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Damage Identification of Metal-Composite Bonded Joints using Electromechanical Impedance

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ABSTRACT

In critical applications such as the aerospace, marine and automotive industries, it is very important to maintain the safety of every component of the structures and also to monitor their conditions periodically. Since the use of composite has been more widely utilized to promote a better strength-to-weight ratio, it is especially crucial to foresee a combination of metal and composite in a single structure. However, the adhesively bonded joint is very unpredictable and it is remarkably difficult to estimate its failure. Therefore, it is extremely necessary to perform Structural Health Monitoring (SHM) to identify if damage appears at the joint. Traditional non-destructive approaches are less accurate; vibration causes a change in the stiffness of the sensor causing a false alarm. The EMI method is used in which the dynamic properties of metal-composite bonded joints are examined to identify damage in the structure. A defect that modifies the structure's physical properties, for instance, its stiffness and damping will cause the real part of the impedance response to be shifted to lower frequencies when the electromechanical impedance (EMI) method is performed on Metal-to-metal single lap joint, Metal to thick composite single lap joint, Metal to thin composite single lap joint. The damage quantifying metric Correlation Coefficient Deviation Metric (CCDM) of value 1.1386 and Root Mean square Deviation (RMSD) value of 0.7281 indicates the highest damage depth in the case of Metal to thick composite single lap joint.

1. Introduction

Joints are very important when analysing the behaviour of a structure due to its tendency to failure that is higher than any other points in the same structure. This is because a joint is usually a location where the load applied is transferred from one component to another and the initiation and propagation of failure are likely to occur and may affect the whole structure. In terms of adhesively bonded joints, the adhesive used tends to fail way before the adherents do. The reason is mainly

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because of the weaker mechanical properties of the adhesive as compared to the adherents that it is joining.

Bonded joints are very common in critical applications like aerospace, automotive as well as in marine and bonding dissimilar materials are used to enhance the strength of the structure by taking advantage of each other's properties. There are times when bonding dissimilar materials would be very crucial in their application. Therefore, the materials used must possess the highly required criteria for selecting materials in manufacturing the parts. For example, when manufacturing wing components, it is very important to select materials that have a high strength-to-weight ratio to carry high cyclic loading and also to maintain the high performance of the aircraft by reducing its weight.

Mechanical joints or bonded joints can be used to link materials together. Adhesives are used in bonded joints to bind two or more materials together. The use of mechanical fasteners like rivets or bolts is required for mechanical joints, on the other hand. Compared to mechanical joints, bonded joints are more favoured since they may be assembled without invasive procedures like drilling Ahn *et al*., [1]. As said by Derewońko *et al.*, [2], the adhesion and cohesion forces between the adhesive and the substrates transfer the load in metal-composite bonded joints. It is unquestionably true that the joint itself determines the structural integrity of the components involved in a bonded joint. As a result, it's crucial to give the joint special attention, which can be done by checking its strength. Kweon *et al.*, [3] said that the utilization of adhesive when attaching metal to composite could also be troublesome due to the high sensitivity of the joint concerning external conditions like humidity and temperature. Besides that, the uncertainty of how well structural integrity can last in the long term is also alarming in its applications. Furthermore, the failure of the bonded joints that tend to occur incontinently could create serious disasters, especially in essential applications like the aerospace industry.

Damages in bonded joints like adhesive bonding could be difficult to discover and a Non-Destructive Test (NDT) must be done on a structure to identify it. However, traditional NDT is not very accurate when it is used to identify damage in bonded joints. Therefore, a vibration-based Structural Health Monitoring (SHM) system is presented to replace the old NDT approaches. In a vibration-based monitoring approach, the existence of damage would modify the damping and stiffness of the overall structure and this will be reflected in the change of the natural frequencies, modal damping and mode shapes.

One of the related works relating to this sort of SHM is the perceptive repair by Ogisu *et al.*, [4] where he employed piezoelectric transducers (PZT) coupled with Fiber Bragg Grating (FBG) to sense the delamination and debonding of the adhesive layer. In the same year, Qing *et al.*, [5] observed that the adhesive's geometry and characteristics will influence the electromechanical impedance, resonant frequency and also the amplitude of the sensor signal which is from the PZT patch. To track the deterioration in a bonded joint, piezoelectric transducers and accelerometers. He later discovered that the changes in the joint's dynamic behaviour were brought on by the damage. By obtaining the frequency response functions (FRFs), Gavriloski *et al.*, [6] employed a vibration-based approach to detect damage in a joint made of titanium adhesively attached to carbon fibre reinforced polymer (CFRP).

In the experimental analysis, Teflon was utilized at the joint to simulate damage and the structure's dynamic responses were watched and analysed. Numerical modelling was utilized by Sadowski *et al.*, [7] to examine the behaviour of three different types of joints: adhesive joints, riveted joints and hybrid joints. While the rivet was represented using a 4-node tetrahedral element, the steel laps and plate used in the double lap joint were modelled using an 8-node brick element with limited integration. For the adhesive component, an eight-node three-dimensional cohesive element was utilized. Liu *et al.*, [8] predicted the interlaminar and intralaminar damage evolution using an ABAQUS model of composite laminates.

According to Rosiek *et al.,* [9], the EMI approach makes use of piezoelectric transducers (PZT) that are mounted to the model and whose oscillations directly alter the electrical impedance frequencies. Hu *et al.,* [10] proposed a statistical method to measure the damage quantitatively. They provided a new parameter in this method and used correlation coefficient deviation metric (CCDM) and root mean square deviation (RMSD) to detect the damage. According to Na *et al.,* [11], this method can yield superior results when the defect is in the thickness direction as opposed to the breadth direction when detecting adhesive damage in composite construction. To get the intended results, the positioning of the transducers concerning the surface of the structure was also crucial.

The present study aims to identify the damage in metal-composite bonded joints using the electromechanical impedance method. Furthermore, it analyses the damage in the metal-composite bonded joint by calculating the damage indicators and other statistical approaches.

2. Materials and Methods

The electromechanical impedance (EMI) method was performed experimentally to identify the presence of damage in the structure. Three cases were considered to get more insight regarding the analysis and damage identification in a bonded joint as shown in Table 1 and Figure 1.

Table 1
Three cases are considered in the project and their descriptions

Case	Model
Case I	Metal to metal single lap joint
Case II	Metal to thick composite single lap joint
Case III	Metal to thin composite single lap joint

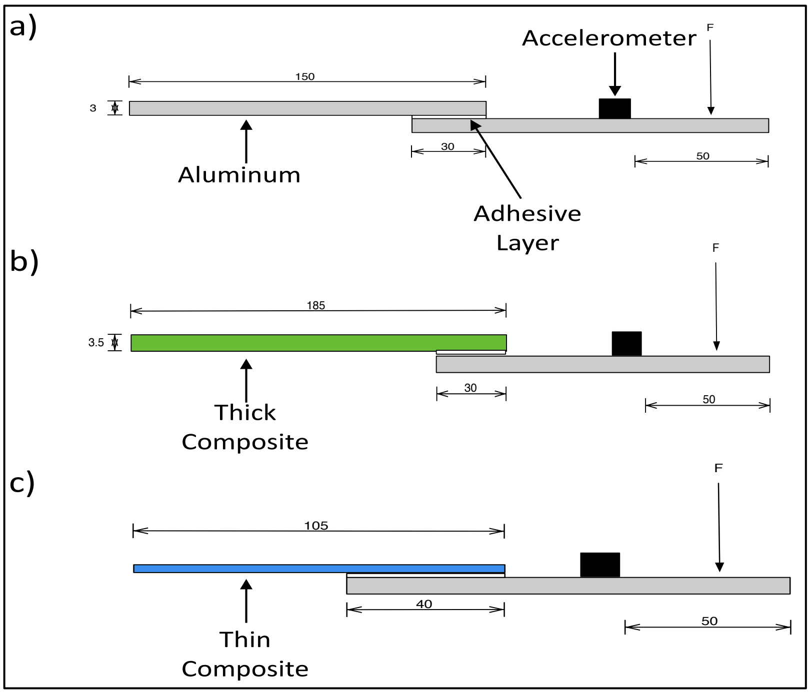


Fig. 1. The healthy model from (a) Case I (b) Case II (c) Case III bonding. The aluminium sheets were bonded as soon as possible after they were cleaned to prevent reoxidation at the surface which reduces the bond quality

2.1 Specimen Preparation

An adhesively bonded single lap joint was chosen to be used for experimental work and the type of damage at the joint was a half debonding of the adhesive layer. The aluminium alloy specimens were obtained in a wide sheet with 3mm thickness before it is cut into the desired dimension. For the metal part, the selected dimension was 150x30x30 mm and the reason why this dimension is used is to allow feasible bonded area when it is combined with the composites later on. The surface of the aluminium plates was cleaned using the degrease-abrade-degrease technique with a suitable solvent which is acetone, wipes and also a piece of sandpaper as shown in Figure 2. Firstly, the metal surface was degreased with acetone and wipes. Secondly, it was carefully abraded by using sandpaper. Finally, it was degreased again before it was ready for

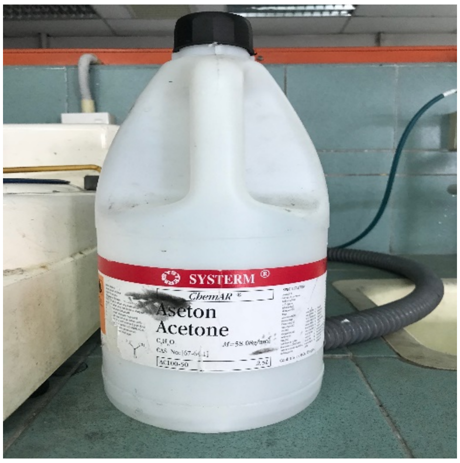


Fig. 2. The acetone used for surface preparation of metal aluminium before bonding

An adequate amount of adhesive was placed at the bond area and another aluminium plate was placed joining the two plates to form a single lap joint. The adhesive layer was left to cure for 24 hours before it could be used for the experiment. The same steps were repeated for other models except for the ones that were used to simulate the damage at the bond area. A double-sided foam tape was placed at the half portion of the bond area indicating the 50% debonding in the adhesive layer. Table 2 displays the mechanical properties of Aluminium 6061. As for the composite specimens, a Carbon Fiber Reinforced Polymer (CFRP) was chosen because of its regular application in the aerospace industry. Two models of CFRP were considered in this experiment the first one was a thick specimen with unknown properties and the other one was a twill weave woven CFRP thin sheet (referred to as “thin” composite) with known properties.

Table 2
Mechanical properties of the Aluminium 6061

Property	Modulus of Elasticity, E (GPa)	Poisson's Ratio	Density (kg/m3)
Value	68.9	0.33	2700

The properties of the twill weave woven composite are listed in Table 3.

Table 3
Mechanical properties of the twill weave woven composite

Property	Longitudinal Elastic Modulus, E_l (GPa)	Transverse Elastic Modulus, E_l (GPa)	Major Poisson's Ratio, v_{12}	Minor Poisson's Ratio, v_{22}	Shear Modulus, G_{12} (GPa)	Shear Modulus, G_{23} (GPa)
Value	94.67	4.88	0.2592	0.0134	1.77	1.48

The dimensions of the Aluminium plate, thick composite, thin composite and adhesive are listed in Table 4.

Table 4
Dimensions of specimens and adhesive layer used in the experiment

Material	Aluminium Plate	Thick Composite	Thin Composite	Adhesive Case I & II	Adhesive Case III
Dimension (mm)	150x30x3	185x85x3.5	105x25x1	30x30x1	40x25x1

The formula to calculate the tabulated properties is as follows:

$$E_l = E_f V_f + E_m V_m \quad (1)$$

$$E_t = \frac{E_f E_m}{E_f - V_f(E_f - E_m)} \quad (2)$$

$$v_{12} = v_f V_f + v_m V_m \quad (3)$$

$$v_{22} = \frac{E_t}{E_l} v_{12} \quad (4)$$

$$G_{12} = \frac{G_f G_m}{G_f V_m + G_m V_f} \quad (5)$$

$$G_{23} = \frac{E_t}{2(1 + v_{23})} \quad (6)$$

with $v_{23} = 1 - v_{22} - \frac{E_t}{3K}$, (7)

and $K = \left[\frac{3V_f(1-2v_f)}{E_f} + \frac{3(1-V_f)(1-2v_m)}{E_m}\right]^{-1}$ (8)

where E_f= fiber modulus, E_m= matrix modulus, V_f= fiber volume fraction, V_m= matrix volume fraction, v_f= fiber Poisson's ratio, v_m= matrix Poisson's ratio, G_f= fiber shear modulus, G_m= matrix shear modulus, K= composite bulk modulus

2.2 Electromechanical Impedance Method

In this method, a piezoelectric transducer (PZT) was attached to a metal part, 30 mm from the edge. A square-shaped PZT PIC151 patch is a wrapped copper nickel patch that was used in all cases. Before it was ready to be attached to the structure, the positive and negative terminals of the patch were initially soldered with the wires which then were connected to the crocodile clips and finally to the analyser as shown in Figure 3.

Fig. 3. Electromechanical Impedance Method (EMI) experiment setup

The equipment for this method were:

i. Agilent 4294A Precision Impedance Analyzer (PIA) with 40 Hz to 110 MHz frequency range and ± 0.08% accuracy
ii. ZT patch type PIC 151
iii. Cable wires as illustrated in Figure 4.

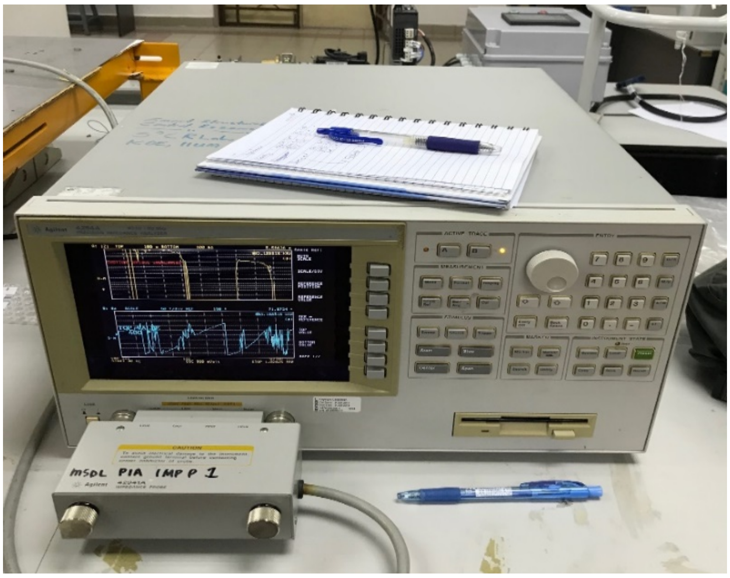


Fig. 4. The Agilent 4294A Precision Impedance Analyzer used for the EMI method

Firstly, the structure with the attached PZT patch was placed on a flat surface and the cables were connected to the PIA. Secondly, calibration was done using three data acquisition calibration procedures which are Open, Short and Load. Thirdly, after the calibration was done, the structure was ready for the data measurement by selecting the equivalent series resistance R-X as the measurement parameter. Next, an appropriate frequency range was selected which shows the impedance signal with the most stable and highest number of peaks. The data was then collected and stored on a floppy disk.

The same procedures were repeated in other cases except for the calibration part. From the data obtained, a plot of the real values of the measurement and the frequency was plotted to show the difference between a healthy and damaged structure. Finally, a calculation of the Root Mean Square Deviation (RMSD) parameter and Coefficient Correlation Deviation Metric (CCDM) was performed.

3. Results and Discussion

3.1 Frequency Range

As discussed earlier, the changes that occur in the structural physical properties will cause the impedance plots to differ. Therefore, we can immediately know that damage is present in the structure studied. For this method, all calibration properties were the same such as the oscillation level, but the range of frequencies was different for each case depending on the clarity of the impedance response. The frequency range used for each case is shown in Table 5.

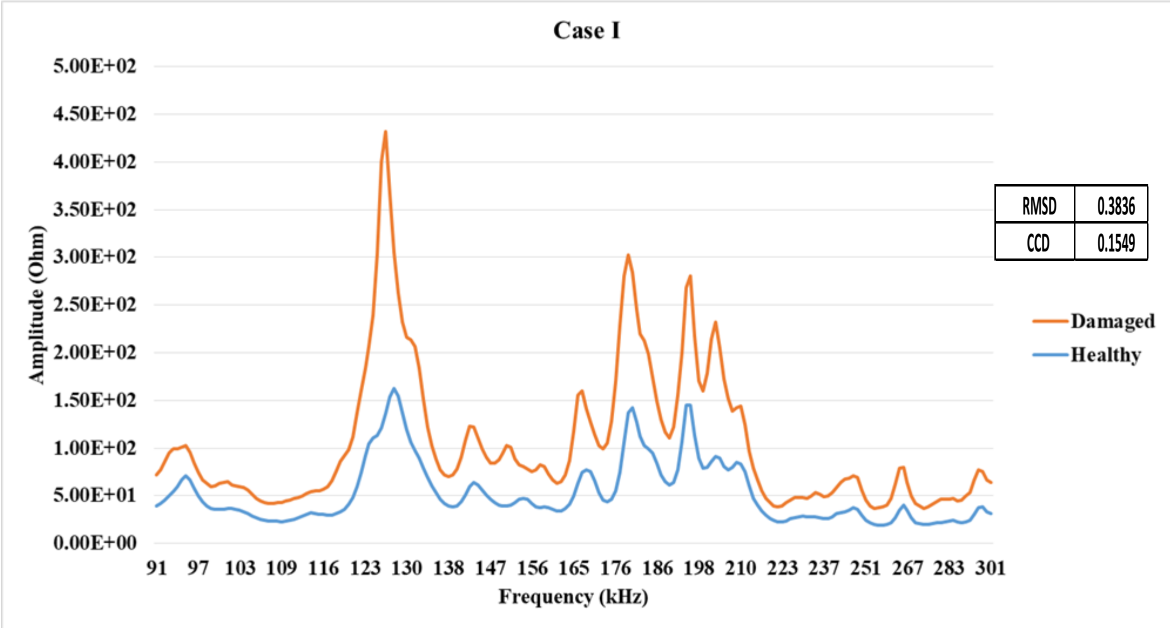
Table 5
Frequency ranges used for the EMI method

Case	Frequency Range (kHz)
Case I	90-300
Case II	100-400
Case III	50-300

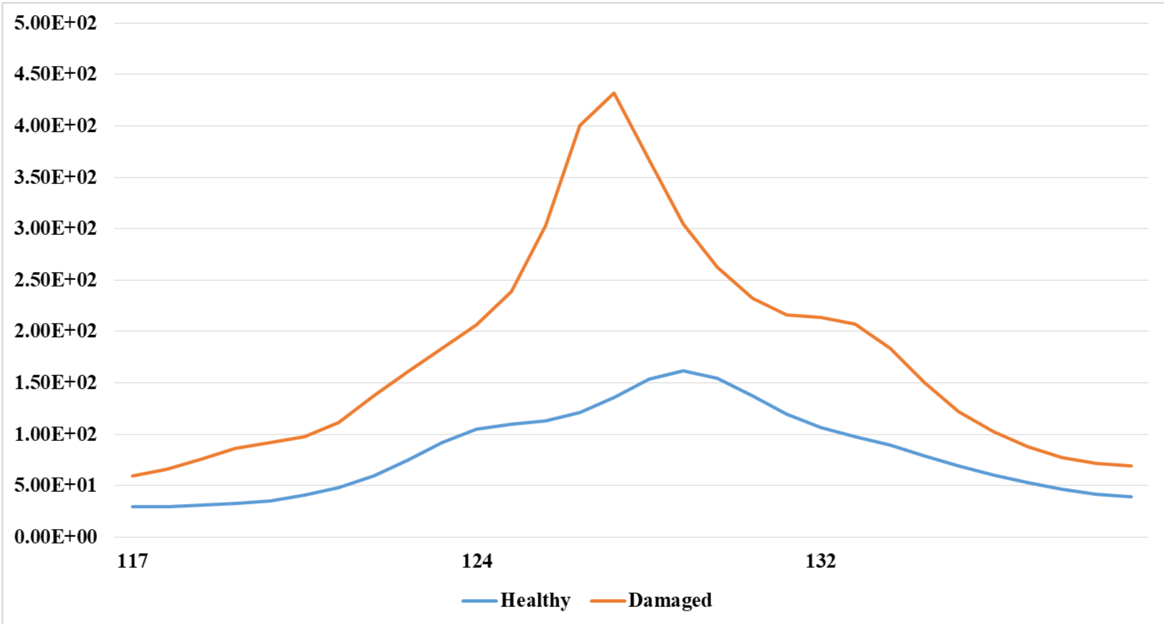
From the results obtained using this method, the real part of the impedance was considered for the impedance plots. The reason is because, according to Giurgiutiu *et al.,* [12] only the real part of the impedance truly reflects the dynamic properties of the structure. Besides that, the real parts are more sensitive to the changes which makes it more suitable to be focused on to monitor damage. Therefore, it was concluded that the impedance real part indicates the natural frequencies of the structure of the study. Hence, only the real part was discussed in the next section.

3.2 Experimental Results

The results for all cases I, II and III are presented in Figure 5, Figure 6 and Figure 7, respectively. It can be seen that the impedance responses of damaged structures shifted to the left.

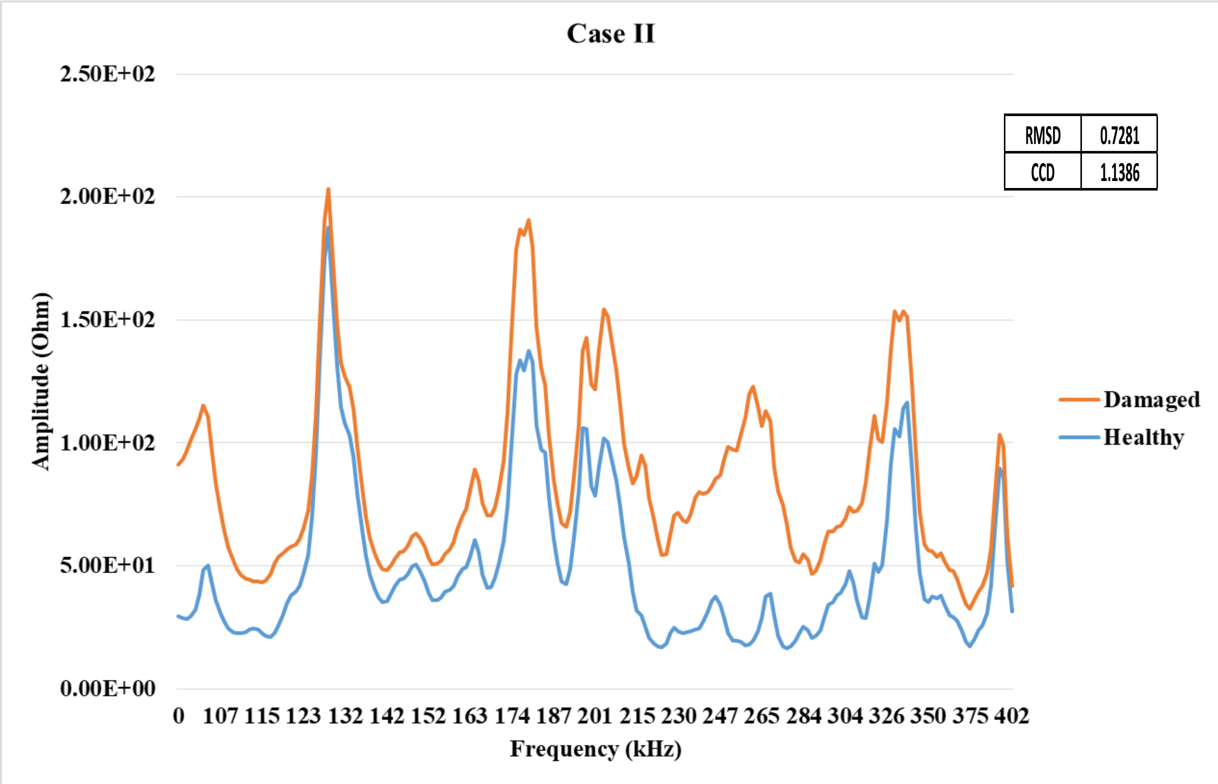


(a)

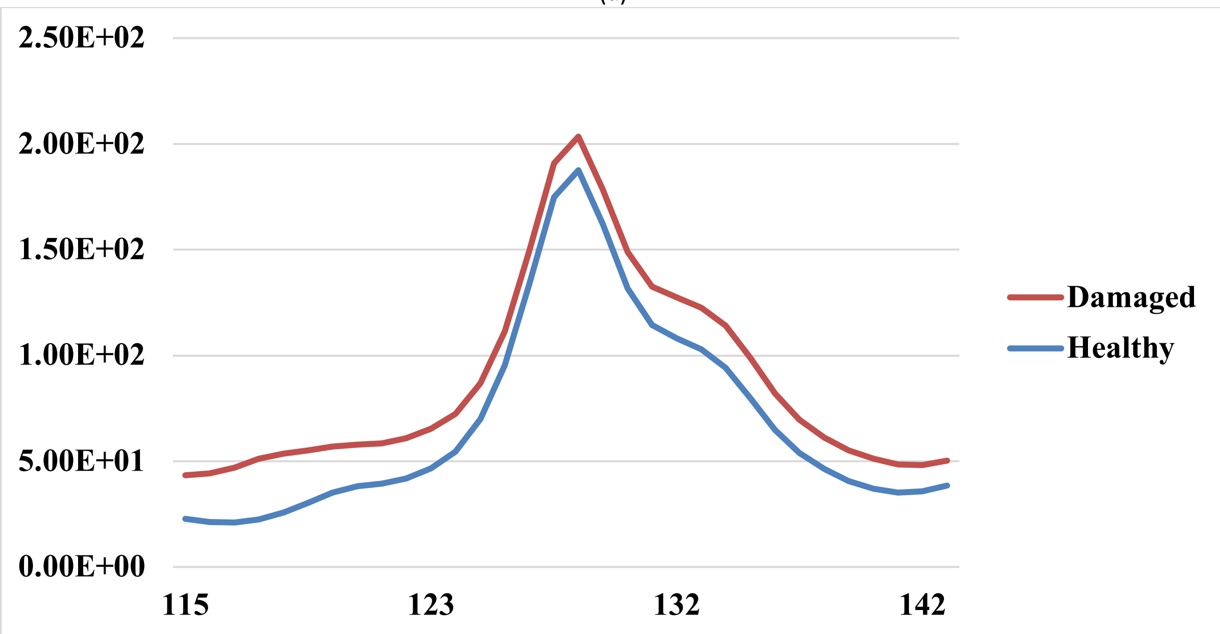


(b)

Fig. 5. Real part of impedance response with magnified peak and RMSD and CCDM values for Case I



(a)



(b)

Fig. 6. Real part of impedance response with magnified peak and RMSD and CCDM values for Case II

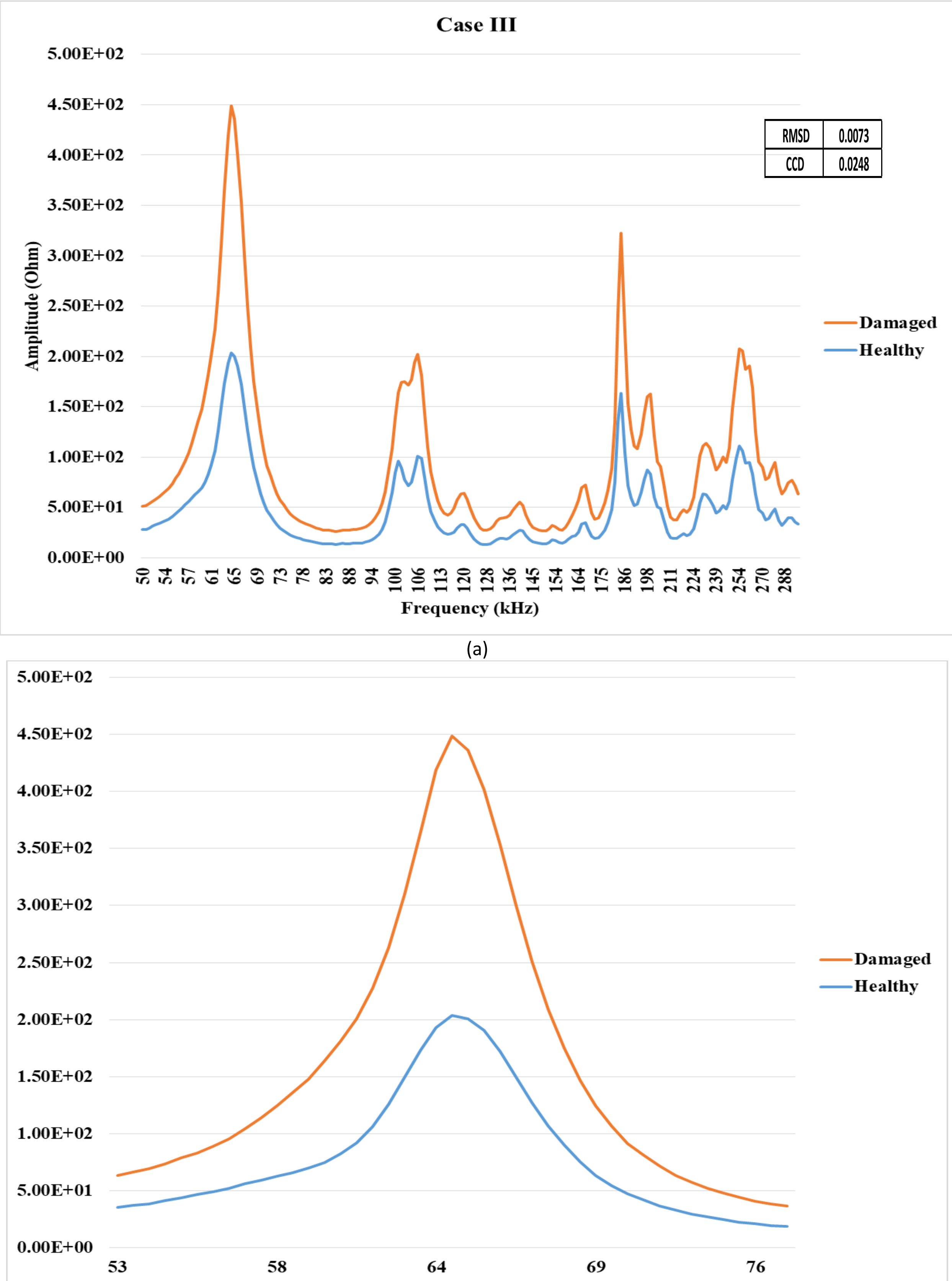


Fig. 7. Real part of impedance response with magnified peak and RMSD and CCDM values for Case III

At the same time, some of the peaks for the damaged structures may grow larger in amplitude as compared to the healthy ones. Besides that, some new peaks emerged in the impedance plots. The most obvious one can be seen in Case II in the 200-300 kHz frequency range. These new peaks may be the result of bigger damage that is present in the structure.

Shifting of the impedance responses of damaged structures indicates that there are changes in the physical properties, especially its damping and stiffness, that affect its dynamic properties. Therefore, it can be concluded that this method is very useful and obvious response changes can be observed easily to identify damage in the bonded joint. However, a quantitative approach can also be done to monitor the damage.

3.3 Damage Metric Indices

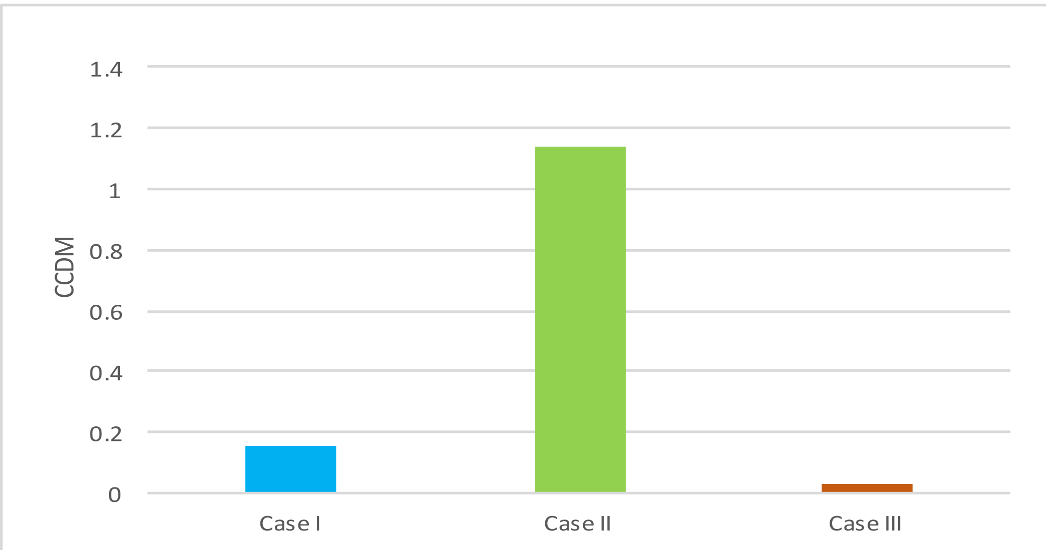
To quantify the damage in the metal-composite bonded joints, two damage indicators have been used to see the level of intensity of the damage. Firstly, the Correlation Coefficient Deviation Metric (CCDM) and secondly, the Root Mean Square Deviation (RMSD). The formulae for these expressions are shown in Eq. (9) to Eq. (11). The results for each expression are shown in Figure 8 and Figure 9.

Correlation coefficient deviation metric (CCDM):

$$CCDM = 1 - CC$$
$$\text{With } CC = \frac{C_{ov}}{\sigma_h \sigma_d} \quad (9)$$

$$C_{ov} = \frac{1}{N}\sum_{i=1}^{N}(h_i - \bar{h})(d_i - \bar{d}) \quad (10)$$

where
σ_h = Standard deviation for healthy structure impedance values
σ_d = Standard deviation for damaged structure impedance values
h_i = Healthy structure impedance value
$\bar{h}$ = Mean value for healthy structure impedance
d_i = Damaged structure impedance value
$\bar{d}$ = Mean value for damaged structure impedance

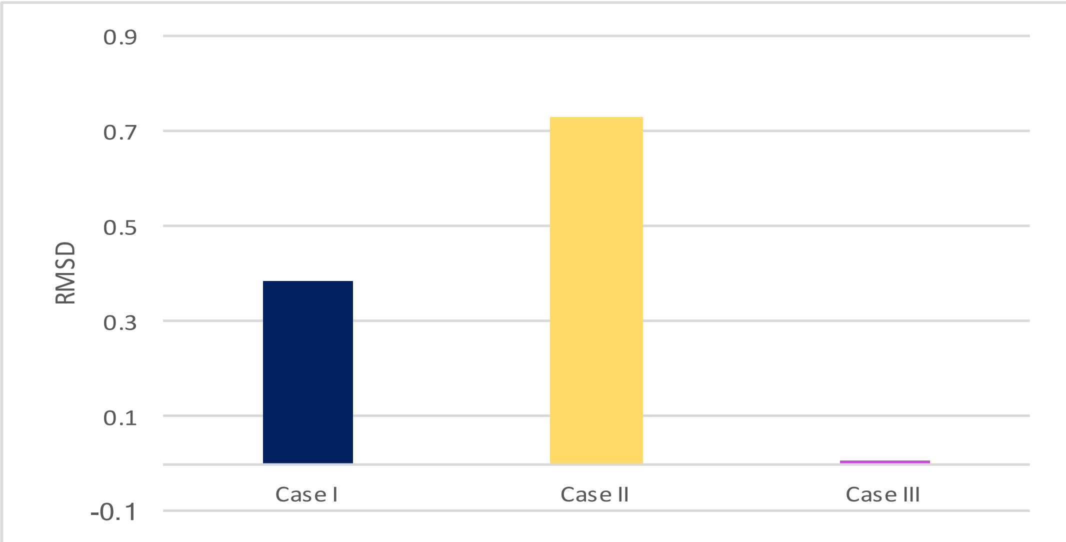


	Case I	Case II	Case III
CCDM	0.1549	1.1386	0.0248

Fig. 8. CCDM values for Case I, Case II and Case III

Root means square deviation (RMSD):

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(d_i - h_i)^2}{\sum_{i=1}^{N}(h_i)^2}} \tag{11}$$



	Case I	Case II	Case III
RMSD	0.3836	0.7281	0.0073

Fig. 9. RMSD values for Case I, Case II and Case III

For these two quantitative approaches to monitor the damage, it can be seen that the damage in Case II is the highest followed by Case I and finally Case III. These calculations reflect the impedance response that can be observed in the impedance plots earlier in this section. As discussed, the damage in Case II is deemed to be the highest and this is proved by the presence of new harmonics in the response and now it is shown in the calculations of CCDM and RMSD. In conclusion, similar to the vibration-based method, quantification of the damage is required to further understand the damage occurrence in the metal-composite bonded joint.

4. Conclusion

The electromechanical impedance technique application for damage identification in metal-composite bonded joints was discussed. There were three cases considered which are metal-to-metal bonded joint, metal-to-thick composite bonded joint and lastly metal to metal-to-thin composite bonded joint. Due to intense damage in Case II, there are new peaks emerged between 200 to 300 kHz. Two quantitative approaches to monitor the damage have been considered namely root mean square deviation (RMSD) and correlation coefficient deviation metric (CCDM). The damage severity is reflected in these two damage indicator parameters and is more useful to monitor the damage than by only looking at the responses.

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References

[1] Ahn, Junghyun and Nicole Duffala. "Metal-to-Metal and Metal-to-Composite Bonded and Bolted Structural Joints." *Encyclopedia of Aerospace Engineering* (2010). https://doi.org/10.1002/9780470686652.eae209

[2] Dereworko, Agnieszka. "Prediction of the failure metal/composite bonded joints." *Computational Materials Science* 45, no. 3 (2009): 735-738. https://doi.org/10.1016/j.commatsci.2008.07.018

[3] Kweon, Jin-Hwe, Jae-Woo Jung, Tae-Hwan Kim, Jin-Ho Choi and Dong-Hyun Kim. "Failure of carbon composite-to-aluminum joints with combined mechanical fastening and adhesive bonding." *Composite structures* 75, no. 1-4 (2006): 192-198. https://doi.org/10.1016/j.compstruct.2006.04.013

[4] Ogisu, Toshimichi, Masakazu Shimanuki, Satoshi Kiyoshima, Yoji Okabe and Nobuo Takeda. "Feasibility studies on active damage detection for CFRP aircraft bonding structures." *Advanced Composite Materials* 15, no. 2 (2006): 153-173. https://doi.org/10.1163/156855106777873923

[5] Qing, Xinlin P., Hian-Leng Chan, Shawn J. Beard, Teng K. Ooi and Stephen A. Marotta. "Effect of adhesive on the performance of piezoelectric elements used to monitor structural health." *International Journal of Adhesion and Adhesives* 26, no. 8 (2006): 622-628. https://doi.org/10.1016/j.ijadhadh.2005.10.002

[6] Gavriloski, Viktor and Jovana Jovanova. "Vibration analysis of cantilever beam for damage detection." *FME Transactions* 42 (2014): 311-316. https://doi.org/10.5937/fmet1404311d

[7] Sadowski, T., M. Kneć and P. Golewski. "Experimental investigations and numerical modelling of steel adhesive joints reinforced by rivets." *International Journal of Adhesion and Adhesives* 30, no. 5 (2010): 338-346. https://doi.org/10.1016/j.ijadhadh.2009.11.004

[8] Liu, P. F., Y. H. Yang, Z. P. Gu and J. Y. Zheng. "Finite element analysis of progressive failure and strain localization of carbon fiber/epoxy composite laminates by ABAQUS." *Applied Composite Materials* 22 (2015): 711-731. https://doi.org/10.1007/s10443-014-9432-1

[9] Rosiek, M., A. Martowicz and Tadeusz Uhl. "An overview of electromechanical impedance method for damage detection in mechanical structures." *Germany, sn* (2012). https://doi.org/10.1002/9781118536148.ch6

[10] Hu, Xianyan, Hongping Zhu and Dansheng Wang. "A study of concrete slab damage detection based on the electromechanical impedance method." *Sensors* 14, no. 10 (2014): 19897-19909. https://doi.org/10.3390/s141019897

[11] Na, Wongi S. and Jongdae Baek. "Adhesive Defect Monitoring of Glass Fiber Epoxy Plate Using an Impedance-Based Non-Destructive Testing Method for Multiple Structures." *Sensors* 17, no. 6 (2017): 1439. https://doi.org/10.3390/s17061439

[12] Giurgiutiu, Victor and Andrei Zagrai. "Damage detection in thin plates and aerospace structures with the electro-mechanical impedance method." *Structural Health Monitoring* 4, no. 2 (2005): 99-118. https://doi.org/10.1177/1475921705049752