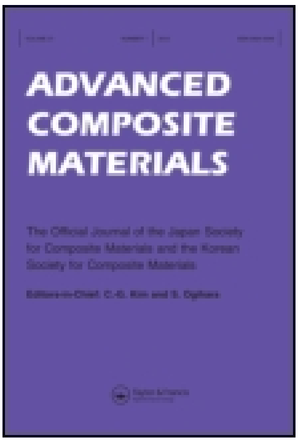

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Structural health monitoring of a full-scale composite structure with fiber-optic sensors

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Abstract—Structural health monitoring systems capable of assessing structural integrity during manufacture and service would allow us to keep them up-to-date and to increase their lifetime and safety in use. We installed fiber-optic sensors into a full-scale composite structure of a Japanese experimental re-entry vehicle and monitored temperature and strain distributions of the fuselage during the manufacturing process. The results obtained us with important information about the process control and the structural quality. The sensing system used in the manufacture could measure strain also in structural tests with static load. Although the strain measured by the fiber-optic sensor was averaged data depending on the spatial resolution, the overall deformation of the structure could be found, because strain was acquired extensively and continuously along the sensing fiber. The achievement of this study shows applicability of fiber-optic sensors to structural health monitoring for composite structures.

Keywords: Structural health monitoring; CFRP; cure; fiber-optic sensors; temperature; strain.

1. INTRODUCTION

The purpose of structural health monitoring is to render a structure safer at lower cost. Structural health monitoring systems capable of assessing structural integrity during manufacture and service would allow us to keep them up-to-date and to increase their operational lifetime and safety during use. The economic impact of such a system is tremendous, based on the following principal effects: (i) reducing maintenance cost, (ii) extending life of structures by condition-based maintenance, and (iii) market advantage.

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In systems, a sensing technology to acquire information concerning the structural integrity is as important as analysis technology. Recently, fiber-optic sensors have been developed actively, and they can measure many kinds of physical quantities. Since they also have excellent operational characteristics, such as immunity from electromagnetic interference, durability and capability to realize distributed configuration, they are supposed to be suitable sensors for structural health monitoring. A composite monocoque structure is one of the most attractive objects to which fiber-optic sensors are applied, because it can be easily equipped with fiber-optic sensors during manufacture and may be used to monitor the cure of composite materials in real time and to monitor the in-service structural health.

We applied fiber-optic sensors to a monocoque structure made of a carbon fiber reinforced plastic (CFRP) in order to measure temperature and strain in the cure process and in the structural tests after manufacture. The structure was a full-scale model built as a prototype to demonstrate feasibility of a Japanese experimental reentry vehicle, HOPE-X (H-II Orbiting Plane-Experimental) [1]. The fiber-optic sensors used in the monitoring were distributed sensors that could measure temperature or strain in arbitrary positions along an optical fiber. Real time monitoring of temperature and strain was successfully implemented during the post-cure. The results were used to assess the temperature control in the oven and to evaluate deformation of the structure. Furthermore, in the structural tests, strain was measured using the same sensing system used in the cure and we monitored strain distributions of the fuselage subjected to static load.

2. DESIGN AND MANUFACTURE OF HOPE-X

HOPE-X, which is shown in Fig. 1, is an experimental reentry vehicle which has been developed by National Aerospace Laboratory (NAL) and National Space

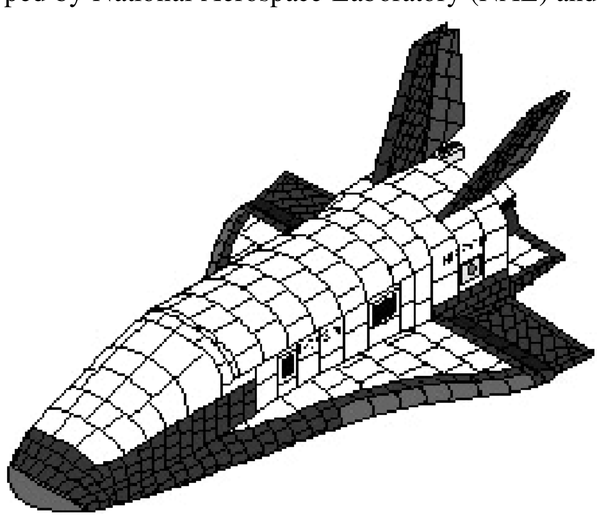

Figure 1. Outlook of HOPE-X.

Development Agency of Japan (NASDA) over several years. It is about 13 m long, 9 m wide and is planned to be launched by an H-IIA launch vehicle. Recently, the structural concept of HOPE-X has been changed from a conventional aluminum semi-monocoque structure to a composite monocoque structure shown in Fig. 2. Most components of the fuselage are made of either single skinned and sandwich CFRP structures. The composite material for the HOPE-X is TR30/#850 developed by Mitsubishi Rayon. The structure comprises two primary parts, upper-fuselage and lower-fuselage with wings. These parts are reinforced by a number of frames and longerons. The manufacturing processes are schematically shown in Fig. 3. The two primary parts and the composite reinforcements formed by stacking prepregs were cured at 100°C under vacuum pressure. This cure process is called pre-cure in this paper. They were jointed by adhesive bonding after the pre-cure. The assembled fuselage was cured at about 180°C in free-standing state to give it heat resistance. We call this process post-cure. In both the pre-cure and the post-cure, the oven used

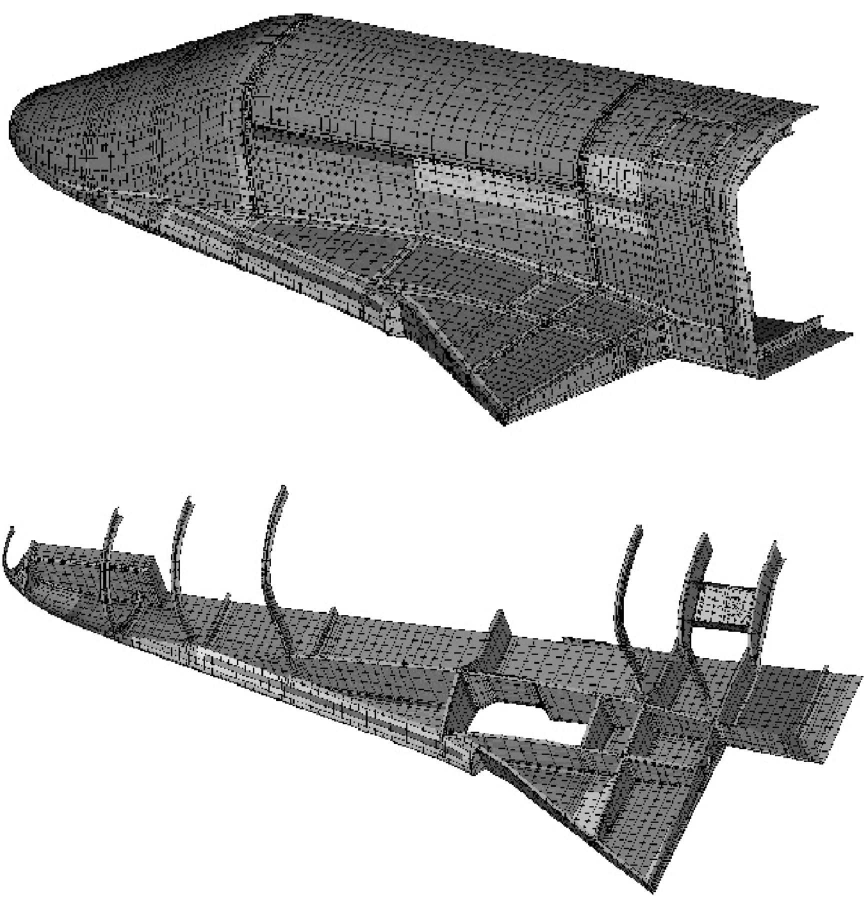

Figure 2. Monocoque structure of HOPE-X.

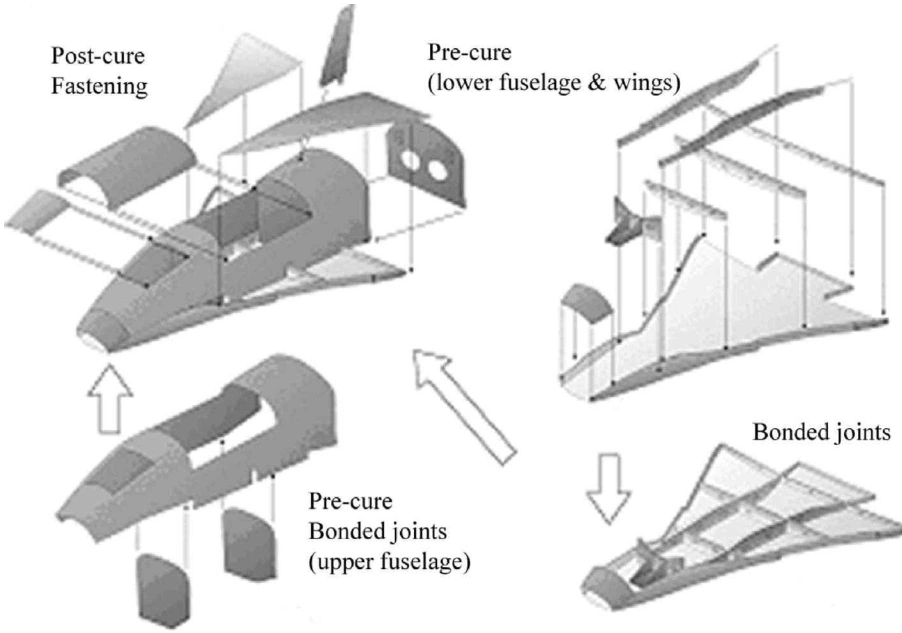

Figure 3. Manufacturing process of the fuselage.

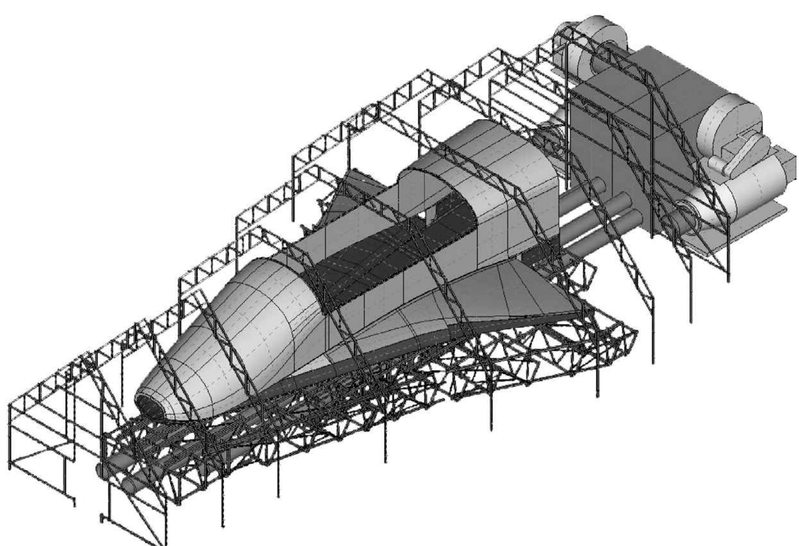

Figure 4. The fuselage in the post-cure.

consisted of steel-flames and insulated walls [2]. The oven without the walls and the assembled fuselage in free-standing state are shown in Fig. 4. Finally, several parts were fastened to the fuselage.

In the post-cure, unexpected damage or deformation might occur due to uneven stress and temperature distributions in the fuselage. So we attempted to monitor strain and temperature distributions.

3. SENSING SYSTEM USING FIBER-OPTIC SENSORS

The sensing system was required to measure overall strain and temperature efficiently. It comprised measuring instruments, sensing fibers and PCs.

Two types of measuring instruments, Fiber Optic Temperature Laser Radar (FTR) and Brillouin Optical Time Domain Reflectometer (BOTDR), were used for temperature and strain measurements. Raman and Brillouin scattering that can be exploited in distributed sensing is light that is inelastically scattered by interaction with optical and acoustic phonons, respectively [3]. It is known that the intensity ratio of the two components of Raman scattering, i.e. Stokes light and anti-Stokes light, is a function of temperature [4]. FTR developed by Hitachi Cable can measure temperature by detecting this intensity ratio [5]. In addition, temperature distributions along an optical fiber can be obtained from FTR which measures the intensity of Raman backscattering light generated at every point in the fiber based on Optical Time Domain Reflectometry (OTDR) methods. Temperature measured using FTR is approximately equal to an averaged value for about 3 m of its spatial resolution and the data are acquired at intervals of 1 m along the fiber. It has been used for the temperature monitoring system for an underground power cable line, and in other applications [6]. On the other hand, BOTDR developed by Nippon Telegraph and Telephone Corporation (NTT) can measure strain as a function of position along an optical fiber by detecting the frequency shift of the Brillouin gain spectrum which is sensitive to strain [7, 8]. This frequency shift is also sensitive to temperature [9]. This means that temperature compensation is required in strain measurements. Strain measured using BOTDR is approximately equal to an averaged value for 1 m and its readout resolution is 0.1 m. BOTDR was applied to strain monitoring of Japanese racing yachts for the America's Cup [10]. The configurations of FTR and BOTDR for measurements in the post-cure are shown in Table 1.

Table 1.
Configurations of FTR and BOTDR

Instrument	FTR	BOTDR
Temperature accuracy	$\pm 2^\circ$C	$\pm 1^\circ$C
Strain accuracy	NA	$\pm 30\ \mu\varepsilon$
Spatial resolution	3 m	1 m
Readout resolution	1 m	0.1 m
Acquisition time	3 s	5 min

The sensing fibers were installed into the outer skin of the fuselage after the pre-cure and assembled with adhesive bonding. A multi-mode fiber coated with Teflon was used as the sensing fiber of FTR and its outside diameter was 0.90 mm. On the other hand, a conventional single mode fiber coated with ultraviolet curable resin was used for BOTDR and its diameter was 0.25 mm. Although the ultraviolet curable resin coating is changed in quality at 180°C of the post-cure temperature, the sensing performance of BOTDR did not change in a laboratory test performed before the cure. The sensing fibers were arranged mostly in longitudinal direction and partly in the transverse one, as shown in Fig. 5. We fixed them on the CFRP structure by using epoxy resin as adhesion bond. Both the sensing fibers of FTR and BOTDR on the fuselage are 54.8 m in length. The positions of these marks from z of the ingress point are shown in Table 2. A CAD application was used to decide the arrangement and to calculate the lengths of the sensing fibers. The fibers

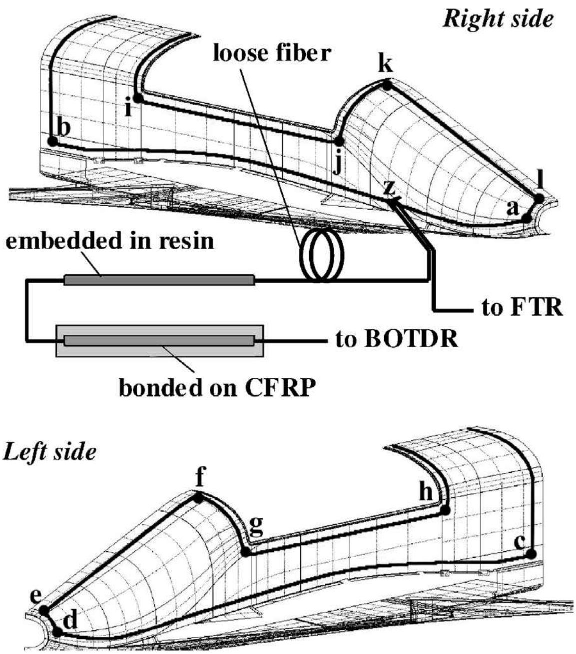

Figure 5. Sensing fibers for FTR and BOTDR.

Table 2.
Distances of the marks from the ingress point

Mark	z	b	c	d	e	f	g
Distance (m)	0.0	8.0	14.0	25.4	25.8	30.0	31.4
Mark	h	i	j	k	l	a	z
Distance (m)	36.6	40.2	45.4	46.8	51.0	51.4	54.8

out of the fuselage in Fig. 5 were used to compensate for temperature or to evaluate effects of adhesion bond on the sensing fiber in strain measurements. These optical fibers include the fibers let loose in the oven, embedded in the resin and bonded on the CFRP plate. Their lengths are about 20 m, 1 m and 1 m, respectively. By using FTR and BOTDR, we could monitor temperature and strain distributions of the fuselage along the sensing fiber during the post-cure. The measuring instruments were connected with PCs for remote control, data acquisition and analysis.

4. RESULTS AND DISCUSSION

4.1. Temperature monitoring in the post-cure

By hot air and a number of heaters, the oven was heated from 30°C room temperature to about 170°C during the post-cure. The temperature measured after the post-cure was about 40°C. The temperature distributions of the fuselage monitored in real time by FTR are shown in Fig. 6. The letters inscribed in the figure correspond to those in Fig. 5 and the open circles represent the results measured by the thermocouples adjacent to the sensing fiber. The temperature values of FTR are in good agreement with those of the thermocouples. The distributions are almost uniform in the fuselage, so we can say that temperature in the oven was controlled adequately.

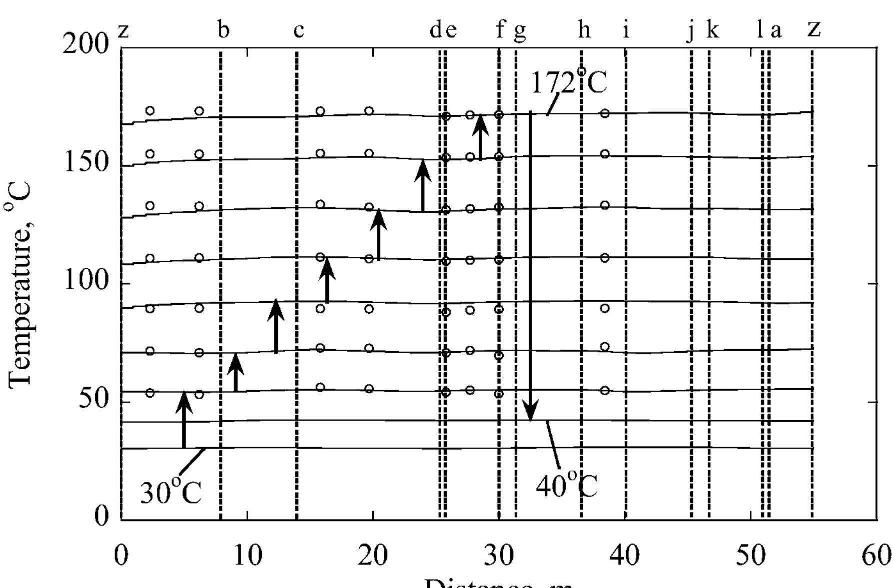

Figure 6. Temperature distributions of the fuselage.

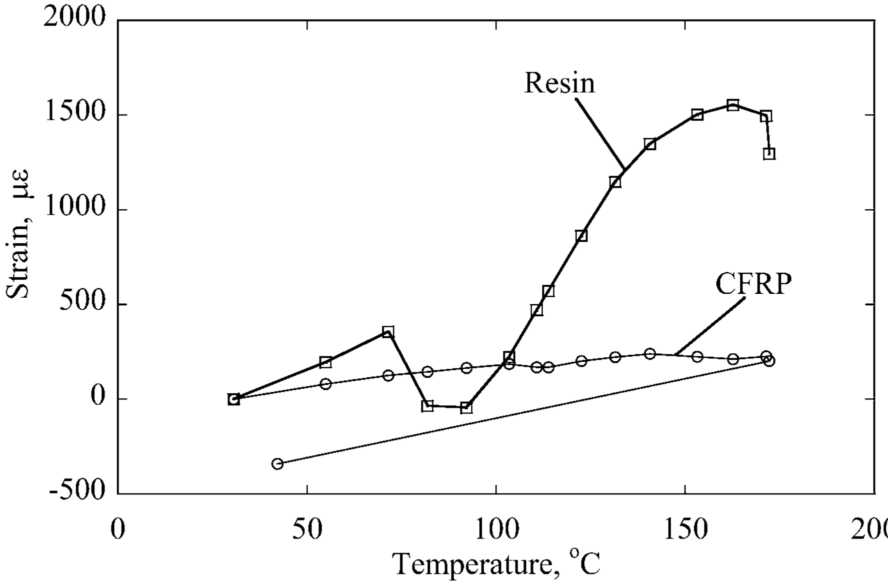

Figure 7. Strain histories of the fibers out of the fuselage.

4.2. Strain monitoring in the post-cure

We monitored strain distributions at a few hour (about 10°C) intervals during the post-cure. Strain distributions of the fuselage are determined by the following step. First, the initial strain measured at the room temperature before the cure is subtracted from the strain measured during the cure. Second, in order to implement the temperature compensation, the offset is calculated by separating the thermal strain and the temperature dependence of the loose fiber. The temperature dependence of the loose fiber is equal to that of the sensing fiber on the fuselage surface. Finally, the strain along the sensing fiber of the fuselage is obtained by subtracting the offset from the strain obtained in the first step. In this case, we assume that temperature was even anywhere in the oven.

Strains of the fiber bonded on the CFRP plate and the one embedded in the resin were measured by BOTDR in order to verify the effect of adhesive resin to strain measurements during the post-cure. Their strain histories are shown in Fig. 7. From the figure, it can be seen that the resin was expanding largely during the cure. Although we were afraid that such deformation of the adhesive resin would affect deformation of the CFRP plate or that of the fiber bonded on it, it seems that the fiber was expanding and contracting following the CFRP plate without being influenced by the adhesive resin. Therefore, we can regard the strain of the sensing fiber as that of the fuselage.

The strain distributions at 72°C, 103°C, 172°C and 42°C (after the cure) are shown in Fig. 8. Strain increases gradually as temperature increases. At 172°C of the nearly maximum temperature during the cure, the strain of the fuselage distributes from 200 $\mu\varepsilon$ to 400 $\mu\varepsilon$. At 42°C after the cure, the residual strain is about -200 $\mu\varepsilon$.

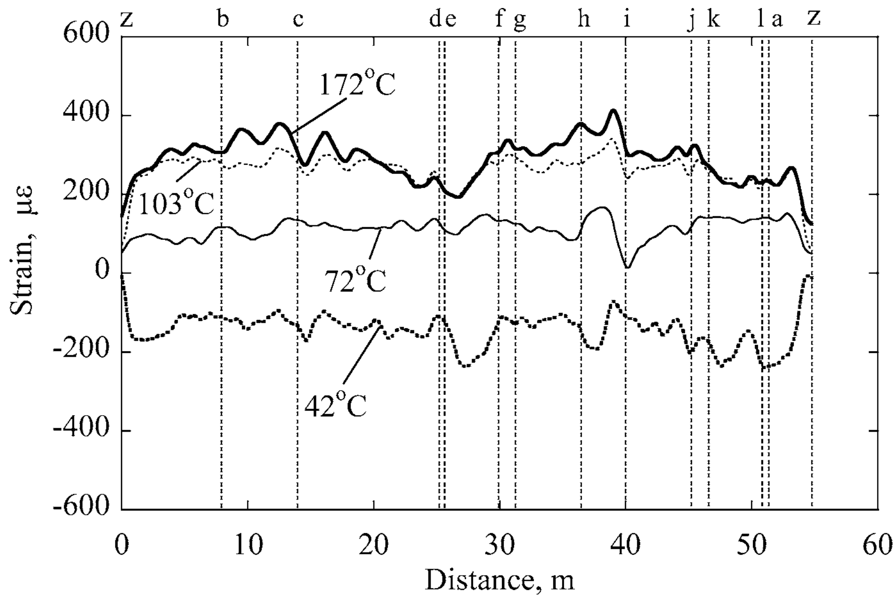

Figure 8. Strain distributions of the fuselage during/after the post-cure.

The strain values are to approaching to zero near 'z' of the ingress/egress point because they are average data including strain between the fuselage and the loose fiber. Since there is no abnormal strain in the distributions during/after the post-cure, we can consider that there has been no harmful deformation in the fuselage.

4.3. Strain monitoring in the structural tests

In the structural tests, the fuselage was fixed at the rear end like a cantilever. It was subjected to downward or upward load at the nose. The strain distributions measured with BOTDR in both the loading cases are shown in Fig. 9. Strain values measured by using Fiber Bragg Grating (FBG) sensors adjacent to the sensing fiber are also shown. Although the strain of BOTDR is smaller than that of FBG due to the difference of the spatial resolution, we can find the overall deformation of the fuselage from the strain distributions.

5. CONCLUSIONS

By using fiber-optic sensors, we could successfully monitor temperature and strain distributions of full-scale composite structure during manufacture. The results provided important information about the process control and the structural quality. Furthermore, the sensing system used in the cure could also measure strain of the fuselage subjected to static load in the structural tests. The strain measured using the fiber-optic sensor was averaged data depending on the spatial resolution. The overall deformation of the fuselage could be found, because strain was

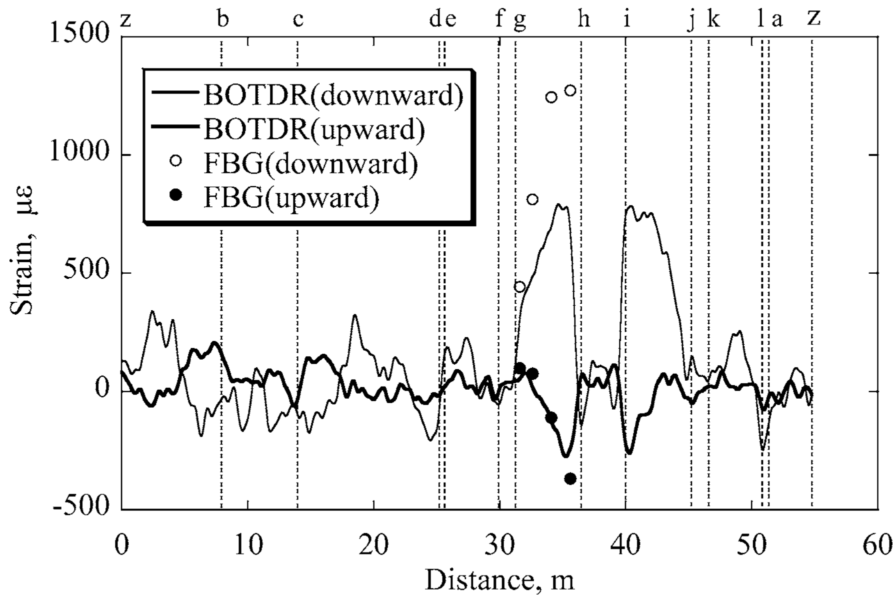

Figure 9. Strain distributions of the fuselage in the structural tests.

acquired continuously along the sensing fiber. The achievement of this study shows applicability of fiber-optic sensors to structural health monitoring for composite structures.

Acknowledgements

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