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VIBRATION-BASED STRUCTURAL MONITORING APPLIED ON HYBRID BONDED JOINTS

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Abstract. *The advent of composite co-cured and co-bonded integrated construction in aircraft structures has lead to the replacement of fastened joints with bonded joints between the skins and the stiffeners. Skin-stiffener debondings could occur due to impact or other operational reasons and it is usually internal. Damage detection of bonded components, which are often vital elements in many structures, is crucial for the prevention of failure of the entire structure. The vibration-based methods have been investigated by different researchers as an alternative technique to be used in the structural health monitoring (SHM) systems. Hence, this work consists of investigating experimentally through the vibration-based method, the dynamic behavior changes in a bonded metal-composite structure using piezoelectric transducer and accelerometers in order to monitoring the damage. The damage is an artificial debonding in the joint, which was simulated by inserting Teflon tapes within the joint. In-situ inspection was ensured by accelerometer and piezoelectric transducers (PZT) bonded to the structure. In fact, analyzing of FRFs (frequency response functions) and/or mode shapes, obtained via the traditional Fourier Transform (FT), it was possible to detect failure. Thus, the experimental results obtained from the accelerometers were compared to the data provided by the smart composite sensors (PZT). Finally, it was discussed the advantages and limitations of the experimental analysis and the detection technique, which depends on the vibration-based methods.*

Keywords: *bonded hybrid joints, smart composites, experimental dynamics analyses, structural health monitoring*

1. INTRODUCTION

During the last decades, mainly driven by the aircraft industry, shipbuilding and power generation, numerous studies have been conducted in order to establish the use of composite materials as an alternative safe, effective and economically viable in the development of new products. In the case of reinforced polymeric composites, it is possible to perform assembly by a bonding process between both composite-composite and metal-composite (hybrid structures) parts. According to Higgins (2000), adhesive bonding of aeronautics primary structures is intensively used on current aircraft projects as a direct alternative of riveting process. However, the degradation of the adhesive layer over the time remains an issue and the inspection of the adhesive layer is complex task since subsurface damages must be removed. Traditional non-destructive techniques (NDT) utilize a variety of methods, ranging from a simple tap test to more complicated approaches, like ultrasonic or thermography techniques. Each of these techniques is limited in accuracy and applicability. Also, a significant amount of equipment and expertise is required to perform the inspection procedures. Although there is some limited success in specific cases, in general, NDT methods have proven successful for bond-line assessment (Qing *et al.*, 2006a).

To overcome these limitations (accuracy and application), it is necessary to develop a cost-effective in-service Structural Health Monitoring (SHM) system to monitor and to assess the instantaneous state of aircraft structures. Thus, several SHM approaches have been developed and evaluated for monitoring bonded joints. Chiu *et al.* (2000) developed a “perceptive repair” or smart system, which will provide information about the in-service performance of the repair and the associated structure. The focus was based on the detection of debonding in the adhesive layer between the repair and the metallic parent part. Some criteria of that smart system were economical, reliable and, preferably, self-powered. Finally, the authors proposed that a piezoceramic material could be used in the smart system because of easy application. Zou *et al.* (2000) presented a review on the model-based delamination detection methods and the application of vibration-based model-dependent damage detection methods in composite structures. Mickens *et al.* (2003) developed a simple vibration-based method of damage detection for monitoring ageing structures. The method intended to detect damage during operation of the aircraft before the damage propagation and the catastrophic failure of aircraft components. The technique used four piezoelectric patches alternatively as actuators and sensors in order to send and receive vibration diagnostic signals. The results obtained by the authors aided to concept a sensor tape in order to detect damage at joints in an aircraft structure. Baker *et al.* (2004) developed methodologies for simulating structural health monitoring (SHM) systems considering adhesively bonded composite repairs of Australian military aircraft. In particular, there was an emphasis on the development of techniques for embedding optical fiber sensors to produce SHM systems. Ogisu *et al.* (2006) presented a feasibility study for employing a damage monitoring system by using a PZT (piezoelectric) actuator and a Fiber Bragg Grating (FBG) optical fiber sensor. The authors showed that it could be detected several types of damage, such as delamination and debonding. Thus, a conceptual design was implemented in order to employ the novel system. Compressive tests were carried out using the coupon specimens with an embedded small-diameter or standard-diameter optical fiber sensor. In addition, it was verified by the researchers that the coupon specimen with an embedded small-diameter optical fiber did not show any degradation of its material properties.

Qing *et al.* (2006a) introduced a real-time active Smart Patch System (SPS) based on smart layer technology for monitoring the integrity of bonded repairs. Three applications were presented: (1) monitoring of the cure progress of the bonded repair adhesive, (2) detection of the initial artificial debonding between the composite patch and the metal structure, and (3) monitoring of the damage repaired by a bonded patch, which is under fatigue cycles. Qing *et al.* (2006b) investigated experimentally the effect of adhesive thickness and its elastic modulus on the performance of adhesively bonded piezoelectric elements, which are used for structural health monitoring. The piezoelectric elements were adhesively bonded to aluminum plates. Hence, the experimental results showed that an increase in adhesive thickness changes the electromechanical impedance and the resonant frequency of the piezoelectric elements as well as the amplitude of the sensor signal. White *et al.* (2007) presented experimental investigations on representative carbon/epoxy composite scarf and over-ply joints. Piezoelectric elements were used to excite and measure the response of the repaired structure. The frequency response signature of the repaired structure with simulated debondings was found to differ significantly from that one with undamaged repair, considering two sets of boundary conditions. Soejima *et al.* (2008) developed a novel damage monitoring system, which can monitor the integrity of composite structures in aircrafts. In that system, FBG sensors were used as sensors, and piezoelectric transducers (PZT) were used as the generators of elastic waves, which propagated in the structure to be inspected. Damages such as debonding and delamination were introduced in the bonded sections of the skin and stringers by impact loadings. Zagrai *et al.* (2008) proposed a structural health monitoring (SHM) approach based on nonlinear ultrasonic response for rapid diagnostics of structural connectors and joints. Experimental studies showed variation of the nonlinear response of the joints due to applied structure loads by the authors.

Baker *et al.* (2009) demonstrated the effectiveness of the strain-based SHM approach for monitoring the boron/epoxy patch repair of a critical fatigue crack in an F-111C wing. In addition, conventional strain gages were used in the SHM system. White *et al.* (2009) described a development of an SHM technique for the detection of debonding in composite bonded patches based on frequency responses. Two commonly used repair schemes, the external doubler repair and the scarf repair, were investigated by the authors. Experimental analyses were conducted by using the frequency responses of the repairs with and without defects considering different boundary conditions. It was verified that damage could be detected through changes in the frequency responses for both types of repairs. Quaegebeur *et al.* (2011) proposed a structural health monitoring strategy in order to detect debondings in a composite lap-joint. The investigated structure was a composite carbon/epoxy part bonded to a titanium plate, and artificial debondings were simulated by inserting Teflon tapes of various dimensions within the joint. Finite element analyses and experimental tests were carried out in order to validate the efficient detection of the damage and to evaluate the accuracy of damage size estimation. Esmaeel *et al.* (2011) calculated the Energy Damage Index (EDI) based on a novel vibration-based damage detection methodology by using the Empirical Mode Decomposition (EMD), which is used to predict damage due to absence of bolts in common industrial bolted joints. Finite element model, which use the implicit dynamic solver of the commercial software Abaqus^{TM}, and experimental tests were carried out. Results showed that the EDI based on the EMD method is a powerful tool not only for detecting the damage, but also for estimating the progression of the damage in bolted joints.

Medeiros *et al.* (2012) presented a study case about the usage of health monitoring metrics and techniques for detecting damage by using numerical simulations (Finite Element Analysis) and experimental data (vibration test) of a cantilever beam. The approach based on Frequency Response Function (FRF) is used. Also, Ribeiro *et al.* (2012) and Medeiros *et al.* (2013) presented an investigation about the damage effects on the structural response, considering filament winding composite tubes damaged by impact loading. The computational analyses were carried out by using an impulse load, which excited the structure, and piezoelectric, which measured the output data. The results showed that the application of vibration-based methods for detecting damage is feasible. Borges (2012) investigated experimentally and numerically through the vibration-based method the changes in a metal-composite bonded joint using piezoelectric patch and accelerometers in order to monitoring the damage in the joint. This damage, artificial debonding, is simulated by inserting Teflon tapes within the joint.

As observed at the literature discussed earlier, it is possible to verify many works about structural health monitoring in bonded joints, but it is not common to find scientific contributions, which study hybrid metal-composite bonded joints. Moreover, considering these specific contributions, it is very rarely to have works about structural health monitoring of Carbon Fiber Reinforced Polymer (CFRP) parts bonded to a titanium plate with or not damage. To overcome this scientific problem, researchers present vibration-based methods to perform SHM system in composite structures. It is import to say that the vibration-based method uses not only piezoelectric transducer but also accelerometers to measure frequency response functions (FRFs). The design of a SHM system involves not only the integration, acquisition and visualization but also the analysis and interpretation of the data. In fact, the data studies are required to distinguish the damaged structures from the undamaged ones and it has received considerable attention in the technical literature. Since the SHM system will produce an enormous amount of data, it is important to select the appropriate information. Then, an innovative analysis of measured data and accurate interpretation of extracted features are required in order to provide an effective diagnostic and/or prognostic of the structure. Thus, a successful SHM system involves selection and placement of sensors suitable for measurement of key parameters, which influence the performance and the integrity of the structure. Therefore, this work consists on investigating experimentally through the vibration-based method, the dynamic behavior changes in a bonded metal-composite structure using piezoelectric transducer and accelerometers in order to monitoring the damage. The damage is an artificial debonding in the joint, which was simulated by inserting Teflon tapes within the joint. In-situ inspection as ensured by accelerometer and piezoelectric transducers (PZT) bonded to the structure. In fact, analyzing of FRFs (frequency response functions) and/or mode shapes, obtained via the traditional Fourier Transform (FT), it was possible to detect failure. Thus, the experimental results obtained from the accelerometers were compared to the experimental results provided by the smart composite sensors (PZT). Finally, it was discussed the advantages and limitations of the experimental analysis and the detection technique, which depends on the vibration-based methods.

2. MANUFACTURING OF THE SPECIMENS AND EXPERIMENTAL ANALYSES

In the present study, single lap hybrid bonded joints of titanium and CFRP parts was manufactured by using an epoxy adhesive film. The CFRP plate is made of 7 plies stacked in $[0/90°]_7$ layup configuration. This material is specified by Hexcel^{TM} as M20/G0904/47 (epoxy and carbon fiber bidirectional), which is an epoxy resin M20 reinforced by bidirectional textile carbon fiber G0904. After the cure process recommended by Hexcel^{TM}, the CFRP plate has 47% fiber volumetric fraction. In fact, the composite parts are obtained from a composite plate following the specifications provided by Military (2002) and by Hexcel^{TM}, using a vacuum bag method and hand layup lamination process. This manufacturing procedure was selected because it is the most widespread and it is used in repair situations involving such materials. It is important to mention that the vacuum bag technique ensures versatility and operational facility, which can be performed at controlled environment (e.g. laboratories) or even in field (for instance, a repair installed in the aircraft component).In addition, thermal blankets have been used to promote the heating of the composite material during the curing process (*c.f.*, Table 1). Subsequent to this process, the composite plate was cut into six specimens with 390 mm of length, 25.5 mm of width and 1.7 mm of thickness. It is noteworthy that the use of seven layers is due to the fact that many different structures with thicknesses ranging from 1.5 to 2.0 mm were found in the aircraft maintenance area.

Table 1. Cure cycle for the specimen (ASTM D3039/D3039M).

Parameters	**Values**
Vacuum (in. Hg)	23
Heat up (°C/min.)	3
Cure temperature (°C)	120
Time dwell (min.)	90
Cool down (°C/min.)	-3
Final cure temperature (°C)	50

The metallic part was made of a titanium alpha-beta alloy Ti6Al4V (AMS4911). This material has excellent mechanical properties as well as impact resistance. Thus, in order to cut the titanium parts from the plates, it was used a guillotine-type knife parallel. Then, it was made up milling the edges for better finishing and assembly of the final set. The titanium part geometries consist on 390 mm of length, of 25.9 mm of width and 1.6 mm of thickness.

The adhesive is made of the film EA934NA epoxy Henkel^{TM}. However, Hysol EA934NA is a bi-component thixotropic paste adhesive, which cures at room temperature and possesses better strength values when the cure process occurs at 300°F / 149°C. The thixotropic nature and good compressive strength values are very important for potting, filling and fairing, as well as for shim applications. Hysol EA934NA is qualified as MMM-A-132 Type 1, Class 3 for room temperature cure. It is important to highlight that the damage is an artificial debonding in the joint, which was simulated by inserting Teflon tapes within the joint.

In order to carry out the vibration tests of the hybrid bonded structures, it was used an accelerometer and a piezoelectric transducer (smart composite). By one side, the PCB Piezotronix accelerometer (part number 333B30)has the following specifications: modal array, ceramic shear ICP, sensitivity 100 mV/g, measurement range from 0.5 to 3k Hz. By other side, the smart transducer is made of Lead-Zirkonate-Titanate (PZT) ceramic type Midé QP10n. In fact, the piezoelectric transducer consists of a piezoelectric layer made of PZT ceramic and epoxy matrix, which is covered with thin electrodes on the top and bottom side. More details about this transducer can be found at Medeiros (2012).

Piezoelectric ceramic is capable of providing a very precise signal of voltage due to very small amounts of imposed strain as a sensor. The same effect is true in reverse, i.e. a signal of strain is provided by the transducer due to the voltage applied. Hence, a controlled input signal can produce an efficient response in the material, when the device is used as an actuator. In this work, the PZT transducer was used only as a sensor, not as an actuator. The piezoelectric transducer was bonded in the titanium surface using a vacuum bag for compacting and removing volatile during the cure process of the adhesive, which was performed at room temperature. Figure 1 shows the entities used during the experimental tests and important specifications of dimensions.

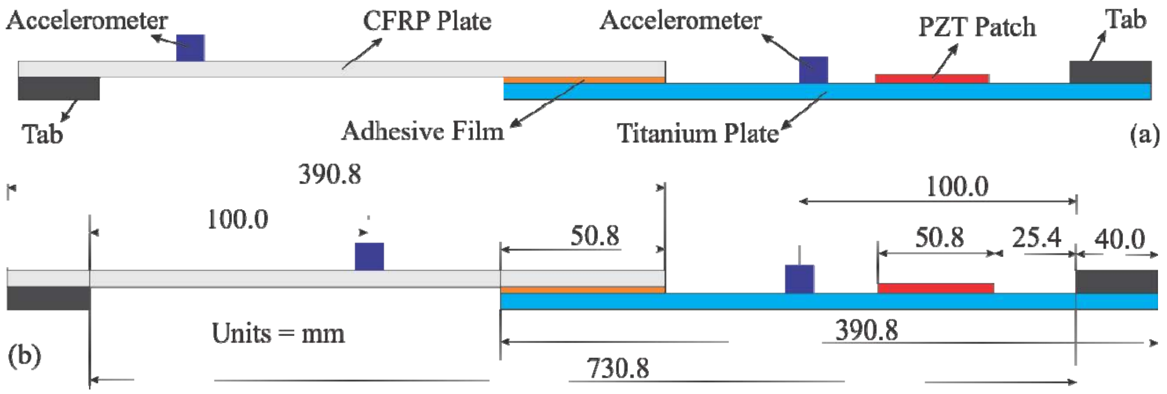

Figure 1. Experimental model: (a) single lap hybrid bonded joint with accelerometer and piezoelectric transducer attached to the titanium part and (b) important dimensions.

Four experimental models were studied in order to represent different scenarios, which the joint can be subjected in operation (in service – Fig. 2). The first model (Model 1) represents the intact joint, i.e. without damage. It should be used as reference for comparison with other cases. Therefore, the dynamic responses for this structure were treated as the dynamic signatures of the joint. The second model (Model 2) contains a damage area in the joint, which corresponds to 50% of debonding. As commented earlier, these two models were monitored by accelerometers in order to identify the damage influence on the dynamic behavior of the joint. After that, the third and fourth models (Model 3 and Model 4) were similar to the first e second models, respectively. However, these models were monitored by PZT transducer attached to the metallic plate (*c.f.*, Fig. 2). These models can evaluate the monitoring capacity of the bonded joint hybrid structure, undamaged and damaged, by accelerometer and piezoelectric transducers. As commented previously, in order to simulate the debonding, a constant non-adhering film (Teflon film) is placed between the adherents (metallic and composite parts), during the curing process of the hybrid joint.

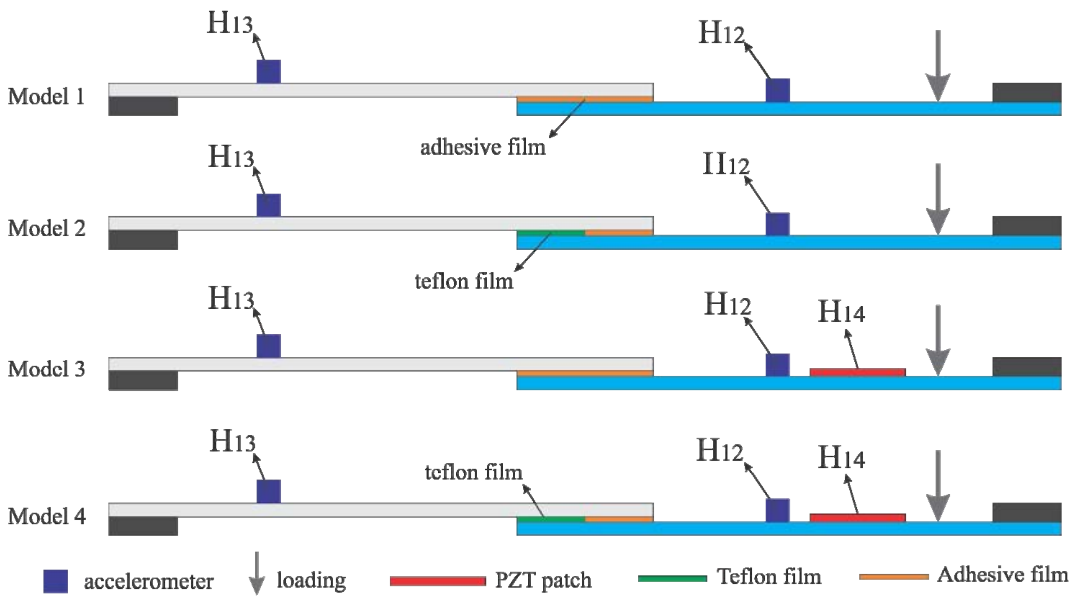

Figure 2. Schematic representation of each experimental model (studied specimens)

The experimental analyses consist of verifying dynamically the response of the hybrid joint. The data acquisition set-up used in the experimentation was controlled by a PHO 200 LDS (signal acquisition Photon II), which is a plug and play, multifunction analog, digital and timing I/O board for USB bus computers (Fig. 3). The input signals were generated by using an impact force hammer (PCB Piezotronix part number: 0860 – Fig. 3). This type of input can excite over a wide range of frequencies. This is important because different damages can affect different frequency ranges of a structure, and the resonant and antiresonant characteristics of a structure are good indicators of damage. In fact, this approach is a more global indicator of damage compared to methods, which use single frequency tone bursts and wave reflection. The FRFs can indicate damage, which is inside the structure, whereas they may not be as sensitive to small damage on the surface as compared to wave propagation methods.

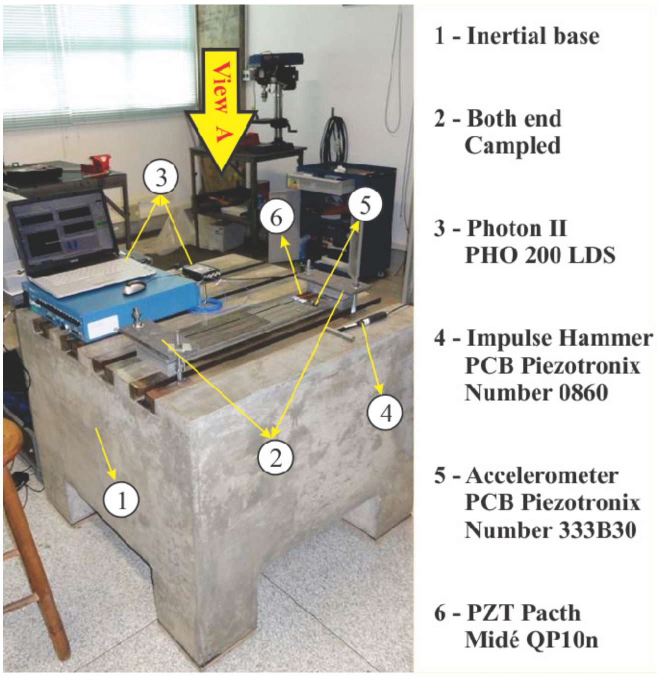

Figure 3. General set-up of the experimental tests

Some important aspects need to be considered due to the specimen assembly. For this reason, all the specimens were assembled together in order to minimize undesired effects caused by the clamped devices, for example, pre-stress due to assembly (Fig. 4). However, these effects were not evaluated during the experimental analyses, because the specimens were fixed together and the axial load created by the clamped device was kept as low as possible in order to avoid changes in the dynamic behavior of the specimens (*c.f.*, Fig. 4). However, it was not considered the vibration effects from one specimen to others and vice-versa.

Based on the experimental set-up shown by the Fig. 4, it was investigated the vibration-based damage identification for hybrid joints. It is important to notice that the fundamental idea for this method consists on the principle that the damage changes the physical properties (damping and stiffness) of the structures. Hence, these changes cause modifications in modal properties (natural frequencies, modal damping and mode shapes). For instance, it is possible to observe reductions in stiffness due to cracks. Therefore, damage can be identified by analyzing the changes in vibration behavior of the structure. Hence, the knowledge of the vibrational behavior of a structure can be used to determine the existence as well as the location and extension of damage. As known, dynamic responses can be expressed in the time or frequency domain. For linear systems, there is a little loss of information when the data are converted from the time domain to the frequency domain. In this work, the FRFs are obtained from the ratio between the FFT (Fast Fourier Transform) of the response (output) and the FFT of the excitation (input). Thus, an impulse force signal was used to excite the structure (input) and the output was measure by using PZT transducer and accelerometers. In each case, excitation signals from an impact hammer were applied as perpendicular loading on the titanium part, and the output signals were obtained from the positions, where accelerometers (H_{12} and H_{13}) and PZT sensor (H_{14}) are attached (*c.f.*, Fig. 2). Each time signal gathered consisted of 8192 points and they were sampled until 1000 Hz. The number of averaging individual time records was selected to be five in order to reduce the random fluctuation in the estimation of the FRFs. After the data acquisition, they were saved in a file to be analyzed by using a signal processing software (Dynamic Signal Analyzer – Photon II). Finally, in order to identify the debonding damage, the FRFs for undamaged and damaged joints were compared.

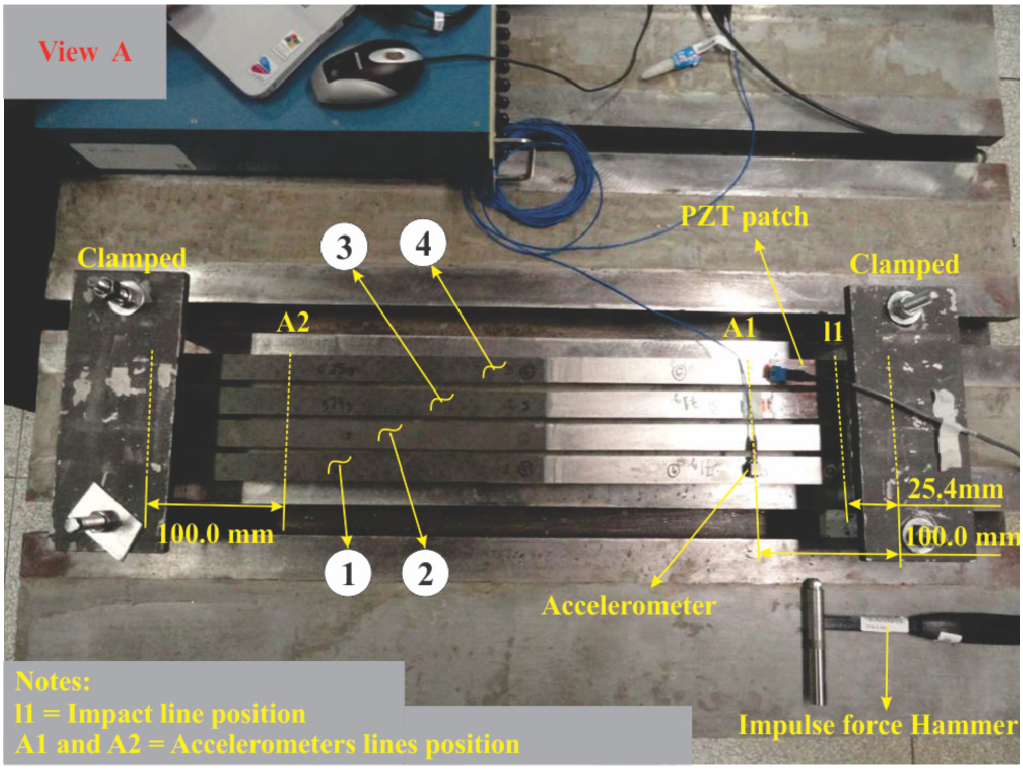

Figure 4. Assembly and position of the specimens

3. RESULTS AND DISCUSSION

First of all, the peaks of the measured FRFs contain significant information of the hybrid joints, such as natural frequencies, damping and, it may be possible to identify damage. In order to evaluate the potentialities and limitations of SHM system, which uses vibration-based damage identification, three case studies were investigated by using the experimental models shown previously. In the first case study (Case Study 1), it was not only investigated the vibration feature of the hybrid joint, but also the influence of the PZT transducer in the dynamic structural response. Hence, in this study, it was used the Model 1 and the Model 3. In the second case study (Case Study 2), it was evaluated the damage model by using accelerometer (without PZT transducer). Thus, it was used the Model 1 and the Model 2. Finally, the third case study (Case Study 3) consists of evaluating the damage model by using PZT transducer. Therefore, it was analyzed the Model 2 and the Model 4. It is worth to mention that once the frequency increases with the presence of PZT transducer, the FRF response becomes more dependent on the structure in the neighborhood of the sensors and actuators.

3.1 Case Study 1 - Influence of PZT Transducer

The experimental Model 1 (intact without PZT sensor) was carried out in order to use as a reference for the development of the vibration characteristic for the hybrid joint. The experimental Model 3 (intact with PZT sensor) was performed in order to verify the influence of the piezoelectric sensor in the dynamic structural response. Thus, there is a comparison between the experimental FRFs, measured by accelerometers, for the both end clamped joints with and without piezoelectric transducer (*c.f.*, Fig. 5 and Fig. 6). Based on the dynamic responses, it is noted primarily the changes of natural frequencies. These changes are due to not only the increase of mass, but also by the changes in the stiffness with the presence of the PZT sensor.

Regarding to the signal measured by accelerometer, it is important to observe that the FRF curves are much clearer below 500 Hz. Thus, it may be difficult to observe changes in the FRFs due to debonding, considering frequency ranges higher than 500 Hz. Another important aspect to be observed regarding to the accelerometer signal was a slight difference in the signal from the accelerometer (H_{13}) with and without the PZT transducer, especially between 200 Hz and 350 Hz (*c.f.*, Fig. 6).

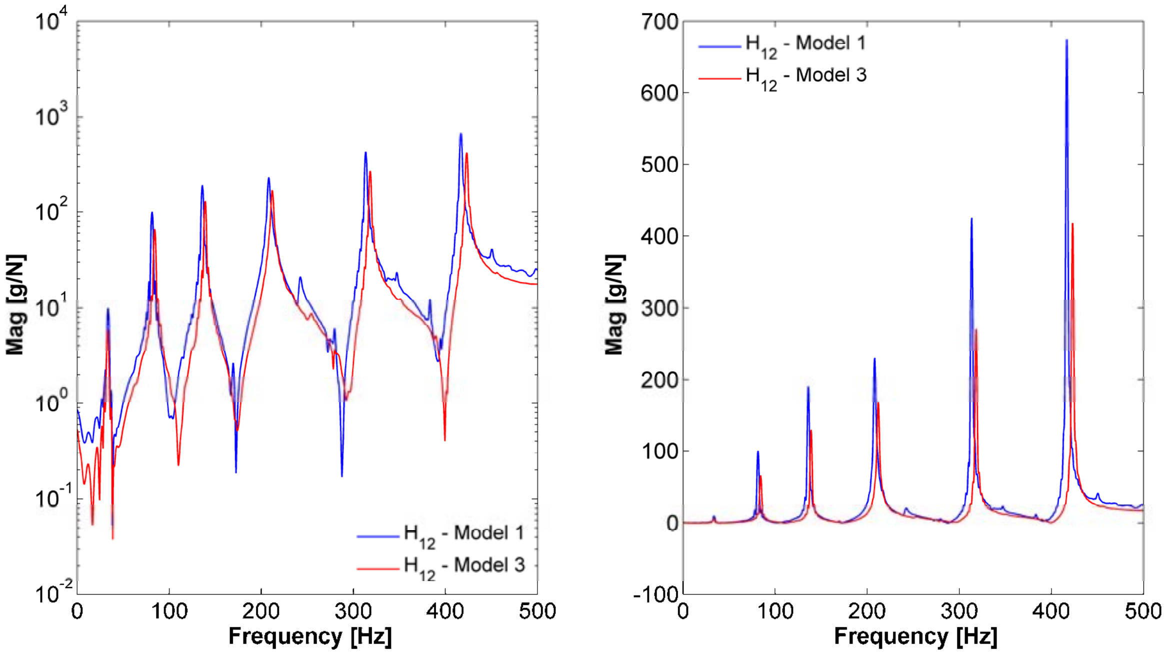

Figure 5. With *vs.* without piezoelectric transducer FRFs for H_{12}, Model 1 and Model 3 – Case Study 1

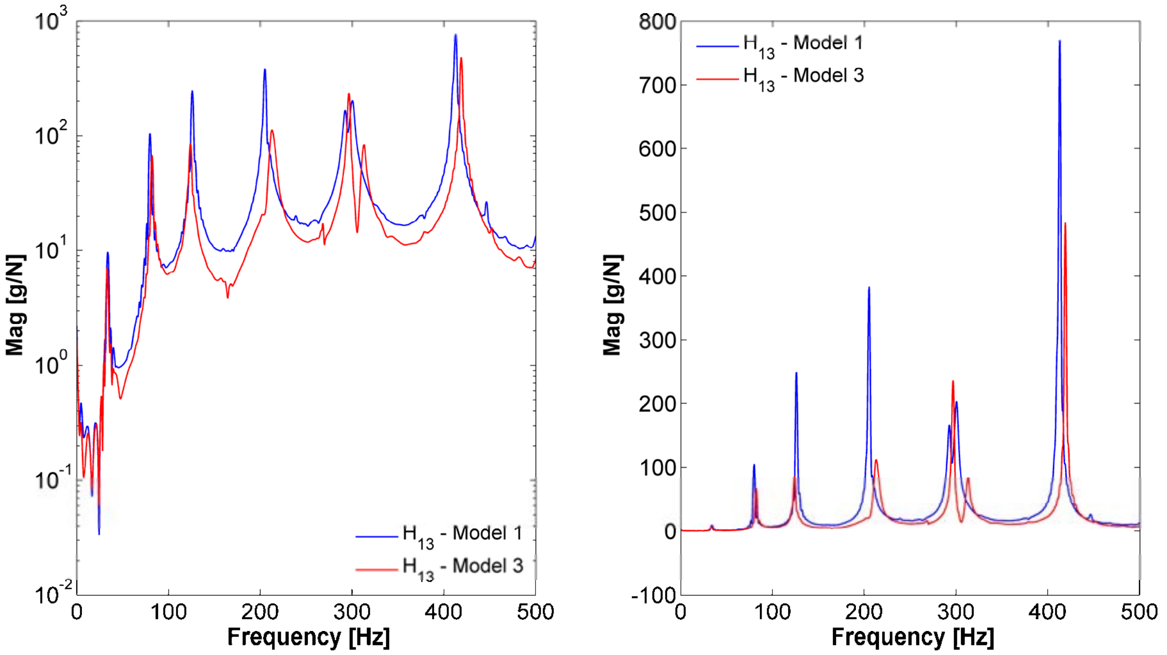

Figure 6. With *vs.* without piezoelectric transducer FRFs for H_{13}, Model 1 and Model 3 – Case Study 1

3.2 Case Study 2 - Damage detection without PZT transducer

The case study 2 consists of analyzing hybrid single lap joint specimen, with and without damage, by using accelerometers. The FRFs for the intact and damaged joint are shown in Fig. 7 and Fig. 8.

Regarding the damage in the experimental Model 2, it shows that it lost structural stiffness due to the debonding failure. As commented earlier, the experimental tests were carried out by using the same set-up for both models, i.e. it was used the same assembly. Thus, the changes observed in the FRFs could not be created by the differences in assembly procedures.

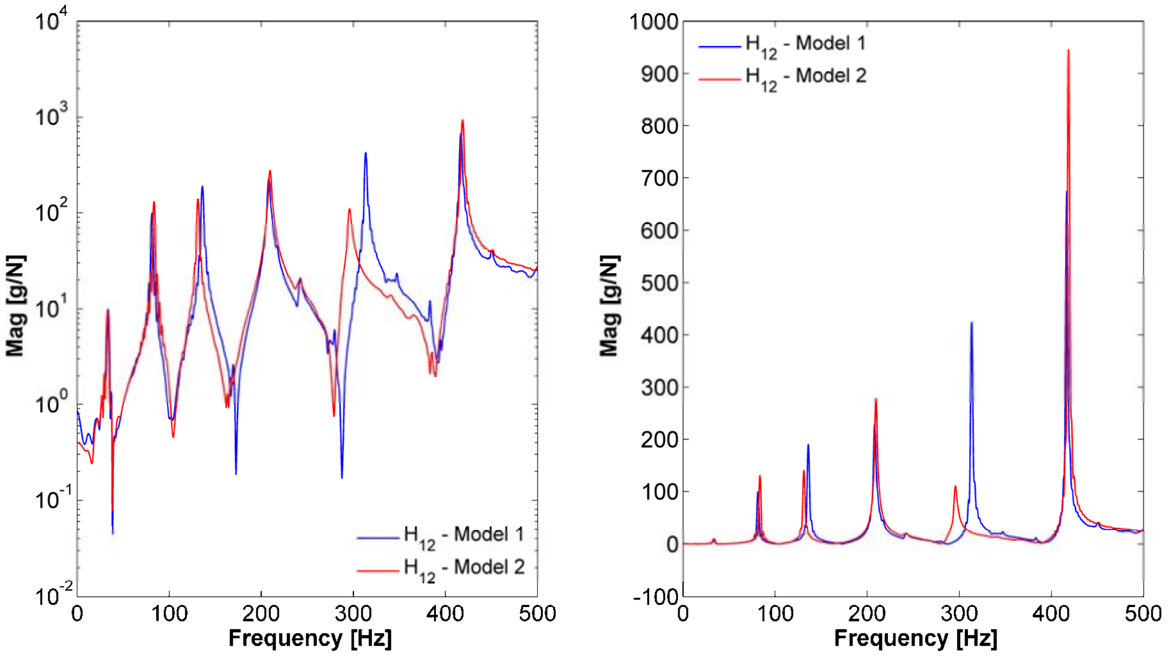

Figure 7. Intact *vs.* damaged FRFs for H_{12}, Model 1 and Model 2 – Case Study 2

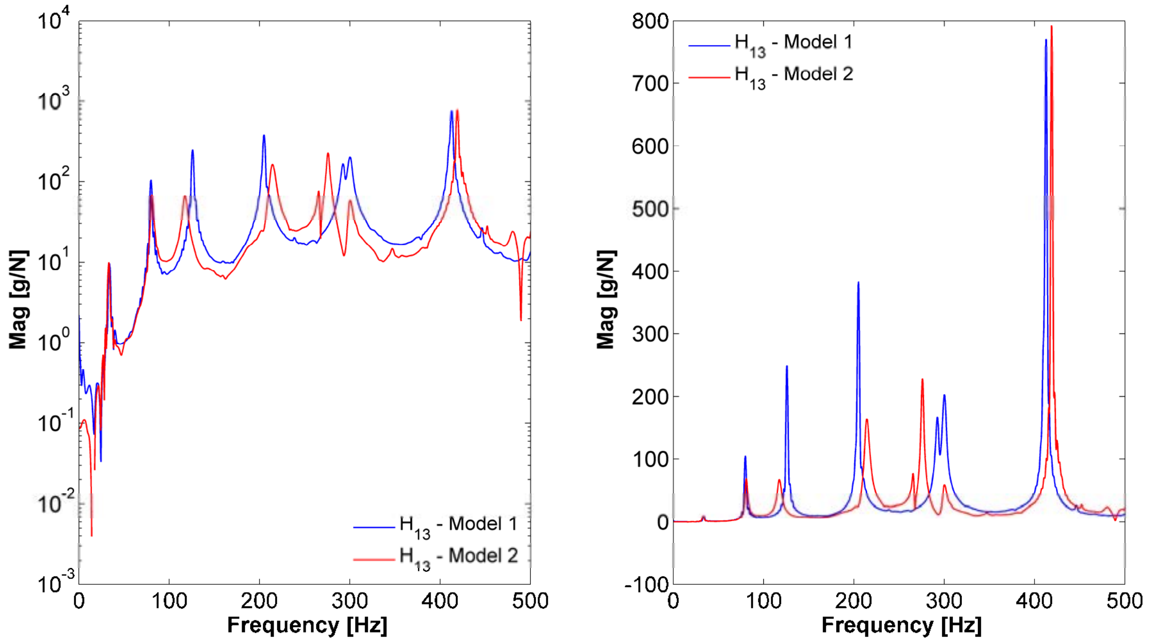

Figure 8. Intact *vs.* damaged FRFs for H_{13}, Model 1 and Model 2 – Case Study 2

3.3 Case Study 3 - Damage detection with PZT transducer

The case study 3 was carried out in order to evaluate the applicability of the vibration-based monitoring technique by using PZT sensors. For both measured procedures (accelerometer and PZT), it is evident that the damage investigated in this study produces modifications in the FRFs. These changes are shown by the lower frequencies, but they are more pronounced at higher frequencies (above 500 Hz). However, as commented before, the signal response is not so clear for these frequency ranges. In fact, there is a frequency reduction, which can be explained by classical structural dynamics. This behavior was expected because the joint loses ability to transfer loading with the debonding area in the joint. Comparing the FRFs by using a PZT transducer and the accelerometers, it was verified that the damaged model has a lower stiffness (*c.f.*, Fig. 9 to Fig. 11).

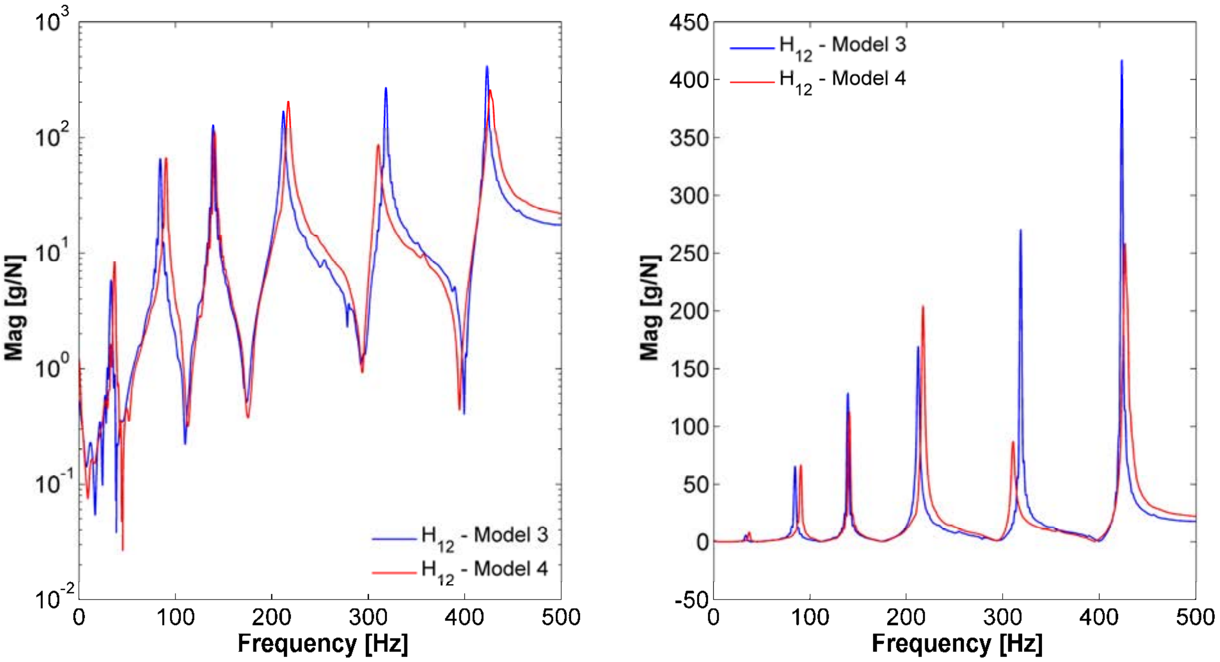

Figure 9. Intact *vs.* damaged FRFs for H_{12}, Model 3 and Model 4 – Case Study 3

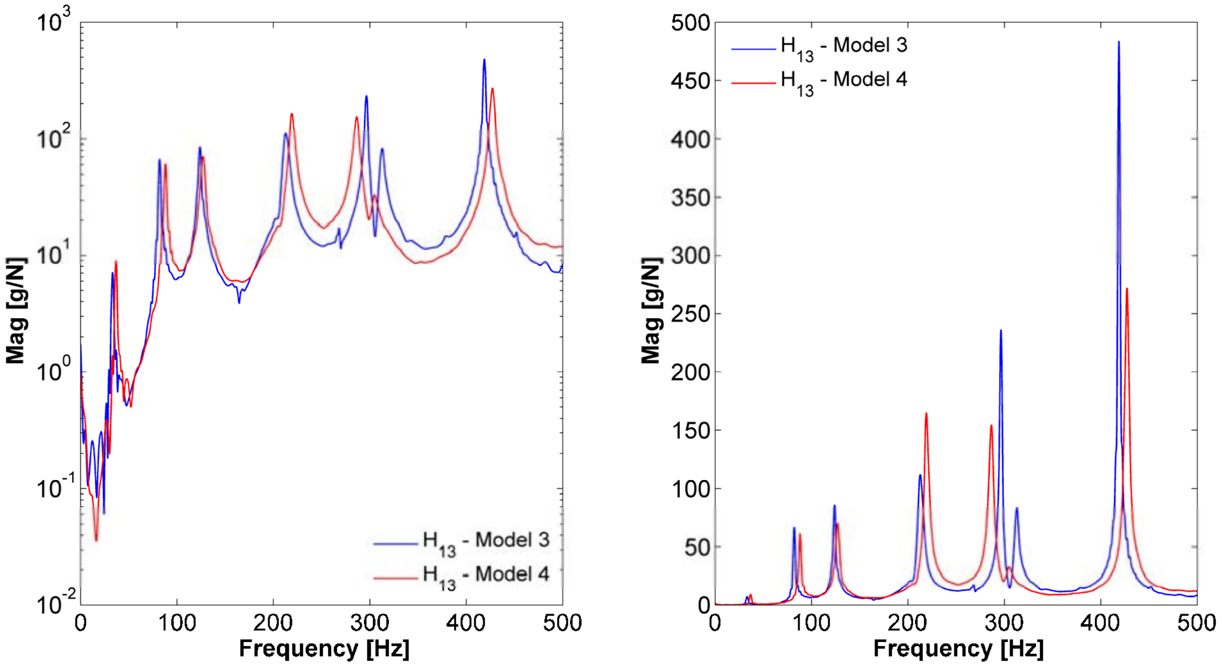

Figure 10. Intact *vs.* damaged FRFs for H_{13}, Model 3 and Model 4 – Case Study 3

Furthermore, the signals obtained by both the accelerometer and the piezoelectric transducer exhibit good consistency, although there are low differences between the signal from the accelerometer and the PZT transducer. In addition, the resonance peaks of the PZT are above the peaks presented by accelerometers. This indicates that the PZT transducer also influence on the damping of the joint.

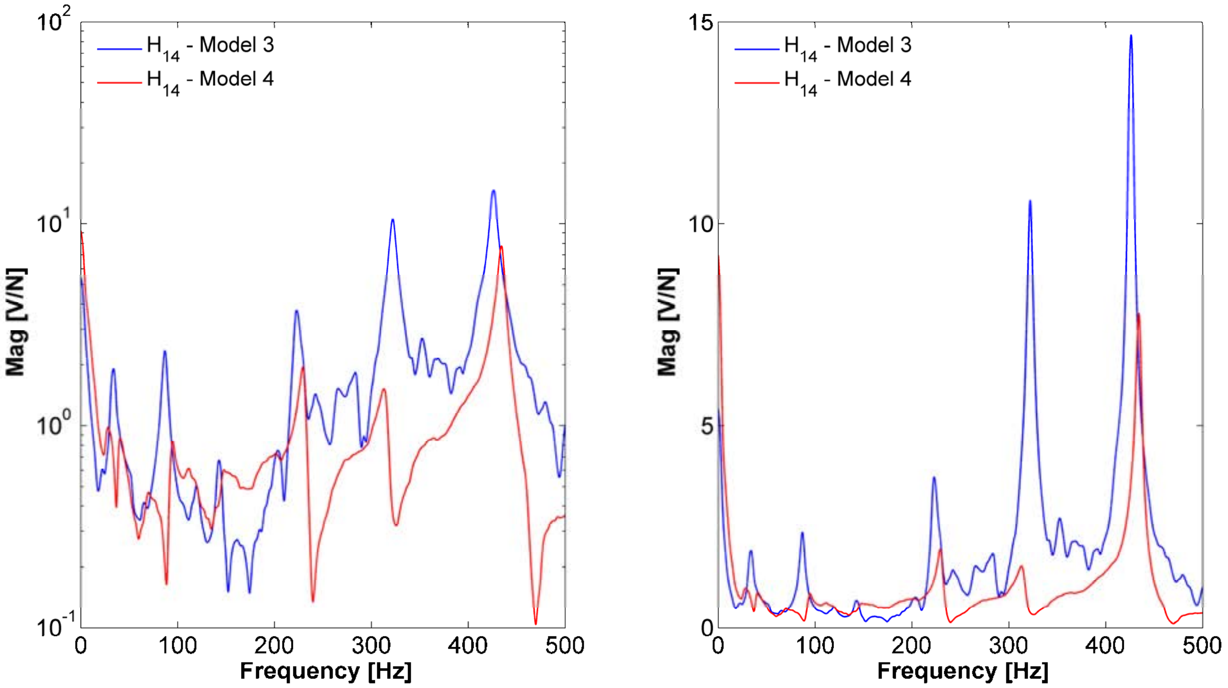

Figure 11. Intact *vs.* damaged FRFs for H_{14}, Model 3 and Model 4 – Case Study 3

As observed from the FRFs, it is possible to identify the damage in the hybrid joint but, sometimes, depends on the size and location of the damage, as well as the interest frequency range, it is very complicated to do this task. By other side. the FRF is desirable from the viewpoint of applications for SHM systems, because structural FRFs are sensitive to small changes and damage in a structure. To quantify this sensitivity, a damage indicator was developed to calculate the difference in the FRF responses between intact (undamaged) and damaged structures. The damage indicator for the structure is developed considering firstly the percent difference between the magnitude of the FRFs of the undamaged and damaged structures. Any physical quantity can be used to compute the FRF, such as acceleration/force, velocity/force, displacement/force, strain/force or PZT (piezoelectric) sensor voltage/PZT excitation voltage. The damage indicator *D* is obtained by computing the mean value of *y(f)* for the frequency range of interest.

$$y(f) = \mathrm{abs}\left(\frac{\left|H^{i}\right| - \left|H^{d}\right|}{\left|H^{i}\right|}\right), \tag{1}$$

$$D = \frac{\Delta f}{f_2 - f_1}\sum_{i}^{n} y_i(f), \tag{2}$$

where the superscripts *i* and *d* denote the intact and damage structures, respectively, and the vertical bars represent the magnitude of the function. Also, f_1 is the lower frequency and f_2 is the upper frequency of the range of interest and Δf is the frequency increment between measurement points. In addition, the equations (1)-(2) provide a damage indicator, which gives a normalized measurement of damage in the structure. These values once collected for different sensor/actuator pairs can roughly quantify the amount of damage in a structure. The *D* expression returns values greater than zero if any variation in the structural dynamic behavior occurs, and D will return “zero”, if there is not any damage in the structure.

The *D* values for these analyses are given in Table 2. These values were obtained by a piezoelectric (H_{14}) and a point, which corresponds to the position of the accelerometer (H_{12} and H_{13}). It is important to notice that D(a,b) indicates the point, which is loaded (a), and the point, which is the sensor (b), as given in Fig. 1. It was observed that the damage indicator values for D(1, 2), D(1,3) and D(1,4) were different and the highest value was obtained for accelerometer attached to the composite part. This difference can be explained due to the relation between the sensors and the loading position. The closer this distance, less interference are inserted in the data.

Table 2. Damage indicator for the structure.

Damage Indicator	**Intact**	**Damaged**
D(1,2)	0.0	0.1819
D(1,3)	0.0	0.4949
D(1,4)	0.0	0.1492

The seemingly large value of D occurs because the damage indicator involves division of FRFs. When damage occurs to structures with small damping, the FRFs for the intact and damaged structures misalign. Thus, because they are functions with many peaks and valleys the small misalignments in frequency can cause large changes in their division when the damage indicator function is computed.

4. CONCLUSION

The potentialities and limitations of frequency response techniques for the detection of debonding damage in hybrid joints by using piezoelectric devices has been experimentally demonstrated for set of boundary condition.

The experimental test used to simulate intact and damaged hybrid joints may be used as an alternative to design and to evaluate SHM systems, which uses piezoelectric sensors. Furthermore, the results using only one PZT sensor indicate a severe limitation of the applied methods to provide information about the location or type of damages. In fact, to these tasks, it is recommended a net of PZT sensors. Therefore, the applied method with only one PZT sensor is suitable for a system SHM, which is simply used to identify the presence or not of the damage in the structure.

Although the experimental results have shown some limitations of the vibration-based methods, there are many advantages in employing the method based on FRFs in a SHM system for hybrid joints. For example, vibration-based methods combined to modal analysis provide global as well as local information of structural health condition and do not require direct human accessibility to the structure. In some cases, the PZT sensor can be embedded in the laminate structure. Also, the methods are cost effective and easy to operate, and they have the potential for damage detection in flight (in service). Therefore, it is possible to conclude that there is a great future perspective for the application of vibration-based methods using PZT sensors on SHM systems for hybrid metal-composite joints.

Finally, the application of SHM to hybrid joint has the advantage that the area to be monitored is small and known in advance. Thus, apart from the benefits to repair certification, the application of SHM transducer repair is an excellent precursor for more widespread application of this technology. Adhesively bonded joints are an ideal starting point for real-time, in-situ monitoring due to well defined mechanisms and locations of failure in structural repairs.

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