Research on damping performance of elastomer/carbon fiber epoxy composite

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Abstract
The preparation method of the composite material with damping layer and the influence of the position of the single-layer damping layer in the composite material on the damping coefficient have not been studied in detail. In this paper, the most commonly used composite molding methods, the hot autoclave and hot patch method, to manufacture elastomer/carbon fiber reinforced epoxy resin (elastomer/CER) composites. Then, the effects of the manufacturing method and the position of the elastomer on the short beam shear strength and damping performance of the co-cured composite were studied. The novel results show that the composite manufactured by the hot autoclave has high shear strength, but the damping factor of the composite is relatively weak. The addition of the damping layer has little effect on the shear strength of the composites of the hot patch instrument, and the damping factor of the composites with an elastic layer in the middle can reach 0.0683, which is 4.1 times that of the composites without the damping layer, and 2.5 times of the composites with an elastic layer in the middle of the hot autoclave manufacturing.

1. Introduction
In the fields of aviation, navigation, and automobiles, equipment will generate impulse shock due to environmental influences, and pulse impact can cause brittle fractures for foundations, bearings, and electronics [1–3]. High damping materials can suppress the pulse impact, thereby reducing the probability of brittle fracture and increasing the life of the structure. Due to the low density, high strength, high rigidity and corrosion resistance of carbon fiber composite materials, the preparation of high damping carbon fiber composite materials has become the focus of many researchers.

Researchers have used a variety of methods to increase the damping of fiber composites, such as adding nanoparticles, nanotubes, piezoelectric patches and viscoelastic materials to the entire matrix [4, 5]. Jeffrey J. Kim [6] evaluated the effects of different carbon nanotubes (CNT) surfactant treatments, orientations and concentrations on the damping and stiffness of new types of hybrid CNT-carbon/epoxy composites. It is shown that a 10% volumetric concentration of highly aligned CNT yarns treated with a non-ionic surfactant, located at the interlayers and oriented along the loading direction, provides superior damping and stiffness characteristics. CNT composites with superior damping main dissipation mechanism is frictional sliding [7, 8]. Huang, CY [9] introduced silica nanoparticles together with rubber particles into epoxy resin through the sonication process, then treated the epoxy resin as matrix and impregnated into the fiber layer through a vacuum hand lay-up process to form a composite laminate. Experimental results indicated that with the incorporation of the silica nanoparticles together with the rubber particles, the reduction of flexural stiffness of fiber composites, while the damping properties of laminates were improved. Saviz, MR [10] studied the vibration characteristics of laminated composite plate with surface-bonded piezoelectric layers/patches, and analyzed the structural coupling between the panels and piezoelectric actuators. Some examples with new features are given, showing that the piezoelectric patch significantly improves the damping characteristics of the plate for suppressing the
geometrically nonlinear transient vibrations. Although adding nanoparticles, nanotubes, and piezoelectric patches to the entire matrix improves the damping performance, it also brings some disadvantages, such as uneven dispersion of nanoparticles or nanotubes, which will damage the shear strength of the composite, and the complexity of piezoelectric materials can cause reliability problems. Rao, MD found that composites co-cured with viscoelastic materials can enhance the damping capacity of a composite structural system with little reduction in stiffness and strength [11]. Troncossi, M [12] analyzed the effect of viscoelastic material layers on the damping performance of carbon/epoxy sheet through experiments. The results of the impact hammer test and the excitation measurement of the exciter show that the presence of only one layer of viscoelastic material can triple the damping characteristics of the carbon fiber composite sheet. Hujare, PP [13] studied the influence of the thickness of the constrained damping material on the modal loss factor of a vibrating structure. The measurement is carried out on the sandwich beam structure. The experimental results show that the thickness ratio of the constrained layer (damping material) to the constrained layer should be equal to one-half to achieve maximum damping in the vibrating structure. Fairlie, G. [14] studied the effects of the stacking sequence and fiber orientation on the damping properties of hybrid flax/carbon fiber-reinforced composites. The results show the most important layer when it comes to damping properties is the external layers. By adding an external flax layer into an epoxy/carbon fiber-reinforced composite considerably enhanced its damping ratio by 53.6% and by adding two layers increased it by 94%. The results indicated a high potential for the automotive semi-structural applications to improve damping properties of the vehicle. Although the literature in recent years has shown that the addition of a damping layer can improve the damping of composite materials, there is no detailed study on the influence of the manufacturing method of the composite with damping layer and the position of the single damping layer in the composite on the damping factor.

In this article, an elastomer/carbon fiber reinforced epoxy resin (elastomer/CFER) composite material is prepared by the hot autoclave and the hot patch and its damping and mechanical properties are studied. The microstructure of the co-cured composite interface was analyzed by infrared spectroscopy and ultrasonic C-scan. At the same time, the influence of the preparation method and the position of the elastomer on the shear performance and damping performance of the co-cured composite short beam was studied.

2. Experiment

2.1. Materials

Unidirectional carbon fiber reinforced epoxy resin prepreg ZT7G/LT-03A, purchased from China Aviation Composite Materials Co., Ltd., is a medium and low temperature curing epoxy resin. SMACWRAP® (abbreviated as elastomer) is light-weight and high-damping viscoelastic material purchased from the MontBlanc Technologies group which can be compatible with the curing of prepreg or pre-impregnated composite fiber processes to improve the damping characteristics of the material. Ethanol (absolute alcohol, \( \geq 95.0\% \)) was purchased from Sinopharm Chemical Reagent Co., Ltd. Auxiliary materials, such as vacuum bag film (Lpplon ® DPT1000), release film (Wrightlon ® 5002), release cloth (Release Ease234 TFP), sealing tape (GS-213-3), pressure sensitive tape (Airkap 1), purchased from Airtech Advanced Materials Group (China).

2.2. Preparation of elastomer/carbon fiber epoxy composite

First, the paving of prepreg and elastomer damping material. The prepreg (ZT7G/LT-03A) is laid according to the method of \((0/45/90/-45)\), where the number represents the direction of the carbon fibers in the prepreg, 0 degrees is the direction of the long side of the material, and the parameter s represents the symmetry of the layup sequence, that is, the stacking sequence of the carbon fibers in the prepreg is 0 degrees, 45 degrees, 90 degrees, 45 degrees, 90 degrees, 45 degrees, 90 degrees, 45 degrees, and 90 degrees respectively. And elastomer damping material is added to the surface, 1/4 and middle layers of the prepreg. As shown in figure 1(a), place the damping material on the middle layer of the prepreg. Second, the molding process of elastomer/carbon fiber epoxy composites. The first step is to scrub the mold with alcohol. In the second step, place the release film, release cloth, prepreg, pressure sensitive tape, release cloth, release film, and sealing tape on the mold in sequence, and seal with vacuum bag film. In the third step, the prepreg is heated and pressurized to manufacture by using a hot autoclave or a hot patch instrument, and the curing curve is shown in figure 1 (b). Finally, the finished sheet was cut into five test pieces with a size of \(230 \times 10\) mm, which were used for the damping test. The corresponding material numbers are shown in table 1.

2.3. Characterization

NOVASCAN Phased Array Ultrasonic Detector, made in Guangzhou Doppler Technology Co., Ltd., is used to measure the internal structure of the elastomer/CFER. A spectrometer (Nicolet is 50, Thermofisher, USA) which from 600 cm\(^{-1}\) to 4000 cm\(^{-1}\) was used to obtain Fourier transform infrared (FTIR) spectra. The camera
Fourier Infrared Spectroscopy (FTIR) and photograph are used to analyze the changes before and after use of SMACWRAP® (referred to as elastomer) to prove the compatibility of the damping material with the curing of prepreg. It can be seen from the internal photos of figure 2 that the color of the elastomer that participates in the curing of the prepreg is obviously darker than that of the unused elastomer. From the infrared spectrum of SMACWRAP®, it can be seen that the characteristic peaks in the pure elastomer 1008.11 cm⁻¹, after the elastomer participates in the curing of the prepreg, the red shift becomes 1011.96 cm⁻¹. Compared with other peak strengths of pure elastomers, the strength has been weakened, which further shows that the elastomers and the material, it is designed to place the damping material, PTFE, in the laminate composite material formed by the hot autoclave has good quality, basically no internal defects and only contains the damping material, which has better permeability in the resin. It can be seen from the figure 3(a) that the laminate composite material formed by the hot autoclave has good quality, basically no internal defects and only contains the damping material, which has better permeability in the resin. It can be seen from the figure 3(b) of the hot patch instrument manufacturing that the white background indicates that there is no low-wave reflection when the ultrasonic is irradiated on the composite material board. The reason is that the quality of the hot patch manufacturing composites is not good, and impurities or bubbles will absorb the ultrasonic waves. The board containing polytetrafluoroethylene is yellow,

(P20 mobile phone, Huawei Technologies Co., Ltd., China) was used to take a photo. The damping test mainly implements constant amplitude sweep frequency excitation on the sample, and records the time domain response of the test piece amplitude, the testing equipment used consists of a data acquisition instrument (INV3062C), an eddy current sensor (WT-c5), a non-contact vibration exciter (JZF-1), a power amplifier (DG1022U) and a signal generator (HC300G).

3. Results and discussion

3.1. Characterization of elastomer/carbon fiber epoxy composite

Fourier Infrared Spectroscopy (FTIR) and photograph are used to analyze the changes before and after use of SMACWRAP® (referred to as elastomer) to prove the compatibility of the damping material with the curing of prepreg. It can be seen from the internal photos of figure 2 that the color of the elastomer that participates in the curing of the prepreg is obviously darker than that of the unused elastomer. From the infrared spectrum of figure 2, it can be seen that the characteristic peaks in the pure elastomer 1008.11 cm⁻¹, after the elastomer participates in the curing of the prepreg, the red shift becomes 1011.96 cm⁻¹. Compared with other peak strengths of pure elastomers, the strength has been weakened, which further shows that the elastomers and the compatibility of prepreg.

The NOVASCAN phased array ultrasonic detector detects the internal structure of composite materials under different molding processes. The detector mainly detects three types of images, including S-scan, A-scan and C-scan. A-scan is to perform imaging processing on the signal received at a certain point position. S-scan refers to the two-dimensional image superimposed by all A-scans under a specific channel, which is the image in the scanning process. C-scan shows the cross section of the sample which also best shows the internal structure of the sample. In order to better simulate whether the damping material is stratified in the laminate composite material, it is designed to place the damping material, PTFE, in the laminate composite material on the 1/2 layer of the laminate, the corresponding C-scan (as shown in figure 3) from left to right. In the ultrasonic C-scan image of the composite material, the left ordinate and abscissa represent the moving distance of the ultrasound probe respectively, and the right ordinate represents the reflected wave intensity of the ultrasonic wave. As can be seen in figure 3(a), the laminate composite material formed by the hot autoclave has good quality, basically no internal defects and only contains the damping material, which has better permeability in the resin. It can be seen from the figure 3(b) of the hot patch instrument manufacturing that the white background indicates that there is no low-wave reflection when the ultrasonic is irradiated on the composite material board. The reason is that the quality of the hot patch manufacturing composites is not good, and impurities or bubbles will absorb the ultrasonic waves. The board containing polytetrafluoroethylene is yellow,

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Table 1. Sample numbers of elastomer/carbon fiber epoxy resin damping composites under different molding processes and different lamination methods.

| Sample code | Manufacturing method | Laying method |
|-------------|----------------------|---------------|
| R-none      | Hot autoclave instrument | (0/45/90/−45)s |
| R-0         | Hot autoclave instrument | (0/45/90/−45)s |
| R-1/4       | Hot autoclave instrument | (0/45/90/−45)s |
| R-1/2       | Hot autoclave instrument | (0/45/90/−45)s |
| Z-none      | Hot patch instrument  | (0/45/90/−45)s |
| Z-0         | Hot patch instrument  | (0/45/90/−45)s |
| Z-1/4       | Hot patch instrument  | (0/45/90/−45)s |
| Z-1/2       | Hot patch instrument  | (0/45/90/−45)s |
indicating that the ultrasonic wave is reflected in the middle layer, and the penetration performance is very poor. In comparison, the penetration effect of only the damping material is better. However, compared with the material formed by hot autoclave, the formed sheet has poor quality and poor permeability. To sum up, the preparation of co-cured elastomer/carbon fiber epoxy composite should choose the hot autoclave molding method as much as possible.

3.2. Mechanical performance analysis
The shear strength test is carried out at room temperature and atmospheric environment, referring to the ASTM D 2344 test standard. The experiment uses an orthogonal method to compare the effects of the two forming methods and the location of the damping material on the shear strength of the material short beam. It can be seen from figure 4 that, regardless of where the damping material is placed, the material formed by the hot autoclave have a higher short beam shear strength compared to the hot patch instrument. The main reason is that the hot autoclave molding pressure is large and the internal defects of the material are less, as shown in the ultrasonic c-scan of the material in figure 3.

Figure 2. Infrared spectra and photos of the use of elastomer before and after.

Figure 3. C-scan pictures of composite materials prepared by different molding processes. (a) the hot autoclave, (b) the hot patch instrument.
Control the molding method of the hot autoclave unchanged and change the position of the damping layer on the composite laminate. It can be found that when the damping material has the surface layer, the shear strength is the largest. This is because the surface layer damping material does not affect the interlayer strength of the laminate. The intermediate shear strength has the greatest impact on the interlaminar shear strength, and the specific reason has been discussed from the perspective of mechanics. The stress of the entire beam is shown in Figure 5(a). Sun, X.F. [15] pointed out in the book Mechanics of Materials that when the beam is bent, there is a shear force on the cross-section of the beam, and there will be a corresponding shear stress, and the variation of the shear stress ($\tau$) along the section thickness (that is, with the coordinate $y$) on the cross-section of a straight beam of equal plane is expressed as:

$$
\tau = \frac{F_s}{2I_z} \left( b^2 \frac{y^2}{4} - y^2 \right).
$$

where, $F_s$ is the shear force on the cross section, $I_z$ is the inertia moment of the entire cross section about its neutral axis, $b$ is the sample thickness. It can be seen that $\tau$ varies according to a quadratic parabola along the section thickness (Figure 5(b)). When $y = \pm \frac{1}{2}b$, that is, the farthest distance from the neutral axis on the cross section, the shear stress $\tau = 0$, and when $y = 0$, that is, at each point on the neutral axis, the shear stress reaches the maximum value $\tau_{\text{max}}$. This conclusion also shows that the intermediate shear stress is the largest. Throughout the composite beam, damping (rubber) material damage is the key to controlling the failure of the entire composite. According to the above force analysis, the shear stress of the damping layer in the 1/2 layer is
significantly higher than that in the 1/4 layer, so the entire material is more likely to be damaged when the damping layer is in the 1/2 layer.

When the forming method of the hot patch instrument is unchanged, no matter how the position of the damping layer changes, its shear strength has little effect. At this time, the main influence on the shear strength of the material is the internal defect of the material.

3.3. Damping performance analysis

The asymmetry of the layup will cause the cured composite material board to warp. The composite material of the 1/4 layer of the damping layer warps seriously and will not be selected in the design. Only composite materials without an elastic layer, an elastic layer on the surface, and a 1/2 elastic layer were selected for the damping performance test. Refer to the cantilever beam method in GB/T 16406 (Acoustics-Flexural resonance testing method for damping properties of acoustical materials, National Standard of the People’s Republic of China) at room temperature, as shown figure 6, the size of the test piece with and without the elastic layer is 230*10*1.2 mm and 230*10*1 mm, respectively, and the working section is 207 mm. The whole test system consists of two parts: excitation and test. The signal generator sends a signal to the exciter, the exciter applies a simple harmonic excitation force to the sample, and the detector detects the vibration signal of the sample, which is amplified and sent to the recorder. During the experiment, keep a constant exciting force, constantly change the frequency, and measure the resonance curve of the sample. From the resonant peak frequency and the resonant peak width, the loss factor of the material can be calculated. This work only compares the damping factor under first-order and second-order resonance. Damping factor is also called loss factor. The larger the damping factor, the stronger the shock absorption capacity of the material. The calculation formula of the damping factor is as follows: \[ \tan \delta = \frac{\Delta f}{f} \] where \( f \) is the resonance frequency; \( \Delta f \) is the resonance peak width (the difference between the high and low frequencies corresponding to the peak value of 0.707 times). The damping factor (\( \tan \delta \)) of the composites increases with the decrease of the resonance frequency, and the damping factor (\( \tan \delta \)) decreases with the decrease of the bandwidth of the resonance peak. The \( \tan \delta \) has a dominant relationship with the resonance peak frequency and its bandwidth. It can be further expressed by the sharpness of the resonance peak. The sharper the resonance curve, the smaller the loss factor and the weaker the damping ability. The smoother the resonance curve, the larger the damping factor and the better the damping performance of the corresponding material. It can be seen from the figure 7 that the second-order resonance curve of the composite material with an elastic layer in the middle is smoother, compared with the other two materials, so the damping effect of the second-order resonance is more obvious.

From the first-order resonance curve in figure 7, the first-order damping factor and elastic modulus can be further obtained, corresponding to table 2. For the composite formed by the hot patch instrument, the composite with an elastic layer in the middle has the strongest damping effect, with a damping coefficient of 0.0683, which is 4.1 times that of the composite without a damping layer under the same molding method, and 1.4 times higher than the composite with the damping layer on the surface of the same manufacturing method. For the composite formed by the hot autoclave instrument, the addition of the damping layer does not significantly improve the damping effect. It may be due to the excessive pressure during the co-curing of the damping layer and the carbon fiber composite material, the damping layer is severely squeezed and cannot be

Figure 6. Schematic diagram of the damping test experimental device.
released, so the damping effect of the material is not improved significantly. The damping factor the composite with an elastic layer in the middle formed by the hot autoclave is 0.02771, which is two-fifths of the composite with an elastic layer in the middle formed by the hot patch instrument.

The modulus of elasticity can be regarded as a measure of the difficulty of elastic deformation of the material. The elastic modulus of the material can also be calculated from the resonance curve. The calculation formula is as follows: 

\[ E = \frac{f^2}{\pi^2 a b^3} \]

where \( E \) is the elastic modulus, \( L \) is the length of the working section at the cantilever beam test, \( m \) is the mass; \( a \) is the width of the sample; \( b \) is the thickness of the sample; the elastic modulus can be regarded as an index to measure the elastic deformation of the composites. The greater the value of elastic modulus, the greater the stress that causes the material to undergo a certain elastic deformation, that is, the greater the rigidity of the material, the smaller the elastic deformation will occur under a certain stress. It can be seen from Table 2 that different manufacturing methods have little effect on the elastic modulus of the same composite material. Compared with different materials, the elastic modulus of the composite material with damping layer is smaller, that is, under the same stress, it can withstand larger elastic deformation and the material is more flexible.

Table 2. The first-order damping factor and elastic modulus of composites

| Elastomer Method       | Damping factor | Elastic modulus (MPa) |
|------------------------|----------------|-----------------------|
|                        | 0              | 1/2                   |                        |
| The hot autoclave      | 0.0171         | 0.0250                | 0.02771                |
|                        | 36.56          | 29.02                 | 30.13                  |
| The hot patch          | 0.0166         | 0.0479                | 0.0683                 |
|                        | 33.63          | 27.86                 | 29.13                  |

Figure 7. Resonance curve of composite. (a) R, (b) R-0, (c) R-1/2, (d) Z, (e) Z-0, (f) Z-1/2.
4. Conclusion and outlook

This article uses the hot autoclave and hot patch method to manufacture elastomer/carbon fiber reinforced epoxy resin (elastomer/CFER) composites. Then, the microstructure of the interface of carbon fiber epoxy composite and elastomer was analyzed by infrared spectroscopy and ultrasonic C-scan. The results show that the interface of carbon fiber epoxy composite and elastomer has strong interaction. At the same time, the effects of the manufacturing method and the position of the elastomer on the short beam shear strength and damping performance of the co-cured composite were studied. The addition of the damping layer has little effect on the shear strength of the composites of the hot patch instrument, and the damping factor of the composites with an elastic layer in the middle can reach 0.0683, which is 4.1 times that of the composites without the damping layer, and 2.5 times of the composites with an elastic layer in the middle of the hot autoclave manufacturing. This work can be applied to the manufacturing process of aircraft and ships to reduce structural vibration and increase service life. It can also be used in the repair process of metal cracks to inhibit the further expansion of cracks and improve the reliability of equipment repair.

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