XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

STRUCTURAL HEALTH MONITORING FOR COMPOSITE STRUCTURES

Daniel L. Balageas
Serge Bourasseau
Marc Dupont
Michel Lemistre
Henri Kaczmarek
Daniel Osmont
Office National d'Etudes et de Recherches Aérospatiales
Damage and Solid Mechanics Department
BP 72
92322 Châtillon cedex, France

Abstract*. Structural health monitoring results from the integration into the structure of non destructive techniques. Health Monitoring Systems (HMS), built-in during the process in the case of composite structures, are able to give a diagnosis during all the life of the structure which becomes "smart" or "intelligent". After a discussion on the strategy for such systems, the existing sensing techniques which can be used, and a rapid overview of the possible solutions, illustrative examples are given based on the research under progress at Onera (French Agency for Aerospace Research).*

Key words: *Composite structure, Health monitoring system, Non destructive testing, Optical fiber sensors, piezoelectric transducers.*

1. INTRODUCTION

Due to their remarkable strength-to-weight ratios, structures made of composite materials are more and more used in aircraft industry. Nevertheless, their vulnerability to low velocity impacts, which can produce serious damages like delaminations and fiber or matrix cracking decreasing their strength or stiffness, is a serious problem which must be addressed, in particular because, often, these damages are not visible by surface inspection and their detection requires heavy classical Non Destructive Testing means like X-rays, ultrasonic C-scan, stimulated infrared thermography or tapping. For large structures, such NDT operations are time consuming and need to have the aircraft out of service, which is costly. In fact, aeronautical composite structures are calculated presently such that they can withstand all service loading even with impact damages, being designed with very conservative factors. Equipped with HMS they could be much lighter, taking full advantage of the remarkable properties of composites.

A possible solution could consist to integrate structural Health Monitoring Systems (HMS) inside the structure during its process. This type of system could permanently monitor the occurrence of damaging impacts or, from time to time, give a diagnosis concerning the possible damages occurred since the previous test or their evolution. The classical maintenance operations could be partially replaced by integrated NDT systems, automatic and controlled by the aircraft on-board computer (permanent monitoring) or by rapid inspection systems controlled by out-board computers.

The aim of this paper is to give a rapid overview of the HMS, which are presently objects of research and development for aerospace structures. Of course, HMS are envisaged for other types of structures, with particular issues which will not be tackled here. Readers interested by these problems can look at proceedings of specialized conferences on structural health monitoring or of more general conferences on smart structures and materials where all types of applications are presented (see list of proceedings at the end of the references). After a discussion concerning the various possible systems, a description of the more recent works in progress at Onera will be given as an illustration.

2. THE POSSIBLE WAYS TO MONITOR THE STRUCTURE HEALTH

Health monitoring of structures is performed using sensors either bonded on the structure surface or integrated inside the structure during its manufacturing. Generally, the structure is only considered as "smart" in the second case. Nevertheless, this is questionable. In fact, instrumented structure can be considered as a smart structure if the sensors are taken into account at the design stage, are permanently attached to the structure and considered as a part of it, and finally if the integrated system includes "intelligent" signal processing. The parameters to be monitored can be strain, vibration modes, acoustic emission (AE), ultrasonic wave propagation, electric properties, mechanical impedance, etc.

2.1. Surface mounted sensors versus embedded ones

As said before, the sensing devices can be either bonded on the structure surface or embedded. If the second solution has the advantage to offer a better protection to the sensors against environment, its drawbacks or difficulties are multiple:

- the presence of the sensor can decrease the mechanical strength of the structure,
- the reparability is more or less excluded,
- the connection with outside systems can be difficult in real complicated structures.

To prevent the first difficulty, mechanical tests of instrumented coupons and comparison to sound material are necessary whatever be the sensor type and the embedding technology. The second drawback is particularly severe since the sensor life must be at least as long as the structure life, which in turn is becoming longer and longer due to the cost saving politics applied in aeronautics. The remedy lay in adding extra sensors giving redundancy to the system. Finally, the connectics problem is important and can guide the choice of the type of sensors.

2.2. Optical Fiber Sensors (OFS) versus piezoelectric transducers

As regards the first drawback mentioned concerning embedded sensors, it is clear that the smaller the sensor, the weaker the effects on the structure strength. For that reason, since the beginning of research on smart structures, Optical Fiber Sensors (OFS) have been the objects of the major part of the works. A good review on OFS for composite structures can be found in the paper of R.M. Measures (1993). The advantages of OFS are numerous: very small size (of the order of the ply thickness), light weight, resistance to corrosion and fatigue, immunity to electrical interference, compatibility with composites.

The OFS are generally used as strain sensors, but others parameters can be measured: temperature, humidity, chemical species, etc. One of the main problems encountered with OFS is their concomitant sensitivity to strain and temperature. A large amount of work is still in progress on this question. Recent developments concern more complex OFS capable of measuring at the same time several parameters.

The fiber serves both as sensor and conduit for the signal. The fiber itself can be the sensor (distributed sensor) or several localized sensors (specially prepared parts of the fiber) can be multiplexed. Distributed sensors, for instance based on Optical Time Domain Reflectometry, OTDR, seem attractive, but in practice are neither robust (a single break in the fiber make a large portion of it out of work) nor economical (OTDR system with a centimetric resolution is very expensive). In the case of distributed OFS, the measurand is determined over a specific part of the fiber, making the OFS similar to a conventional strain gage. The strain is measured by affecting the light transmission (intensity, phase, polarization, modal distribution, or wavelength) in this part of the fiber, due to various possible interaction phenomena. To these different types of interactions correspond various types of OFS. In practice, only four types of OFS are used for strain and temperature monitoring in smart structures: Perot-Fabry, two-mode, polarimetric and Bragg grating sensors. Details on the principle and practical realizations can be found in Measures (1993) and all proceedings of general conferences on smart structures.

Piezoelectric sensors are of two types: ceramic and polymeric. In fact, the advantages of the second type (polyvinylidene fluoride or PVDF), which are low cost, low mass, wideband frequency, and high internal damping, are counterbalanced by a major drawback that impedes to use them in composite structures and is the fact that they have a temperature stability lower than the curing temperature of most of composite materials. The most commonly used piezoelectric ceramics are the PZT (Lead Zirconate Titanate). In sensors, the piezoelectricity is used to convert the strain into electric signal. One of the interests of this type of transducer, is its reversibility. The sensor can be used as an actuator too, giving possibilities of active health monitoring systems (see later).

Generally, the PZT sensors are shaped in discs of small thickness (of the order of some tenths of millimeter). The main drawbacks of this type of sensor are high mass, lack of flexibility and intrusivity, especially when compared to OFS. This explains why researchers were reluctant at the beginning to use them for HMS and preferred to use OFS. Nevertheless, for some years, the number of R & D works using PZT sensors is increasing. This can be explained by several reasons:

- they permit damage detection with high sensitivity, even with large-mesh networks,
- they are versatile since they can be used as shown later: i) in “passive” and “active” ways, ii) not only during the life of the structure, but also during the process of the material,
- it is now proved that, if they are correctly designed and embedded, they do not weaken the structure and can be used even with large deformation of the composite structure.

2.3. Damaging event monitoring versus damage monitoring

To monitor the structural health of composite structure two main strategies are possible: detection of the damaging event and detection of the damage itself. Here “detection” means: occurrence, localization, and severity evaluation. The first attitude needs a permanent monitoring, in flight and on the ground as well. For composite, the damaging events are essentially high-velocity impacts of atmospheric particles (hailstones and birds) and low-velocity impacts due to fall of tools during maintenance operations. The second alternative consist to check from time to time the structure health by comparing the preceding state registered during the previous check to the actual one. The advantage of the first solution is that the real-time diagnosis is possible permitting to take into account the structure modification instantaneously, for instance by modifying the flight conditions. This can be particularly useful for military aircraft, which are submitted to severe conditions.

The permanent monitoring only needs sensors. It is a “passive” method. A possible technique consists in detecting the acoustic emission associated with the impact (see Fig. 1 left). Piezoelectric sensors are well suited for this purpose (Tracy et al., 1996, Wölfinger et al., 1998, Dupont et al., 1999), but OFS, perhaps, could be used too, as shown by Blaha et al. (1993)

The second strategy can be either “passive” or “active”. In the first case, the sensor must be in the damaged region, registering permanent strains due to the damage. OFS are used for this purpose. The weakness of this “passive” technique lies in the fact that it needs a small mesh for the sensor network and consequently a high number of sensors. In the second case, stimulation is produced in view to induce a structural response, analyzed by the sensors. The stimulation can interest the full structure for modal or static analysis, or only a small region for acousto-ultrasonic excitation (see Fig. 1 right). Static loading could be analyzed by OFS as strain gages and modal stimulation either by OFS or piezoelectric sensors. The third possibility, the acousto-ultrasonic technique, is possible using piezoelectric transducers for both excitation and detection (Tracy et al., 1996, Moulin et al., 1997, Lemistre et al. 1999). The last technique has two advantages: the same transducers can be used alternatively as emitters and receivers, and the evaluation of the transmitted or reflected stress waves give information on the whole structure situated in between the emitter and the receiver. Due to attenuation generally low, the distance between them can be large (several tens of centimeters in carbon/epoxy laminates) without decreasing the sensitivity of the signal to the defect. This sensitivity is generally higher in the acousto-ultrasonic stimulation, since it is local, than in the full structure excitation techniques. The possibility of replacing piezoelectric transducers by OFS in such a technique is envisaged: OFS (Fabry-Perot and Bragg sensors) are able to detect ultrasonic waves, and it has been demonstrated recently that Lamb waves can be generated by laser ultrasonics driven by embedded optical fibers (Balageas, 1999).

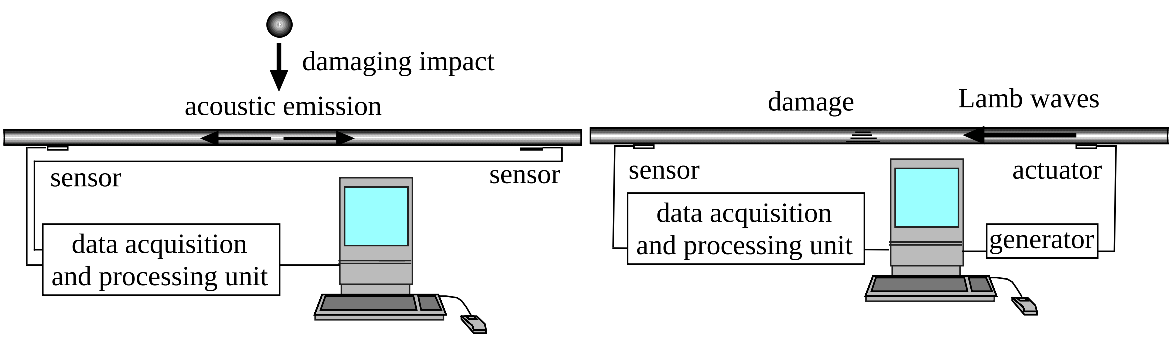


Figure 1: Possible use of a piezoelectric transducer network. *Left*: acoustic emission technique; *right*: acousto-ultrasonics, or Lamb waves based technique.

Table 1 sums up the possible uses of OFS and piezoelectric sensors in the active and passive techniques briefly described above. Table 2 presents the compared sensitivities of the various possible techniques, which can be used for structural health monitoring using OFS and/or piezoelectric sensors. This table is based on both Onera experience and on a paper by Boller et al. (1999).

Table 1: Possible passive and active techniques using OFS or piezoelectric sensors

Monitored phenomenon	Passive		Active	
	OFS	Piezo	OFS	Piezo
Damaging impact	possible, but not easy; few examples	well suited: acoustic emission technique; several examples		
Damage	possible, sensor must be in the damaged region		possible: static and modal stimulation	possible: modal stimulation or acousto-ultrasonic technique

Table 2: Compared sensitivities to damage of the HMS using OFS or piezoelectric sensors

Measurement principle	Sensors		damage sensitivity of the technique
	OFS	Piezo	
Strain measurement	possible, but not easy	not possible	locally sensitive: sensor must be in the damaged region
Modal analysis	possible	possible	more sensitive to crack than to delamination; in this case, delamination must be 10% of the sensed area
Acoustic emission	hardly possible	possible	sensitive even if the network mesh is large; needs sophisticated data reduction techniques
acousto-ultrasonic (Lamb waves analysis)	very hardly possible	possible	Sensitive, even if the network mesh is large; needs elaborate data reduction techniques

Finally, the fact that OFS and piezoelectric sensors can be used to monitor the process of the material too, has to be pointed out - see for instance Shen et al. (1996). OFS can measure strain and temperature, indicating when the cure is complete, and piezoelectric sensors can follow the evolution of the mechanical properties allowing the completion of the cure to be detected.

2.4. Other techniques

Although less used than the previously described techniques, the following ones must be mentioned:

- electric technique (resistivity measurement possible for carbon fiber composites),
- mechanical impedance, mainly used for process monitoring (Perrisin-Fabert et al. 1992, Clopêt et al. 1999),
- electromagnetic technique based on the analysis of the magnetic component of an electromagnetic field through the structure (work in progress at Onera).

3. EXAMPLE OF HMS FROM ONERA'S WORKS

3.1. Passive HMS using OFS for radome sandwich structure

Modern radomes for the subsonic or slightly supersonic range are generally made of composite sandwich structures that are particularly sensitive to accidental in-flight or/and on-the-ground impacts. Induced damage detection is a major matter of concern, since impact damage may lead to important degradation of the radome strength. The current NDE methods are not well suited for operational conditions. To overcome these drawbacks, an innovative way might be the use of integrated sensors systems, especially OFS. Such systems present a supplementary interest that it can be used during flight. Two damage detection systems integrated in a composite sandwich structure are in evaluation phase. Details can be found in (Bocherens, 1998). One is based on microbending sensitive fibers analyzed by Optical Time Domain Reflectometry (OTDR), while the other is based on Fiber Bragg Grating (FBG) sensors. For both techniques, the principle of the damage detection system is based on the hypothesis that damage induces permanent local strains into the material and therefore in the optical fiber sensor.

Figure 2 presents the way the fiber for OTDR analysis is installed inside a sandwich coupon of dimensions 150 mm x 150 mm. Typical localization results are presented after a 10 J impact. The OTDR signal is perturbed at several locations around the real impact and the center of gravity of these points is very near from the real impact point. The choice of the insertion level is critical and strongly dependent on the sandwich structure.

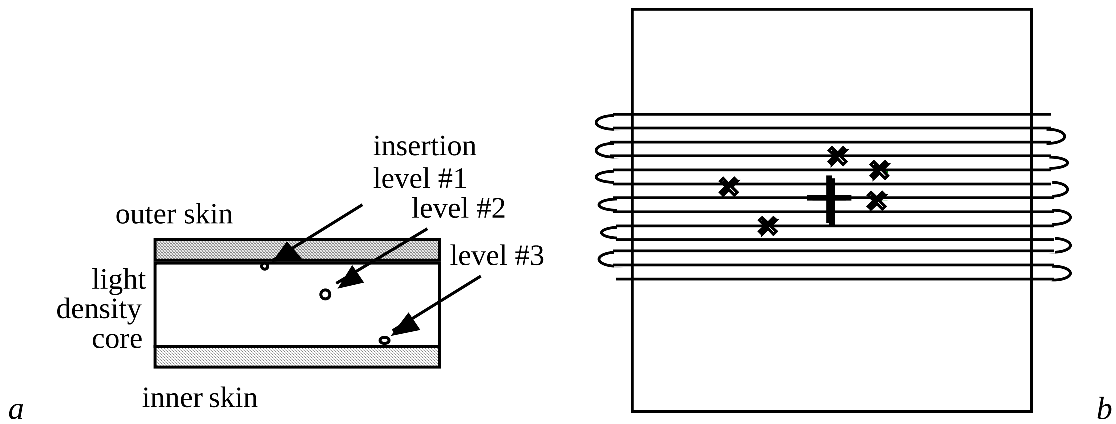


Figure 2: Coupon equipped with OTDR system: a) possible insertion levels for the fiber, b) fiber arrangement in the coupon, with the real 10 J impact site (+) and the defect locations derived from OTDR signals (x).

A coupon equipped with several Bragg gratings is presented in Fig. 3 to study the influence of the impact/sensor distance on the sensitivity of the OFS. Figure 4 presents the evolution with time of the OFS signal resulting from successive impacts. From the analysis of such signals and the knowledge of the relation between impact energy and area of the damage, it is possible to compare the detection range of the Bragg OFS and the actual damage mean radius. The same comparison is made with the OTDR experiments.

From these experiments it is concluded that both microbending sensitive fibers analyzed by OTDR and Fiber Bragg Grating are able to detect the damage only at a distance from the impact center not larger than the mean radius of this damaged area. Furthermore, for low values of the impact energy, the sensor detection curve decreases more rapidly than the damage radius, indicating that the detection at the damage threshold could be problematic.

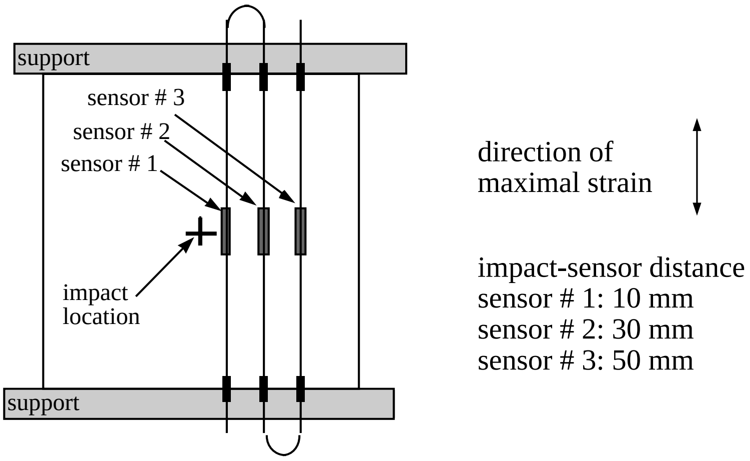


Figure 3: Integrated FBG sensor arrangement into a sandwich material coupon

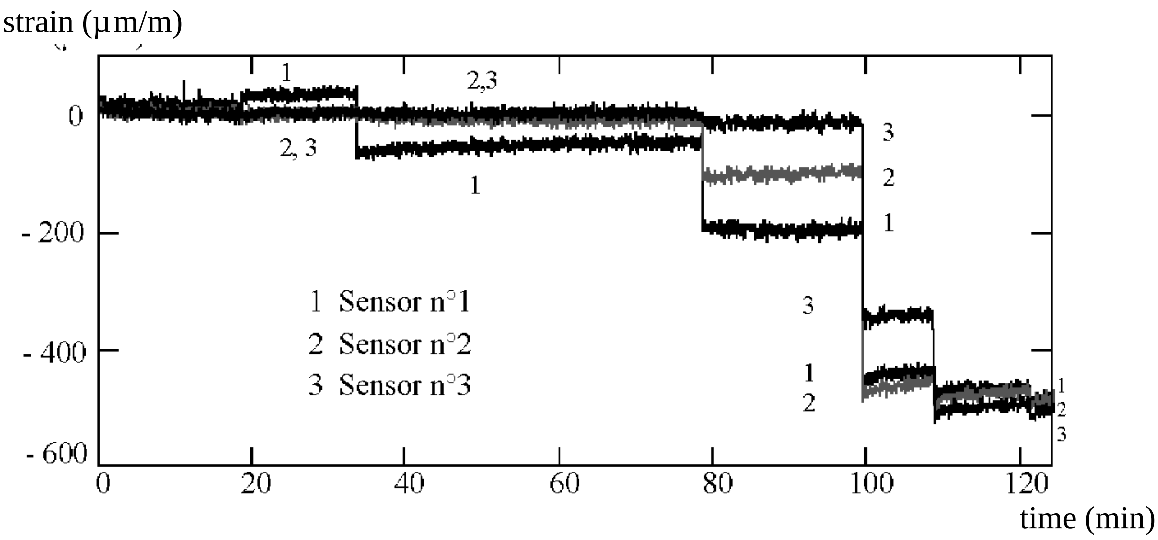


Figure 4: Strain measured by FBG sensors, resulting from successive impacts (E = 6, 8, 10, 12, 15, 18, and 20 J for respective values of time = 12, 18, 34, 78, 100, 108, and 122 min).

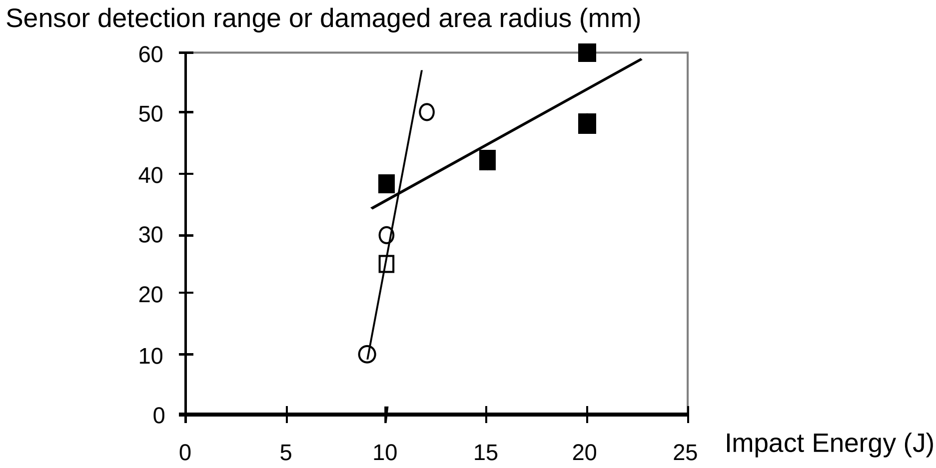


Figure 5: Comparison between OTDR (❑) and FBG sensors (❍) detection ranges to the best estimate of actual damaged area radius (◆).

3.2 Passive HMS for damaging impact detection in carbon/epoxy composite using acoustic emission (AE), from (Dupont et al., 1999).

Studies of low velocity impacts on carbon-epoxy plates lead to the following results: i) there is a threshold in the impact energy for damaging, which depends on the nature, lay-up, and thickness of the plate; ii) the damage generation is accompanied by a strong AE, mainly in a frequency range of several hundreds of kHz (see Fig. 6); iii) the high frequency waves generated during the damage creation propagate on long distances in carbon/epoxy structures.

From this, we can conclude that: i) the apparition of high frequencies in the impact signal delivered by a sensor attached to the structure is a means to discriminate between damaging and non-damaging impacts, ii) the comparison between high frequency acoustic signals received by the various sensors has the potential information allowing to localize the acoustic source (impact location) and to evaluate the extension or severity of the damage. Furthermore, since the attenuation is low, the so-defined health monitoring diagnosis can be used on a large structure equipped with piezoelectric transducers arranged in a large mesh network.

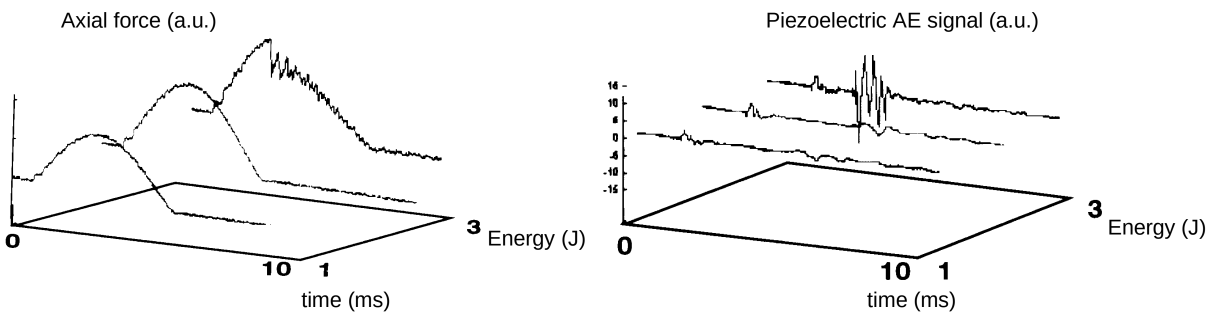


Figure 6: Damage threshold detection by piezoelectric transducers (high frequency vibrations apparition) correlated with the shape change of the force on the impactor head.

Attempts to use the differences between the arrival times of the signal at the piezoelectric transducers have been made. The signals are difficult to interpret, since several propagation modes are excited at the same time, and their velocities are depending on the direction of propagation. This is true even for quasi-isotropic composites when the frequency range interested by the measurement is relatively high (higher than 100 kHz) - present case. Thus, a precise localization of arrival times needs the knowledge of the direction and frequency dependency of the velocities and makes the localization algorithm complicated.

The present analysis use a unique parameter to establish the full diagnosis (occurrence, localization and severity of damage): the high-frequency root mean square value of the electric signal registered by the piezoelectric sensors: $<s> = [(1/T) \int_0^T s^2 \, dt]^{1/2}$.

In this expression, t is the time and s is the electric signal integrated upon a frequency band to be chosen. It can be considered as a severity factor. A non-null severity factor registered by one of the transducers allows detecting the damage threshold overshoot.

The procedure used allows to identify the amplitude A_S and the coordinates (x_S, y_S) of the source, by minimizing the function which measures the discrepancy between all measured displacements $<u_i> = <s_i>/\tau_i$ and the corresponding displacements that would be generated by a point source located at the impact point, $<u_{S,Di}>$. Here τ_i is the transfer function of sensor i.

In the present work, the simplest case, corresponding to the minimization of $\Sigma_i (<u_{S,Di}> - <s_i>/\tau_i)^2$, is considered and the transfer function τ_i is uncalibrated. The only unknowns to identify are the coordinates of the impact (x_S, y_S). They are depending on two parameters ξ and λ, ξ being the attenuation for a propagation distance equal to the wavelength λ. For each set of registered signals, several localizations are calculated, each one corresponding to a pair of values of ξ and λ. The parameter ξ is varied between 0.001 and 0.01. The wavelength, $\lambda = c/f$, is deduced from an assumed velocity c for a frequency f = 500 kHz, mean value of the frequency domain in which the signals are integrated [400 kHz - 600 kHz]. The velocity is supposed to be that of the A_0 or S_0 modes.

Each coupon (500 mm × 500 mm) is equipped with four piezoelectric transducers located at a distance of 6.5 cm from the edge On Fig. 7, the coupon is larger and equipped with more transducers to compare AE technique et acousto-ultrasonic method (see later). Figure 8 present the localization results. The accuracy is good: ± 38 mm, a distance to be compared to the damage size, ranging from 20 to 70 mm.

The simplicity of the algorithms must allow integrating easily the data reduction and storage of the diagnosis in a miniaturized electronic device attached to the structure (next step of the research).

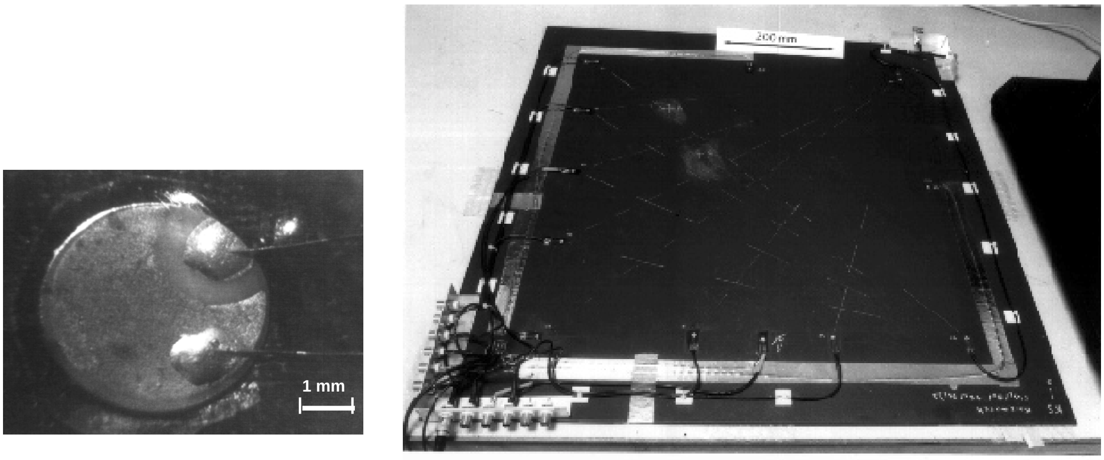


Figure 7: C/epoxy plate (700 mm × 700 mm) – *right* -, instrumented with miniaturized piezoelectric sensors - *left* -.

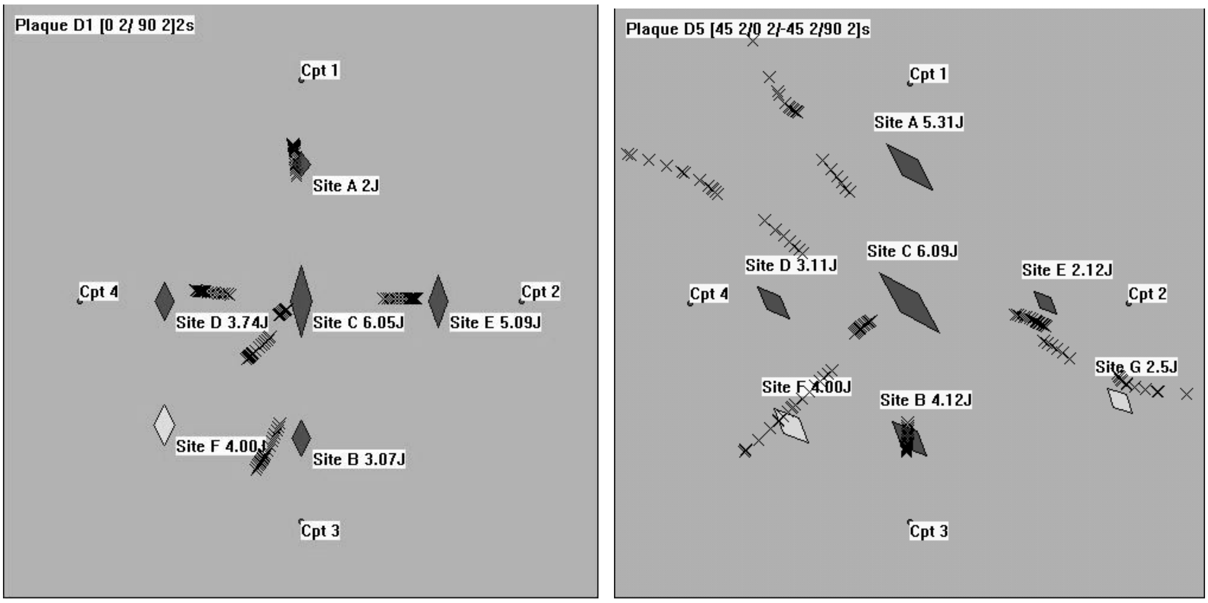


Figure 8: Localization of impacts calculated from piezoelectric sensor signals for different values of the parameters ξ and λ (x) in the case of coupons D1 (cross-ply) and D5 (quasi-isotropic), made of composite T300-914 C-epoxy, with dimensions: 500 x 500 x 2 mm.

3.2. Active HMS for damage detection in carbon/epoxy composite using acousto-ultrasonic technique

The transducers used for the acoustic emission detection of damaging impacts presented in Fig. 7 can be used as a wave generator too. This is demonstrated by visualizing the Lamb waves generated by a similar transducer embedded inside a C/epoxy laminate plate using a speckle interferometric technique called "shearography" (Krapez et al., 1999). Figure 9 shows how the visualization is achieved and presents an image of the out-of-plane displacements associated with the propagation of the *So* mode generated by the disc-shaped transducer (100 µm-thick, 5 mm-dia.). The same transducers are employed for AE and acousto-ultrasonic testing since the same range of frequency is used.

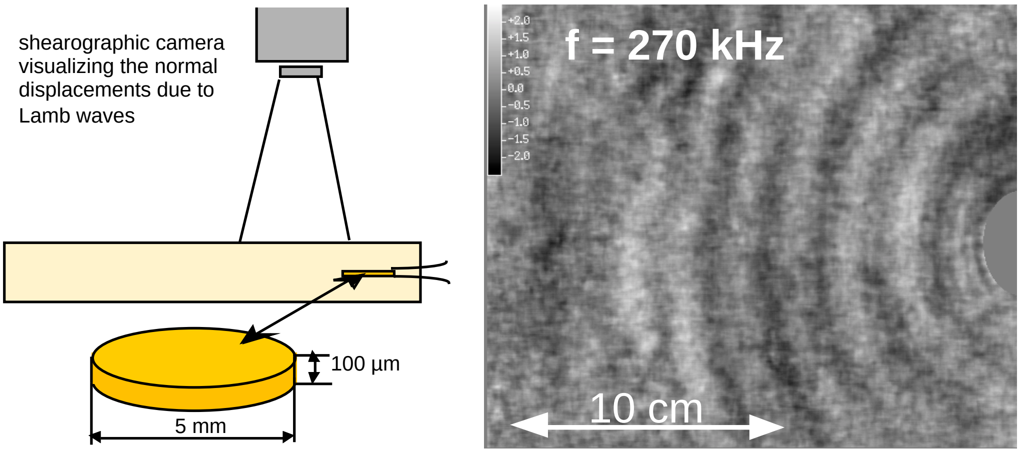


Figure 9: Visualization of the Lamb waves generated by a disc-shaped piezoelectric transducer embedded in a C/epoxy composite.

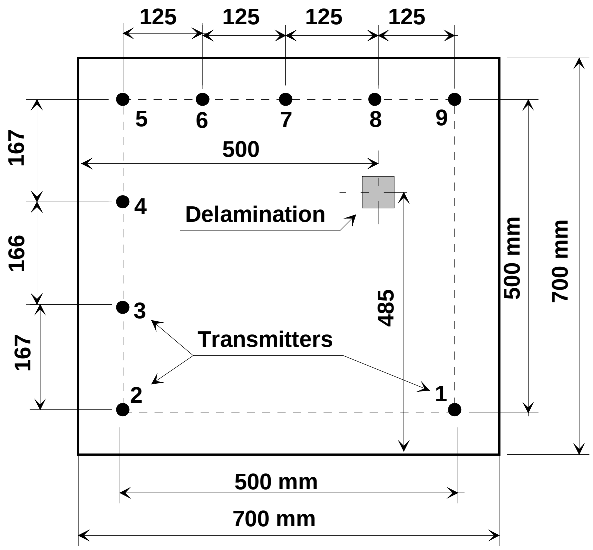
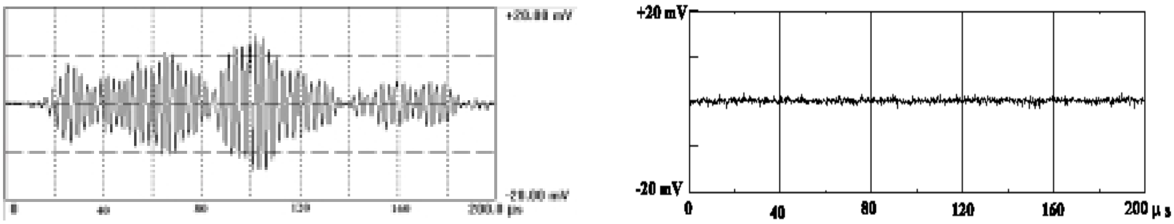


Figure 10: Experimental arrangement for acousto-ultrasonic detection

Figure 10 presents the transducer arrangement on the plate of Fig. 7. The material is a 16 plies C/epoxy $[45_2, 0_2, 45_2, 90_2]_s$, of dimensions: 700 mm x 700 mm x 2 mm. Nine piezoelectric disc-shaped transducers (diameter 5 mm, thickness 0.5 mm) have been stuck on the plate, three of them being used as emitters (1, 2 and 3), the others as receivers. A delamination of about 2 cm x 2 cm has been generated by a 4 J impact. The analysis used the symmetric fundamental mode *So* at 365 kHz.

Nine propagation paths have been analyzed (three paths for each emitter: 1-5, 1-6, 1-7, 2-6, 2-7, 2-8, and 3-6, 3-7, 3-8), with and without delamination. The signals emitted by transducers 1, 2 or 3 are bursts of 10 periods, modulated by a square window, at a repetition rate of 10 ms. Figure 11a shows the algebraic difference between the signal for a given path after impact and the reference signal received before impact. This difference is only noise when considering two successive reference signals (see Fig. 11b). Although being ten times smaller than the original signal, the algebraic difference is significant of the damage presence.

It is assumed that the damage is a diffracting object, which can generate different propagation modes, each one having a characteristic velocity of propagation. The calculated and experimental dispersion curves of figure 12 show that only three modes exist in the frequency domain below 400 kHz. For 365 kHz, these three modes are *So*, fundamental symmetric mode (phase velocity: 6 km/s), *S'o*, shearing mode (phase velocity: 3.5 km/s) and A_0, fundamental antisymmetric mode (phase velocity: 1.5 km/s).



(a) (b)

Figures 11: (a) Algebraic difference between signal obtained with damage and reference (no damage); (b) Difference between two reference signal

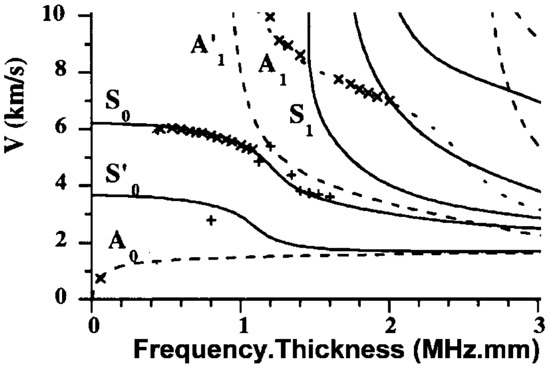


Figure 12: Dispersion diagram of a quasi-isotropic material

Relationship (1), where D_0 is the distance between emitter and receiver, d_1 the distance between emitter and damage, d_2 the distance between damage and receiver, V_0 the velocity of the S_0 mode (6 km/s), V_1 the velocity of S_0, S'_0 or A_0 modes (6 km/s, 3.5 km/s or 1.5 km/s),

$$t_d = d_1 / V_0 + d_2 / V_1 - D_0 / V_0 \qquad (1)$$

gives the time delay t_d between the reception of the fundamental mode S_0, by the direct path (D_0 with V_0) and of another mode (S_0, S'_0 or A_0) by the second path (d_1 with V_0 followed by d_2 with V_1), for each propagation path and for each emitter. Table 1 gives the values of t_d for S_0, S'_0 and A_0 modes with three propagation paths, for the three emitters.

Table 3: Calculated time delay for each mode (three propagation paths for each emitter)

Path	1/7	1/6	1/5	2/8	2/7	2/6	3/8	3/7	3/6
t_d (µs) for mode S_0	4	12	17	8	30	56	12	38	66
t_d (µs) for mode S'_0	27	47	67	22	53	92	26	60	102
t_d (µs) for mode A_0	100	160	226	67	125	205	71	132	215

The simple echo of the S_0 mode on the damage is unexploitable because the time delay is, in several propagation paths, lower than time duration of the emitted burst which is about 25 µs (see Table I). On the contrary, the time delay obtained with the A_0 mode is often greater than the time window of the signal which is 200 µs. Only the signal due to the shearing mode S'_0 can give easily exploitable data.

Figure 13 shows a time-frequency diagram performed by continuous wavelet transform CWT (complex Morlet function) on the algebraic difference between the signal obtained with damage and the reference in the case of the propagation path 2-7. Grey scale gives the normalized magnitude in dB (0, -20). The first burst arrives at 35 µs and gives the t_0. The second one arrives at 90 µs, corresponding to a time delay t_d $(t_1 - t_0)$ = 55 µs. It corresponds probably to the S'_0 mode (see Table 3).

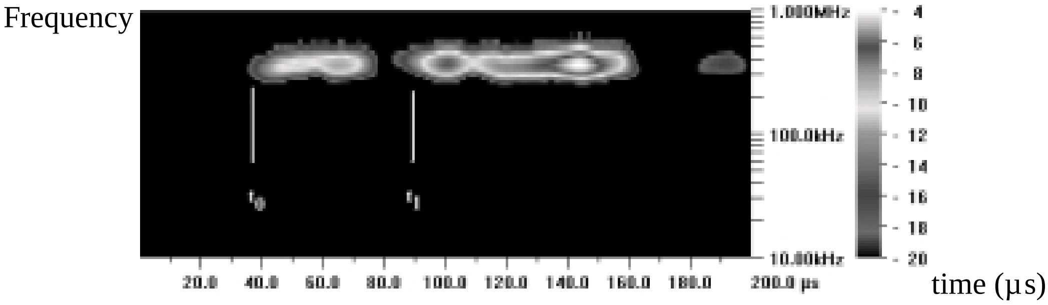


Figure 13: Time-frequency diagram of the differential signal for propagation path 2-7.

To isolate the characteristic signal due to S'_0 mode from the received signal, in order to determine the time delay with more accuracy, DWT (Discrete Wavelet Transform) has been used. The same process applied to each propagation path gives good results. It is possible to isolate the shearing mode S'_0, in each case. So, it is possible to determine the time delay t_d between the beginning of the signal and the appearance of the S'_0 mode, for each propagation path, in order to calculate the defect location.

There is one Eq. (1) per propagation path, three equations by emitter. The resolution two by two of the three equations related to the same emitter, gives nine systems of two equations (three by emitter). The result of this calculation is shown in Figure 14, where the crosses (X) show the locations given by emitter 1 (paths: 1-7, 1-6, 1-5), the boxes ( ) by emitter 2 (paths: 2-8, 2-7, 2-6), the circles (O) by emitter 3 (paths: 3-8, 3-7, 3-6). The presence of damage is estimated in an area about 75 cm^2 (15 cm X 5 cm) around the delamination (2 cm X 2 cm). The center of gravity of the so-identified impact location is distant from 2.6 cm from the actual impact site.

For data reduction, wavelet transform providing a time position of each frequency component included in the signal spectrum is a very helpful tool. Applied to Lamb wave signals, this process allows to extract a particular mode generated by a diffracting object such as a delamination. In this case, the shearing mode *S'o* has been identified and isolated and the damage has been localized with a good accuracy.

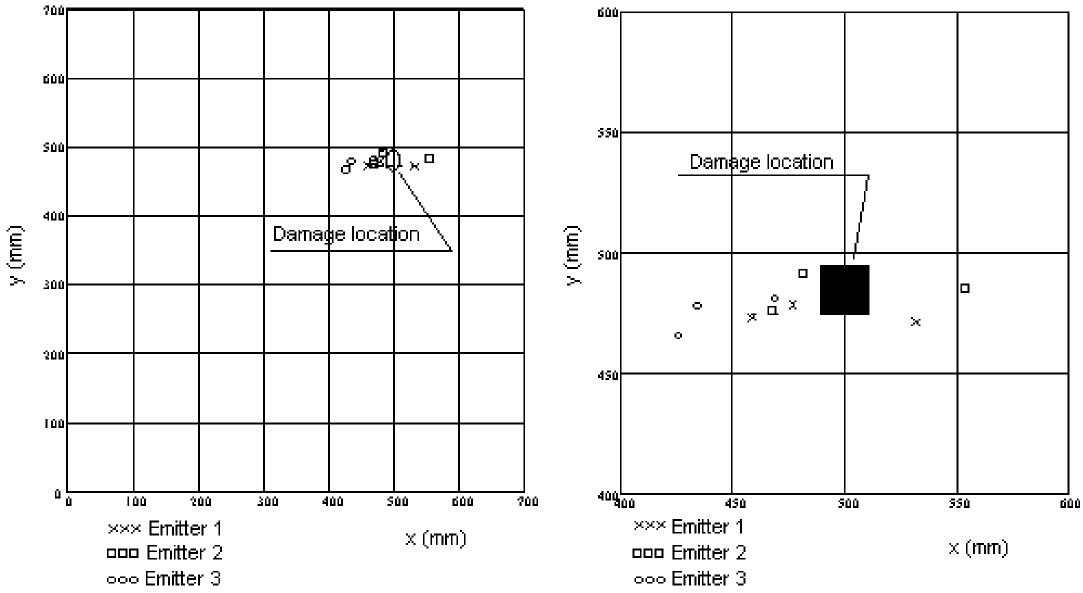


Figure 14: Damage localization resulting from the wavelet transform analysis.

4. CONCLUSIONS

The aim of this rapid overview was to show the wide variety of the techniques presently evaluated for structural health monitoring systems, which could be integrated in composite structures in a near future. The examples, taken from the experience of Onera, are presented for illustrative purpose. They are just focused on the detection and localization of the damaging event or of the damage itself. The accuracy of the localization is good, especially with the acousto-ultrasonic technique. Developments are in progress to give information on the nature and extension of the damages.

REFERENCES

Balageas, D., Jaroslavsky, N., Lepoutre F. and Krapez, J.-C., 1999, Laser generated Lamb waves using embedded fibre optic delivery system, Review of Progress in Quantitative Non destructive Evaluation (QNDE), July 19-24, 1998, Snowbird, Utah, USA, vol. 18 B, pp. 1963-1969.

Blaha, F.A. & McBride, S.L., 1993, Fiber-optic sensor systems for measuring strain and the detection of acoustic emission in smart structures, Proceedings of the 75th Meeting of the AGARD Structures and Materials Panel, October 7, 1992, Lindau, Germany, AGARD-CP-531, pp. 21.1-21.11.

Bocherens, E., Bourasseau, S., Dewynter-Marty, V., Dupont, M., Ferdinand, P. and Berenger, H., 1998, Damage detection in a radome sandwich material with integrated fiber optic sensor, Proceedings of the 4th International Conference on Smart Structures and Materials, 6-8 July, Harrogate, U.K.

Boller, C., Biemans, C., Staszewski, W.J., Worden, K. and Tomlinson, G.R., 1999, Structural damage monitoring based on an actuator-sensor system, Proceedings of the Smart

Structures and Integrated Systems SPIE Conference, March 1-4, 1999, Newport-Beach, California, USA, ed. N.M. Wereley, SPIE Proceedings Series, vol. 3668, pp. 285-294.

Clopêt, C.R., Pullen, D.A., Badcock R.A., Ralph B., Fernando, G.F. and MahonS.W., 1999, Mechanical impedance measurements for improved cost effective process monitoring, ibidem, pp. 665-673.

Dupont, M., Osmont, D., Gouyon, R. and Balageas, D.L., 1999, Permanent monitoring of damaging impacts by a piezoelectric sensor based integrated system, Proceedings of the Second International Workshop on Structural Health Monitoring, September 7-10, 1999, Stanford, California, USA.

Krapez, J.-C., Taillade, F., Lamarque, T. and Balageas, D.L., 1999, Shearography as a tool for imaging Lamb waves in composites and their interaction with delaminations, Progress in Quantitative Non destructive Evaluation (QNDE), July 19-24 1998, Snowbird, Utah, USA, vol. 18 A, pp. 905-912.

Lemistre, M., Gouyon, R., Kaczmarek, H. and Balageas, D.L., 1999, Damage localization in composite plates using wavelet transform processing on Lamb wave signals, Proceedings of the Second International Workshop on Structural Health Monitoring, September 7-10, 1999, Stanford, California, USA

Measures, R.M., 1993, Fiber optic sensing for composite smart structures, Proceedings of the 75^{th} Meeting of the AGARD structures and materials Panel, October 7, 1992, Lindau, Germany, AGARD-CP-531, pp. 11.1-11.43.

Moulin, E., Assaad, J., Delebarre, C., Kaczmarek, H. and Balageas, D.L., 1997, Piezoelectric transducer embedded in a composite plate: Application to Lamb wave generation, Journal of Applied Physics, vol. 82, n. 5, pp. 2049-2055.

Perrisin-Fabert, I., Feve, M., Jayet, Y. and Merle, G., 1992, Monitoring thermoset polymerisation by using piezoelectric measurements, Journal Applied Polymer Science, vol. 46, pp. 1087-1093.

Shen B.S., Tracy, M., Roh, Y.S. and Chang, F.K., 1996, Built-in piezoelectrics for processing and health monitoring of composite structures, AIAA-96-1310-CP, pp. 390-397.

Tracy M., Roh, Y.S. and Chang, F.K., 1996, Impact damage diagnostics for composite structures using built-in sensors and actuators, Proceedings of the Third ICIM/ECSSM'96, Lyon, France, June 3-5 1996, pp. 118-123.

Wölfinger C., Arendts, F.J., Friedrich, K. and Drechsler, K., 1998, Health-monitoring-system based on piezoelectric transducers, Aerospace Science and Technology, vol. 2, n. 6, pp. 391-400.

Proceedings of the main recent conferences on HMS

Proceedings of the Third ICIM/ECSSM'96, Lyon, France, June 3-5 1996, ed. Gobin P.-F. and Tatibouët, J., SPIE Proceedings Series, vol. 2779, 1996..

Structural Health Monitoring, Current status and Perspectives, Proceedings of the First International Workshop on Structural Health Monitoring, September 18-20, 1997, Stanford, California, USA, ed. F-K. Chang, Technomic Publ. Co., Lancaster, Basel, 1997.

Proceedings of the 4th International Conference on Smart Structures and Materials, Harrogate, U.K. July 6-8, 1998, ed. Culshaw, B.

Proceedings of the 5th International Symposium on Smart Structures, San Diego, California, USA, March 1-5, 1998, SPIE Proceedings series, vol. 3329, SPIE, Bellingham, Washington, USA, 1999.

Proceedings of the Smart Structures and Integrated Systems SPIE Conference, March 1-4, 1999, Newport-Beach, California, USA, ed. N.M. Wereley, SPIE Proceedings Series, vol. 3668, SPIE, Bellingham, Washington, USA, 1999.

Smart Structures and Integrated Systems, Proceedings of the Smart structures and Materials SPIA Conference, March 1-4, 1999, Newport-Beach, california, USA, ed. N.M. Wereley, SPIE Proceedings Series, vol. 3668, SPIE, Bellingham, Washington, USA, 1999.

Proceedings of the Second International Workshop on Structural Health Monitoring, September 8-10, 1999, Stanford, California, USA, ed. F-K. Chang, Technomic Publ. Co., Lancaster, Basel, 1999.