A Comparative Study of Adhesively Bonded Composite Patch

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ABSTRACT:

Advanced fiber reinforced composite materials are increasingly being used in the manufacture of aerospace structures due to their strength and high strength to weight ratios. In these structures, fastened joints are indispensable for the assembly of structural components. As a result, the development of efficient methods for the design and analysis of fastened composite joints has been the focus of numerous researches over the years. In this study, strain monitoring was investigated in a single sided patched structure. An aluminium (Al-2024 T3) substrate which was repaired with a graphite / epoxy patch is considered under tension. The predictions of the present analysis are verified against those obtained by a three-dimensional ANSYS FE model and the experimental measurements. The measured and predicted strain values are in agreement, verifying the accuracy of the predicted tensile loads.

Keywords: Composites; Aircraft; Bonded Composite Repairs; Adhesive; FM 300; Stress; Analytical modeling; Finite element method.

1. INTRODUCTION

There has been an escalating tendency towards operating commercial and military aircraft structures

throughout the past thirty years. In 1973, researchers first proposed the repair of cracked metal aircraft structures using adhesively bonded patches fabricated from composite materials /1/. A number of analytical, numerical and experimental analyses have been carried out to develop design systems for composite repairs of metallic aircraft structures. Selected papers will be studied here.

Most of the composite repairs have been carried out on military aircraft /2/. Currently, Textron has advanced the application of bonded repairs to civilian aircraft by fixing bonded doublers on Federal Express 747s for assessment /3/. One of the continuing investigations to improve the accuracy of bonded repairs is AMRL's work on judgment models for damage tolerance, such as the consequences of first flaws in bonded repairs /4, 5/. In addition, AMRL is working on a broad methodology for bonded repairs since this is the key to offering a commercial solution for a broader variety of repair process. Accurate experimental determination of thermal residual strains is necessary for a more accurate visualisation of the actual load experienced by the bonded repairs for the critical load cases that decide the feasibility of a repair.

Ong and Shen published a paper /6/ about composite patching repair. In this paper, the authors studied the adhesive-bonded composite patching repair of cracked aircraft structure. To do this, they used three room temperature adhesives with single-lap shear and fatigue tests. They observed that after adhesive-bonded repairs

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with carbon or boron-fibre composite patches, the fatigue life of a cracked aluminium panel is extended 60–100 times.

In 1978, a paper was published on thermal residual stresses for carbon fibre reinforced cracked composites via X-ray diffraction method /7/. Carbon/epoxy patches were used to let X-rays penetrate to the metal surface instead of the more usual boron/epoxy patches. These measurements proved the high thermal stresses existing in the bonded repair samples. Moreover, in thermal residual stress measurements in the reinforcement, stress measurements were also detained around a machined crack sample. The measured thermal residual stresses near the machined crack tip indicated notable scatter based on the remote thermal residual stress. The thermal residual stresses were explained in terms of stress intensity factors, which seemed to be quite high and incompatible with previous test data, by AMRL researchers on the growth of stress corrosion cracks in reinforced examples /7/. Those surveys led to some suggestions by Baker to lower thermal residual stresses in a composite repair. He concluded that the heated area should be lowered to enlarge the force offered by the nearby structure. The adhesive should be cured at the lowest viable temperature. If possible, the patch structure should be pre-stressed in compression with the patch application at a level which will partly or fully cancel the residual tensile stress on cooling /8/.

Raizenne *et al.* /9/ carried out a study on the experimental confirmation of three-sided graphite composite patches. In this study, they arranged six different patches with the stacking sequence of $(0)_{10}$, $(90)_{10}$ and $(\pm 45)_5$ bonded to 7075-T651 Al-substrate. They used FM 73 as adhesive layer to bond the graphite/epoxy composite to the Al-substrate, and static, fatigue and flatwise tension tests were applied for the mechanical properties of the patch. They studied the patches at three different temperatures of -30°C , 20°C and 60°C . Using seven strain gauges bonded to different places on the patch and Al-substrate, static and fatigue loading did not result in patch failures or a decrease in patch efficiencies. Albat /10/ examined thermal residual stresses in bonded composite repairs on cracked structures. In this study, he produced seven different patches with $(0)_7$, $(90)_7$ and $(45)_7$ stacking sequence. He

utilised FM 73 adhesive layer to stick the boron/epoxy composite onto the 2024-T3 Al substrate. The residual and thermal residual strains are measured by means of 44 strain gauges bonded to various seats on the patch and Al-substrate as well as embedded between composite and Al-substrate. He mainly examined the patches at 21°C and -56.5°C . A theoretical analysis was carried out for a double-sided patch; he proposed a model, and the results were compared with the experimental values. Latterly, he studied the sample using the finite element method and compared it with experimental results. There was good agreement, particularly for thermal residual strains in these samples.

A composite skin having a circular cutout that was repaired /11/ with a patch is considered under tension. The predictions of that analysis are verified against those obtained by a three-dimensional ANSYS FE model and experimental measurements.

Another work /12/ was to conduct a preliminary examination of the use of reduced-temperature cure cycles for the reduction of residual stress during patch repair. The work also studied the evolution of adhesive properties during the cure process in order to develop optimized cure cycles to achieve a combination of minimum residual stresses and cycle time, and maximum level of cure in the patch adhesive.

In another paper, FCG behavior of pre-cracked Al 7075/T6 substrates with bonded composite patches was investigated experimentally and analytically /13/.

In another study /14/, the finite element method was used to analyse the behaviour of repaired cracks with bonded composite patches in mode I and mixed mode by computing the stress intensity factors at the crack tip. The effects of the patch size and the adhesive properties on the stress intensity factors variation were highlighted. The plot of the stress intensity factors, according to the crack length in mode I, shows that the stress intensity factor exhibits an asymptotic behaviour as the crack length increases. In mixed mode, the obtained results show that the Mode I stress intensity factor is more affected by the presence of the patch than that of mode II. Externally bonded composite patches have proved to be an effective method of repairing cracks or defects in aircraft structures. Considerable researches have been performed to develop the technology of bonded

composite repairs in aircraft structures. Alan Baker pioneered these researches at the aeronautical and maritime research laboratory for the Royal Australian Air force.

A study /15/ was performed to develop an analytical method to characterize these thermal stresses and to estimate their effects on a cracked metallic skin repaired with an adhesively bonded composite patch. Even though the adhesive during bond formation is better characterized by a constitutive description which incorporates its dependence on the rate of mechanical deformation and on the thermal history, however, for simplicity, the adhesive is modeled there as a linear elastic material with a zero stiffness and a glassy modulus at temperatures above and below its glass transition temperature, respectively.

Another paper /16/ reported on the development of a “perceptive repair” or “smart” system which provided information on the in-service performance of the repair and the associated structure. The paper focused on the detection of disbond in the adhesive layer between adherend and the metallic parent structure. Since this is a relatively new area, a series of numerical studies were initially performed to reveal the salient features of the signals expected. Those numerical findings were subsequently confirmed experimentally /16/.

A recent paper presented the results of a design study of bonded patch repair of thick sections in aircraft structure. The objectives of that work were (1) to explore appropriate procedures for three-dimensional finite element analysis of bonded repair of thick sections using the commercial packages MSC/Patran and MSC/Nastran, and (2) to examine the effectiveness of various patch configurations in reducing the stress in the original structural component. A global-local hierarchical modeling approach was developed to analyze a structural component without and with composite patches. A potential repair for primary structure in an F/A-18 aircraft was chosen as the basis for that study /17/.

Another paper /18/ also reported the experimental results of two composite-to-metal double-lap joints, and the numerical determination of the mixed mode strain-

energy release rates along the observed crack paths using the finite element method. Due to limited fatigue test results, only a qualitative correlation was made between the observed fatigue failure behaviour and the calculated energy release rates /18/.

In recent work, strain monitoring was studied by Findik *et al.* /19/ in a single sided patched structure. The thermal residual strains were defined in graphite/epoxy composites on Al-2024 T3 substrate. Five samples were manufactured, and several strain gauges were bonded on the patch Al-substrate. Thermal and thermal residual strains were measured after one- and two-step curing at different temperature and the results were compared with each step as well as previous work.

In the present work, an aluminium plate was repaired with a composite patch is considered under tension. The predictions of the present analysis are verified against those obtained by a three-dimensional ANSYS FE model and the experimental measurements.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

2024-T3 Al substrates are supplied from the ALCOA Company, as rolled form; the thickness of the substrate is 0.130 in. (3.30 mm). 2024-T3 aluminium, which is a high strength, solution treated, cold worked and naturally aged aluminium alloy with 4.5% copper and 1.5% magnesium, was chosen due to its widespread use in the aircraft industry. The substrates are carefully machined in the National Research Council Workshop to the dimensions of $50 \times 305 \times 3.30 \text{ mm}^3$.

Graphite epoxy preregs used are Hercules AS4/3501-6 due to their satisfying the strength and stiffness requirements. The thickness is 0.2184 mm per ply. Film adhesive selected is CYTEC FM 300 as candidate material. The thickness is 0.20 mm for one layer of FM 300. The weight of one layer of FM 300 is given as 390 gsm.

The coefficients of thermal expansion (CTE) of Al, gr/ep and adhesive (FM 300) are given respectively as 23.45, 0.5 and $50 \mu\epsilon/^\circ\text{C}$.

2.2. Al surface preparation

Surface preparation of the aluminium prior to patching is an extremely critical element of the composite repair operation. It controls the durability of the repair, a property which is very hard to verify. If the surface was prepared properly, cohesive failure should appear. Detailed testing is also used to give more insight into the durability of the bond and thus assesses the quality of the surface preparation. Care to the details of the surface preparation procedure is therefore critical. Al surface preparation is done according to the previous work /9/.

2.3. Graphite patch production

The patch specimen contains 10 layers of graphite prepreg and one co-cured layer of adhesives (FM 300U). The co-cured layer of adhesive improves the properties of the graphite/epoxy prepreg by replacing the graphite prepreg epoxy system with a toughened epoxy. The detailed data about graphite patch production are given elsewhere /20/.

2.4. Mechanical tests

Static testing of the present specimen was carried out using an MTS TestStar II system on a 100 kip load frame. The dimensions of the static testing specimen are given in Section 3. The testing of the lap-shear specimen was conducted at room temperature using an MTS Test Star II system on a 22 kip load frame. The load and strain data were recorded using a computerised data acquisition system. The lap-shear samples are prepared to the ASTM standard of D 5868-95 and the details are given in the appendices.

3. GEOMETRICAL MODEL

Consider a thin elastic aluminium plate having the following dimensions: height $H_p=300$ mm, width $W_p=50$ mm and thickness $e_p=3$ mm. The elastic properties of the material are: Young's modulus $E_p=72\,400$ MPa and Poisson ratio $\nu_p=0.33$. The plate is subjected to uniaxial tensile load giving a remote stress state of $\sigma=140$ MPa.

There is no crack supposed to be in the plate, but Al-plate needs to be bonded with graphite/epoxy patch having dimensions: width W_r and thickness e_r . The material properties of the patch are: Young's modulus $E_r=81.8$ GPa and Poisson's ratio $\nu_r=0.3$. The adhesive properties are: shear modulus G_a and thickness e_a . The plane stress conditions are assumed. Since the geometry and loading is symmetric, only one half needs to be analysed. Fig. 1 shows the geometrical model.

Table 1

Mechanical properties of aluminium 2024-T3, FM300 adhesive and graphite epoxy/Hercules AS4/3501-6

Material	Aluminium 2024-T3	FM300 adhesive	Graphite epoxy/Hercules AS4/3501-6
Young's modulus, E (N/mm ²)	72400	2756	81800
Poisson's ratio, ν	0.33	0.3	0.31

Fig. 1: Geometrical model of the present patched structure (all dimensions are centimeters).

4. FINITE ELEMENT METHOD

A layered structure is essentially a three dimensional structure. A three-dimensional finite element or mathematical modelling of such a structure will involve several degrees of difficulty. In this research simplifying

assumptions are made which allow us to delineate the essential features of the reaction. These assumptions are:

- Discrete layers can be associated with adhesive bond.
- Every layer is measured as an individual two-dimensional structure under a state of plane-stress.
- It is assumed that the adhesive layer is homogeneous, linear elastic and isotropic.
- The surface shear transmitted through the adhesive is assumed to perform as surface traction on the adherends.
- The adhesive is assumed to distort only in shear and this deformation is regular all over the adhesive thickness.

The shear stress in the adhesive is given by

$$\tau = \frac{G_a}{e_a} (u_1 - u_2)$$

where u is the displacement in layers 1 and 2 (plate and patch).

The adhesive force is obtained by using the adhesive shear stress as surface tractions on the layer and integrating. Since the surface tractions are proportional to the relative displacement of the two layers, the adhesive force can be expressed in terms of nodal displacements of the top and bottom layer. This gives a stiffness matrix for the adhesive elements.

The total structure (plate and patch) is meshed using standard eight noded serendipity elements with quadratic shape functions. These elements execute well for elastic analysis [21]. Fig.2 shows typical mesh model of the plate and the patch.

Procedures of the modeling approach are as follows:

- i. apply the displacement boundary conditions, generated as simulation or obtained from real structures.
- ii. obtain the displacement boundary conditions from the best patched configuration and these conditions to the model; and
- iii. run analysis of the model and examine the performance of the repair.

- iv. a penalty factor is applied to find out the stress and strain values in FEM analysis.
- v. the displacement scale is magnified as 5 times for the better observing the movement.

Fig. 2: (a) Boundary conditions of finite element model, (b) detailed mesh of patch, (c) detailed mesh of bonded.

4.1 Model of Substrate and Patched Case

The commercial finite element package ANSYS was used to generate the model of the repaired structure. Linear 3D solid elements (SOLID45) were used to model the substrate, as shown in Figure 4, and there were 1664 elements and 2282 nodes in the model of substrate. General plate elements (SOLID45) of uniform thickness were used to model the patches, as shown in Figure 5, and no adhesive was modeled in the model for the sake of simplicity. Therefore, there were no additional degrees of freedom in the patched model. The model generated was submitted to the analyzer, ANSYS, for stress analysis and only a few seconds of time were needed for analysis.

4.2 Simulation of Model with Finite Element Method

In this study, a finite element method is used for analytical investigation. In order to do this, ANSYS commercial software is used. First of all, the working conditions are determined for the ANSYS program. Consequently, a penalty function was defined to simulate behavior of model better and eliminate some possible numerical differences. The model is formed as a 3 dimensional environment, so ANSYS was used as software for this work. ANSYS uses a finite element method for numerical solutions to different problems in the present analyses. Then, the suitable element type is determined (SOLID 45) and in all components of the model, a SOLID 45 - 8 node 3D brick element was used as the element type. SOLID 45 is used for the three-dimensional modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

5. ANALYSES AND RESULTS

As boundary conditions in the analyses, with sequence 1000, 2000, 3000, 4000, 5000 and 6000, N forces were applied as withdrawal loads from one side of the specimen model. Meanwhile from the other side of the model, all degrees of freedom were fixed as constraints. Therefore the total analysis number is six. The model form described is 3D and this simulates the specimen material, which consists of an aluminium alloy Al 2024 T3, an adhesive FM300U and an epoxy-graphite based patch; a linear isotropic material model was used. For each one of these materials, the Young's modulus, Poisson ratio and room temperature values were entered in the program. As a result of this, a layered model was made of three components. Each layer of the component's finite element mesh was created one by one. Before this step, components were glued for synchronous mesh or reciprocal element location of each components using a "glue" option. In Fig. 3, boundary conditions are shown of the finite

element model. In this figure, arrows represent withdrawal loads. Since the adhesive model is very small and between Al 2024 and patch layers, it has disappeared. In Fig. 4, the displacement tendency shows the model's nodes for 6000 N analysis. Displacement geometry appears as a circular form in the patched area. This tendency is similar to the real experiments [19].

Fig. 3: Boundary conditions and the meshed patched structure.

Fig. 4: Displacement results in the nodal solution of the patched structure (magnified $\times 5$).

In Fig. 5, strain results are illustrated for 6000 N analysis. Displacement results are magnified $\times 5$ for improved viewing. In Figure 6, stress is shown for 6000 N analysis. According to the results, stress concentration area and maximum value are shown. The value stress area which is at the bottom of the model.

namely the Al 2024 alloy component's free surface, is also presented.

Fig. 5: Strain concentrations in the nodal solution of the patched structure (magnified $\times 5$).

Fig. 6: Stress concentrations in the element solution of the patched structure (magnified $\times 5$).

The color in this area is orange-red. The minimum value is on the top of the surface of the patch. In Fig. 6, the resistance to movement between the layers by bonding is easily seen. The material model's performance is enough to make correct assumptions about the simulation, since it is clear that the weakest area will be the bottom side of the patched zone, as shown in Fig. 6.

In Fig. 7, a comparison is shown of the experimental and numerical results of these investigations. A good

degree of similarity was seen between the numerical and experimental methods [19]. The largest deviation is in the 5000 N analysis, but this margin is under the 10% limit. When 6000 N, which is the maximum load, was applied the maximum strain was approximately $2900\mu\epsilon$ for the numerical simulation (FEM) and $3150\mu\epsilon$ for the experimental work.

For graphic result values, 4 points were selected on the model as the approximate strain-gage locations, as in the previous experiment (see Fig. 2). These points are nodes of the meshes and are called nodes 1,2,3 and 4.

Fig. 7: Strain / load relationship for experimental and finite element methods.

In Fig. 8, a stress- strain relationship comparison is shown between the experimental and the numerical study. Tendencies of the strain increments with stress are similar but margins are different at the node 1 point. With load increment, model answers are increased by degrees. In Fig. 9, a similar situation is shown in node 2. The cause of different values for the experimental and numerical results is deviations between location dimensions of the 4 nodes and strain-gages. In Figs. 9 and 10, similar comparisons are shown in nodes 3 and 4 according to the stress-strain relationship. The same tendency is seen clearly for experimental and numerical results in these graphics [19]. However, the experimental result increment ratio is higher than the numerical results in Fig. 10. Friction force is ignored for this numerical study, because the glue option does not include friction force. This situation can cause the difference.

Fig. 8: Strain / stress relationship for Node 1 in the experimental and finite element method.

Fig. 9: Strain / stress relationship for Node 2 in the experimental and finite element method.

Fig. 10: Strain / stress relationship for Node 3 in the experimental and finite element method.

As a result, when one looks at the graphics together, it is seen that total stress results are near $3000\mu\epsilon$ and stress values are approximately 320 MPa for numeric and 330 MPa for experimental [19]. For small forces it is a good sequence and when force increases this sequence becomes coarser. In Fig 11, these results are presented together. According to these results, it can be

said that the model's behavior against tensile forces is near to linear.

Fig. 11: Strain / stress relationship for maximum stress in the finite element method.

5. CONCLUSIONS

A numerical approximation for this and similar problems can be used with some accuracy, but care should be taken to select a joint option. The glue method, which was used in these experiments, is a good method to preview and find out model behavior for patched structures. In addition, analysis is run easily and quickly despite the use of a 3D model. However, this method is not sufficiently sensitive for final decisions, so it should be accepted as merely a mid step in numerical analysis. For final or more accurate results, some contact algorithms which contains friction forces should be used. For subsequent works, these options can be used.

Another important point is the selection of the material model. In this work, every material was assumed as a linear isotropic structure. Defining it as a non-isotropic composite model that leads to friction forces between layers may give better results. But in this situation, for 3D models CPU times will increase somewhat, and the PC may be locked. Often, when sophisticated 3D models and algorithms or material models are used, similar problems occur with the software or/and hardware. In the present study, strain monitoring was studied in a single-sided patched structure. An aluminium (Al-2024 T3) substrate was repaired with a graphite / epoxy patch and considered under tension. The predictions of the present analysis

were verified against those obtained by a three-dimensional ANSYS FE model and the experimental measurements. The measured and predicted strain values are in agreement, verifying the accuracy of the predicted tensile loads.

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