Numerical Simulation and Improved Correlation Techniques for Low Energy Impact Detection and Damage Characterization with Elastic Waves on Composite Structures

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Abstract

Thin-walled composite aircraft structures commonly used on fuselage and wing skins are prone to in-service impacts that could compromise the structural integrity and could be hard and expensive to detect by traditional methods. The development of a Structural Health Monitoring (SHM) System able to detect and characterize this kind of impacts can reduce the cost for maintenance and inspection and furthermore the results obtained from this system could be used to improve the analysis and design of the structure. However, one of the main challenges of a SHM system is the detection and location of impacts as well as the characterization of the resulting damages.

A SHM system based on the detection of the elastic waves generated by an impact has been developed by Airbus Defence and Space In order to increase the knowledge of the structural response under impact, a set of Numerical Simulations using Explicit Finite Element analysis codes have been performed: These simulations cover different typical aircraft structures and they have been validated against physical tests; however the correlation between simulations and tests present some complexity due to its sensibility to a great number of undetermined factors, the difficulties of wave characterization and the determination of wave times of arrival to a specific location. Due to that complexity, a surrogate modelling optimization process, developed with our partner Mathlas, has been introduced in order to improve the correlation between test and analysis. The target of this study is to develop a robust simulation methodology which could support the development of a reliable Structural Health Monitoring System for real aircraft structures reducing the number of physical tests and improving the methodologies for FEM-Test correlation.

The paper presents details of the different FE Models and test specimens, results from simulation and tests and highlights the advantages and challenges of this simulation and correlation methodology.

1. Introduction

The interest in Structural Health Monitoring (SHM) Systems, that are able to detect and characterize events such as impacts for in-service aircraft, is increasing. One of the main challenges for these systems is the evaluation of low energy accidental impact effects on structures. The Aeronautical Industry tries to focus on Barely Visible Impact Damage (BVID) on thin-walled composite structures such as fuselage panels or wing's skin due to the potential risk it can present.

Airbus Defence and Space (Airbus DS) Structural Integrity Team, in collaboration with ETSIA-UPM and Mathlas has designed a set of Numerical Simulation methodologies, validated with physical tests, to increase the knowledge of the structural response of the structure in terms of elastic waves. The main target is to support the implementation of SHM-Techniques based on Guided Lamb Waves, GLW, (Sánchez-Iglesias, 2016). In addition, a methodology for optimizing some parameters of the simulations is presented, that aims to improve the correlation between test and simulation.

In this article a set of simulations reproducing the characteristics of some impacts produced over aircraft composite subcomponents is presented. The impacted subcomponents are reinforced composite skin panels, representative of a characteristic architecture (stiffeners & frames) of different sections of composite aircraft structures. The structures have been impacted at different locations and with different energies using a gravity impactor with characteristic energies of typical in-service events. The objective of the set of impacts is to capture the response of the structure in terms of GLW. For this purpose, the surfaces of the panels have a piezoelectric sensor network installed, in this case PZT discs (Moon, 1973).

The authors selected the Finite Element Method to perform the numerical simulation of the impacts due to its capabilities to represent arbitrary geometries with a high level of complexity. Abaqus®/Explicit has been considered to currently be one of the best suited tools for this job. The FEM model's simulation of PZT voltage time series are correlated with the test result's real PZT sensors voltages measurements in order to get confidence on this kind of simulations and validate the methodology.

Correlation between FEM simulations and tests measurements present some sensibility to several uncertain parameters. In particular, the study has highlighted some difficulties of wave characterization in terms of the determination of wave times of arrival (ToA) to a specific location. Due to that complexity, an optimization process has been defined to improve the correlation in terms of ToA. This process is based on surrogate modelling, and has been developed in collaboration with Mathlas.

The target of this complete study is to develop a robust simulation methodology which could support the development of a reliable SHM System for real aircraft structures reducing the number of physical tests needed improving the methodologies for FEM-Test correlation in terms of GLW.

2. Motivation

The majority of this study has been developed by Airbus DS in the frame of the Clean Sky European Project within GRA-LW platform. Clean Sky is the largest European research programme developing innovative, cutting-edge technology aimed at reducing CO_2, gas emissions and noise levels produced by aircraft. Funded by the EU's Horizon 2020 programme, Clean Sky contributes to strengthening European aero-industry collaboration, global leadership and competitiveness.

Many specific events can be monitored during A/C lifecycle (Figure 1). In particular, one specific part of the project developed by Airbus DS inside Clean Sky project is devoted to the investigation and development of Structural Health Monitoring Systems based on sensors attached permanently to the structure (SAE, 2013) with the capability of identifying events such as impacts on composite structures during service and evaluating the effect of this impact on structural integrity and airworthiness.

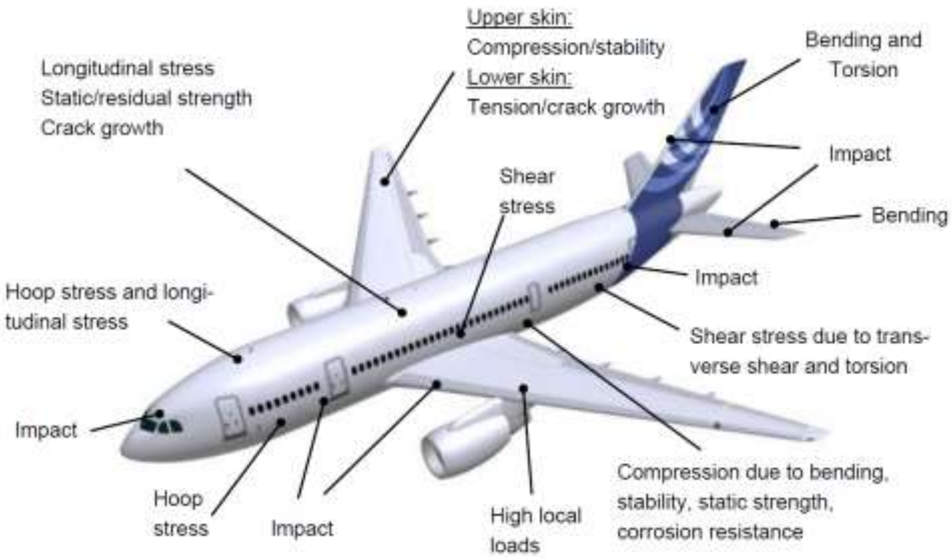

Figure 1 Events or effects to be monitored on an aircraft (Speckmann, 2007).

The objective of the study presented in this paper is the development of a reliable and validated Numerical Simulation methodology that can support the development and improvement of different kind of SHM systems

3. Guided Lamb waves

High velocity impacts against structures generate a high frequency elastic response in the material, that, in thin plates, typical of aeronautic structures, appear in form of travelling waves commonly referred as Guided Lamb waves (GLW).

Lamb waves correspond to a particular kind of elastic wave through an infinite solid constrained by a pair of parallel surfaces (Lamb, 1917). Due to the low damping presented by standard structural materials the GLW can travel long distances with very low attenuation, which makes them suitable for structural health monitoring applications.

Lamb waves can present three different types of propagation modes regarding the particles motion, and different order numbers according to the frequency response:

1. Antisymmetric motion, with out of plane polarization, called flexural mode.
2. Antisymmetric motion, with horizontal in plane polarization, called shear mode.
3. Symmetric motion, with vertical polarization, called pressure mode.

For SHM applications the most interesting types are the zero-order symmetric and antisymmetric (Figure 2).

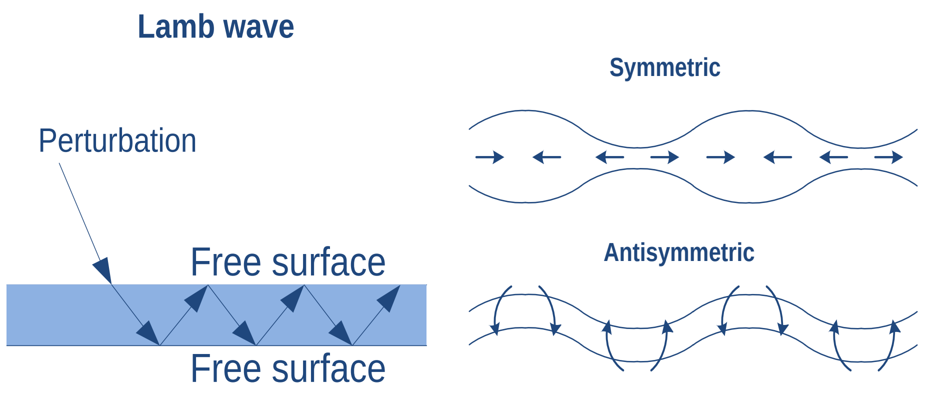

Figure 2 Lamb wave mode shapes

Because of their propagation mechanism these waves can also react strongly even against low energy impacts, suffering the typical wave's phenomena, attenuation, reflection and refraction and can be easily measured and generated by using piezoelectric sensors.

This opens a wide range of applications for GLW because the same sensor could measure the impact structural response and also characterize the resulting damage by actively interrogating the structure in the impact area.

Given that PZT sensors are relatively low weight, they could potentially be permanently installed on a structure, therefore, granting the capability of a permanent real time monitoring system on in-service aircrafts.

4. Experimental Set-Up

Airbus DS, in the frame of Clean Sky project, has developed two Test specimens to support these GLW-based SHM activities:

- A composite stiffened flat panel with longitudinal omega stringers and transversal metallic frames. This panel is installed in a framework as shown in Figure 3.

Figure 3 Flat Panel general view with PZT sensors installed, stiffeners side view (left). Panel with gravity impactor, flat side view (right).

- Double curvature thermoplastic demonstrator panel Figure 4

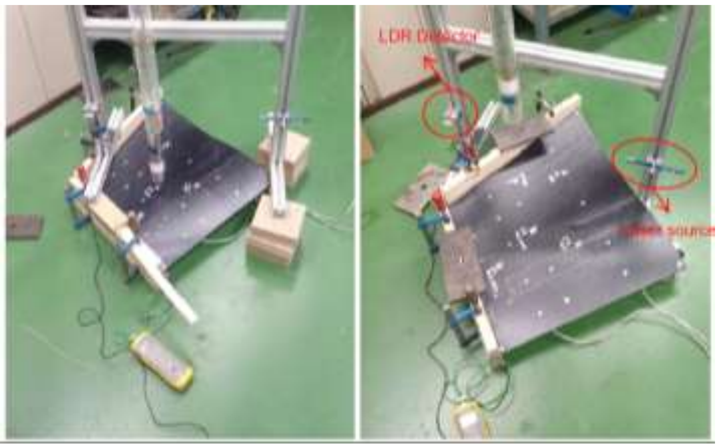

Figure 4 Curved Panel general view with PZT sensors installed. Impact test set-up (ETSIA-UPM)

Both panels have been installed with a network of piezoelectric disc (PZT) at different locations of the panels. The impacts are produced from the flat side using a gravity impactor as indicated in Figure 3 (right) and Figure 4.

The sensor network is connected to data acquisition equipment (and it to the acquisition computer) placed directly by the panel following the schema indicated in Figure 5.

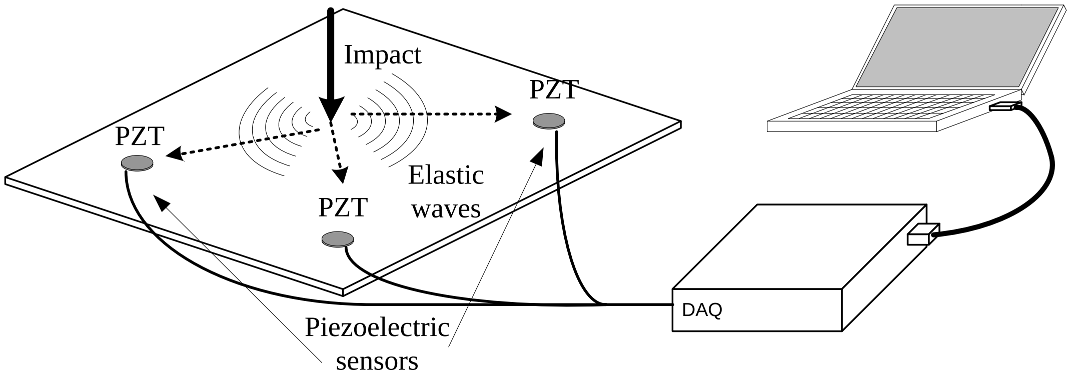

Figure 5 Data acquisition schema for PZT sensors.

The impact response data is acquired using a standard National Instruments® acquisition card. This card runs in-house developed acquisition software based on LabVIEW® environment (ETSIA-UPM). Then the data is stored in a computer and processed using in-house developed Matlab® software.

The acquisition of data is launched using a manual triggering synchronized with the impact (ETSIA-UPM). All data is acquired using National Instruments LabVIEW based software and later processed using Matlab.

The following is a description of the acquisition configuration:

- 8 input channels acquired at a sampling rate of 250 ksps per channel.
- Input range +/- 10 volts.
- Manual acquisition triggering.

The impactor characteristics are the following:

- Mass 3.670 kg.
- Spherical steel tip with 15.8 mm of diameter.

Several impacts are produced in both composite panels in order to correlate them with numerical simulations. Two of the impacts positions and sensors used for acquisitions in flat panels are shown in Figure 6.

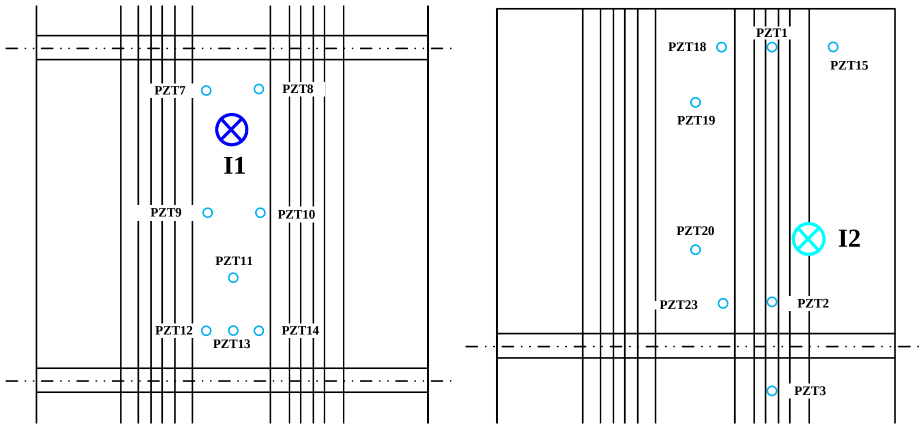

Figure 6 Sensors and impacts positions I1 and I2 (Flat Panel).

Several impacts are produced in I1 and I2 locations. The impacts at 5 Jules energy level have been selected to correlate with Numerical simulations as they are not expected to produce any significant damage.

Due to the limitations on the data acquisition system only 8 sensors can be monitored simultaneously. For this reason, a selection of the closest sensors is performed on each impact. This selection is presented on Table 1.

Impact	**Energy**	**Temperature**	**Damage**	**Acquisition card channel**							
				1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
				PZT sensor number							
I1	5 J	23.3ºC	No	07	08	09	10	11	12	13	14
I2	5 J	24.2ºC	No	18	01	15	19	20	23	02	03

Table 1 Flat Specimen Impact definition.

This is not needed for the curved specimen, as there are only 8 sensors installed in the whole panel. The impact and sensor locations for the curved panel are shown on Figure 7.

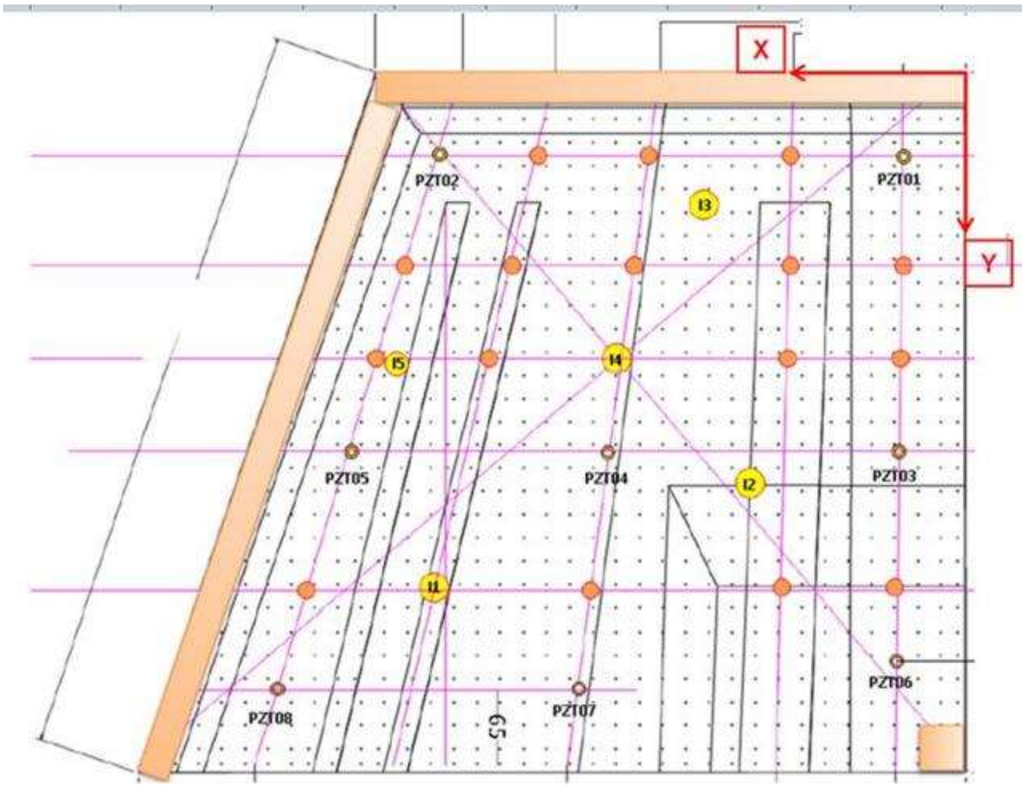

Figure 7 Sensors and impact positions (curved panel)

5. Numerical Simulations

Despite a considerable amount of research effort, due to the complexity associated with GLW propagation, i.e. multimodal nature, dispersion, attenuation, possible reflections from boundaries and other structural features interactions real engineering applications of GLW are still limited. The resulting wave field presents a complex analysis even without taking into account scattering from defects. For this reason, a numerical approach can be very helpful to understand the behaviour of the Lamb waves in a real structure.

The Finite Element Method is especially well suited for problems involving domains of arbitrary shape and is easily available as commercial or freeware software. Since the main emphasis of this problem is the evolution of the signal in the time domain an explicit FEM is used on this report.

In general, we start from Newton's Second Law expressed in matrix format for finite element purposes as:

$$M\ddot{u} + C\dot{u} + Ku = F_{ex} \quad \text{(I)}$$

Where M is the mass matrix, C is the damping matrix, K is the stiffness matrix, F_{ex} is the external loads vector and u, $\dot{u}$ and $\ddot{u}$ is the displacement vector and its time derivatives. The equation can be rearranged to the form:

$$M\ddot{u} = F_{ex} - C\dot{u} - Ku = F_{ex} - F_{in} \qquad \text{(II)}$$

Having a diagonal (lumped) mass matrix the equation becomes trivial to solve, and thus, by using an explicit time domain integration scheme the response of the structure can be simulated.

Given that the geometric space needs to be discretized in such a way that the shortest wavelength of interest is captured (Kocbach, 2000); a large number of increments might be required to solve the model, however, since the stiffness and mass matrix do not need to be formed nor inverted, each time increment becomes computationally inexpensive. This makes the explicit scheme particularly attractive for wave propagation problems.

All the simulations present on this article are performed with Abaqus/Explicit® v6.14-2.

Figure 8 shows a global view of the finite element model used for the flat panel, and Figure 9 for the curved panel. The mesh is not shown on these pictures due to the high element density. Since the amplitude of the wave is sufficiently small, linear elasticity is assumed on the simulation (Drozdz, 2008 and Gravenkamp , 2014).

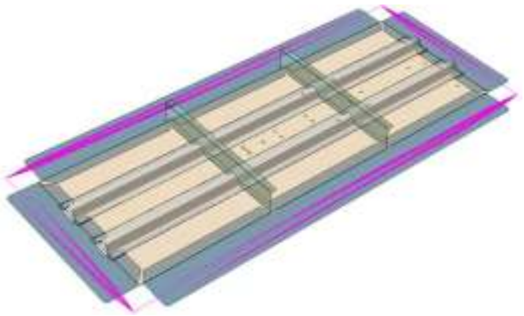

Figure 8 Global view of the FE Model for the Flat Panel

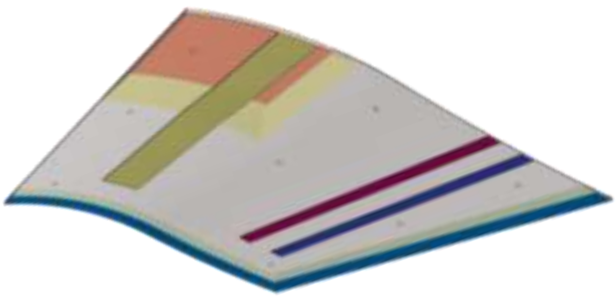

Figure 9 Global view of the FE Model for the Curved Panel

Mesh definition

Composite parts are represented with continuum shell elements (SC8R), as it increases computational efficiency and accuracy. Multiple elements are placed through the thickness to properly represent the transmission of the wave (Han, SeJin 2007).

Due to its low thickness compared to the plate size and to mitigate undesirable hourglassing modes, piezoelectric sensors are modelled as reduced integration shell elements (S4R), sharing nodes with the last layer of the plate elements (Figure 10).

Frames and test tooling are modelled with shell elements and with a far coarser mesh, as the influence they have over the area of interest is limited.

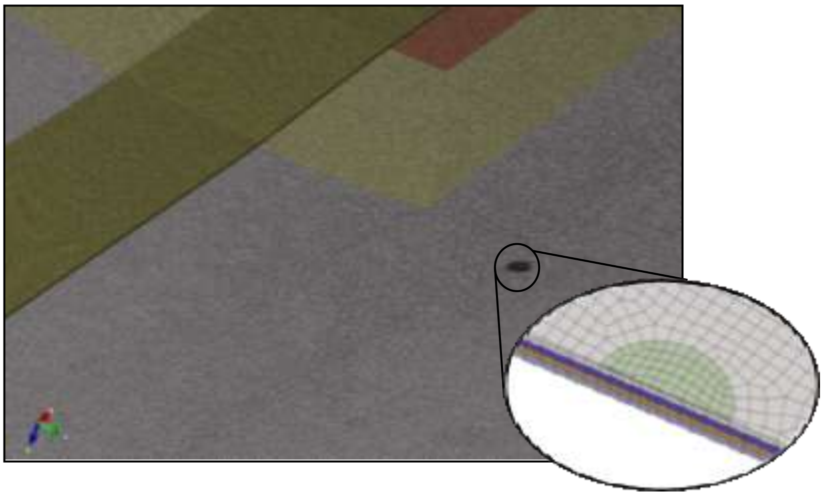

Figure 10 Piezo electric elements mesh detail.

The number of elements per wavelength in the model is a critical parameter due to the aliasing introduced by the discretization. A sufficient number of elements M which must be used to cover a length L with P elements per wavelength is given by (III):

$$M = \frac{PL}{\lambda} = \frac{PLf}{c} \qquad \text{(III)}$$

Where, c is the wave group velocity, λ=c/f is the wavelength and f is the frequency (Kocbach, 2000).

Due to the nature of the problem, the shortest wavelength of interest is the wavelength of the compressional, 10 elements per wave length can give sufficient accuracy for the problem (Kocbach, 2000), and so, by applying the previous equation a maximum element length of 1 mm is guaranteed to be sufficient to satisfy this criterion.

Output data

For verification purposes, displacement output is requested at all nodes of the model, while stress and strain output is limited to the elements representing the piezoelectric sensors.

The analysis simulates a total time of 0.003 s with an output requested a 500 equidistant intervals of time. Figure 11 and 0 show the displacement plot for impact I1 on the flat panel at two instants of time.

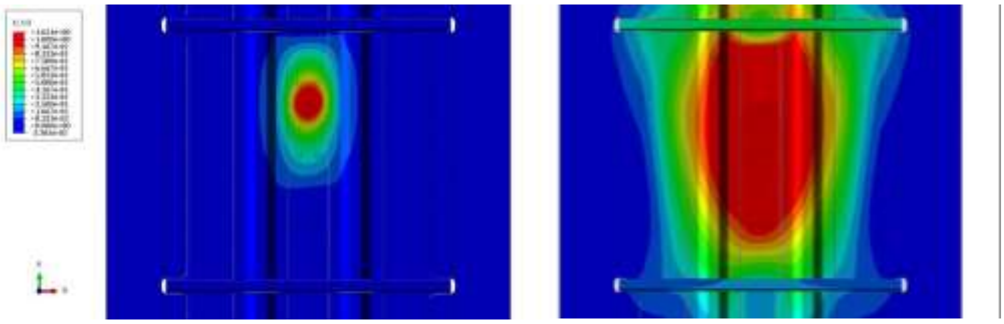

Figure 11 I1 Displacement plot at t = 1.00E-03s and t=3.00E-03s

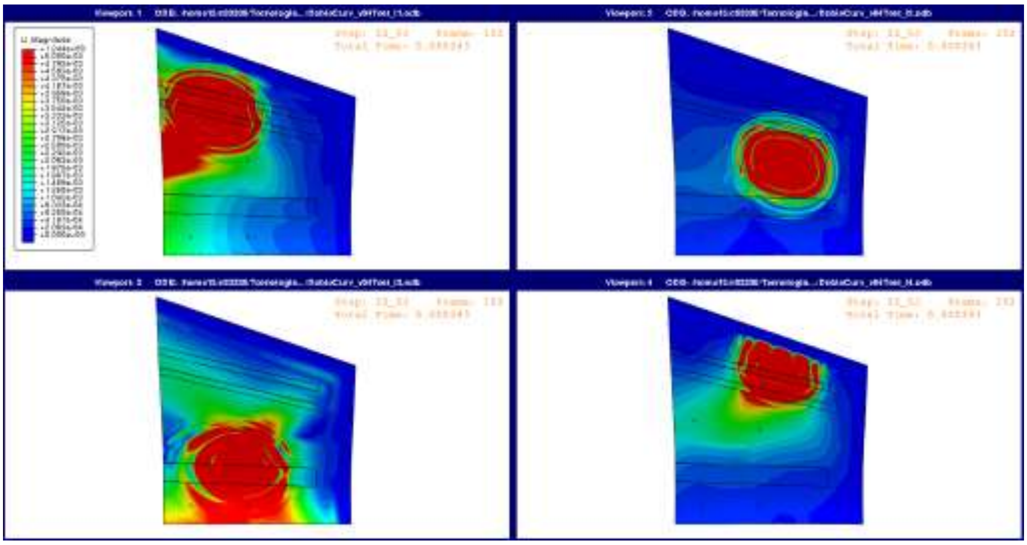

Figure 12 Displacement plot of I1, I2, I3 and I4 on the curved panel at T = 2.43E-04s

The strain values recorded on the elements belonging to each of the piezoelectric sensors is compared with the data recorded on the test. The results are presented on the following section.

6. Numerical Simulation methodology validation

The validation of the simulation methodology is based on the correlation between simulation analysis and experimental tests. The target of the correlation is the matching of the simulated waveform and the acquired waveform using PZT sensors.

To perform this step the signals must be converted into common units, and, in this case, also the simulation output stresses at PZT sensor from MPa to volts using a simplified formula (IV).

$$V(t) = \frac{d_{13} \cdot A_{pzt}}{C_p} \cdot \sigma(t) \qquad \text{(IV)}$$

Where, d_{13} is the piezoelectric constant for the PZT sensor, A_{pzt} is the PZT sensor area and C_p is the PZT sensor capacitance. The results for the flat panel are shown in Figure 13

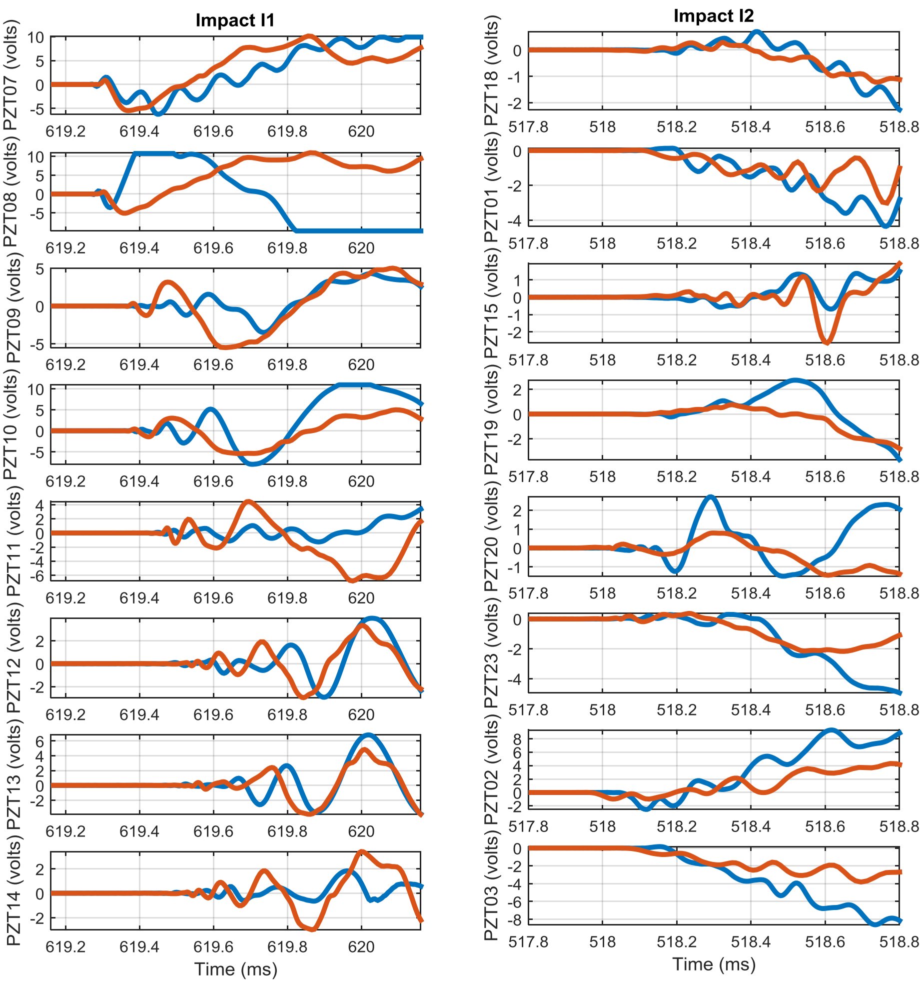

Figure 13 Correlation between experiment and simulation. Flat panel Impacts I1, I2.

Best correlation appears on impacts I3 and I4 as the location is closer to the centre of the panel and far away from the boundary conditions. Results for the curved panel on Impact I3 are shown on Figure 14.

The entire experimental test data to obtain the real values of PZT responses to be used in the correlations and optimizations have been developed in collaboration with ETSIA-UPM partners.

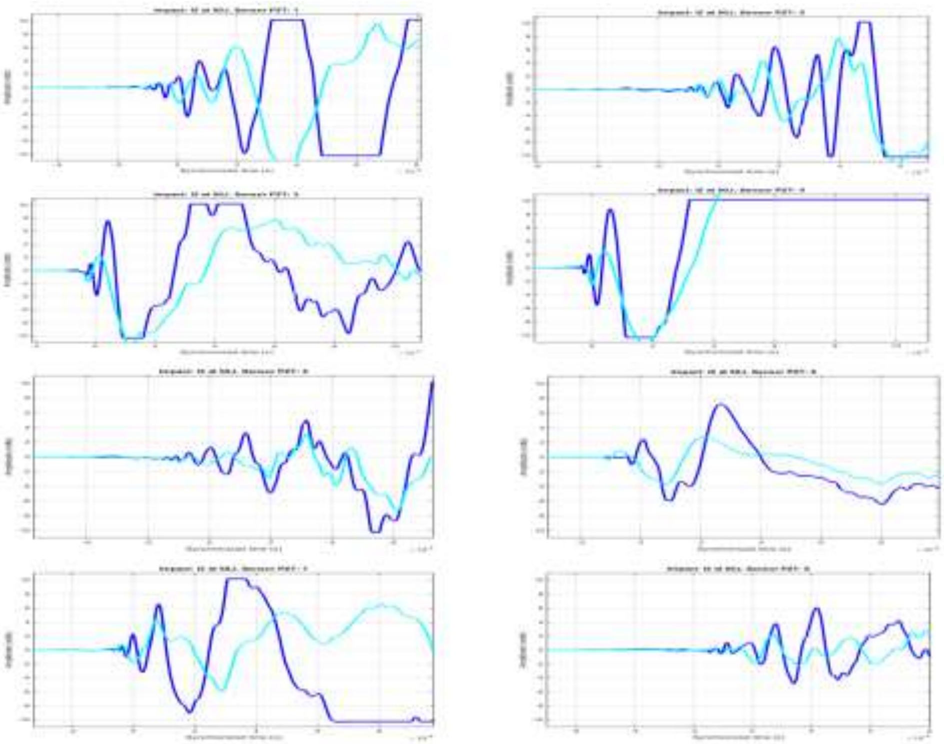

Figure 14 Correlation between experiment and simulation. Curved panel Impact I3

It can be observed on the previous figures that the simulation is able to capture the tendency of most of the signals and predict the behaviour of most of the sensors with an acceptable accuracy. The worst correlation appears on the PZT sensors located closer to the impact and better in the furthermost sensors, but the overall behaviour and adjustment ranges are good.

According to those results, the modelling rule defined in previous chapter has been validated and the FE Model is able to reproduce the main behaviour in terms of GLW response across the panels.

7. Optimization of simulation Parameters

Airbus DS has developed a specific project to study if some parameters used in the Simulation can be optimized to obtain a better accuracy for the correlation. One specific aspects of the correlation between tests and Numerical simulation is focused on establishing the Time of Arrival (ToA) of the GLW to the PZT sensors.

This project has been developed with our partner Mathlas, a company dedicated to identify the best-fit mathematical method for each engineering problem.

The computational cost of the numerical simulation is the strongest constraint of the analysis process. Each analysis could easily take 12 to 15 hours. So, an optimization process based on gradient methods or similar is unfeasible.

Considering these constraints, it has been proposed the development of a Surrogate Based Sequential Optimization (SBSO) methodology. This method is based on an iterative strategy that consists of sequentially sampling the regions of the parameter space where the probability of having an optimum of the figure of merit is a maximal. To identify the region, at each iteration, the method builds a surrogate model of the figure of merit using the already computed points in the parameter space. It has been proposed the use of a Kriging method (Montgomery, 2009) as well as a whole methodology that allows detecting the global optimum minimizing the number of FEM computations.

The SBSO method will depend on some tuning parameters that allow the user to adjust the behaviour of the method. As an example to assess the behaviour of the method this report presents the conclusions obtained with the curved panel DFEM, presented on section 4 in which five calibrated impacts have been applied in different locations along the surface of the panel.

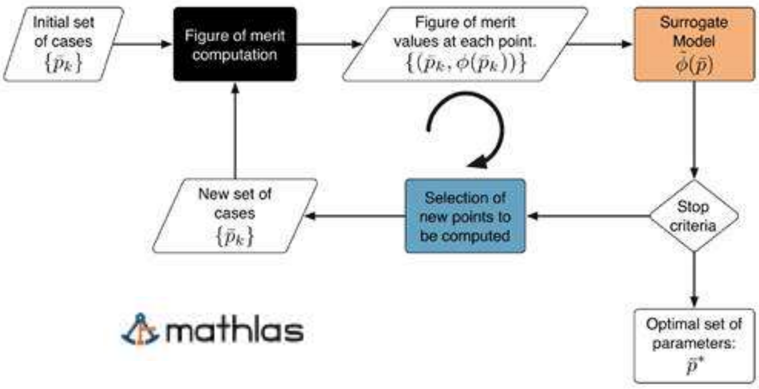

Figure 15 Surrogate model schema (MATHLAS)

For this particular project the following selection of two FEM parameters has been selected as optimization parameters:

- Composite elastic modulus E_{11}
- Structural damping (β)

As mentioned before, one of the critical point of the optimization process is to reduce the number of simulation runs. According to that constraint, in order to select the initial points, a Latin Hypercubes method (Johnson, 1990) has been selected for sampling the parameter space.

The figure of merit (the optimization target function) that has been used in this approach is based on the ToA of the GLW at each PZT sensor. In particular and to avoid different time references between simulation and tests, the time intervals between ToA measured at each PZT with respect to a reference sensor has been selected. For each impact, in both, experimental and FEM results, the reference sensor is the first sensor in detecting the GLW arrival in the experimental results.

The Figure of Merit that will be minimized by the surrogate model is defined as the root mean squared error (RMSE) of the ToA difference, in order to get the parameter set that provides the best approach between simulation and tests in terms of ToA of the Lamb wave to PZT sensors.

The computation of the Figure of Merit requires the evaluation of 5 impacts on the Curved Composite Abaqus model described in section 4; which is a very large CPU-time consuming process. To take this critical constraint into account a Kriging interpolation method (Montgomery, 2009) has been selected to build the mathematical objective function.

The main advantage of the Kriging Method is that, given the input of the Figure of Merit at the known points, the method provides both, an estimation of the Figure of Merit at each point of the parameters space and the estimation of the uncertainty of this figure of merit at this point. According to that output, for the next iteration both the points with high possibility to be close to a minimum and the points with high uncertainty and be selected.

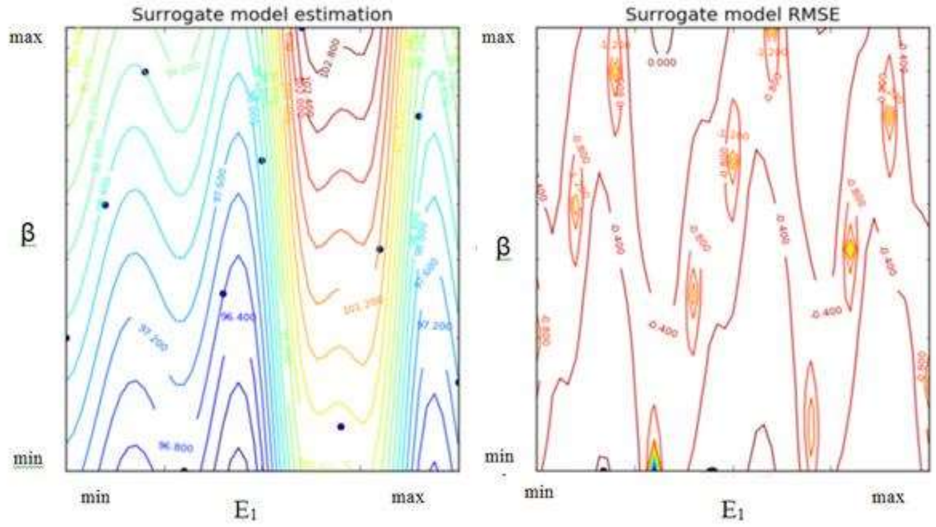

Figure 16 SBSO Initial iteration. Kriging function estimation contours using the 11 initial points (blue dots) selected via LHC (left plot); uncertainty function contours yielded by the Kriging model and candidate points (dots) (right plot) (MATHLAS)

In order to select the next suite of candidates of the parameter space, a complex point selection process has been generated based on Hooke and Jeeves algorithm (Hooke 1960) and Hierarchical Clustering method (Bishop 2006).

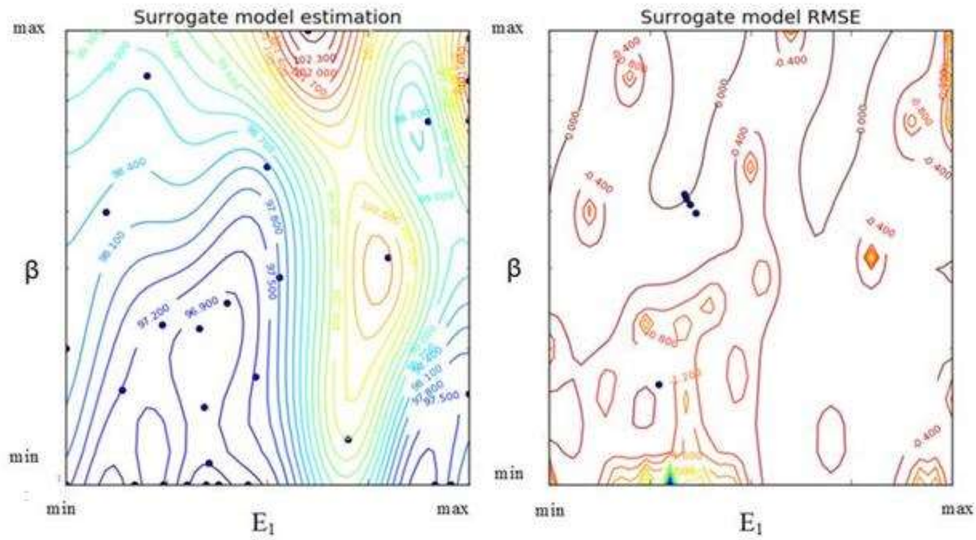

Figure 17 SBSO 10th iteration. Kriging function estimation contours using the 9th iteration points (blue dots) (left plot); uncertainty function contours yielded by the Kriging model and proposed candidate points (right plot) (MATHLAS)

8. Conclusions

During all the test and studies performed during this project, the following conclusions can be stated:

A set of simulations have been run in order to correlate the experimental results in terms of the simulated wave form arriving to the sensor in the first milliseconds. A good correlation has been achieved for most of the sensors; nevertheless adjustments should be made in the structure model and in the PZT modelling in order to improve the results.

The final target should be to gain knowledge in this kind of simulations in order to allow the possibility of virtual testing, reducing the number of physical tests required for functionality validation to the minimum.

As shown in this article, the Explicit Finite Element Model has proven to be a valid tool to simulate the structural behaviour of complex composite structures under low energy impacts and to capture the response at PZT sensors of a SHM system, although some improvements could still be made to enhance the correlation.

Some parameters defined in the Numerical Simulations are suitable to be adjusted to improve the correlation of the Time of Arrival of the elastic waves to PZT sensor. A SBSO model has been generated to optimize two FEM parameters (in the current study, E_{11} modulus and structural damping). This SBSO model is able to find the values for some FEM parameters that optimize the correlation between test and simulations minimizing the number of executions.

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