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A hybrid core layer design concept for high damping carbon fiber reinforced sandwich structures

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Abstract

To improve vibration damping performance of Carbon Fiber Reinforced Plastics (CFRPs), a damping layer is typically sandwiched between two CFRP layers. Herein, a hybrid damping layer design is proposed, to obtain an optimum structure with high performance in both stiffness and damping. The sandwich structure is investigated for different materials of core layer, using different combinations of damping materials. A high-damping CFRP sandwich structure with a wide temperature range is proposed, which uses polyurethane and polyester in the hybrid core layer. The damping property and bending stiffness of the designed CFRP laminate is controllable by using either parallel mode or series mode with different ratios of the damping materials. The Ross-Kerwin-Ungar (RKU) equation is modified to predict the present hybrid core layer structures and reasonable results for both experimental and theoretical prediction were obtained.

Keywords: CFRP, vibration damping, viscoelastic material, RKU equation, dynamic mechanical analysis, sandwich structure

Abbreviations: CFRPs, carbon fiber reinforced plastics; RKU, the ross-kerwin-ungar; DMA, dynamic mechanical analysis; PU, polyurethane; PE, polyester

Introduction

CFRPs are widely used in aircraft and spacecraft, and recently also in automobiles. Vibration and damping properties are crucial for extending the CFRPs to industrial uses. However, the typical CFRP may have very poor damping property (loss tangent is 0.01) in a narrow temperature region. Various efforts have been made worldwide to improve the damping properties of CFRPs.[1–9] Sandwich structures have a high damping capability when viscoelastic materials are used in the core layer.[10–18] This damping treatment offers greater damping capacity with low cost and high efficiency. During vibrations that flex the structure, the constrained core layer undergoes shear deformations and thereby dissipates energy, increasing damping. In contrast, improvements in damping properties with a traditional method generally reduce the mechanical properties of the structures and the damping peak is often limited in a narrow temperature range.

To balance both mechanical properties and damping performance over a wide temperature range, the recent studies have focused on hybrid core technology which may provide a more flexible design for damping materials. A core layer consisting of polymers with different glass transition temperatures (Tg) provides a simple potential solution. The multilayered core part and the polymer blend of the different damping materials could broaden the operating temperature range.[19,20] However, the multilayered core part tends to be thick. Because the damping layer has a low Young's modulus, if the thickness of the damping layer is increased, the bending stiffness of the laminates is reduced, causing delamination between layers. Bending stiffness can be improved by reducing the thickness of the core layer, or by replacing the core material with a higher shear stiffness material.[18,21]

Robinson et al,[22] Lijian et al.[23] improved bending stiffness by using perforated damping sheets in the core layer. During co-curing, the resin flowed through the core layer and ultimately coupled the small holes. The presence of the resin within the damping layer lead to increased shear stiffness which affected the damping and bending stiffness properties of the structure.

In the present paper, a new concept for the hybrid core layer design is proposed. The effects of the composite mode and its area ratio on the damping performance are investigated. This concept may provide an approach to balance mechanical properties and damping performance for various applications. We also assess different combinations of thermosetting and thermoplastic materials in the core layer. A simple core layer structure is proposed, composed of a hard resin part and a viscoelastic part. The developed sandwich structures were measured by dynamic mechanical analysis, which can gauge the variation of loss factor of a material.[17] Experiments and theoretical simulations using the Ross-Kerwin-Unger (RKU) equation are conducted. The theoretical model was established to predict the vibration damping behavior of the developed sandwich structures.

Materials and methods

Plate fabrication

Test specimens of laminates were fabricated using pitch-based carbon fiber prepreg (GRANOC prepreg, E-6026C-12S, Nippon Graphite Fiber Corporation), polyurethane (DiAPLEX, MS5520, SMP Technologies Inc.), and polyester (Neo fade, 4140, Koyo Sangyo Co. Ltd.).

Polyurethane liquefied with a dimethylformamide was loaded to a glass plate using an auto-applicator and dried at 60°C for 2h, then at 80°C for 24h. The polyurethane and polyester films used in the core layer were 0.12mm thick.

In this study, seven samples were prepared (A, B, C1, C2, C3, D1 and D2). Each sample consists of upper and lowers surface layers and an intermediate core layer. The surface layer is made of unidirectional CFRP, and there is no change in the all samples. Samples A, B, C1, C2, C3, D1 and D2 were prepared by changing the structure of the core layer. Samples were prepared by hot pressing molding method. Samples were cured at 130˚C and 2MPa for 1.5h. The specimens were 45mm long, 3mm wide and 1.2mm thick. The core layers of samples A and B were made of a single core material. Samples C1, C2, C3, D1 and D2 were made with a hybrid core layer. The hybrid core layers were prepared by arranging two kinds of core materials on the same plane. As shown in Figure 1, the hybrid core layers were prepared either in parallel mode, in which the core material is arranged parallel to the long axis of the sample, or in series mode, in which the core material is aligned perpendicular to the long axis. The core layer of sample A was made of polyurethane; the core layer of sample B was made of polyester. Samples C1, C2 and C3 were hybrid core layers consisting of polyurethane and polyester. The core layers of samples C1 and C3 were made in series mode. The core layer of sample C2 was made in parallel mode. The area ratios of polyurethane: polyester for samples C1, C2 and C3 were 1:1, 1:1 and 3:1, respectively. The hybrid core layers of samples D1 and D2 were made of polyurethane and epoxy. The prepregs were laminated without including the epoxy core material. Thereafter, the epoxy part was formed by epoxy resin flowing into the part without core material, and the sample was cured. The core layer of sample D1 was prepared in series mode and the area ratio of polyurethane: epoxy was 1:1. The core layer of sample D2 was prepared in parallel mode and the area ratio of polyurethane: epoxy was 1:1. The structure of each specimen is shown in Table 1.

Dynamic mechanical analysis

The bending modes of the sample laminates were measured by dynamic mechanical analysis from 0˚C to 100˚C at a heating rate of 3˚Cmin-1 and a frequency of 20Hz.

RKU equation

The theoretical approach of RKU equation to predict the dynamic properties of sandwich structures is shown as follows,[24]

$$EI\left(1+j\eta\right)=\frac{E_1H_1^3}{6}+E_1H_1\left(H_1+H_2\right)^2\frac{g}{1+2g} \quad (1)$$

$$g=\frac{L^2\left(G'+jG''\right)}{E_3H_2H_3\xi^2\sqrt{C}} \quad (2)$$

Where EI is flexural rigidity per unit width of a composite plate, j is the imaginary unit and η is the loss tangent. E_1 and E_3 are the Young's moduli of the base plate and constrained layer, respectively. H_1, H_2 and H_3 are the thicknesses of the core plate, core layer and constrained layer, respectively. g is the shear parameter. G′ and G″ are the shear storage modulus and shear loss modulus of the core layer, respectively. L is the length of the beam, ξ is a constant related to the natural frequency and C is a correction coefficient.

The shear modulus for materials in series mode is given by

$$G_{series}=\frac{G_{PU}G_{PE}}{G_{PU}A_{PE}+G_{PE}A_{PU}} \quad (3)$$

Where G_{series} is the shear modulus of the entire core layer, G_{PU} is the shear modulus of polyurethane, G_{PE} is the shear modulus of polyester, A_{PU} is the area ratio of polyurethane, and A_{PE} is the area ratio of polyester. The shear modulus for materials in parallel mode is given by

$$G_{parallel}=G_{PU}A_{PU}+G_{PE}A_{PE} \quad (4)$$

Where $G_{parallel}$ is the shear modulus of the entire core layer.

The calculations were carried out with material properties from 0˚C to 100˚C.

Table1 Specifications of the sandwich structures tested

Sample	Material	Core layer mode	Area ratio
A	Polyurethane	Uniform	1
B	Polyester	Uniform	1
C1	Polyurethane, Polyester	Series	PU: PE=1:1
C2	Polyurethane, Polyester	Parallel	PU: PE=1:1
C3	Polyurethane, Polyester	Series	PU: PE=3:1
D1	Polyurethane, Epoxy	Series	PU: Epoxy=1:1
D2	Polyurethane, Epoxy	Parallel	PU: Epoxy=1:1

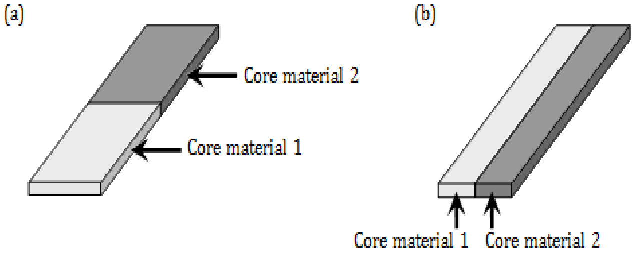

Figure 1 Schematic of the hybrid core layer structures in (A) series mode and (B) parallel mode.

Results and discussion

Effect of the hybrid core layer

Figure 2 shows cross sectional images of samples C1 and C2 with optical microscope. Figure 2a is the series mode (C1) observed in the cross section along the longitudinal carbon fiber direction, and Figure 2b is parallel mode (C2) observed in the cross section of carbon fibers. It is confirmed that no gap is observed in the cross section between polyurethane and polyester.

Figure 3 shows the temperature dependence of storage modulus at 20Hz for samples A, B and C1. With the temperature rising from 10˚C to 20˚C, the storage modulus of sample B decreased rapidly, whereas that of sample A remained almost constant. In contrast, the storage modulus of sample A decreased rapidly from 40˚C to 60˚C. Sample B exhibits a high storage modulus below 10˚C, whereas sample A shows a high storage modulus below 40˚C. Samples A and B have different temperature dependencies in storage modulus owing to different Tg in the core material. It is necessary to pay attention to storage modulus at operating temperature. As shown in Figure 3, the storage modulus rapidly decreases with increasing temperature in all samples.

Sample A rapidly decreased at 40˚C to 60˚C and sample B rapidly

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decreased at 10˚C to 20˚C. However, in sample C1, there were two temperature regions which the storage modulus obviously decreased; first at 10˚C to 20˚C and then at 40˚C to 60˚C. This is because the polyester part of the core layer softened at 10˚C to 20˚C and the polyurethane part softened at 40˚C to 60˚C. A wide temperature dependence of storage modulus can be achieved using the hybrid core layer.

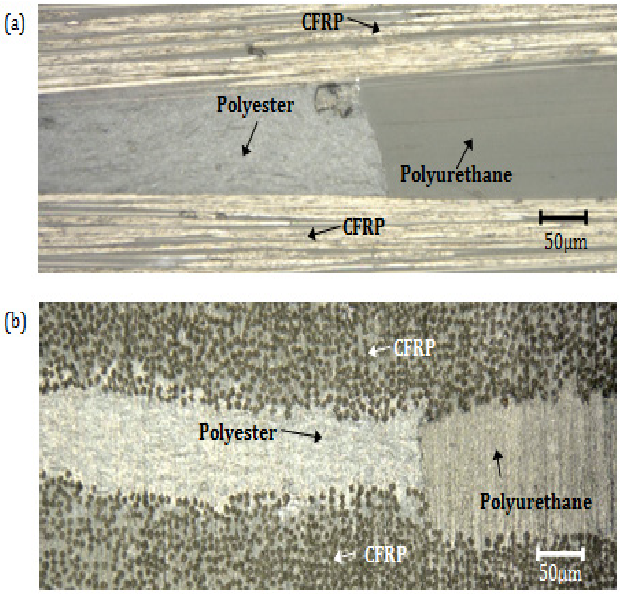

Figure 2 Cross sectional image of core layer with optical microscope, (a) Sample C1 and (b) Sample C2.

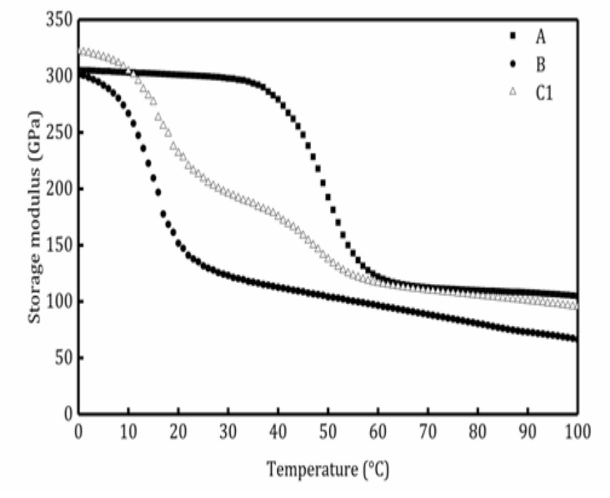

Figure 3 Temperature dependence of storage modulus for samples A, B and C1.

Figure 4 shows the temperature dependence of the loss tangent at 20Hz for samples A, B and C1. As shown in Figure 4, sample A has a single loss tangent peak at around 50˚C. The loss tangent had a maximum peak 0.23 when sample A was heated through Tg of the polyurethane film, at 50˚C. Sample B shows the maximum peak 0.27 at 15˚C, and exhibits high damping at room temperature, which is above Tg of polyester. Figure 4 show that different viscoelastic materials lead to different vibration damping properties. Sample C1 has two prominent peaks at 15˚C and 50˚C, corresponding to the Tg of polyester and polyurethane, respectively. The loss tangent improved to 520% at 15˚C and to 240% at 50˚C, compared with samples B and A, respectively. Moreover, from Figure 4 it can be seen that sample C1 shows high damping over a temperature range that is much wider than that for samples A or B.

These results suggest that, to obtain a better damping capacity, a polyester layer is more suitable when the temperature is lower than 30˚C, whereas a polyurethane layer is preferential at temperatures higher than 40˚C. It is clear that the hybrid core layer can optimize the damping properties and balance bending stiffness of the sandwich structures.

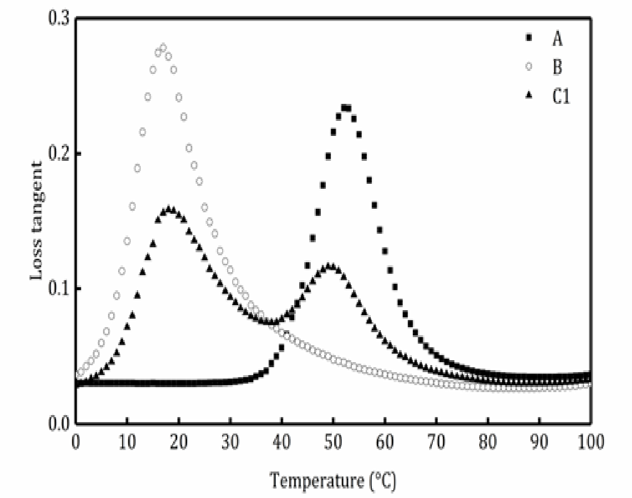

Figure 4 Temperature dependence of loss tangent for samples A, B and C1.

Effect of the composite core layer

Figure 5 shows the temperature dependence of the storage modulus at 20Hz for series mode (sample C1), parallel mode (sample C2) and area ratio change (sample C3). It can be seen from Figure 5 that the storage modulus of sample C2 is higher than that for sample C1 between 15˚C and 100˚C. Sample C1 and sample C2 are composed of the same materials and have the same area ratios. However, the core layer modes are different; the core layer of sample C1 is in series mode, whereas that of sample C2 is in parallel mode. It is considered that the difference between samples C1 and C2 in Figure 5 is due to the difference in core layer mode. In Equation (4), when G_{PU} is larger than G_{PE}, the influence of G_{PU} becomes larger than G_{PE}. Polyurethane has higher shear modulus than polyester, above 0˚C. Thus, the effect of polyurethane becomes stronger in the sample C2.

As for the effect of area ratio of the core layer, Figure 5 shows that sample C3 has a substantially higher storage modulus than sample C1 at between 20˚C and 50˚C. These results are similar to those of sample A. Because the area ratio of polyurethane in the core layer of sample C3 was higher than that in sample C1, the influence of polyurethane became stronger. Sample C2 has high storage moduli up to 40˚C. However, the storage modulus of C1, C2 and C3 are close to each other between 50˚C and 100˚C. This is because polyurethane and polyester became rubbery state between 50˚C and 100˚C, the difference in shear modulus between polyurethane and polyester became small and with a low value. This results in small influence of the core layer modes on the storage modulus of C1, C2 and C3.

Figure 6 shows the temperature dependence of the loss tangent

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at 20Hz for samples C1, C2 and C3. The loss tangent of sample C2 is higher when the temperature is above 45˚C but is lower when the temperature is below 45˚C, compared with that of sample C1. Figure 6 also shows that the loss tangent of sample C3 at 50˚C was 0.21, which is 130 % that of the sample C1. Sample C3 was in series mode, and the area ratio of the core layer was 3:1 (polyurethane: polyester). The loss tangent peak at around 20˚C for sample C3 was lower than those of samples C1 and C2. However, sample C3 had the highest loss tangent peak at 50˚C. The results show that using parallel mode and changing the area ratio of the core layer can improve the core layer stiffness; thus, the damping properties and bending stiffness of the sandwich structure can be optimized.

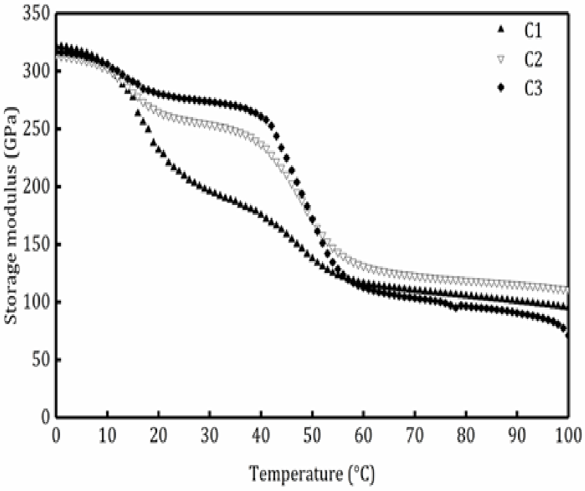

Figure 5 Temperature dependence of storage modulus for samples C1, C2 and C3.

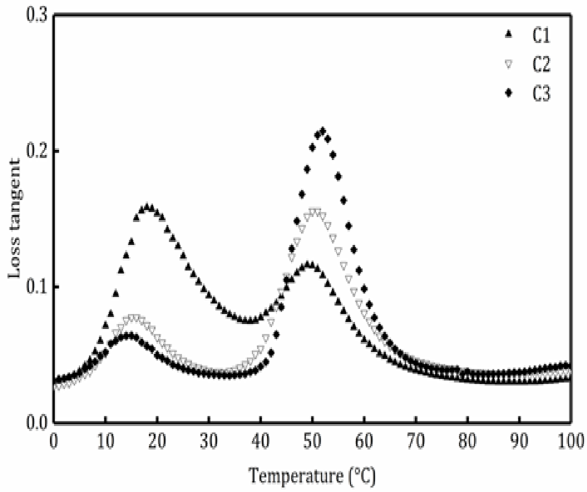

Figure 6 Temperature dependence of loss tangent for samples C1, C2 and C3.

Figures 7&8 show the storage modulus and the loss tangent, respectively, as a function of temperature for samples A, D1 and D2. Samples D1 and D2 have epoxy in the core layer and are in series mode and parallel mode, respectively. Figure 7 shows that sample D1 has a higher storage modulus than sample A between 40˚C and 100˚C. However, it can be seen from Figure 8 that loss tangent peak of sample D1 decreased to 55%, compared with sample A. The shear strain within the core layer decreased as a result of presence of the epoxy leading to a higher storage modulus and a lower loss tangent. Sample D2 has the highest storage modulus at all temperatures. This suggests that, when the core layer was in parallel mode, the storage modulus increased substantially because the core layer is affected by the higher shear storage modulus materials. Epoxy has a higher shear storage modulus between 0˚C and 100˚C than polyurethane, and these results in a higher storage modulus for sample D2 than for sample D1. In contrast, as expected, sample D2 has the lowest loss tangent peak in Figure 8, because the shear strain within the core layer is less than that of sample D1 and A. Therefore the energy dissipation in the core layer of sample D2 is lower than that of sample D1 or A. It is apparent that the storage modulus of sandwich structures is increased by using parallel mode or epoxy in the core layer.

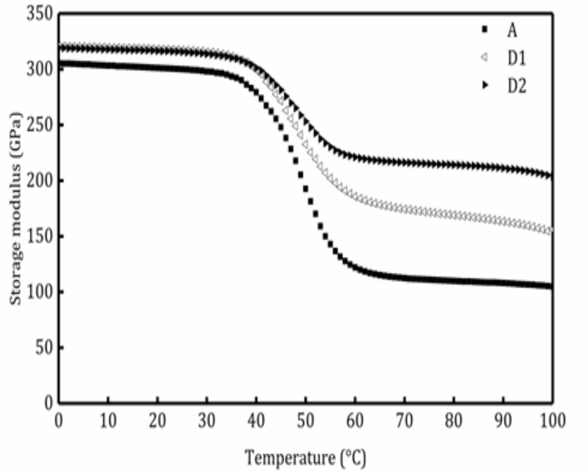

Figure 7 Temperature dependence of storage modulus for samples A, D1 and D2.

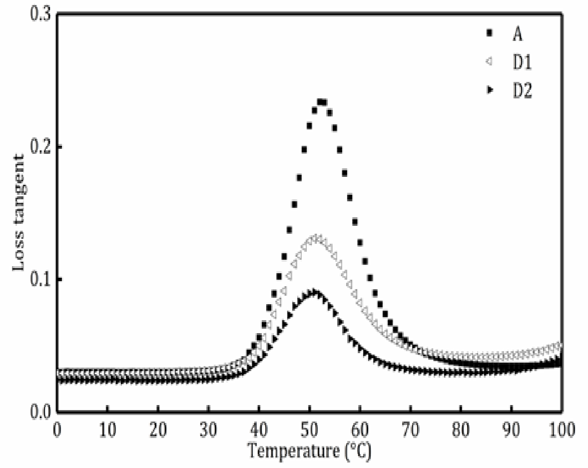

Figure 8 Temperature dependence of loss tangent for samples A, D1 and D2.

Theoretical study

The modified RKU equations in Eqs. (1)-(4) are used to predict the damping property of the present material structures. Figures 9 & 10 show the predicted values and experimental results for sample C2 with a parallel hybrid core layer, storage modulus and loss tangent. The material properties of the core layer of sample C2 are derived based on parallel mode. In the Figure 9, both experimental and predicted curves decrease almost in parallel with the temperature increment. The predicted value of the storage modulus is lower than that from the experimental results. As for the loss tangent, in the measured values, the loss tangent peaks are at 15˚C and 50˚C, while the predicted loss tangent peaks are at 10˚C and 45˚C. A difference of about 5˚C occurred between the predicted value and the measured value. The loss tangent values for predictions are comparable to those of the experimental results. For the case of a series hybrid core layer, such as sample C1, the predicted storage modulus and loss tangent are shown in Figures 11 & 12, and a comparable result between the prediction and the experimental results are also confirmed.

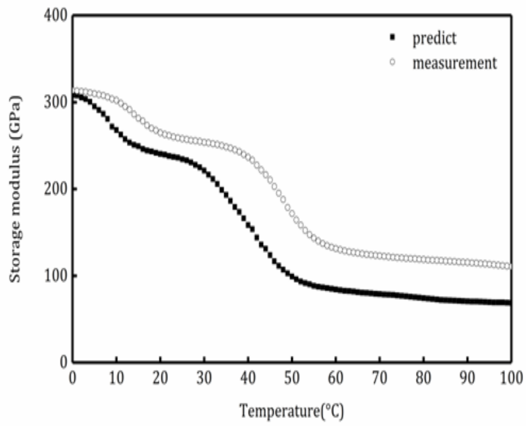

Figure 9 Storage modulus of experimental and predicted values for sample C2.

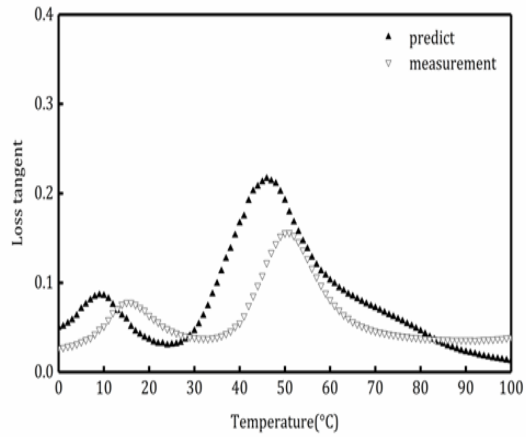

Figure 10 Loss tangent of experimental and predicted values for sample C2.

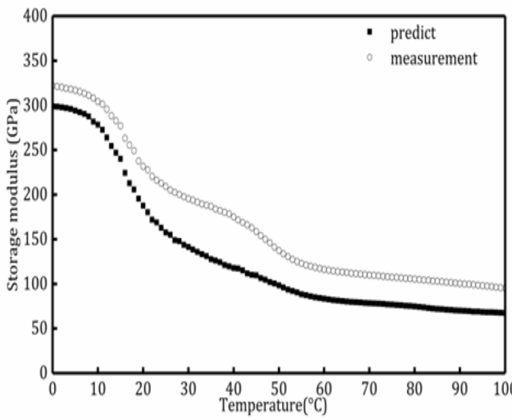

Figure 11 Storage modulus of experimental and predicted values for sample C1.

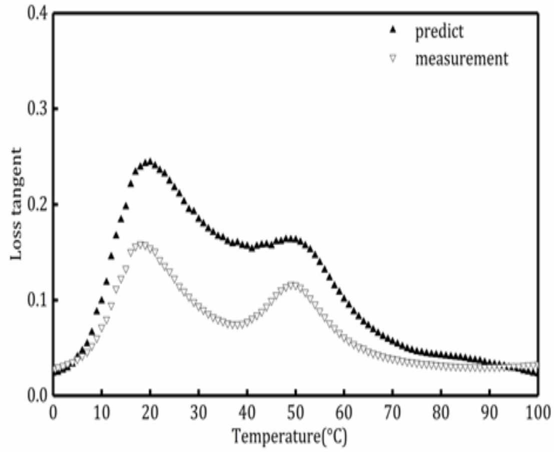

Figure 12 Loss tangent of experimental and predicted values for sample C1.

Conclusion

This paper introduced a new design concept to improve damping properties of composite structures using a low cost, simple and flexible design. The key results are as follows:

a. High damping CFRP laminates effective over a wide temperature range were produced by optimizing the series arrangement of polyurethane and polyester films in the core layer. We developed CFRP laminates with various properties depending on a hybrid core layer.

b. Changing the core layer structure such as by varying the area ratio of the core materials or by changing the design mode of the parallel or series core layer can optimize the properties of the core layer, optimizing the damping and mechanical properties of the sandwich structure.

c. The bending stiffness of sandwich structures is increased when epoxy is used in the core layer.

d. The modified RKU equations provide predictions that similar tendency with experimental results. This confirms that the proposed hybrid core layer and theoretical prediction can contribute to effective damping property design of arbitrary CFRP sandwich structures.

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Conflict of interest

There is no conflict of interest.

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