Simulation of a fiber-optic based SHM system. Application to a bonded repair patch

Alfredo GÜEMES [1], Maria Eugenia REYES [1], Jaime GARCIA-RAMIREZ [1], C. AGUILAR[1], Antonio FERNANDEZ-LOPEZ [1]
[1] Universidad Politecnica de Madrid (UPM), Madrid, Spain

Contact e-mail: alfredo.guemes@upm.es

Abstract. Simulation tools are very useful to understand and optimize NDT systems, and particularly the SHM systems. An algorithm has been proposed to quantify the damage detection capability of a fiber optic sensor network, with a finite number of strain measurements. A damage index is obtained by simulation, dependent of the damage size and position, and the number and distribution of sensors, and also of the noise of the signals; by repeating the simulation under random noise, a POD (Probability of Detection) could be calculated. The analysis is applied to a simple representative experiment, a bonded repair patch, under mechanical and thermal loads.

Introduction

Structural Health Monitoring (SHM) is defined as the process of acquiring and analyzing data from on-board sensors to evaluate the health of the structures [1]. SHM shares with NDT the objective of detecting local damages, but while NDT techniques rely on external instruments, like X-Ray sources and detectors, or ultrasonic probes, which imply that the structural element needs to be accessed and probably dismounted for inspection, for SHM the sensors responsible of getting information must be permanently attached to the structure at fixed positions; the structure can be remotely inspected, without disassembly, without specialized personnel, which imply significant savings in maintenance. Sensors have to be distributed through the structure, because the location for damage occurrence is usually unknown; consequently the sensors need to be small size and cheap, to allow for tens to hundreds of sensors for each structural element. PZT and FOS sensors are the best candidates, and the more widely studied, but alternative solutions like MEMS are also feasible.

Fiber-optic sensors (FOS) are recognized as excellent strain/temperature sensors. It can be said that their technology readiness level (TRL) is about 8–9, they have already been demonstrated in real aircrafts, and they are routinely used in many other industrial applications, like monitoring oil wells. But as said at [2], to get information about damage from strain measurements, additional strategies are needed. Damage information can only be got by processing and comparing the raw signals received from the sensors before and after damage occurrence, in an attempt to identify the "features", or parameters that are sensitive to minor damages and that can be distinguished from the response to loads and environmental disturbances.

To validate an SHM system and enable their large-scale applicability, the effectiveness and damage detection sensitivity of the SHM technique must be quantified with respect to its ability to accurately determine the actual health condition, as it is done for any other NDE method. The effectiveness of the NDE method is quantified by the term NDE reliability, which is defined as “the probability of detecting a crack in a given size group under specified procedures and inspection conditions” [3]. NDE reliability is expressed in terms of the flaw size having a detection probability of 90%, a90. Nevertheless, there is certain statistical uncertainty associated with the value of a90, which is represented by stating a 95% confidence interval. This crack size is represented as a90/95 and serves as an important parameter to quantify NDE reliability. The NASA POD developments for quantifying the NDE capabilities were proposed in the ‘70s and very soon accepted as a standard method. MIL-HDBK- 1823A [4] is currently considered as the state-of-the-art guidance for conducting POD studies by the USAF and other industries. Very succinctly, what is needed is to get, for the given inspection system, a plot similar to the drawing given at Figure 1

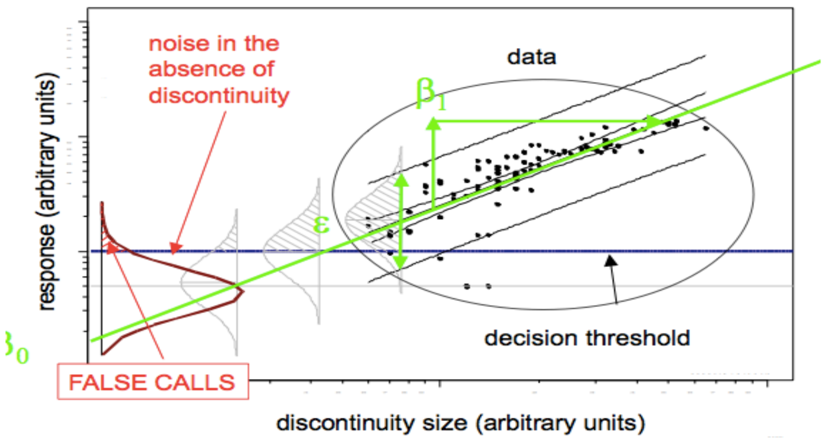

Figure 1. Reliability chart requirements for SHM systems (from Ref 5)

To build such a plot requires a lot of experimental data, which are costly and time consuming; the experimental effort can be reduced with an adequate numerical model of the NDT process. Simulation allows for a deeper understanding of the inspection method, allowing for a larger number of ‘virtual experiments’ conditions and the optimization of the system. And this is particularly true for the case of SHM system, because sensors are at fixed positions, and running real experiments changing the position of the damage respective to the sensors would be costly prohibited.

Monitoring damage in bonded repair patches, instrumented either with PZTs or with FOS, has been a classical exercise for SHM, because certification of bonded structures poses many difficulties, and SHM could be a way to overcome this issue [6]. It has usually been done under a pure experimental approach [7], and because of the limited number of experiments, the conclusions have mainly a qualitative nature, hardly to extrapolate to other cases.

1. Damage detection from strain measurements

Measuring strains is not the same as detecting damage. It is important to recognize that damage is not a physical parameter, it is just a local change in the materials properties or at the structure connectivities (a crack is simply a new boundary), which degrades their structural performances. Damage can only be detected by comparing the response of the structure to some external estimulae (forces, elastic waves, thermal heating, …), before and after damage occurrence.

There are several procedures for doing it, as mentioned at [2], which may be classified as local or global methods. At this paper we deal only with the global methods, able to detect the damage anywhere at the structure.

1.1 Damage detection algorithm

The changes in the global strain field promoted by a local damage are very small a few centimeters away from the crack, and may be easily faded out by natural disturbances or by the noise of the measurement system. Data analysis procedures are needed to identify the systematic deviation caused by the damage. We are using one of the simplest and more robust procedures, the Principal Component Analysis (PCA). The original data are re-expressed in a new orthogonal basis where the data are arranged along directions of maximal variance and minimal redundancy, called the principal components. Damage indicator for this technique is the Q-index. Verified software for doing PCA analysis is available as Matlab tools. Full details are given at [8].

1.2 Simulation algorithm for a fiber-optic based SHM system

The former algorithm may work with experimental data from strain measurements, obtained from mechanical tests on the structure, before and after damage occurrence. A large number of tests are needed in order to get statistical significance. To run several experiments on the pristine structure is quite feasible, but only one case of damage location may be tested, so a limited number of experimental cases can be done.

Strain data can also be generated by a Finite Element Model (FEM). As sketched at figure 2, a conventional FEM analysis can be applied to the structure, and once the sensors position are defined, it is straightforward to get the array of strain data for these positions. Similarly, after the damage position and size is defined, a similar FEM model may be applied, and again the strain data at the sensors position can be produced. It has to be noted that essentially the same FEM model may be used, the crack is simulated just by disconnecting the nodes of the elements around the crack; a refined mesh at the crack tip is not needed, because only the global strain field is needed. It has to be pointed out that everytime something is changed at the FE model, some differences will appear at the numerical results; but to mimic the reality, it is needed to add to the numerical data a random value representing the noise of the measurement system.

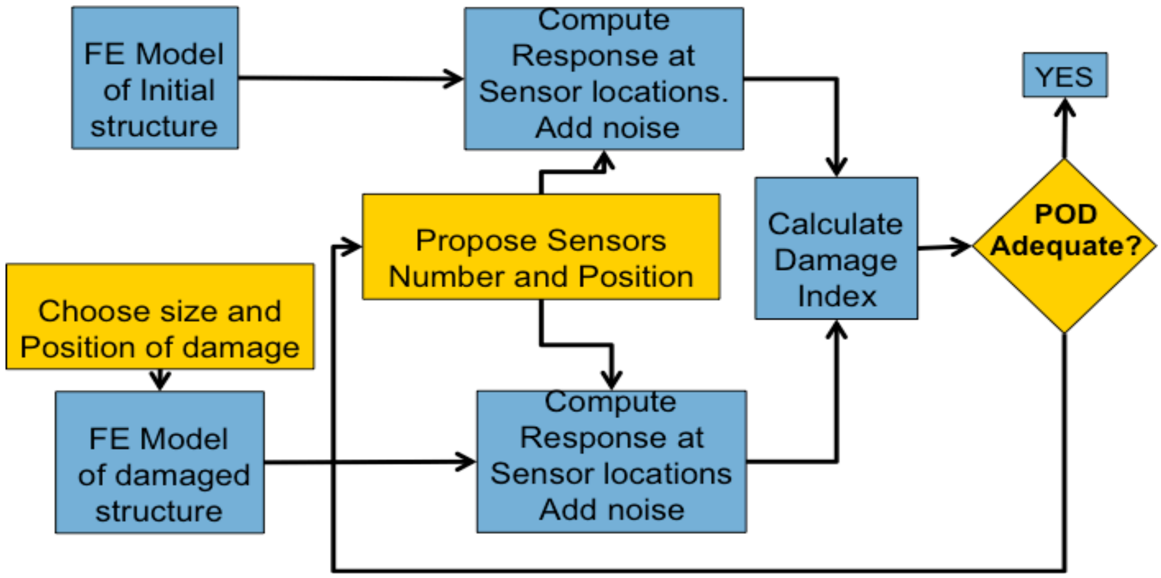

Figure 2. Algorithm for simulation of a strain-based SHM system

1.3 FEM model description

The above-mentioned algorithm is applied to a simple exercise, simulating a repair patch, as sketched at fig 3. The finite element analysis is done with NASTRAN. A linear static analysis of a rectangular aluminium plate is represented with continuous shell elements (CQUAD and CTRIA). The plate is uniformly loaded in one of the edges of the panel and clamped at the opposite side. The length of the panel is large enough to obtain a homogeneous stress distribution in the far field. A single horizontal slit was placed in the middle of the panel. The slit is simulated by releasing the node connectivity throughout the slit length.

An aluminium square cover plate is simulated with the same material as the main plate (Al 7075: E = 71.7 GPa and e = 0.33) and the same thickness (2 mm). This patch is placed on top of the slit and 45 degrees reoriented respect to the principal direction of the panel.
The linear static analysis was repeated after detaching different percentages of the cover plate (0%, 5%, 10%, 15%, 25% and 50%). The detached percentage is simulated by disconnecting the common nodes between the panel and the cover plate from the left side to the right side of the plate. Strain measurements were obtained at the four corners of the crack cover plate in the principal direction of the panel.

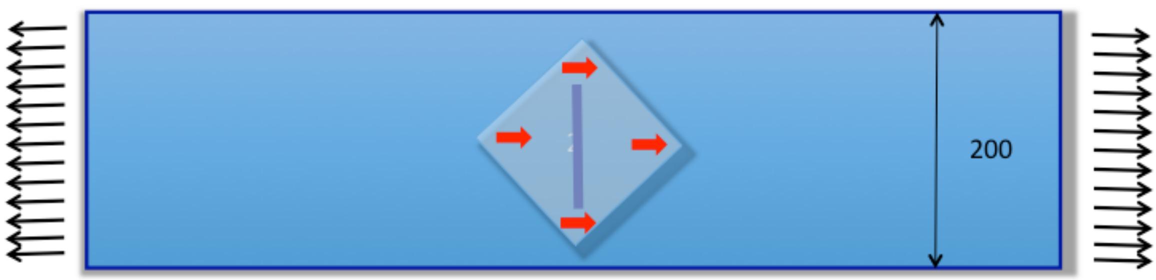

Figure 3. Plate with a bonded repair patch. Red arrow are sensors position

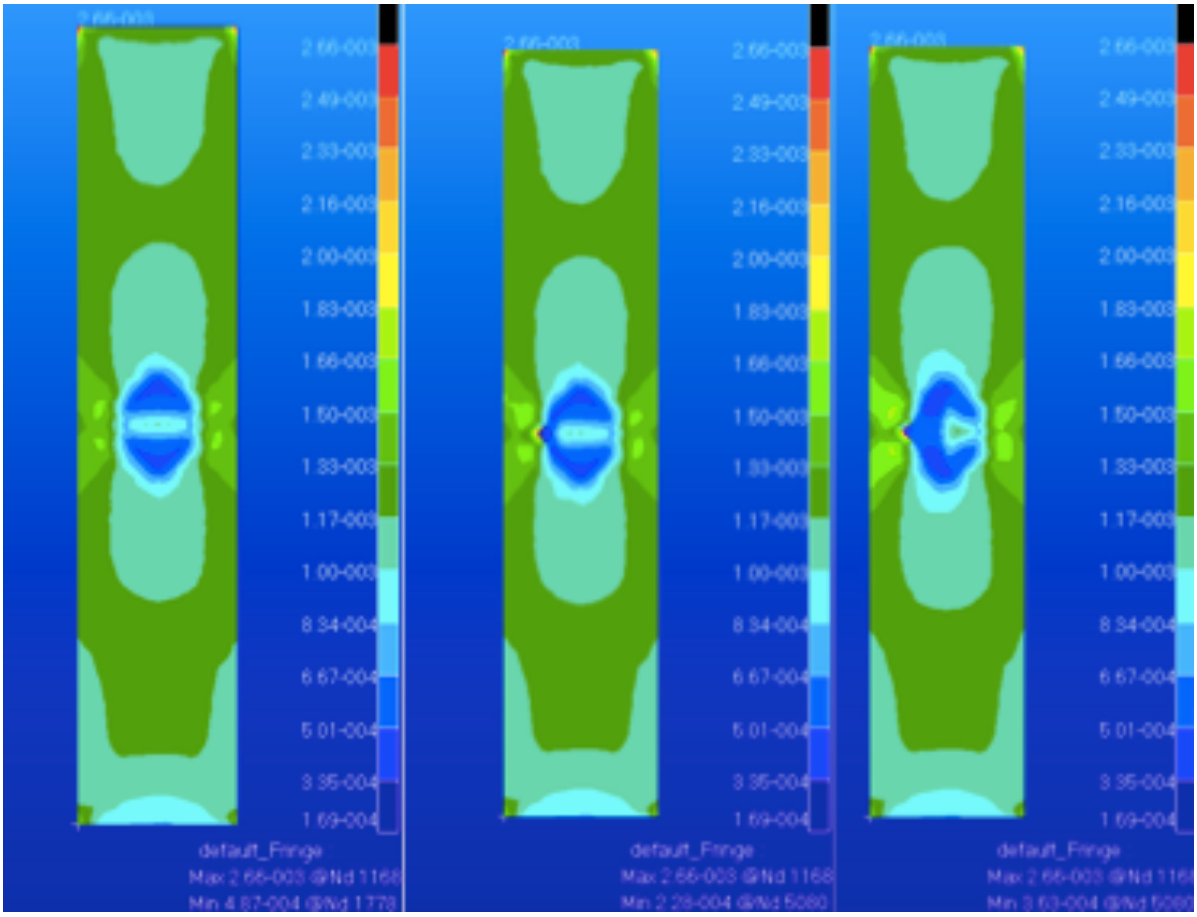

Figure 4. Strain field (longitudinal component) at the pristine structure, and after detaching 25% and 50% , respectively

With clean numerical results, all cases could be distinguished, but after adding a random noise to the data (assuming that noise of the interrogation system has a normal distribution with a standard deviation of 5 microstrains), the differences were not so evident. After applying the PCA, a damage index is obtained for each simulated measurement data, as represented at figure 5. Results are not fully satisfactory for this example; there is a nearly linear dependence of the damage index and damage size, as it should be, but the dispersion of data are growing with the damage size, which impedes the linear regression analysis as explained at [4], which require uniform variance.

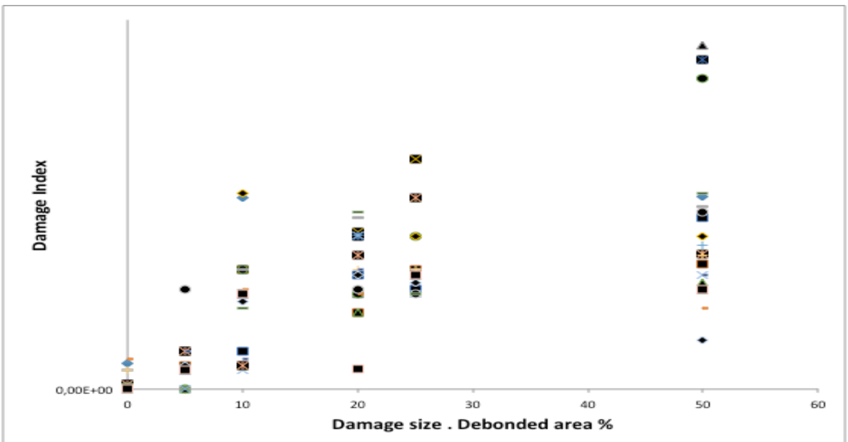

Figure 5. Damage Index .VS. increasing percentage of debonding

2. Conclusions

To validate an SHM system and enable their large-scale applicability, the reliability of the SHM technique must be quantified, with procedures similar to those used for NDT and described at MIL HDBK1823. It required a large number of test data, obtained experimentally or with the help of numerical simulation.

A fiber optic based SHM system is relatively easy to simulate, because optical sensors are just strain sensors; Finite element models allow to reproduce the strain field, with/without damage. At the example worked at this article, a repair patch instrumented with four sensors, it has been found that the dispersion of results grows with damage size, which will do the approach non valid.

A careful analysis of the results shows that it is not due to the modeling itself, but to the data comparison algorithm. PCA is useful to handle large multivariate data sets, but it implies a data compression to the main principal components. When the number of variables is not so large (4 for this analysis), this data reduction introduces significant errors. Other procedures, like the Mahalanobis distance, which does not simplify the data set, would be more efficient for this analysis.

Acknowledgements

This work has been partially sponsored by the DACOMAT Project. The DACOMAT project has received funding from the European Union's Horizon 2020 research and innovation programme under GA No. 761072.

References

[1] Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft. SAE ARP6461 (2013)
[2] Güemes, A. Fernández-López, A, et al., “Structural Health Monitoring in Composite Structures by Fiber-Optic Sensors” Sensors 2018, 18(4), 1094.
[3] A.P. Berens and P.W.Hovey, 1988. Statistical evaluation of NDE reliability in the aerospace industry. Review of Progress in Quantitative Nondestructive Evaluation, Vol. 7B, 1761-1768, Springer, USA.
[4] MIL-HDBK-1823-A, 2009. Nondestructive evaluation system reliability assessment. US Department of Defense.
[5] D. Forsyth, et al., “Development and Validation of the Model Assisted Probability of Detection Method,” QNDE 2009, Providence RI
[6] Alan Baker, Andrew J. Gunnion & John Wang (2015) On the Certification of Bonded Repairs to Primary Composite Aircraft Components, The Journal of Adhesion, 91:1-2
[7] M. Frovel, et al., “Repair Patch Monitoring With Embedded Optical Sensors by a Residual Strain Release Technique”, EWSHM 2014 Proceedings, Nantes
[8] J. Sierra, A. Güemes and L. Mujica. “Damage Detection by Using {FBG}s and Strain Field Pattern Recognition Techniques.” Smart Materials and Structures. 25011-25020. (2013)