

COVER SHEET

Bondline integrity monitoring of adhesively bonded structures via an electromechanical impedance based approach

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ABSTRACT

Bondline integrity is still one of the most critical concerns in the design of aircraft structures up to date. Due to the lack of confidence on the integrity of the bondline both during fabrication and service, the industry standards and regulations require assembling the composites using the inefficient “black-aluminum” approach, i.e. drill holes and use fasteners. Furthermore, current state-of-the-art non-destructive evaluation (NDE) and structural health monitoring (SHM) techniques are incapable of offering mature solutions on the issue of bondline integrity monitoring. Therefore, the objective of this work is to investigate the feasibility to embed piezoelectric sensors into the adhesively bonded joints in order to detect bondlines degradation.

The proposed method makes use of an electromechanical-impedance (EMI) based method, which is a rapidly evolving approach within the SHM family. This approach is based on the use of (i) micro-sensors integrated into adhesive leaving a minimal footprint on the material, (ii) numerical and analytical modeling of the EMI spectrum of the adhesive bondline, (iii) EMI based diagnostic algorithms for monitoring the bondline integrity, and (iv) the experimental assessment via prototype adhesively bonded structures in static (varying loads) environment. The obtained results demonstrate the potential of the approach in providing increased confidence on the use of bonded joints for aerospace structures.

INTRODUCTION

Bondline integrity monitoring is still one of the most critical concerns in the design of aircraft and spacecraft structures up to date. Although adhesively bonded joints have demonstrated superior properties over mechanically fastened joints, current standards still require fasteners even with adhesive because of a lack of confidence on the integrity of the bondline in fabrication and during service. This reduces the benefits of bonding. There are two major types of defects in bondlines, gross defects

and adhesive defects [1]. Debonds between adhesive/adherend and delaminations on substrates, which fit into first category, can be detected via NDE methods like C-scan or ultrasonic reflection [2-5]. Those methods have been proven to be effective to a certain extent. However, specimen preparation takes a long time in all of these methods. Recent work in structural health monitoring, by Ihn and Chang [6-8], has demonstrated the ability to identify debonds in real-time, using built-in piezoelectric discs to generate ultrasonic waves.

An adhesive defect is seen as traction-free contacted surfaces, which show reduced bond strength and are difficult or impossible to detect using conventional NDE [5]. Kissing bonds are one of the major adhesive defects and possess little residual tensile or shear strength. Many factors may lead to kissing bonds, including surface contaminants, adhesive chemistry, inappropriate curing stress, residual stress, moisture ingress, etc. As a result, kissing bonds can appear in a local fashion and the only way to detect them is to measure the local adhesive during fabrication and in service to track its degradation [5, 9-17]. Kissing bonds are the most critical and challenging defect to be detected in bonded joints and significantly influence the confidence of bondline integrity after the joints are placed in service.

Embedding micro/nano sensors inside the adhesive layer has the potential to be an effective solution to this challenge. Upon initial inspection, this approach may not seem feasible because adding new materials inside adhesive will increase the risk of contamination and introduce new defects. However, industry has begun to use adhesive films with fiber scrims inside, to ease handling and improve quality control. Relevant standards have been developed for this practice like BMS 5-121 TY.1. This indicates that this approach is feasible if shrinking the sensors down to the size of typical fibers and making them out of the same materials as current scrims so that the adhesive will have the same mechanical performance as well as the capability to monitor its own integrity degradation level can meet the standards.

METHOD OF APPROACH

In this section we present the development of a process to prepare the adhesively bonded aluminum single lap shear coupons with commercially available PZT sensors (1/8 inch diameter) embedded in the bondlines. After their fabrication, the coupons were loaded under static loading to study the response of the embedded sensors. Single lap joints with PZT sensors embedded were prepared to investigate the relationship between the electromechanical impedance behavior of the sensors and the load history on the lap joints (see Figure 1 and

Figure 2). The samples were prepared following the ASTM D1002 (Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading (Metal-to-Metal)), with 25.4 mm by 25.4 mm (1 inch by 1 inch) of bondline area for one sensor embedded.

Hysol EA 9696 adhesive film provided by Henkel was used to bond two aluminum alloy laps (2024 T5). Hysol EA 9696 is a modified epoxy film designed for applications requiring high toughness including aeronautics. The adhesive of this study was provided by John C. Osborne from Boeing Company. The adhesive films are sealed and stored in the -18 °C freezer in Structures and Composites Lab at Stanford. The surface preparation procedure is designed to follow the ASTM

standard D2651, Standard Guide for Preparation of Metal Surfaces for Adhesive Bonding.

In order to simulate the “kissing” bond behavior, different types of chemicals were tested in order to degrade the bondline strength, including Teflon and graphite powder, two common materials found in manufacturing of carbon composite fibers. Graphite powder was used as the surface contaminate in the latter test due to its large influence on the bond strength (decrease by more than 75 %) and relative ease to handle.

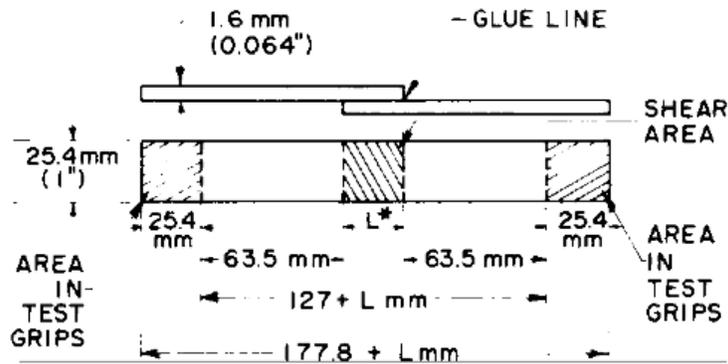


Figure 1. Suggested form and dimensions of test specimen from the ASTM D1002.

Piezoelectric disc sensors fabricated by APC ceramics were embedded into the bondline. The piezo material was Navy II type equivalent with 250 μm in thickness and 3.1 mm (1/8 inch) in diameter. The material properties can be found in Table I.

Due to the thickness of the piezoelectric disc sensors, three to four layers of adhesive film were used to fully encapsulate the sensors. Two varnished wires with diameter less than 100 μm were also embedded to extend the two electrodes of the sensor to the outside of the bondline, which are subsequently connected to an impedance analyzer. The lay-up of the sample is illustrated in

Figure 2. Following the instruction of the manufacturer, the samples were cured under vacuum for 90 minutes at 121 $^{\circ}\text{C}$.

TABLE I. THE PROPERTIES OF THE PIEZOELECTRIC MATERIAL IN APC DISC SENSOR.

Density	Young's Modulus E_{11}	Young's Modulus E_{33}	Relative Dielectric Constant K_T	Piezo Charge Constant d_{33}	Piezo Voltage Constant g_{33}
7.6 g/cm^3	63 GPa	54 GPa	1900	400 pC/N	24.8 mV-m/N

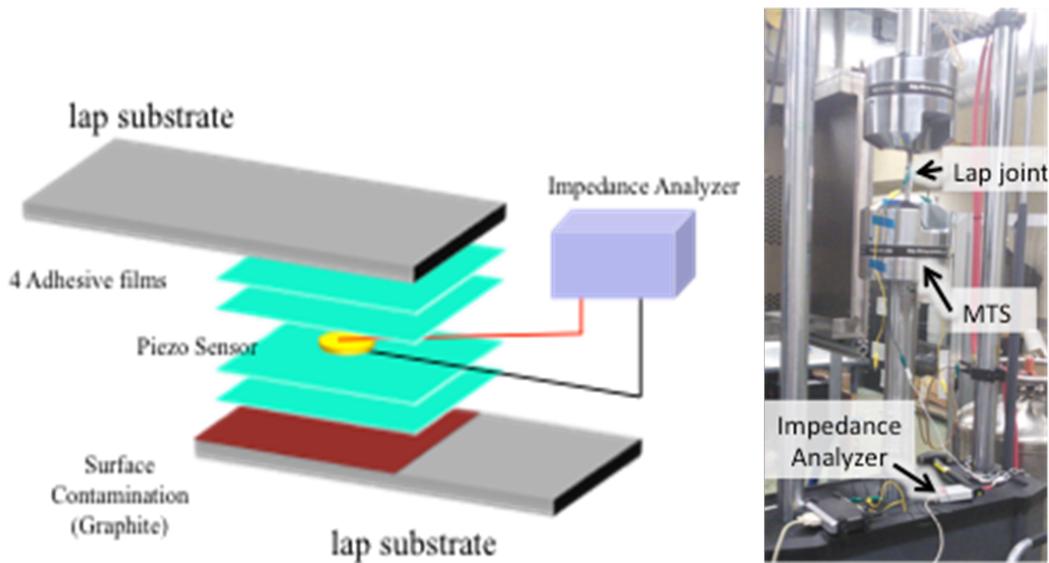


Figure 2. Illustration of a single lap joint with one piezoelectric sensor embedded in the adhesive bondline interface (left) and the experimental test setup (right).

RESULTS

Impedance Behavior of Embedded Piezoelectric Sensors under Loading

The sample was loaded on a MTS (Material Testing System) so that the introduced cyclic load could further degrade the bondline integrity. The overall setup is shown in Figure 2. The implemented cyclic load had an increasing peak load of 111 N (25 pounds) step until sample failure and the impedance was measured under zero-loading condition by a SinePhase Z-check 16777k impedance analyzer. The impedance behavior of the piezo was recorded from 1 kHz to 2.5 MHz with an increment of 2 kHz. Both the real and imaginary impedance data were acquired. The cyclic load with an incremental peak value was exerted on the specimens. A typical load history curve is as illustrated in Figure 3.

After each load cycle, the electromechanical impedance was measured using the impedance analyzer. The typical impedance behavior of the samples is similar to Figure 4. There are two resonant peaks of impedance shown in the measured frequency bandwidth between 500 kHz to 2.5 MHz. The first peak is recorded around 800 kHz and the second peak with lower amplitude is found around 1.7 MHz. The similar impedance behavior was observed throughout all the samples under all loading conditions with slight differences in the frequency and amplitude.

We investigated several damage indices in the existing literature to evaluate the influence of the load cycle on the behavior of the piezoelectric sensors and the bondline integrity. We selected the root mean square deviation (RMSD) as the appropriate damage index, which described the averaged impedance change from the baseline sample without any loading. The definition of RMSD is shown below, where $Z_h(\omega_i)$ is the healthy bond's impedance, $Z_i(\omega_i)$ is the unknown or damaged bond's impedance and ω_i is the frequency interval.

$$\sqrt{\frac{\sum_{i=1}^n [Re(Z_h(\omega_i)) - Re(Z_u(\omega_i))]^2}{\sum_{i=1}^n [Re(Z_h(\omega_i))]^2}} \quad [1]$$

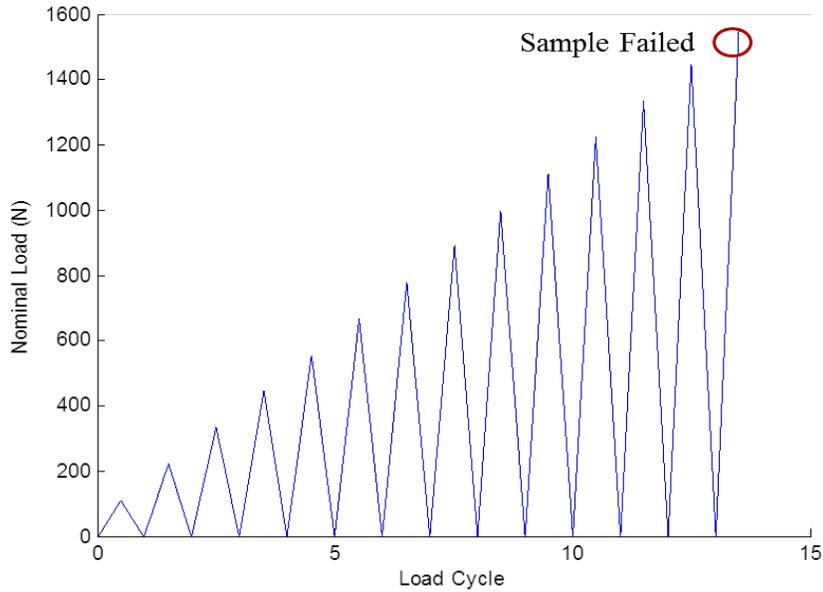


Figure 3. Typical load cycle with the impedance measured under the unloaded condition.

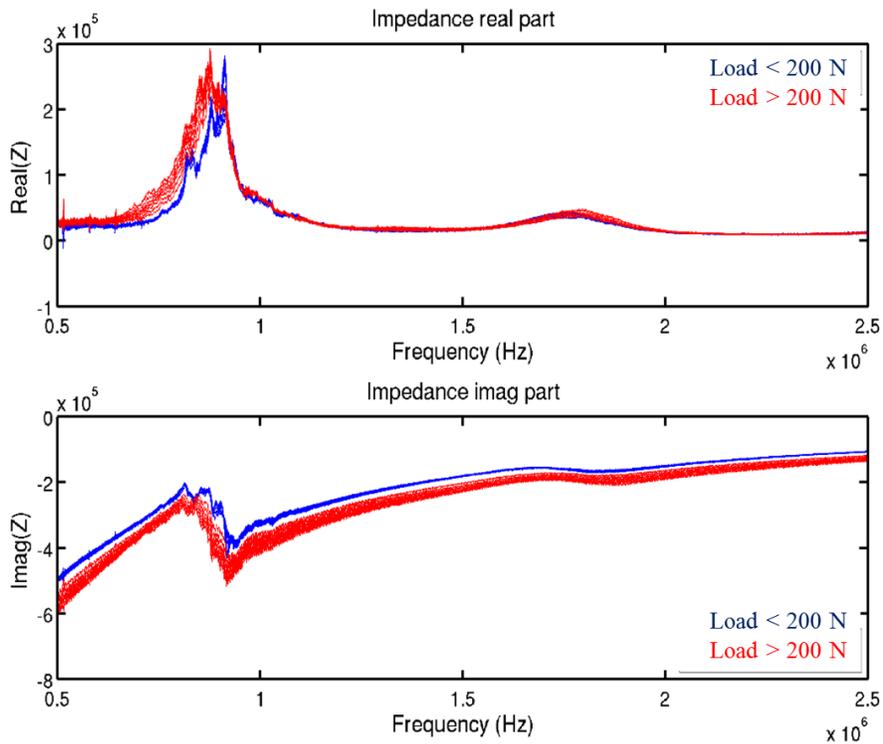


Figure 4. Typical electro mechanical impedance behaviour obtained from experimental samples.

We estimated the damage index around the first peak frequency and within a range of 100 kHz. Regardless of the existence of surface contaminates, all samples showed a similar behavior, i.e. the damage index was relatively constant until the sample was

exposed to a certain level of load cycle and approaching failure. It implied that by measuring the impedance and the deviation of impedance from the intrinsic sample, it is possible to predict the failure of the bonded joint and estimate the degradation of the bondline. For example, as shown in Figure 5, we chose the 2 % damage index as an arbitrary threshold to characterize the bondline state as healthy or degraded.

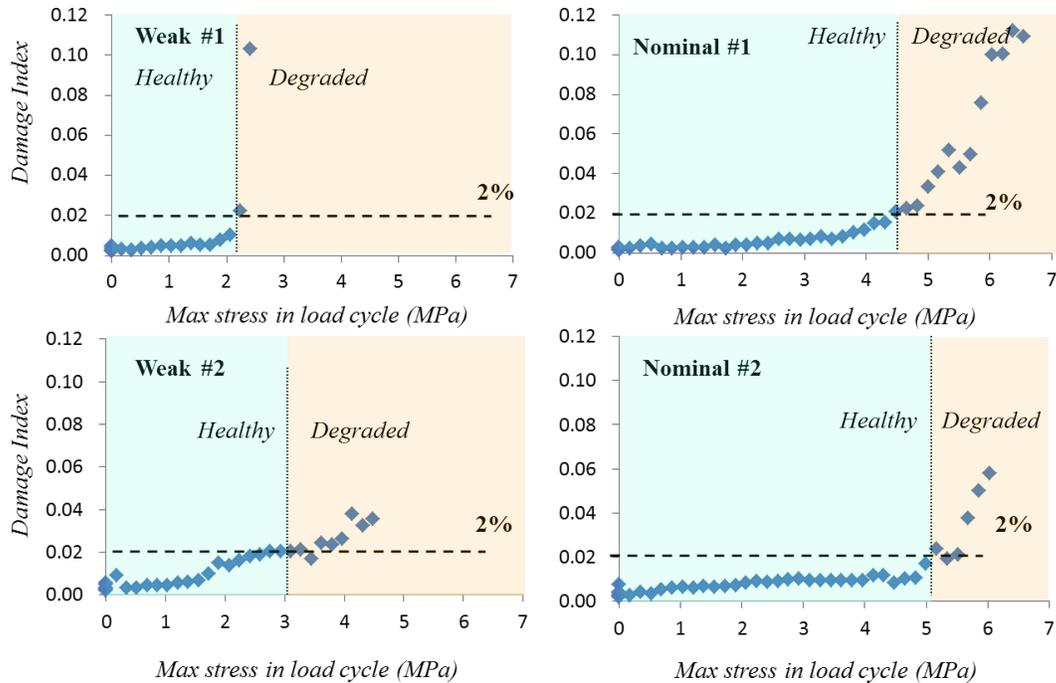


Figure 5: The damage index (root mean square deviation) of both weak and nominal samples exhibited a similar trend.

For the single lap joint, it is known that the shear stress is not uniform along the direction of the load. The stress on the edge of the bondlines is in general greater than the stress in the center. As a result, when the lap joint is exposed to external load, damages are expect to be initiated near the edge and slowly propagate towards the center. In order to investigate the relationship between sensor's location and the impedance deviation (damage index), we placed there sensors into the bondlines. Two sensors were positioned near the edge while the third one was embedded in the center of bondline. After the curing of the adhesive, one sensor on the edge failed to generate any signal and the other two sensors were names Far and Middle respectively as shown in Figure 6. The bondlines failed at 1140 psi and the damage index of the centered sensor increased dramatically after the sample is exposed to 96 % of the strength while the damage index of the sensor on the edge changed at a much lower load level (78 %). This indicated that it is possible to locate the piezoelectric sensor at certain positions, for example where the stress is concentrated, so as to predict the failure of the bondlines in a much earlier stage.

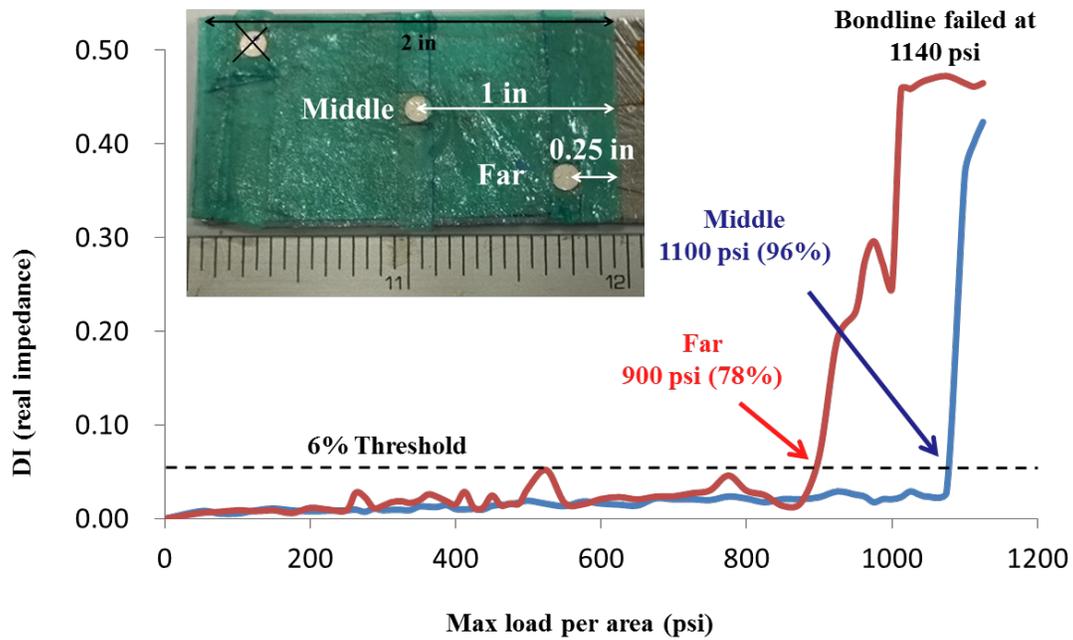


Figure 6. The sensor on the edge is more sensitive to the bondline degradation due to loading than the edged sensor

Finite Element Simulation Study

The finite element model (FEM) has been developed using the commercial software Abaqus 6.12 to simulate the impedance behavior of the embedded sensors in the bondlines. The aim was to obtain an accurate result of the impedance behavior over the large frequency bandwidth using the direct steady-state linear dynamic analysis. C3D8E elements were used to model the piezoelectric material and the mesh had a typical dimension of 100 μm to capture all the motion and deformation of the sensor. The material properties used in the simulations are shown TABLE II.

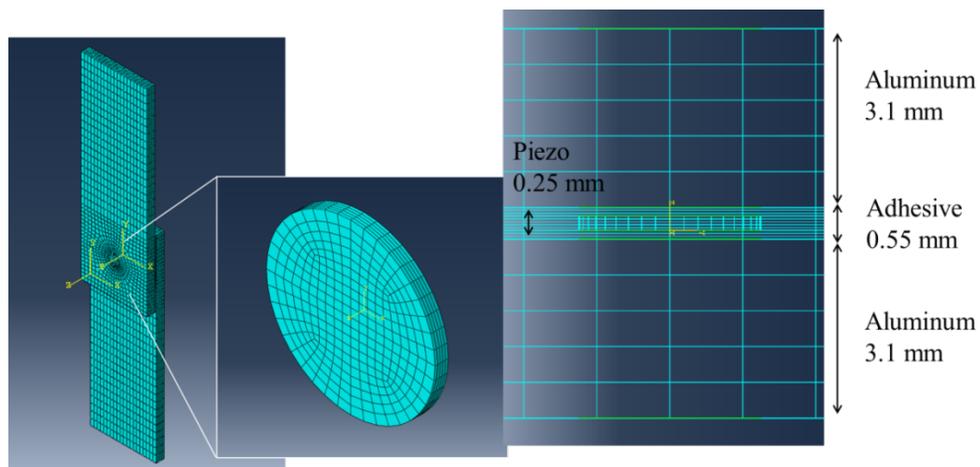


Figure 7. The FEM model and mesh of the bondline with embedded piezo sensor disc.

TABLE II: MATERIAL PROPERTIES (MECHANICAL PROPERTIES) USED IN THE NUMERICAL SIMULATIONS; THE DIRECT PIEZOELECTRIC EFFECT MATRIX [d] AND PERMITTIVITY [ϵ] OF PIEZOELECTRIC MATERIAL IS SHOWN IN MATRICES

Property	Unit	Aluminum Al 2024-T3	CFRP T800S/3900-2	Adhesive Hysol®EA 9696	Piezo PZT-5A
E_{11}	GPa	69.00	156.00	2.60	60.97
E_{22}	GPa	69.00	9.09	2.60	60.97
E_{33}	GPa	69.00	9.09	2.60	53.19
G_{23}	GPa	25.94	3.24	1.00	21.05
G_{31}	GPa	25.94	6.96	1.00	21.05
G_{12}	GPa	25.94	6.96	1.00	22.57
ν_{23}		0.33	0.400	0.30	0.4402
ν_{13}		0.33	0.228	0.30	0.4402
ν_{12}		0.33	0.228	0.30	0.3500
ρ	kg m ⁻³	2700	1540	1100	7750

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 584 & 0 \\ 0 & 0 & 0 & 584 & 0 & 0 \\ -171 & -171 & 374 & 0 & 0 & 0 \end{bmatrix} \times 10^{-12} \text{ C N}^{-1} \quad \epsilon_{\sigma} = \begin{bmatrix} 1730 & 0 & 0 \\ 0 & 1730 & 0 \\ 0 & 0 & 1700 \end{bmatrix} \times \epsilon_0$$

The impedance behavior from 50 kHz to 2 MHz was determined at the interval of 5 kHz. The results of both real and imaginary parts are illustrated in Figure 8 in blue color. The corresponding experimental results are shown in red color. Without any further calibration of the material property as well as the dimension of the bondline, the simulation matched the experimental result to a certain extent in both the frequency and amplitude.

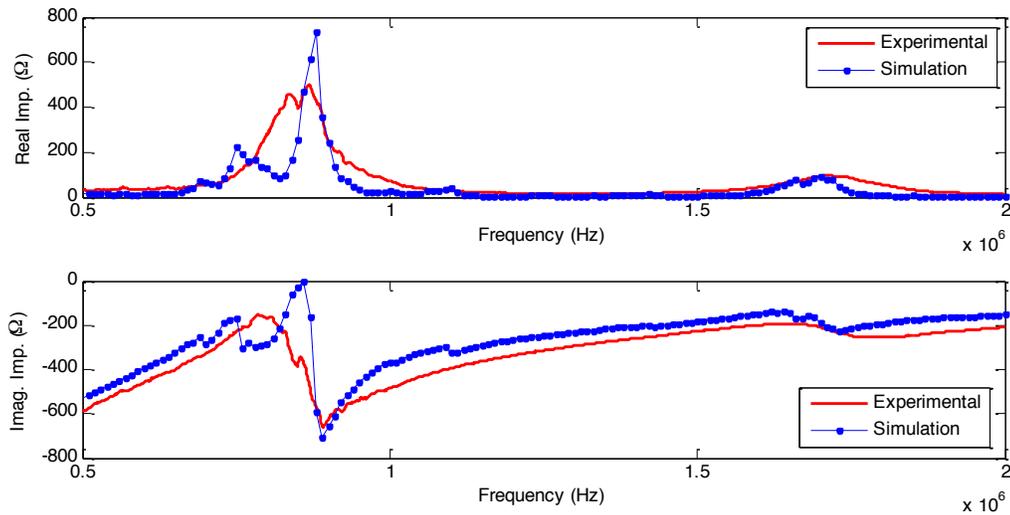


Figure 8. Comparison of numerically simulated and experimentally obtained impedance behaviour for a piezoelectric sensor embedded in the adhesive bondline.

In the literature, it was recommended that the kissing bond could be modeled by decreasing the stiffness of the interfacial element between adhesive and adherent

[2,3]. The typical thickness of the element is 10 μm . The stiffness of the interfacial element was decreased to simulate the bondline degradation due to kissing bond as shown in Figure 9 (left). Part of the bondline area (square shape from top view) was degraded and the rest was intact to reflect the propagation of the degradation as illustrated in Figure 9 (Right). The relationship between the weak bond area and the damage index then was studied.

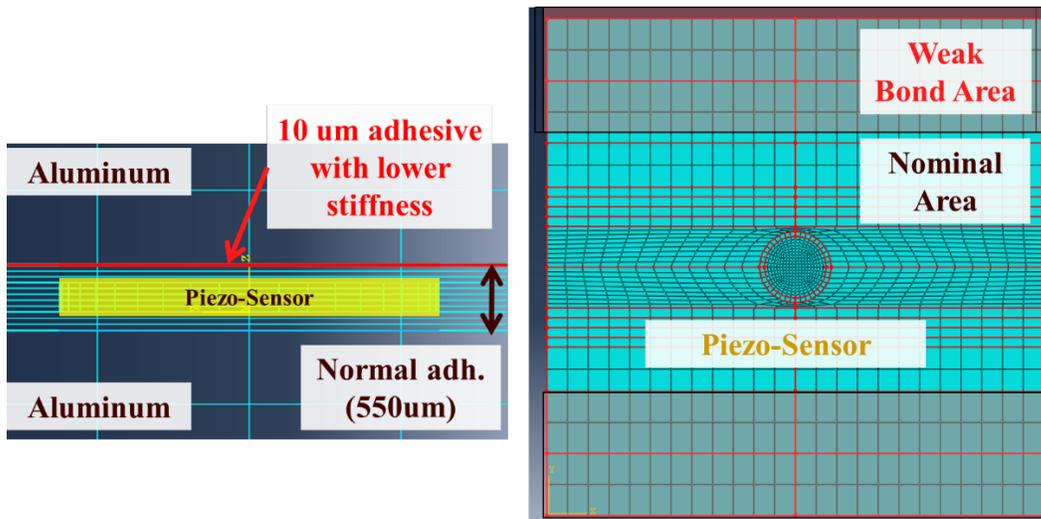


Figure 9. Kissing bond simulation is achieved via the reduction of the stiffness of the interfacial elements (left) and the top view of the bondlines including weak bond area and nominal area (right).

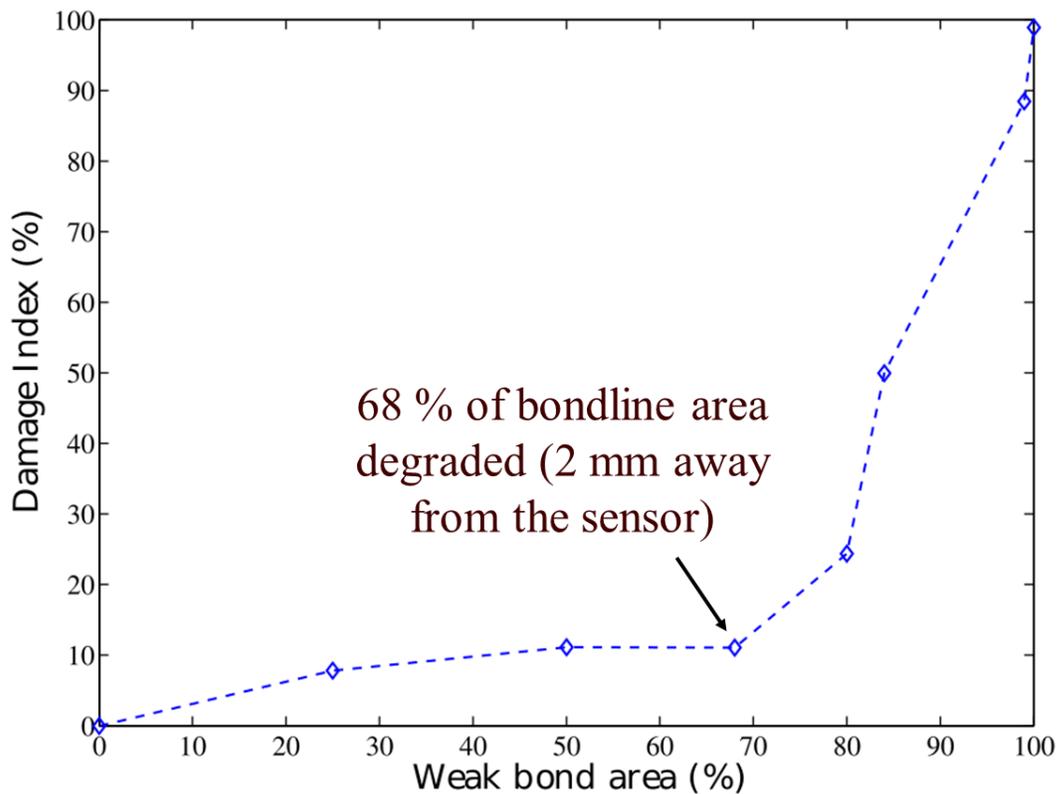


Figure 10. The damage index is relatively constant until 68 % of the bondline area is weak bond.

As illustrated in Figure 10, when the weak bond area is relatively small (less than 50 %) and far away from the sensor, the damage index keeps insensitive to the area size. When the weak bond area makes up 68 % of the bondline area or about 2 mm away from the centered piezo-sensor, the damage index becomes more sensitive to the weak bond area size. The result indicates that the piezo-sensor has a detecting range of around 2 mm under this setting, and it can only pick local bondline degradation. By carefully selecting proper locations for the piezo-sensors, it is feasible to detect the local bondline degradation as the pre-cursor of the global bondline failure.

CONCLUSIONS

Compared to conventional bolted joints, bonded joints have superior mechanical properties in terms of light weight, less stress concentration, etc. However, due to the lack of confidence on the bondline integrity level during fabrication and service, the large adaption of bonded joints onto airplane primary structural components is restricted by regulations and standards. Among all the defects that can be found in adhesive bondlines, one type of interfacial weakness, the kissing bond, is the most challenging one. This is due to the catastrophic failure it can cause to the bondline as well as to the almost impossible early detection using conventional non-destructive evaluation (NDE) or structural health monitoring (SHM) techniques. From the samples of bonded carbon fiber reinforced plastic panels with simulated kissing bond fabricated by Boeing, a loss of more than 50 % strength was observed without any significant change on global stiffness. In order to reproduce the kissing bond in our laboratory setting, several types of chemicals were tested to contaminate the interface between adhesive and adherent in the aluminum single lap joint. Graphite was chosen to reproduce kissing bond for the future study.

With the capability to simulate kissing bond behavior, we developed and tested a break-through technique to monitor the bondline integrity by embedding piezoelectric sensors into the bonded joints. The impedance-based detection algorithms were used by measuring the electromechanical impedance of the embedded sensors. Since the sensors are positioned in the bondlines, close to the interface of adhesive and adherent, where the kissing bond could occur, any small change in the interface would affect the EMI response of the sensor. The EMI behavior of the embedded sensor under static loading was studied. The single lap joints with sensor embedded inside were exposed to an incremental tensile load. The impedance was recorded under zero load condition before a higher load was exerted on the sample. Across all the tested samples, a similar behavior was observed, i.e. the impedance of the sensor is kept constant until a certain load level, after which, the impedance changes dramatically from the pristine state. The root mean square deviation was defined as the damage index to quantify the change of impedance.

A finite element model was also developed to investigate the impedance behavior of the embedded piezo sensor. In order to simulate the behavior of kissing bond, the stiffness of the interface elements of the adhesive was degraded. The degradation of this 10 μm thick element would not affect the global stiffness of the lap joint, however, it would affect the impedance behavior of the embedded sensors significantly. Preliminary simulation results matched with the experimental result qualitatively and

similar trend of the decrease of resonant frequency was seen when the sample was prone to failure.

Future work will include the study of the effect of the sensors' locations in the bondlines in order to improve the detectability; to validate the impedance-based algorithms under dynamic and fatigue loading; and the development of piezo-electric sensors with smaller dimension so that much less parasitic effect would be introduced when the sensor was embedded in the bondlines. An innovative piezoelectric ceramic sensor is being developed at Stanford via screen-printed techniques. The screen-printed electric ceramic piezo-sensors can provide the needed EMI performance for the impedance-based algorithms for bondline integrity monitoring and meet the thickness requirements (typically 20~30 um) for bondlines application.

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