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EFFECT OF BONDING MATERIAL ON SURVAIVABILITY OF SURFACE-ATTACHED EDDY CURRENT SENSORS

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Abstract. Structural health monitoring relies on the correct functionality of surface-attached or embedded sensors to detect changes in the condition of the investigated part. Departures from a baseline signal indicate variations in the properties of the part, as for example, fatigue crack initiation and growth in cyclically loaded structures. In the case of printed circuit board, planar eddy current copper coils, special considerations have to be taken in order to assure that the sensing coil is properly operating in the high strain field of a growing crack. Bonding materials with appropriate elastic properties, used to attach the eddy current sensors to the structure, need to be carefully selected as to minimize load transfer from the part to the coil traces. Micro-cracking and fatigue of the coil material could locally modify the electrical resistance of the coil and provide erroneous damage indications. In this work, two adhesives of largely different stiffness are used to attach spiral eddy current coils meant to monitor growing fatigue cracks initiated from fastener holes in aluminum alloy specimens under cyclic uniaxial tensile stress. Only the more flexible adhesive material allowed survivability of the eddy current sensor. The rigid one is believed to facilitate load transfer from the metallic substrate, resulting in micro-cracking in the coil's traces that affect the electrical response supposed to indicate the damage growth. In this work, the empirical findings are supported by numerical simulation looking into variations of the bonding material stiffness and thickness. These outcomes are meant to aid in the selection of the adhesives that will assure proper functionality and survivability of the surface-attached eddy current sensors in structural health monitoring for damage detection applications.

Key words: Finite Element Model, Structural Health Monitoring, Eddy Current, Printed Circuit Board Coil, Fatigue Crack, Adhesive, Load Transfer

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1 INTRODUCTION

On-board, in-situ condition assessment with miniaturized, embedded sensors advocates for changing the maintenance philosophy from a time-based to a condition-based approach, a concept named *retirement for cause*. In the long run, this approach is seen to reduce costs, improve safety of the mission and increase availability of the platform. In many instances, condition-based monitoring consists of in-situ non-destructive testing (NDT) techniques for on-demand inspections without structure disassembly. Miniaturization of sensors, along with advances in printed electronics, are supporting the field of condition monitoring.

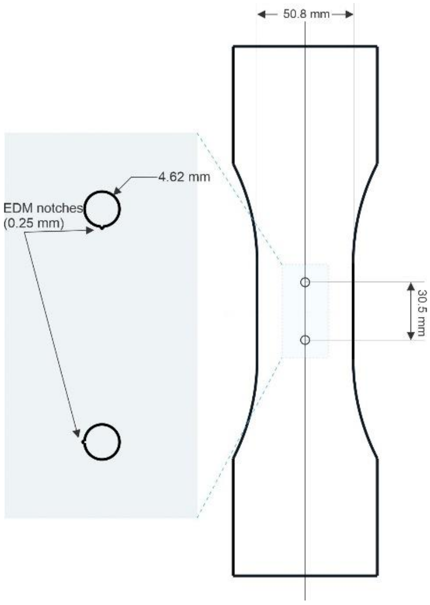
Ideally, the link between damage indication and physical damage, i.e. between the sensor signal feature and discontinuity is proportional. In reality, this is not clearly defined and could results in a high number of false positives (i.e. indication of damage when no damage is present.) The evaluation of damage is routinely performed via comparison to a reference or a baseline signal of the same sensors from an earlier instance. This approach is employed in the case of slow-growing, cumulative type of damage, such as corrosion or fatigue cracking. However, in order for it to be effective, it is assumed that the sensor operation stays the same and all the external conditions are not affecting the outcome of the measuring. On the other hand, the same conditions that are producing damage in the structure could damage the monitoring system.

The eddy current is one of the mainstream nondestructive testing methods, used for the inspection of metallic components and structures, especially in the nuclear and aerospace industries, but not only. In this work, printed circuit board (PCB) spiral coils are proposed for eddy current detection and monitoring of fatigue cracks initiated at the fastener holes in aluminum aircraft structures. By passing a time-varying current through the coil, it creates a magnetic field coupled to the part under test that induces eddy currents in the latter. Planar circular PCB coils are flexible, surface conformable, easily attached to the surface of the part and suitable for embedment in multi-layered structures. In addition, they are light weight, occupy small volume and are economical to produce.

When the sensor and the substrate material have synchronous mechanical performance, the crack monitoring sensor has a sacrificial role [1] and the lack of response of the sensor is used as a binary screening system of crack growth. An important role is that of the bonding material used to attach the sensor to the structure, since a rigid bond would transfer the load to the sensor and cause them to fail, while a weak bond would cause the sensor to detach during loading [2]. In this work, the sensor survivability is essential not only for crack detection, but also for crack growth monitoring. It examines the bonding material's elastic properties and its role in transferring the load to the crack monitoring sensor.

2 EXPERIMENTAL DETAILS

Metallic structures exposed to cyclic loading are prone to crack initiation and growth. In order to detect these cracks long before they become critical, planar circular PCB coils are attached symmetrically around fastener holes of 4.62 mm diameter in 7075-T6 aluminum alloy coupons of 6.35 mm thickness. The gauge area of the test piece is of 50.8 x 50.8 mm. Two holes, with a center-to-center distance of 30.5 mm are introduced in each coupon. To be effective, not only the coils functionality and outputs should be reliable, but the bonding material used to attach them to the structure needs to be light, thin, and durable. A schematic of the test coupon is shown in Figure 1, with a detailed view of the two holes, each containing a starter electrically discharge machining (EDM) notch of 0.25 mm. The bottom notch is acting as a stress concentrator to favor plastic deformation and it is expected to initiate a crack growth under the tensile stress applied to the coupon. The crack orientation with respect to the coil windings allow maximum electromagnetic interaction and sensitivity [3]. The upper notch is not expected to grow a crack, but is introduced as a reference for the eddy current flow around the bottom one. The coupon was cyclically loaded at 15 Hz using a sine wave with an amplitude of 55 MPa and a stress ratio of 0.1.



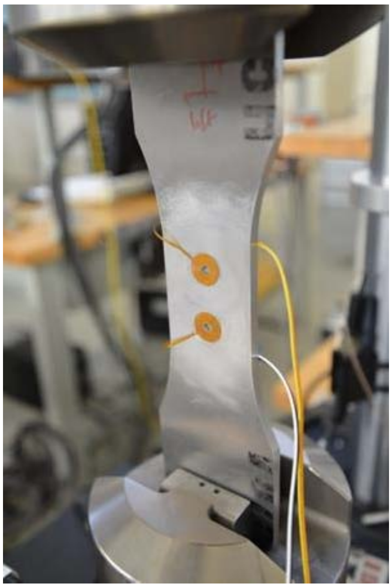


Figure 1: Left: schematic representation of the test coupon, with a detailed view of the holes and EDM notches. Right: photograph of the instrumented coupon in the loading frame.

In this work, the spiral coils are operating in an absolute mode, meaning that the same coil is used for excitation and sensing. The driving current through the coil is creating the magnetic field that induces eddy currents in the part, while these are creating a secondary field which, in turn, modifies the voltage drop across the coil [4]. The eddy current flow path and density are indicative of the part electromagnetic properties, including the presence of geometrical discontinuities due to the presence of defects. A crack is essentially a barrier in the free flow of the eddy currents and it is a local drop in the material conductivity. The monitoring coil impedance with the growing crack was found to be a sensitive empirical parameter [4].

The PCB coils used in this study are 17.5 μm thick copper traces, of 300 μm width and approximately the same spacing between the traces. To assure electrical insulation and environmental protection, the copper traces are encapsulated between two layers of polyimide of 50 μm thickness, with only the end connectors exposed. In this study, two coupons were tested, each using a different bonding material to attach the planar coil to the aluminum part. The coupons were instrumented with the two surface-bonded coils each, as shown in Figure 1, but differing in terms of the bonding material. For the first coupon, a typical general-purpose adhesive was used, *i.e.* M-Bond 200 from Micro Measurement [5] with the bond layer thickness of 25 μm. This is a general purpose adhesive, commonly used to attach strain gauges to aircraft structures. For the second coupon, SI 5140RTV from Loctite [6] was used. This more flexible silicone-based adhesive was expected to reduce the load transfer to the coil. The silicone adhesive layer in this case was 100 μm. The elongation at break for the two bonding materials, as given by the manufacturers, are more than 5% for the M-Bond 200 and more than 150% for the SI 5140 Loctite.

2.1 Experimental setup

The crack growth curve is obtained by using marker bands on an un-instrumented coupon. The crack growth curve is shown in Figure 2 below. For the coupons instrumented with attached planar coils, the same crack growth curve is assumed, although the number of cycles necessary to nucleate the crack could (and did) vary. The crack nucleation is dependent on many macroscopic and microscopic variables and the latter ones are responsible the crack initiation. For the two instrumented coupons, the crack length at the end of the test is measured via surface eddy current scans [4] and the crack growth equation is used to determine when the crack started growing. Since the number of cycles necessary to have a nucleating crack could vary from specimen to specimen, depending on surface condition and grain boundaries arrangement, the crack growth curve of the instrumented specimens is assumed to have the same shape as the one obtained a-priori on the un-instrumented one, but translated by a constant value for the number of cycles for which the crack starts to grow. Therefore, the crack length at the end of the test is determined by surface scans eddy current at the far-side of the coupons (opposite to the ones on which the planar coils are attached) and the crack length at various probing intervals determined based on the equation from the un-instrumented specimen.

The impedance through the coils is determined as the ratio of the voltage drop across them to the current passing to a series resistance. The relative change in the impedance of the crack-monitoring coil with respect to the reference one was found to be a sufficiently sensitive feature for further analysis [4]. The presence of a crack lowers the mutual coupling between the part and the monitoring coil, resulting in an increased coil impedance.

The fatigue test was stopped at various intervals to take impedance measurements in static conditions. These measurements were performed while the coupons were unloaded and in loaded conditions at maximum applied stress of 55 MPa (8 ksi). Since a malfunction of the coil is apparent only in the loaded conditions, it is assumed that micro-cracking in the copper traces of the crack monitoring coil are increasing its resistance. Independent measurements of the reference coil's resistance indicate a constant value, irrespective of the applied load to the specimen.

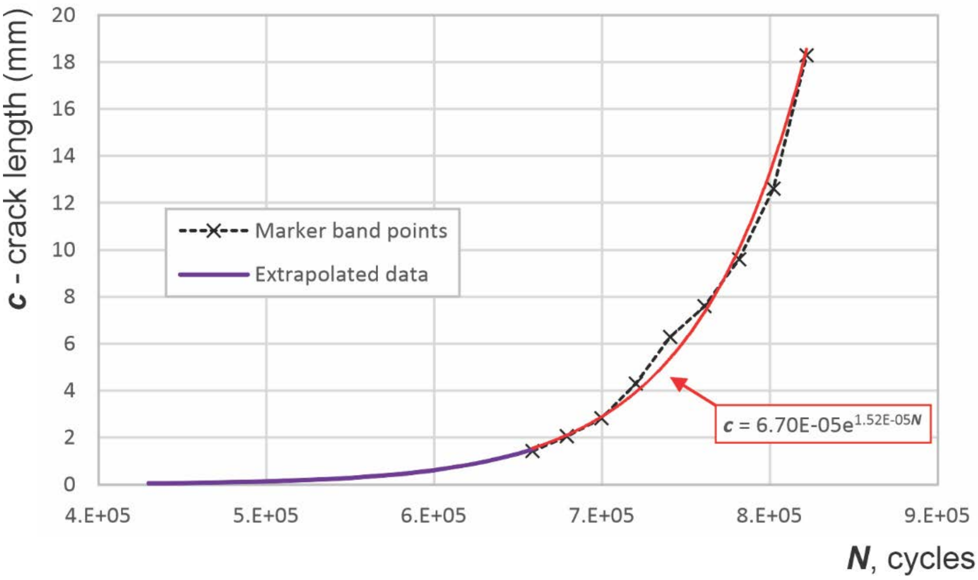


Figure 2: Crack growth curve obtained using marker bands. The crack length, ***c*** varies exponentially with the number of cycles, ***N***.

2.2 Experimental results

For crack detection and monitoring purposes, the impedance of the monitoring coil, denoted by Z, is evaluated as a relative change from the one of the reference coil, Z_{ref}. Electromagnetic numerical simulations also indicated the highest sensitivity to conductivity changes at driving frequencies to be around 1 MHz [4]. The experimental results of the relative impedance change with the estimated crack length for the driving frequencies of 0.5, 1.0, 2.0 MHz were analyzed. In Figures 3 and 4, the relative change of inductance is shown when a static load of 55 MPa (8 ksi) was momentarily applied during the data recording. In Figures 3 and 4 the crack length is measured from the tip of the 0.25 mm long, 0.25 mm wide starter notch.

For the M-bond adhesive, the relative change in the coil impedance shows a distinctive jump in values around the crack nucleation, just at the tip of the 0.25 mm starter notch, as due to the plastic damage created by the local stress concentration. While this behavior has value in terms of screening for a crack, as a “go – no go” binary approach, it could not be employed for crack growth monitoring. On the other hand, when using the more flexible adhesive, the silicon-based Loctite Si 5140 RTV, the relative impedance of the coils display a monotonous growth with the crack length. Therefore, it is determined that a material of higher fracture strength would be beneficial in terms of sensor survivability and its capability to monitor crack growth.

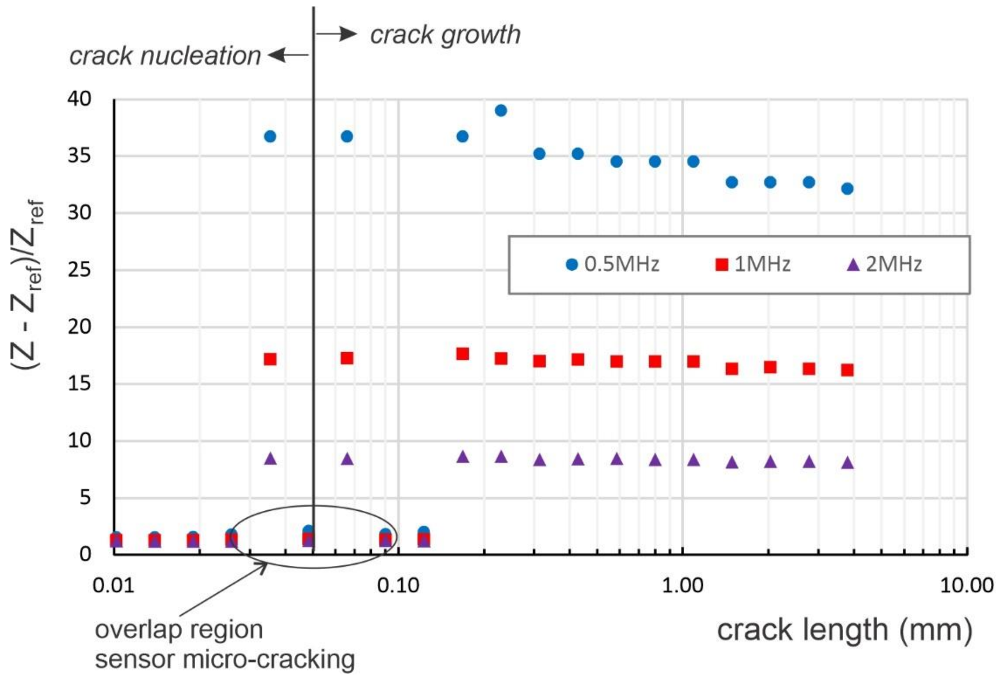


Figure 3: Relative change in impedance with respect with the crack length when M-Bond 200 adhesive is used

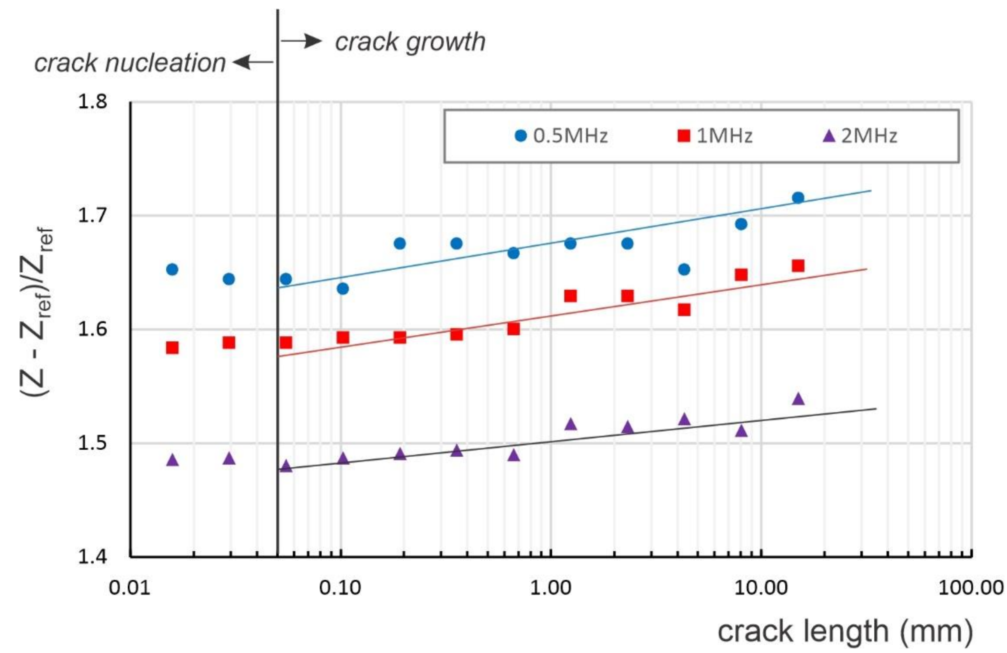


Figure 4: Relative change in impedance with respect with the crack length when Loctite Si 5140 RTV adhesive is used

3 SIMULATION DETAILS

3.1 Simulation setup

A finite element model (FEM) of the aluminum alloy test coupon with the adhesive layer and the planar eddy current PCB coil in its protective polyimide layer was developed in Ansys Workbench [7]. Two different models were developed for each of the two bonding materials: (i) the M-bond 200, and (ii) the Loctite SI 5140 RTV. Various notches were introduced in the model to simulate crack growth, of 0.25, 0.5, 1.0, 1.5 and 2 mm length, all of 0.25 mm width.

The planar eddy current coil was modeled as an isotropic material of a Young's modulus of 100 GPa and a Poisson ratio of 0.34, corresponding to copper. The polyimide tape used as a protective layer on top and bottom of the coil, was also modeled as a polyamide/nylon isotropic material with a Young's modulus of 2.78 GPa and Poisson ratio of 0.41, as available from the Ansys material library. The M-bond 200 adhesive layer was approximated as an epoxy resin isotropic model with a Young's modulus of 3.78 GPa and a Poisson ratio of 0.35. The Loctite SI 5140 RTV adhesive properties were approximated by using a first order Mooney-Rivlin hyperelastic model corresponding to the Loctite SI 5404 RTV silicone adhesive, as described in [8].

Due to the physical component geometry, the FEM used Ansys first-order shell elements (SHELL181). These shell elements are suitable to model thin shells (such as the adhesive layer, coil and polyimide film) and moderately thick shells, such as the aluminum coupon used here. The FEM modeled only the hole with the growing notch, as shown in Figure 5. This model had a total number of approximately 12500 nodes with 11500 shell elements (as shown in Figure 6).

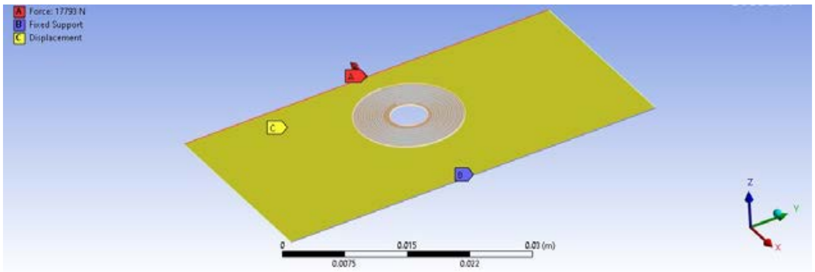
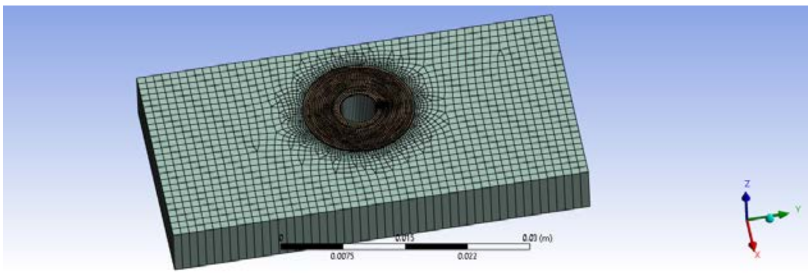
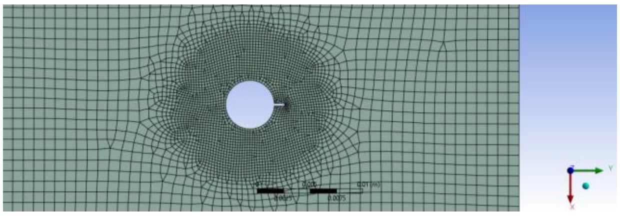


Figure 5: Schematic of the model with a fixed support and a 17.8 kN static load applied

(a)




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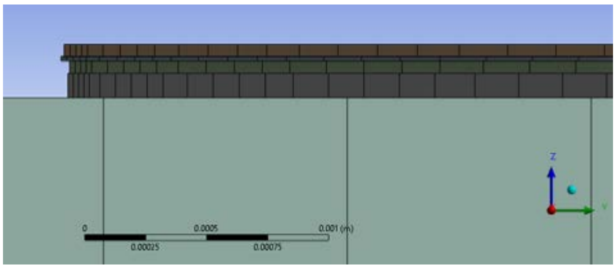

(c)

Figure 6: Meshing details showing: (a) Shell element thickness, (b) 1 mm long notch in block, (c) stratified view of all the materials

3.2 Simulation results

The FEM analyses were parametrically conducted for various notch lengths assuming that both resin epoxy (M-bond 200) and Loctite adhesive layers were 100 micrometers thick. Figure 7 shows the Von Mises stress distribution on the coil and indicates that the highest stresses occurred on the first and second coil turns.

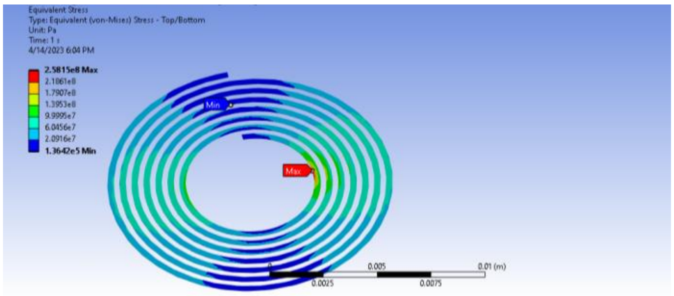

Figure 7: Von Mises stress in copper coil for Loctite adhesive and a 1.0 mm long notch

The maximum equivalent Von Mises stresses in the copper coil are summarized in Figure 8 and Table 1. It is noticeable that in the coil bonded with Loctite, the maximum Von Mises stress exceeded the yield stress in the copper alloy (280 MPa) for a crack length longer than 1.0 mm and exceed the ultimate stress (430 MPa) for crack lengths longer than 1.5 mm. In the epoxy resin-glued planar Cu coil, the maximum Von Mises stress exceeded the yield stress in the copper alloy (280 MPa) for a crack length longer than 0.25 mm (i.e. the starter notch size) and exceed the ultimate stress (430 MPa) for notch lengths longer than 0.5 mm. The results in Figure 7 indicate that the Loctite adhesive transmitted less stress to the copper traces, allowing its survivability for a longer duration. It is easily seen that the M-Bond 200 adhesive led to yielding in the copper coil for all crack lengths and glue layer thicknesses after the notch exceeding the initial 0.25 mm length.

Table 1: Maximum Von Mises stress in copper coil vs. notch length and adhesive type (100 μm thick adhesive)

notch (mm)	0.25	0.5	1.0	1.5	2.0
Loctite adhesive	1.36E+08	1.47E+08	2.58E+08	4.10E+08	8.89E+08
M-bond adhesive	2.12E+08	4.42E+08	1.2E+09	1.7E+09	2.1E+09

Figure 8: Maximum Von Mises stresses in copper coil for the M-bond (resin) and Loctite (RTV) adhesives

4 DISCUSSION

In structural health monitoring, the use of structure-attached sensors depends on their sensitivity, reliability, durability, and survivability. In this work, planar printed circuit board eddy current coils were considered for fatigue crack detection and monitoring. Based on experimental and numerical findings, it is argued that the bonding material has a significant role in the load transfer from the monitoring structure to the copper sensor trace, and therefore, to the sensor's survivability.

The elongation at break (i.e. the fracture strength) of Cu is 60%, while of 7075-T6 aluminum alloy is 11%. The polyimide material, which encapsulates the Cu coil, has an elongation at break of 55%. In comparison, the elongation at break for the M-bond adhesive is only 5%, while for the Loctite Si 5140 RTV is 150%.

In the case of the M-bond adhesive, the load transfer causes damage to traces of the coil, although their electrical continuity is not completely broken. The FEM results point along the lines of the experimental observations in that the Loctite adhesive layer transmits less strain energy to the copper coil and helps allows its survivability for longer cracks. Further improvements of the model would include an elasto-plastic model of the copper material so that a true post yield behavior could be analyzed. A harmonic analysis, modeling fatigue, could not yet be run in Ansys Workbench due to the nonlinear material behavior of the RTV adhesive.

5 CONCLUSION

Structure-attached sensors for structural health monitoring or in-situ nondestructive testing are supporting the lifecycle maintenance of critical structures change from a time-based to a condition-based one. In the application discussed here, printed circuit board eddy current sensors are suitable for in-situ damage detection and monitoring. Their miniaturization, low weight, manufacture speed and costs, custom geometries, and surface conformability are only a few of their advantages. They allow for on-line condition assessment and on-demand maintenance, with the goals of increasing safety, availability, while reducing expenditures. Thin, flexible, custom-designed PCB eddy current coils are suitable for integration during the structure initial assembly or at the time of maintenance overhaul.

Despite its advantages, the use of structurally bonded sensors relies on the sensors' survivability in high-demand operational conditions. This work investigated the role played by the adhesive material used for attachment of the planar coils to the metallic structure. While electromagnetic coupling relies on thin and uniform bond layers, the load transfer from the high strain regions existing at the tip of a growing crack is dependent on the mechanical properties of the adhesive.

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