally the potentially good damping characteristics of the fiber network sandwich specimens. The vibration tests on these specimens showed that the lighter specimens possess five times more damping and on the average a 15 dB lesser vibratory level than the heavier ones. Despite the complexity of the fabrication process, large fiber network sandwich specimens are relatively successfully reproduced.

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