Patch shape and size effect on performance of in-situ scarf patch repair in aircraft panel

Kishan Dwivedi 1 and Himanshu Pathak 1*

1School of Engineering, Indian Institute of Technology Mandi, Mandi, Himachal Pradesh-175005, India.
*Email: himanshu@iitmandi.ac.in

Abstract. Patch repairing technique is effective and efficient approach to enhance structural performance of aged aircraft panels. The presented work emphases on studying the patch shape and size effect on scarf composite patch repair of aluminium aircraft panel under thermal, thermo-elastic and mechanical load. In this work, patched repaired structural member has been simulated by ABAQUS software to find out the performance of patch repair in term of patch thickness and patch shape. Five different patch shapes are chosen to analysis: circular, square, hexagonal, rectangular and trapezoidal with different patch thickness 1, 2, 3, 4, 5 mm. The Heat transfer and coupled temp-displacement analysis has been performed under cure temperature 394 K for in-situ patch repair model. The analysis of the critical von-Mises stress and heat flux load distribution in composite patch repair system allows us to estimate performance in composite patch repair system. The results show that patch shape and size has significant effect on magnitude of heat flux load and induced von-Mises stress. Trapezoidal shape of composite patch repair has lower value of von-Mises stress and heat flux load as compared to all four shapes of composite patches.

1. Introduction

Structural members used in aircraft application subjected aerodynamic loading in service condition. These loads can weaken the structural member and reduces the load carrying capacity. The out-dated way to deal with such problems involves mechanical fasteners with metallic patches. The composite patch repair have several benefits over mechanical fastened repairing method, such as strength and life of patch repair system is improved, obstacle in crack propagation [1]. For best performance of a bonded repair, it is essential to fully understand the thermal response of these repairs, which can in future improve their processing, and design of repair methods and guiding principle for composite structures [2]. Difference in thermal expansion coefficient (alpha) at the contact surface of patch and panel is responsible for create the thermal stress during curing process so that studies of curing process is become so important for effective patch repair. [3]. Patch thickness is one of the important parameter for studies of one side composite patch repair [4]. Rachid et. al. [5] studies different shape of patch repair like rectangular shape, H shape, arrow shape and analyse the effect of repair durability and efficiency on patch repair of aircraft structure by using three dimensional finite element method. He reported that the repair efficiency of arrow shape of patch repair is higher then compare to rectangular and H shape of patch repair. Benyahia et. al. [6] studied circular, elliptical shape of patch repair and make a comparison between them through stress intensity factor analysis at crack tip under thermal and mechanical load by using 3D finite element method. It has been found that circular shape of patch repair can improve the efficiency of repair because this shape have less value of stress intensity factor. Kashfuddoja et. al. [7]
studied for oval, ellipse, circular, octagonal, square, rectangle shape of patch repair and estimate the effect of patch shape on efficiency of repair by using 3D finite element method. He analyse the peel stress and stress concentration factor for finding the optimum shape of patch repair. T.D. Breitzman et. al. [8] studied for optimum of scarf composite patch repair in tensile load condition by using 3D nonlinear analysis. The presented work predicted distribution of stress over adhesive and conclude for efficient composite repair design. Tie Y. et. al. [9] studied for impact analysis of square, rhombus, circle, hexagon, octagon shape of patch repair by using experimental and numerical method. Optimal impact resistance were presented for patch repair model. It was found that circular patch lead to better impact resistance behaviour.

From the literature discussion, it can be concluded that both thermal and mechanical analyses were done to predict structural performance of patch repairing model. However, in-situ patch repair problem is not much more explored by scientific community. The present work analyses performance of in-situ patch repairing problems under thermal and mechanical loading environment. Following objectives laid down for the presented work:

- Heat transfer, coupled temp-displacement and mechanical load analyses have been presented using three dimensional finite element method.
- Performance prediction of square, circular, hexagonal, rectangular and trapezoidal shape patch repair.
- Numerical results are presented in the form of induced von-Mises stress and heat flux.

2. Geometrical and materials models

Consider an elastic repaired panel is made of aluminum material have following dimensions: width 30 mm, length 30 mm and thickness 5 mm. This aluminum panel is repaired with circular, square, hexagonal and rectangular shape of patch repair have boron / epoxy material. Heating blanket in patch repair system is made of silicon material have following dimension like width 10 mm, length 10 mm and thickness 1 mm. The following dimension of different shape of composite patch is mentioned bellow.

- Circular composite patch: Radius 5 mm and patch thickness is varies like 1, 2, 3, 4, 5 mm.
- Square composite patch: length 10 mm, width 10 mm and thickness is varies like 1, 2, 3, 4, 5 mm.
- Hexagonal composite patch: max length 10 mm, max width 10 mm and thickness is varies like 1, 2, 3, 4, 5 mm.
- Rectangular composite patch: length 10 mm, width 4 mm and thickness varies like 1, 2, 3, 4, 5 mm.

Trapezoidal composite patch have dimension of two parallel side is 20 mm, 10 mm, and both tapered side length is 7.07 mm and width 10 mm, thickness 5 mm. The dimension of aluminum panel for trapezoidal composite patch repair is given as 15 mm, 10 mm for parallel side, width 10 mm and thickness 5 mm. Heating blanket have following dimension like width 10 mm, length 20 mm, thickness 2.5 mm for trapezoidal composite patch repair. Heating blanket is subjected to cure temp 394 K, and it is assumed that material like aluminum, composite patch and silicon have the elastic and isotropic property. The elastic property of patch, panel, heating blanket is given in table 1.

![Figure 1: Trapezoidal composite patch repair.](image-url)
Figure 2: Circular composite patch repair (a) Top view (b) Side view.

Figure 3: Square composite patch repair (a) Top view (b) Side view.

Figure 4: Hexagonal composite patch repair (a) Top view (b) Side view.
Figure 5: Rectangular composite patch repair (a) Top view (b) Side view.

Figure 6: Trapezoidal composite patch repair with both ends are fixed.

Figure 7: Circular composite patch repair with fixed end (a) Top view (b) Side view.
Figure 8: Square composite patch repair with fixed ends (a) Top view (b) Side view.

Figure 9: Hexagonal composite patch repair with fixed end (a) Top view (b) Side view.

Figure 10: Rectangular composite patch repair with fixed ends (a) Top view (b) Side view.
Figure 11: Top view of circular (a) unpached repair (b) patched repaired, fixed at one end and have tensile traction load on other end.

Figure 12: Top view of square (a) unpached repair (b) patched repair, fixed at one end and have tensile traction load on other end.

Figure 13: Top view of hexagonal (a) unpached repair (b) patched repair, fixed at one end and have tensile traction load on other end.
Figure 14: Top view of rectangular (a) unpached repair (b) patched repair, fixed at one end and have tensile traction load on other end.

3. Finite element modelling

Three dimensional finite element analysis is carried out in this current work by using ABAQUS software. The finite element model consist of three subsections like, composite patch, aluminum panel and silicon heating blanket. The aluminum plate is mesh with three solid element in the direction of thickness and the heating blanket is mesh with one solid element in direction of thickness, and composite patch are mesh with 10, 8, 6, 4, 2 solid element in thickness direction respectively for 5, 4, 3, 2, 1 mm thickness for all shape of composite patch. Aluminum panel have 1617, 1680, 2160, 2160 number of element for circular, square, hexagonal, rectangular shape of composite patch repair, silicon heating blanket have 100 number of element for circular, rectangular, square, hexagonal shape of composite patch repair model. The circular composite patch have 768, 1536, 2304, 3072, 3840 number of element for 1, 2, 3, 4, 5 mm thickness of patch respectively. The square composite patch have 800, 1600, 2400, 3200, 4000 number of element for 1, 2, 3, 4, 5 mm thickness of patch respectively. The Hexagonal composite patch have 320, 640, 960, 1280, 1600 number of element for 1, 2, 3, 4, 5 mm thickness of patch respectively. The rectangular composite patch have 320, 640, 960, 1280, 1600 number of element for 1, 2, 3, 4, 5 mm thickness of patch respectively. Trapezoidal patch repair model have 165, 2940, 50 number element of aluminum panel, composite patch and silicon heating blanket respectively.

For heat transfer simulation, model (aluminum panel, composite patch, silicon heating blanket) have DC3D8 hexahedral brick element. For coupled temp-displacement simulation, model have C3D8T hexahedral brick element and for mechanical load simulation, model have C3D8R hexahedral brick element.

Simulation have steady state analysis for three different type of “STEP” option like heat transfer, couple temp-displacement and static general. This “STEP” option is used in ABAQUS simulation. The total time period was given one second with maximum number of increment is 100, minimum increment size was given as 1x10⁻⁵ and maximum increment size is one.

Heat transfer and couple temp-displacement analysis of circular, square, hexagonal, rectangular, trapezoidal shape of patch repair in ABAQUS, conducted as follows: material property of aluminum, composite patch, silicon is given as shown in the table 1. Heat transfer is chosen as “STEP” option for heat transfer analysis and for couple temp-displacement is chosen as “STEP” option for couple temp-displacement analysis in ABAQUS. The Cure temp of 394 K was set to surface of the heating blanket and surface film condition as a boundary condition is given on back side of aluminum and composite patch as shown in the figure number from 1 to 10, these both boundary condition is set for both heat transfer analysis and couple temp-displacement analysis. Couple temp-displacement analysis have one
extra boundaries condition in which both opposite end of the aluminum panel is set to “ENCASTER” as shown in the figure number from 6 to 10 for all four shape of composite patch repair.

Mechanical load analysis was carried out for circular, square, hexagonal, rectangular shape of patch/unpatched repair in ABAQUS. Material property is chosen from table 1 and static general is chosen for “STEP” option in ABAQUS. One end of the aluminum panel is given “ENCASTER” boundary condition and in opposite end uniform tensile traction load is applied of magnitude 10, 20, 30, 40, 50 GPa as shown in the figure number from 11 to 14.

Table 1: Materials properties (panel, patch and heating blanket).

| Property, (SI Unit)                  | Panel | Patch | Blanket |
|-------------------------------------|-------|-------|---------|
| Thermal Conductivity, (W/m.K)       | 205   | 0.21  | 150     |
| Density, (Kg/m³)                    | 2710  | 1310  | 2330    |
| Specific Heat Capacity, (J/kg.K)    | 921.1 | 1260  | 710     |
| Thermal expansion Coefficient, (10⁻⁶ °C⁻¹) | 23    | 43    | 2.6     |
| Elastic Modulus, (GPa)              | 700   | 386   | 1790    |
| Poison ratio                        | 0.3   | 0.3   | 0.3     |

4. Result and Discussion

This current work is carried out for to find the best patch shape and size, which can improve the performance of patch repair. The analysis of heat flux and von-Mises stress distribution over the composite patch repair gives a way to find this performance. The five patch shape like circular, rectangular, hexagonal, square and trapezoidal are compared to each other based on their performance.

4.1. Thermal loading

In this section, the variation of the heat flux load over the circular, rectangular, hexagonal, square shape of composite patch repair are compare with different patch thickness for heat transfer analysis as shown in the figure 15. One can note, from this figure 15 heat flux load is decreasing with increase in patch thickness for each shape of composite patch repair. It can also note, in this figure 15 square shape of patch present the lower value of heat flux load and rectangular shape of patch present higher value of heat flux load for all patch thickness. The circular and hexagonal shape of composite patch repair have approximately same value of heat flux load for patch thickness 2, 3, 4, 5 mm and have small difference in value heat flux load for patch thickness 1 mm. The trapezoidal shape of composite patch repair have value of heat flux load is 15310 W/m² in heat transfer analysis, this value of heat flux load is very small then compare the above mentioned all four shapes of composite patch repair. The line contour and legend of heat flux load in heat transfer analysis for circular composite patch repair of thickness 5 mm is present in figure 16.
4.2. Thermo elastic loading

In this section, the variation of induced von-Mises stress and heat flux are consider for circular, rectangular, square, hexagonal shape of composite patch repair and compare with different patch thickness for couple temp-displacement analysis as shown in the figure (17,19). One can note, from the figure 17 rectangular shape of composite patch repair present lower magnitude of von-Mises for all patch thickness, as compared to all four shape of composite patch repair. It can also note that up to 4 mm patch thickness the von-Mises stress is higher for hexagonal shape of composite patch repair but for the 5 mm patch thickness circular shape of patch repair have higher value in compare of all four shape of patch repair. Square shape of patch repair have von-Mises stress lower then compare hexagonal
and circular shape of patch repair but have higher value then compare to rectangular shape of patch repair. The value of the von-Mises stress for trapezoidal shape of patch repair is $1.45 \times 10^{10}$ N/m$^2$ which is lower then compare to all shape of composite patch repair. Line contour of von-Mises stress for circular patch repair of thickness 5 mm in couple temp-displacement analysis as shown in figure 18.

From the figure 19 it can be noted, that the value of heat flux is increasing with composite patch thickness for all the four shape of patch repair. The circular shape of patch repair have higher value of heat flux load and square shape of patch repair have lower value of heat flux load then compare to all four shape of patch repair. The trapezoidal shape of composite have the value of heat flux is $2 \times 10^4$ W/m$^2$ which is too small then compare to heat flux magnitude of all other four shape of patch repair in couple temp-displacement analysis. Line contour of the heat flux load of circular patch repair of thickness 5 mm in couple temp-displacement analysis is present in figure 20.

![Figure 17: Von-Mises stress variation with composite patch thickness in couple temp-displacement analysis.](image17)

![Figure 18: Line contour of von-Mises stress (N/mm$^2$) in circular composite patch repair model of thickness 5 mm in couple temp-displacement analysis.](image18)
4.3. Mechanical loading

In this section the variation of induced von-Mises stress is consider for circular, rectangular, square, hexagonal shape of composite patch/unpatched repair of thickness 5 mm and compare with tensile traction load (10, 20, 30, 40, 50 GPa) for mechanical load analysis as shown in the figure 21. From figure 21, induced von-Misses stress is increasing with magnitude of applied tensile traction load.
The circular shape of patch/unpatched repair model shows higher value of von-Mises stress then compare to all shape of patch/unpatched repair respectively for each tensile traction load. The rectangular shape of patch/unpatched repair model shows lower magnitude of von-Mises stress then compare to all shape of patch/unpatched repair for each tensile traction load. Line contour of von-Mises stress for circular patch repair of thickness 5mm for mechanical load analysis is present as shown in figure 22.

Figure 21: Von-Mises stress variation with tensile traction load in mechanical load analysis.

Figure 22: Line contour of von-Mises stress (N/mm²) for circular composite patch repair of thickness 5 mm in mechanical load analysis.

5. Conclusions

The current work has main aim to compare the performance of square, rectangular, hexagonal and circular shape of patch repair with trapezoidal shape patch repair under the thermal loading, thermo-
elastic loading and mechanical loading. Three-dimensional finite element model has been implemented to perform numerical analyses using ABAQUS package. The trapezoidal shape of patch repair have lower value of heat flux and induced von-Mises stress then compare to all four shape of patch repair in all type of analysis. Trapezoidal shape of patch repair can improve the performance then compare to all four shape of patch repair. Following conclusions can be drawn based on presented numerical investigations:

- Heat transfer analysis result shows least value of heat flux for square composite patch, which improve the repair performance compare to all four shape of composite patch repair.
- Coupled temp-displacement analysis results shows the lower magnitude of von-Mises stress and heat flux load for rectangular and square shape of composite patch repair respectively.
- Mechanical load analysis result shows rectangular shape of composite patch/unpatched repair have least magnitude of von-Mises stress with respect to each tensile traction load, which can improve the repair performance.
- Patch thickness has significant effect on repair performance.

Acknowledgement

Financial support received from Aeronautics Research & Development Board (DRDO), New Delhi, India through grant file no. 1051914 is gratefully acknowledged.

References

[1]Kumar A M and Hakeem S A 2000 Optimum design of symmetric composite patch repair to centre cracked metallic sheet J. of Composite structures., 49, 285-292.
[2]http://digitool.library.mcgill.ca/webclient/StreamGate?folder_id=0&dvs=1578389405604~85, Visited, 15th November 2019.
[3]Naboulsi S and Mall S 1997 Thermal effects on adhesively bonded composite repair of cracked aluminum panels J. of theoretical and applied fracture mechanics., 26, 1-12.
[4]Khan S M A and Essaheb M 2017 Effect of patch thickness on the repair performance of bonded composite repair in cracked aluminium plate J. of materials today: proceedings., 04, 9020-28.
[5]Rachid M, Serier B, Bouiadjra B B and Belhouari M 2012 Numerical analysis of the patch shape effects on the performances of bonded composite repair in aircraft J. of Composites: Part B., 43, 391-397.
[6]Benyahia F, Albedah A and Bouiadjra B A B 2014 Elliptical and circular bonded composite repair under mechanical and thermal loading in aircraft structures Materials Research 2014., 54, 18-24.
[7]Kashfuddoja M and Ramji M2014 Design of optimum patch shape and size for bonded repair on damaged carbon fiber reinforced polymer panels J. of Materials and Design., 54, 174-183.
[8]Breitzman T D, Larve E V, Cook B M, Schoepppner G A and Lipton R P 2009 Optimization of composite scarf repair patch under tensile loading J. of Composite: Part A., 40, 1921-30.
[9]Tie Y, Hou Y, Li C, Zhou X, Sapanathan T and Rachik M 2018 An insight into the low velocity impact behaviour of patch repaired CFRP laminates using numerical and experimental J. of Composite structures., 190, 179-188.