Analysis of cracked aluminum plate repaired with bonded patch

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Abstract

Aluminum sheet patching techniques can help to strengthen and fatigue crack repair in aluminum structures. This study focuses on the effect of using an aluminum sheet to repair a crack in an aluminum alloy plate. The sheet patching will be of the same material as the cracked plate and will be bonded to it using an adhesive layer. The cracked plate will be fixed on one end and have tension on the opposite side. Once the

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effect of using the patching for repair is determined, the geometrical parameters of the sheet patching will be investigated at different crack depths. The main objective of this paper is to study the equivalent stress and total deformation distribution across the plate, adhesive layer, and sheet patch. These studies will be conducted using a finite element simulation software known as ANSYS. Results show that using the sheet patching reduces the stresses and deformation developed around the crack significantly and that the geometrical properties of the sheet patching have a significant effect, especially at high crack depths; however, as the value of these parameters increases, the benefits gained from increasing them decreases.

***Keywords**: fracture analysis, finite element analysis, adhesive bonded, Stresses.*

1. Introduction

When it comes to structures and components, their strength and stability are essential and are one of main requirements or demands that are imposed on the manufacturer. Stability is the ability of any component or structure to resist the influence of different forces that may lead it into a state imbalance [1]. However, any component or structure can experience damage or failure after production, even if they were made with the best quality control. One of the most common examples of damage that a component may experience is the development of cracks, which creates a weak point in the component that will develop much higher stresses and may lead to plastic deformation or failure [2]. This is especially prominent in complex structures that are comprised of multiple plate elements (such as bridges and ships) that are exposed to several of force combinations like compression, bending, shearing and tensile loads under certain conditions [3]. These cracks can occur for a variety of reasons, such as corrosion, chemical attack, fatigue, impact and creep that weaken the structural soundness. Based on this, it is clear that these crack present a danger to the structural integrity of the plate and they must be fixed to avoid failure. The behavior of cracked plates have received more attention by many modern researchers [4,5,6] and many studies have investigated the problem under different loads such as tensile loads [7,8,9] and thermal loads [10,11]. These studies employed multiple experimental, theoretical and numerical methods and one of the widest most used numerical method is the finite element method. Finite element method has been one of the preferable techniques for tackling a wide difference of practical problems efficiently [12]. It can be employed to solve problems by altering the input data. Among the numerical methods, finite element method (FEM) has been extensively used with success and countless studies on various adhesively bonded joints via this technique were performed by many authors [13,14,15].

The properties of the Young's and shear moduli, strength of the bulk adhesive are based on data from relevant manufacturers and publications [12,16]

1. Materials properties

The material and mechanical properties of the aluminum alloy it is shown in table (1).

Table 1 Aluminium alloy material and mechanical properties

Density	2770 kg/m3
Young's modules	71GPa
Poisson's ratio	0.33
Tensile yield strength	280MPa
Compressive yield strength	280MPa
Tensile ultimate strength	310MPa

The sheet patching will be of the same material welded to the rectangular plate via an adhesive bond at the location of the crack. The adhesive chosen for this study is an epoxy resign and was taken from a previous study [11,15] and its mechanical properties are shown in tables (2).

Table 2 Mechanical properties of the Adhesive LY3505/XB3405

Young's modulus	3500MPa
Poisson's ratio	0.35
Tensile strength	85Mpa

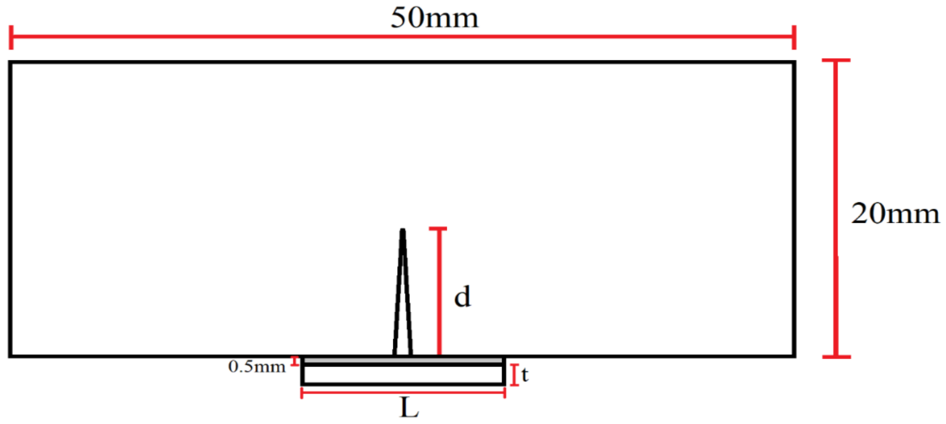


Figure 1 Model design for plate with crack and patch repair

Where d is the crack depth, L and t are the patch repair length and thickness respectively. The dimensions of the plate will remain the same at 50mm×20mm with the exception of the crack depth, which will change depending on the study. The patch repair thickness and length will also change depending on the study; however, the adhesive bond thickness will remain constant at 0.5mm. Table (3) shows each of the dimensions and their possible values.

Table 3 Dimensions of each model and their possible values

Dimension	Value (mm)
Patch repair thickness (t)	1-2-4-6-8-10
Depth of crack (d)	6-8-10-12
Length of patch repair (L)	10-15-20-25-30-40

2. Mathematical Model

In this study, a static analysis is used to perform the analysis. A static analysis is an analysis method that calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. Static analysis can still determine the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. (ANSYS Inc, 2010). For any static structural analysis, the mathematical model includes the boundary conditions set and the solution parameters desired. In the following sections, the static structure mathematical model shown and discussed.

2.1. Boundary Conditions

The boundary conditions taken into consideration are fixed points on the right side with a tensile pressure from the opposite side, as shown in figure (2).

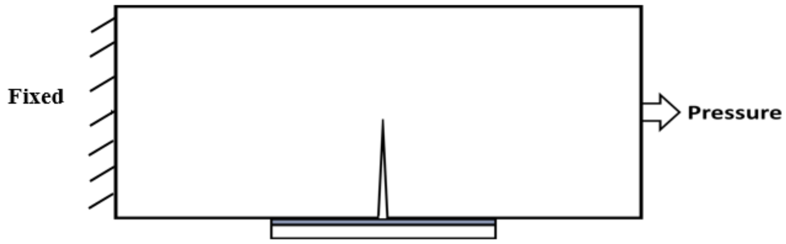


Figure 2 Boundary conditions with fixed on the left side and a tensile pressure from the opposite side as for the value of the pressures used, values of 10MPa, 15MPa and 20MPa will be used.

3. Numerical Analysis Method

The structural analysis simulation was done using a three dimensional static finite element method using an ANSYS package known as ANSYS Static Structural. This software uses a Newton-Raphson solution method to solve the problem. The loads were applied in one step over a 10s period. The problem can be solved either directly or iteratively or left in program control, so that the program can determine the better choice, which is what was done in this study.

In the **mesh** procedure, the meshing of the Model is performed. Since ANSYS Static Structure uses a finite element method to perform the simulation, a mesh is necessary in order to solve and run the simulation. The selection of the mesh is of great importance, since it directly affects the results produced. The selection of the mesh (especially in 3D models) requires a careful balance between cell count and cell size, where generally the smaller the cell the more accurate the result is but on the other hand it increases the cell count which requires more computing power and time to solve. The mesh and its selection will be discussed in a separate section.

3.1. Geometry

In the geometry section, both the 3D models of the study with the weld and the study without the weld are created using an integrated modeling software known as design modeler. The aluminum alloy plate is divided into three sections to help separate the section with the crack with the rest of the plate; this will help in the process of acquiring the results specifically at the crack. This however will not affect the results since all of these sections will be treated as one part. As for the adhesive layer and the patch, each component will be treated as a separate component to ease result acquisition and meshing. Figures (3) and (4) show the 3D model for the study with the patch in isometric and front view respectively and figures (5) show the 3D model for the study without patch in isometric view.

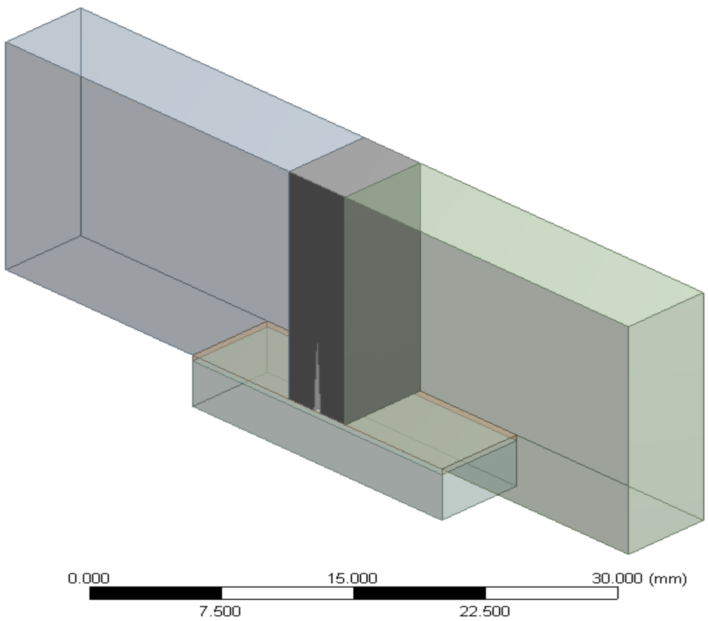


Figure 3 3D model for the study with the patch in isometric view

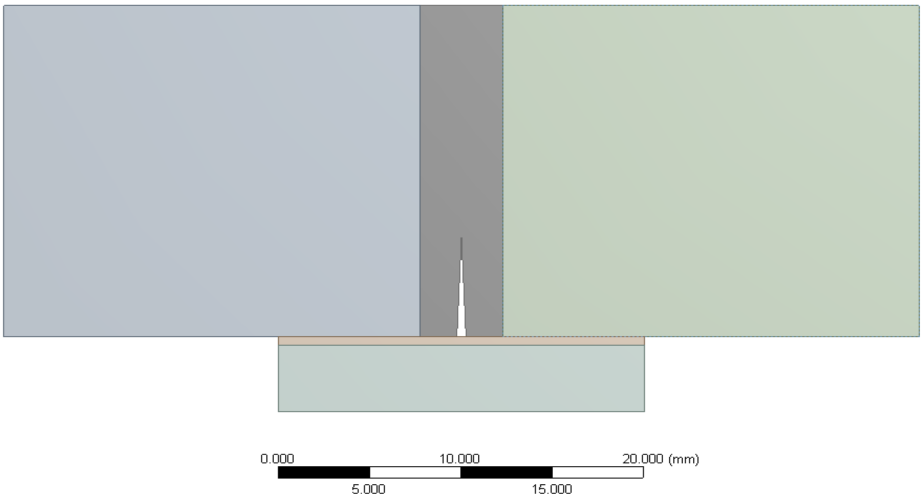


Figure 4 3D model for the study with the patch in front view

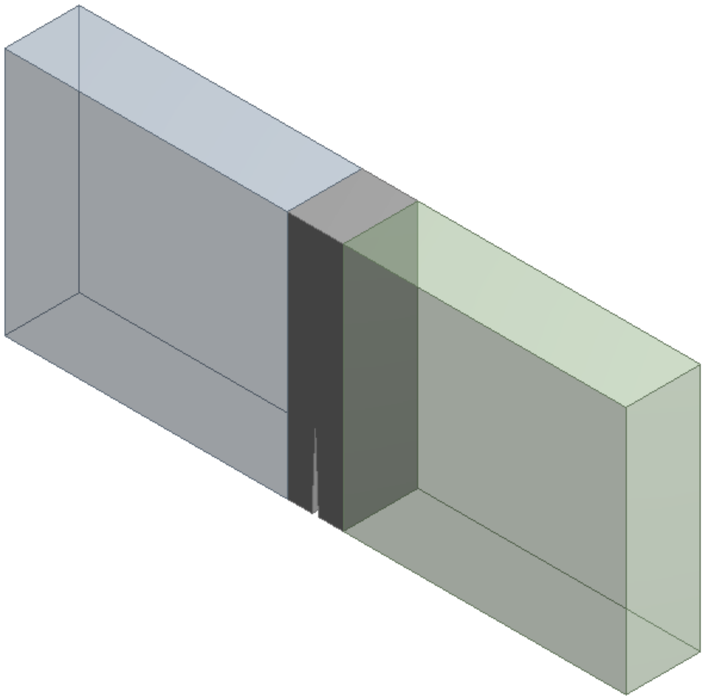


Figure 5 3D model for the study with no patch in isometric view

3.2. Mesh

In meshing, the domain of the model is divided into smaller and simpler domains, each of these domains is known as a cell or element and a group of cells creates a grid or a “mesh”. Since a larger domain is divided into smaller and simpler domains, it is necessary to connect the data of each of these cells to its neighboring cells, methods that used to achieve this are known as solvers such as finite element that is used in this study (Inc. ANSYS, 2012). As a general rule, smaller or finer meshes lead to more accurate results, however, they lead to more cell counts, this increases the computational power as well as the time needed to complete the simulation and in some cases it can cause instability in the simulation. Therefore, selecting an appropriate mesh includes creating a balance between the accuracy of the results gained and the size of the mesh used, however, this is especially hard to achieve when meshing complex geometries, such as components with sharp angles, such as the top edge of the crack. Multiple meshes were tested for each study; however, due to the limited computational power available in the computer used for the simulation, some meshes were excluded. The mesh chosen for the model with patch had 3407243 nodes and 821790 elements and the mesh chosen for the model without patch had 3129730 nodes and 754650 elements. Figure (6) show the meshing for the study with a patch from a front view.

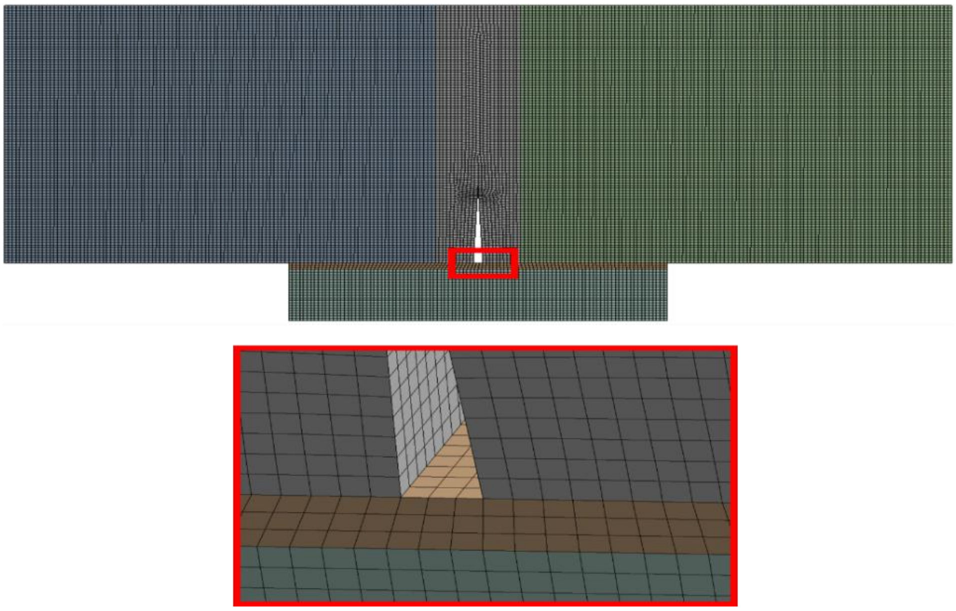


Figure 6 Meshing of the study with a patch from a front view

4. Result Analysis and Discussion

The results include the equivalent stress and total deformation in the form of graphs.

a) Effect of using aluminum patch

Before studying the effect of each patch parameter, it is necessary to determine the significance of using the patch in reducing the stress. For this study, the model with no patch and a model with a patch will be compared to one another at various crack depths. The model with a patch will have a patch with a 4 mm thickness and 20 mm length. Figures (7) show the comparison between the total deformation for both the model with and without patch at various crack depths at 10 MPa, 15 MPa and 20 MPa pressure respectively.

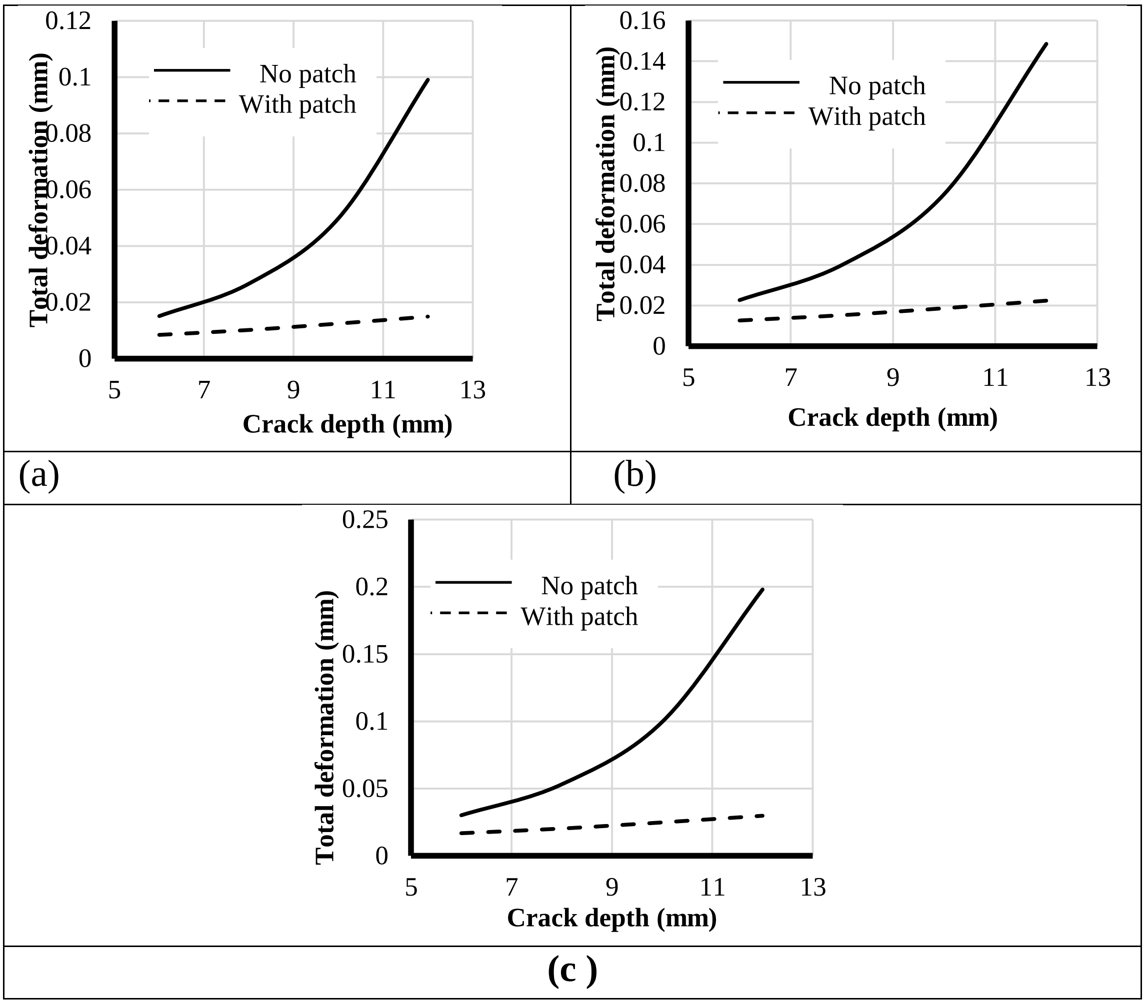


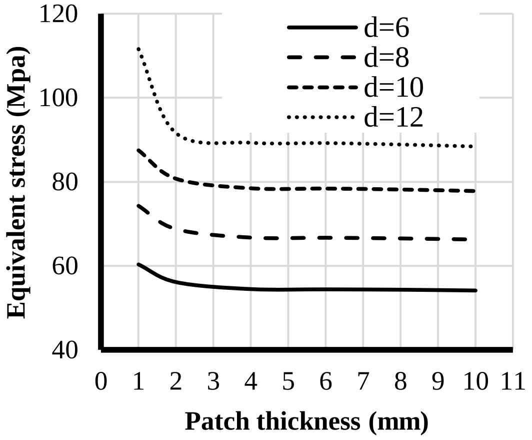
Figure 7 Comparison between the total deformation for both the model with and without patch at various crack depths: (a) 10MPa pressure, (b) 15 MPa pressure and (c) 20 MPa pressure

b) Effect of patch repair geometrical parameters

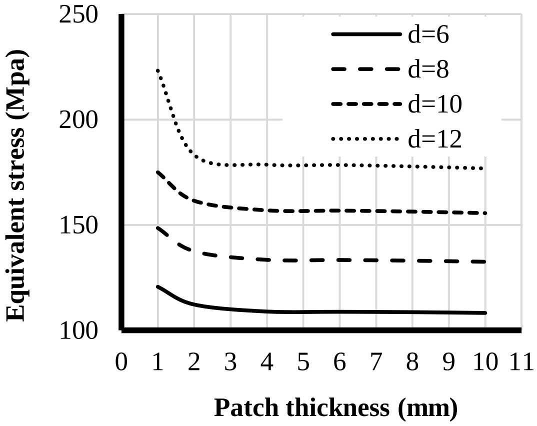
To study the effect of the patch geometrical parameters, namely, the patch thickness and length, the equivalent stress and total deformation are studied at various crack depths.

- **Equivalent stress**

The effect of increasing the patch thickness at different crack depths is shown in figures (8) for 10MPa and 20MPa respectively at 20mm patch length. Results show that increasing the patch thickness from 1mm to 2mm lead to a significant drop in the equivalent stress at all four crack depths with the drop becoming more significant at higher crack depths, especially at crack depth of 12mm, which saw a 17% drop as opposed to 10mm which had a 7.7% drop. This means that as the crack depth increases, the effect of increasing the patch thickness becomes more significant. As for the rest of the patch thicknesses, there was a small decrease in equivalent stress with the increase from 2mm to 4mm, however beyond that the decrease in stress is extremely insignificant to be worth considering. Both graphs also show that increasing the pressure has a linear effect on the equivalent stress at each patch thickness and crack depth, where doubling the pressure led to doubling the equivalent stress.



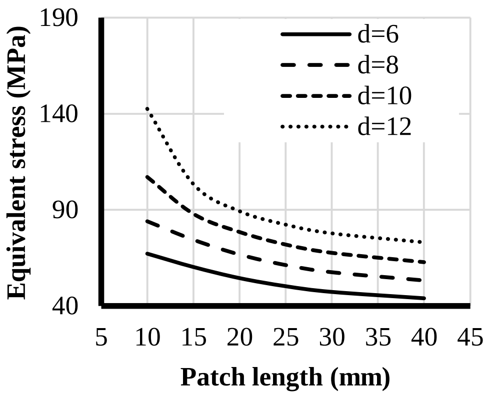
(a)



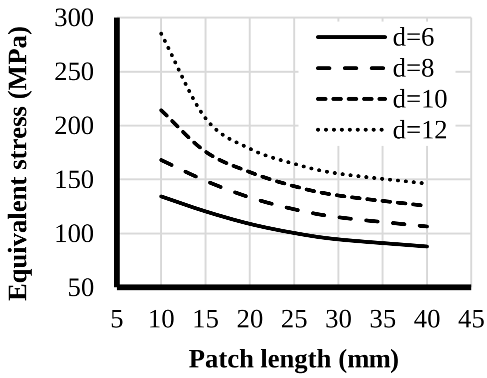
(b)

Figure 8 Effect of increasing the patch thickness on equivalent stress at different crack depths and 20mm patch length: (a) at 10MPa and (b) at 20MPa

The effect of increasing the patch length on the equivalent stress is shown in figure (9) at various crack depths for 10MPa and 20MPa respectively at 4mm patch thickness. From the results, it is clear that increasing the patch length decreases the equivalent stress produced by the tension with a significant drop occurring when increasing the length from 10mm to 15mm, which becomes more significant at higher crack depth values. This drop is especially important at crack depth of 12mm and pressure of 20MPa, where the equivalent stress there exceeded the yield strength of the material at 10mm length and was then dropped below the yield strength with a significant margin of safety at 15mm length (approximately 65% of the yield strength). It was also observed that the effect of increasing the patch length beyond 15mm starts to steadily decrease and it is expected that eventually there will be no significance in increasing the length



(a)



(b)

Figure 9 Effect of increasing the patch length on equivalent stress at different crack depths and 4mm patch length: at (a) 20MPa and (b) 10Mpa

- Total deformation

The effect of increasing the patch thickness on the total deformation at different crack depths is shown in figure (10) for 10MPa and 20MPa respectively at 20mm patch length. Results show that increasing the patch thickness from 1mm to 2mm lead to a significant drop in the total deformation, which is consistent with the results of the equivalent stress. The effect of increasing the patch thickness on the total deformation followed a similar pattern to its effect on the equivalent stress and similar observations are made. The effect of increasing the patch length on the total deformation at different crack depths is shown in figure (11) for 10MPa and 20MPa respectively at 20 mm patch length.

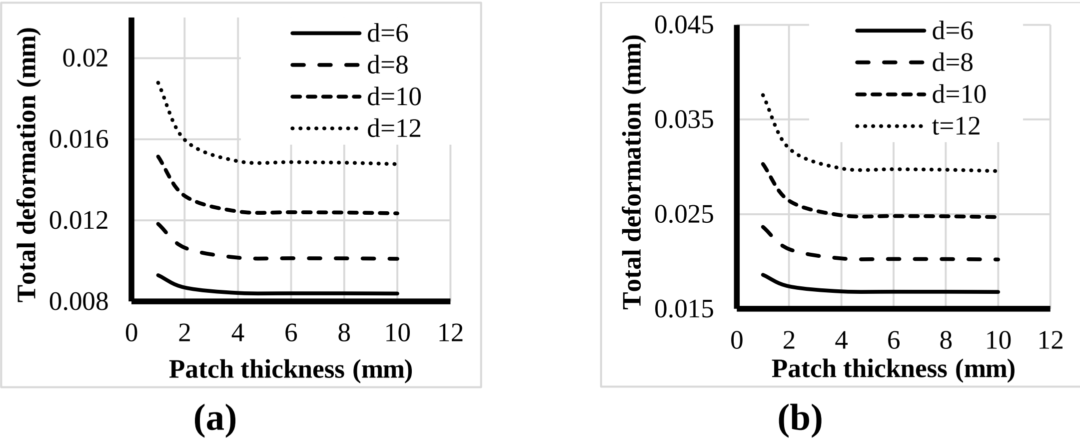


Figure 10 Effect of increasing the patch thickness on total deformation at different crack depths and 20mm patch length at: (a) 10MPa and (b)20MPa

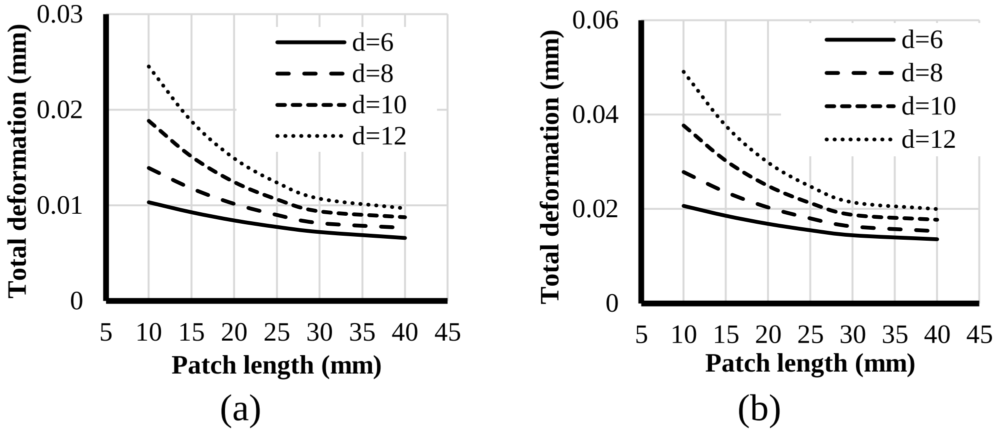


Figure 11 Effect of increasing the patch length at different crack depths and 4mm patch thickness at: (a) 10MPa and (b) 20MPa.

From the results, it is clear that increasing the patch length has the same effect on the total deformation as it had on the equivalent stress. Increasing the patch length decreases the total deformation produced by the tension with a significant drop occurring when increasing the length from 10mm to 15mm, which becomes more significant at higher crack depth values and its significance decreases with the increase in patch length.

5. Conclusions

In this paper, the effect of using a patch to repair an aluminum alloy plate undergoing tension was studied along with the effect of geometrical parameter of the patch. The study was modeled, meshed and simulated using ANSYS Static Structural to test the integrity of the design as well as study the stress and deformation distribution across the plate. Based on the results there are multiple conclusions that can be made, which are:

1. The patch had a significant effect on the both the equivalent stress and total deformation.
2. Increasing the patch thickness has a significant effect; however, the magnitude of the effect quickly drops off as the thickness increases.
3. Increasing the patch length has a significant effect; the gradually decreases in, magnitude as the length increases.
4. At higher crack depths, the significance of increasing the patch thickness and length increases.
5. Increasing the tension does not affect the percentage of decrease in both the equivalent stress and deformation and only increases the magnitude in a linear manner.

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