Influence of Combined Loading Effect on Plate with Hole Analysis by Finite Element Method

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Abstract— ***The Finite Element (FE) analysis of infinite plate is made for alloy steel and super alloy material. The plate is weakened by a cylindrical circular hole and oblique hole of radius r with oblique angle α is considered. The applied load should be remotely means away from local hole region, the load is considered as uniform tensile load, in the direction parallel to the plane of the plate, bending and combined load. The numerical technique Finite Element Method (FEM) is used here for analysis. A different component, material with different obliquity was used for engineering stress analysis. The work covers plate hole diameter-width (d/w) ratio is 0.1 for first prediction of stress analysis. These components having cylindrical circular & oblique hole is considered for present study. The long twisted blade of gas turbine blade will be treated as infinite plate with oblique/ cooling holes constituting a geometrically complex and three- dimensional body that is subjected to the action of mechanical load such as mainly centrifugal force, Stress concentration and stress distribution around hole is a major challenging field in research also they are highly specialized applications in aerospace, marine and defence. When the circumferential stresses along the boundary of the hole edge are induces, the effect of localized stress field which have been successfully analysed to predict maximum stresses and their stress concentration a hole edge point. The stresses around discontinuity in geometry in mechanical engineering field are a main area for designers to design a components and structures for their integrity. The results of FEA technique are in good agreement with experimental values obtained by previous authors on the basis of available net area of cross section, thus providing a means of analysing more effectively and realistic Gas turbine blade, aerofoil using FEA software NX-NASTRAN-NX, V8.2.***

Keywords— *Aerospace Components, Finite Element Method (FEA), Infinite Plate, Oblique angle, Stress Concentration, Stress Analysis,.*

1. Introduction

The three-dimensional elastic stress analysis with discontinuous in geometry is very important for academicians and researchers for safe-life of components/structures, most analytical studies were based on two-dimensional linear theory of homogeneous and isotropic materials. To predict and to determine stress concentration factors is of practical importance for many engineered components and structures because geometric discontinuities are frequently the site of failure, localized stress around discontinuities in geometry such as holes, shoulders, and grooves cannot be predicted using elementary stress formula. The concentration of stress resulting from these abrupt transitions is frequently too high to be attributed solely to the decrease in net cross sectional area. Stress concentration factors, often determined experimentally or computationally. The main objective of the work is to analyse the stress field/distribution around hole in a series of thick, wide, flat plate. The infinite plate with oblique hole subjected to unaxial tensile, bending and combined load. The work covers, circular cylindrical hole with different obliquity. The results for unaxial tensile, and bending have been compared with those determined using mathematical calculations in order to verify the Finite Element(FE) results. The force lines/stress that cause of highly localized or accumulation of stress near the change of cross section or clustering of stress lines at the point of discontinuity is termed as stress concentration. The predication of stresses can be determined by taking ratio of the maximum stress to the normal stress (σ_{Max}/ (σ_{Nor}) is designated as stress concentration factor (k_t). The stress concentration factor solely depends on the geometry, mode of loading and type of material selected. The stress concentration factors are often determined computationally or experimentally.

An skew/oblique hole is one whose axis is not normal to the infinite plate which it penetrates. This approach gives true stress-concentration effects. Here it may not be assumed that a lower Stress concentration factor(SCF) will necessarily give a lower maximum stress. This is because the nominal stress based on the net area will vary as geometrical parameters' of the discontinuity are changed, whereas the nominal stress based on gross area will remain constant. At the intersection with a plane surface an oblique cylindrical hole gives rise to an elliptical trace and produces an acute angled edge. Such type of holes is commonly found at interpenetrations in pressure vessels and as lacing-wire passages in turbine blades. In any ideal, linear elastic component, the Geometrical configuration of these holes can be circular, elliptical or it may be a square depending on design requirements, the stress distribution are of great importance in the field of mechanical engineering like academinations, designers and researchers.

For consideration, in the case of complex geometry with oblique/cooling holes it is very difficult to predict stresses around oblique hole. The most of stress analysis has been carried out using photoelasticity and stress-frozen method, it is costly and time consuming. Today with the advances in digital computer technology and available analysis software we can use more effectively for stress analysis around notches. The Complex At the intersection with a plane surface, a skewed cylindrical hole gives rise to an elliptical trace and produces an acute-angled edge which, for large angles of obliquity. Theoretical study of the elastic-stress field in a plate with a skew hole has been given by Authors A.Tafreshi. & T.E. Thorpe. In this work oblique holes with various obliquity.

1.1 Notations

The required following symbols & notations were considered for infinite plate with oblique hole.

- w Width of the infinite plate(mm)
- t Thickness of the infinite plate(mm)
- l Length of the infinite plate(mm)
- d Cylindrical hole diameter(mm)
- θ Angular coordinate in plane normal to hole axis(degree)
- ⌀ Angle between major axis of elliptical intersection of Hole In plane of plate and direction of applied uniaxial range 0-90° (degree)
- α Oblique Angle between hole axis and plate normal range 0-90°
- a Semi major axis of the ellipse(in the x-direction, in mm)
- b Semi minor axis of the ellipse(in the y-direction, in mm) distances from hole to edge of plate and end of plate (mm)
- dl Displacement(mm)
- P Remotely applied uniform tensile load (N)
- E Young's modulus(N/mm^2)
- ρ Density of material (Kg/mm^3)
- μ Poison's Ratio

A typical application of oblique/cooling hole on gas turbine blade with rotor as shown in figure1.

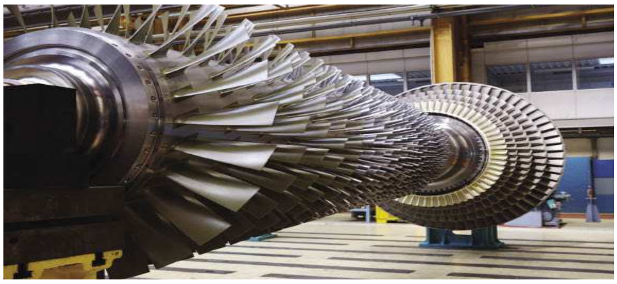


Figure 1: Typical Gas turbine blade arrangement

The cross section of infinite plate with cylindrical oblique hole for different obliquity, geometry and notations as shown in figure 2.

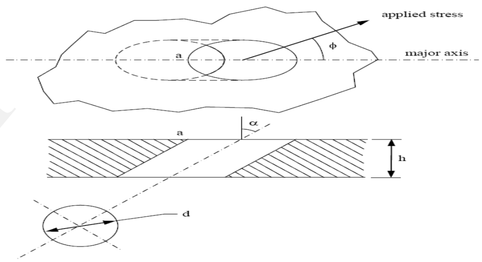


Fig. 2: Oblique hole geometry and Notation.

2. Methodology Used: Finite Element Method (FEM)

2.1 Models Analysed

The infinite plate with oblique hole is considered for analysis, the thickness is 6mm, and width is 50mm and total length of 400mm is considered for analysis. The hole diameter is 5mm and two angle of obliquity for two different materials are taken. All the three different loading system is applied in the direction of the length of the specimen. In some consideration as infinite plate for a width and length of plate such that the effects of the plate edges and boundary conditions on the hole stress were negligible. As a result, infinite plate conditions were attained in the region of the hole (w/d=10 or greater then 10). These same geometrical parameters of plate are considered for present analysed model work covers a practical useful of hole variables (**α,** ⌀ , w/d). Here the component is considered to be infinite plate with the following equation:

$$\frac{w}{d} \geq 10$$

Component. No.	Oblique Hole Angle (α)	Ratio d/w
1	0°	0.1
2	15°	0.1
3	30°	0.1

w = Plate width(mm), d = Hole diameter (mm)

Below figure 3 show numerical type of methodology is used for engineering stress analysis, the schematic flow of Finite Element (FE) analysis.

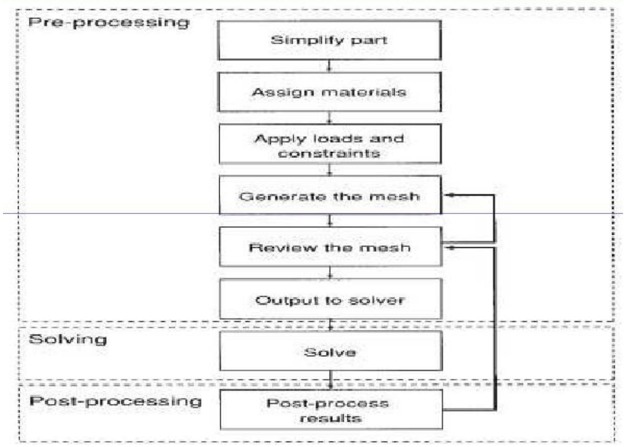


Fig. 3: Methodology used for Finite Element Analysis (FEA)

Finite element method is a powerful technique used for analysis of elastic stresses around cylindrical oblique hole. Here, a general method of Finite Element Analysis (FEA) is used. The results of stress contours for plain stress condition are obtained, and they are very in good agreement with experimental results. This helps us to predict the distribution of stresses around oblique hole in mechanical engineering field.

2.2 Geometry & Oblique Hole Details

The infinite plate with geometrical details 300(l) x50(w) x6(t) mm with hole diameter 5mm were considered for study and analysis of stress around oblique hole as shown in figure 4.

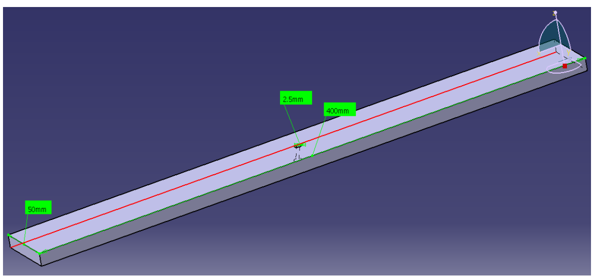


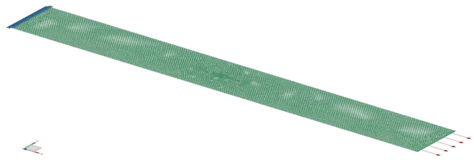
Fig. 4: Geometrical modelling of the component

The circular cylindrical hole axis is normal to the surface of the component and cylindrical oblique hole axis inclined some angle with the surface of component, details as given in table1.

Table 1: Oblique hole details

2.3 Finite Element (FE) Mesh Generation

The following geometrical modelling is used



commercial package CATIA V5. Finite Element(FE) model, discritization, applying boundary conditions and material properties have to be followed by pre- and post-processing of the Finite Element (FE) using MSC/PATRAN and NX-NASTRAN NX 8.2. For better accuracy, CTETRA Hexahedral element was used in FE model here. MSC/NASTRAN – NX V 8.2 is used as analysis tool to predict the stresses around holes. Finite Elements (FE), their mesh generators use an automatic technique that checks element failure and takes care of convergence values. Work can be extended for different hole obliquity with same thickness and ratios (d/w=0.1). Number of elements resulted from the automatic meshing of the MSC/PATRAN software package which minimized element distortion hole, which are not uniformly distributed. To save computational time and cost, the meshes were refined in the critical area (around the oblique hole), where the stresses had a rapid variation until convergence was achieved. Large size elements were used elsewhere. None of the elements were excessively elongated or distorted. In this way the number of elements was optimized to give accuracy at a reasonable cost. The angles α and were important parameters in the number of elements required for the models. For more or high values of α and the number of required elements was very high. The computational analysis is carried out using NASTRAN -NX V8.2. Finite Element (FE) model as shown in figure 5.

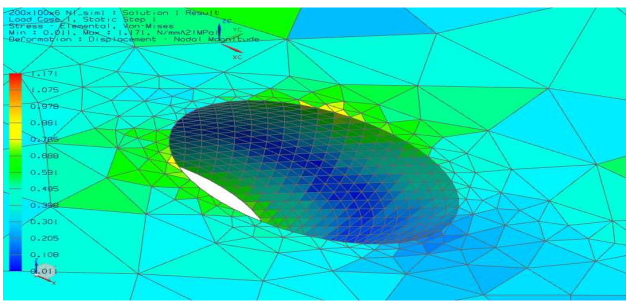


Figure. 5: Typical Finite element mesh for flat infinite plate with oblique hole.

The Finite Element (FE) model details of infinite plate

Material Name	**Modulus of Elasticity (E) N/mm^2**	**Poisson's Ratio (μ)**	**Density (ρ) Kg/mm^3**
Alloy steel (Low Carbon Steel)	2 X 105	0.3	7.85 X 10-6
Super alloy (Nickel)	1.9 X 105	0.305	8.908 X 10-3

used for analysis as given in table 2. CTETRA 2nd-order hexahedral element is preferred for more stiffness, accuracy & properties.

Table 2: Finite Element (FE) model details.

2.4 Boundary Conditions

Type of constrains & loading considered for stress analysis of infinite plate with circular & oblique hole subjected to uniform tension load 500N and bending load 500 N-mm as shown in figure 6 and figure 7.

Fig. 6 and fig. 7: Different boundary conditions (Loading and Constraints) for flat infinite plate with oblique hole.

2.5 Material & Properties used

Stress analysis is carried out for different materials. Linear elastic stresses around hole for low carbon steel, Nickel and their properties were considered for analysis around hole local region. For study & stress analysis following material properties is considered as shown in table 3.

Table 3: Material Properties of carbon alloy steel & superalloy steel

Finite Element(FE) analysis solver MSC/NASTRAN – NX V8.2 is used to solve the pre-processor data file. There is a good correlation between the FEA and experimental results from different earlier worked authors. The results are presented in post- processor in the form of stress contour/ simulation and tabular form.

3. Results and Discussion

3.1 Finite Element Analysis (FEA) Results

The distribution of stress contours around holes for different oblique angles subjected to remotely applied uniform tensile and bending load as shown in figure 8 to figure 16. The maximum induced stress present at hole edge surface towards width wise and gradually decreases to minimum along horizontal. Also it is observed maximum stress at hole edge changes as oblique angle increases.

Sl. No	**Oblique Hole Angle (A)**	**Finite Elements**	**Elements Sizing**	**No.of Nodes**	**No. of Elements**
1	0	2nd-order CTETRA	1.5	132563	28345
2	15		1.0	864472	170725
3	30		1.75	123652	27643

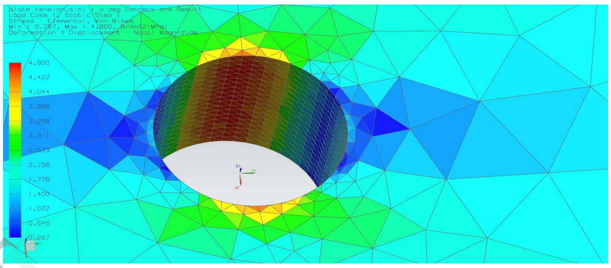


Figure 8: Typical view of stress contour around 0^0 normal hole for steel in tension.

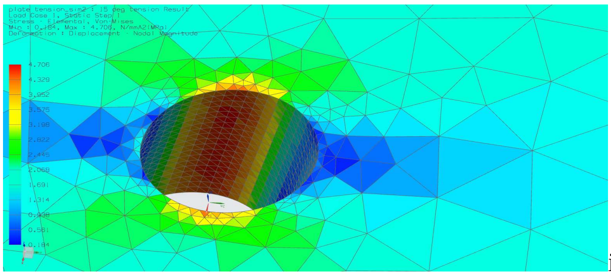


Figure 9: Typical view of stress contour around 15^0 Oblique hole for steel in tension.

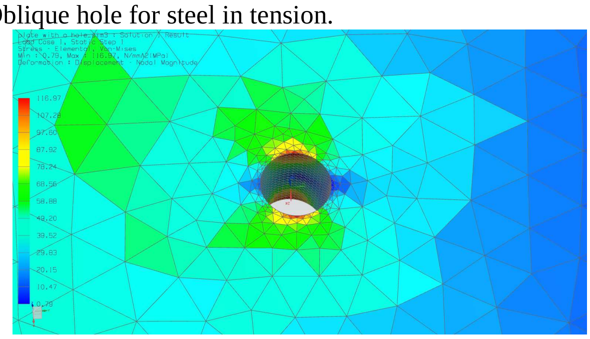


Figure 10: Typical view of stress contour around 30^0 Oblique hole for steel in tension.

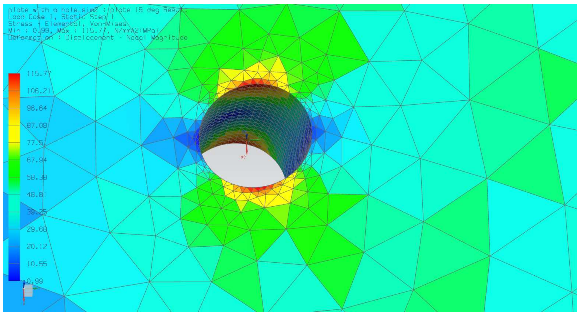


Figure 11:Typical view of stress contour around 0^0 normal hole steel in bending.

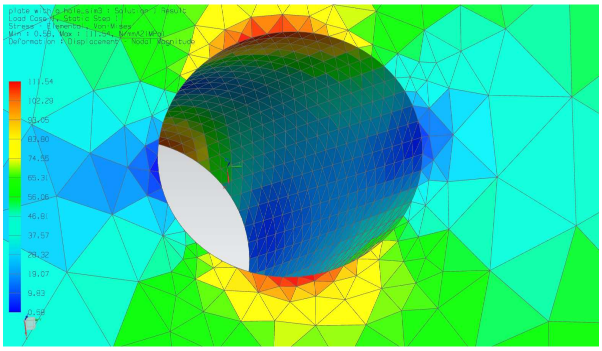


Figure 12:Typical view of stress contour around 15^0 Oblique hole steel in bending.

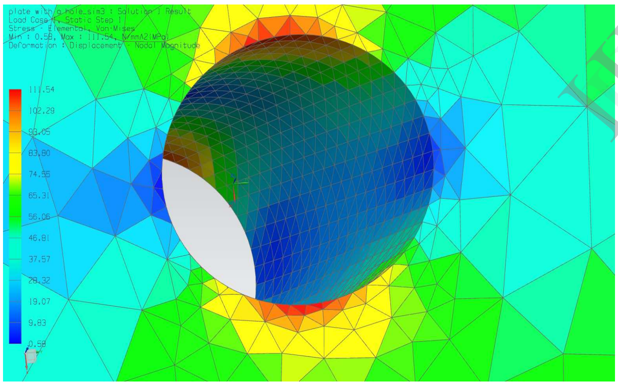


Figure 13:Typical view of stress contour around 30^0 Oblique hole steelin bending.

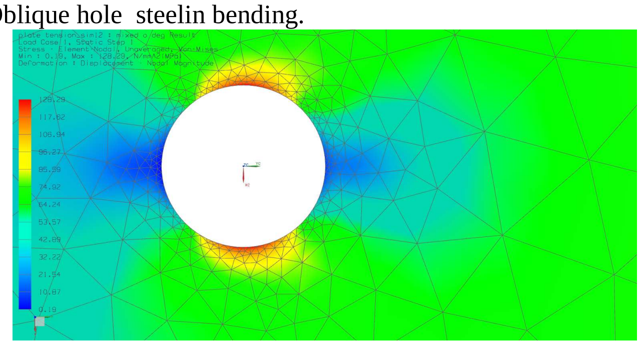


Figure 14:Typical view of stress contour around 0^0 normal hole in combined (Tension and Bending) load.

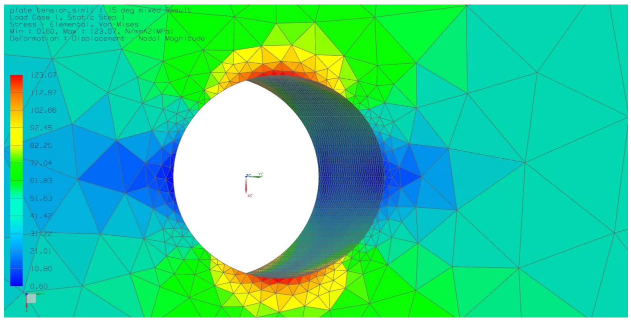


Figure 15:Typical view of stress contour around 15^0 oblique hole in combined (Tension and Bending) load.

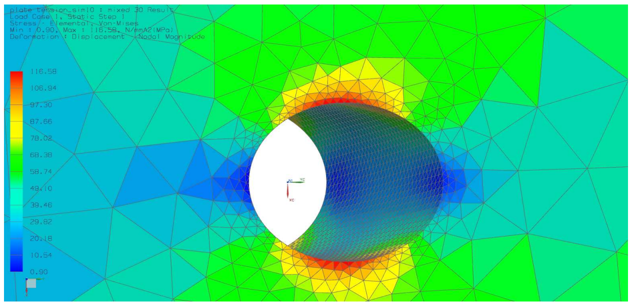


Figure 16:Typical view of stress contour around 30^0 oblique hole in combined (Tension and Bending) load.

The stress analysis around holes was obtained for different obliquity and results are shown in plots figure 17 to 20 for alloy steel in tension. Also, the results are shown for alloys steel from figure 21 to 24 for bending load and figure 25 shows alloy steel for combined load. The influence of loading effect on alloy steel and superalloy material for different obliquity when they are subjected to uniform tensile, bending and combined loading. Results shows very good along circular and oblique hole edge.

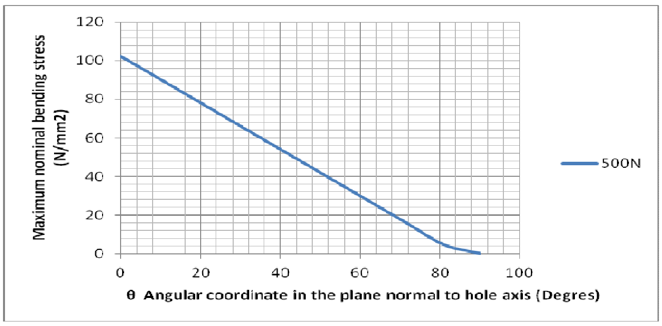


Figure17 : Shows plots of maximum nominal stress Vs. angular coordinates for steel in tension 500N **($\alpha=0^0$)**

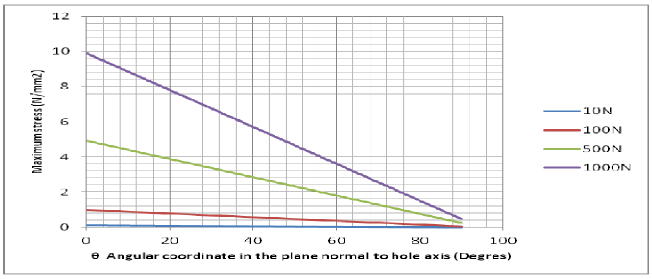


Figure 18 : Shows plots of maximum nominal stress Vs. angular coordinates for steel in tension. **(α=0^0)**

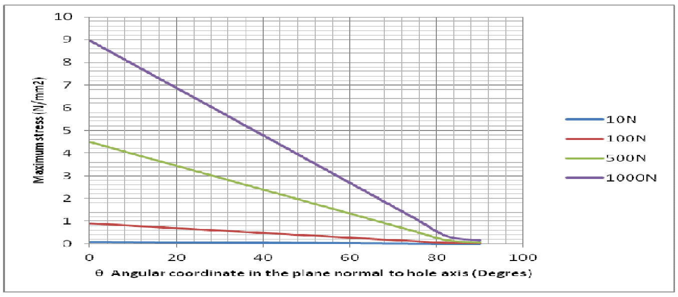


Figure 19 : Shows plots of maximum nominal stress Vs. angular coordinates for steel in tension. **(α=15^0)**

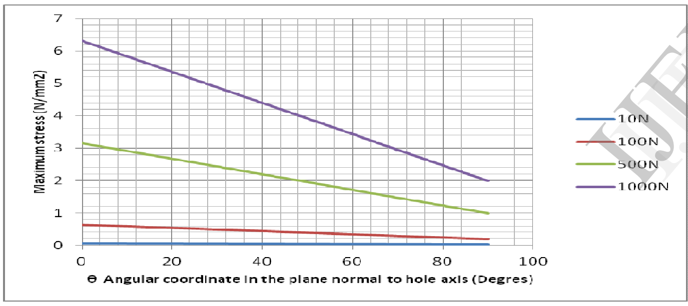


Figure 20 : Shows plots of maximum nominal stress Vs. angular coordinates for steel in tension. **(α=30^0)**

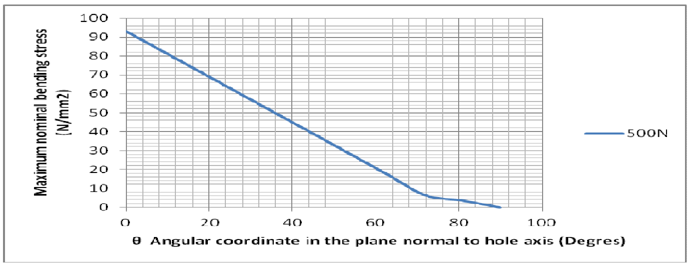


Figure 21 : Shows plots of maximum nominal bending stress Vs. angular coordinates for steel in bending at 500N **(α=0^0)**

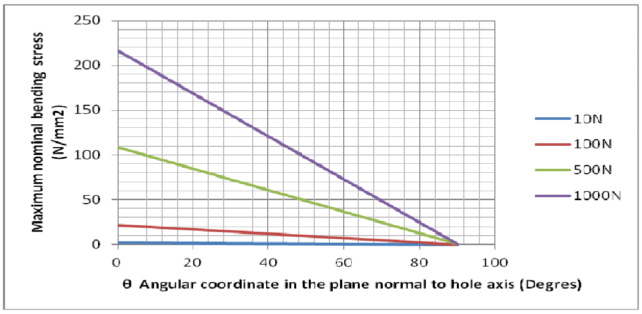


Figure 22: Shows plots of maximum nominal bending stress Vs. angular coordinates for steel in bending. **(α=0^0)**

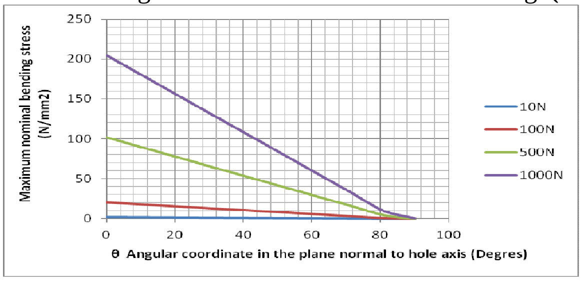


Figure 23: Shows plots of maximum nominal bending stress Vs. angular coordinates for steel in bending. **(α=15^0)** load.

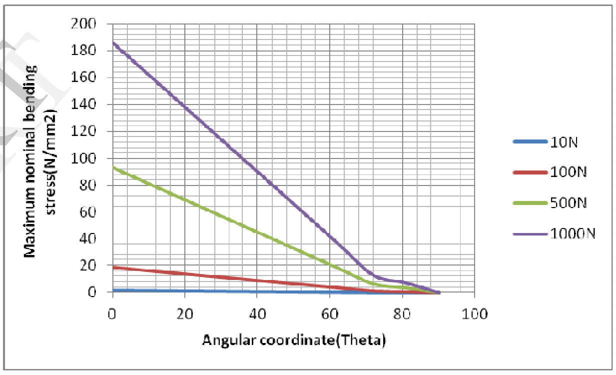


Figure 24: Shows plots of maximum nominal bending stress Vs. angular coordinates for steel in bending. **(α=30^0)**

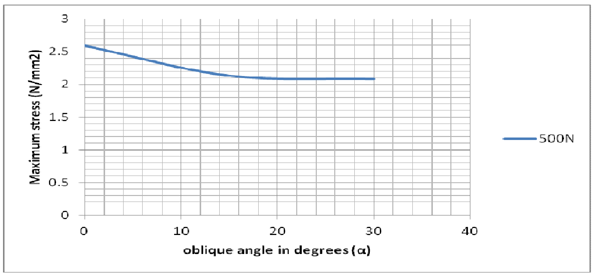


Figure 25: Typical plot of combined load 500N for alloy steel.

The stress analysis around holes was obtained for different obliquity and results are shown in plots figure 25 to 28 for super alloy in tension. Also, the results are shown for super alloys from figure 29 to 33 for bending load and figure 34 shows alloy steel for combined load.

The Finite Element analysis software NX- Nastran V8.2 is used.

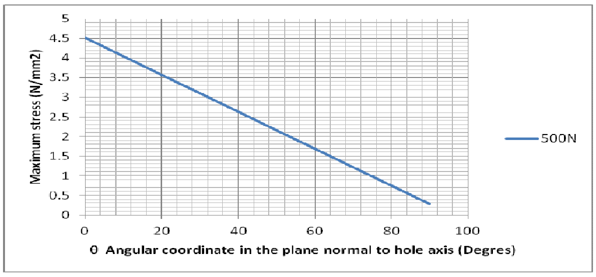


Figure 26; Shows Max. stress Vs. angular coordinate for super alloy Nickel in tension 500N.

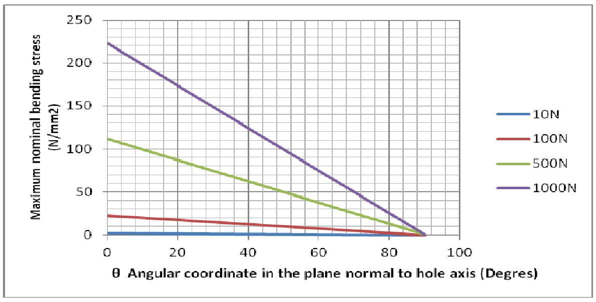


Figure 27; Shows Max. stress Vs. angular coordinate for super alloy Nickel in tension **(α= 0^0).**

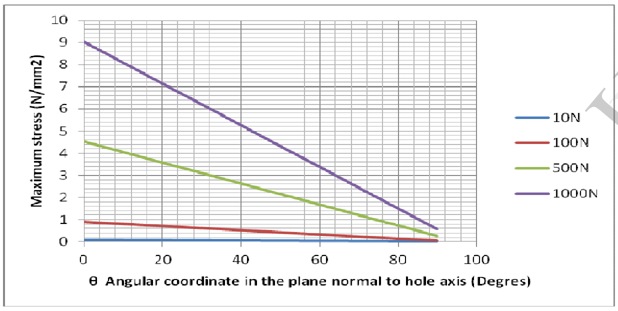


Figure 28; Shows Max. stress Vs. angular coordinate for super alloy Nickel load **(α=15^0).**

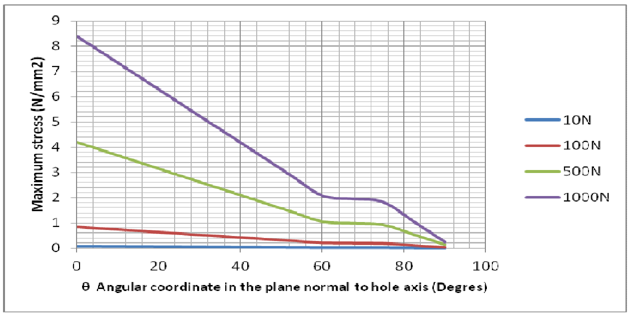


Figure 29; Shows Max. stress Vs. angular coordinate for super alloy Nickel in tension load **(α=30^0).**

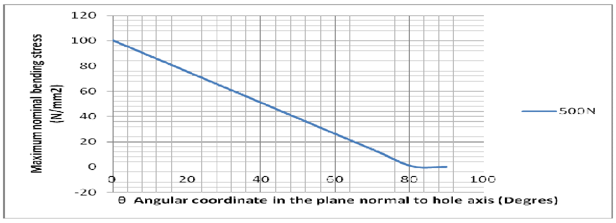


Figure 30: Shows plots of maximum nominal bending stress Vs. angular coordinates for nickel in bending at 500N **(α**=0^0 **)**

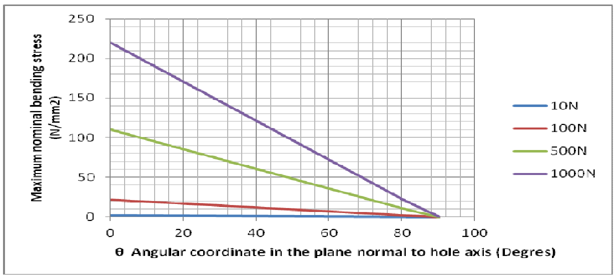


Figure 31: Shows plots of maximum nominal bending stress Vs. angular coordinates for nickel in bending. **(α= 0^0).**

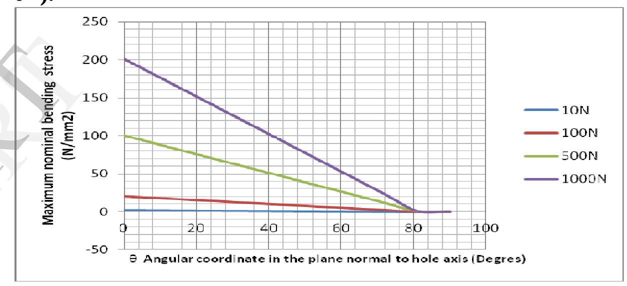


Figure 32: Shows plots of maximum nominal bending stress Vs. angular coordinates for nickel in bending. **(α= 15^0).**

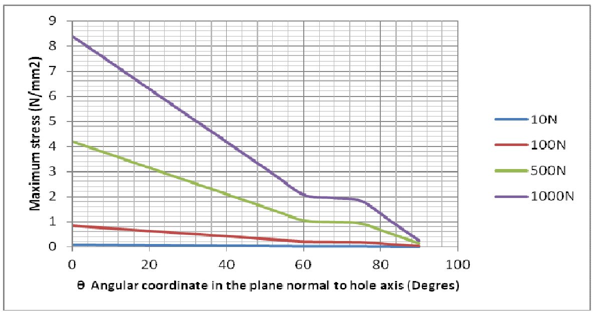


Figure 33: Shows plots of maximum nominal bending stress Vs. angular coordinates for nickel in bending. **(α= 30^0).**

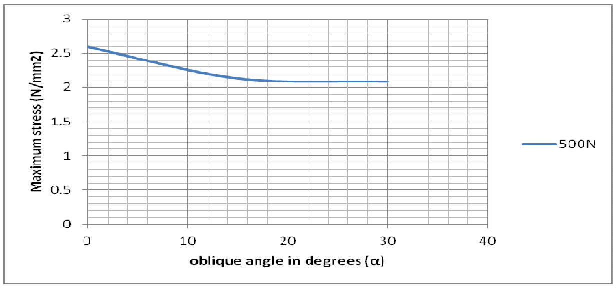


Figure 34: Shows plots of maximum nominal bending stress Vs. angular coordinates for combined of alloy steel and nickel in bending. **($\alpha = 0^0$).**

Below figure 35 and 38 shows typical overall plots when in tension at angular coordinates is 0 , 15, 30 and 90 degree when alloy steel in tension.

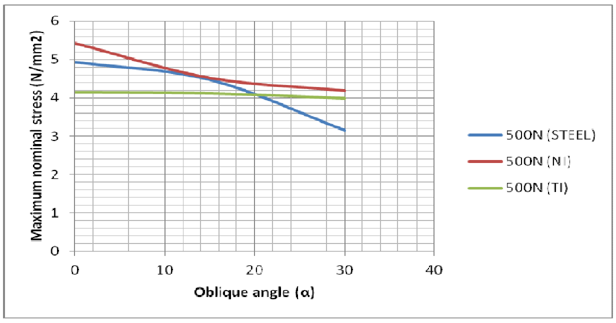


Figure 35: A typical overall mixed plot in tension (Theta=0 deg.)

Figure 36: A typical overall mixed plot in tension (Theta= 15 deg.)

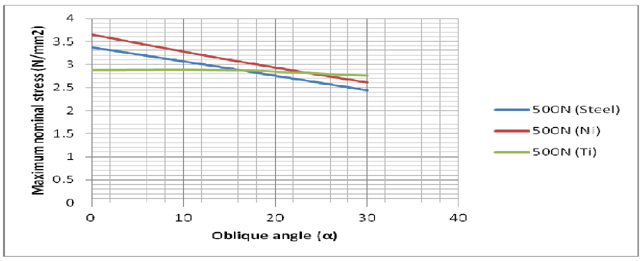


Figure 37: A typical overall mixed plot in tension (Theta= 30 deg.)

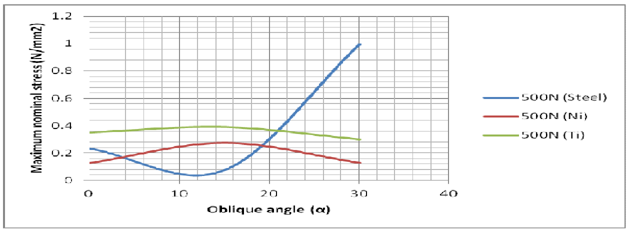


Figure 38: A typical overall mixed plot in tension (Theta= 90 deg.).

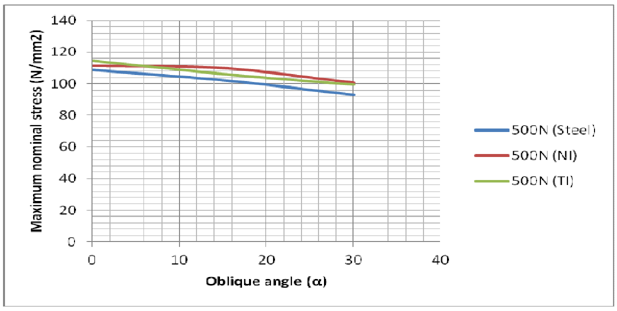


Figure 39: A typical overall mixed plot in bending (Theta= 0 deg.)

The typical variation when maximum bending stress vs. angular coordinnate is 0 and 90 degree with overall mixed plot for bending as shown in figure 39 and 40.

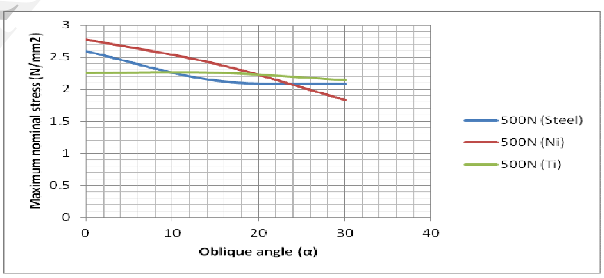


Figure 39: A typical overall mixed plot in bending (Theta= 30 deg.)

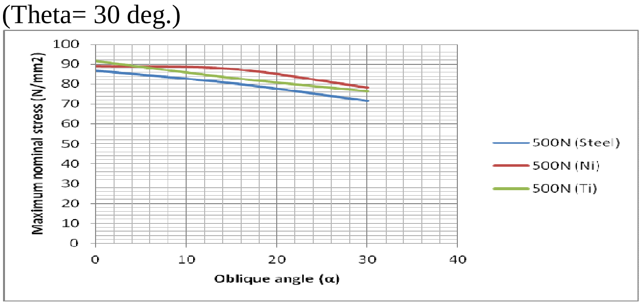


Figure 40: A typical overall mixed plot in bending (Theta= 90 deg.).

The above finding results of both alloy steel material & super alloy Nickel material when infinite plate is subjected to uniform tension, bending and combined load will be considered as plane stress condition & stress analysis is carried out based on that only and it is observed that localized stresses around edges of oblique hole. The above results are also presented in the form plots of angular coordinate 'θ' in the plane normal to hole axis Vs. induced maximum stress by Finite Element(FE) analysis around edges of hole as shown in figure 13 to 14 for alloy steel material and from figure. 15 to 16. For Super alloy material.

The stress contour around oblique hole edge in particular variation of stress field along angular coordinates from $\theta = 0$ to 90^0 is a important study area especially, at $\theta = 0$ & 90^0. The distribution of stress intensity for maximum stress vs. obliquity (α= 0, 15 and 30 deg.) at $\theta = 0$ & 90^0 is shown in figure 17 to 34.

The study & analysis of stress field over angular coordinate of oblique hole edge is presented and shown in figure 39 to figure 40.

● The stress contour with simulation shows very clearly the distribution of stresses around hole edge for circular hole and oblique hole edges is studied successfully, the results shows at edge of hole minimum at angular coordinate ($\theta = 0^0$) and increases substantially till ($\theta = 90^0$) see figure 17 to 24 for both the materials.

● It is observed that in figure 17 to 20 for steel in tension and figure 21 and 24 shows bending stress variation, it is clearly understood changes after 45 degree angular coordinates. of stress contour for steel for circular and oblique angle 15 to 30 degree, stress decreases as angular coordinate increases.

● As maximum stress decreases with angular coordinate also (θ to 90^0) as shown in figure 17 to 24 for alloy steel and aerospace nickel material as shown in figure 25 to fig 33, the distribution of stresses from up to ($\theta = 60$ to 75^0) is almost constant, further, decrease as well as varies considerably maximum stress till ($\theta = 90^0$) is observed.

● It is also observed & when comparison is made, Maximum stresses with different oblique angles, in super alloy material nickel, the stresses gradually decrease (from $\theta = 0^0$ to 90^0) as shown in figure 39. but in alloy steel is decreases for angular coordinates from 0 deg. to 18 deg. almost after that substantially increases as oblique angle increases till 75 to 90 deg.

● It is with all to be summarized from typical plots fig. 39 and fig. 40 in alloy steel and aerospace materials it is clearly observed at ($\theta = 0^0$) there is almost same amount of stresses for oblique angle ($\alpha=0^0$), maximum stress changes is more for alloy steel & less in nickel and titanium material. In alloy steel maximum induced stress gradually decreases up to 0 to 20 degree oblique angle & keeps on increases further ($\alpha=60^0$). As we seen in nickel and titanium maximum stress increases ($\alpha=25^0$) & after that slowly decreases over the obliquity.

● By observation from figure 21 to 24 for steel in bending, it is clearly observed that, distribution of bending stress around hole and oblique hole. The variation of bending stress is maximum at outer surface of the fibre at discontinuity in geometry an d gradually decreases nearer to neutral axis. It is also observed that maximum bending stress for aerospace materials at angular coordinate 0 degree and decreases at angular coordinate 90 degree. Thus, elastic stress analysis is carried out due to bending stresses, which is help full for prediction of stresses around hole for safe design of components.

Also, we can concluding from typical plot from figure 39 and figure 40 in alloy steel at ($\theta = 90^0$), it is vice-versa of figure 17, for oblique angle ($\alpha=0^0$), maximum stress is less in alloy steel & more in nickel material. As oblique angle increases, the stress slowly decreases in alloy steel up to ($\alpha=15^0$) & further decreases some what more till ($\alpha=30^0$) as compared to superalloy nickel material.

Conclusions

A study and analysis with systematic approach is carried out for analysis of engineering stress around notch type of circular and oblique hole. By study and analysis of series of thick flat plate for regular circular and oblique hole is carried out successfully for both alloy steel and aerospace material. It is observed from analysis results and their distribution of localized elastic stresses is very important for safe- life design in mechanical engineering components and structures, also it is major challenging field in designing of components before failure or yielding of component. The work is successively analyzed for infinite plate subjected to uniform tensile, bending and even combined loading for different obliquity. The experimental results show that the maximum stress ratio increases with increase of angle of obliquity. Also the results obtained can be applied to the plates with a ratio of hole diameter to width of the plate. As oblique angle increases, the distribution of stress slowly decreases in alloy steel up to angular coordinate ($\theta = 0^0$ to 90^0) & further increases some what more till ($\theta = 80^0$) as compared to superalloy and nickel material. Finally, it can be concluded that alloy steel material are more reliable in general engineering applications. Thus, a study of elastic stress distribution around discontinuity in geometry is important in general and aerospace components for safe- life for integrity in design.

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