Health monitoring of flexible composite plates: a MEMS-based approach

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ABSTRACT

Layered composite plates subjected to cyclic or low-velocity impact loadings are typically affected by local failures linked to delamination, i.e. debonding between adjacent laminae. Micro electro-mechanical systems (MEMS) have been recently proposed as sensing components of surface-mounted structural health monitoring systems, aimed to detect such delamination events in real-time.

Here, we show some experimental results to get insights into the capability of MEMS accelerometers to detect delamination, and identify its magnitude. We also discuss a topology optimization-like approach to smartly deploy sensors over plates of complex geometry, so as to locate a delamination of unknown position.

Keywords: micro electro-mechanical systems (MEMS), layered composites, delamination, structural health monitoring.

1 INTRODUCTION

Composite laminates subjected to cyclic or low-velocity impact loadings can fail because of the inception and propagation of interlaminar cracking (delamination). Since delaminated zones are typically shadowed by the external laminae, composite structures are in need of either expensive maintenance programs or sensing (health monitoring) systems. In the first case, structural components are repaired or substituted before delamination attains a critical threshold; in the second case, sensors need to provide a warning message in real-time, whenever the aforementioned critical threshold is foreseen to get approached.

Several methodologies to monitor (smart) composite plates have been recently proposed, and typically consist in embedding fiber Bragg gratings [1,2] or piezoelectric sensors [3,4]. Even if such sensors are very accurate, their size exceeds the thickness of a single lamina; therefore, the composite microstructure gets distorted. The strain state in the region surrounding the sensors turns out to be affected by the presence of the sensors themselves, and the overall structural damage tolerance is usually reduced [4].

In Section 2, we investigate the capability to detect delamination of a surface-mounted MEMS-based health monitoring system, recently proposed in [5]. Since MEMS sensors are pervasive but not invasive, they can be deployed in very dense arrays over the whole structure, without affecting its dynamics. With reference to a standard double cantilever beam test, we show some experimental results obtained by using a commercial off-the-shelf three-axis, digital output MEMS accelerometer [6,7] held fixed to the specimen. By exciting the composite to progressively and smoothly increase the delaminated area, the analysis of the MEMS output in the frequency domain (specifically the peak at the excitation driving frequency) has allowed to obtain results in good agreement with a theoretical beam-bending model of the specimen response.

In case of more complex structural geometries, a methodology needs to be devised to deploy the sensors so as to attain the requested sensitivity to sense/detect delamination. In Section 3, we provide some details of a topology optimization-like tool to smartly deploy sensors, as proposed in [5,8]. A major outcome of this study is that evenly spaced sensors do not show optimal sensitivity to damage, wherever it is located.

2 DELAMINATION DETECTION

In [9], Achenbach stated that "*sensors should be: small (microsensors); autonomous (accelerometer, antenna, battery); cheap, robust, maintainable and repairable; accurate, known pod [probability of detection]; properly coupled to structure; suitable for wireless transmission to central station; densely distributed; capable of measuring both local and system-level response; designed to measure relevant damage parameters.*" MEMS sensors can basically feature all the aforementioned requirements.

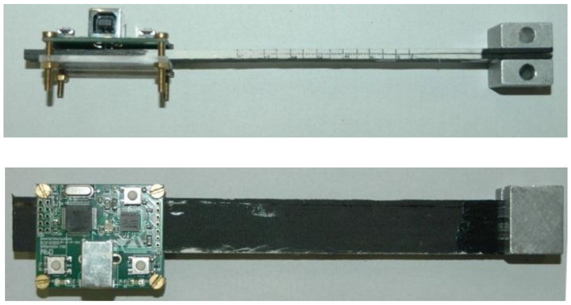

Figure 1: Side and top views of the specimen-MEMS board system.

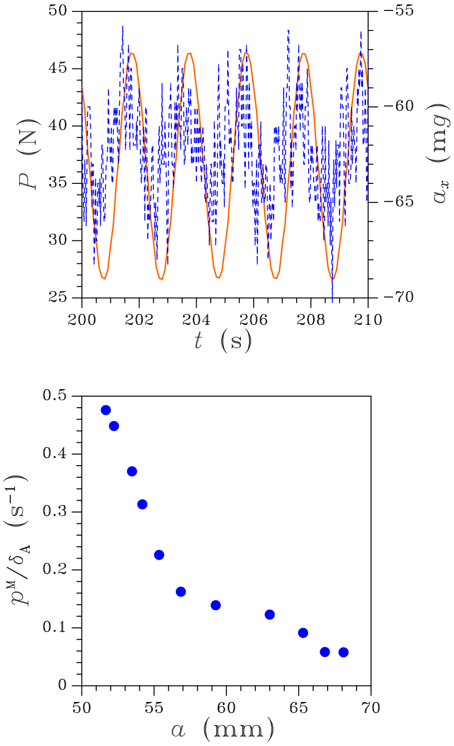

Figure 2: Experimental (top) load *vs* time (orange curve) and acceleration vs time (dashed blue curve) plots, and (bottom) normalized frequency peak *vs* crack length plot.

Dealing with health monitoring systems for composite laminates, in [5] we collected the first results of an experimental campaign aimed at assessing the capability of MEMS accelerometers to detect in real-time the potential propagation of a pre-existing delamination. We applied a slowly-varying, cyclic load (actually, displacement) to a double-cantilever beam (see Figure 1), according to:

$$u(t) = u_0 + \delta_A \sin(2\pi f_u t) \qquad (1)$$

where: u_0 is the average displacement in a cycle; δ_A is half the amplitude of a cycle; f_u is the driving frequency of excitation. The typical outcomes of the test are gathered in Figure 2 (top), in terms of measured variation of load P and acceleration a_x (x being the load direction). While the load sinusoidally varies (at constant crack length a), the acceleration turns out to be affected by a noise, which spoils the quality of conveyed information.

We therefore provided a beam-bending interpretation of the results, to get insights into the structural effects driving the measured a_x evolution. Because of the small thickness to crack length ratio, shear deformations of the composite beam are disregarded. The compliance C of the specimen, i.e. the coefficient linking the load-point displacement u to the load P, can then be written as:

$$C = \frac{u}{P} = 8\,\frac{a^3}{E_l B h^3} \qquad (2)$$

where: E_l is the effective Young's modulus of the composite in the longitudinal direction; B and h are the beam thickness and height, respectively. We now write the measured acceleration a_x as:

$$a_x = \varphi P \qquad (3)$$

where φ is a constant parameter. Accounting for Eqs. (1) and (2), we obtain:

$$a_x = \frac{\varphi}{C}\left[u_0 + \delta_A \sin(2\pi f_u t)\right] \qquad (4)$$

The magnitude of the Fourier transform of (4) reads:

$$p^{\mathrm{M}} = \frac{\varphi}{C}\left[u_0 \delta(f) + \frac{\delta_A}{2}\delta(f \pm f_u)\right] \qquad (5)$$

where $\delta(\cdot)$ stands for the Dirac delta. At $f = f_u$, leaving on the right hand side only the contributions arising from the test set-up, it holds:

$$\frac{p^{\mathrm{M}}}{\delta_A} = \frac{\varphi}{2C}\delta(f - f_u) \qquad (6)$$

Eq. (6) allows to link the crack length a, nested in C (see Eq. 2), to the normalized frequency peak p^{M}/δ_A; relevant results are shown in Figure 2 (bottom), as obtained by progressively increasing u_0 every 100 cycles during the test. p^{M}/δ_A is depicted against the measured evolution of a, showing excellent sensitivity to the damage state in the laminate.

Hence, by only sensing the rotation of the MEMS accelerometer, felt as a variation of the measured components of the gravity acceleration, we have provided a delamination length-sensitive health monitoring scheme.

3 SENSOR DEPLOYMENT

To detect a damage (or delamination) of unknown location, we discuss here a methodology centered around a topology optimizer. We assume the plate to be space-discretized into finite elements, and model its behavior according to first-order shear deformation theory, see [8].

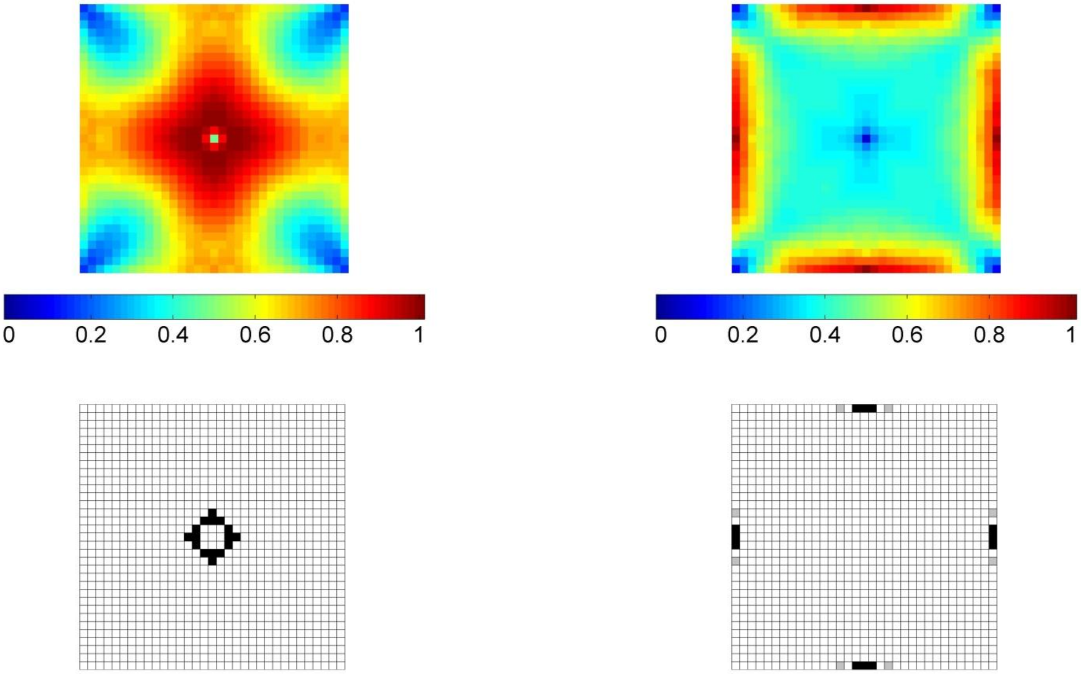

Figure 3: Simply supported plate. Left: unscaled optimization scheme; right: scaled optimization scheme. Top: objective functions; bottom: optimal deployment of $\bar{N} = 16$ sensors.

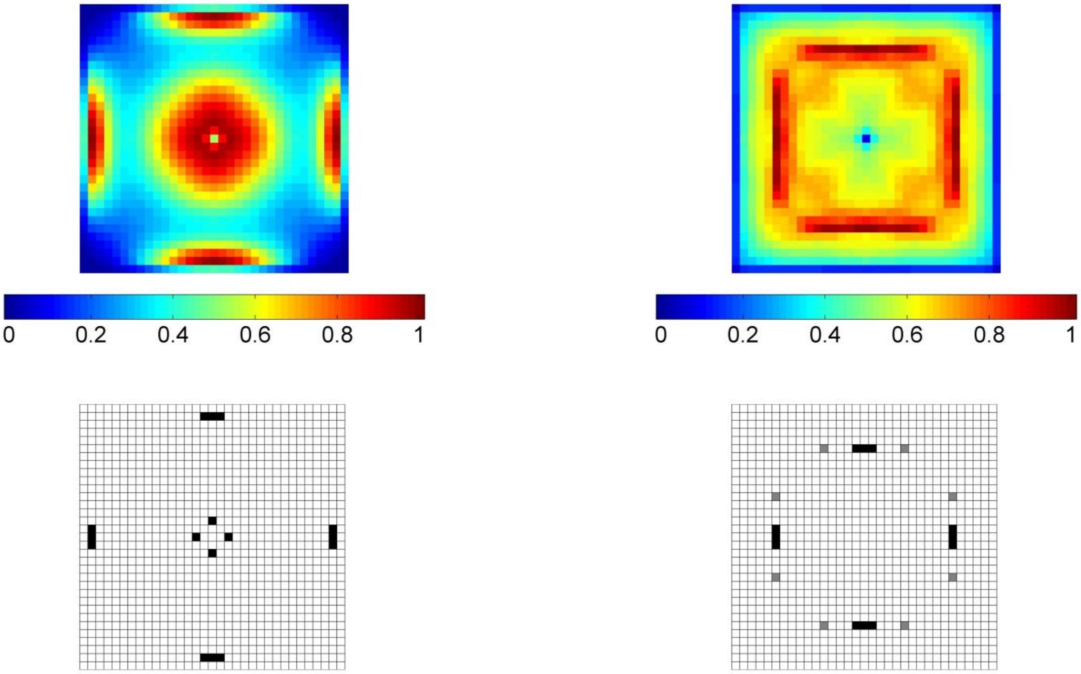

Figure 4: Clamped plate. Left: unscaled optimization scheme; right: scaled optimization scheme. Top: objective functions; bottom: optimal deployment of $\bar{N} = 16$ sensors.

To optimize the topology of a network of MEMS accelerometers used as sensing elements, we account once again for their capability to detect local rotations. We therefore adopt an objective function (to be maximized) as follows:

$$\mathcal{F} = \sum_{k=1}^{n} \alpha_k \left[\sum_{i=1}^{n} x_i^p \left\| \boldsymbol{\vartheta}_{ki} - \hat{\boldsymbol{\vartheta}}_i \right\| \right] \tag{7}$$

subject to the condition $\sum_{i=1}^{n} x_i \leq \bar{N}$. Here: n is the number of finite elements of the plate/shell-like space discretization; $\left\|\boldsymbol{\vartheta}_{ki} - \widehat{\boldsymbol{\vartheta}}_i\right\|$ represents an appropriate norm of vector $\boldsymbol{\vartheta}_{ki} - \widehat{\boldsymbol{\vartheta}}_i$ (like, e.g. the L^2 norm); $\widehat{\boldsymbol{\vartheta}}_i$ and $\boldsymbol{\vartheta}_{ki}$ are, respectively, the elemental rotations obtained in the undamaged case and when damage is located in the k-th element; x_i are the elemental values of a discrete density field, taking values in the range $0 \leq x_i \leq 1$, that accounts for the possible presence of the sensor over the i-th element; α_k are weights adopted to scale the structural effects linked to each damage location; $\bar{N}$ is the assigned maximum number of sensors to be deployed; $p \geq 1$ is an algorithmic parameter, used to penalize intermediate densities and approach pure 0-1 distributions of sensors over the finite elements. Handling three-axis accelerometers, each entry of vectors $\widehat{\boldsymbol{\vartheta}}_i$ and $\boldsymbol{\vartheta}_{ki}$ is provided by a local norm of the elemental rotation about the in-plane axes of an orthonormal reference frame, see [5,8].

In [8] we proposed two alternative formulations as for weights α_k: the former (unscaled) one consists in keeping $\alpha_k = 1\ \forall k$, and therefore maximizes the sensitivity of the monitoring system to the amplitude of the measured rotations; the latter (scaled) one consists in using $\alpha_k = \left(\max_i x_i^p \left\|\boldsymbol{\vartheta}_{ki} - \widehat{\boldsymbol{\vartheta}}_i\right\|\right)^{-1}$, and allows to obtain a sensor placement optimal for any damage location, balancing all the possible sources.

The two formulations were shown to differ in terms of optimal deployments provided. As for the simply supported plate, Figure 3 depicts the two objective functions here proposed, and the relevant optimal deployments of $\bar{N} = 16$ sensors. The unscaled scheme always leads to sensors focused around the center of the plate; on the other hand, the scaled scheme provides optimal placements distributed along the boundary of the plate, symmetric with respect to mid-side elements. As for the fully clamped plate, results are gathered in Figure 4. As expected, both the objective functions avoid placements along the plate boundary, where rotations are constrained. The optimal deployment provided by the unscaled formulation consists in two major zones, a first one close to the plate center and a second one close to the sides. The scaled formulation provides instead a rational evolution of the deployments from the simply supported case, with optimal locations moved toward the center of the plate.

The results here collected have shown that dense patterns characterize the optimal solutions. Hence, a homogeneously deployed array of sensors does not represent the optimal approach to detect damage, independently of boundary conditions and damage location.

4 CONCLUDING REMARKS

In this work, we have discussed two topics of a surface-mounted MEMS-based health monitoring system for laminated composites: the sensitivity of the monitoring scheme to delamination length, and the optimal deployment of the sensors over plates. Next steps of the present study will be: the assessment of the robustness of the offered monitoring system; a coupling with a Kalman-like filter, to effectively identify the location and amplitude of delamination on the basis of the MEMS output.

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