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A Study of the Mechanical Properties of Patch-Bonded and Riveted Repairs on Cracked Al 6061-T6 alloy Structures

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ABSTRACT

A comparison of riveted and bonded repairs, bearing and net tension failures, on Al 6061-T6 plates is presented. The results are then compared with previous papers about bonded repairs on different patch materials and shapes. Aluminum alloys, including 6061-T6, have a face-centered-cubic crystal structure. Under normal circumstances, these types of crystal structures do not exhibit cleavage fractures even at very low temperatures. In aluminum-based structures, the cracked plate structures are frequently repaired using mechanical fasteners - either rivets or bolts - even though patch-bonding techniques are applied to repair and reinforce the structure. Static test results indicate that the riveted repairs are affected by the position of the rivets. When using the same size of patch, the bonded repair technique is stronger; the rate of elongation is also increased. From FEM analysis, it is revealed that the origin of patch debonding in patch-bonded structures is the edge of the patch along to the tensile strength.

Keywords : Bonded repair, Net failure, Bearing failure, Al 6061-T6 alloy , Size effect, Material effect, Mechanical fastener

1. Introduction

It is currently required that mechanical structures are lightweight, strong and low priced. Aluminum alloys satisfy these requirements and generally high-strength aluminum alloys (5000 series, 6000 series) are suggested as suitable materials. In particular, 6061-T6 aluminum alloys, which have FCC (Face-Centered Cubic) structures, do not demonstrate cleavage fracture behaviors at room temperature, or even very low temperatures. In other words, these fracture behaviors are independent of temperature and demonstrate trans-granular, ductile tearing type at fracture mode. Additionally, aluminum alloys have equal toughness values at even very low temperatures. Hence, for aircrafts exposed to various cruise conditions, very low temperatures in supersonic flight, and high temperatures in ground parking, aluminum alloys are good structural materials.

As aluminum alloys are widely used as structures, engineers tend to focus on the repair and reinforcement of these structures.

Recently, mechanical joints have been made so that the joint can be later disassembled and reconstructed in an uncontrolled environment. The machining of holes in the members to be joined to accommodate mechanical attachments obviously weakens the load carrying capability of the members, producing concentrated stresses on the bearing surfaces, resulting in local stress risers. On the other hand, bonded joints do not have any of the problems that appear in mechanical joints. But bonding should not be attempted unless stringent cleaning and processing steps can be adhered to within a controlled environment. Because of safety no additional defect, many engineers recommend bonded-joints 1).

Usually there are two types of failures in patch repairs: bearing failure, and net failure. Bearing failure appears mostly in mechanical repairs, though net failure is shown in bonded repair. Net failure shows usually steady and safety failure phases until extreme fracture. Patch bonded repair is therefore suggested as a good reinforcement method in cracked aircraft structures. In the case of rivet reinforcements, patch repaired structures are affected by the number and diameter of the rivets. Additionally, the size of rivet head, and rivet material, also have an effect on the strength of the structures

Stewart[2] has demonstrated that simultaneous mechanical and bonding repair is effective for crack inhibition.

The present paper describes an experimental and analytical evaluation of the tensile response of variable types of patch-repaired specimens. It presents a comparison of rivet-repaired specimens with bond-repaired specimens. Moreover, the effect of patch size and shape in patch-repaired specimens is demonstrated by experimental result and finite element analysis.

2. Preparation of specimens and experiments

2.1 Materials

2.1.1 Structural Materials

6061aluminum alloys, usually 6xxx series (Al-Si-Mg-Cr), demonstrating both anticorrosive qualities and strength, are used for the experiment. The chemical compositions and mechanical properties of Al6061-T6 alloy are Mg (1.00%), Si (0.60%), Mn (0.28%), Cr (0.20%), Fe (0.05%) and Aluminum.

2.1.2 Patch materials

Al 2024-T3, Al 6061-T6, Carbon/Epoxy, Glass/Epoxy and Woven Carbon/Epoxy composite are used as patch materials. All composite patch materials are manufactured with 5ply prepregs, and the thickness of each patch is approximately 0.4mm plate.

2.1.3 Adhesive films

FM73 Adhesive Film (American Cyanmi Co.) is applied to adhere to the two materials. Available usage temperature of this film is -67°F~180°F, and the weight is 0.03psf (pound per square foot). According to the technical order of the manufacturer, the specimens are molded at 250°F for 1hr. Table 1 shows the general properties of the adhesive films.

Table 1 General properties of the adhesive films

Service temp.	-67°F to 180°F
Product name	FM-73
Supplier	American Cyanamid
Cure cycle	1hr 250°F
Film weights	0.03

2.2 Specimen preparation

Tensile specimens are cut from the aluminum 6061 plates treated under T6 heat-treatment conditions (520°C for 1hr, 175°C continuously for 8hr) as described in ASTM B 557-94 [3]. A bolt crack hole is created in the center of the specimen, and scratches around the hole or surface are removed clearly

2.2.1 Specimen shapes

The basic shape of the specimen was designed according to ASTM guidelines. In the center of the specimen, a 10mm diameter hole was created using a drill and hole cutter. Specimens (thickness 0.8mm; total length 240mm; and width 100mm) are produced. The gauge length of the specimen is 50mm.

2.2.2 Specimen molding and manufacture

The entire bonding process follows the directions of manufacturer. First, erase all scratches on the specimens and polish the specimen with no. 1000 emery paper. Next, clean the surface with acetone. Finally, put an adhesive film between the cracked aluminum plate and the patch material, and then form the specimen at 120°C for 1hr at a pressure of 0.28±0.03Mpa. (Fig.1)

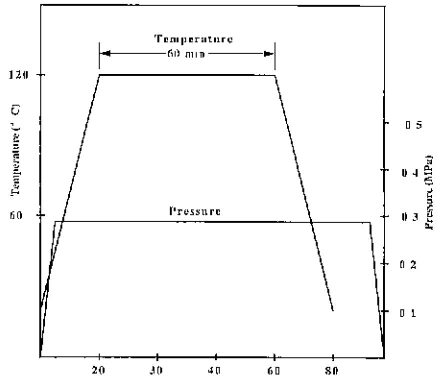


Fig. 1 Diagram of the specimen cure cycle

In the case of repairing or reinforcing with rivets, a Squeeze riveter (Chicago Pneumatic Co. USA) is utilized.

Fig.2 shows the rivet repair and reinforcement specimen. The patch size is 30×30, and four-point riveting was carried out using 5/32inch rivets. The shape of bond-repaired specimen is similar to Fig.2. Yoon[4),5)] shows the specimen in detail.

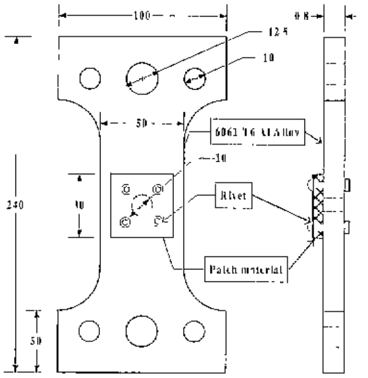


Fig. 2 Shape and dimension of rivet-jointed patch repair aluminum plate specimen with crack hole.

2.3 Experimental facilities and procedures

A new clip is tested for tensile strength. It has been designed to prevent slip and bearing failure. It has 3 bolt-holes: two 10mm diameter holes and one 12.5mm diameter hole.

Universal tester equipment (INSTRON) is used for tensile testing. Its crosshead speed is fixed at 0.01mm/sec.

2.4 Finite element modeling

A typical composite patch-bonded repair consists of three elements, (i.e., the host aluminum panel, the composite patch and the adhesive layer).

For the specimen, only a quadrant of the structure was analyzed because of its symmetry and the sheet was idealized as in Fig.3. A finite element analysis of the configuration is done using a commercial code I-DEAS and ABAQUS version 5.8 on an IBM Risc 6000. The model is a typical single-sided patch configuration. The 8-noded element was selected for the present study. The plate nodes are located on the mid-planes of the aluminum plate and patch. The adhesive nodes lie along the patch-adhesive and adhesive-aluminum plate interfaces The adhesive layer is then modeled as a solid for its transverse shear stiffness and axial stiffness.

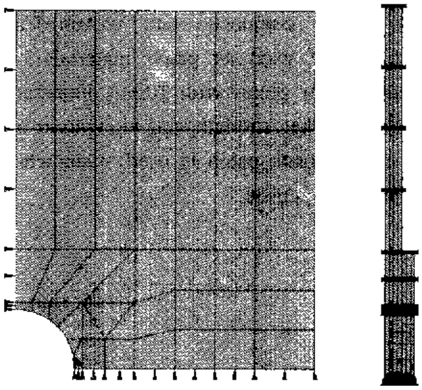


Fig. 3 Finite element model of reinforced specimen

3. Results and discussion

3.1 Effects of Holes on Fracture

Fig.4 shows the experimental fracture loads (P) when there are variable size holes (diameters 1.6, 2.0, 3.0, 3.2mm) in Al 6061-T6 specimens. The horizontal axis shows the hole's diameter (D) and specimen's width (W).

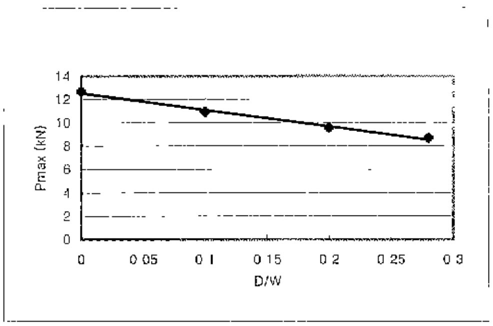


Fig. 4 Tensile load vs. D/W values of the specimens with holes.

On the other hand, the vertical axis indicates the fracture load (P). From these results, a regressive equation was drawn. [6]

$$P_{\max} = -14.278(D/W) + 12.59 \tag{1}$$

3.2 Effects of patch materials on tensile strength

Fig.5 shows the test results on the specimens reinforced with different patch materials .

Al 2024-T3, Al 6061-T6, Carbon/Epoxy composite, Glass /Epoxy composite and Woven Carbon/Epoxy composite are used as patch materials on Al 6061 aluminum alloy plates with 10mm diameter holes. The results show that strength and elongation are excellent when a composite patch is used, even when the same patch material is used.

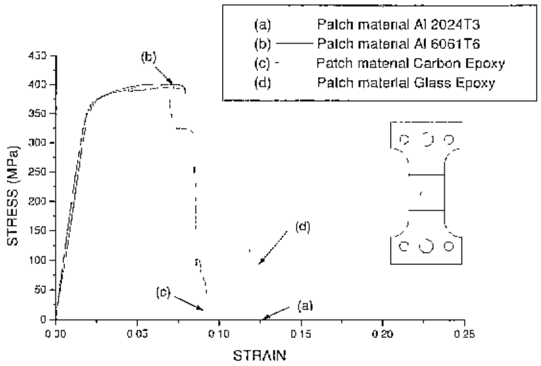


Fig. 5 A comparison of stress-strain curves for different patch materials

Composite patches are widely available as engineers can design composite patch materials for specific crack shapes and loading conditions.

3.3 Effects of patch shape on tensile strength

Fig.6 manifests the effects of Carbon/Epoxy patch shapes on tensile strength.

5 kinds of patches (40×20, 20×40, 30×30, 40×40 and 50×50mm in length and breadth) are applied. The 40×20mm patch is most effective in terms of tensile strength. This confirms that longer patch in length to crack progress direction is more effective to control crack growth.

3.4 Effects of rivet reinforcement on tensile strength

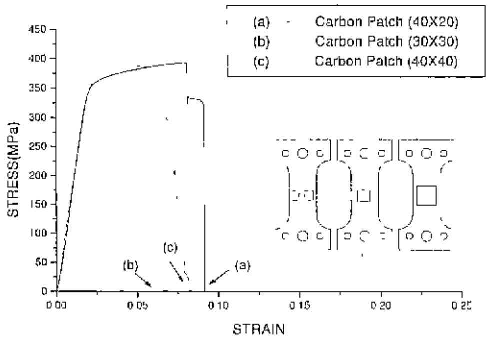


Fig. 6 A comparison of stress-strain curves for different patch sizes

When comparing Fig.5 and Fig.7, the bond repair is good in strength and stable in the crack-growth. Although, the rivet repair does not exhibit net failure behavior, it does reveal bearing failure. Usually, bearing failure is influenced by the strength of both the rivet and the structure itself. Conversely, net failure is affected by the bonding between the structure and the patch.

From these results, bond repair is shown to be a more efficient repair technique.

3.5 Fracture behaviors depending upon patch method

In this paper, the fracture behavior of patch-repaired specimens was observed in bonded and riveted repairs respectively.

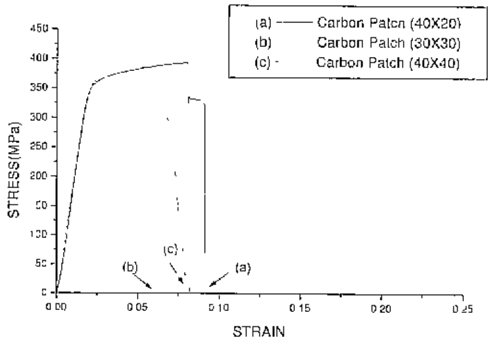
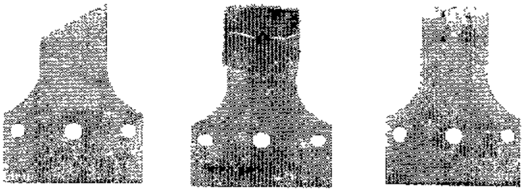


Fig. 7 A comparison of stress-strain curves for different patch shapes



(a) (b) (c)

Fig. 8 Fracture shape for tensile test of (a) no patch bonded specimen, (b) patch bonded specimen, (c) patch riveted specimen.

None of the patch-repaired specimens showed a roof-sloping fracture on one side only. This means that the alloy plates have directional properties as most materials have It is very useful to control fracture behavior. Patch-repaired specimens however appear a horizontal fracture behavior on the basis line of the crack hole. This is why the patch-bonded area on the specimen plays an important role in increasing the initial crack. On other hand, the rivet-repaired specimens exhibit a bridge between the rivet and the center hole. This looks like a saw type fracture (Fig.7). This behavior is dependent on the distance between the crack and rivet. It also depends on the worker's riveting techniques.

Consequently, bonding repaired specimens, which show net fracture behaviors, are safe methods of inhibiting in fracture mode. This net fracture behavior has an effect on changing the fracture direction.

3.6 A finite element analysis of the effect of different patch sizes on center-hole specimens

The stress contour plots for the 40×20 carbon/epoxy composite patch repair specimen are viewed in Fig.9. In this patch size, it is demonstrated that though the upper part has a low stress concentration [Fig.9 (a)], the stresses are concentrated on the side part of the center hole [Fig.9 (b)] and the upper edge-border corner of the patch.

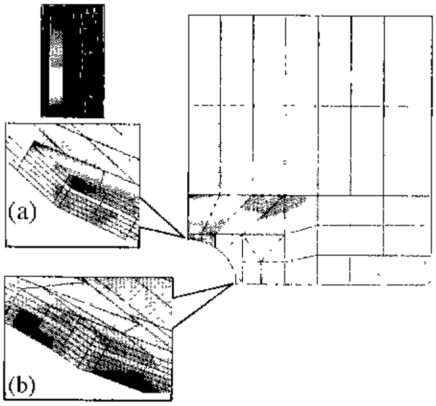


Fig. 9 Stress contours for a 40×20 size patch-repaired specimen with a center hole at applied static tensile strain (a) an upper part of the hole, (b) a side part of the hole.

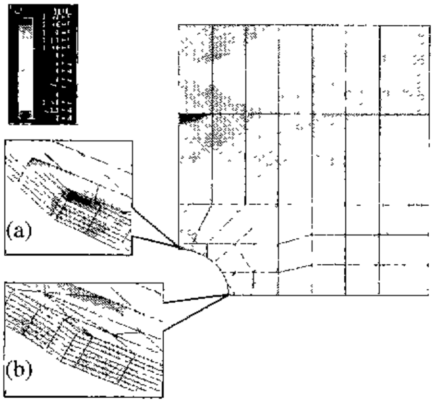


Fig. 10 Stress contours for a 20×40 size patch-repaired specimen with a center hole at applied static tensile strain (a) an upper part of the hole, (b) a side part of the hole.

Fig.10 shows stress contour at the patch repair specimen with size 20×40 carbon/epoxy composite. In this patch size, it is similarly revealed that though the upper part has a low stress concentration [Fig.10 (a)], the stresses are concentrated on the side part of the center hole [Fig.10 (b)] and the upper edge-border part of the patch. The stress concentration regions are however wider than Fig.9 in upper edge-border part of the patch.

4. Conclusion

Patch repairs, especially bonding repairs, are particularly effective in terms of strength. There are, however, some differences in strengths and elongations.

A longer patch is more effective in bonding in crack progressive directions and arraying fiber direction. parallel to the load direction.

By contrast, rivet patch repairs form a bridge between the crack and rivet hole. Bonding is therefore suggested as a better method to repair cracked structures. Finally, net fracture behaviors are present in patch-bonded structures.

Significantly, high stress is present on the sides of the hole and low stress on the upper side of the hole. As high stress is also present on the edge of the tensile patch direction, the debonding behavior starts from the edge of the patch on upper side of the hole.

Reference

1. A.A.Baker, and R.Jones, "Bonded repair of aircraft structures," Martinus Nijhoff Publishers, Dordrecht, pp. 1 - 30. 1988.
2. M.L.Stewart, "An Experimental Investigation of Composite Bonded and/or Bolted Repairs Using single Lap Joint Designs," AIAA-97-1339, pp. 2752 - 2760, 1997.
3. ASTM B 557-94, "Standard Test Methods of Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products," pp. 1-14, 1998.
4. Y.K.Yoon, G.G.Kim. J.J.Park, and H.S.Yoon. "The failure analysis of patch bonded repair on Al 6061-T6 alloy structures with crack bolt hole," Proceedings of the KSME 2000 Spring Annual Meeting A, pp. 148~152, 2000.
5. Y.K.Yoon, G.G.Kim, and H.S.Yoon, "The Effect of Patch Geometry on the Failure of Repaired Al 6061-T6 alloy structures with a Bolt Crack Hole," Proceeding of the KSPE 2000 Spring Annual Meeting, pp. 84~87, 2000.
6. T.H.Hyde, and E.Ollerton. "Applied stress analysis," Elsevier Science Publishers, London, pp. 234 - 242. 1990.