Damping properties of carbon-fiber reinforced epoxy composites with several viscoelastic interleaf films

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ABSTRACT

The aim of this study is to characterize the damping properties of carbon-fiber reinforced interleaved epoxy composites. Several types of thermoplastic-elastomer films, such as polyurethane elastomers, polyethylene-based ionomers were used as the interleaving materials. The damping properties of the composite laminates with / without the interleaf films were evaluated by the mechanical impedance method. The viscoelastic properties of interleaf polymer films were reflected in the damping properties of the corresponding interleaved laminates. Both the loss tangent and the stiffness of the interleaf polymer films under the resonant frequency of the laminates were important parameters that controlled the loss factor of the interleaved laminates. Besides, the damping properties of interleaved laminates depend not only on the viscoelastic properties of the interleaf polymer films but also on the laminate sequence. The stiffness of the intra-laminar region, which can be controlled by the fiber arrangements, the elastic modulus of the fibers or the volume fraction of the fibers, would give the considerable effect on the local strain of the interlaminar films and control the damping properties of the interleaved laminates.

1. INTRODUCTION

Vibration and noise constitute a major subjects to be solved in the general use of machines in aerospace, automobile, power plants, construction applications and so on, where carbon fiber reinforced composites are employed [1-4]. The aim of this study is to characterize the damping properties of carbon-fiber reinforced interleaved epoxy composites. Several types of commercial-based thermoplastic-elastomer films, such as polyurethane elastomers, polyethylene-based ionomers and polyamide elastomers were compared as the interleaving materials for composite laminates. The damping properties of the composite laminates with / without the interleaf films were evaluated by the mechanical impedance method. Also, the effects of the lay-up arrangements of the carbon fiber prepregs on the damping properties of the interleaved laminates were examined.

2. RESULTS & DISCUSSION

Four types of thermoplastic elastomer films were used as interleaf materials. The characteristic of each type of thermoplastic elastomer is summarized in Table 1 (Tg of each polymer was determined by dynamic mechanical analysis). The thickness of the thermoplastic elastomer films was set at 30•m.

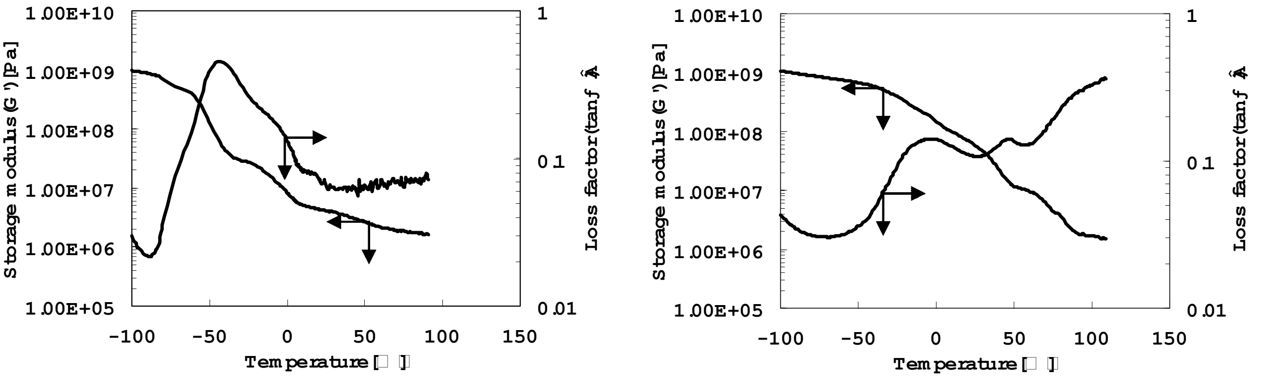
Table 1. Thermoplastic elastomer films as interleaf materials

Material	code name (producer)	Tg(□)□
Thermoplastic polyurethane (polyether type) (NISSHINBO)	MOBILON	□ 57
Ethylene / methacrylic acid / acrylic ester copolymer type ionomer*) (Mitsui DuPont Polychemical)	H1855	□ 7
Polyamide-12 type copolymer ‡ T (DAICEL Chemical Ind., LTD.)	DAIAMID 3100	41
Polyamide-12 type copolymer ‡ U (DAICEL Chemical Ind., LTD.)	DAIAMID 7000	29

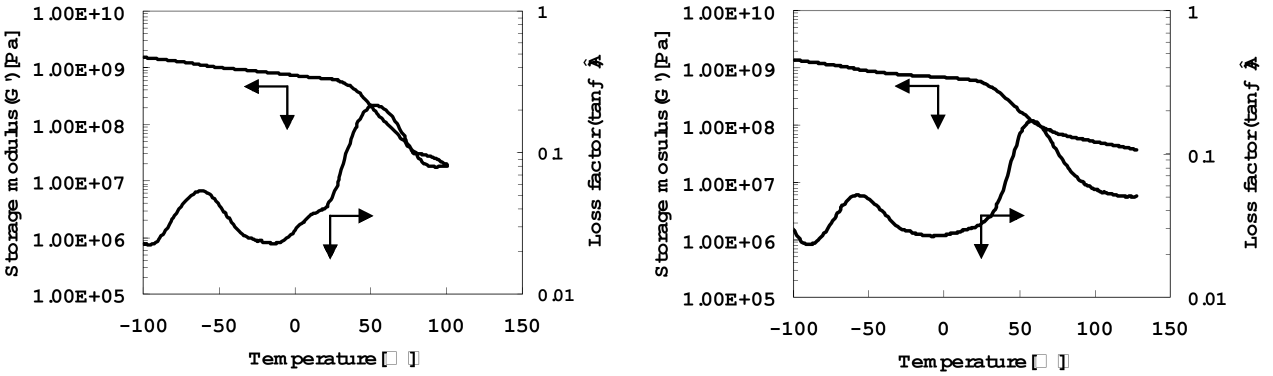
□ – methacrylic acid:10wt%, acrylic ester:10wt%, Zn ionization ratio: 70%

The temperature and frequency dependencies of the viscoelastic properties (storage modulus: G’ and mechanical loss tangent: tan•) of polymer films were evaluated by the dynamic mechanical analysis (DMA) method in shear mode. Samples were tested over a wide temperature range between –100• and 150• with a heating rate of 0.5•/minute.

The temperature dependencies of the viscoelastic properties (storage modulus: G’ and mechanical loss tangent: tan• at 10Hz) of each polymer film were indicated in Figure 1.



(a)Thermoplastic polyurethane **(b)Polyethylene-based ionomer**



(c)Polyamide-12 type copolymer ‡T **(d)Polyamide-12 type copolymer ‡U**

Figure 1. Dynamic viscoelastic properties of interleaf films, measured at 10 Hz

From the DMA data, the peak value of tan• with the peak temperature and the tan• at 25• of each polymer were summarized in Table 2. Thermoplastic polyurethane had the highest peak value of tan• among interleaf polymers used in this study. However, the peak value of tan• was at •43•, and the tan• value at 25• (at which damping tests for composites were conducted) of the thermoplastic polyurethane was less than that of polyethylene-based ionomer.

Table 2. Tanƒ Âof interleaf films
(from dynamic mechanical analyses, measured at 10 Hz)

	Thermoplastic polyurethane	Ethylene-based ionomer	Polyamide-12 type copolymer ‡T	‡U
tanƒ Âpeak value	**0.45**	**0.14**	**0.22**	**0.17**
tanƒ Âpeak temperature	**□ 43□ □**	**0□ □**	**53□ □**	**58□ □**
tanƒ Âat 25□ □	**0.06**	**0.11**	**0.05**	**0.03**

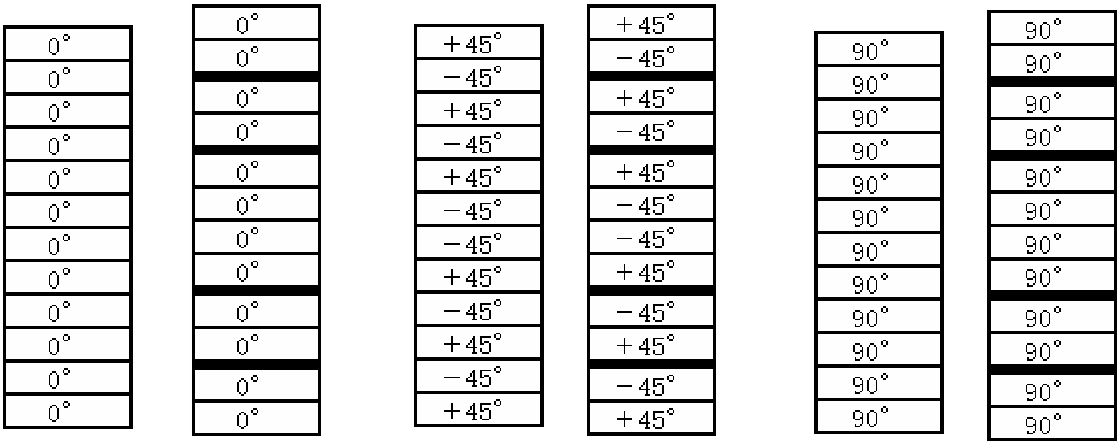
Next, the damping effects of interleaf films in composite laminates were evaluated.

Three types of carbon fibers / epoxy resin unidirectional prepregs were supplied by Toray Industries, Inc. The characteristics of each prepreg are summarized in Table 3. Same epoxy matrix resin was used for all prepregs. The tensile modulus of elasticity of the carbon fibers T700SC was 230GPa and that of the carbon fibers M40S was 380GPa, respectively. The nominal content of the carbon fibers in the prepregs was set at 70 wt% or 76wt%, which corresponds to 63vol% or 68vol%, respectively.

Table 3. Three types of carbon fiber reinforced epoxy prepregs

	Carbon fibers	Tensile modulus of fibers	Volume fraction of fibers	Epoxy resin
1.	T700S	230GPa	63%	2521R
2.	T700S	230GPa	68%	2521R
3.	M40S	380GPa	68%	2521R

The prepregs were cut into 200mm (in length) by 150mm (in width) rectangles with the fibers oriented at 0°,±45°or 90° in the length direction and were laid-up in several flat laminate sequences shown in Figure 2 on the non-interleaved or the interleaved laminates. The thick solid lines in Figure 2 indicate the locations of the interleaf films in the rectangular-shape laminates. The laminated prepregs were pre-compacted in a nylon-bag sheet under vacuum pressure. The cure cycle for the laminates consisted of being placed in a hot-press at 130• for 90 minutes under pressure of 500kPa. The parts were then removed from the hot-press and allowed to cool to room temperature while remaining on the tool. Test specimens were cut by using a diamond saw from the cured laminates.



(0□)12 Interleaved (0□)12 (□ 45□)3S Interleaved (□ 45□)3S (90□)12 Interleaved (90□)12

Figure 2. Lay-up sequences of flat laminates (non-interleaved and interleaved)

The polymer films were surely located between fiber reinforced plies with keeping the original thickness. Well adhesion between the films and epoxy resins was achieved in all laminates.

The damping property (loss factor •) of the composites was measured by mechanical impedance, in which the specimen is forced to vibrate at its center, as shown in Figure 3. The unidirectional or (±45°)n laminates beam specimens were rectangular in shape, 180mm (in length) x 10mm (in width). A schematic representation of the measured resonance curve is shown in Figure 4. The loss factor is computed using the relationship as following equation (1):

$$\bullet = \bullet f / fn = (f_2 - f_1) / fn \quad (= \tan\bullet) \qquad (1)$$

where • is the loss factor, •f is the bandwidth of frequency at 3dB below from the peak amplitude, and fn is the resonant or peak frequency.

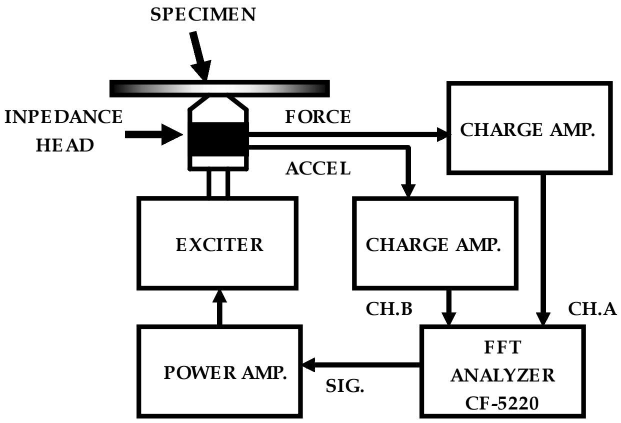


Figure 3. Measuring of the loss factor of composites

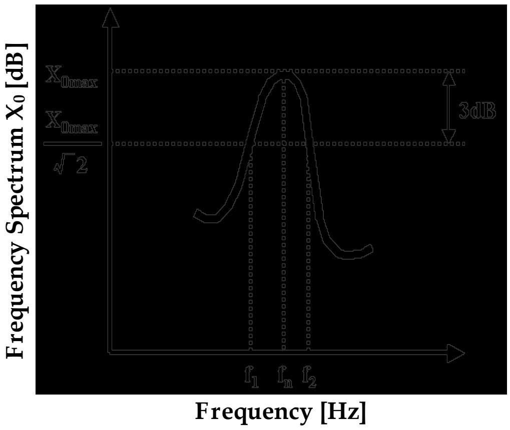


Figure 4. A schematic representation of a resonance curve

Figures 5, 6 and 7 show the loss factors of the interleaved and non-interleaved laminates with a lay-up of (0°)$_{12}$, (±45°)$_{3S}$, and (90°)$_{12}$, respectively, as a function of the resonant frequencies. The resonant frequencies of the laminates were mainly dominated by the stacking sequence of the plies. Laminates had several vibration modes. For example, (±45°)$_{3S}$ laminates without interleaf films exhibited the first resonance at 97Hz, the second at 609Hz, and the third at 1731Hz, shown in Figure 6. In the thermoplastic polyurethane interleaved laminates, the first resonance occurred at 99Hz, the second at 582Hz, and the third at 1511Hz. In the ethylene-based ionomer interleaved laminates, the first resonance occurred at 103Hz, the second at 648Hz, and the third at 1813Hz. These resonant frequencies of the interleaved laminates were approximately equal to those of non-interleaved laminates.

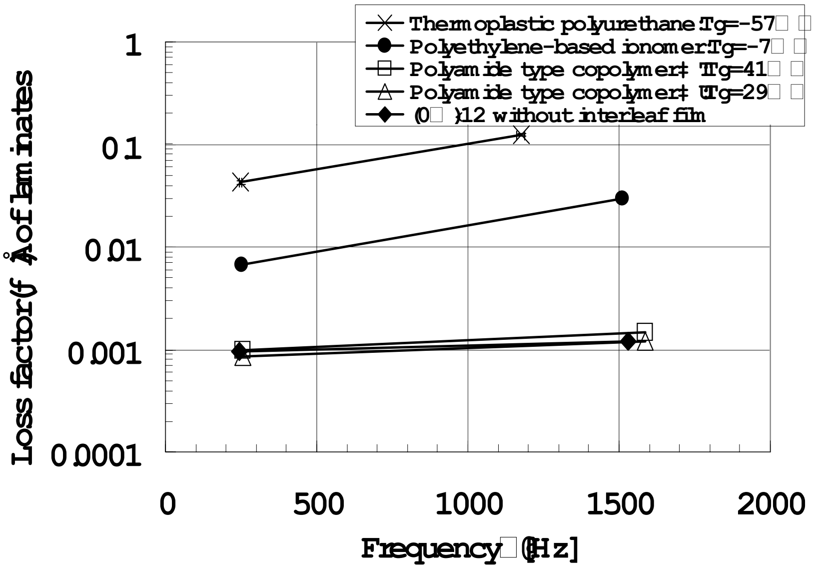


Figure 5. Damping effect of interleaved laminates (0□)$_{12}$ at resonant points

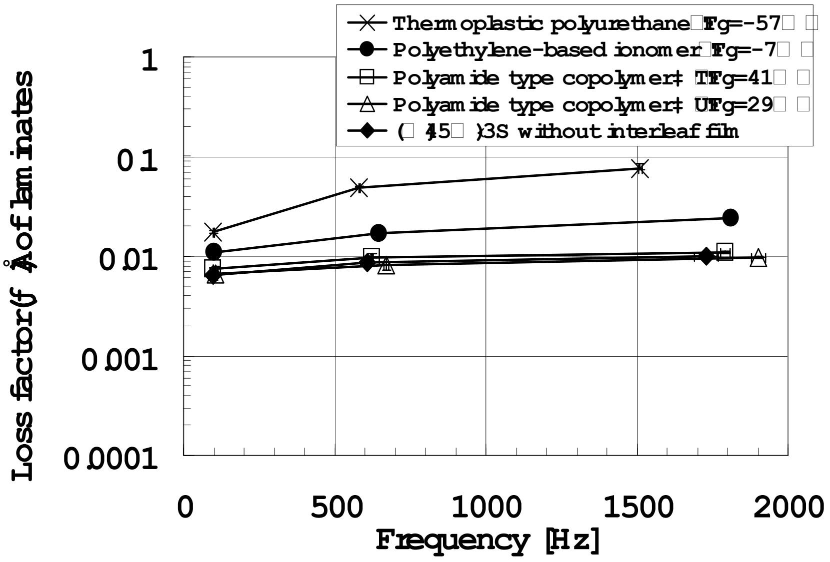


Figure 6. Damping effect of interleaved laminates (□ ±45□)$_{3S}$ at resonant points

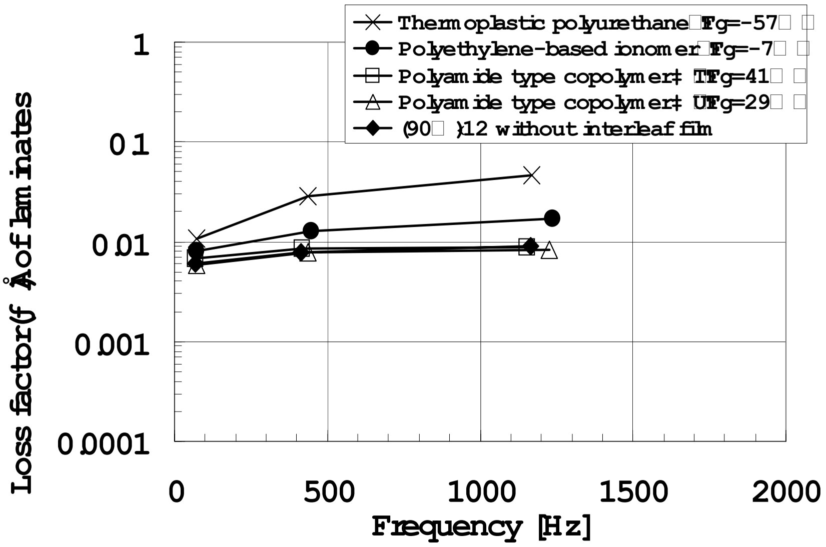


Figure 7. Damping effect of interleaved laminates (90□)$_{12}$ at resonant points

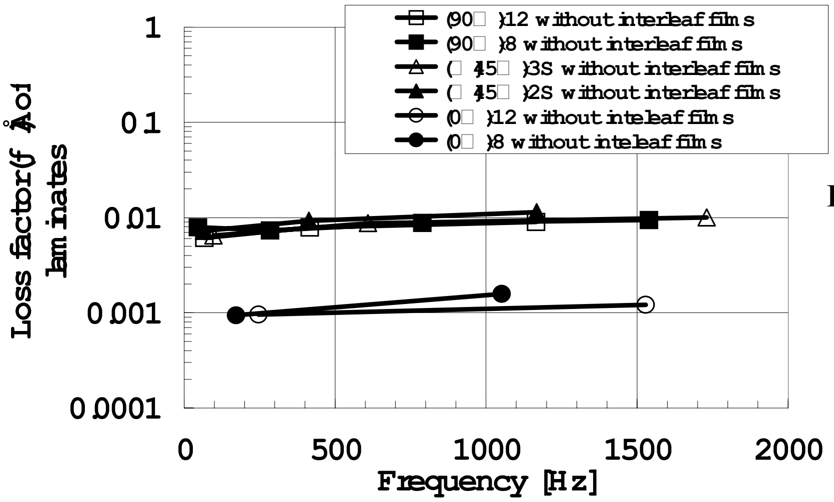


Figure 8.
Damping properties of non-interleaved laminates depending on lay-up sequences and numbers

However, a considerable difference occurs in the polyurethane interleaved laminates, especially in the higher resonant frequencies, which is probably caused by the low stiffness of the polyurethane films. Same tendency was noticed in the (0°)$_{12}$ and (90°)$_{12}$ laminates.

Less thickness (lay-up number) of laminates gave lower resonant frequencies, but the loss factors were not influenced clearly in each stacking sequence, as shown in Figure 8.

Interleaved composites using thermoplastic polyurethane or polyethylene-based ionomer polymers had higher damping loss factors than non-interleaved composites as shown in Figures 5, 6 and 7. Thermoplastic polyurethane had the highest damping effect among them. It was also seen that the damping effect became higher with being higher the resonant frequency.

In order to correlate the properties of polymer films to the damping properties of the interleaved laminates, the master curves of tan•and G’ for thermoplastic polyurethane and polyethylene-based ionomer should be drawn. Eight frequencies (0.1, 0.2, 0.5, 1, 2, 5, 10, and 20Hz) were used to probe the dynamic response of the each polymer films, and their master curves on tan•(Figure 9) and G’ (Figure 10) were drawn from the DMA experiments by shifting in accordance with time-temperature superposition. The base temperature of the master curve for time-temperature superposition was set at 25•.

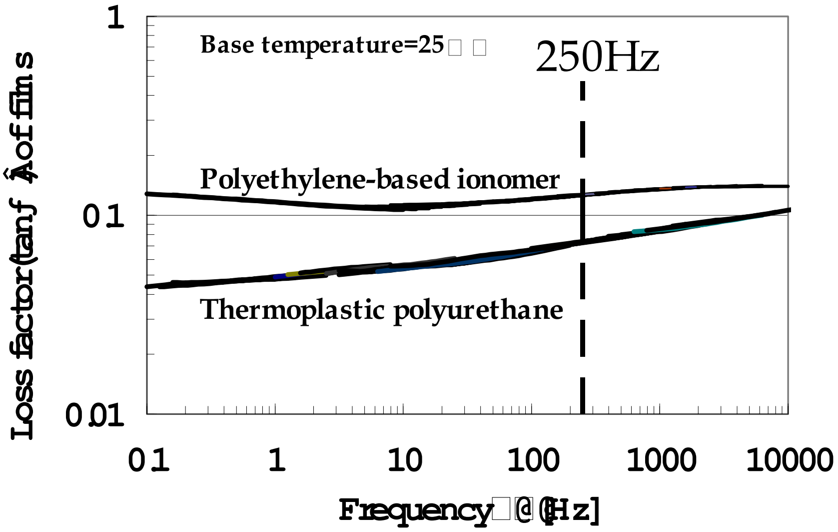


Figure 9. Master curves on loss factor (tanƒ Âof thermoplastic polyurethane and polyethylene based ionomer film

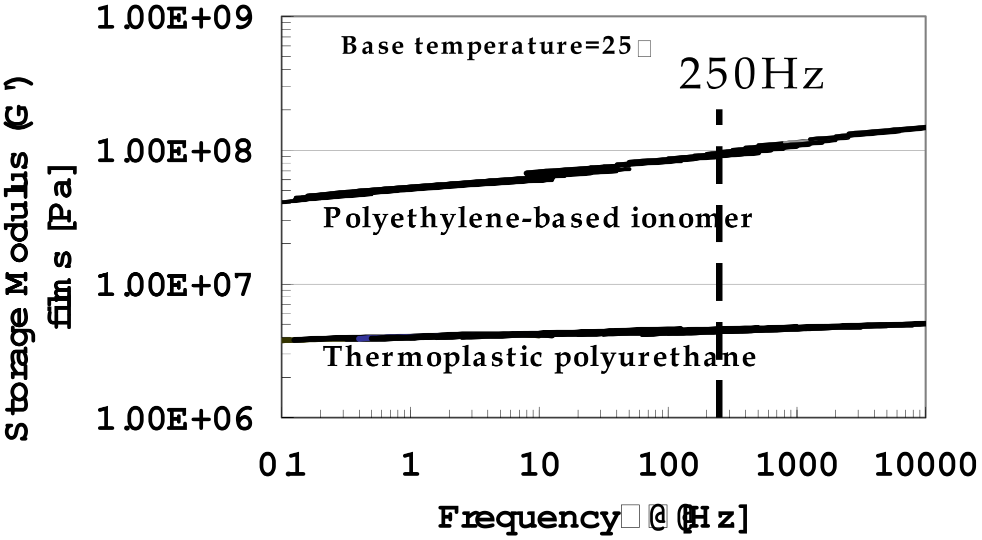


Figure 10. Master curves on storage modulus (G’) of thermoplastic polyurethane and polyethylene based ionomer film

The tan•of the original data were measured at lower frequencies (less than 20Hz) than the resonant frequencies (higher than 100Hz) of composites. Using the master curves, the value of tan•of the polymer films at a particular high frequency could be estimated over a wide frequency range. The estimated tan•value of polyethylene-based ionomer at 250Hz (close to the first resonant frequency of (0°)$_{12}$ laminates) at 25• is higher than that of the tan•value of thermoplastic polyurethane, as shown in Figure 9. However, the loss factor•of the laminates with the polyurethane films was higher than that of the laminates with the polyethylene-based ionomer films. There was not so simple relationship between the loss factor •of the laminates and the tan•value of these polymer films at the high resonant frequencies for corresponding laminates.

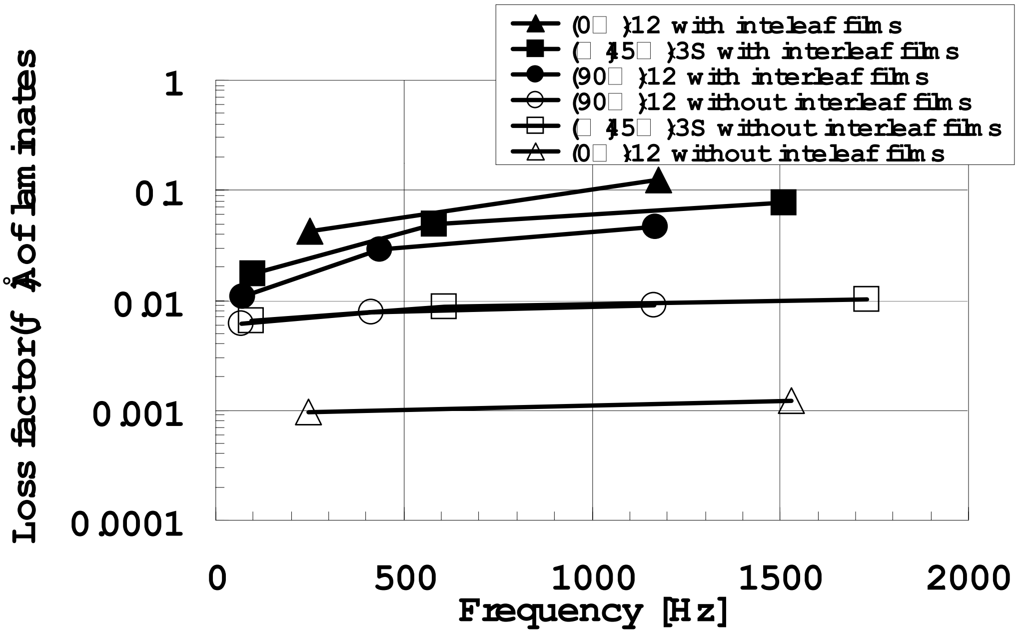
Tan•is the ratio of loss modulus to storage modulus during 1 cycle vibration of the material. The absolute amount of energy loss should be a function of the actual strain as well as the tan•of the material. In general, the exothermal energy dissipation H of a material during 1 cycle of sine vibration is given using the relationship as following equation (2):

$$H = \bullet\bullet_0^2 G''(\bullet) = \bullet\bullet_0^2 \tan\bullet G'(\bullet) \qquad (2)$$

where $\bullet_0$ is the maximum strain of the vibration, G' is the storage modulus, G" is the loss modulus, tan•is the mechanical loss tangent, and • is the frequency of the vibration. The energy dissipation (H) is proportional to the strain($\bullet_0$) squared.

In the case of using lower stiffness interleaf films, higher strain in the films would be easily achieved in the interlaminar region at the resonant frequencies and would absorb more energy. Thermoplastic polyurethane had much lower stiffness than polyethylene-based ionomer, as shown in master curve of Figure 10. It is therefore logical to conclude that the low stiffness of the polyurethane as well as the tan• at 25• would have a considerable effect on the high loss factor•of the interleaved laminates using the polyurethane films.

For simple laminate sequences without interleaf films, the loss factor of (90°)$_{12}$ or (±45°)$_{3S}$ laminates was higher than that of (0°)$_{12}$, as shown in Figure 11. In different from the order of these original loss factors of simple laminates, however, the loss factor of (0°)$_{12}$ laminates with thermoplastic polyurethane films was greater than that of (90°)$_{12}$ or (±45°)$_{3S}$ laminates using the same interleaf films.

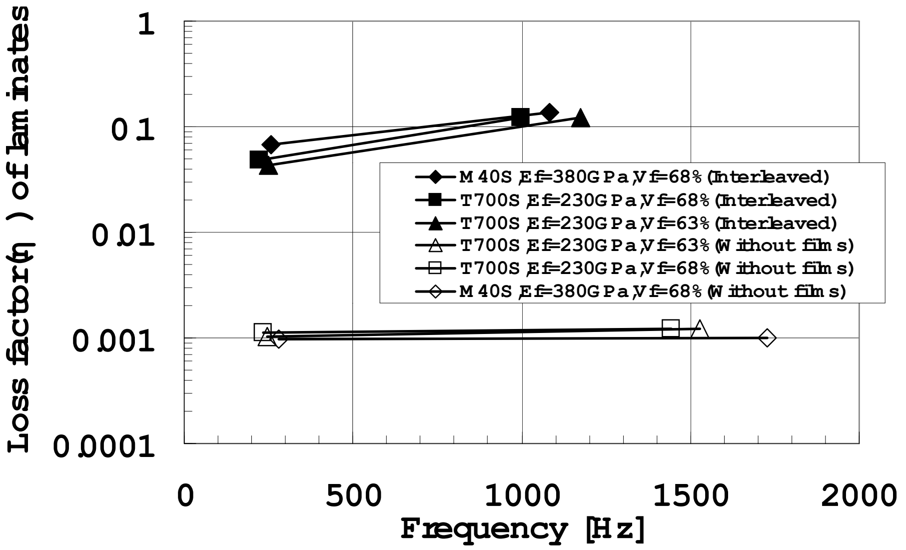


Fi gure 11. Damping properties of thermoplastic polyurethane interleaved laminates and non-interleaved laminates depending on the lay-up sequence

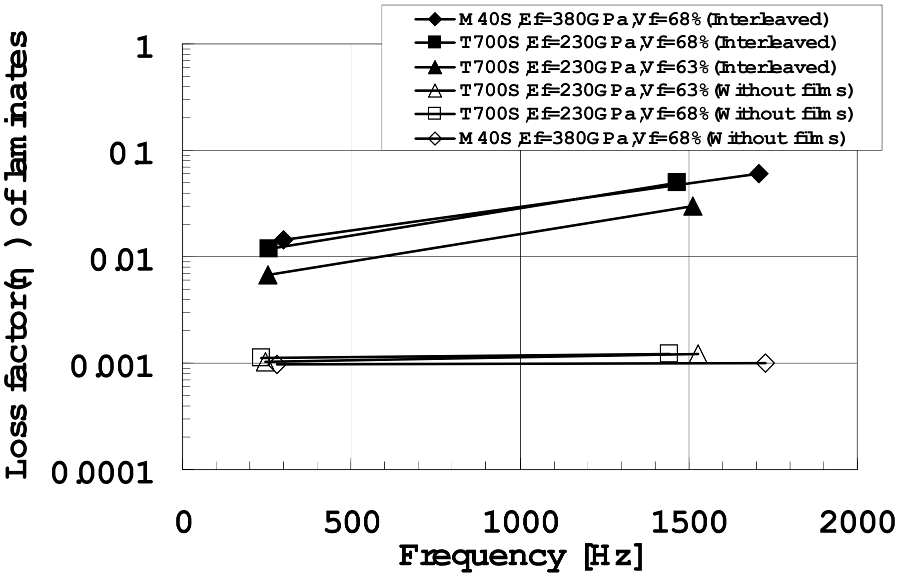
This indicates that the damping properties of interleaved laminates depend not only on the viscoelastic properties of the interlaminar polymer films but also on the laminate sequence. The arrangements of the reinforcing carbon fibers control the stiffness of the intra-laminar region and would have considerable influence on the amount of local strain of the interlaminar films.

The stiffness of the intra-laminar region can be controlled by changing the elastic modulus of the fibers and the volume fraction of the fibers as well as the fiber arrangements. In order to make laminates with high stiffness, “M40S” whose tensile modulus of elasticity is 380GPa was used as another carbon fiber, which can be compared with laminates using “T700S” which have standard modulus of elasticity (230GPa). Also, high volume fraction of the fibers gives high stiffness to the laminates, needless to say.

Figures 12 and 13 show the effect of the modulus of elasticity and the volume fraction of the carbon fibers on the damping properties of interleaved laminates in the same laminate sequence of $(0°)_{12.}$ Thermoplastic polyurethane and polyethylene-based ionomer was used as interleaf films in Figure 12 and Figure 13, respectively. Higher elastic modulus of fibers leads higher loss factor of the interleaved laminates. Higher volume fraction of fibers also leads higher loss factor of the interleaved laminates.



Fi gure 12. Damping properties of thermoplastic polyurethane interleaved laminates and non-interleaved laminates, depending on the elastic modulus and the volume fraction of the carbon fibers (laminate sequence: 0□ 12)



Fi gure 13. Damping properties of polyethylene based ionomer interleaved laminates and non-interleaved laminates, depending on the elastic modulus and the volume fraction of the carbon fibers (laminate sequence: 0□ 12)

The stiffness of the laminates without interleaf films were evaluated by the three point bending (3PB) method using span(L) / sample thickness (D) of 32. It can be considered that the flexural modulus of elasticity (Ef) calculated based on the ASTM D790 method represents the stiffness of the intra-laminar region of the interleaved laminates.

Figure 14 shows the relation between the elastic modulus of intra-laminar region and the loss factors of the several laminates of $(0°)_{12}$, $(\pm45°)_{3S}$ and $(90°)_{12}$. Without using interleaf films, the loss factor of the laminates decreases as the elastic modulus of the laminates increases. Besides, in the case of thermoplastic polyurethane interleaved laminates, as the stiffness of the intra-laminar region becomes higher, the loss factor of interleaved laminates increases. The high local shear strain of the interlaminar films would be generated by the existence of high stiffness intra-laminar region, which leads the high damping effect on the interleaved laminates.

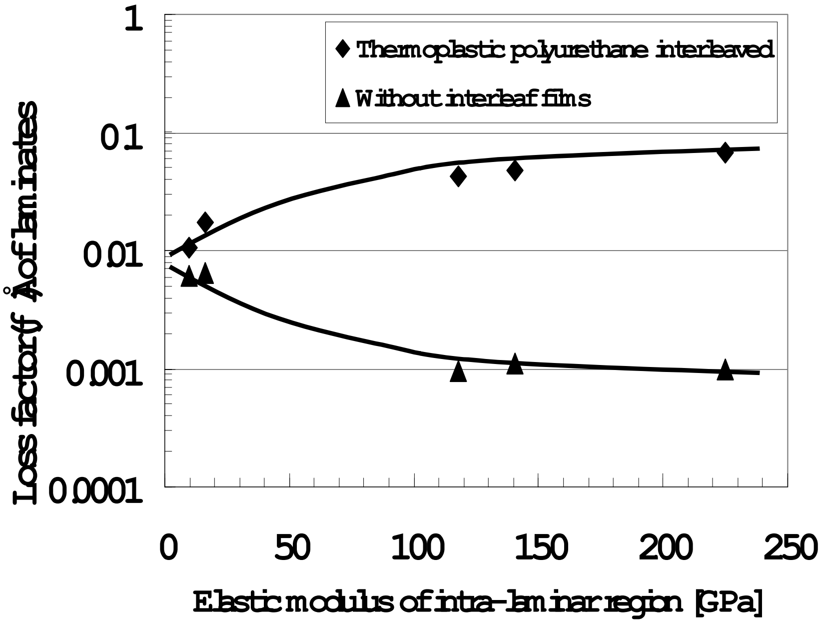


Figure 14. Relation between elastic modulus of intra-laminar region and the loss factors of the laminates, with or without thermoplastic polyurethane interleaf films

The epoxy matrix resin is most unlikely to have an effect in this discussion, since the same matrix resin was used for all laminates. In addition, the Tg of the matrix resin was over 100•, which was much higher than that of interleaved polymer films. The tan• at 25• of the epoxy matrix resin was lower than that of the interleaf films, and the storage modulus G' at 25• of the matrix resin was over 3GPa, which was much higher than that of the films.

3. CONCLUSIONS

(1) The viscoelastic properties of interleaf polymer films were reflected in the damping properties of the corresponding interleaved laminates. Both the loss tangent and the stiffness of the interleaf polymer films under the resonant frequency of the laminates were important parameters that controlled the loss factor of the interleaved laminates.

(2) The damping properties of interleaved laminates depend not only on the viscoelastic properties of the interleaf polymer films but also on the laminate sequence. The stiffness of the intra-laminar region, which can be controlled by the fiber arrangements, the elastic modulus of the fibers or the volume fraction of the fibers, would give the considerable effect on the local strain of the interlaminar films and control the damping properties of the interleaved laminates.

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