Structural Health Monitoring of a Smart Composite Bridge Using Guided Waves and Acoustic Emission Techniques

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STRUCTURAL HEALTH MONITORING OF A SMART COMPOSITE BRIDGE USING GUIDED WAVES AND ACOUSTIC EMISSION TECHNIQUES

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ABSTRACT

This paper is dealing with the development of a structural health monitoring (SHM) system implemented on a composite footbridge during the regional project "Pays de la Loire" called DECID2. The SHM system was made out of complementary techniques: strain sensors based on optical fibers (out of concern in this present work) and ultrasonic techniques that are presented in this document. Due to the huge size of the composite bridge (20 m * 3 m), only its most critical areas are monitored as the assembling parts and the most solicited areas. To access the structural integrity of the footbridge, two complementary monitoring strategies were presented in this paper:
- a real-time acoustic emission monitoring system to detect fibre breaks,…
- and a monitoring system using guided waves to evaluate the resin degradation.
Both of these SHM systems use the same miniature ultrasonic patches that are used alternately as acoustic emission sensors and as ultrasonic guided waves actuators. The first step of this work was to develop these patches, and then to set up each monitoring systems and characterize their damage sensitivity. Finally, two composite footbridges were built at the EMC2 Technocampus and IFSTTAR in France to serve as demonstrators.

KEYWORDS : *Structural Health Monitoring, Acoustic emission, Guided waves, composite footbridge.*

1 INTRODUCTION

In recent years, advances in composite development and manufacturing have contributed to emerge fiber reinforced polymers (FRPs) as a practical material for structural engineering applications [1]. By offering a number of advantages over steel (non-corrosive, high strength and lightweight), FRP are gradually replacing conventional steel reinforcement and rapidly gaining recognition by taking a prominent place in civil engineering. Moreover, much research on the use of pultruded structural shapes for civil engineering applications have shown the undeniable potential for the use of Glass-fiber reinforced polymer (GFRP) [2].

Composite bridge may deteriorate due to overloads or changing load patterns which are far from being predictable easily. The lack of sufficient maintenance and defects evolution between two periodic inspections can bring catastrophic consequences. To overcome these limitations and master the durability and reliability in service, civil structure may to be equipped with Structural Health Monitoring (SHM) systems. Various monitoring strategies were proposed in the literature such as Acoustic Emission (AE) [3-4], optical fibre [5-6] or guided wave (GW) [7] which has been proven to be viable SHM techniques. The employment of these three techniques together is very effective as they are complementary.

This paper is dealing with the development of a structural health monitoring (SHM) system implemented on a composite footbridge. Due to the huge size of the composite bridge (20 m * 3 m), only its most critical areas are monitored as the assembling parts and the most solicited areas. To access the structural integrity of the footbridge, two complementary monitoring strategies were discussed in this paper:

- a real-time acoustic emission monitoring system to detect fibre breaks,…
- and a monitoring system using guided waves to evaluate the resin degradation.

Both of these SHM systems use the same miniature ultrasonic patches that are used alternately as acoustic emission sensors and as ultrasonic guided waves actuators. The first step of this work was to develop these miniaturized ultrasonic patches. Then, the setup of each system was determined and their sensitivity to damage was characterized. Finally, two composite footbridges were built and instrumented with the developed SHM systems.

2 MATERIALS OF THE COMPOSITE FOOTBRIDGES

The material under study is a pultruded composite material made with continuous glass fibers and a vinylester resin as matrix. The fiber volume fraction is 66% [6]. Test specimens were manufactured from rectangular shaped profiles (section dimensions: 16mm x 40mm). They were diamond saw-cut and the dimensions of the specimens were 320mmx40mmx16mm. These dimensions follow the recommendations of the EN ISO 178 standards. The distribution of fibers in terms of positions and diameters are inhomogeneous (Figure 1). One may also note that fibers are not perfectly straight. Some fibers intersect the image plane and others make an angle with the main direction (Pultrusion's direction). Finally, some porosity and additives are observed in the microstructure.

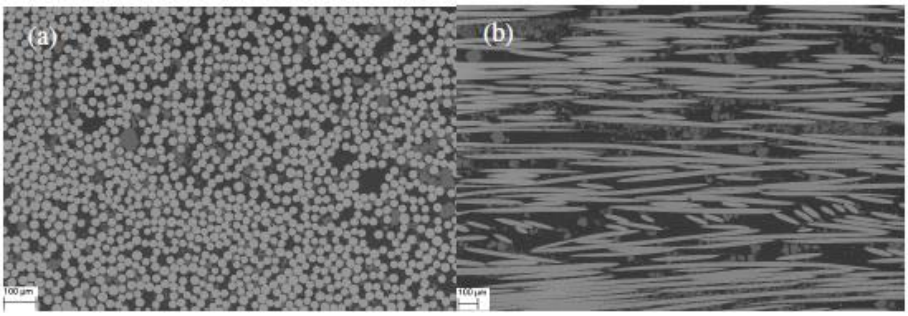

Figure 1: SEM microstructure observation.

3 MINIATURIZED ULTRASONIC SENSORS

3.1 Sensor design

Both of these SHM systems use the same miniature ultrasonic patches that are used alternately as acoustic emission sensors and as ultrasonic guided waves actuators. The first step of this work was to develop these miniaturized ultrasonic patches. The ultrasonic sensor which was chosen for this work is a piezoelectric thin disc with 200 µm thickness and 20 mm diameter. It was coated with two electrodes to get ease of welding to the upper surface. This patch is directly bonded to the pultruded surface with environment-resistant glue. The glue has been tested previously in immersion test for one month at 40°C and showed good aging resistance in terms of mechanical strength and acoustic coupling. The connector includes a coaxial environment resistant "BNC cable" welded directly to the patch upper surface. To protect patch and welds, two different coating are used: an epoxy resin for the mechanical protection and polyurethane clear coats to ensure UV and water resistance. Patches (Figure 2) qualification required several tests to evaluate its resistance to hygro-thermal aging, sensitivity and durability.

Figure 2: Miniature ultrasonic patches

3.2 Sensitivity and durability of miniaturized sensors

Sensitivity are evaluated with Hsu-Nielsen source (leads break 2H03) at 5 cm distance from patches (after coating). Amplitude measured is about 72 dBae which is less than value obtained for standard AE sensors (90 dBae). Patch sensors background noise are also compared to standard sensors and was evaluated to 10 dBae in the case of both sensors. Through the measurements of these two parameters, it was concluded that theses patches can be used as acoustic emission sensors although they are less sensitive to damage detection than their conventional counterparts. It will remain thereafter to determine the level of sensitivity of theses patches to damage detection in pultruded profiles which will allow the deduction of their spacing in the final structure.

To avoid patch hygrothermal ageing, clear coating polyurethane was used to protect patches and resin layer against moisture. In order to validate this coating, an immersion test was performed at 40°C during one month. This polyurethane coating showed good ability to protection against moisture and hygrothermal aging.

The influence of severe weather like cold and frost on the patches and instrumentation performances was also supported. Safe operability of patches and preamplifiers was verified by inserting them into a freezer at -18°C. Sensitivity measurement tests before and after exposure confirm that preamplifiers and patches remain operational during the cold. Thus, it was concluded that low temperature does not deteriorate the patches protection and their performance.

The mechanical strength of patches depends on the piezoelectric ceramic disc and its welds because they are the limiting factors in terms of shock-resistance, knowing that the bonded interface will face fatigue phenomena. Mechanical durability is therefore evaluated by fatigue bending tests performed on pultruded composite bars (vinylester matrix and glass-fibers) that were instrumented by two ultrasonic patches. The fatigue cycle was conducted at a constant amplitude triangular waveform with a frequency of 2 Hz and 36000 cycles per strain level. Durability was assessed by measuring sensitivity by leads break after each strain level cycles (0.12% to 1.065%). The results show that mechanical test did not alter patches sensitivity and their coating.

4 ACTIVE MONITORING OF PULTRUDED BEAMS USING GUIDED WAVES

Monitoring of pultruded profiles is based on two complementary methods (active and passive) using the same sensors (patches). In the case of active surveillance, slow mechanical resin degradation is detected when using guided waves.

The first step was to simulate analytical wave propagation in a composite bar and then to select the most sensitive Lamb waves to the resin ageing. Figure 3 shows wave propagation modelling results in the cases of intact resin and 50% degraded resin. The mode A_0 generated at low frequency seems to be a good candidate to evaluate vinylester resin degradation. This is explained by the fact that low frequency A_0 mode has a perpendicular displacement component to the plane of the bar.

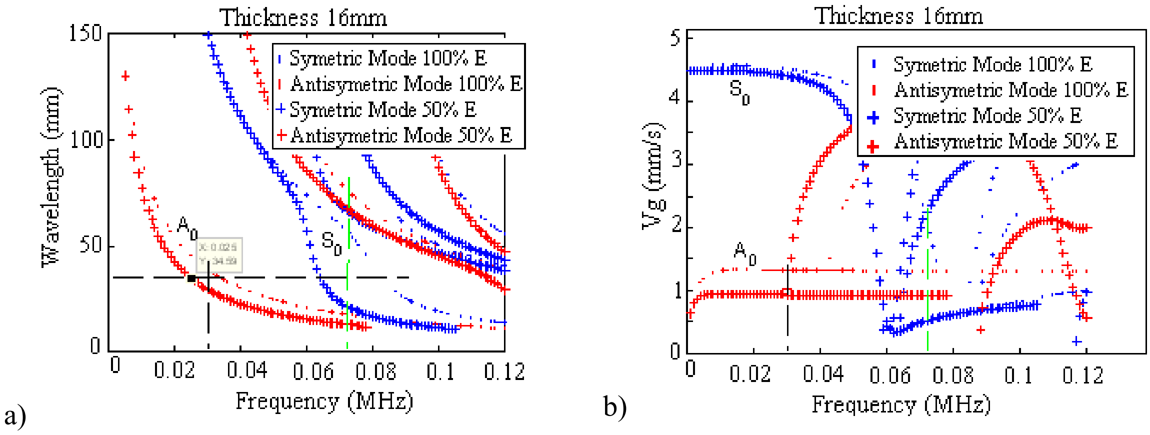

Figure 3: Dispersion curves on vinylester bar (intact and degraded): a) Wave length, b) Group velocity.

To meet the health monitoring system requirements, ultrasonic patches are chosen for generating and detecting A_0 mode. Diameter and thickness of patches are selected to generate the desired wave length (λ= 34.59 mm; f=30 kHz) in pultruded bars. The wave propagation velocity plotted as a function of the resin Young's modulus highlight the reduction of A_0 mode velocity with the decrease of Young modulus. In order to quantify mode A_0 sensitivity to the decrease of resin stiffness, a compression test (perpendicular to fibres direction, Figure 4) monitored by guided waves was performed on a composite bar at various temperatures (20°C, 50°C, 75°C and 100°C).

Figure 4: Compression test at temperature up to 100°C.

Two patches are therefore used, one as an emitter and the other as a receiver. A burst signal with a magnitude of 10 V_{pp} was generated every 10 ms at a frequency of 30 kHz. For each temperature, a load test was performed up to 50kN (within the elasticity area) to calculate Young's modulus. Guided wave measurements were made at each temperature in order to determine the influence of stiffness loss on guided wave propagation. It is interesting to note (Figure 5) that the decrease of resin's stiffness due to increasing temperature, results in the increase of the arrival time of the A_0 Lamb mode. For a loss of 39% of resin stiffness, a delay time of 33 µs was measured. Thus, these experiments have confirmed the decrease of the A_0 wave velocity with the reduction of the resin's stiffness.

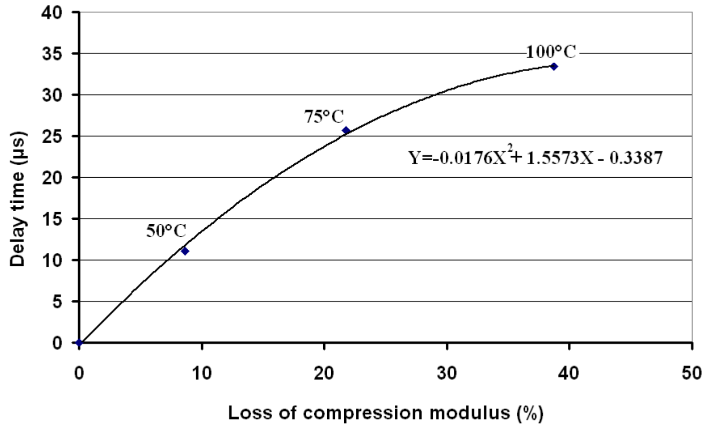

Figure 5: Delay for the arrival time of A0 mode versus loss of resin stiffness.

5 PASSIVE MONITORING OF PULTRUDED BEAMS USING ACOUSTIC EMISSION

5.1 Acoustic fingerprints of damages occurring in pultruded bars

Miniaturized patches are also used in the acoustic emission health monitoring system to detect sudden damages such as matrix micro-crackings, fibre breaks… close to the assembling parts or to the most stressed areas of the footbridge. To implement this system, the first step was to characterize the acoustic fingerprints of the damages occurring in pultruded samples during mechanical tests. The different types of damage occurring in the pultruded bars were identified using conventional acoustic emission sensors (Mistras R15) during loading-unloading bending test (Figure 6). From the test start to the end of the linear strain-stress region (0.8% deformation), AE multiparametrics analysis revealed one single population associated with multiple matrix damage and few broken fibers (Figure 6a). Upper than 0.8 % deformation, two new AE populations appear related to fiber breaks and delaminations (Figure 6b). During loading-unloading test, the Felicity ratio determines the beginning of damage which is estimated at a strain value of 0.25%. For this strain, acoustic amplitude activity is still lower than 52dB which is indicating the existence of mostly matrix damage.

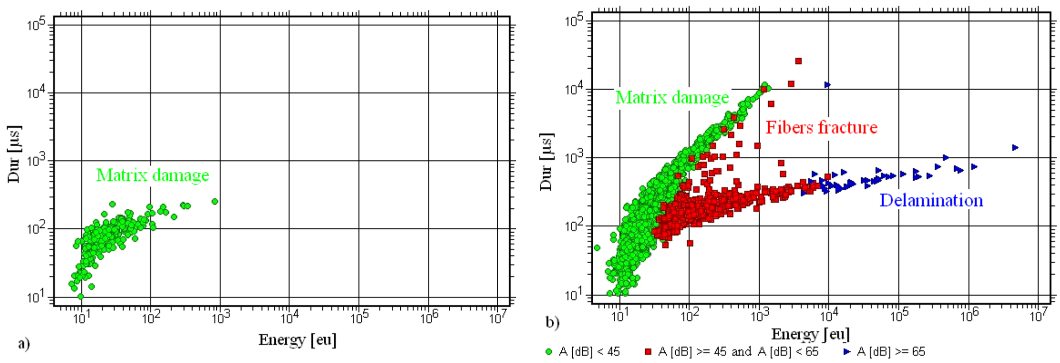

Figure 6: Located events population for the linear stress-strain region (ε< 0,8%); b) Located events population for $\varepsilon \geq 0,8\%$. (R15 sensors).

Fatigue tests were performed to assess the mechanical behavior of pultruded material and its AE response. The correlation between AE (Figure 7) and mechanical behaviour gives additional explanation about fatigue damage mechanisms evolution. During the first level (ε=0.11%), no AE was recorded. It is worthy noting that only one AE population is found during the second stage (ε=0.23%) in accordance with quasi-static tests and Felicity ratio. This may mainly correspond to matrix damage. During the third stage (ε=0.42%), some AE signals appear and begin to form a second population. This population strongly increases during the last two stages. Plotting stress versus strain indicates that strain remained constant at the first four stages and increases during the two last stages (Figure 8). This confirms that the exceedance of the linear stress-strain region (which is related to fiber failures) has occurred at 0.8% strain and 241MPa stress in accordance with quasi-static tests. Therefore the second population could be related to fiber breaks.

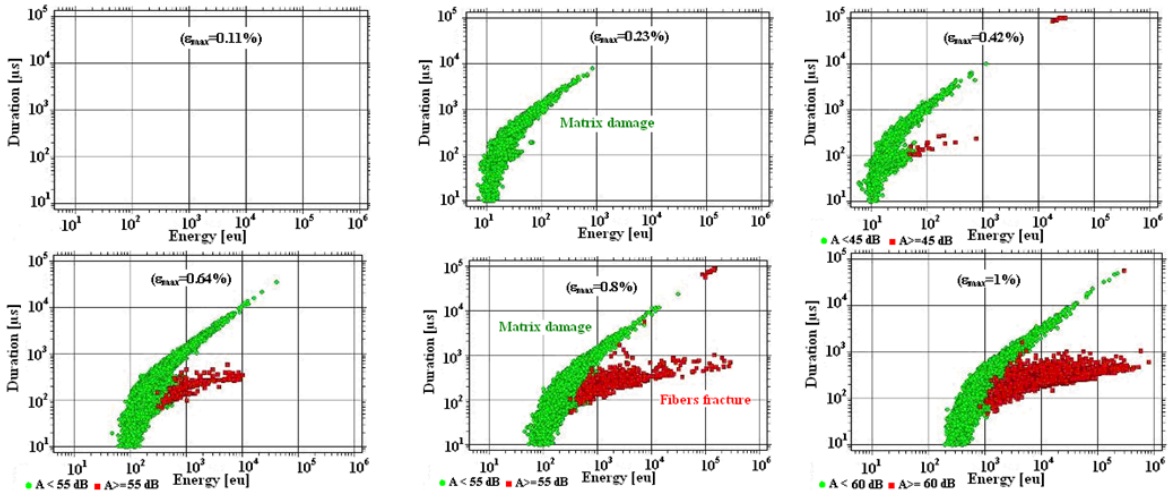

Figure 7: AE activity during fatigue test: stage 1 (ε=0.12%) to stage 6 (ε=1%). (R15 sensors).

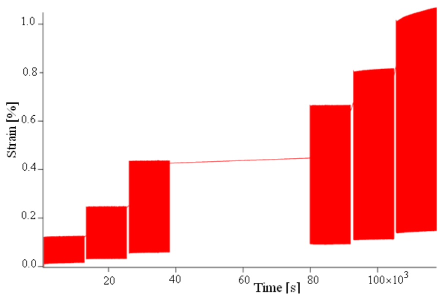

Figure 8: Strain evolution during fatigue test.

5.2 Definition and qualification of AE SHM system using miniaturized sensors

In order to determine the type of damage detected by ultrasonic patches, the same qualitative analysis was applied for different tests (quasi-static, load-unload, and fatigue). Thus, the ability of patches to detect different damage mechanisms is supported based on results obtained by R15 sensors. Acoustic emission activity recorded during quasi-static and loading-unloading tests is zero for maximum strains lower than 0.8%.

Bending loading-unloading tests showed the existence of a threshold strain from which there is a loss of stiffness. Knowing that matrix damage does not change significantly the stiffness of the composite, this loss of stiffness is mainly attributed to fibers breaks. Patches began to detect AE from a strain of 1%. This early detection fits well with a loss of stiffness due to fibers breaks which corresponds to the apparition of the second AE population recorded by the R15 sensors. Therefore, it can be concluded that patches are only sensitive to fibers failures and they are unable to detect the onset of matrix damage.

AE parameters from patches recording were determined. Maximum values of theses parameters (Amplitude, duration, energy) increased with load and strain but mean values vary very slightly. Average amplitudes detected do not exceed 54 dB.

Fatigue bending test confirms that fatigue damage detected by patches (related to fibers breaks) is the same as the one detected during quasi-static tests for strain higher than 1%.

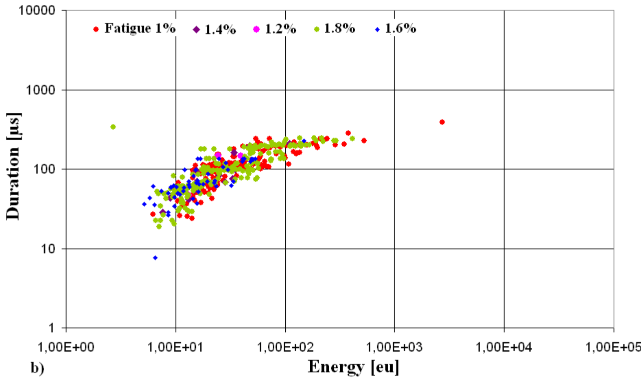

Figure 9: AE detected during the 6th phase of fatigue test and detected during loading-unloading bending test Compression test at temperature up to 100°C.

The onset of damage detected using patches is located at the middle of the specimen and is characterized by average amplitude of 41dB. According to attenuation measurement (0.58dB/cm) and detection threshold of 35dB, the maximum distance between two patches, for damage detection in bridge composite structure, is set to 15 cm.

5.3 Effects of climatic conditions on the reliability of AE system

The climatic conditions such as frost, wind, rain and hail were studied to determine the abilities or limitations of AE system to discriminate them from damages using ultrasonic patches. AE recording was performed outside during cold weather at -9°C and showed that frost, light rain and wind does not disturb AE measurements. Only a low increase of background noise was observed due to wind (very low compared to the threshold). However, for heavy rain and hail, discrimination between damage and noise is difficult using simple analysis. Frequency and statistical analysis could be applied to improve classification. Location analysis appears to be an effective method for noise discrimination.

5.4 Conclusions

So, this part permitted us to define the sensor locations, their spacing within the composite bridge and the damage criterion. The influence of climatic conditions such as frost, wind, rain, and hail on the structural health monitoring system was also studied in order avoid false alarms.

6 CONCLUSIONS: BUILDING OF TWO SMART COMPOSITE FOOTBRIDGES

Finally, two composite footbridges were built at the EMC2 Technocampus and IFSTTAR in France to serve as demonstrators (Figure 10). They are made from pultruded composite (glass fiber/vinylester) that are provided with a structural health system in the form of embedded optical fibers and miniaturized ultrasonic sensors glued to the bars. Both active (guided waves) and passive (acoustic emission) structural health monitoring systems were installed. Active method can detect the resin stiffness degradation using guided wave and passive method (acoustic emission) can detect and locate fibres breaks. In this work, miniaturized ultrasonic sensors are developed and validated by various environmental and mechanical tests. Their ability to detect fibers breaks was demonstrated despite a low sensitivity compared to standard AE sensors. Model prediction of A_0 mode sensitivity to resin stiffness loss was validated by quantitative mechanical experiments at various temperatures. Sensors are installed at critical areas, namely the highest bend area and near bolts. The acoustic emission monitoring system is remotely controlled via an internet connection and configured to warn the supervisor by email-sending once an active damage is detected. The real time detection and location of the degradation provides safety of installation and users and will avoid catastrophic failure.


a) b)

Figure 10: a) Demonstrator composite Footbridge; b) Miniatures sensors for bolt assembly monitoring.

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