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Summary report of the structural health-monitoring project for smart composite structure systems

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Abstract—The R & D status of our structural health-monitoring group (SHMG) in 1999 is summarized. Activities of the SHMG are conducted as a university–industry collaboration program at the University of Tokyo, along with ten research organizations. Research themes include (1) the development of high-performance sensor system technology with newly developed sensors, (2) the development of a damage detection and self-diagnosis system for structural integrity based on micromechanical damage identification, and (3) the development of application technology for model structures. The sensor technology includes (1) the development of a small-diameter optical fiber sensor, (2) damage suppression in composite laminate systems with embedded shape-memory alloy films, and (3) the development of maximum strain memory sensors with electrically conductive composite systems. The sensor output is correlated with the underlying damage evolution in structures such as aircraft, satellites, high-speed trains, and large-scale civil infrastructures.

Keywords: Smart composites; structural health monitoring; optical fiber sensor.

1. INTRODUCTION

Light-weight composite material systems have been progressively used as structural members in various applications. However, more use has been proposed as primary structural members under severe operating conditions. In such applications, durability evaluation and health-monitoring systems are two key technologies to be investigated.

I have proposed the so-called ‘experimental micro-mechanics of composites’ to bridge the gap between material fabrication and macroscopic mechanical properties. Based on *in situ* observation using optical, scanning electron, and/or scanning acoustic microscopes with loading devices, microscopic deformation and damage

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have been quantified. Moreover, theoretical models have been established for damage evolution. These efforts can provide the methodology for the durability evaluation or the damage tolerance design of composites [1–9].

In real structural applications, however, since the strains applied to the composite structures are random and uncertain, real-time strain monitoring is necessary to predict the present damage status in composites based on the above durability evaluation method. Moreover, if the damage can be detected by using sensors, a more reliable estimation of the damage status or the residual life can be made.

In Japan, a new 'R & D for Smart Material/Structure System (SMSS)' project started in October 1998 as one of the Academic Institutions Centered Programs supported by NEDO (New Energy and Industrial Technology Development Organization), Japan. This SMSS project includes four sub-themes: (1) structural health monitoring, (2) smart manufacturing, (3) active/adaptive structures, and (4) actuator materials development. I act as a group leader in the structural health-monitoring group, which consists of ten research organizations. Our structural health-monitoring group (SHMG) is currently developing a health monitoring system that conducts real-time damage detection and self-diagnosis, as well as damage control in light-weight composite structural systems.

The research themes include:

(1) the development of high-performance sensor system technology with newly developed sensors;

(2) the development of a damage detection and self-diagnosis system for structural integrity based on micro-mechanical damage identification; and

(3) the development of application technology for model structures.

The sensor output is correlated with the underlying damage evolution in structures such as aircraft, satellites, high-speed trains, and large-scale civil infrastructures. The latest results in SHMG research efforts are reported for each research theme.

2. SUMMARY OF RESEARCH

2.1. Detection of transverse cracks in CFRP laminates with FBG sensors — University of Tokyo

Fiber Bragg Grating (FBG) optical fiber sensors have been developed to measure strain, temperature, etc., through the shift of the wavelength peak in the reflected light. A uniform strain within the gage section (typically 10 mm) is normally assumed. When an FBG sensor is embedded in 0° ply to detect transverse cracks in a 90° ply, a non-uniform strain distribution due to the initiation and evolution of transverse cracks causes the wavelength distribution in the reflected light (Fig. 1) [10]. Figure 2 shows the stress and crack density as a function of the strain measured by a strain gage and an FBG sensor. Careful examination of the wavelength distribution can be used to detect the evolution of transverse cracks in

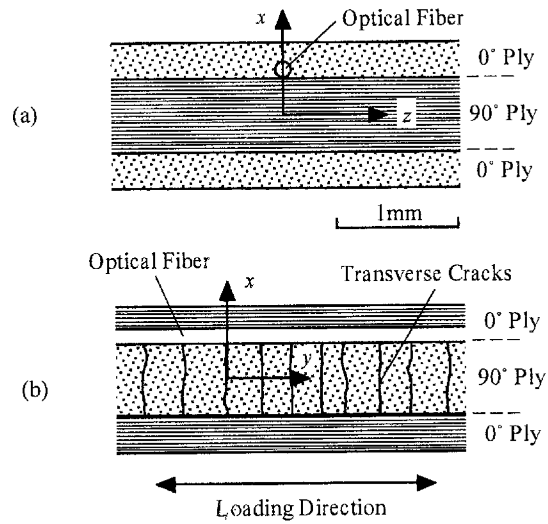

Figure 1. Cross-sections of CFRP cross-ply laminate with an embedded FBG sensor. (a) Normal and (b) parallel to loading.

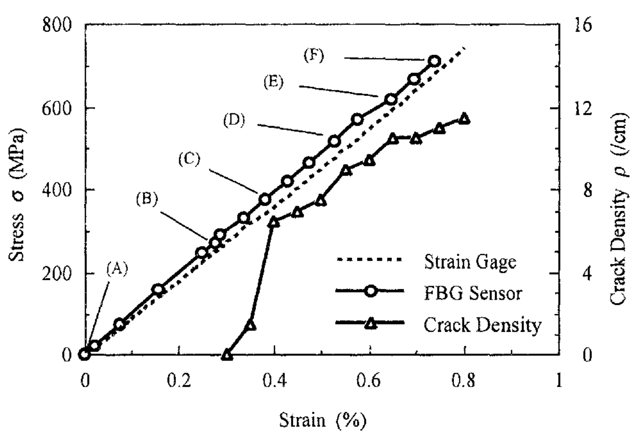

Figure 2. Stress and crack density versus strain measured by a strain gage and an FBG sensor.

composite laminates (Fig. 3). With increasing transverse crack density, the shape of the reflection spectrum was distorted; the intensity of the highest peak decreased, some peaks appeared around it, and the spectrum became broad. When the crack density was close to saturation, the spectrum became narrow again and the highest peak recovered its height. These experimental observations can be well explained by the theoretical prediction [10].

2.2. Development of small-diameter optical fiber sensors — Hitachi Cable

The first notable accomplishment in our university–industry collaboration was the development of small-diameter optical fibers (Fig. 4) and their application to FBG

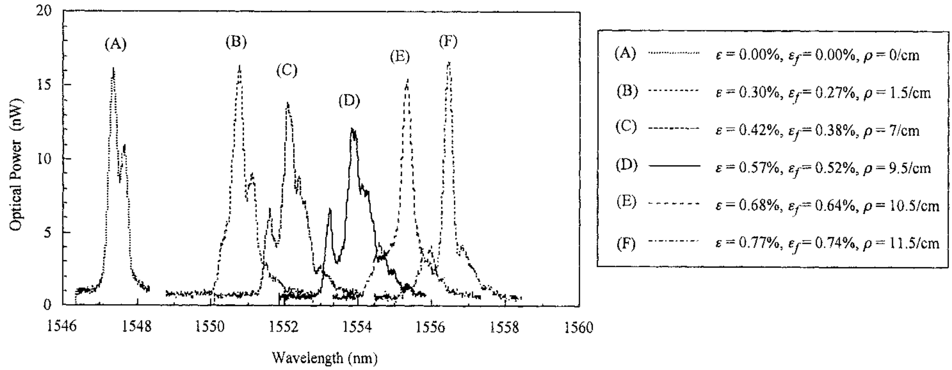

Figure 3. Reflection spectra at various tensile strains corresponding to (A)–(F) in Fig. 2.

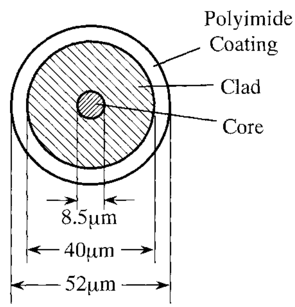

Figure 4. Small-diameter OFS.

sensors. The developed optical fiber is 40 μm in cladding diameter and 52 μm in polyimide coating diameter and can be easily embedded within one CFRP ply of 125 μm in thickness. Such optical fibers have mechanical properties similar to those of conventional optical fibers of 125 μm in cladding diameter and do not cause any reduction in the strength of composites when embedded parallel to reinforcing fibers in laminae [11]. The developed FBG sensors also have optical sensitivities similar to those of conventional 125 μm-cladding diameter FBG sensors. The polyimide coating is highly compatible with epoxy or other high-temperature polymer matrixes of CFRP composites under high-temperature exposure during fabrication and also in high-temperature use.

2.3. Identification of impact damage parameters in composites using embedded optical fiber sensors — Kawasaki Heavy Industries

The real-time detection of an impact load on composite laminates has been successfully achieved with embedded small-diameter optical fibers [12]. Figure 5 shows a small-diameter optical fiber embedded parallel to the reinforcing carbon fibers in $[0_2/90_2]_S$ cross-ply laminates. Instrumented Charpy impact tests were carried out and the optical loss during impact was recorded as a function of time simultaneously with the impact load and the surface strains measured by strain

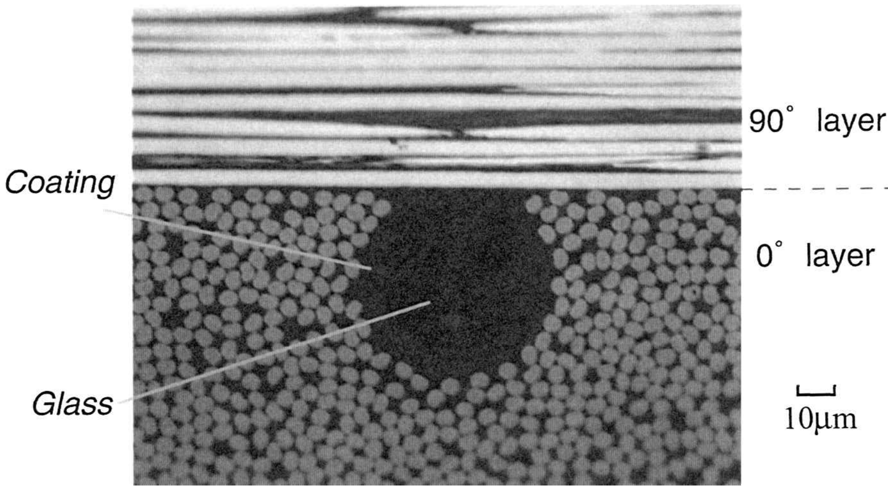

Figure 5. Small-diameter optical fiber embedded within a lamina.

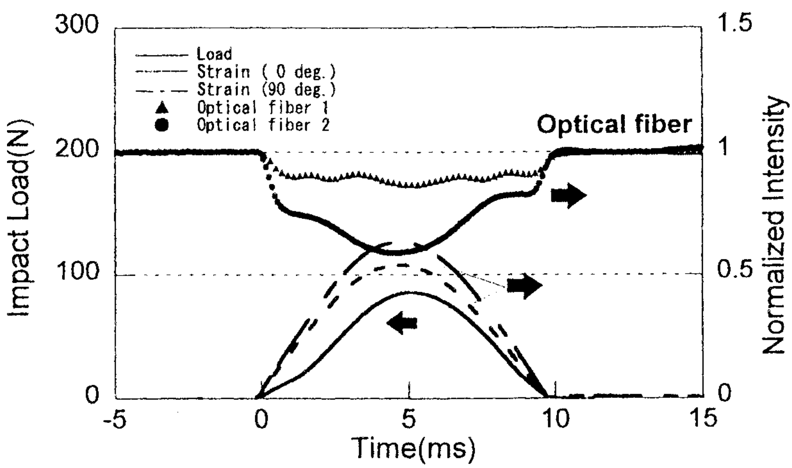

Figure 6. Impact responses of the normalized optical intensity, impact load, and specimen surface strains in $[0_2/90_2]_S$ cross-ply laminates.

gages (Fig. 6). The bending loss can be observed only during impact loading. The magnitude of the optical loss was found to be proportional to the magnitude of the impact load.

2.4. Strain and damage monitoring of CFRP space satellite structures using optical fiber sensors — Mitsubishi Electric

Honeycomb sandwich panels with thin CFRP face sheets are normally used as space satellite structures and are subjected to severe thermal and mechanical environmental conditions. Low-cost fabrication is a prime requirement for future satellites and a structural health-monitoring system is essential during fabrication

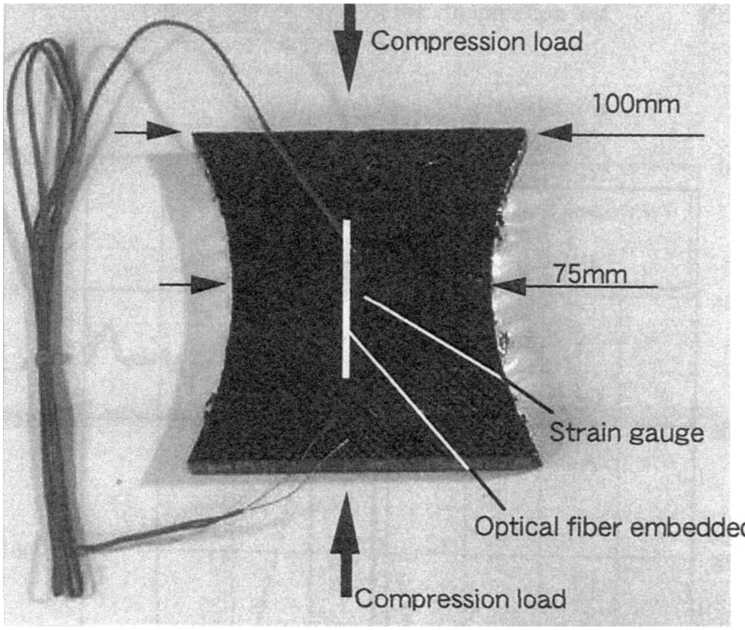

Figure 7. Compression test of a sandwich panel.

as well as in practical use [13]. Figure 7 shows a specimen for the simple compression test of a honeycomb sandwich panel where a small-diameter optical fiber is embedded within CFRP face sheets. The change in optical intensity can be an excellent indicator of compression failure in such structures, as shown in Fig. 8.

2.5. Damage suppression and control in CFRP laminates with embedded SMA foils — Fuji Heavy Industries

Shape memory alloy (SMA) foils are embedded and used to suppress and control microscopic damage, such as transverse cracks and delamination, in CFRP laminates [14]. The improvement of the interlaminar shear strength (ILSS) between SMA foils and CFRP laminae has been investigated using spattering, sol–gel, ion-plating, and anodic oxidation. A high ILSS was obtained similar to that of CFRP laminates alone. SMA foils were stretched into the phase transformation region. Then they were embedded in CFRP laminates with the deformation maintained by the fixture jig during the fabrication, in order to introduce the shrinking stress in 90° plies. Such shrinking stresses were found to suppress the evolution of transverse cracks in cross-ply laminates (Fig. 9).

2.6. Quantitative evaluation of the electric properties of CFGFRP hybrid composites as maximum strain memory sensors — Toray

The failure of low-elongation carbon fibers in CFGFRP hybrid composites under tensile loading causes an increase in electrical resistance and can be used to detect

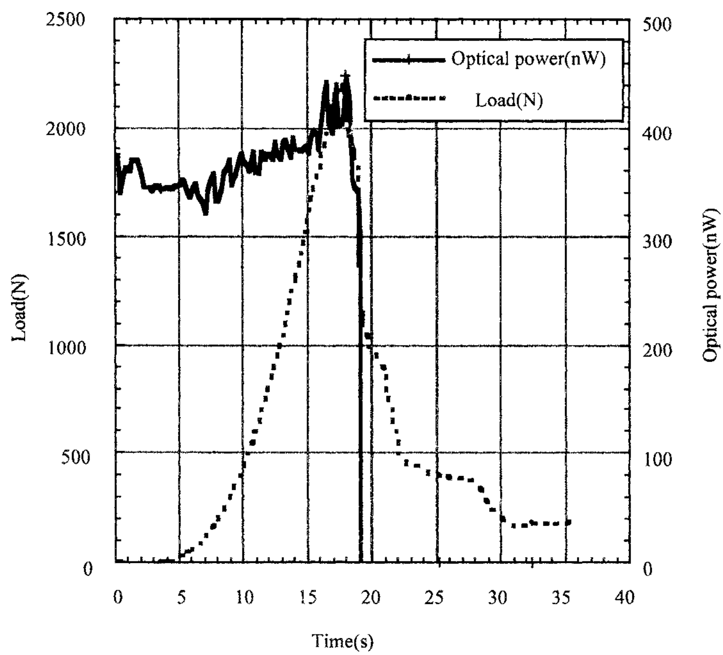

Figure 8. Optical power loss by compression failure.

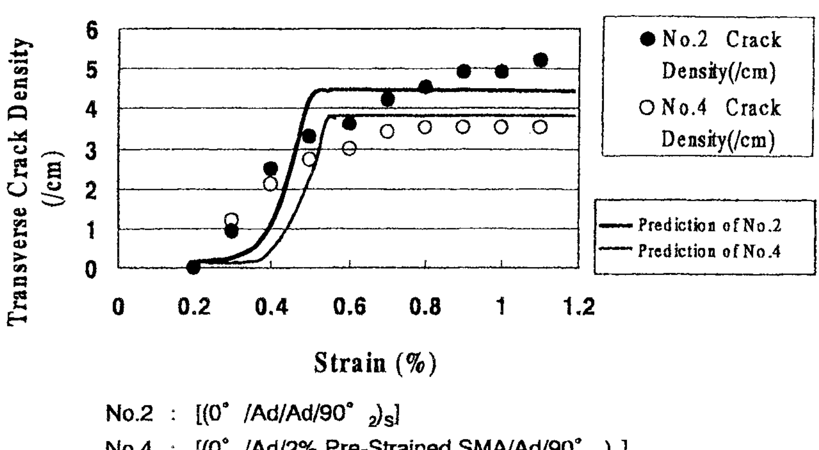

Figure 9. Transverse crack density as a function of the strain at room temperature for without (No. 2) and with (No. 4) embedded 2% pre-strained SMA foils.

the maximum strain applied to composites after unloading. A systematic study was conducted to evaluate quantitatively the relationship between fiber failures and electrical resistance [15]. Figure 10 shows the fiber failures observed in CFGFRP hybrid composites in tension. Based on such quantitative observations, a Monte Carlo simulation was conducted to predict the change in electrical resistance due to

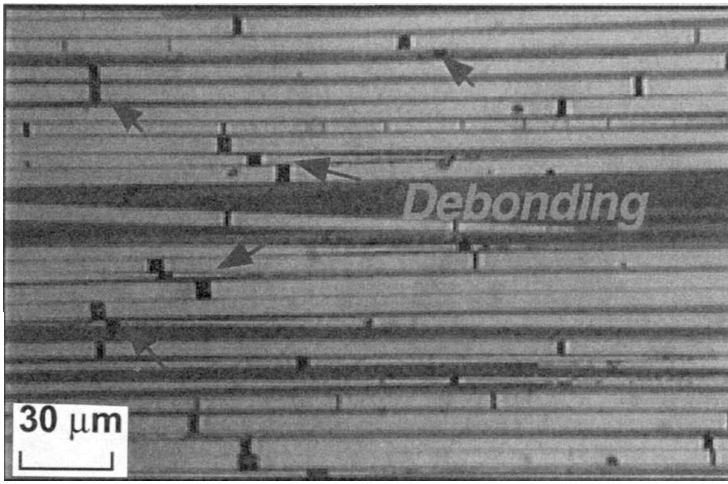

Figure 10. Fiber failure in CFGFRP hybrid composites.

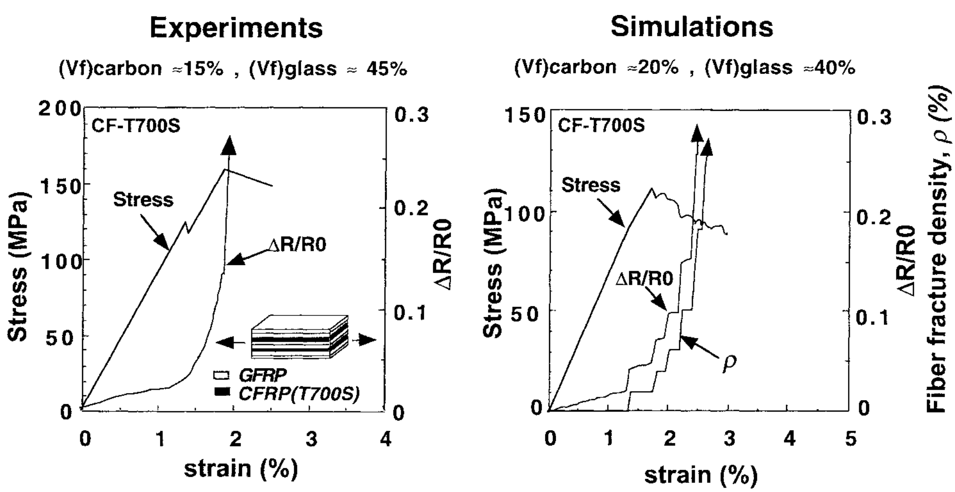

Figure 11. Comparison between experimental results and prediction.

tensile strain and fiber failures. As shown in Fig. 11, good agreement was obtained between the experimental results and the prediction.

2.7. Self-diagnosis function of electrically conductive FRP containing carbon particles — JFCC

Carbon particles or flakes were dispersed into the epoxy matrix to introduce a high electrical conductivity in glass fiber unidirectional or textile composites [16]. Compared with CFGFRP hybrid composites, a higher sensitivity could be obtained. Moreover, a linear resistance change due to tensile strain was achieved in a wider strain range, as shown in Fig. 12. The residual resistance after unloading

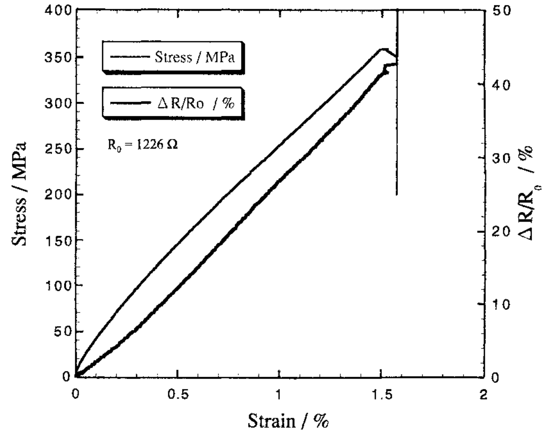

Figure 12. Electrical resistance and stress *vs.* strain.

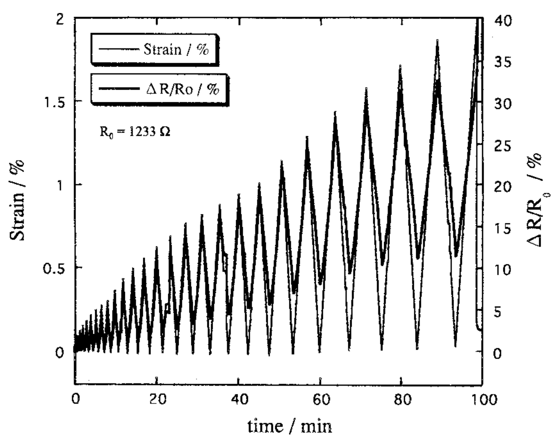

Figure 13. Maximum and residual resistance.

increased with increasing applied maximum strain (Fig. 13). This composite has an appropriate self-diagnosis function as a low-cost sensor to be embedded in concrete infrastructures.

2.8. Impact damage monitoring of composite structures using an integrated acoustic emission (AE) sensor network — Aerospatiale Matra

An integrated AE network system is being developed for practical industrial use in aircraft structures [17]. A learning-by-experience approach was developed to assess the AE behavior of a composite structure. The principle is to generate artificial AE events due to impact loading at several arbitrary points on the test specimen (Fig. 14). Recording the acquired waveform parameters enables the system to learn the structure. Then the system can receive real AE events upon impact in real time

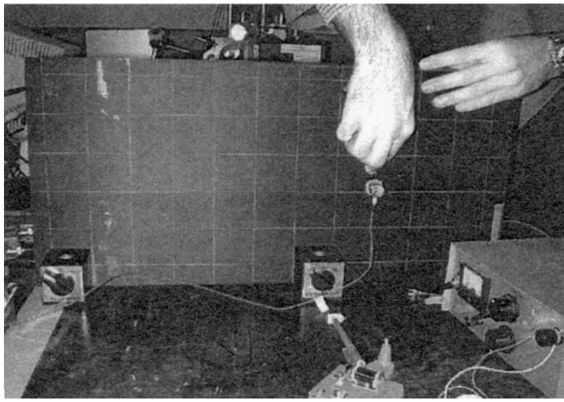

Figure 14. Specimen and AE event generator.

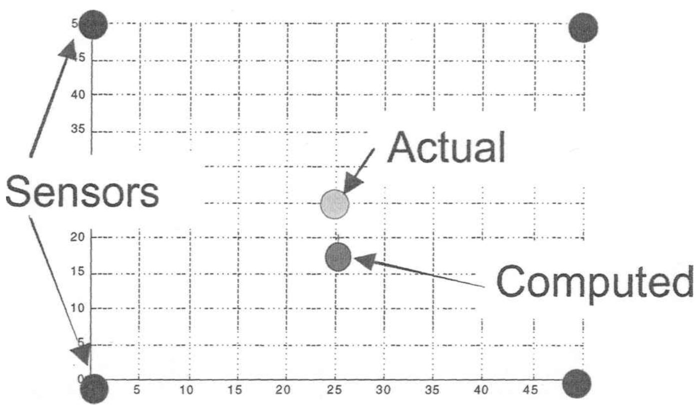

Figure 15. Interpolation and localization of impact.

in order to estimate the impact amplitude and to make an accurate localization of the source of impact (Fig. 15).

2.9. Other research themes

Due to lack of space, only titles are cited for three other research themes:

(1) *Integrated global and local strain measurement using distributed BOTDR (Brillouin Optical Time Domain Reflectometry) and FBG sensors — Mitsubishi Heavy Industries.* Improvement of spatial resolution, temperature compensation, and dynamic strain measurement are conducted. Integrated BOTDR and FBG strain measurement systems are being made for aerospace structures [18].

(2) *Damage detection of transparent composites using light transmission and reflection measurement for high-speed (Magrev) trains — Hitachi.* Damage such as transverse cracks, delamination, and fiber failures in semi-transparent alumina fiber-reinforced epoxy composites is detected using a light transmission

and reflection technique under severe electromagnetic and low-temperature conditions for load-supporting structures in Magrev trains [19].

(3) *Development of FBG sensor elements and real-time monitoring systems for large-scale infrastructures — Shimizu*. A multiplex FBG sensor element network system is established for the structural health monitoring of infrastructures. In particular, a real-time monitoring system is installed to record strains and deformations in hysterisis dampers for urban earthquake mitigation [20].

3. CONCLUSIONS

The latest results as of 1999 have been summarized in the structural health-monitoring project for smart composite structure systems in Japan. Some original accomplishments were made based on correlation studies on the sensor output and the underlying damage evolution in composites.

This research was conducted as part of the 'R & D for Smart Material / Structure System' Project within the Academic Institutions Centered Program supported by NEDO (New Energy and Industrial Technology Development Organization), Japan.

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