CERTIFICATION OF APPROVAL

FINITE ELEMENT SIMULATION OF RESIDUAL STRESSES IN COLD-EXPANDED PLATE

by

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Bachelor of Engineering (Hons)

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Approved by,

_____

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TRONOH, PERAK

SEPTEMBER 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHD HAFIZUDDIN BIN HASHIM

ABSTRACT

In aircraft and aerospace industry, the fastener holes are widely present because a lot of its mechanical parts need to be connected by rivets or bolts. However, these holes experience external forces which cause a tensile stress on the surface which lead to the fatigue cracks and eventually lead to fatigue failure of the structure. Hence, cold expansion method has been used to improve the fatigue behaviour of structures by inducing compressive residual stresses around the holes when a tapered mandrel is forced through the fastener hole that is a little smaller than the mandrel. In this study, finite element simulations had been carried out for cold expansion process in order to determine the residual stresses field around two cold-expanded holes by varying the centre distance between two holes and the thickness of the material. Moreover, the effect of through thickness position has also been investigated by considering the residual stresses distribution at different position such as at the entrance face, at the middle thickness and at the exit face of the material. Aluminium alloy 7075-T6 was used as the material of the model developed in ANSYS. The results show the effect of different adjacent holes distance on the residual stresses field. As the distance between the holes is increasing, the residual stresses will decrease. Moreover, the simulation has highlighted the effect of the plate thickness and the through thickness position on the residual stresses distribution. The compressive residual stresses increase as the plate thickness increase.

ACKNOWLEDGEMENT

First and foremost, I would like to extend my sincere gratitude to my supervisor Dr Saravanan Karuppanan for being a wonderful mentor in guiding, supporting and assisting me, also for his knowledge shared with me through the year, which are simply precious.

Last but not least, to my parents and colleagues, thanks for always standing by me and keep supporting me until I managed to complete this Final Year Project within the allocated time.

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CHAPTER 1

INTRODUCTION

1.1   Background of Study

The aircraft and aerospace industry has developed a variety of technique to strengthen and enhance the fatigue life of fastener joints. This is because the joints in aircraft and aerospace industry are mainly connected by rivets or bolts and nuts through the fastener holes that exist on the body parts. This type of joint makes the parts to be assembled and dissembled easily and it also transmits the load acting on the structure. However, the machined hole tends to cause stress concentration when a cyclic load is acting on it and eventually leads to decrease of fatigue life. In order to increase the fatigue life of the material, some methods have been developed such as the shot peening and the split sleeve cold expansion method. The most commonly used is split sleeve cold expansion method. In aircraft industry, fastener holes with hole diameter ranging from 5 mm to 40 mm had expansion ratio between 2% to 6% depending on the material and application. Generally for the normal application, 4% cold expansion ratio will be chosen [1]. Split sleeve cold expansion technique is a mechanical method of inducing beneficial compressive stresses around circular holes to offset the applied tensile stress resulting in improved fatigue life [2]. This technique enhances the fatigue life of fastener joints by developing compressive residual stresses on the area where the fatigue cracks are expected to initiate. The schematic of the split sleeve cold expansion process is shown in Figure 1.1[12].

The process of split sleeve cold expansion method is simple where it uses a tapered mandrel which is pre-fitted with a lubricated split sleeve that goes through the fastener hole and will develop a compressive residual stresses as the material is plastically deformed through the hole edge. This compressive residual stresses remain tangential to the hole edge as the mandrel is being drawn out from the hole. This will reduce the growth of a fatigue crack when the material undergoes tensile or

cyclic load. The use of split sleeve is to reduce mandrel pull force and to ensure correct radial expansion of the hole.

The residual stress distribution depends on many conditions such as the cold expansion ratio, material properties, the position and the size of the hole and so on [3]. Ozdemir and Hermann (1999) noticed that the change in plate thickness can determine a different distribution of the residual stresses [4]. Hence, the effect of plate thickness in the distribution of residual stresses using cold expansion process has been investigated. Moreover, the effect of adjacent holes has been investigated by varying the centre distance between holes (c/d). The holes have constant diameter where $c/d = 2$, $c/d = 4$, $c/d = 6$ (distance between the holes). In this study, aluminium alloy 7075-T6 was used as the material of the model and the thickness of the plate was varied according to the ratio between the thickness and the hole diameter (t/d). Moreover, this model was developed and simulated in ANSYS.
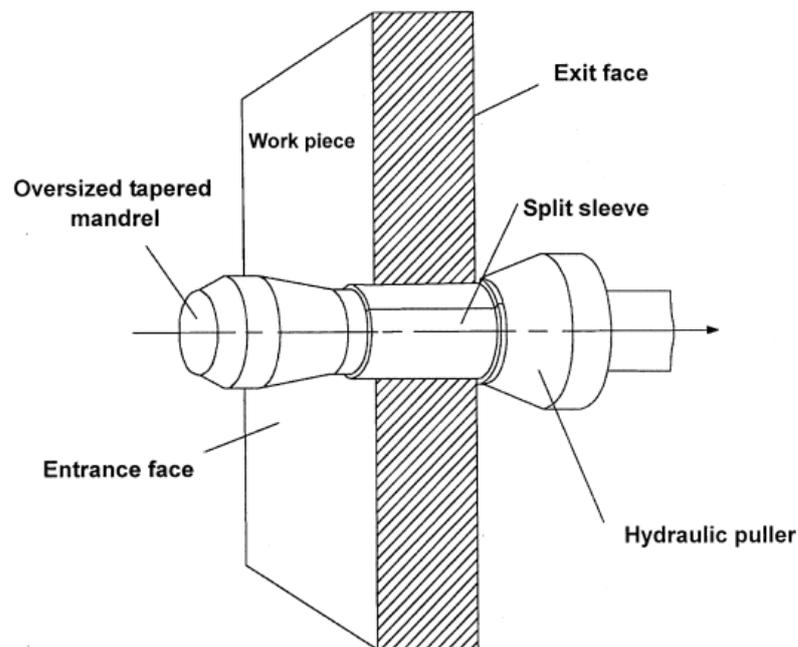
Figure 1.1: The schematic of the split sleeve cold expansion process

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1.2   Problem Statement and Motivation of Study

Residual stresses play an important role in the aircraft and aerospace applications to prevent failure of components. Residual stresses are stresses that remain within the body along a cross section of the component after the original cause of the stress such as mechanical or thermal load has been removed. Compressive residual stresses can:

- Delay crack formation and enhance the fatigue life.
- Prevent the opening of edge cracks.
- Fasten parts together.

In aircraft and aerospace, the cold expansion method is commonly used for fasteners holes. The joints in aircraft and aerospace industry are mainly connected by rivets or bolts and nuts through the fastener holes that exist on the body parts. The machined hole tends to cause stress concentration when a cyclic load is acting on it and eventually leads to decrease of fatigue life.

The change in the plate thickness can result in a different distribution of the residual stresses. This factor is important to be investigated because in some applications, we need to vary our design thickness to make it function effectively. Moreover, at different distance of adjacent holes there will be different residual stresses distribution. Therefore, in this project, the effect of plate thickness and the effect of adjacent holes to the residual stress distribution due to cold expansion method will be investigated.

1.3   Objectives and Scopes of Study

The objectives of this study are to understand measure and study on how residual stresses are developed by split cold expansion process method by using Finite Element Analysis (FEA). The effect of plate thickness and the effect of adjacent hole will be investigated. Finite element simulation will be conducted by using ANSYS software and the material for this project is Aluminium 7075-T6.

CHAPTER 2

LITERATURE REVIEW

2.1   Residual Stresses

Residual stresses can be defined as the stresses that remain within the body in the absence of mechanical load or thermal load. Residual stresses also occurred without the external cause. There are many factors that contribute to residual stresses distribution in mechanical structure such as inelastic deformations and heat treatment process. The most common causes of residual stresses are during manufacturing processes. In manufacturing, various processes are being used to make components and products for the customer. Some of the technology processes that are being used in manufacturing industry such as welding, moulding, casting, heat treatment, machining, plastic deformation during bending, rolling or forging will induce the residual stresses in the manufactured object [5].

Furthermore, there are also thermal residual stresses that occurred because of the differential expansion when a metal is heated or cooled. In order to produce residual stresses, both the thermal treatment and restraint of the component must be present. Residual stresses can cause visible distortion of a component. It is useful to estimate the magnitude or direction of the residual stresses. Residual stresses also can prevent failure of a component but there are also processes that can induce excessive tensile residual stresses that will lead to the failure of a component. Moreover, tensile residual stresses are counter balanced by compressive residual stresses. Residual stresses are three-dimensional and can be measured by various method such as x-ray diffraction, ultrasonic methods, magnetic methods, electronic speckles pattern interferometry, hole drilling and strain gage technique.

2.2   Split Sleeve Cold Expansion Process

A fastener hole that was subjected to a cyclic load will produce stress concentration around the fastener hole and eventually lead to fatigue cracks. In order to reduce the effect of the stress concentration around fastener hole, various techniques have been developed by companies generally in aircraft and aerospace industry. One of the techniques is by using split sleeve cold expansion process. A cold worked process is widely used to generate beneficial residual stresses into an annular region around the hole [4]. The propagation of a fatigue crack is inhibited by using this technique. Fatigue Technology Inc. (FTI, 1994) was the one that developed the split sleeve cold expansion (Figure 2.1 [6]) technique that can improve the fatigue life of structures by inducing compressive residual stresses around the fastener holes. The function of the split sleeve is to reduce the shear stress of the material surrounding the fastener holes and to ensure that only the radial pressure is applied on the plate. But, the hoop residual stresses are distributed asymmetrically because of the opening of the split in the sleeve.

The beneficial effect derived from the cold expansion process is entirely dependent on the magnitude and distribution of the induced residual stresses around the hole [6]. The typical residual stresses distribution at a cold expanded hole is shown in Figure 2.2 [6]. According to many researchers, the residual stresses induced are distributed in a non uniform manner around the hole and varies in the thickness direction of the plate.

According to Ozedemir and Hermann (1999), the change in the plate thickness can cause a different distribution of the residual stress of the plate [4]. The compressive residual stresses are lower at the entry side compared to the exit side.

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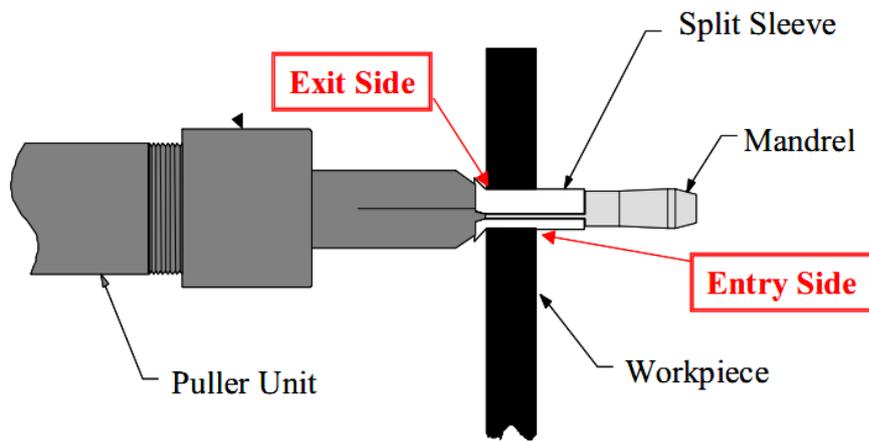
Figure 2.1: FTI Split sleeve cold expansion process
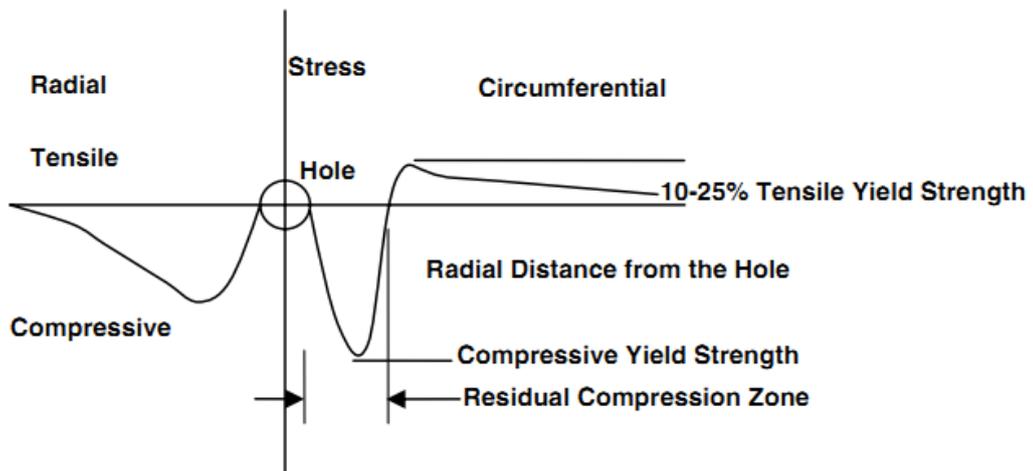
Figure 2.2: Typical residual stresses distribution at a cold expanded hole

2.3   Finite Element Simulations of Residual Stresses induced by a Cold Expansion Process.

The research done by V. Nigrelli and S. Pasta [4] was to investigate the residual stress distribution of a plate at different through-thickness positions (entrance face, mid-thickness and exit face), the effect of the plate thickness and the effect of the split sleeve. The finite element simulations of residual stresses was carried out by using 5083-H321 aluminium plate at 4% nominal interference to investigate the cold expansion behaviour and ASTM E 646-00 standard was used as the test method to calculate the power curve parameters.

For the simulation, they used a circular disk with 2.9 mm radius hole, 25 mm outer radius and 5 mm as the plate thickness. They also used tetra elements with four nodes for the mesh of the plate and the split sleeve (Figure 2.3[4]). As stated by Guo, 1993, the exact dimension for the outer radius did not affect the result near the hole edge if the outer radius is large. From this research, they concluded that:

i.   The hoop residual stresses around the hole where compressive residual stresses and the values of the residual stresses are decreasing from the exit to entrance face.

ii.   As the plate thickness increase, the compressive residual stresses also increase.

iii. For the opening of the split in the sleeve, it also effect the hoop residual stresses distribution which are lower at the surface. The low residual stresses distribution will result in early fatigue crack propagation by reducing the beneficial effect induced by cold working process.
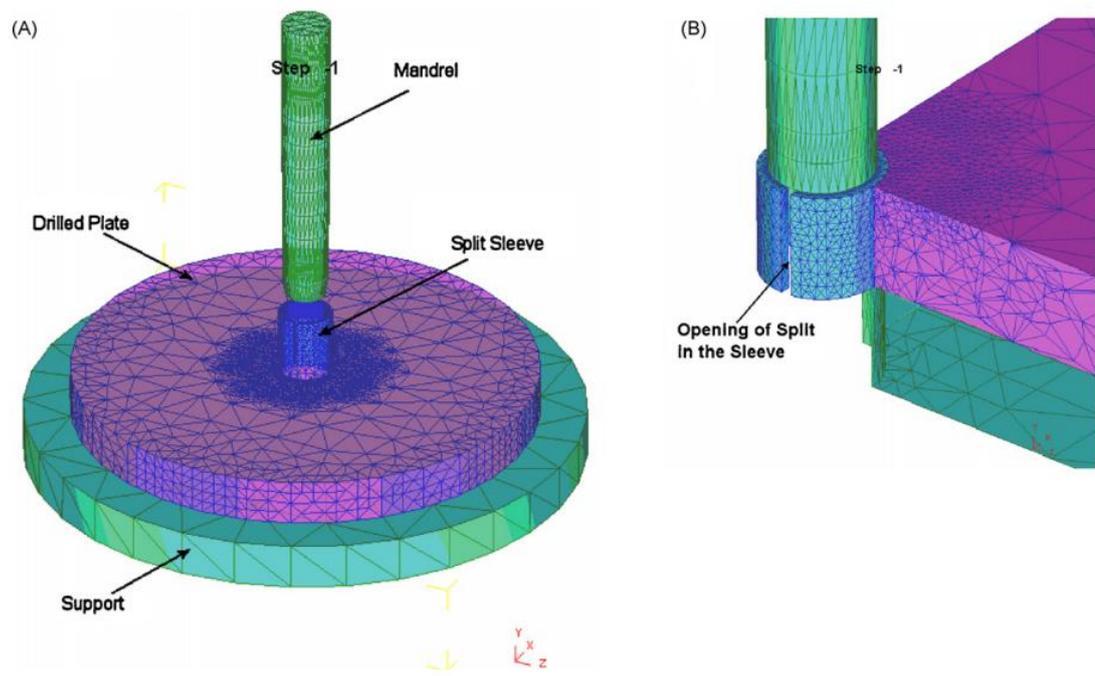
Figure 2.3: FE model used to simulate the cold expansion process of the hole:
(A) Complete model and (B) Detailed view of hole edge

CHAPTER 3

METHODOLOGY

3.1   Project Flow

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                    ┌─────────────────────────┐
                    │    Literature Review    │
                    └─────────────────────────┘
                                 ↓
          ┌──────────────────────────────────────────┐
          │  Identify the dimensions, material and    │
          │        other parameters of the model      │
          └──────────────────────────────────────────┘
```

FYP 1

- Literature Review
- Identify the dimensions, material and other parameters of the model
- Find the inner pressure that caused 0.25 mm hole diameter increment (4% cold expansion ratio) using ANSYS
- Create 2-D and 3- D Model using ANSYS for *c/d*=2, *c/d* =4, *c/d* =6

FYP 2

- Create 3-D Model using ANSYS for different plate thickness (*t/d* =1, *t/d* =2 and *t/d* =3)
- Analysis of the 3-D Model at different through thickness positions (at surface, middle thickness and exit surface)
- Compare the FEA result with the literature review
- Discussion and Conclusion

Figure 3.1: Process flow of the project

3.2   Model Parameters

In this project, a plate containing two holes each with diameter, $d = 6$ mm and with a centre distance c between the holes will be used, as shown in Figure 3.2. The dimensions of the plate were: width, $w = 45$ mm, height, $h = 45$ mm and thickness, $t/d = 1$, $t/d = 2$ and $t/d = 3$.

Thickness, $t = 6$ mm, 12 mm, 18, mm
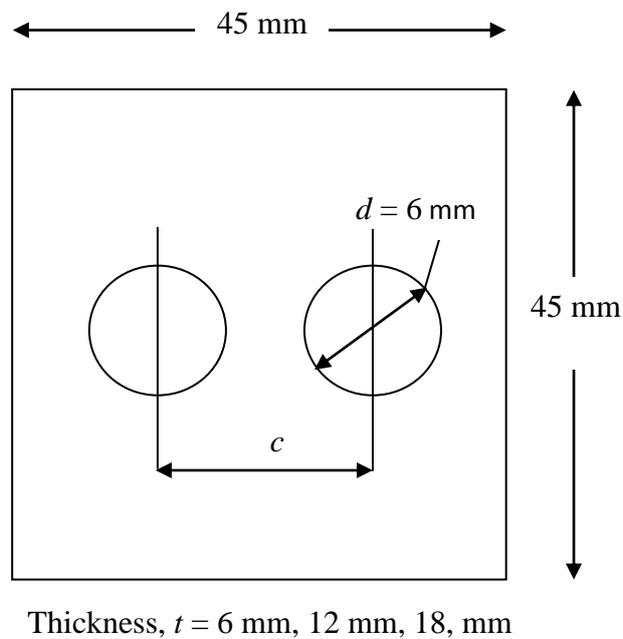
Figure 3.2: Dimension of the model

In this project, in view of symmetry, only one quarter of the plate was used for modelling in ANSYS. The dimensions are as follows: width, $w = 22.5$ mm, height, $h = 22.5$ mm and hole diameter, $d = 6$ mm.
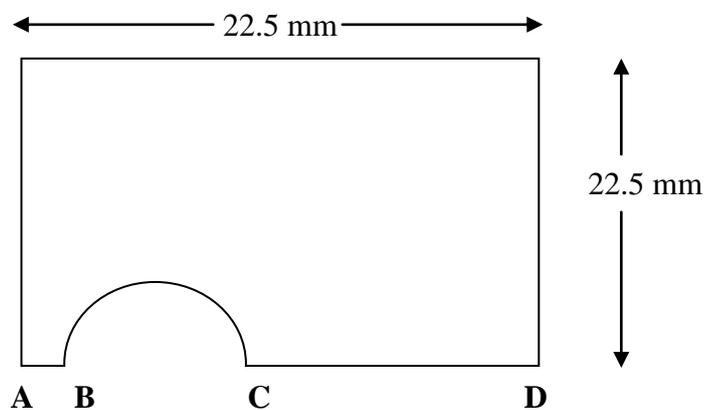
Figure 3.3: One quarter of the plate

3.3   Materials Properties

The material for this model is Aluminium alloy 7075-T6. The material properties of the model are as shown in Table 3.1.

Table 3.1: Mechanical properties of 7075-T6 Aluminium alloy

Mechanical Properties	Unit
Yield Strength	506 MPa
Ultimate Tensile Strength	582 MPa
Modulus of Elasticity	72 GPa
Poisson's Ratio	0.32

Engineering stress versus strain value for material 7075-T6 Aluminium alloy is shown as in Table 3.2

Table 3.2: Engineering stress versus strain value

Strain	Stress (MPa)
0.005	360
0.0075	470
0.01	500
0.02	530
0.03	540
0.04	550
0.05	560
0.06	570
0.07	580
0.08	590
0.09	600
0.10	610
0.11	620
0.12	630

3.4   Modelling in ANSYS

Only one-quarter of the entire plate was modelled by considering the symmetry of the model and loading. The plate was modelled in two-dimension and three dimension. The material used was aluminium alloy AI7075-T6 with modulus of elasticity, E = 72 GPa, Poisson's ratio, v = 0.32 and yield strength, σ_{ys} = 506MPa. A true stress-strain data was used in the simulation in order to analyze the elasto-plastic behaviour.

3.5   Two-Dimensional (2-D) Finite Element Modelling

In two-dimensional modelling, only the adjacent holes will be modelled and analyzed. The centre distance between two holes were varied with c/d = 2, c/d = 4 and c/d = 6. The steps for an example modelling for c/d = 2 are given below.

3.5.1   Defining element types

For 2-D modelling, the element that will be used for the model is the PLANE82. PLANE82 is a higher order version of the 2-D, four-node element (PLANE42). It provides more accurate results for mixed (quadrilateral-triangular) automatic meshes. Thus, it can tolerate irregular shapes without as much loss of accuracy. The 8-node elements have compatible displacement shapes and are well suited to model curved boundaries.

    i.   **Main Menu > Preprocessor > Element Type > Add/Edit/Delete > Add > Solid > 8node82 (PLANE 82)**

3.5.2   Defining material properties

Material properties may be linear or nonlinear, isotropic, orthotropic, or anisotropic, constant temperature or temperature dependent. In this study, only non-linear analysis has been applied to the process operation. The true stress versus true strain graph for material Aluminium alloy 7075-T6 is as shown as in Figure 3.4.

i. **Main Menu > Preprocessor > Material Props > Material Models > Structural > Linear > Elastic > Isotropic**

ii. **Enter the modulus of elasticity, EX = 72e9. Poisson's ratio, PRXY = 0.32**

iii. **Main Menu > Preprocessor > Material Props > Material Models > Structural > Nonlinear > Inelastic > Rate Independent > Kinematic Hardening Plasticity > Mises Plasticity > Multilinear (General)**

iv. **True stress and true strain data being filled.**
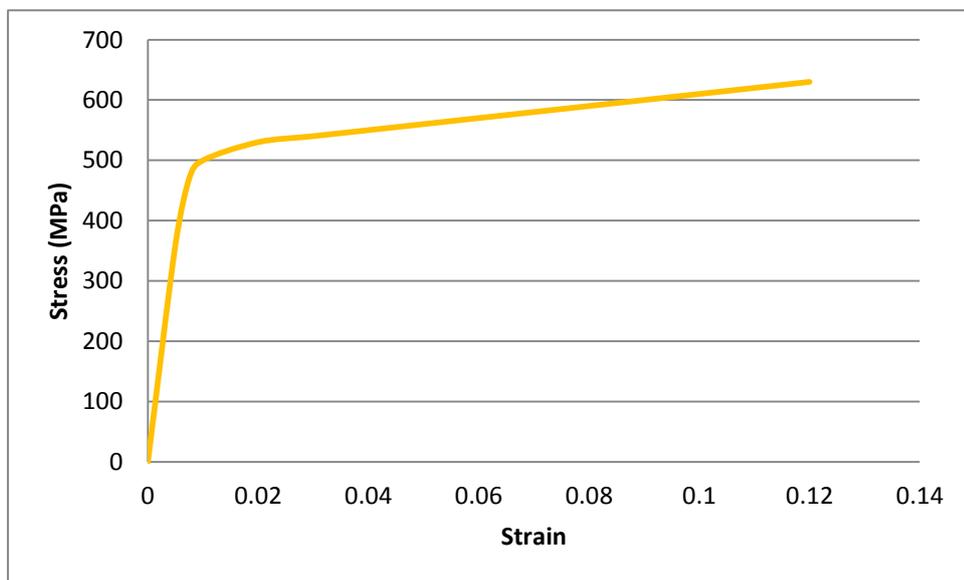
Figure 3.4: True Stress v True Strain graph for Aluminium alloy 7075-T6

3.5.3 Creating model geometry

The model was created by using the parameters that being decided earlier.

i. **Main Menu > Preprocessor > Modeling > Create > Areas > Rectangular > By Dimension** (Figure 3.5)
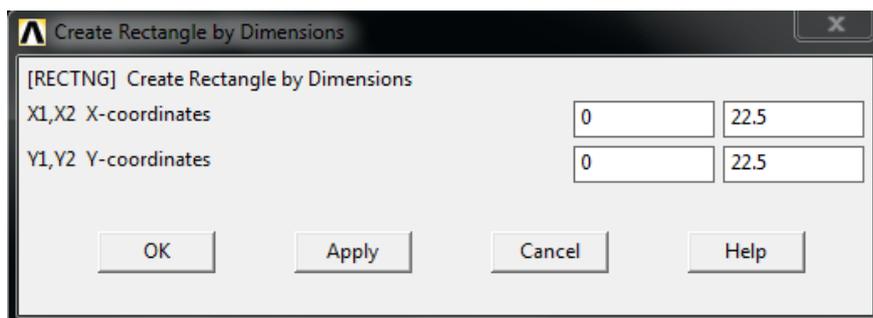
Figure 3.5: Parameters of the model

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ii. **Main Menu > Preprocessor > Modeling > Create > Areas > Circle > Partial Annulus** (Figure 3.6)
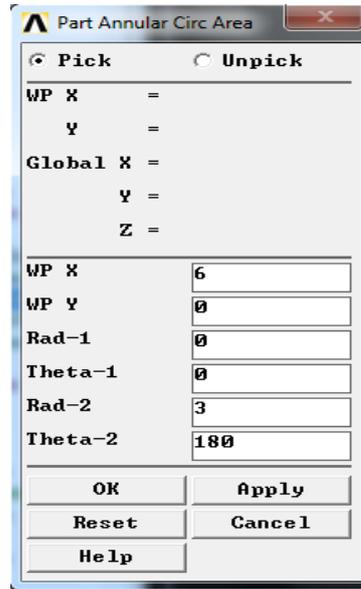
Figure 3.6: Circular sector coordinates

iii. **Main Menu > Preprocessor > Modeling > Operate > Booleans > Substract > Areas** (Figure 3.7)
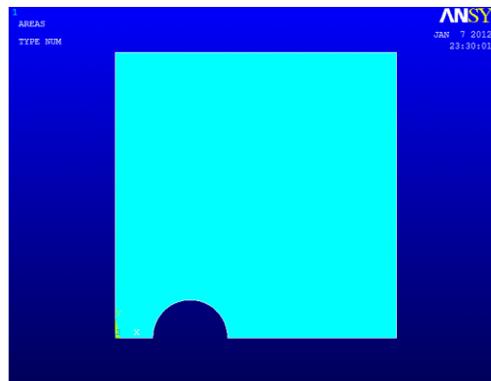
Figure 3.7: Quarter of the model

3.5.4 Meshing

In meshing process, the model will be divided into many cells and some point will be represented by nodes. For this model, the mesh size was being controlled and the mesh selected is Quad and Free. The meshed model is shown in Figure 3.9.

i. **Main Menu > Preprocessor > Meshing > Mesh Tool** (Figure 3.8)
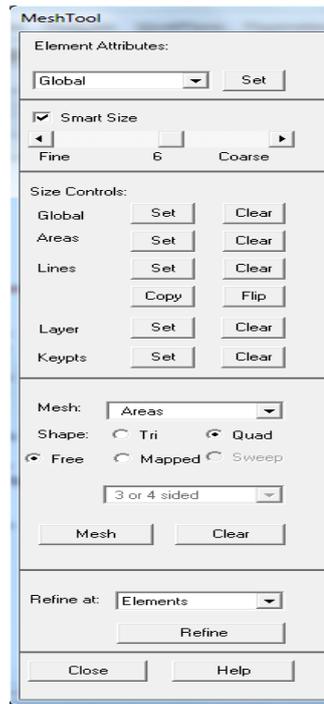
Figure 3.8: Mesh Tool
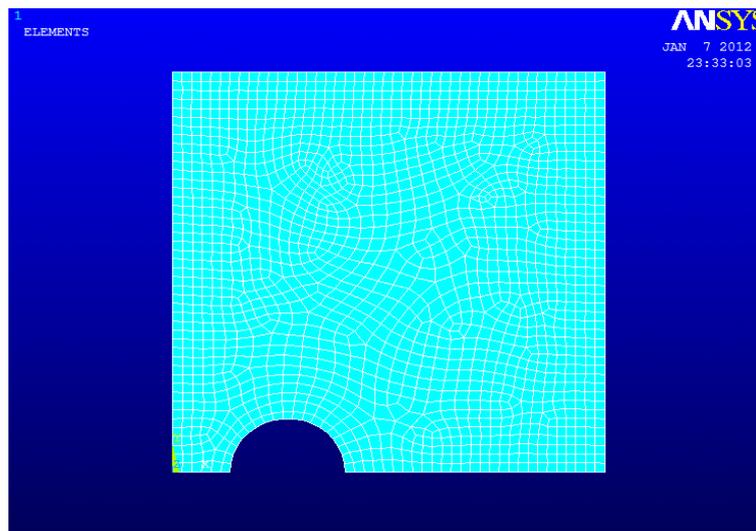
Figure 3.9: 2-D model mesh

3.5.5 Defining analysis type

For this study, the static analysis was being used. Moreover, the solution controls setting was also being modified.

i. **Main Menu > Solution > Analysis Type > New Analysis > Static**

ii. **Main Menu > solution > Analysis Type > Sol'n Controls**

(Figure 3.10 and Figure 3.11)
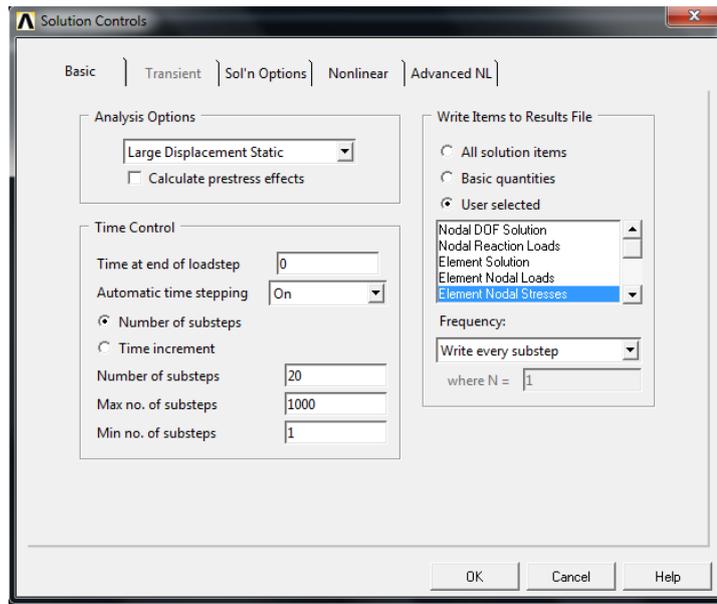
Figure 3.10: Solution controls setting (Basic tab)
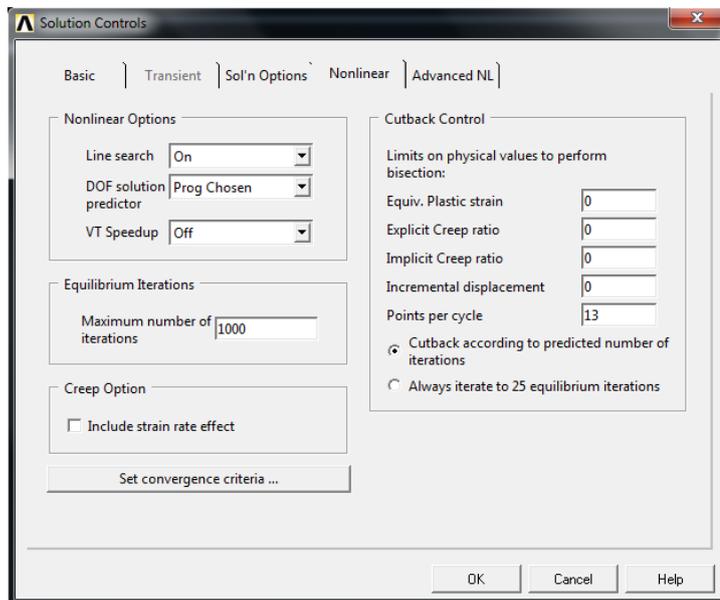
Figure 3.11: Solution controls setting (Nonlinear tab)

3.5.6   Specifying boundary conditions

In this study, two types of boundary conditions were specified which are the symmetry boundary conditions and the fixed boundary conditions.

i.   Main Menu > Preprocessor > Loads > Define Loads > Apply > Structural > Displacement > Symmetry B.C. > On Lines

For 2-D, the symmetry boundary condition being selected as shown by the arrow in the Figure 3.12
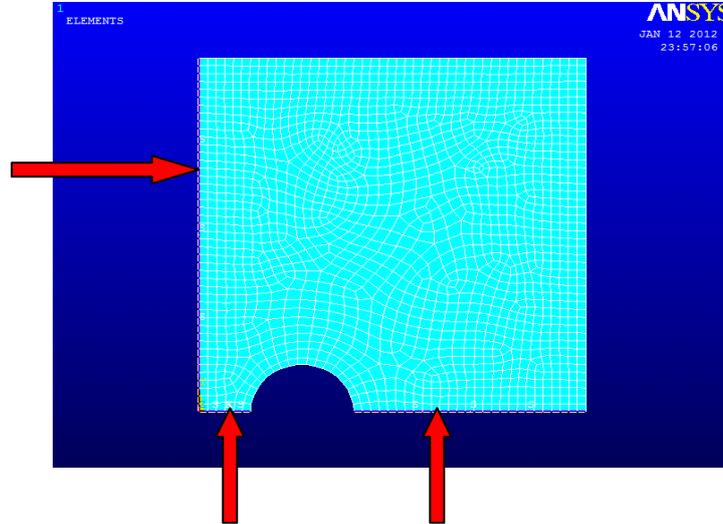
Figure 3.12: 2-D Symmetry Boundary Condition

ii.   Main Menu > Preprocessor > Loads > Define Loads > Apply > Structural > Displacement > On Lines

For 2-D, the fixed boundary condition being selected as shown by the arrow in the Figure 3.13
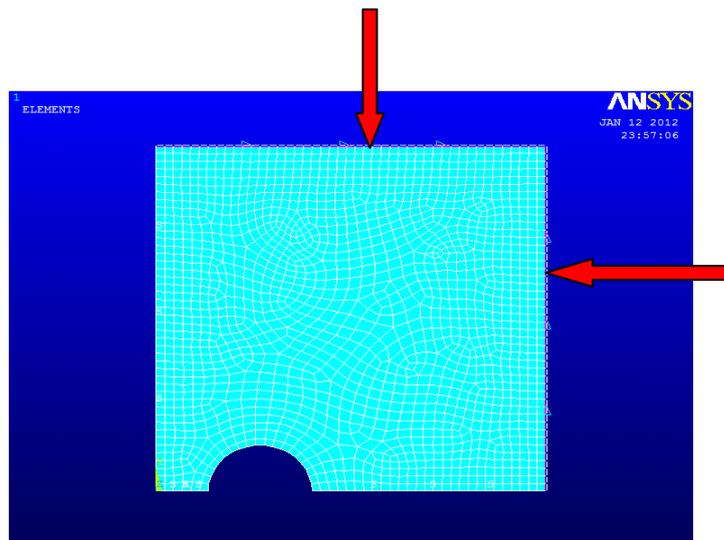
Figure 3.13: 2-D Fixed Boundary Condition

3.5.7 Applying pressure

In 2-D model, the pressure is being applied at the line of the hole. The pressure is being applied to the hole stage by stage as follow:

i. **Main Menu > Preprocessor > Loads > Define loads > Apply > Structural > Pressure > On Lines.**
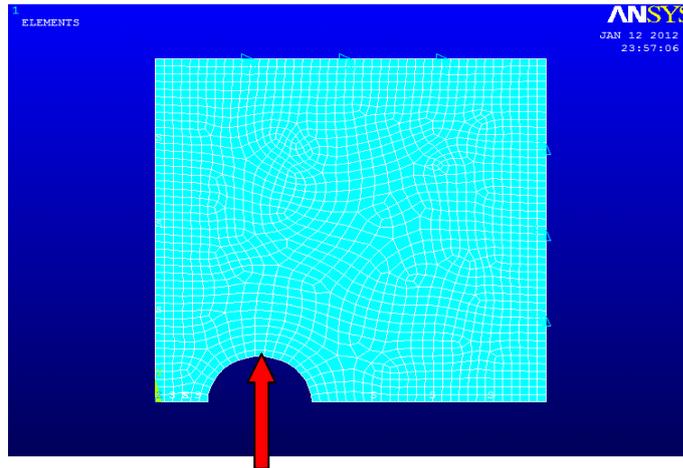
Figure 3.14: Applied pressure on 2-D model

ii **Then, in the Apply PRES on Lines pop-menu, load pressure value being entered as 500e6.**

iii. **Main Menu > Solution > Load Step Opts > Write LS File. In the pop-up window, the Load Step File number being entered as 1.**

iv. **Steps (i) until (iii) are being repeated for pressure value 550e6, 600e6, 657.5e6 and 0. The Load Step File number specified as 2, 3, 4 and 5.**

3.5.8 Solve

i. **Main Menu > Solution > Solve > From LS Files. Starting LS file number 1 until LS file number 5.**

3.5.9 Steps from 3.5.1 until 3.5.8 are being repeated for $c/d = 4$ and $c/d = 6$.

3.6   Three-Dimensional (3-D) Finite Element Modelling

In three-dimensional modelling, the adjacent holes and the plate thickness will be modelled and analyzed. The centre distance between two holes were varied with $c/d = 2$, $c/d = 4$ and $c/d = 6$ and the plate thickness were varied with $t = 6$ mm, $t = 12$ mm and $t = 18$ mm. The modelling steps for $c/d = 2$ with $t = 6$ mm are given below.

3.6.1   Defining element types

For 3-D modelling, the element that will be used for the model is the SOLID92. SOLID92 has quadratic displacement behaviour and is well suited to model irregular meshes. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

   i.   Main Menu > Preprocessor > Element Type > Add/Edit/Delete > Add > Solid > 10node92 (SOLID 82)

3.6.2   Defining material properties

The material properties for the model in 3-D modelling is the same as the material properties for the model in 2-D.

   i.   Main Menu > Preprocessor > Material Props > Material Models > Structural > Linear > Elastic > Isotropic

   ii.   Enter the modulus of elasticity, EX = 72e9. Poisson's ratio, PRXY = 0.32

   iii.   Main Menu > Preprocessor > Material Props > Material Models > Structural > Nonlinear > Inelastic > Rate Independent > Kinematic Hardening Plasticity > Mises Plasticity > Multilinear (General)

   iv.   True stress and true strain data being filled.

3.6.3   Creating model geometry

    i.   **Main Menu > Preprocessor > Modeling > Create > Areas > Rectangular > By Dimension**

    ii.   **Main Menu > Preprocessor > Modeling > Create > Areas > Circle > Partial Annulus**

    iii.   **Main Menu > Preprocessor > Modeling > Operate > Booleans > Substract > Areas**

 iv.   **Main Menu > Preprocessor > Operate > Extrude > Areas > Along Normal. In the pop-up window, the length of extrusion was being entered as 6.** (Figure 3.15)
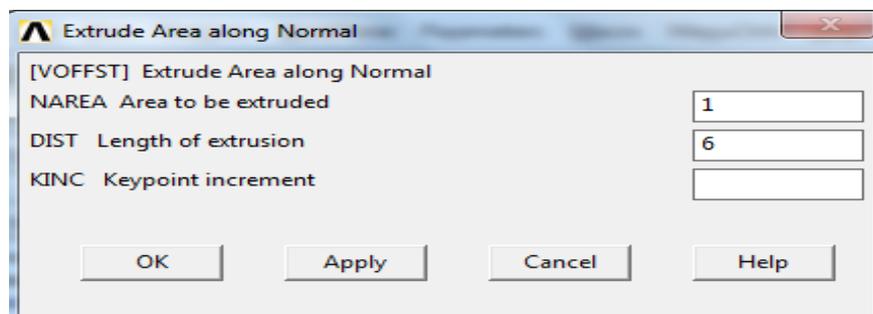
Figure 3.15: Length of extrusion

3.6.4   Meshing

    i.   **Main Menu > Preprocessor > Meshing > Mesh Tool**

    ii.   **In the Mesh Tool pop-up window, click Refine.**
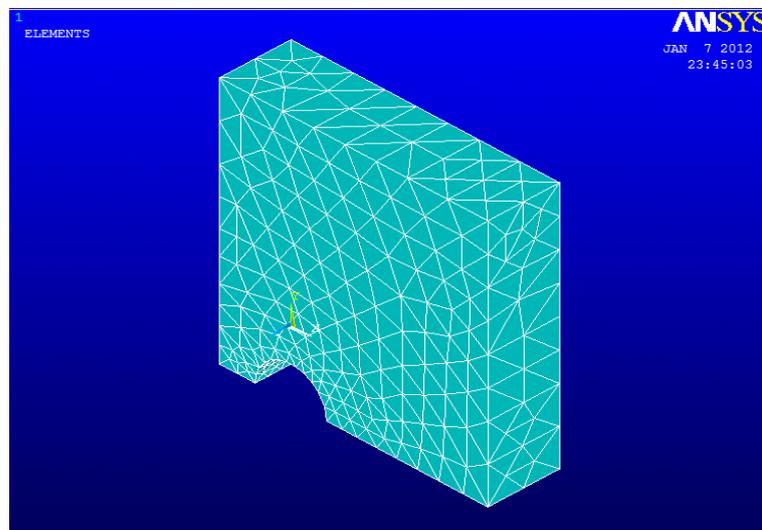
Figure 3.16: 3-D model mesh

3.6.5 Defining analysis type

For 3-D model, the analysis type is the same as the 2-D model.

i.   **Main Menu > Solution > Analysis Type > New Analysis > Static**

ii.   **Main Menu > solution > Analysis Type > Sol'n Controls**

3.6.6 Specifying boundary conditions

i.   **Main Menu > Preprocessor > Loads > Define Loads > Apply > Structural > Displacement > Symmetry B.C. > On Areas** (Figure 3.17)
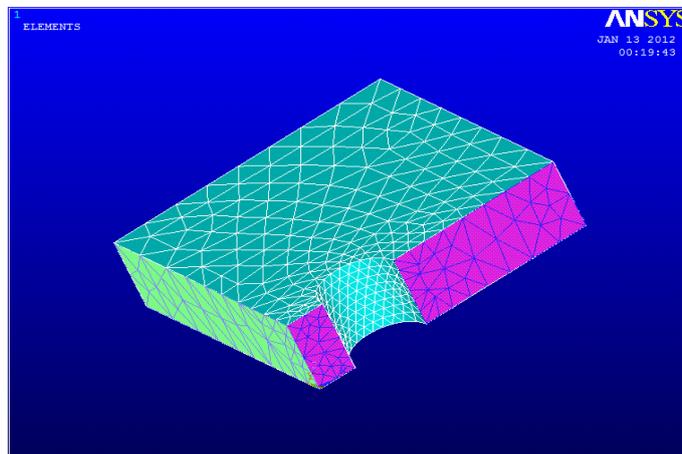
Figure 3.17: 3-D Symmetry Boundary Condition

ii.   **Main Menu > Preprocessor > Loads > Define Loads > Apply > Structural > Displacement > On Areas** (Figure 3.18)
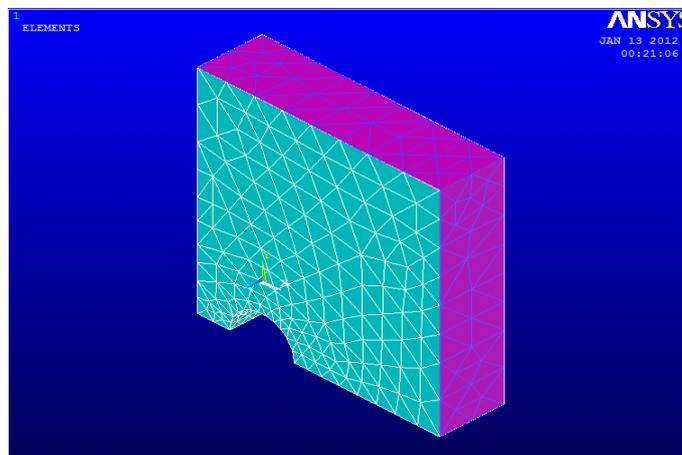
Figure 3.18: 3-D Fixed Boundary Condition

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3.6.7 Applying pressure

  i.   **Main Menu > Preprocessor > Loads > Define loads > Apply >
          Structural > Pressure > On Areas.** (Figure 3.19)
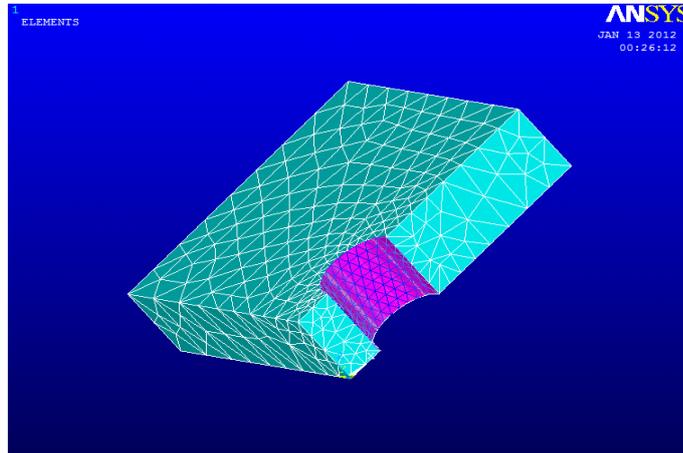
Figure 3.19: Applied pressure on 3-D model

  ii   **Then, in the Apply PRES on Lines pop-menu, load pressure value
          being entered as 500e6.**

  iii. **Main Menu > Solution > Load Step Opts > Write LS File. In the
          pop-up window, the Load Step File number being entered as 1.**

  iv.   **Step (i) until (iii) are being repeated for pressure value 550e6,
          600e6, 657.5e6 and 0. The Load Step File number specified as 2, 3,
          4 and 5.**

3.6.8 Solve

  i.   **Main Menu > Solution > Solve > From LS Files. Starting LS file
          number 1 until LS file number 5.**

3.6.9 **Steps from 3.6.1 until 3.6.8 are being repeated for *c/d* = 4 and *c/d* = 6 with
          t = 12 mm and *t* = 18 mm.**

3.7   Project Gantt chart

3.7.1 Final Year Project 1 Gantt chart

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■													
2	Study on Project Background		■	■												
3	Literature Review on Split Sleeve Cold Expansion Method			■	■	■	■									
4	Literature Review on Residual Stresses			■	■	■	■		Mid Semester Break							
5	Literature Review on Finite Element Analysis			■	■	■	■									
6	Submission of Extended Proposal						■									
7	Proposal Defence											■				
8	Find the correct inner pressure using ANSYS									■	■	■	■	■		
9	Submission of Interim Draft Report														■	
10	Submission of Interim Report															■

3.7.2 Final Year Project 2 Gantt chart

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Finite Element Modeling using ANSYS for different plate thickness	■	■	■	■	■	■	■		■	■	■				
2	Analysis of the results obtained	■	■	■	■	■	■	■		■	■	■				
3	Pre-EDX								Mid Semester Break				■			
4	Submission of draft report													■		
5	Submission of dissertation (softbound)													■		
6	Submission of technical paper													■		
7	Oral presentation														■	
8	Submission of dissertation															■

3.8 Summary of the Finite Element Modelling

Table 3.3: Summary of the Finite Element Modelling

Case	Model	*c/d*	Thickness, *t*	Element type	DOF	No. of element
1	2-D	2	6	PLANE 82	10304	1655
2	2-D	4	6	PLANE 82	10280	1651
3	2-D	6	6	PLANE 82	10454	1680
4	3-D	2	6	SOLID 92	15198	2991
5	3-D	4	6	SOLID 92	20631	4174
6	3-D	6	6	SOLID 92	12672	2413
7	3-D	2	12	SOLID 92	30837	6680
8	3-D	2	18	SOLID 92	33750	7169
9	3-D	4	12	SOLID 92	32037	6844
10	3-D	4	18	SOLID 92	52701	11736
11	3-D	6	12	SOLID 92	23283	4742
12	3-D	6	18	SOLID 92	33009	6882

3.9 Key Milestone

The key milestones that will be completed for FYP 1 are listed below:

1) Study on the split sleeve cold expansion method.
2) Study on the residual stresses and finite element simulation.
3) Decide the parameter of the model
4) Find the required pressure using ANSYS for 2-D and 3-D.

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The key milestones that will be completed for FYP II are listed below:

1) Finite Element Analysis for different adjacent hole distance using ANSYS.
2) Finite Element Analysis for different thickness using ANSYS.
3) Finite Element Analysis at different through thickness using ANSYS

3.10 Tools and Equipments

The software used in this project are:

1) ANSYS – To analyze the model.
2) Microsoft Office 2007 – To produce the report.

CHAPTER 4

RESULTS AND DISCUSSION

4.1   Required Pressure

The 4% cold expansion ratio is chosen for this project. In order to find the correct load or pressure applied to the hole that causes diameter increment of 0.25 mm (4% cold expansion ratio), we used trial and error method for 2-D and 3-D Finite Element Analysis (FEA) simulation. The result between the trial and error method for 2-D and 3-D FEA simulation, was almost the same when applying the same pressure.

Table 4.1: Trial and error method result using FEA simulation to find the required pressure

Pressure (MPa)	Two-Dimensional Radius Increment (mm)	Three-Dimensional Radius Increment (mm)
600	0.0651	0.0774
630	0.0131	0.0998
650	0.1182	0.1187
655	0.1209	0.1220
657.5	0.1245	0.1250

Based on the table above, we can conclude that the pressure that will cause 4% cold expansion ratio (radius increment 0.125mm) for two-dimensional modelling and three-dimensional modelling is 657.5 MPa

4.2   Two-Dimensional (2-D) Finite Element Modelling with different adjacent holes distance

In order to investigate the effect of the distance between the holes in the residual stress distribution, two-dimensional finite element modelling is used. The plate contained two 6 mm diameter holes with a central distance, *c*. The central distance between the two holes are being varied by using the ratio of central distance, *c* over holes diameter, *d* (*c/d* = 2, *c/d* = 4 and *c/d* = 6). Moreover, only one-fourth of the entire plate is modelled considering the symmetry of the model and loading.

Below are the results of the 2-D Finite Element Modelling using ANSYS with 4% cold expansion ratio for *c/d* = 2, *c/d* = 4 and *c/d* = 6.
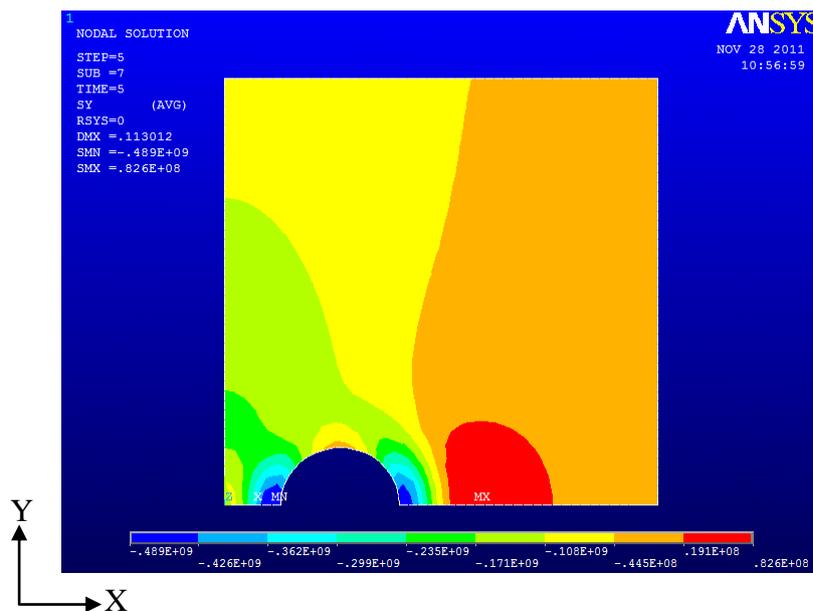
Figure 4.1: Stress contour distribution in y-direction for *c/d* = 2
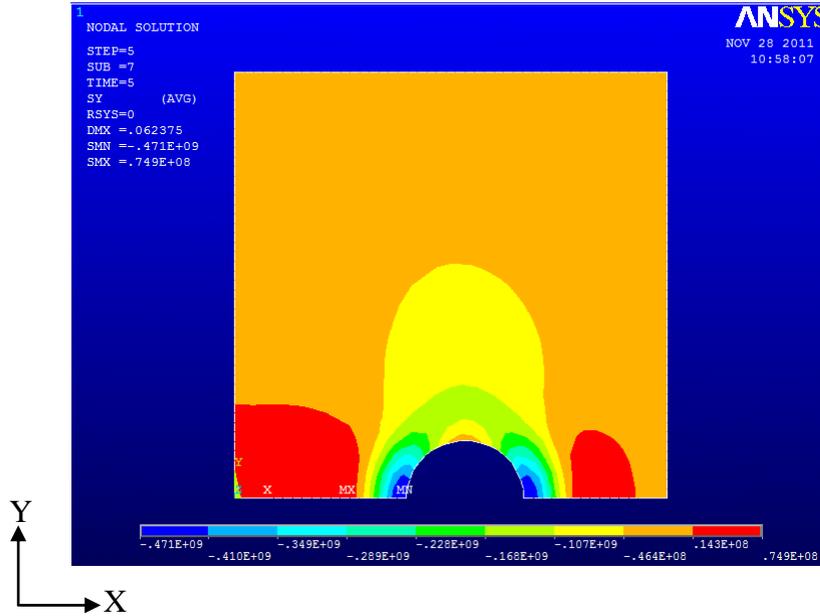
Figure 4.2: Stress contour distribution in y-direction for *c/d* = 4
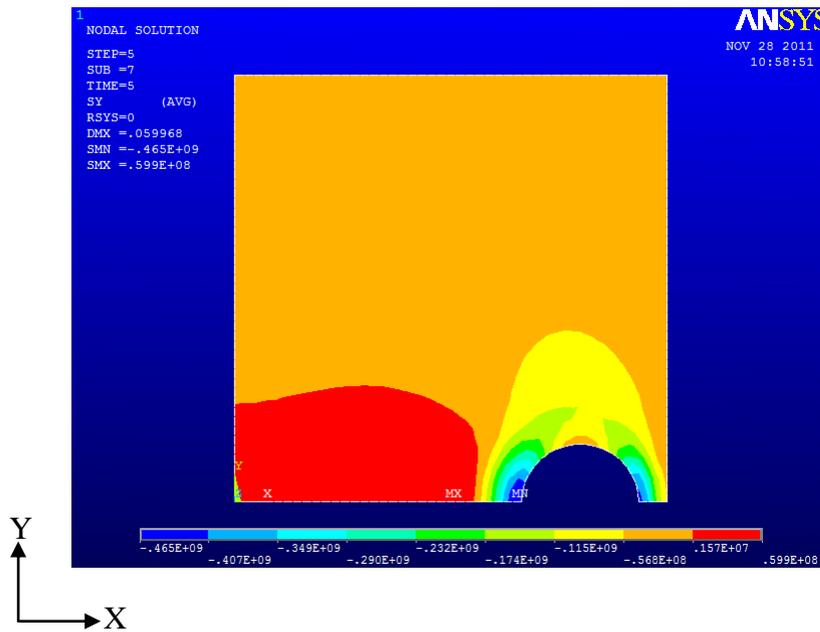
Figure 4.3: Stress contour distribution in y-direction for *c/d* = 6

Based on the results above, we can see that, for different central distance between the two holes there were different stress contour distribution. This shows that, different central distance between holes does effect stress contour distribution. Then, the result is being analyzed using Microsoft Excel for different central distance between holes.

For this analysis, the distance from hole was set to 3mm and the distance being divided by the radius of the hole (r = 3mm) to get the normalized distance from hole. Then, the stress distribution is measured in y-direction and being divided by the yield stress of the material (σ_{ys} = 506MPa) to get the normalized stress. This is because in y-direction, the stress values obtained from the finite element analysis were compressive compared to stress values in x-direction. So, stress in y-direction is more relevant to our study.

Table 4.2: Normalized stress versus Normalized distance for c/d = 2, c/d = 4, c/d = 6

c/d = 2		c/d = 4		c/d = 6	
Distance	Stress	Distance	Stress	Distance	Stress
0.00	-0.93	0.00	-0.92	0.00	-0.92
0.05	-0.94	0.05	-0.92	0.05	-0.92
0.10	-0.95	0.10	-0.92	0.10	-0.92
0.15	-0.96	0.15	-0.93	0.15	-0.92
0.20	-0.96	0.20	-0.89	0.20	-0.88
0.25	-0.94	0.25	-0.84	0.25	-0.82
0.30	-0.92	0.30	-0.78	0.30	-0.75
0.35	-0.88	0.35	-0.72	0.35	-0.68
0.40	-0.80	0.40	-0.64	0.40	-0.60
0.45	-0.72	0.45	-0.56	0.45	-0.52
0.50	-0.63	0.50	-0.48	0.50	-0.44
0.55	-0.55	0.55	-0.40	0.55	-0.36
0.60	-0.47	0.60	-0.32	0.60	-0.29
0.65	-0.39	0.65	-0.24	0.65	-0.22
0.70	-0.32	0.70	-0.18	0.70	-0.15
0.75	-0.27	0.75	-0.12	0.75	-0.10
0.80	-0.22	0.80	-0.06	0.80	-0.04
0.85	-0.18	0.85	-0.01	0.85	0.01
0.90	-0.17	0.90	0.03	0.90	0.04
0.95	-0.15	0.95	0.07	0.95	0.07
1.00	-0.14	1.00	0.10	1.00	0.10
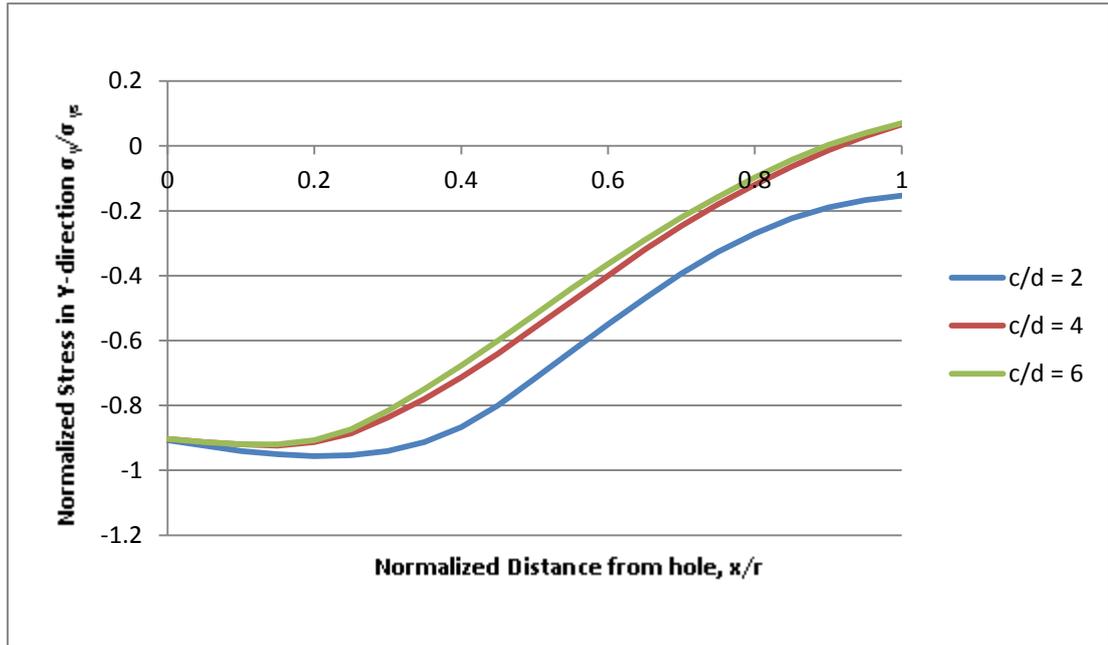
Figure 4.4: Stress distribution in y-direction for *c/d* = 2, *c/d* = 4 and *c/d* = 6

Figure 4.4 shows the variation of the stress distribution for different adjacent hole distance. From the figure, we can see that the highest stress distribution happen when the *c/d* = 2. Furthermore, as the distance between the holes is increasing, the residual stresses will decrease until when the *c/d* = 6 and the graph plot for *c/d* = 6 is almost the same as *c/d* = 4. We can conclude that there is no influence of the adjacent holes on the residual stresses if the distance between the holes is greater than six times of the hole diameter.

4.3　Limitations of the Two Dimensional (2-D) Model

Cold expansion method is a process to develop a compressive residual stresses that is tangential to the hole edge. The two-dimensional model was not capable to predict accurately the residual stresses because the tangential residual stresses distribution cannot be found from two dimensional models. It is only can be found in three-dimensional model.

Furthermore, it is also not capable to account for friction as well as surface roughness variations through the thickness of the plate during the cold expansion process. These limitations have motivated the three dimensional finite element modelling showed below.

4.4　Three-Dimensional (3-D) Finite Element Modelling with different adjacent holes distance

Figures below show that the residual stresses distribution of 3-D Model with 4% cold expansion ratio for $c/d = 2$, $c/d = 4$ and $c/d = 6$.
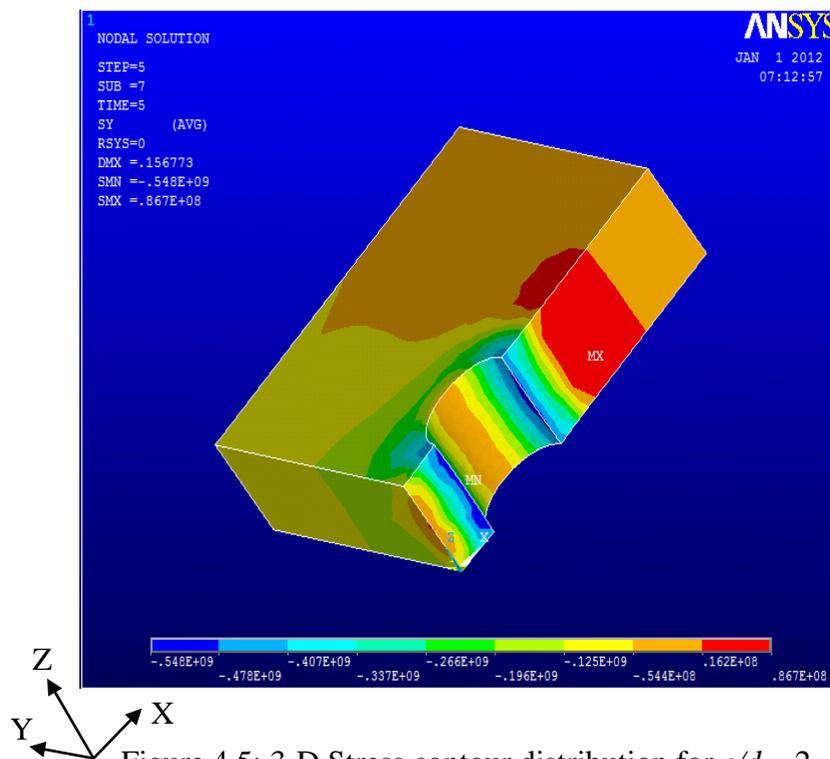
Figure 4.5: 3-D Stress contour distribution for $c/d = 2$

Figure 4.6: 3-D Stress contour distribution for *c/d* = 4

Figure 4.7: 3-D Stress contour distribution for *c/d* = 6
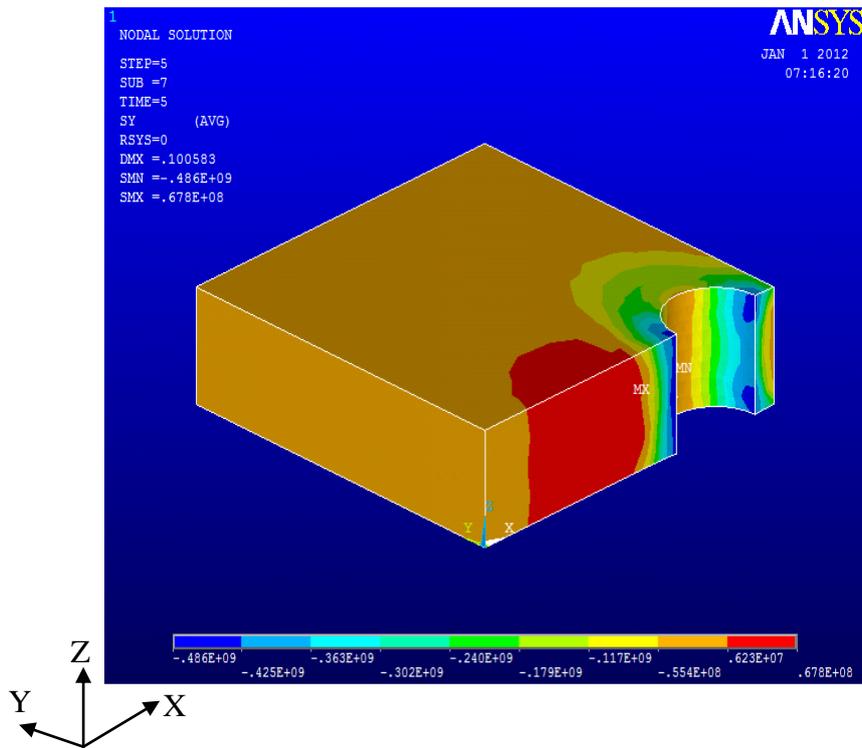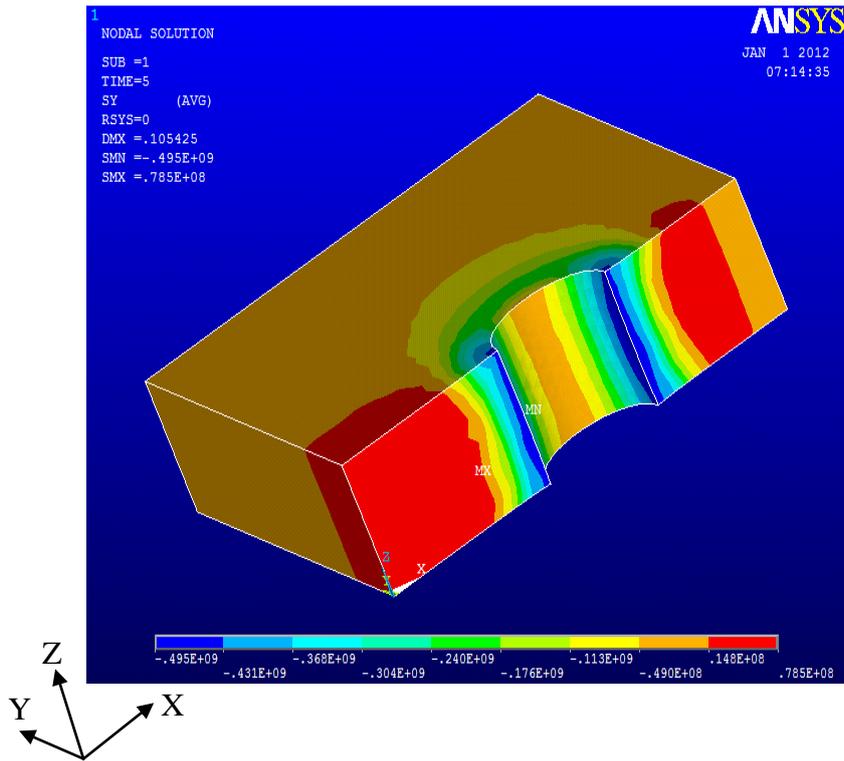
Based on the figures above, there were different stress contour distributions for the three-dimensional models with different central distance between holes. This shows that, different central distance between holes does effect stress contour distribution.
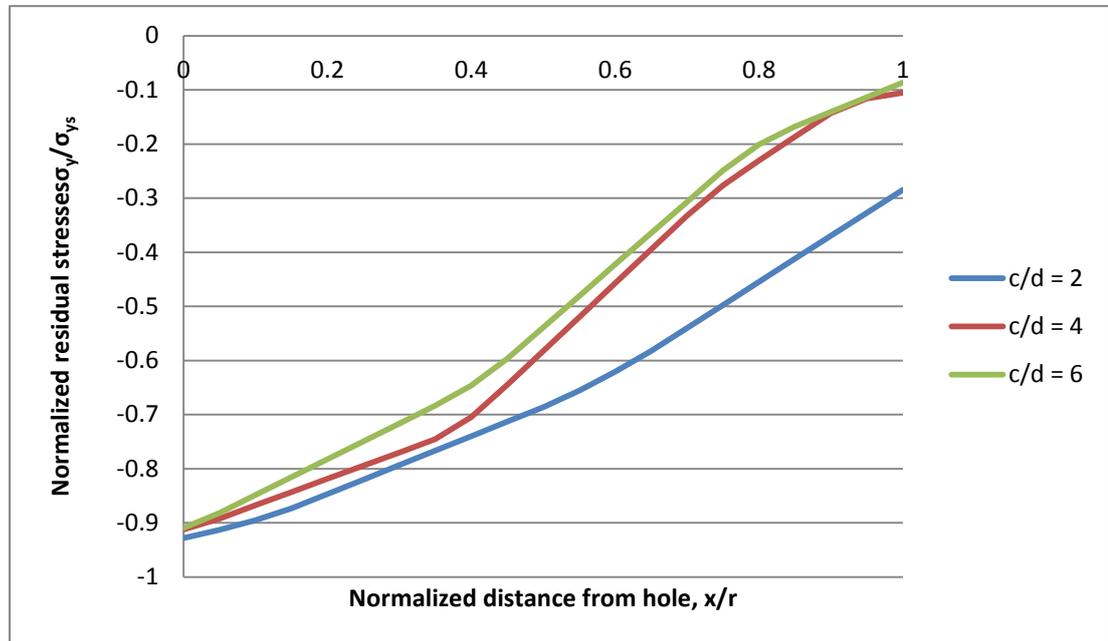
Figure 4.8: 3-D Stress distribution in y-direction for *c/d* = 2, *c/d* = 4 and *c/d* = 6

Figure 4.8 shows the variation of the stress distribution for different adjacent holes distance in three dimensional models at the entrance face of the plate. Figure 4.8, shows that the highest stress distribution happen when the *c/d* = 2 compared to *c/d* = 4 and *c/d* = 6.

From the figure, the centre distance of the two cold expanded holes can lead to a significant change in the compressive residual stresses distribution. Figure 4.8 also shows that an increase in the centre distance between the cold expanded holes results in a decrease in the compressive residual stresses around the cold expanded holes.

Then, the normalized tangential residual stresses at point B (refer Figure 3.3) were being analyzed. Point B is plotted across the thickness ($t = 6$ mm) of the specimen for the different adjacent holes distance ($c/d = 2$, $c/d = 4$, and $c/d = 6$). The result is showed below.
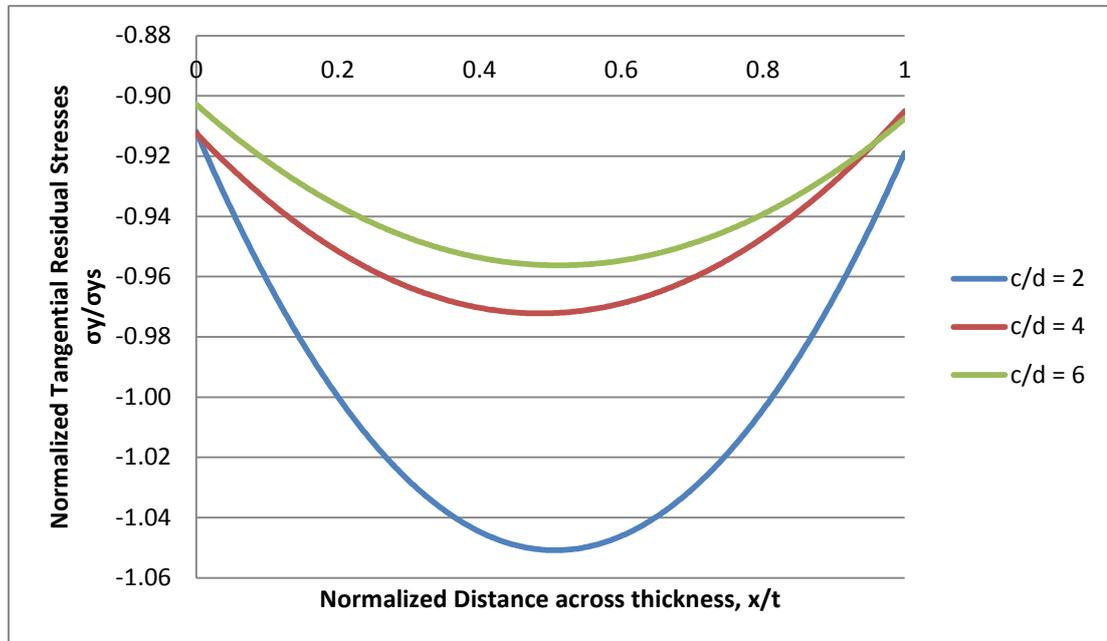
Figure 4.9: Tangential residual stresses distribution for $c/d = 2$, $c/d = 4$ and $c/d = 6$

Figure 4.9 shows the tangential residual stresses distribution for different adjacent hole distance with 4% cold expansion ratio. From the figure, we can see that the tangential residual stresses distribution varied for different adjacent holes distance. The highest tangential residual stresses distribution was when $c/d = 2$.

From the figure, we also can see that for different adjacent holes distance ($c/d = 2$, $c/d = 4$ and $c/d = 6$) the tangential residual stresses is the highest at the mid-point. This is because the material at the mid-thickness section flows in radial and hoop directions, and therefore high tangential residual stresses are generated.

4.5 Three-Dimensional (3-D) Finite Element Modelling with different plate thickness

For this analysis, the residual stresses in different cold-expanded plate thickness will be investigated. In order to investigate the effect of different plate thickness in the residual stress distribution, three-dimensional finite element modelling was used. Only one-fourth of the entire plate is modelled considering the symmetry of the model and loading. The plate contained two 6 mm diameter holes with a central distance, *c.*

The central distance between the two holes are being varied by using the ratio of central distance, *c* over holes diameter, *d* (*c/d* = 2, *c/d* = 4 and *c/d* = 6). Then, for each plate with different central distance, the plate thickness are being varied by using the ratio of thickness, *t* over hole diameter, *d* (*t/d* = 1, *t/d* = 2 and *t/d* = 3). This analysis is focused at the hole edge. Below are the results of the 3-D Finite Element Modelling using ANSYS with 4% cold expansion ratio for *c/d* = 2, *c/d* = 4 and *c/d* = 6 with *t/d* = 1, *t/d* = 2 and *t/d* = 3.

4.5.1 Three-Dimensional Model for *c/d* = 2 with *t/d* = 1, *t/d* = 2 and *t/d* = 3
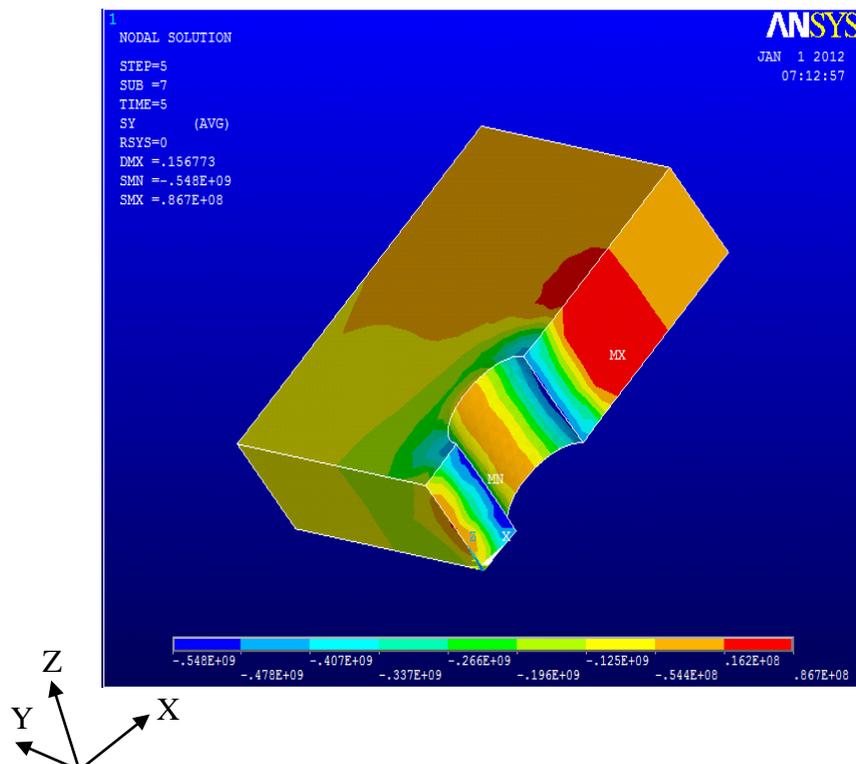
Figure 4.10: 3-D Model for *c/d* = 2 with *t/d* = 1

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Figure 4.11: 3-D Model for *c/d* = 2 with *t/d* = 2

Figure 4.12: 3-D Model for *c/d* = 2 with *t/d* = 3
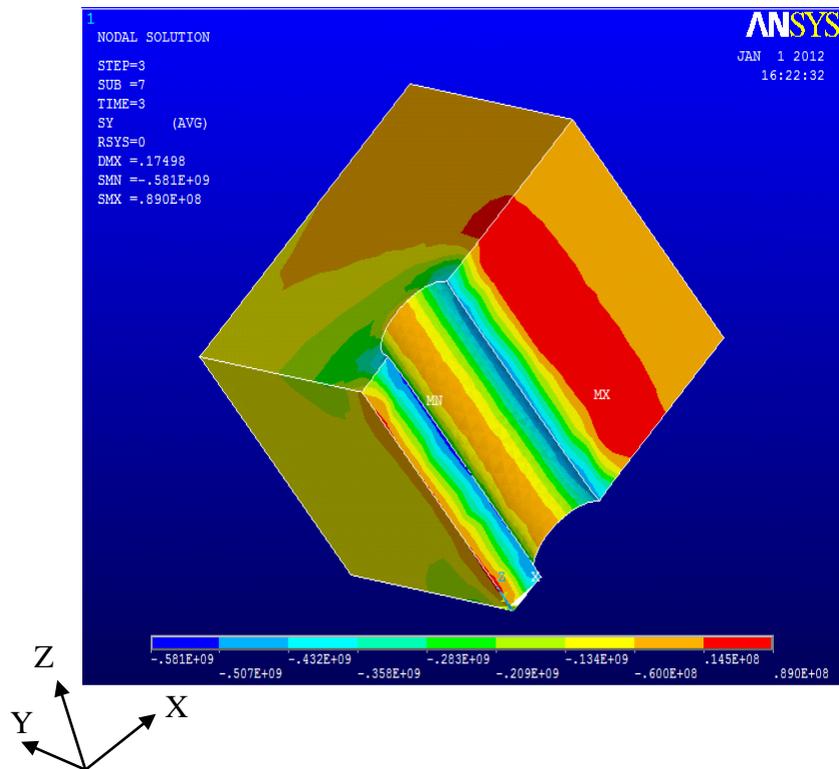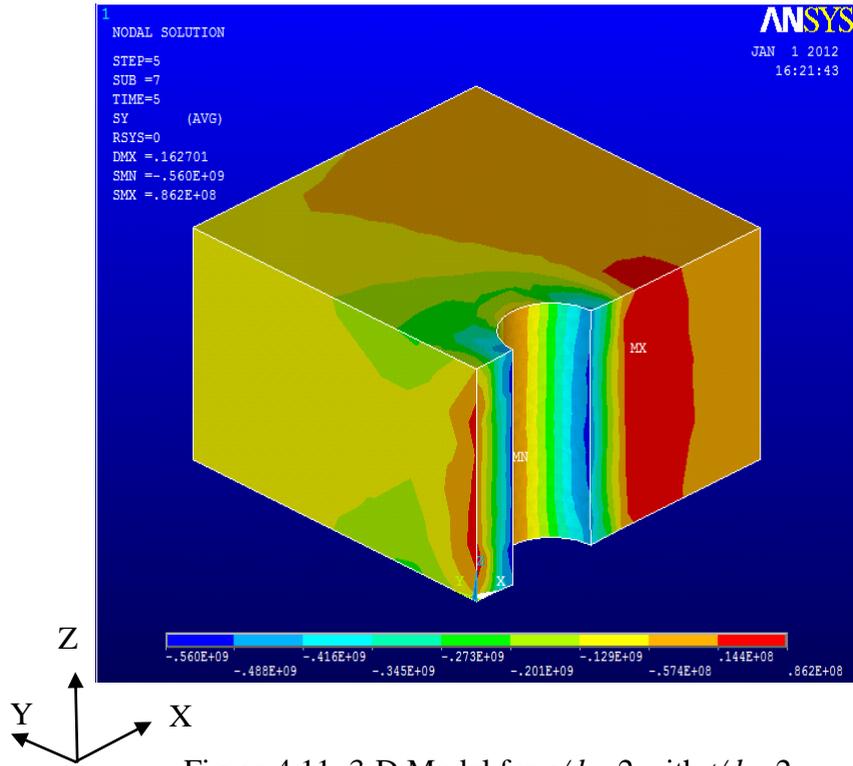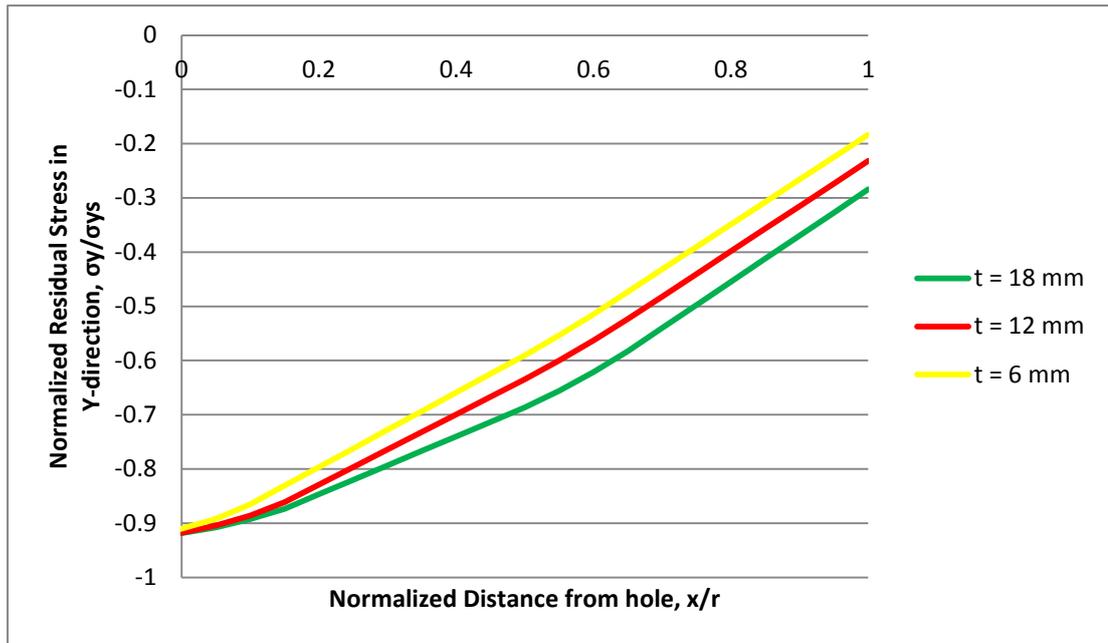
Figure 4.13: Residual stresses distribution for *c/d* = 2 with *t/d* = 1, *t/d* = 2 and *t/d* = 3

From Figure 4.13, we can see that the highest compressive residual stresses are when the plate thickness is 18 mm. The compressive residual stresses are being analyzed from the hole edge of the plate (plate surface). It is seen from Figure 4.13, the maximum compressive stress is found close to the hole edge. Then the compressive residual stresses value decrease rapidly away from the hole edge. This shows that, the compressive residual stresses increase as the plate thickness increases from 6 mm to 18 mm. The dimensions of the models were identical, and therefore the difference between the stress distributions of these specimens reflects the effect of plate thickness.

The state of stress changes from the plane-stress to the plane-strain condition with the increasing thickness. Hence, the residual stresses produced after cold expansion process becomes more compressive. For a thin plate (6 mm), material constraint and the resistance against pressure applied is low. Therefore, the elastic-plastic boundary created gradually spreads from the hole edge. In a thick plate (18 mm), additional pressure applied to the hole due to an increase in material constraint. The applied pressure creates a large plastic zone around the hole and consequently, extensive compressive residual stresses are created. The plate thickness is very effective in increasing the maximum compressive stress in the cold expansion process.

4.5.2 Three-Dimensional Model for *c/d* = 4 with *t/d* = 1, *t/d* = 2 and *t/d* = 3
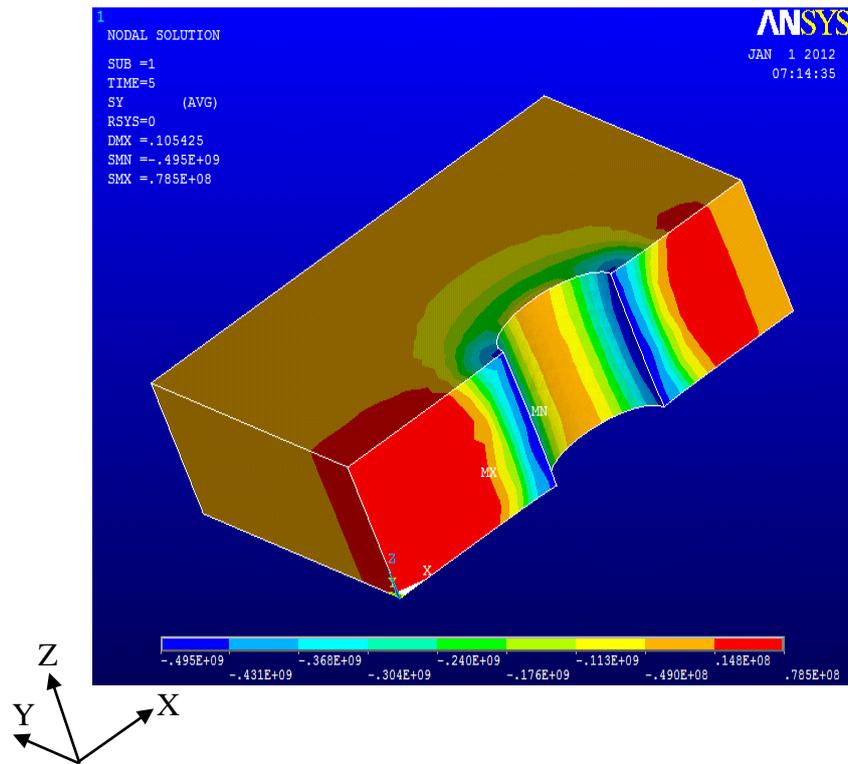
Figure 4.14: 3-D Model for *c/d* = 4 with *t/d* = 1
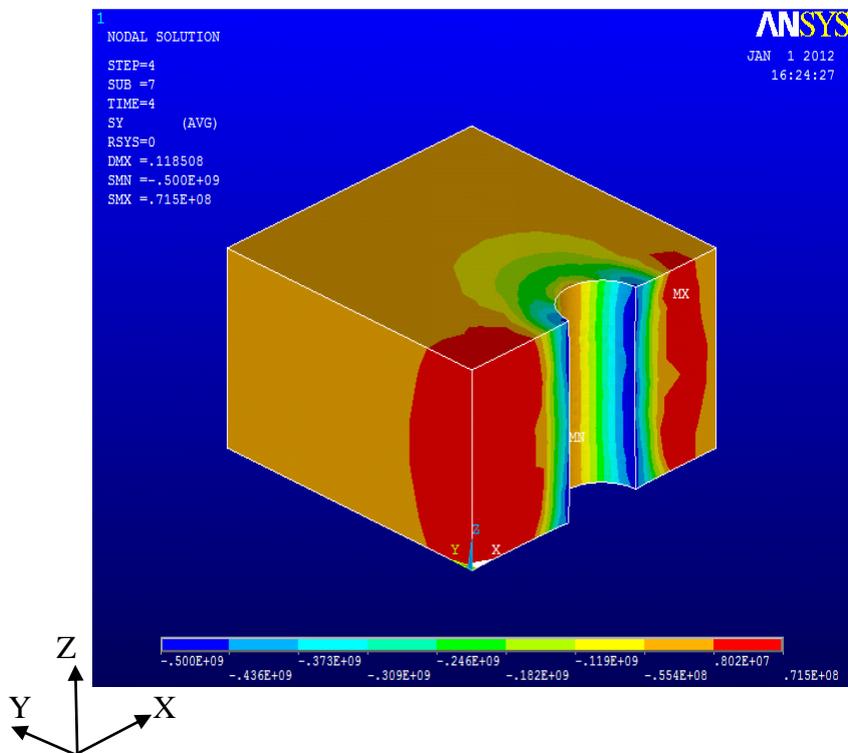
Figure 4.15: 3-D Model for *c/d* = 4 with *t/d* = 2
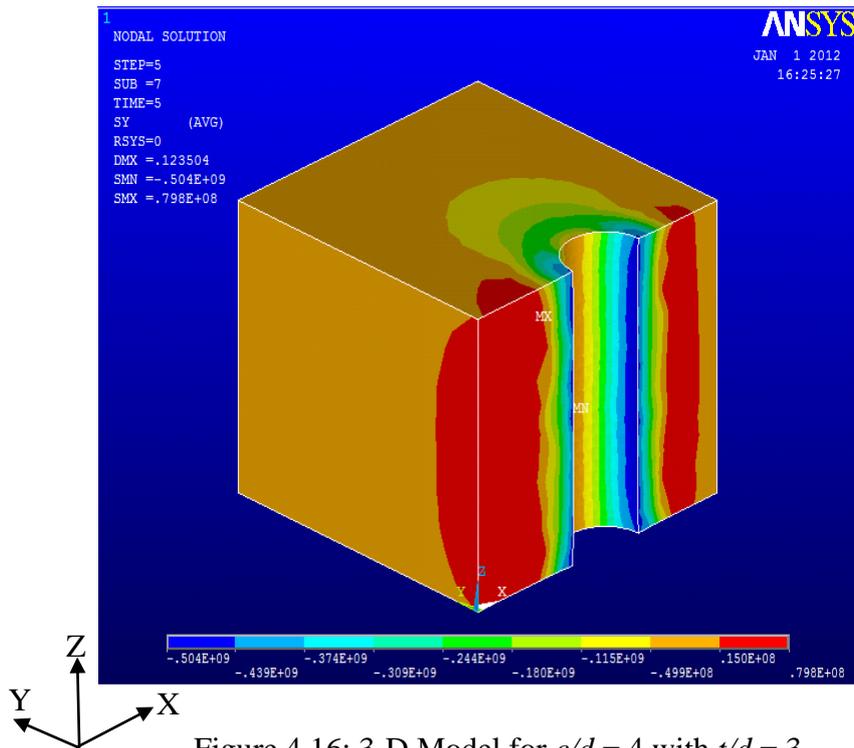
Figure 4.16: 3-D Model for *c/d* = 4 with *t/d* = 3
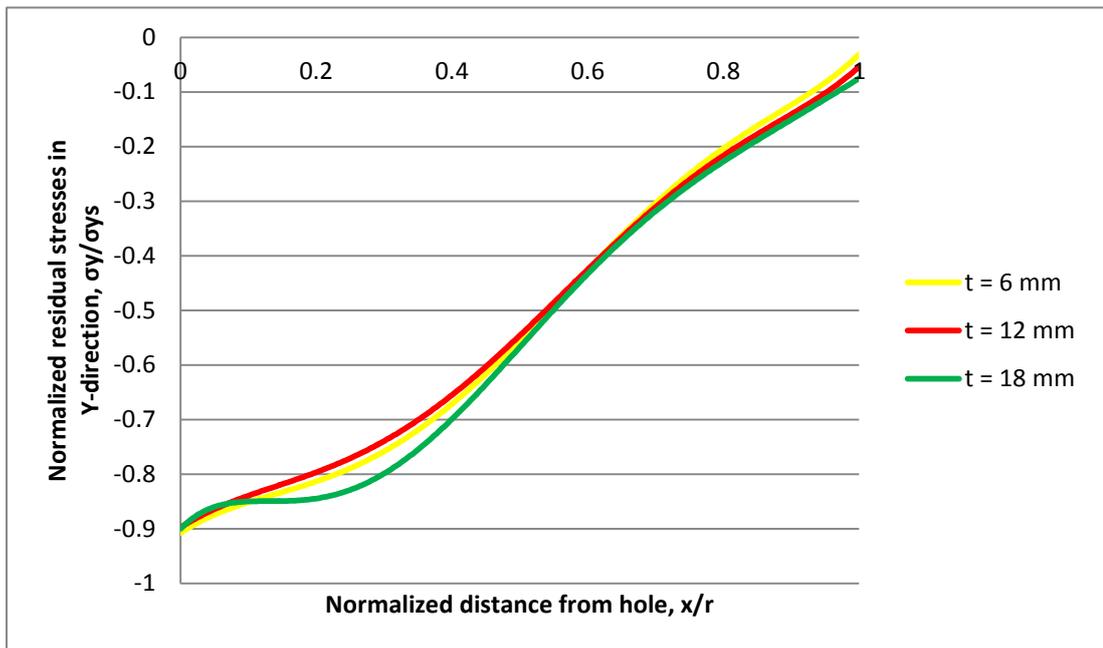
Figure 4.17: Residual stresses distribution for *c/d* = 4 with *t/d* = 1, *t/d* = 2 and *t/d* = 3

From Figure 4.17, the compressive residual stresses increase as the plate thickness increase. It is seen from the Figure 4.17, the maximum compressive stress is found close to the hole edge. Then the compressive residual stresses value decrease rapidly away from the hole edge.

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4.5.3 Three-Dimensional Model for *c/d* = 6 with *t/d* = 1, *t/d* = 2 and *t/d* = 3
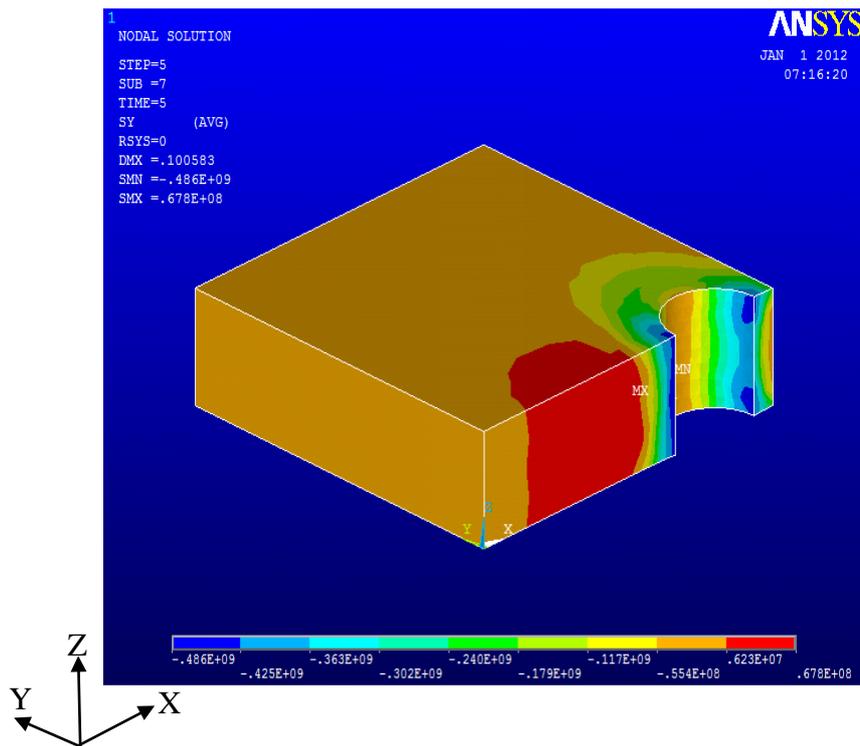
Figure 4.18: 3-D Model for *c/d* = 6 with *t/d* = 1
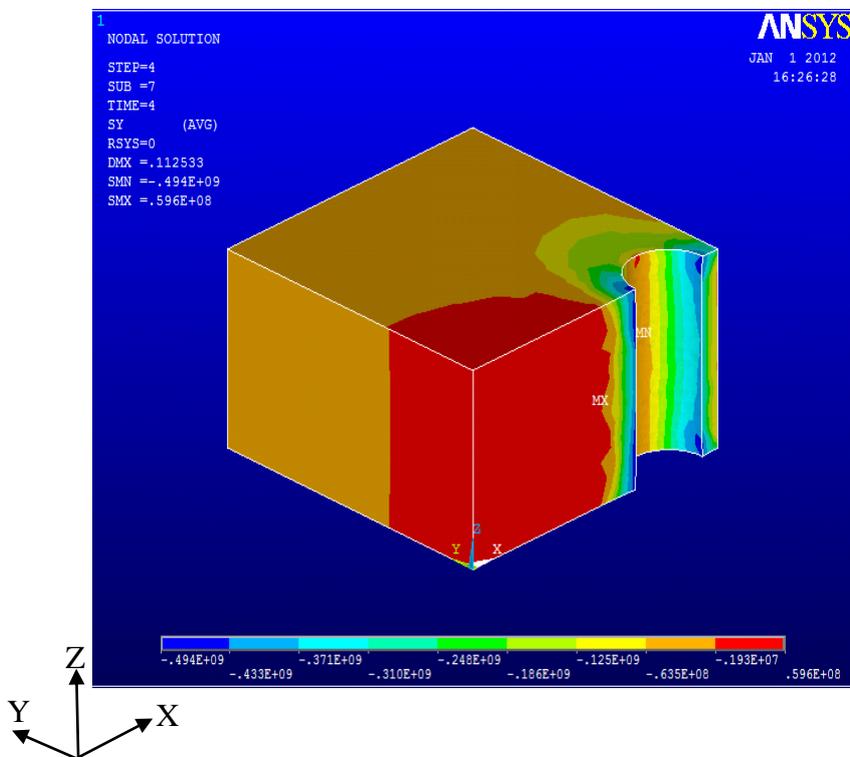
Figure 4.19: 3-D Model for *c/d* = 6 with *t/d* = 2
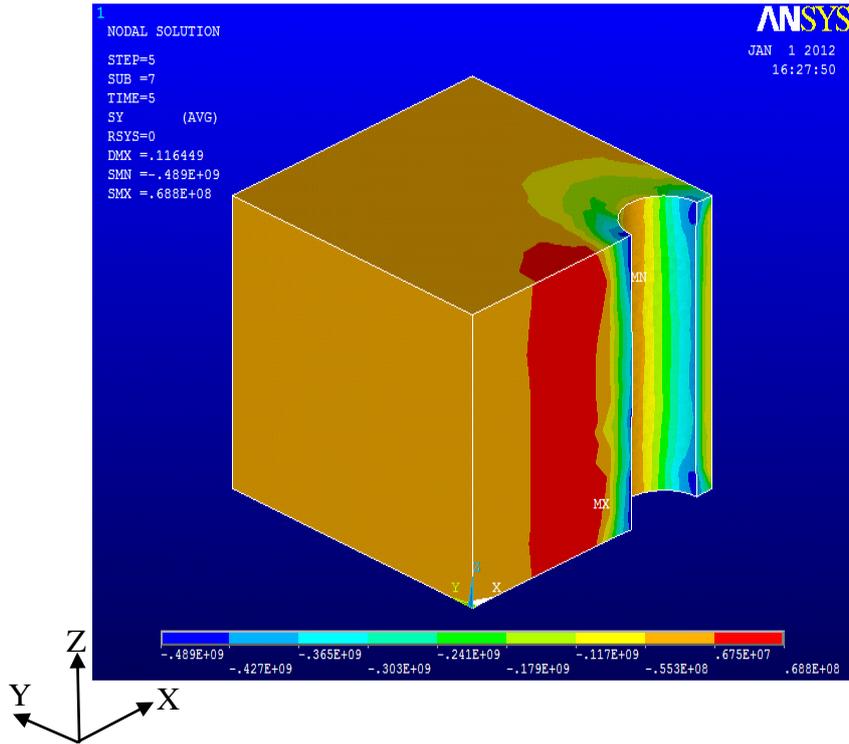
Figure 4.20: 3-D Model for *c/d* = 6 with *t/d* = 3
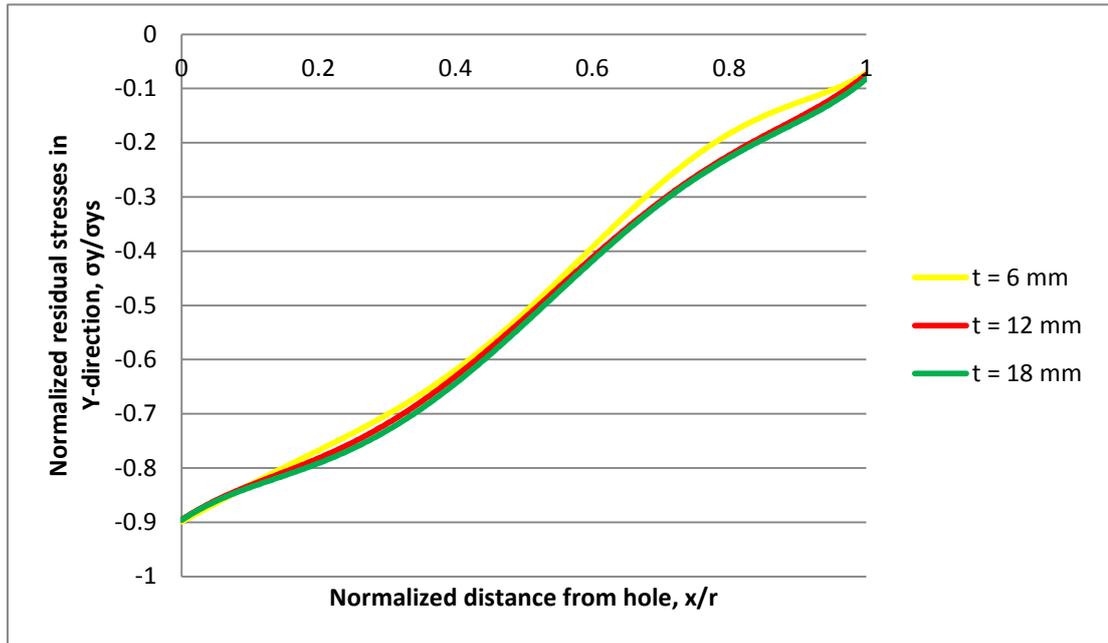
Figure 4.21: Residual stresses distribution for *c/d* = 6 with *t/d* = 1, *t/d* = 2 and *t/d* = 3

From Figure 4.21, the compressive residual stresses increase as the plate thickness increase. It is seen from the Figure 4.21, the maximum compressive stress is found close to the hole edge. Then the compressive residual stresses value decrease rapidly away from the hole edge.

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4.6 Comparison of different adjacent holes (*c/d* = 2, *c/d* = 4 and *c/d* = 6) with different plate thickness (*t/d* = 1, *t/d* = 2 and *t/d* = 3)

From the comparative result, the *c/d* = 2 is the critical distance where we can see clearly the distribution of the compressive residual stresses distribution compared to different adjacent holes distance (*c/d* = 4 and *c/d* = 6). For *c/d* = 4 and *c/d* = 6, the compressive residual stresses distribution for different plate thickness is almost the same.

4.7 Three-Dimensional (3-D) Finite Element modelling at different through thickness positions (entrance face, middle face and exit face)

In order to investigate the effect of different through thickness position in the residual stress distribution, three-dimensional finite element modelling was used. Only one-fourth of the entire plate is modelled considering the symmetry of the model and loading.

The plate contained two 6 mm diameter holes with a central distance, *c*. The central distance between the two holes are being fixed for *c/d* = 2. The plate thicknesses were varied as follow 6 mm, 12 mm and 18 mm. This analysis is focused at the hole edge.

Figure 4.22 shows the different through thickness position at the hole edge. The results of the 3-D Finite Element Modelling using ANSYS with 4% cold expansion ratio for different through thickness position (entrance face, middle face, and exit face) were shown in Figure 4.23, Figure 4.24 and Figure 4.25.
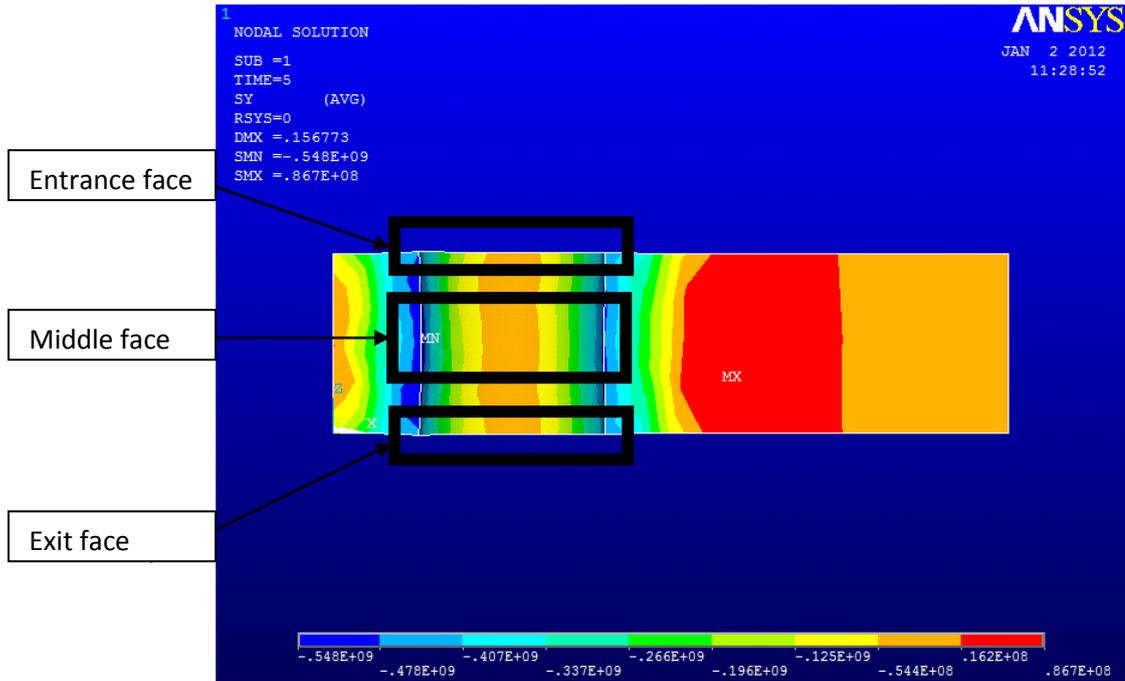
Figure 4.22: Through thickness position
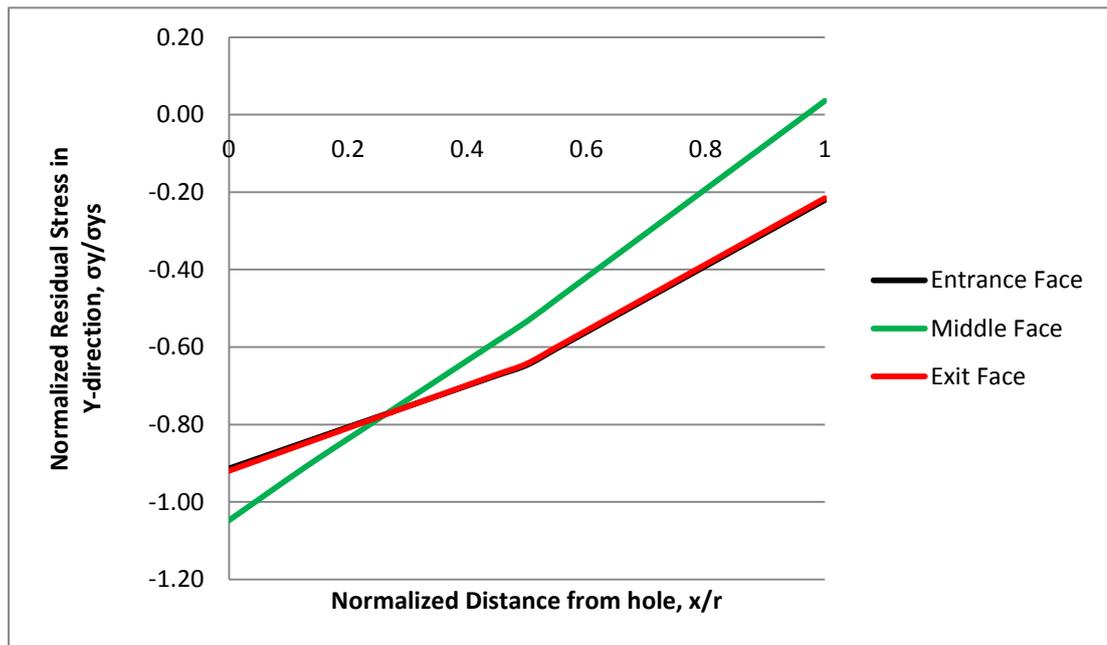
Figure 4.23: Residual stresses at different through thickness position (t = 6 mm)

From Figure 4.23, the compressive residual stresses on the entrance face and the exit face are lower than the stresses on the mid-thickness. Low compressive residual stresses on entrance face and the exit faces were caused by the shear stress from the axial movement of the mandrel (applied pressure). Furthermore, for 6 mm plate thickness, the compressive residual stresses on the entrance face are close to those at

the exit face. These show that, a homogeneous distribution of compressive residual stresses is obtained for 6 mm plate thickness.
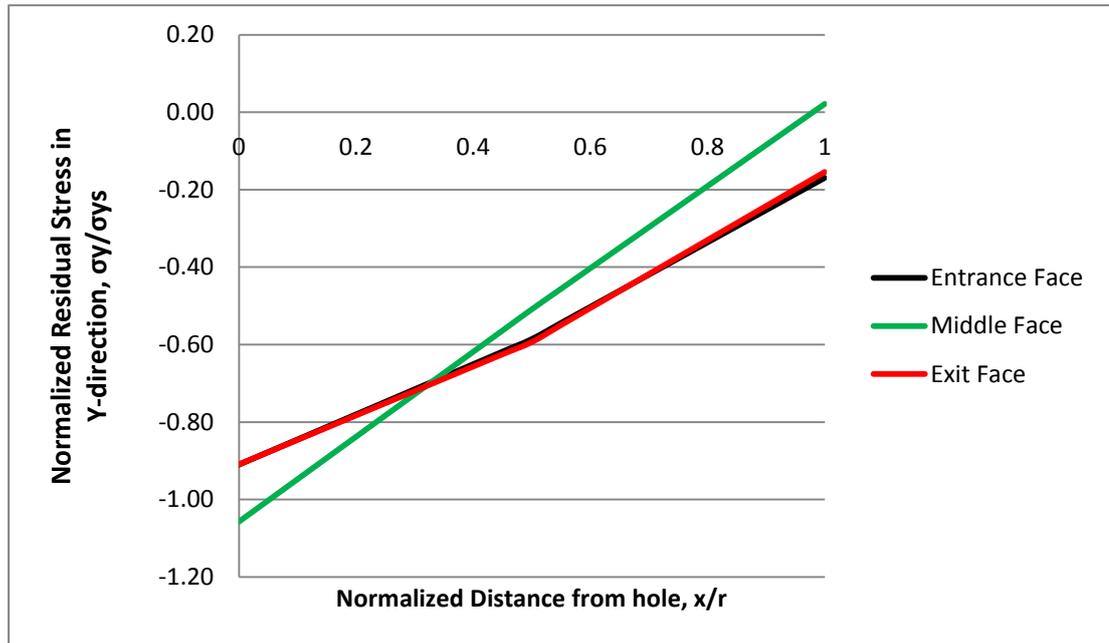
Figure 4.24: Residual stresses at different through thickness position ($t = 12$ mm)
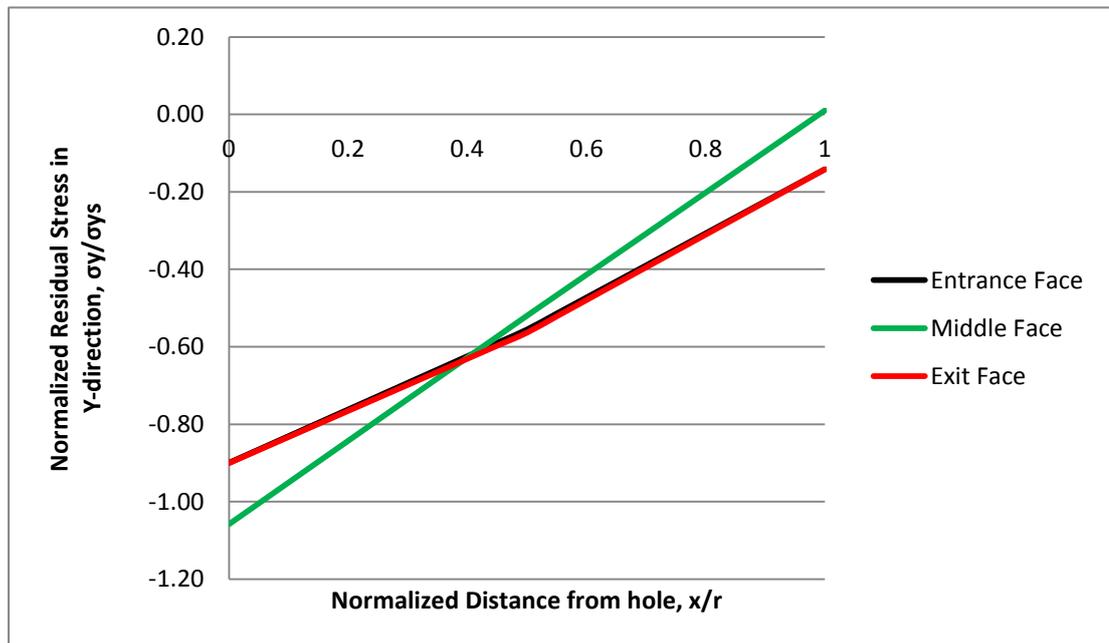
Figure 4.25: Residual stresses at different through thickness position ($t = 18$ mm)

Based on Figure 4.23, Figure 4.24 and Figure 4.25, we can see that the trend distribution of the compressive residual stresses at entrance, middle face and exit is the same. Although the trend distribution looks the same, the values for compressive residual stresses for different thickness were different.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1   CONCLUSION

Two-dimensional and three-dimensional Finite Element Analysis (FEA) simulations of cold expansion for different adjacent holes distance were carried out using ANSYS software and material model used was aluminium alloy 7075-T6. This FEA was carried out to determine the effect of the adjacent holes distance to the residual stresses. The simulation process was performed at 4% cold expansion ratio (radius increment of 0.125mm) and the distance of the adjacent holes were varied, $c/d = 2$, $c/d = 4$ and $c/d = 6$.

From the results of the simulation, we can conclude that when the distance between the holes is increasing, the residual stresses will decrease until the distance between the holes is more than six times of the hole diameter, which is $c/d > 6$. Furthermore, when $c/d = 2$, the residual stresses is the highest. So, we can conclude that in this project, the $c/d = 2$ is the critical distance between the hole.

The effect of different plate thickness in the residual stress distribution was also investigated. We can conclude that the compressive residual stresses increase as the plate thickness increase. Moreover, the different through thickness position was also being investigated and the result showed that the compressive residual stresses on the entrance face and the exit face are lower than the stresses on the mid-thickness.

It can be concluded that the adjacent holes and the plate thickness does effect the distribution of the compressive residual stresses. Cold expansion method under the influence of different thickness is a useful method to increase the fatigue life of a material.

5.2   RECOMMENDATION

The use of the split sleeve in Fatigue Technology Inc. (FTI) is to avoid material tearing and to protect the hole from strong friction. It is said that the opening of the split in the sleeve influences the compressive residual stresses distribution around the hole edges. Furthermore, the split sleeve causes non-symmetric stress distribution because of the lack of pressure on the plate at the opening of the split sleeve. Consequently, low residual stresses occurred in the opening zone and the zone of low residual stresses is called the pip location. So, for future study, the effect of the split sleeve should be studied to verify this theory.

Methods of expansion also effect the compressive residual stresses distribution. There is other method other than Fatigue Technology Incorporated (FTI) that is being used to cold expand fastener holes by using a sleeveless roller burnishing (RB) technique. When a hole is cold expanded by the RB process, extensive plastic flow in the through-thickness direction makes the material at the hole edge to behave in the plane-stress condition and therefore, resulting in lesser compressive residual stresses distribution and close to the hole edge.

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