Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Mechanical and optical properties of optical fiber embedded super hybrid material

Osamu Haga [a], Hirosi Asanuma [b] & Hideo Koyama [c]
[a] Faculty of Engineering Chiba University, Yayoi-cho 1-33, Inage-ku Chiba 263, Japan
[b] Faculty of Engineering Chiba University, Yayoi-cho 1-33, Inage-ku Chiba 263, Japan
[c] Faculty of Engineering Chiba University, Yayoi-cho 1-33, Inage-ku Chiba 263, Japan
Version of record first published: 02 Apr 2012.

To cite this article: Osamu Haga, Hirosi Asanuma & Hideo Koyama (1998): Mechanical and optical properties of optical fiber embedded super hybrid material, Advanced Composite Materials, 7:3, 239-248

To link to this article: http://dx.doi.org/10.1163/156855198X00174

Adv. Composite Mater., Vol. 7, No. 3, pp. 239–248 (1998)

Mechanical and optical properties of optical fiber embedded super hybrid material

OSAMU HAGA, HIROSI ASANUMA and HIDEO KOYAMA

Faculty of Engineering Chiba University, Yayoi-cho 1-33, Inage-ku Chiba 263, Japan

Abstract—This paper describes conditions for embedding optical fibers into the super hybrid plate without losing its optical communication function, and describes also the mechanical properties of the optical fiber embedded super hybrid material and transmission characteristics of this new material. Mechanical properties of this new material made under optimum conditions were investigated in detail by experimental and FEM analyses. Reactions of the embedded optical fiber were investigated when such external forces as tension, compression and bending were applied on this new material and the mechanisms of generation of transmission loss were also made clear.

Keywords: Smart material; optical fiber; composite material; fiber metal laminate; optical transmission.

1. INTRODUCTION

A super hybrid material which is a laminated material composed of several aluminum-alloy sheets and unidirectional FRP sheets has been developed as a new structural material for aircraft which has quite excellent static and dynamic properties [1–4]. Because the optical fiber is an excellent sensor for multipurpose usage and can be embedded into the FRP layers easily, it has become an influential means of the creation of smart materials and structures. Many efforts have been made to obtain a smart material by embedding optical fiber into ordinary FRP. Many researchers have been published their reports concerning this idea to date. For example, Fukuda and Osaka studied the mechanical properties of optical fiber embedded CFRP [5]; and Candhi and Thompson described this idea extensively in their book [6]. Therefore, there have been no examples using the super hybrid material which has more complex structure compared with ordinary FRP. This research is part of an effort to embed optical fiber into it and obtain a new material which has both the function of a structural material and an optical communication function; and moreover to attempt to make the optical fiber have functions as a sensor, including functions of health monitoring.

2. EXPERIMENTS AND FEM ANALYSIS

Figure 1 shows the structure of the super hybrid material and the method of embedding optical fiber (OF) into it. The components used were an aluminium-alloy sheet (A5086-H18, with the thickness of 0.4 mm), KFRP unidirectional prepreg sheet (with the thickness of 0.1 mm) and optical fiber (quartz-system multi-mode fiber, with plastic coated outer diameter of 250 μm, without plastic coated outer diameter of 125 μm and core diameter of 50 μm). Molding pressure was controlled by using a hot press, and the materials were hardened at the temperature of 120°C. Figure 2 shows the configuration of each test specimen. The coating of the embedding part of the optical fibers was removed.

For the purpose of obtaining ultimate strain, tensile tests of the optical fiber were made. The gauge length of test fiber was 100 mm. Grip ends of the fiber were embedded into the super hybrid plate in the same way as was used for the other test pieces. Average ultimate strength was obtained from 20 samples; then it was converted into ultimate strain assuming that Young's modulus of optical fiber is 70 GPa.

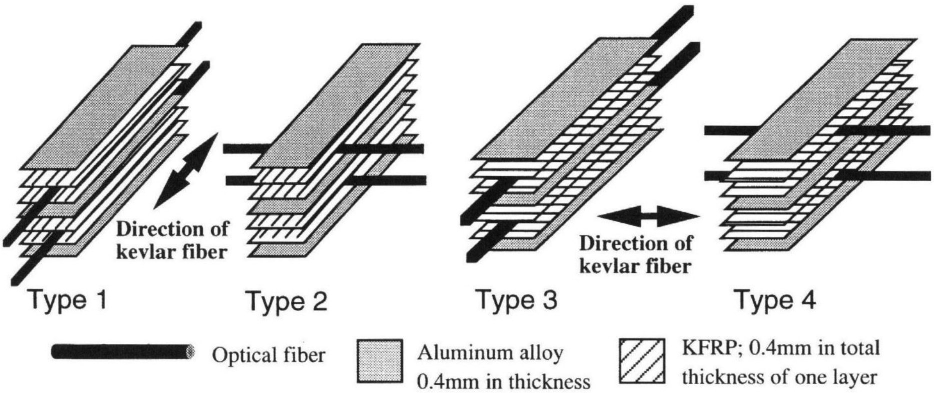

Figure 1. Schematic diagram of constitution of the super hybrid material with an optical fiber. The material consisted of 2 KFRP layers sandwiched by 3 aluminum layers and total thickness is 2.0 mm in the plan.

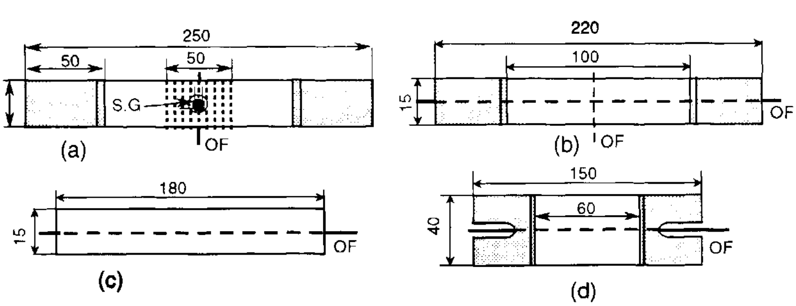

Figure 2. Geometry of the test specimens: (a) is the tensile test specimen for investigation of the effect of embedding pitch of the optical fiber(s); (b)–(d) are those to measure the transmission loss of light power; (b) for tensile test; (c) for bending test; and (d) for in-plane compressive test, respectively.

On-load transmission loss characteristics tests were conducted in terms of 4 types of a simple tensile test, in-plane simple compression test (by binding the side with a buckling-prevention jig), and four-point bending test with a distance between two supporting points of 150 mm and between two applying force points of 70 mm. Under each of the above-mentioned load conditions, the relations between stress–strain–optical transmission loss were obtained. In the tests of simple tension and four-point bending, the test specimens were given several kinds of load, and then the conditions of the OF in the specimens were observed with a digital microscope. Based on the results of the microscopic observation of cross section of the materials of Type 2 and Type 4, FEM models shown in Fig. 3 were made. Then, the relationship between orientation pitch of the OF and elastic coefficient and internal-stress distribution of the material subjected to the tensile strain of 0.1%

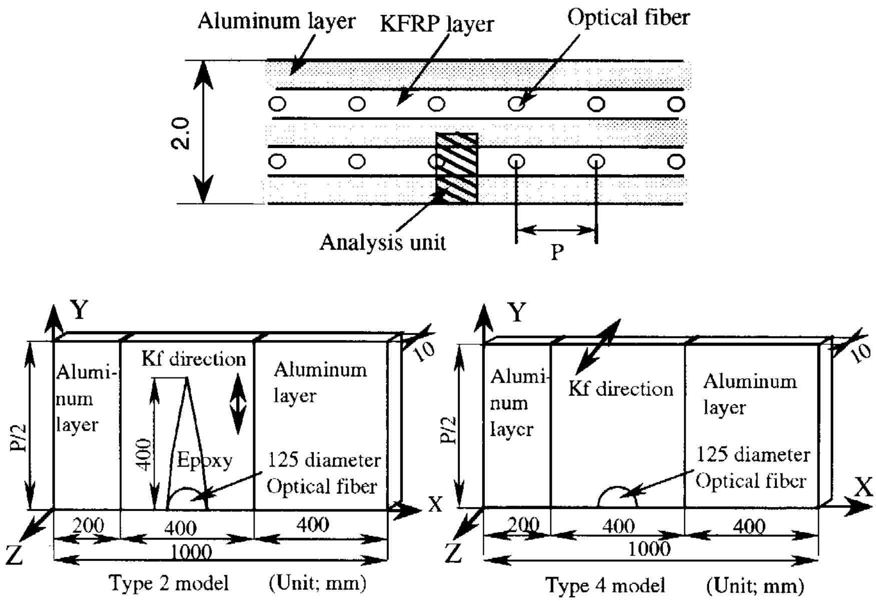

Figure 3. Geometry of models for FEM analysis.

Table 1.
Elastic moduli of constituent materials used for FEM analyses

	Young's modulus (GPa)		Shearing modulus (GPa)		Poisson's ratio		
	E_L	E_T	G_{RT}	G_{LT}	ν_{RT}	ν_{TL}	ν_{LT}
KFRP	64.0	3.40	1.30	2.60	0.30	0.03	0.41
Aluminum	72.0		27.1			0.33	
Epoxy resin	3.40		1.28			0.30	
Optical fiber	72.5		29.5			0.23	

L — parallel to the fibers; T, R — perpendicular to the fibers.

in the direction of the y-axis were examined. Elastic moduli of constituent materials used for FEM analyses are shown in Table 1.

3. RESULTS AND DISCUSSION

3.1. Effects of optical fiber embedding on material properties

Relations between optical fiber embedding conditions (molding type, orientation pitch of OF and molding pressure) and transmission loss of the laminated materials of Type 1 and Type 4 (the cases where OF and Kevlar fibers are parallel to each other) and Type 2 and Type 3 (the cases where OF and Kevlar fibers are orthogonal to each other) are shown in Table 2.

It was possible for all embedding types and all orientation pitch of optical fiber to transmit light when they were made by a molding pressure of 0.2 MPa. If they were formed by a 0.5 MPa molding pressure, however, Type 1 and Type 4 specimens with all orientation pitch of optical fiber could transmit light with the loss less than −1.3 dB but Type 2 and Type 3 specimens could not transmit light at all. No influence of the orientation pitch of OF on the transmission loss was recognized in this experimental study. In terms of material strength, there were no differences between molding pressure of 0.2 MPa and that of 0.5 MPa. Accordingly, molding pressure was get at 0.2 MPa.

Next, the effects of OF orientation pitch on tensile properties of super hybrid material obtained by experiments for the case of OF embedding method of Type 2 and Type 4 are shown in Table 3. It can be estimated that the modulus of elasticity shows almost no difference from the case where the OF is embedded with a 1 mm

Table 2.
Relationship between optical fiber embedding conditions and transmission loss

Molding type	Transmission loss	
	Molding pressure 0.2 MPa	Molding pressure 0.5 MPa
Type 1 and Type 4	Less than −1.0 dB	Less than −1.3 dB
Type 2 and Type 3	Less than −2.8 dB	Impossible to transmit

Table 3.
Mechanical properties of the optical fiber embedded super hybrid material obtained by experiments

Specimen type	Type 2				Type 4			
Orientation pitch of OF	1 mm	3 mm	5 mm	∞	1 mm	3 mm	5 mm	∞
Young's modulus (GPa)	66.7	68.2	68.2	64.4	48.9	46.8	46.6	45.8
Poisson's ratio	0.33	0.33	0.32	0.31	0.23	0.24	0.25	0.23
Tensile strength (MPa)	720	750	760	720	230	230	220	230
Ultimate strain (%)	2.2	2.2	2.2	2.2	3.6	4.0	3.7	3.8

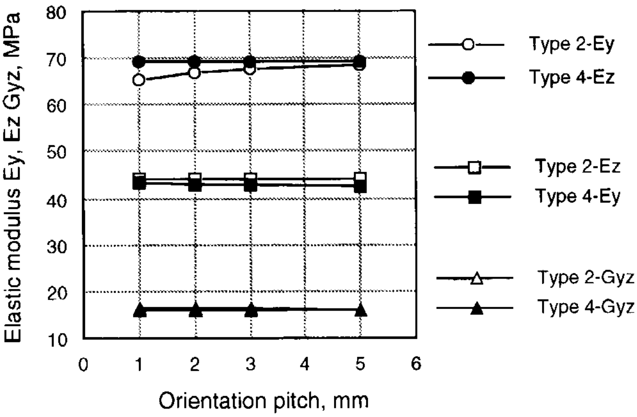

Figure 4. Relationships between orientation pitch of optical fiber and modulus of longitudinal and transverse elasticity.

pitch up to the case of infinite pitch, which is the case where only one piece of OF is embedded in a specimen.

Relationships between orientation pitch and in-plane elastic moduli of E_y, E_z and G_{yz} (see coordinate system in Fig. 3) obtained by FEM analysis are shown in Fig. 4. A little dependence on orientation pitch is recognized in the case of E_y of Type 2 specimen; however, others are independent of it. From Table 3 and Fig. 4, one may conclude that the embedding of optical fibers has no effect on the tensile properties of the super hybrid material.

3.2. Mechanism of generation of transmission loss

3.2.1. In the cases under tensile load. Results are shown in Fig. 5. The upper part of the graph is the stress–stain diagram and the lower part is light transmission loss–tensile strain diagram. Transmission loss of Type 1 and Type 3 increased radically with the strain of 0.8 and 0.4%, respectively. Then the loss began to grow step by step and finally the materials were completely opaque to transmitted light. Tensile ultimate strain of the OF was 0.8% on the average from the result of the tensile test, and transverse cracking strain of the KFRP layer is 0.4%: the radical increase of transmission loss of Type 1 was caused by fracture of the OF and that of Type 3 was by transverse cracking of the KFRP layer. According to the observation of the conditions of embedding of OF at various strain levels of tensile tests, many broken portions were confirmed, as shown in Fig. 6. It was made clear from this fact that the discontinuous form of transmission loss was caused by multiple failure of OF.

In the cases of Type 2 and Type 4 test specimens, which were stretched in the direction perpendicular to the OF axis, it was found that optical transmission was possible up to the point close to the fracture of the hybrid material. However, as the radical increase of transmission loss of Type 4 specimen was recognized in the range of 1.8 to 2.0% strain, it is considered that the bending fracture of OF was

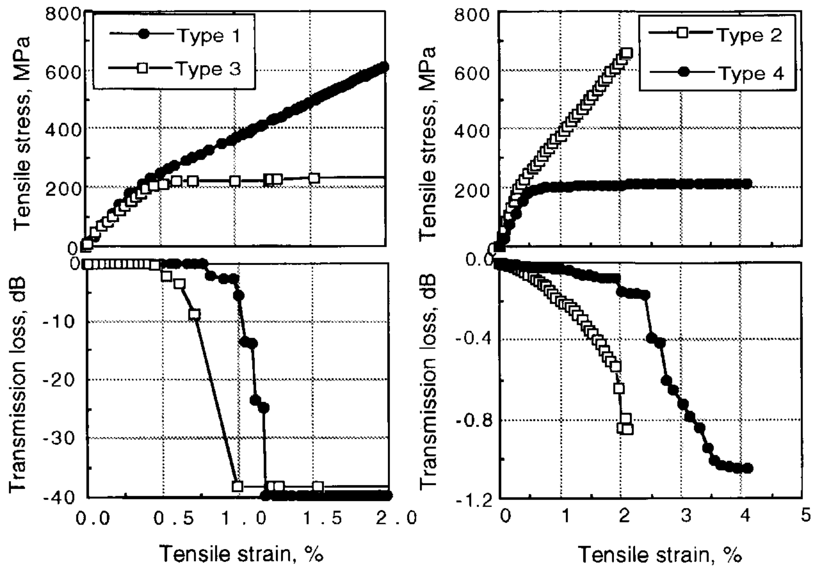

Figure 5. Relationships among tensile strain, tensile stress and transmission loss of light power under a tensile loading.

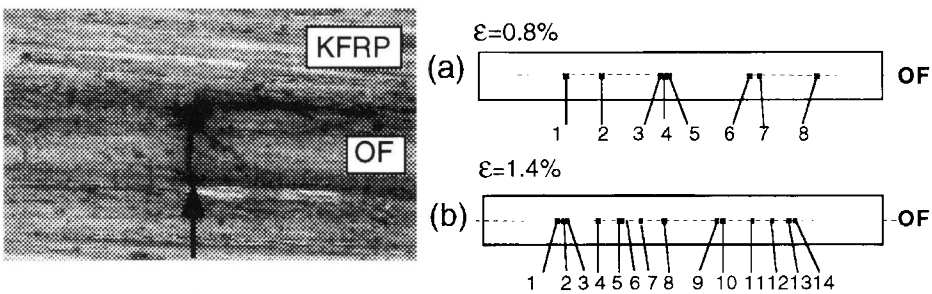

Figure 6. Photo of the optical fiber breakage (black arrow) and the locations of Type 1 specimen at a strain of 0.8% (a) and a strain of 1.4% (b).

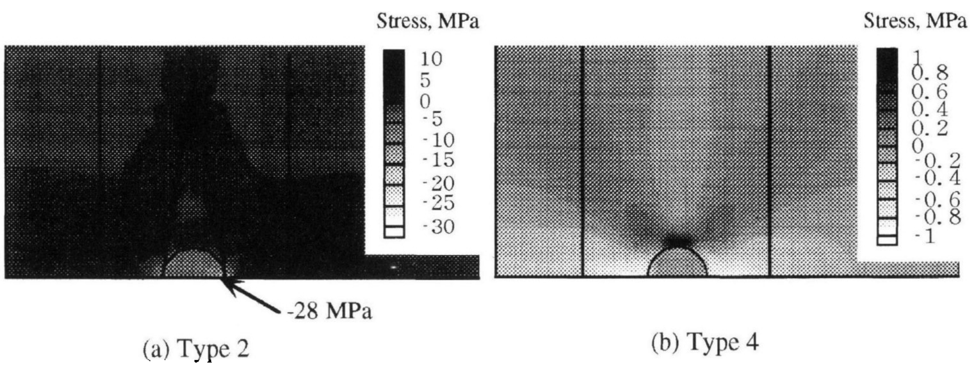

Figure 7. Internal stress distribution of Type 2 and Type 4 materials by FEM analysis.

produced in this case. It is suggested that this was caused by transverse cracking of the KFRP layer produced around the optical fiber. An additional experiment showed that some breakage of OF was found to have arisen, but no breakage of Type 2 specimen was recognized until just before the break of the test piece. Therefore, their capability of optical transmission for communication is considered to be at less than the strain of 1.8%. It may be seen from Fig. 5 that transmission loss of Type 2 is much greater than that of Type 4 under 1.8% strain. Results of FEM stress analyses conducted to make clear this reason are shown in Fig. 7. The figure shows δ_x distribution (cf. Fig. 3). It was found that compressive stress arose at the point of contact of OF and reinforcing fiber in the case of Type 2 specimen. The value of the stress reached up to 20–30 times the value in the case of Type 4 specimen. Cross section of OF in Type 2 material is distorted into an elliptic shape due to this stress and this causes transmission loss. This is the reason why transmission loss of the Type 2 specimen is much greater than that of the Type 4 specimen under 1.8% strain.

3.2.2. In the cases under compressive load. Experimental results of in-plane compression are shown in Fig. 8. It is obvious from the figure that transmission loss increases radically starting from the stress of about 190 MPa. According to our previous study [4], compressive strain of the hybrid material at this compressive stress is estimated to be about 0.25%. Since the compressive fracture of OF can never be considered to occur at this strain level, the cause of radical increase of transmission loss seems to be a radical buckling fracture of the hybrid material plate. Actually, buckling fracture of the hybrid plate arose at the stress of 200 MPa on the narrow free plane of about 10 mm between the reinforcing tab at the compressed edge of the test specimen and the buckling-control jig. The stress of the KFRP layer at this moment is about 280 MPa by taking into consideration the residual stress based on the difference of thermal expansion coefficient from the Al layer, and KFRP is said to generate kinks and yield under such value of stress [7] — this

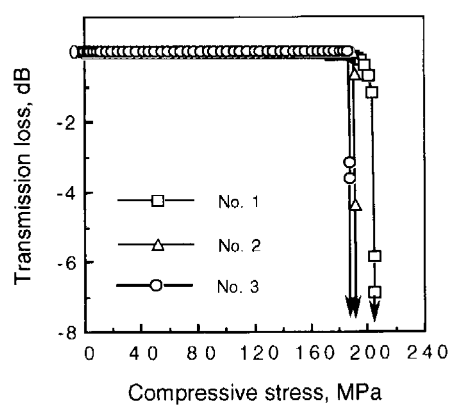

Figure 8. Relationship between in-plan compressive stress and optical transmission loss.

seems to have become the trigger of the buckling fracture of the hybrid plate. It is concluded that the OF radically caused at the same time a bending fracture and transmission loss increased rapidly.

3.2.3. In the cases under bending load. Figure 9 shows the results obtained for Type 1 and Type 3 materials. In the case where the OF is located on the stretching side, transmission properties showed similar behavior to that under simple tensile load, and transmission loss rapidly increased step by step. In the observation of OF after the bending tests, multiple fracture of OF was found. At this point, the nominal distortion of the OF central line converted from curvature was about 0.8% in Type 1 material and about 0.5% in Type 3, which means almost the same behavior as that under simple tensile load. That is to say, the radical increase of transmission loss is due to OF fracture, and it is shown in the case of Type 3 specimen that generation of transverse cracks is detected in the FRP layer. On the other hand, on the compressing side, there was no radical increase of transmission loss even in the case where the compressive strain of the OF center converted from curvature became 0.8% or more. This is a quite different phenomenon in comparison with the case of in-plane simple compression. It is shown that within the range of a curvature of 0.0 to 0.02, KFRP does not cause any kink on the compression side of bending even under the yield strain, and no buckling fracture of the laminated sheet arises.

Consequently, it emerges that whether the test specimens are subjected to bending load or tensile load can be determined by the method of observing transmission loss of two OFs embedded in the KFRP layer on both sides of a neutral layer of the hybrid material.

It also emerges that when the application of bending load to the hybrid material is known in advance, the communication function can be maintained by arranging the

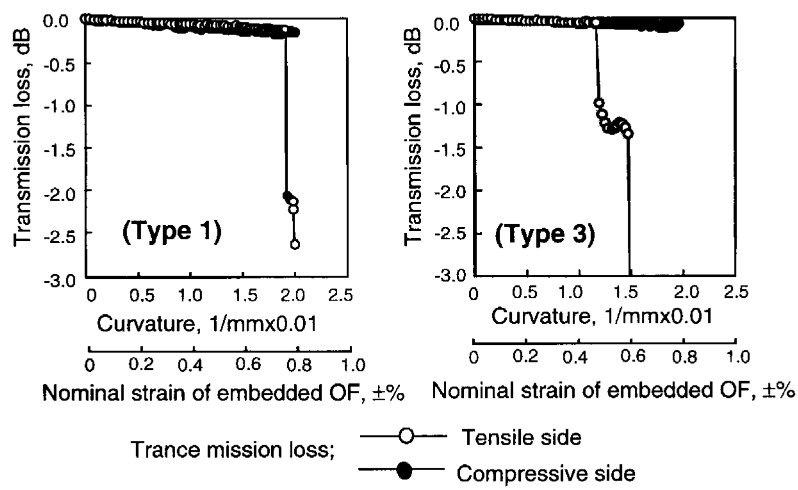

Figure 9. Experimental results of bending test for Type 1 and Type 3 materials.

OF on the compressing side up to the moment of a great bending distortion of the hybrid material.

4. CONCLUSIONS

The method to embed optical fiber into a super hybrid material and the mechanical and optical-transmission characteristics of the optical fiber embedded super hybrid material have been examined and the following conclusions have been reached.

(1) It is possible to embed optical fiber into a super hybrid laminated material, and the new material has comparatively low transmission loss.

(2) When the pitch of optical fiber embedding is 1 mm or more, the embedding has no effect on the mechanical characters of the super hybrid material.

(3) Appearance of transverse cracks of KFRP layer in the super hybrid material can be detected by the optical fiber embedded orthogonally to reinforcing fiber.

(4) Unless tension is applied to embedded optical fiber, optical transmission is possible to the point where the hybrid material becomes broken.

(5) In-plane compressive buckling of the hybrid material can be detected by embedded optical fiber.

(6) It is possible to determine if either a tensile load or a bending load is applied to the hybrid material by monitoring each optical fiber embedded in the KFRP layers on both side of a neutral layer of the hybrid plate.

Acknowledgements

The authors wish to thank Furukawa Aluminum Co., Ltd. for providing a large quantity of aluminum sheets and Fujikura Co., Ltd. for providing much optical fiber for this investigation.

REFERENCES

1. L. B. Vogelesang, R. Marissen and J. Schijve, A New Fatigue Resistant Material: Aramid Reinforced Aluminum Laminate (ARALL), Report LR-322, Delft University of Technology, pp. 1–39 (1981).
2. A. Vlot, Inspection and repair of fiber metal laminate aircraft fuselage structures, in: *Proc. 38th Int. SAMPE Symp.*, pp. 1391–1402 (1993).
3. O. Haga, H. Koyama, K. Kawada and K. Ogawa, Residual stress control of Al/CFRP multilayered hybrid material, in: *Residual stress III: Science and Technology*, H. Fujiwara, T. Abe and K. Tanaka (Eds), Vol. 1, pp. 76–81. Elsevier Science Publishers, London (1992).
4. O. Haga, H. Koyama and K. Kawada, Mechanical properties of a new type super hybrid material, *Adv. Composite Mater.* **5**, 139–149 (1996).
5. T. Fukuda and K. Osaka, Measurements of strain in graphite–epoxy composites with embedded optical fibers, in: *Proc. 2nd Japan Int. SAMPE Symp.*, pp. 555–562 (1991).

6. M. V. Gandhi and B. S. Thompson, in: *Smart Materials and Structures*, p. 216. Chapman & Hall (1992).
7. M. M. Sohi and T. Hahn, Kink band formation in unidirectional composites under compression, in: *Composites '86: Recent Advances in Japan and the United States*. K. Kawata, S. Umekawa and A. Kobayashi (Eds), pp. 417–423. Japan Society for Composite Materials, Tokyo (1986).