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Development of CFRP/damping-material laminates

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Abstract—New materials, that possess high damping characteristics and high strength properties, have been studied in carbon fiber reinforced plastics (CFRP). These materials are referred to as CFRP/damping-material laminates in this paper. The CFRP/damping-material laminates investigated here are composed of unidirectional carbon/epoxy prepreg sheet and polyethylene based damping material sheet, which is used as an interleaf. Cantilever beam tests revealed the high damping properties of these laminates. Loss factor values for these composites are from 5 to 50 times as large as those for conventional CFRP. These values could be predicted by using an analysis based on a constrained layer treatment for all but two specimen types, which exhibited high damping properties under longitudinal vibration. The interleaving effect on mechanical strength is also presented.

Keywords: CFRP; damping material; loss factor; laminate; mechanical property; structural material.

1. INTRODUCTION

A significant number of spacecraft failures and anomalies are related to severe vibration occurring during launch and ground tests. Vibration reduction offers not only an increase in satellite reliability but also a decrease in development and operating costs.

Carbon fiber reinforced plastics (CFRP) have been widely used for spacecraft structures, due to their high-stiffness and low-density properties. However, these composite materials are unsuitable for obtaining low-vibration structures. When these materials are employed, structures are usually fabricated using adhesively bonded joints, which replace bolts and rivets. This seriously reduces the damping caused by friction at joints (structural damping) and so makes material damping far more important in comparison with conventional structures. CFRP has low vibration damping properties (loss factor $n = 0.001-0.01$), similar to conventional structural materials. It is thus imperative that the vibration damping properties of fiber reinforced composites are improved, especially for space applications.

New kinds of carbon fiber reinforced plastics have been developed in the present work to improve the vibration damping capability. These materials were fabricated

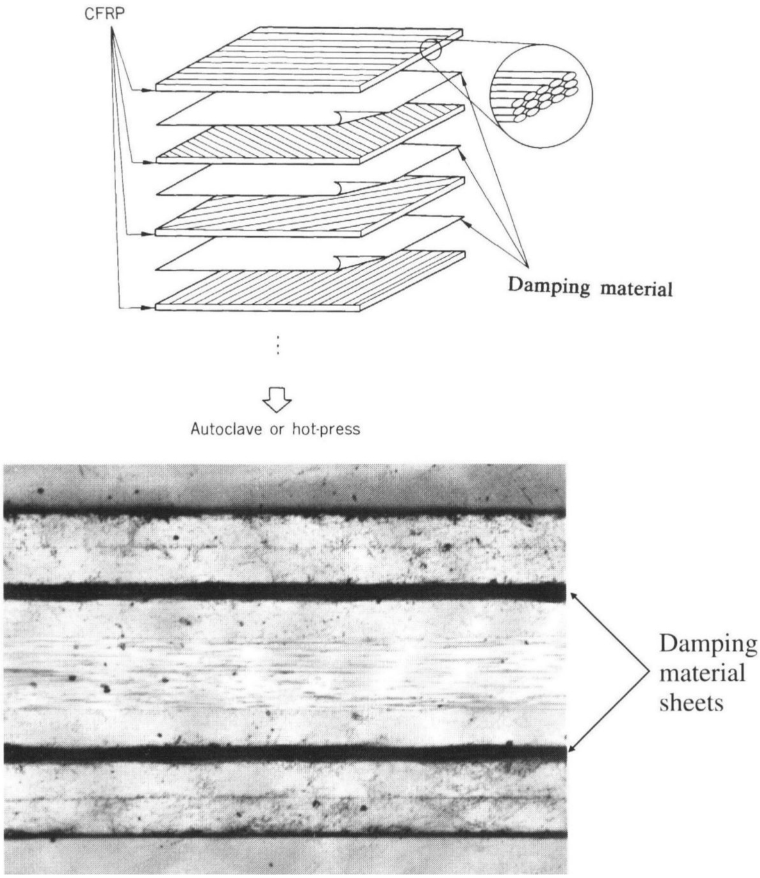

Figure 1. CFRP/damping-material laminates.

by sandwiching a damping material at the layer interfaces in CFRP (see Fig. 1) [1]. This paper presents vibration damping properties, tensile and compression strengths for CFRP/damping-material laminates, as well as discussing the application of these materials to spacecraft.

2. MATERIALS AND METHODS

Unidirectional prepreg sheets (T800/#2500, TORAY Industries, Inc.) and polyethylene based damping materials were used throughout this study. The damping-material sheets were about 70 μm thick and were sandwiched between thermo-adhesive surface layers. The maximum loss tangent value ($\tan\delta$) for the damping sheet was about 0.9 at room temperature. Figure 2 gives the stacking sequence for the various laminates formed using a vacuum bagging/autoclave curing technique. Type I or Type VIII are $[0°/\pm 45°/90°]$s quasi-isotropic based laminates. Type I

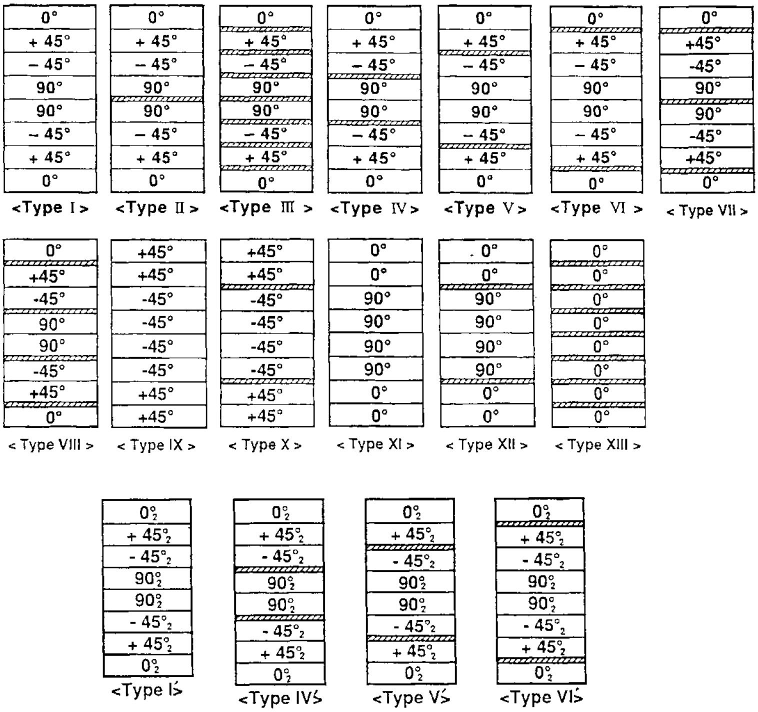

Figure 2. Stacking sequence for CFRP/damping-material laminates.

is a conventional CFRP. Type II through Type VIII are CFRP/damping-material laminates. Type IX and Type X are $[+45°_2/-45°_2]$s angle-ply based laminates, and Type XI and Type XII are $[0°_2/90°_2]$s cross-ply based laminates. Type I′ and Type IV′ through Type VI′ are 16 ply $[0°_2/\pm 45°_2/90°_2]$s quasi-isotropic based laminates.

A cantilever beam test was conducted to obtain the dynamic mechanical properties for these composite laminates. The loss factor η was determined by the decay curve for vibration. The flexural modulus values for individual composites were calculated using the natural vibration frequencies for the beams. Test beam dimensions were 250 mm × 30 mm. Furthermore, dynamic mechanical properties, under longitudinal vibration, were measured by a viscoelastic spectrometer at 100 cps. Test beam dimensions used were 30 mm × 3 mm. Tensile strengths were evaluated with an Instron type testing machine. Test specimen dimensions were 210 mm × 25 mm in Type I through Type XII specimens, and were 210 mm × 15 mm in Type I′, Type IV′ through Type VI′ specimens. Tension fatigue tests were conducted using an electro-hydraulic fatigue testing machine at a frequency of 10 cps. The stress ratio (ratio of minimum stress and maximum stress) was fixed at 0.1. Compression strength for Type I′, Type IV′ through Type VI′ laminates was measured using a Celanese (ASTM D3410) fixture. Test specimen dimensions were 100 mm ×7 mm with a 10 mm gauge length. The impact resistance was measured using an electro-hydraulic testing system [2]. The rectangular specimen was 210 mm × 130 mm and the rim, with a diameter of 100 mm, was fixed to the supporting fixture to apply a multiaxial impact stress. The mass of the dart was 2030 g, and a dropping height of 500 mm was used, which gave an initial impact velocity of 2.8 m/s.

3. VIBRATION DAMPING PROPERTIES [3, 4]

Figure 3 presents the loss factors and flexural moduli for Types I through XII in the third mode vibration at 30°C. It can be seen in this figure that loss factor values for the CFRP/damping-material laminates are 5 to 50 times larger than those for conventional materials (Type I, Type IX, and Type XI laminates). Furthermore, these properties depend strongly on both the number of damping sheets and their

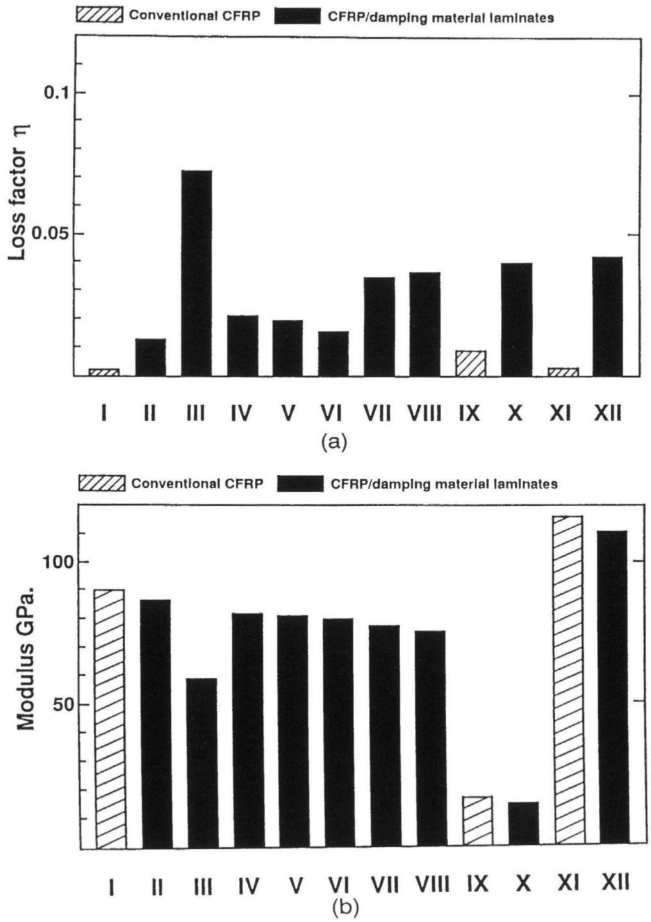

Figure 3. Loss factor and flexural modulus for laminates in 3rd vibration mode. (a) Loss factor. (b) Flexural modulus.

incorporated positions. On the contrary, the flexural moduli for the CFRP/damping-material laminates exhibit slightly lower values than the conventional materials. The degree of change in flexural modulus decrement, which was caused by the damping material interleaves, is very small, in comparison with the loss factor increment.

The analysis, developed by Ross, Kerwin and Ungar (referred to hereafter as the RKU analysis), was used to predict damping properties under flexural vibration for the CFRP/damping-material laminates [5]. Good agreement was obtained between predicted values and experimental values, except for the results of the Type III and Type XI laminates. These results indicate that the RKU analysis is applicable for predicting damping properties for CFRP/damping-material laminates. On the other hand, the experimental values for Type III and Type X laminates are about three times greater than the predicted values. These two laminates exhibited large loss factor values under longitudinal vibration, in addition to flexural vibration. The RKU analysis is strictly applicable to materials which possess isotropic properties. Consequently, the high damping capability under longitudinal vibration, as well as the large discrepancy between predicted and measured values for Type X and Type III laminates, are probably caused by the anisotropic properties of these CFRP laminates. High damping capability under longitudinal vibration is especially important in spacecraft applications.

4. MECHANICAL STRENGTH [4, 6]

Tensile, tensile fatigue and compression strength tests were conducted to obtain the effects of the interleaf on mechanical strength.

4.1. Tensile strength

Experimental and computational tensile results for Type I through Type VIII laminates are listed in Table 1. These values were obtained from the 25 mm wide specimens. Some of CFRP/damping-material laminates show larger ultimate load (UL) values, in comparison with the conventional Type I specimen. Type II, Type IV, Type VI and Type VIII laminates, whose UL values are 26.4 kN, 26.1 kN, 26.4 kN, and 26.1 kN, respectively, have 3 to 5% larger UL values, in comparison with the Type I value, 25.2 kN. The largest UL value was obtained in the Type VII specimen. This UL value was 27.1 kN (8% higher). The coefficient of variation

Table 1.
Tensile strength for $[0°/\pm 45°/90°]_s$ based laminates

	Type I	Type II	Type III	Type IV	Type V	Type VI	Type VII	Type VIII
UL (kN)	25.2	26.4	22.9	26.1	25.1	26.4	27.1	26.1
C_V (%)	5.7	3.1	6.5	4.3	2.8	4.9	1.4	1.8

Table 2.
Tensile strength for $[0°_2/\pm45°_2/90°_2]s$ based laminates

	Type I′	Type IV′	Type V′	Type VI′
UL (kN)	43.8	50.3	41.2	45.2
C_V (%)	4.0	0.6	2.1	1.2

(C_v), which is related to tensile strength reliability, is also listed in Table 1. C_v values for CFRP/damping-material laminates, except for the Type III laminate, are lower than the value for the Type I laminate. This result suggests that CFRP/damping-material laminates have highly reproducible tensile strengths. The reason for these improvements in CFRP/damping-material laminates is considered to be due to the consequence of suppressing the multiple splitting in the 0° angle layer and delaminations between the 45° and 90° angle layers, which are a predominant fracture mode in the conventional Type I specimen.

The fracture mode for CFRP/damping-material laminates was quite different from that for conventional CFRP. In the conventional CFRP, the delaminations between the 90° and 45° angle layer were generated at about 80% of the UL. The ultimate failure occurred in a catastrophic fashion with multiple longitudinal splits. Similar delaminations were observed only in the Type VI specimens. Another CFRP/damping-material laminate, which was loaded to over 80% of the UL, exhibits no delamination between layers. Furthermore, in view of the multiple splits mode, Type III, Type VI, Type VII and Type VIII specimens, where the damping materials are placed between the 0° and 45° layers, indicates behavior unlike that for conventional CFRP. Table 2 lists the tensile strength for the sixteen-ply $[0°_2/\pm45°_2/90°_2]s$ quasi-isotropic based laminates. The ultimate load (UL) values are presented for the 25 mm wide results, which were calculated from the 15 mm wide test results. Type IV′ is especially large (15% increase). Figure 4 shows typical failed specimens for the sixteen-ply based laminates. In this figure, the differences in the 0° failure mode were verified. A damping material sheet, between the 45° and 0° angle layers (Type VI′), suppresses the multiple splitting in the 0° angle layer.

4.2. Fatigue

Figure 5 shows a comparison of average fatigue lives for the fixed applied maximum cyclic load for the various types of laminate. This value of the maximum cyclic load corresponds to the 75% stress level, when the maximum cyclic stress value is normalized using the ultimate tensile strength for Type I. As a result, Type II and Type IV exhibit longer fatigue lives, when compared with Type I. The reason for this improvement in fatigue resistance for Type II and Type IV is considered to be due to suppressing the delamination damage. Fatigue lives for Type VI, Type VII and Type VIII decreased slightly, with respect to Type I, in spite of improved load carrying capability in tension.

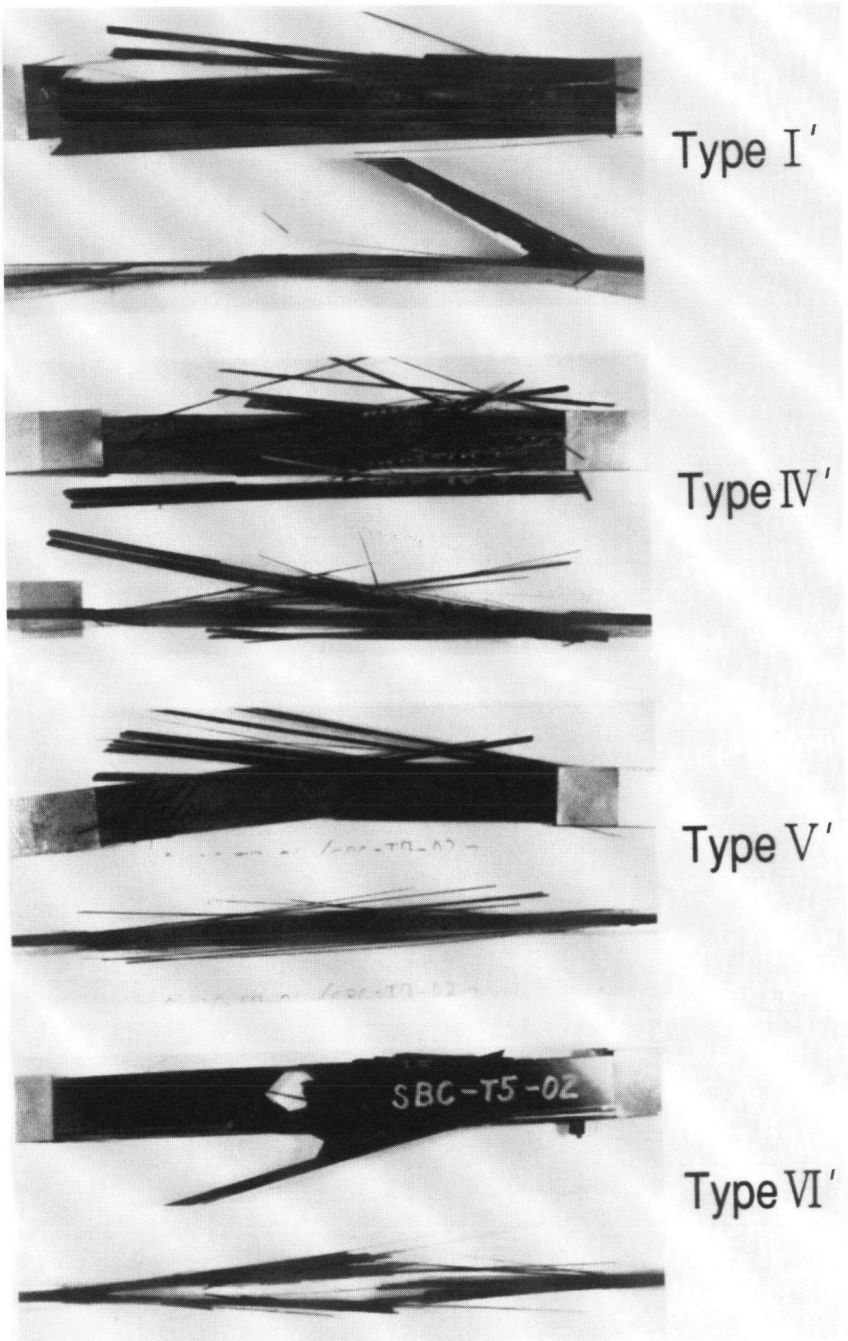

Figure 4. Typical failed specimens for $[0°_2/\pm45°_2/90°_2]$s based laminates.

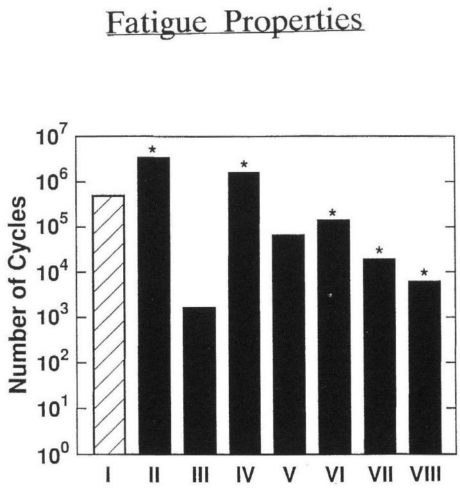

Figure 5. Fatigue lives for the various types of laminates under a fixed cyclic load.

From these results, the interleaf between the 0° and 45° layers was found to reduce the fatigue life. This may be basically due to the temperature rise, which occurred in the specimen while being subjected to fatigue loading, resulting in softening of the interleaf material. In such a situation, splitting failure tends to occur easily by the softening of interleaf material between the 0° and 45° layers. Splitting damage deteriorates the load carrying capability for the 0° layer, thus reducing the fatigue resistance [5].

4.3. Compression

The compression strength for Type IV′, which had largest tensile strength, compared favorably with the Type V′ data, although both were 15% lower than the conventional Type I′. On the other hand, Type VI′ laminates, where damping sheets were placed between the 0° and 45° layers, exhibit a slightly larger UL value, with respect to the conventional Type I′.

4.4. Impact

After impact, the extent of damage was observed using as ultrasonic C-scanner. The degree of impact damage was represented by the sum of the delamination area between individual layers. The sum of delamination was 1581 mm^2 for the conventional CFRP (Type I′). The CFRP/damping-material laminates exhibited lower values. The sum of a delamination areas were 1190 mm^2 for Type VI′, 426 mm^2 for Type IV′, and 304 mm^2 for Type IV′. The interleaf between the 45° and 90° layers was most effective for improving the impact properties.

5. APPLICATION

5.1. Spacecraft structure

A tube structure, for use in spacecraft, with a diameter of 400 mm and a height of 500 mm was made up from CFRP/damping-material laminates. Figure 6 shows the stacking sequence of the tube. The tube consisted of two cloth-ply layers, twelve unidirectional layers of CFRP, and eight damping material sheets. This sequence was designed to obtain high damping characteristics using the modal strain energy method [7]. Figure 7 shows a photograph of the tube structures made from both conventional CFRP and CFRP/damping-material laminates. The weight

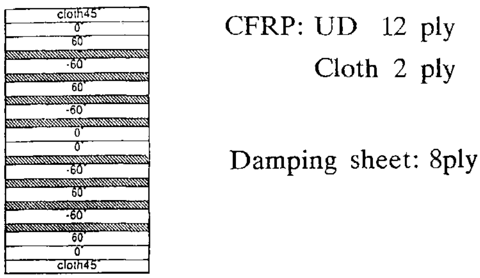

Figure 6. Stacking sequence of the tube structure.

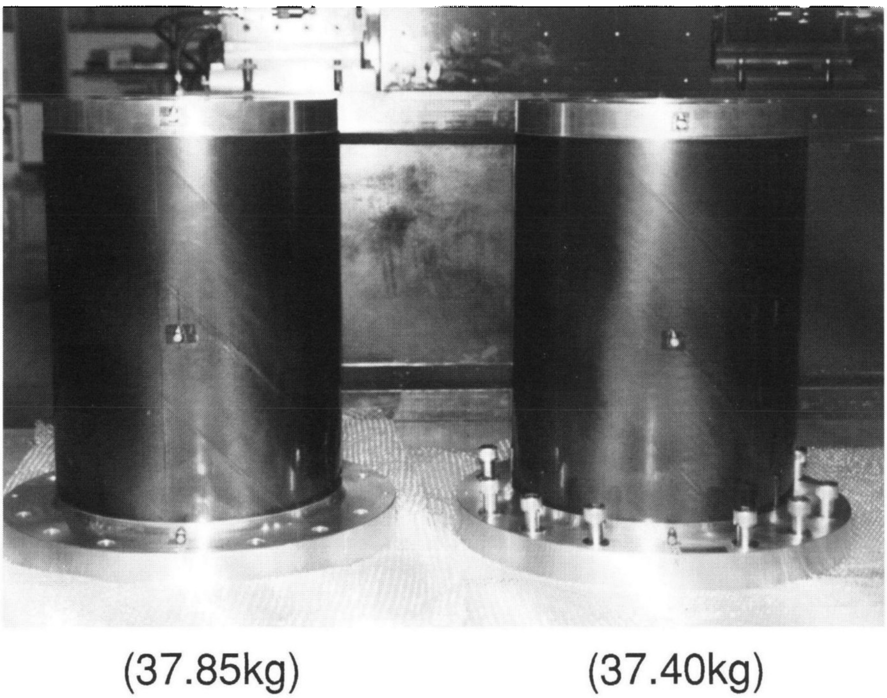

Figure 7. Photograph of the tube structures made from conventional CFRP and CFRP/damping-material laminates.

of the tube made from CFRP/damping-material laminates was 37.85 kg, almost the same as that made from conventional CFRP. The vibration test revealed the high damping properties of the CFRP/damping-material laminates. Loss factor values for these laminates were 0.07 under bending deformation, and 0.03 under stretching deformation, which are more than two to ten times larger than those for the conventional CFRP.

5.2. Environmentally conscious material (ECO-material) [8]

It is necessary to give careful consideration to the ease of disassemblability at the material design stage to promote material recycling efficiently. The disassembly method for CFRP/damping-material laminates was investigated with respect to their stacking structure. The layer separation for CFRP/damping-material laminates was carried out by heating using a hot-press. A flat plate (210 mm × 130 mm) of the Type IV′ laminates was placed on the platen of the hot-press, which had been previously heated to 200°C. Within one minute of setting the plate on the platen, separation of the thin CFRP layers began as the thermo-adhesive surface layer of the interleaf films melted. These individual layers then warped due to the interlaminar stresses in the CFRP. This 'self-separation' for Type IV′ laminates is shown in Fig. 8. An attempt was also made to use CFRP itself as a heat source. CFRP has high electrical conductivity. CFRP/damping-material laminates have larger resistivity values than the conventional Type I laminates. The resistivity values for the Type IV′ and Type III laminates in the 90° direction are particular large (10^4-10^5 Ω cm). The reason for the large values measured in these laminates is considered to be that the surface layer is insulated from inner layers by the interleaf

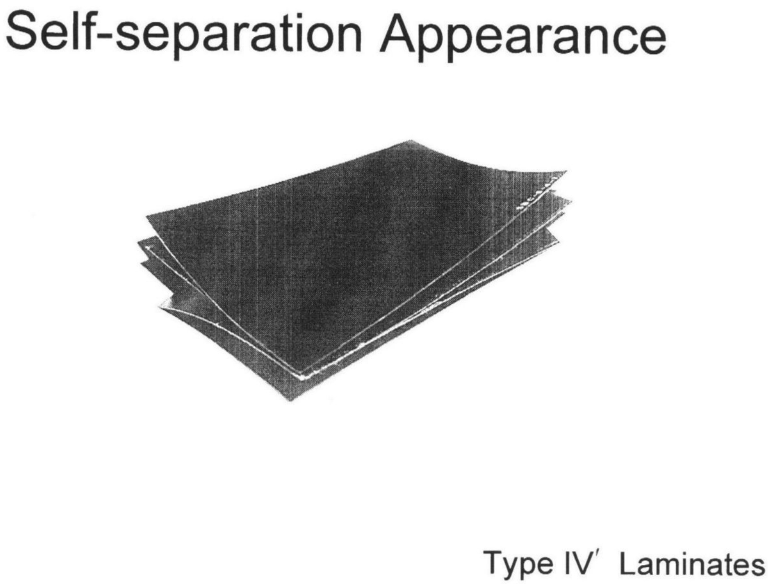

Figure 8. Self-separation appearance for Type IV′ laminates.

films. The incorporation of the interleaf films transforms CFRP laminates into an electrical insulator. The maximum surface temperature (150°C) was obtained when 96 V was applied to the Type IV′ laminates. These results suggest the possibility for disassembling CFRP based structures by utilizing the (exothermic?/insulating) properties of CFRP.

6. CONCLUSIONS

This investigation on CFRP/damping-material laminates led to the following conclusions:

1. CFRP/damping-material laminates have 5 to 50 times larger loss factor values at 30°C, in comparison with the conventional CFRP laminate values. These properties depend on both the number of damping sheets and their incorporated positions. The flexural moduli for these laminates were slightly lower values than those obtained with conventional materials.
2. Loss factor values for CFRP/damping-material laminates could be predicted, except for Type III and Type X specimens, using equations for constrained-layer damping treatments developed by Ross, Kerwin and Ungar. The Type III and Type X specimens showed large loss factor values under both longitudinal and flexural vibration.
3. The damping-material interleaf has been shown to increase the ultimate load bearing capability and to improve the tensile strength reliability in quasi-isotropic laminates, except for the Type III specimens.
4. The ultimate load decrements for Type III and Type X specimens, that have large loss factor values under longitudinal vibration, are extremely large.
5. The interleaf may be most effective for the improvement of fatigue resistance, when it has been sandwiched between the 45° and 90° layers, or between the 90° and 90° layers. On the contrary, the interleaf between the 0° and 45° layers was found to reduce the fatigue life.
6. The interleaf is not very effective for increasing the compression strength. In this case, the interleaf between the 0° and 45° is recommended.
7. The interleaf between the 45° and 90° layers is most effective for decreasing the delamination area caused by an impact force.
8. The tube structure for the spacecraft, made up from CFRP/damping-material laminates, could improve satellite reliability by reducing vibration.
9. CFRP/damping-material laminates can be separated easily for recycling.

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