# On-line identification of delamination – simulation and experiment

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ABSTRACT: The proposed concept of on-line identification of delamination assumes a uniformly distributed net of sensors, acting in pairs, attached to the upper and lower surface of a layered beam structure. Local delamination manifests itself in an apparent difference observed in responses of collocated (paired) sensors. Numerical simulation has been run to validate the idea of tracking the differences of strain signals collected from many sensors uniformly scattered over the structure for some assumed damage location and size. For experimental verification, a net of piezoelectric sensors mounted in pairs to the upper and surface of a glass-fibre reinforced epoxy beam is proposed. The presented monitoring system can provide on-line information about the state of the structure. It is able to detect and assess delamination effectively. The proposed method seems to be dedicated to special kind of structures, for which the application of standard methods is impossible or impractical e.g. in aeronautics.

## 1 INTRODUCTION

Composite (layered) structures, widely used in many engineering applications, frequently suffer from delamination, which changes their dynamic responses [1] and may lead to structural integrity failure. Consequently, there is a strong demand for development of on-line damage detection and health monitoring techniques for this kind of structures.

Currently available, traditional non-destructive testing (NDT) methods are mostly model-free approaches, examining the problem from the experimental viewpoint only. The most popular NDT methods are:

- ultrasonic,
- acoustic,
- magnetic field,
- thermal field,
- radiographic,
- eddy current.

The majority of them, require full accessibility to a structure during tests, and cannot be used for real-time monitoring of structures which are in motion, like airplanes for example.

There has been a discussion about a possibility of implementation of array systems, based on application-dedicated sensors, embedded into a structure or placed onto its surface, able to detect and localize delamination in real time, during the exploitation process. Literature propositions use: optical fibers [2], electric resistance sensors [3], shape memory alloy foils [4].

The system proposed in this paper, aimed at detection and assessment of delamination, has been mentioned in [5] first. It is based on piezoelectric sensors, acting in pairs, mounted on the upper and lower surface of a relatively thin, composite structure e.g. a helicopter rotor. The assessment of structural health relies on analyzing the difference in signals measured by the pairs of sensors (Fig. 1). Damage presence in the structure is communicated by an increased value of the following indicator:

$$\lambda = \int_{t_1}^{t_2} (v_t(t) - v_b(t))^2 dt$$

where $v_t(t)$, $v_b(t)$ are voltage signals measured by pairs of sensors mounted on top and bottom surface of the structure, respectively, $t_1$ and $t_2$ specify the time range for which the calculation is performed. Damage location (extension) is determined by pointing out the pair(s) of sensors for which the indicator $\lambda$ exceeds some threshold value.

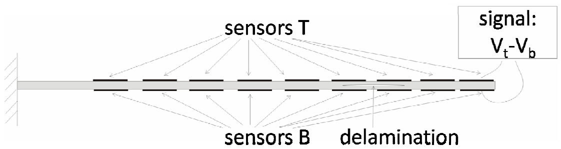



Fig. 1 Dense net of paired sensors able to detect and assess delamination on-line

## 2 NUMERICAL MODEL

For evaluation of effectiveness of the proposed system, a complex numerical model, including mechanical-electrical coupling and contact between layers in the delaminated region, was built. Four blocks supposed to model a composite structure with delamination can be distinguished in the model. The layout of the blocks along the composite is presented in Fig. 2. These blocks are connected together by using additional boundary conditions at the delamination edges.

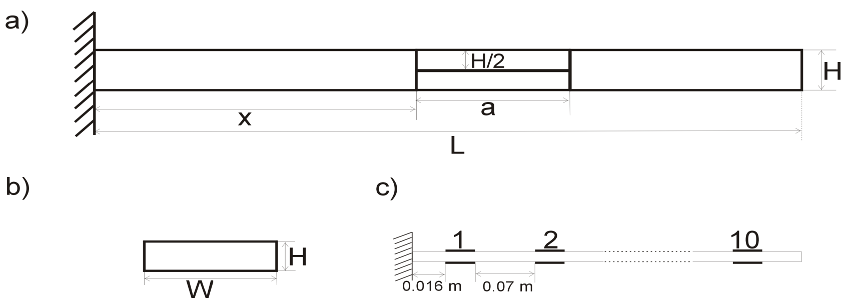



Fig. 2 FE model accounting for delamination: a) longitudinal section, b) cross section, c) pairs of sensors

The equations of motion of a mechanical system for a problem without contact are given by:

$$[M]\{\tfrac{d^2u}{dt^2}\} + [C]\{\tfrac{du}{dt}\} + [K]\{u\} = \{F\} \tag{1}$$

with the boundary condition imposed on displacements:

$$\{u\} = \{u_{bound}\}$$

where [M] - mass matrix, [C] - damping matrix, [K] - stiffness matrix, {u} - displacement vector and {F} - external load vector.

The non-linear effects arising from the contact leads to the modified form of equations (1):

$$[M]\{\tfrac{d^2u}{dt^2}\} + [C]\{\tfrac{du}{dt}\} + [K]\{u\} = \{F\} - \{F_C(u)\} \tag{2}$$

where $\{F_C(u)\}$ is the contact force depending on normal displacements in a local coordinate system. The augmented Lagrange multiplier method was used to determine the contact force value.

When considering the influence of piezoelectric sensors on a mechanical system, it is necessary to take into account a set of coupled constitutive equations, yielding:

$$\begin{aligned} \{T\} &= [c]\{S\} - [e]^T\{E\} \\ \{D\} &= [e]\{S\} + [\varepsilon]\{E\} \end{aligned} \tag{3}$$

where {T} - stress vector, [c] - elastic material constants matrix, {S} - strain vector, [e] - piezoelectric constants matrix, {E} - electric field vector, [ε] - dielectric constants matrix, {D} - electric displacement vector.

As we can see, equation (3) is coupled by the piezoelectric constants matrix [e]. As a consequence, a set of differential equations describing the coupled mechanical-electrical problem including contact has the following form:

$$\begin{bmatrix}[M] & [0]\\ [0] & [0]\end{bmatrix}\begin{Bmatrix}\{\frac{d^2u}{dt^2}\}\\ \{\frac{d^2\varphi}{dt^2}\}\end{Bmatrix}+\begin{bmatrix}[C] & [0]\\ [0] & [0]\end{bmatrix}\begin{Bmatrix}\{\frac{du}{dt}\}\\ \{\frac{d\varphi}{dt}\}\end{Bmatrix}+\begin{bmatrix}[K] & [e]\\ [e] & [\varepsilon]\end{bmatrix}\begin{Bmatrix}\{u\}\\ \{\varphi\}\end{Bmatrix}=\begin{Bmatrix}\{F\}-\{F_C(u)\}\\ \{L\}\end{Bmatrix} \tag{4}$$

where {φ} - electrical potential vector, {L} - electrical load vector. Two kinds of boundary conditions on mechanical displacements u and electrical potential φ have to be considered to complement equation (4):

$$\{u\}=\{u_{bound}\}$$
$$\{\varphi\}=\{\varphi_{bound}\}$$

In absence of external electrical field, the nodal charge load vector vanishes i.e. {L}={0}. This condition is valid when a piezo-transducer works as a sensor (not as an actuator), which is the case of the described application. The external force F is characterized by the known excitation. It is important to set the direction of polarization of the piezo-sensor, which is assumed perpendicular to the sensor surface here.

## 3 NUMERICAL EXAMPLE

Numerical calculation was carried out using the FE package ANSYS. An eight-layer graphite-epoxy cantilever composite beam, depicted in Fig. 2, was analyzed. The eight-node 3D layered finite elements with three degrees of freedom in each node were used for modeling the beam. Additionally, 10 pairs of piezo-sensors were modeled using 3D coupled-field solid elements. Damping and friction were neglected. The length of the beam (L) was 800 mm, width (W) 16 mm and height (H) 8 mm. The fiber volume in the structure was 0.3. The ply layout was assumed symmetrical with respect to the neutral axis i.e. 45/-45/45/-45/-45/45/-45/45. Material properties for graphite and epoxy are presented in Tab. 1.

Tab. 1 Basic material properties of the numerically analyzed graphite-epoxy beam

| | Epoxy (matrix) | Graphite (fiber) |
|---|---|---|
| Young's modulus [GPa] | 3.43 | 275.6 |
| Poisson's ratio | 0.35 | 0.2 |
| Density [kg/m$^3$] | 1250 | 1900 |

Piezoelectric sensors were assumed to be of the piezo-ceramic PZT-4 material, whose characteristics are presented in Tab. 2.

Tab. 2 Extended material properties of the numerically analyzed graphite-epoxy beam

| Elastic material constants matrix [N/m$^2$] | Piezoelectric material constants matrix [C/m$^2$] | Dielectric constants matrix [C/Vm] |
|---|---|---|
| $\begin{bmatrix}13.2 & 7.1 & 7.3 & 0 & 0 & 0\\ & 13.2 & 7.3 & 0 & 0 & 0\\ & & 11.5 & 0 & 0 & 0\\ & & & 3 & 0 & 0\\ & sym & & & 2.6 & 0\\ & & & & & 2.6\end{bmatrix} * 10^{-10}$ | $\begin{bmatrix}0 & 0 & 0 & 0 & 0 & 10.5\\ 0 & 0 & 0 & 0 & 10.5 & 0\\ -4.1 & -4.1 & 14.1 & 0 & 0 & 0\end{bmatrix}$ | $\begin{bmatrix}804.6 & 0 & 0\\ 0 & 804.6 & 0\\ 0 & 0 & 659.7\end{bmatrix}$ |

The objective of analysis was to find the existence and extension of delamination indicated by increased values of λ for specified pairs of sensors. The beam was excited by a sinusoidal force applied to its free end. The time period $<t_1,t_2>$ for integrating the λ value was equal to two periods of the exciting signal. Results were compared for two excitation frequencies: 185 Hz and 230 Hz and three extensions of damage: small-size damage covering 5.5% beam length and placed in between the pair of sensors No. 6, medium-size damage covering 25.5% beam length and placed in between the pairs of sensors Nos. 5, 6, 7 and large-size damage covering 45.5% of the beam length and placed in between the sensors Nos. 4, 5, 6, 7, 8. For both frequencies, delamination existence and extension was evaluated correctly. The results are presented in Fig. 3.

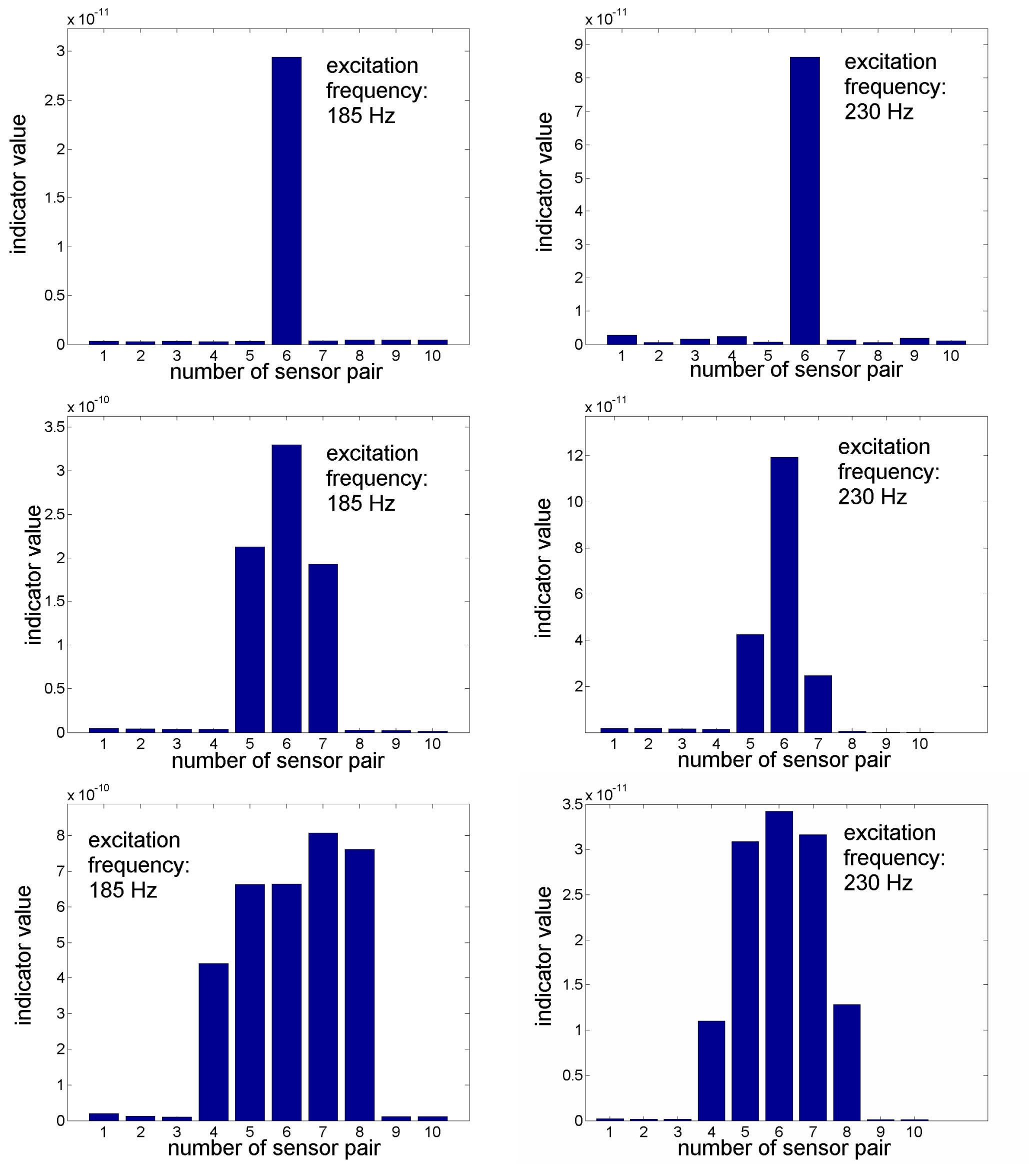



Fig. 3 Values of the indicator λ, showing the existence and extension of delamination, for: a) small-size damage at the excitation frequency 185 Hz, b) small-size damage at the excitation frequency 230 Hz, c) medium-size damage at the excitation frequency 185 Hz, d) medium-size damage at the excitation frequency 230 Hz, e) large-size damage at the excitation frequency 185 Hz, f) large-size damage at the excitation frequency 230 Hz.

4 EXPERIMENTAL INVESTIGATION

Verification of the proposed method was carried out experimentally. For this purpose, a layered composite beam (length 720 mm, width 30 mm, height 3 mm) composed of glass fiber mat embedded in an epoxy matrix. The structure was excited with a continuous sinusoidal signal by a piezo-electric actuator shown at the top part of Fig. 4. Eight pairs of piezo fibre composite (PFC) sensors (active length 20 mm, active width 4 mm, active height 0.5 mm) were glued on the top and bottom surfaces of the beam with an equal spacing of 30 mm. Delamination of 35 mm length was introduced in the mid plane of the beam in between the pair of sensors No. 4, as shown in Fig. 5b. Values of the indicator $\lambda$ for each sensor pair at 320 Hz excitation frequency are presented in Fig. 6. Clear message about the existence and extension of defect is given.

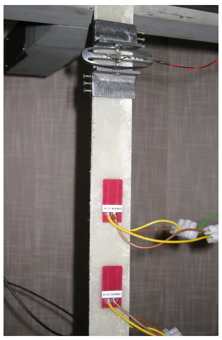
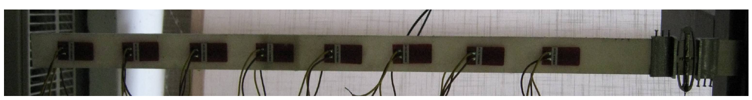


Fig. 4 Actuator and 2 PFC sensors mounted on a glass fibre-epoxy beam

a)



b)

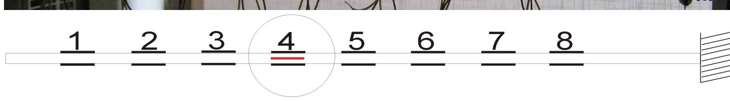



Fig. 5 a) The experimentally tested beam, b) a scheme of the beam with the location of delamination

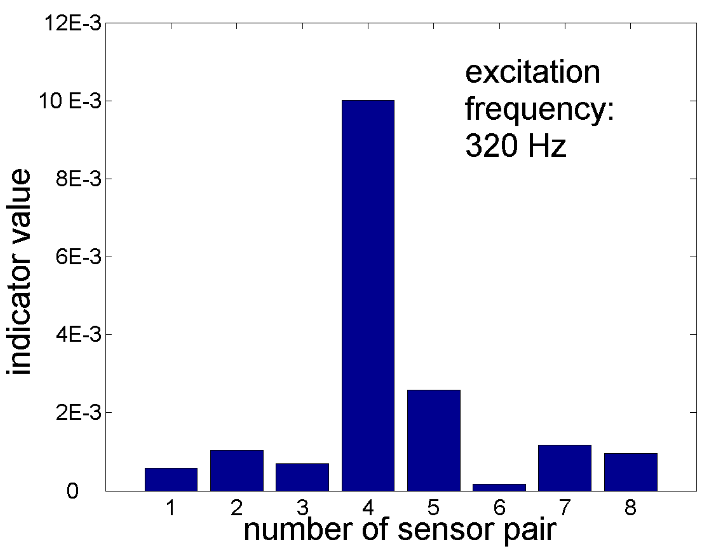



Fig. 6 On-line identification of delamination by the PFC sensors (pair No. 4 indicates damage)

The obtained results show that there is an apparent growth in the proposed indicator λ in the location where delamination occurs in a composite structure. The level of indicator λ for delamination zones in comparison to healthy zones is one order of magnitude higher. It is also clear that the extension of delamination can be determined by pointing out the pairs of sensors with the increased λ (compare Fig. 3).

It is a very promising observation that delamination of small extent can be effectively detected (less than 5% of the beam length as described above). If so, a warning can be communicated to the user almost at the onset of defect development. If a small delamination happens to be in between the neighboring sensors, the indicator λ value grows for both the sensors.

## 5 CONCLUSIONS

The paper is focused on identification of delamination in the on-line mode. In order to accomplish the task a net of densely and evenly distributed sensors over the top and bottom surfaces of an investigated beam is required. By examining differences in responses of collocated pairs of sensors, delamination existence and extension can be determined by performing a very quick calculation in real time. Numerical simulations confirm the correctness of the proposed idea. Also experimental work verifies the concept positively. Even small-size delamination could be effectively detected.

The authors firmly believe that the proposed solution (patent pending) has a chance of application in composite beams subjected to dynamic loading. The characteristic of this loading may be unknown. An example of such application could be the blade of a helicopter rotor during engine operation. Failure of such a composite blade due to delamination may lead to a crash.

Further research will be devoted to analysis of the level of threshold, which indicates delamination, depending upon various factors e.g. the dimensions or excitation of the tested beams. The influence of noise on the signals collected by sensors will be studied for various parameter sets. Implementation issues will be of concern as well.

## ACKNOWLEDGEMENTS

The financial support from the projects “Smart Technologies for Safety Engineering - SMART and SAFE” – TEAM Programme – granted by the Foundation for Polish Science and “Health Monitoring and Lifetime Assessment of Structures” – MONIT – POIG.01.01.02-00-013/08-00 from the EU Structural Funds in Poland is gratefully acknowledged.

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