INVESTIGATION FOR OPTIMUM PLACEMENT AND SENSING FEASIBILITY OF DIELECTRIC SENSORS TO COMPOSITE PATCH REPAIRED STRUCTURES

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Abstract: The increasing utilization of composite materials in the aerospace industry is due to the great advantages offered. Nevertheless these applications introduce the need of higher levels in structural integrity identification both during fabrication and in service of the specified materials. In addition the need for decrease of cost dictates more efficient repairs, avoiding replacement of components and simultaneously ensuring safety. The above facts have led to the investigation of combining a repair technique, Composite Patch Repair (CPR), with Structural Health Monitoring (SHM) by dielectric sensors. The initial and most important parameter in such a complex application is to define, given all the parameters set by the mode of repair and the sensing capabilities, the optimal sensor placements onto the flawed structure.

After performing stress analyses and determination/evaluation of the numerical results, an experimental investigation takes place is assessing the practical application. The drilling of stress relieving holes around the area of a crack before the application of CPR is considered. Stress Intensity Factors (SIF) are calculated by utilizing the finite element (FE) method. A representative case of bonded composite repair of a cracked metallic structure is examined and a series of 3D elasticity linear static FE models are developed. SIF reduction is found to be depended on both the holes' diameters and of the holes distance from the crack line. The SIF results taken for an optimally placed set of stress relieving holes show an improvement of SIF reaching a maximum value of 15.5%. The experiments are designed according to the numerical results but also bearing in mind the possibility of incorporating commercially available sensors in the specified structure geometry. Results demonstrate life increase, and offer the capability of housing commercially available sensors in the specified structure geometry.

Finally, further experimental investigation regarding SHM by dielectric sensors, exhibited identification of initiation as well as cure completion. In general, curing is completed prior to the end of the temperature treatment a fact that can potentially lead to important cost reductions.

Keywords: Carbon fibres, Fatigue, Finite element analysis (FEA), Life prediction, Composite Patch Repair, Structural Health Monitoring.

1. Introduction

As composite high strength and low density materials are being increasingly used in- amongst others-aerospace applications, the need for understanding and characterization rises.
The manufacturing process of such materials is crucial to the quality and overall integrity that they will exhibit. This fact leads to the need of monitoring not only the life in service of such components but also the processes taking place during their generation.
One of the applications that have grown with the advancement of composite materials is Composite Patch Repair. In most cases total replacement of a damaged structural element is not justified in terms of cost, leading to the solution of a repair. Thus, the design, analysis and repair technology present a challenge. This technique is subject to quality reassurance of the composite patches also during the curing process.
The established capabilities of dielectric sensors for the recording of useful results as far as flow and/or cure levels is concerned [1, 2], led to their selection of this technique.
Identification of practical difficulties during implementation to the composite patch repaired structure had to be realized and overcome. Initially it is possible for the specified sensors to be placed in direct contact to the outmost ply of the composite patch but this technique only serves for preliminary experiments as it may lead to scaring of the composite. This study initially addresses the dielectric sensor placement problem onto a repair. The consideration of altering the finite boundaries of a structure so as to serve for placement of sensors and at the same time guaranteeing integrity was the first step.
Many cases of holes at the vicinity of a crack have been already studied [3], [4]. Such circular holes can decrease stresses near the crack tip. These holes are used in the aerospace industry for preliminary stress relief but were never combined with CPR [5].
The case of an orthogonal plate with a centrally located crack was examined, in which two holes are drilled over and under the crack line. The center of both holes lies on the same line that strikes the centre of the crack (Figure 1). This configuration guarantees similar conditions for both tips of the crack. The entirety of finite element models were constructed using the commercial package ANSYS [6].

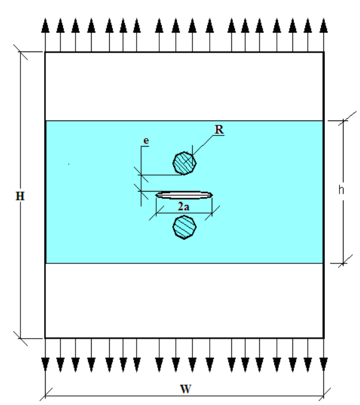

Figure 1: Schematic of the repaired structure.

2. Model Description

As a representative airplane skin repair an aluminium plate of 2024 T3 alloy was selected with dimensions 50mm X 50mm X 2.5mm (H=50mm), with a crack of 10mm (2a=10mm) vertical to the direction of the principle load. The plate is considered to be loaded under a tensile stress of σ_0 = 100MPa. For the repair a 4 ply pre-impregnated (Epoxy resin- Boron fibres) patch was selected, with dimensions h=15mm and width equal to that of the plate. The composite ply is applied to the aluminium plate via an epoxy adhesive, (0.13mm thickness after curing).

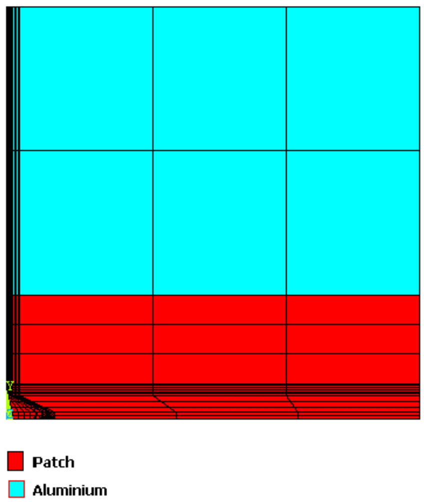

Figure 2a: Correlation of materials and mesh (repaired side).

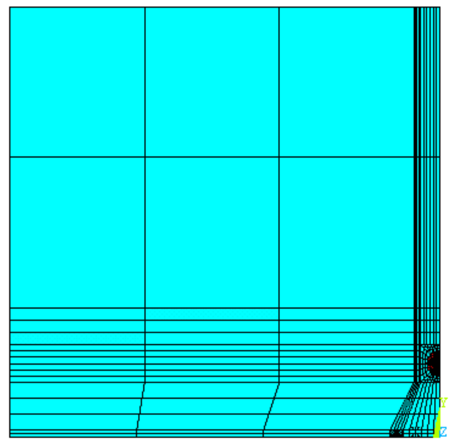

Figure 2b: Mesh (unrepaired side).

Figures 2a and 2b correlate the materials and introduce the examined plate mesh. Figure 3 illustrates the refinement of meshing (deemed mandatory due to the alteration in integrity) both at the region of the crack tip and the hole circumference.

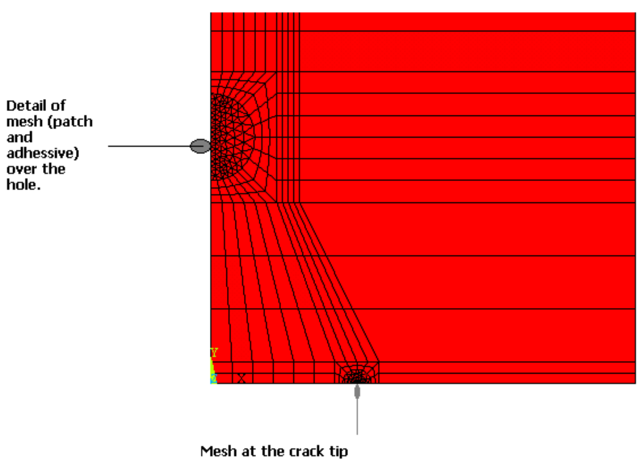

Figure 3: Mesh in detail.

3. Stress intensity factor computations

Two holes are assumed in this plate as earlier mentioned. The hole's radius is denoted R and the ratio of hole radius versus crack half length R/a is taking the following values $0.1, 0.2, 0.3, 0.4, 0.5$. The distance between the crack plane and the hole boundary near it is denoted by e. For ratio a a range of 0.6 to 1.8 is set. Large increase of the distance e tends to eliminate the influence that these holes offer with respect to crack propagation thus were not taken into consideration.

The SIF for the case of a cracked plate (prior to CPR and defense holes), is computed using equation (1):

$$K_0 = F_0 \sigma_0 \sqrt{\pi\alpha} \quad (1) \qquad \text{where} \qquad F_0 = \left[\sec\left(\frac{\pi\alpha}{W}\right)\right]^{1/2}$$

Which leads to a SIF equal to $398.826\ \mathrm{N/mm^{3/2}}$.

Furthermore, a model representing a repaired model without the introduction of defense holes was created. The results of SIF, which were taken from the 'plain' model were used for comparison to the 'full' model (CPR and defense holes). The following results present the plate's status prior to the introduction of holes (Table 1).

Table 1: SIF values for the damaged plate.

K_I (Front)	K_I (Mid)	K_I (Lower)
186.60 $\mathrm{N/mm^{3/2}}$	292.46 $\mathrm{N/mm^{3/2}}$	345.96 $\mathrm{N/mm^{3/2}}$

The basic subject of this research is to quantify the decrease of K introducing the defense hole technique as complimentary to the repair with composite patches and afterwards to establish the parameters (R, e) for the optimal results with regard to the particular structure. SIF readings were collected from 3 different node paths. These regions were (Figure 4) at the aluminium surface sharing a boundary with the adhesive film (front), at the centre of the substrate, with respect to the Z axis (middle) and on the unrepaired side (lower).

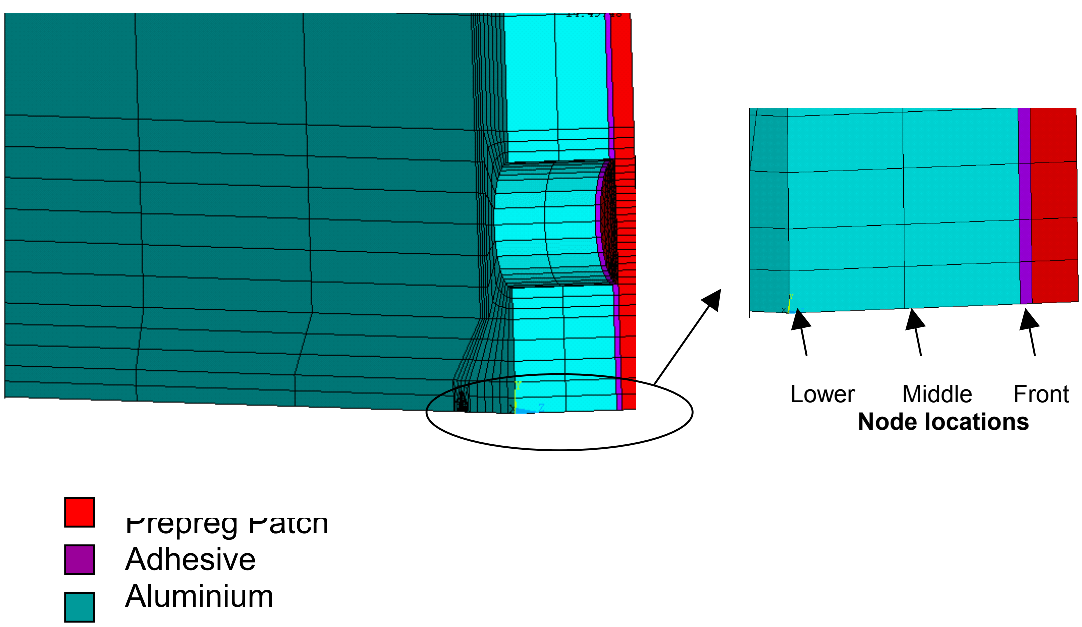

Figure 4: Definition of node paths.

The results that present particular interest are identified at the unrepaired side and the reason dictating this fact is the out of plane displacement caused due to the one sided repair as the stiffness on the repaired structure results in bending of the unrepaired side, raising the SIF.
The neutral axis is no longer situated on the same plane with that of loading thus translating the initial tension to out of plane bending. Due to this bending, the unrepaired side of the plate suffers surplus tensile loads, a fact that further opens the crack [7]. After the introduction of holes, the SIF is decreased in all selected node paths. This decrease reaches its maximum at the path situated on the unrepaired side, which proves the suitability of the defense holes technique as complimentary to the repair with composite patches.

4. Numerical results

Two contradicting factors influence the displacement and stress fields when stress relieving holes exist above and below the crack [8]. Firstly, the circular hole acts as an obstacle for the stress flux in the plate forcing it to avoid the crack and secondly, the topical reduction of the plate stiffness, due to the removal of material (holes). The first factor tends to reduce the intense phenomena at the area of the crack tips, while the second tends to increase it. It is obvious that in the area of ratios R/a examined in this paper, increase of the holes radius leads to domination of the first factor and hence the SIF reduction. The results were treated in the same manner, i.e. SIF values were taken through the previously defined node paths and in accordance to the two investigated variables of the configuration in the form of ratios:

- Radius of hole over half the length of crack, (R/a).
- Distance between the plane of the crack and the end of the hole over half the length of crack, (e/a).

In addition, the resulting values of SIF are filtered to produce a percent decrease when incorporating the defence holes from the standard CPR configuration. The following formula was used.

$$\%RD = \frac{K_I(Patched + Holes) - K_I(Patched)}{K_I(Patched)} * 100 \qquad (2)$$

As distance e increases, the effect of the defence holes weakens. This can be more clearly demonstrated in Figure 6 concerning the upper surface of the plate. As the node path leaves the vicinity of the patch this phenomenon is reduced (Figure 7).

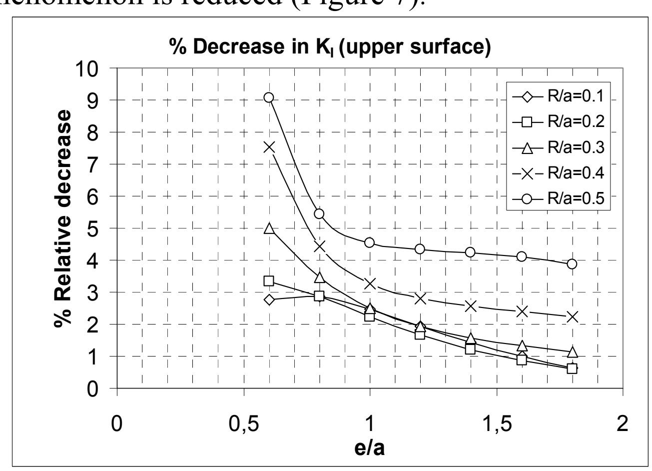

Figure 6: Percent relative decrease of SIF at the upper surface.

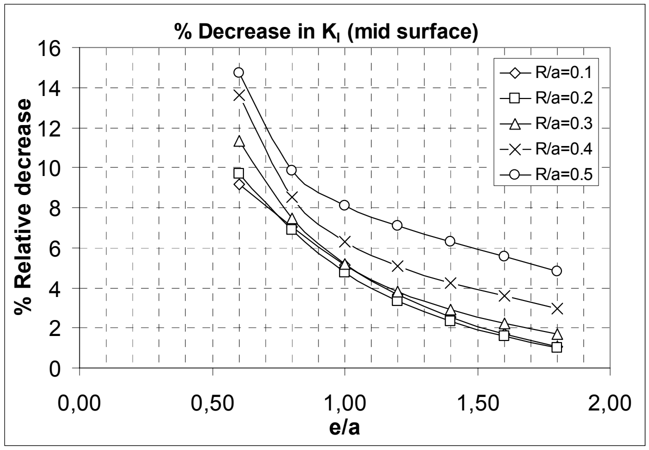

Figure 7: Percent relative decrease of SIF at the middle surface.

In general, increasing the hole radii, the provided decrease of SIF is in turn raised. As far as the mid surface is concerned, R/ a ratios seem to offer similar SIF reductions.
Figure 8 offers results for the plate's lower surface. As explained previously, this is the most crucial area of the plate, demanding adequate SIF reduction. The maximum decrease of 15.5% was observed at a radius of 2.5 mm and a hole distance from the crack plane (e) of 3mm.

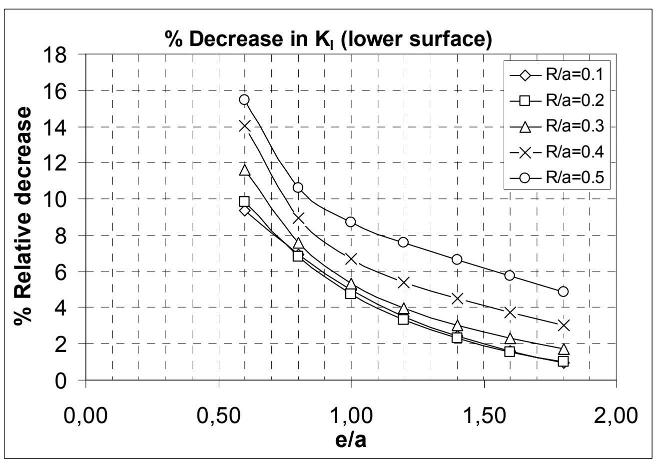

Figure 8: Percent relative decrease of SIF at the lower surface.

5. Discussion of numerical results

Applying CPR, the most common practice is to use a one side patch. As determined in this study, this causes the increase of SIF at the non supported side of the configuration. This problem can be overcome by introducing holes before repair, leading to a relative decrease of up to 15.5%. The analysis carried out proves that as distance e increases, the effect of the defence holes weakens. As the node path leaves the vicinity of the patch this phenomenon subsides. In general, as the hole radii were raised, the provided decrease of SIF was in turn raised. For the specific configuration it is deduced that the maximum decrease was observed at a radius of 2.5 mm and a hole distance (e) from the crack plane, of 3mm.

6. Experimental verification

The next step was the experimental verification. Acknowledging the capabilities that dielectric sensors have to offer in terms of useful results [9], the next step was the realization-underlining of introducing them to the CPR technique. Firstly, it is possible to embed these sensors into a silicon blanket, as far as the curing phase is concerned only, thus enabling direct contact with the outmost ply of the composite patch. This procedure involves scarring of the patch (engraving of the sensor) which can induce structural degradation of the repair. The alternate embedding strategy for the sensors, which eliminates scarring of the patch, involves positioning at the lower face or the repair (measuring the adhesive and the first ply of composite). Taking into consideration the capability of using a wireless dielectric sensor and at the same time acknowledging the beneficiary results (numerical analysis) that drilling of defense holes presented, the author [9] reached the novel combination of inserting wireless dielectric sensors into defense holes which also serve to the decrease of SIF. Additionally this method satisfies the demands and restrictions that on-line Structural Health Monitoring (SHM) poses, coincidentally integrating the specified repair into a smart patch.

7. Fatigue specimens

The substrate was a 2017 T4 aluminium alloy cut in plates of dimensions 300×80×3 mm (length × width × thickness) with a centrally placed notch of 10×1 (length × width), vertical to the loading axis as seen in Figure 9.

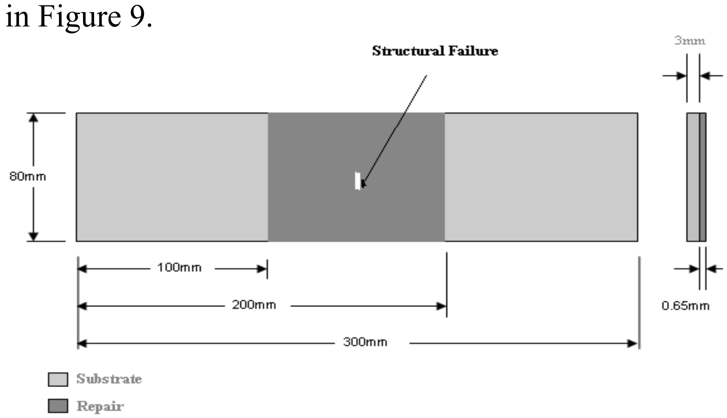

Figure 9: Basic geometry.

The optimum radius was decided (numerical analyses) to be R=2.5mm with a distance e=3mm from the plane of the notch. This geometric configuration will be referred to as small Version (small V). Furthermore, after research for commercially available dielectric sensors, the smallest diameter was that of 9mm. This fact generated the need of preparing specimens with a radius of 4.5mm and a distance from the plane of the notch, e=6mm (large V) so as to obtain the ability of sensor placement (Figure 10).

Figure 10: The two examined geometries.

The curing process was conducted with the use of a portable curing console (GMI ANITA OT) which is used in real time industrial repairs. The patches were of 4 unilateral plies (HexPly M20 of Hexcel).

8. Experimental Results

Testing was performed on an Instron 8801 device capable of delivering cyclic loading up to 10 tons. The maximum stress applied was equivalent to 45.2% (193.3 MPa) of the UTS. The loading range was set at 13.2 kN. The frequency was set at 20 Hz. Room temperature was at 28°C during testing. The results were fully repeatable in the entirety of the specimens. The typical response of a notched plate under fatigue is presented in the graph of Figure 11 and acts as a baseline for the more specific cases. Comparing the behavior of specimens with a plain repair and those with defense holes (small V) complementing the repair, a smoother crack propagation can be determined but also a small life increase of 2.24%. The comparison between plain repairs to a large V complemented repair presents a similar behavior regarding crack propagation and an increased total life under fatigue of 39.8%.

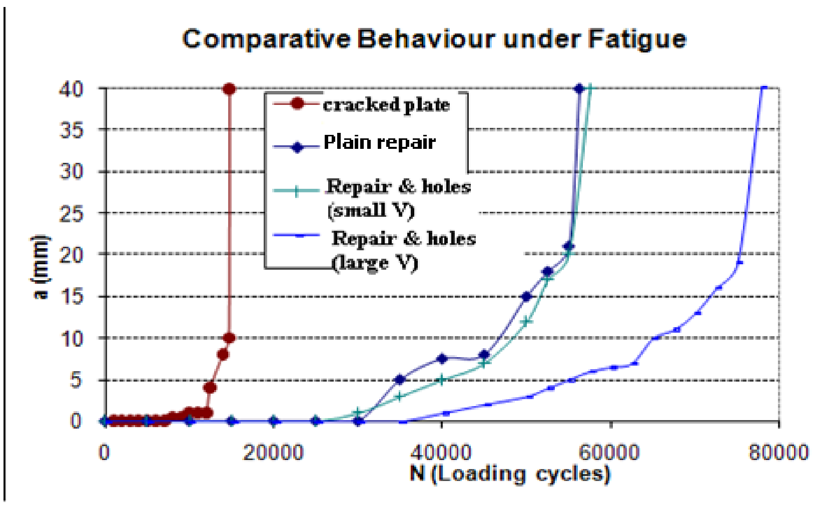

Figure 11: Comparison under fatigue loading.

9. Discussion of experimental results

The experimental examination of defense holes showed interesting and promising results. In the case of 4.5 mm diameter holes the technique only offers a small life increase compared to the plain repair but presented smoother crack propagation. The most encouraging results were derived from the 9 mm diameter defense holes as the behavior of the structure is retained with a notable life increase and at the same time offers the capability of housing commercially available sensors in the specified structure geometry.

10. Dielectric sensing

The final step of this study was to conduct experiments so as to evaluate the sensing capability of implementing dielectric sensors to the curing phase of CPR [10].

The curing console GMI ANITA OT uses thermocouples for temperature identification. Further to these, dielectric sensors were used. Two dielectric sensors were placed into a silicon blanket and were coupled with surplus thermocouples for precise temperature monitoring locally. The placement was on the upper (free) surface of the patches (Figure 12). As a first step, these experiments aimed at the assessment of results recorded from the sensor system with respect to the end of curing as well as their validation. The experiment data is presented below followed by evaluation.

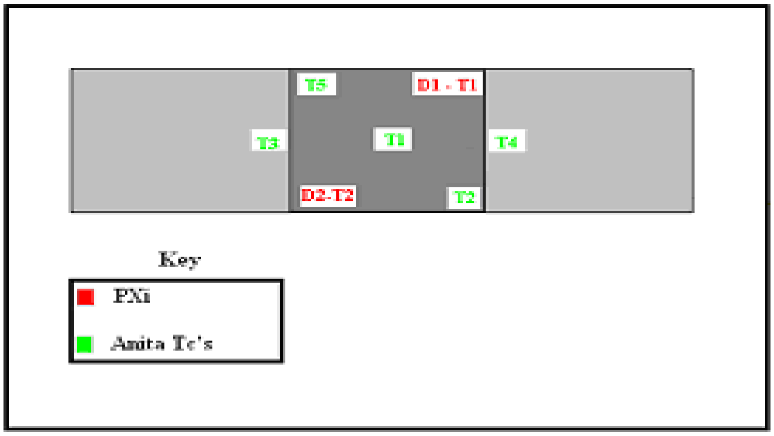

Figure 12: Placement of sensors.

For the experiment, the curing cycle followed was the optimum for the materials used (4 plies M20 from Cytec for all the experiment series) with a plateau at 130^{o}C for 120 minutes and with a heating/cooling rate of 3^{o}C/min. In Figures 13a and 13b phases of the entire experimental process are presented.

Figure 13 a: Dielectric sensor embedded into a blanket. The coupling thermocouple can be vaguely observed.

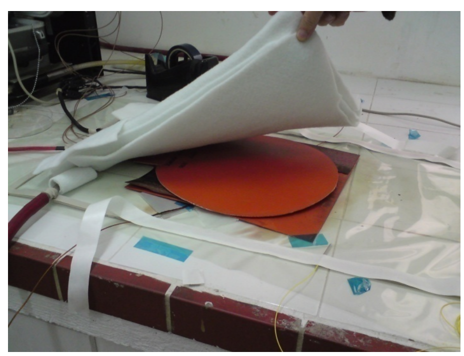

Figure 13 b: The orthogonal blanket bearing the dielectric sensors and thermocouples. Above it, the circular heating blanket, just one step before closing up of the vacuum bag.

The dielectric sensor data analysis for this particular experiment offered the following conclusions:

- Sensor 1 offered sufficient data, whereas sensor 2 preformed with limited capacity (due to extended use).

- The differentiation of temperature was significantly limited as the primary thermocouple was placed on the patch. Thermocouples collected measurements not exceeding the 5 ^{o}C margin with respect to the programmed temperature profile (Figure 14). The thermocouples near the dielectric sensors showed increased temperature by 10 ^{o}C.
- It is observed from the Z"max readings (especially from sensor 1) that viscosity is reduced as temperature reaches 100 ^{o}C, a phenomenon that continues during the temperature plateau. Dielectric sensors locate the start of reaction 45 minutes into the plateau (Figure 15).

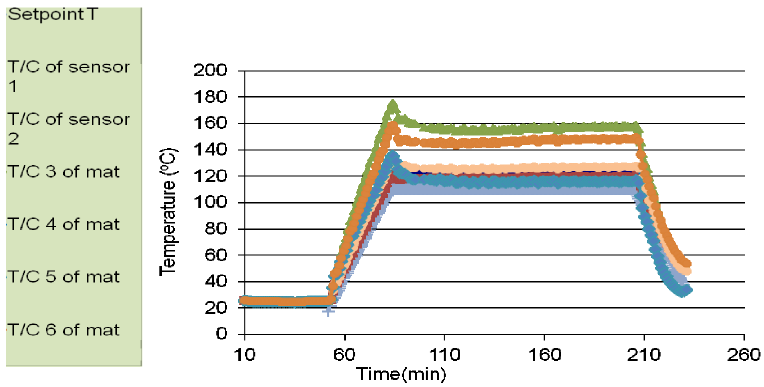

Figure14: Programmed temperature values compared to values near the dielectric sensors.

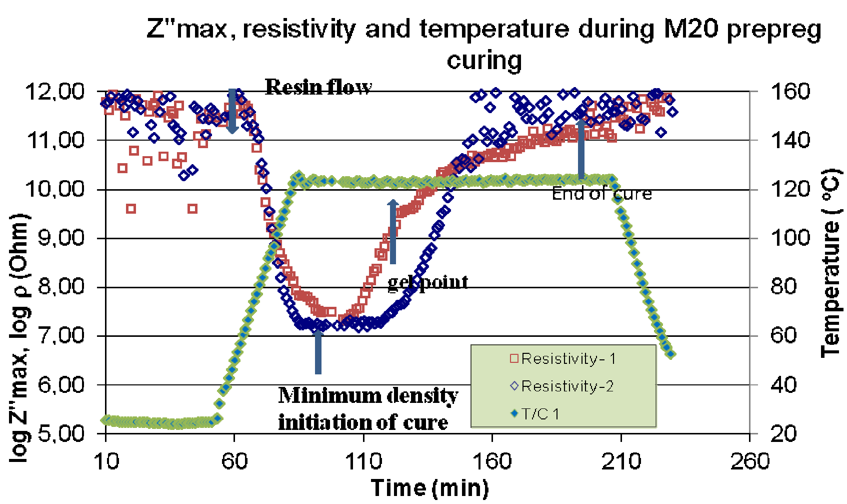

Figure 15: Basic points of interest regarding impedance results.

11. Discussion of Dielectric sensor results

The results of this line of experiments are promising. Conclusions are drawn below.

1. The identification the initiation of cure is possible (minimum density observation).

2. The end of cure can be identified when impedance values reach a plateau (end of cure).

3. Curing is completed prior to the end of the temperature plateau (which is recommended). An overall reduction of the curing cycle at an industrial status followed by the certification of quality offered by dielectric sensors will lead to important cost reductions.

12. Conclusions

The numerical and experimental investigation resulted to positive results, demonstrating life increase post alteration of the specified structure geometry thus enabling the capability of housing commercially available sensors.
Further experimental investigation regarding SHM by dielectric sensors, exhibited identification of initiation as well as cure completion.

Acknowledgments

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