Effects of Bolt Misalignment on Stress Around Plate Hole

Wenguang Liu and Weiyan Lin

Abstract In this article, a numerical method is used to investigate the effects of bolt misalignment on the stress distribution around plate hole. Firstly, a bolted joint specimen having two holed plates and one bolt was designed. Subsequently, a three-dimensional parametrical finite element model of the bolted joint plate was developed by using Python language and Abaqus package. Thereafter, the effects of bolt misalignment on the stress distribution around plate hole was analyzed under the fixed pre-tighting force and external lateral load. Results indicate that the stress around plate hole is changed when the center of bolt is misaligned to the center of plate hole. But the stress concentration zone is not influenced by the misalignment of bolt. The peak value of the stress at the point of the edge of plate hole is related to the degree of misalignment of bolt. And the peak value is happened at the position when $\alpha = 90°$. The stress at $\sigma(90°, 3.3, 180°/0°)$ is the smallest one. It is implied that the misalignment of bolt at $(r, 0°/180°)$ is very helpful to reduce the stress peak at the peripheral point when $\alpha = 90°$.

Keywords Bolted joint · Misalignment · Stress distribution · Plate hole

1 Introduction

Since the advent of the first aircraft, the good selection of materials and the optimized design of components are always considered to be the critical issues if the airplane are to be safety. Mechanical joints, especially bolted joints which are widely used in the assembly of the advanced aircrafts, their safe reliability is being a great issue to the structural design of aircraft [1]. Actually, many of airplane crashes

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are caused because of the failure of bolted joints in the forgoing several decades [2]. In the course of working time, the bolted joint structure of aircraft must endure the vibration force frequently, therefore the stress distribution around bolt hole are controlled by many factors [3]. Such as the geometric shape, the size of bolt hole, the material and dimension ratio of plate, and the pre-tighting force of bolt, and so on. Because of stress concentration around the hole, hole of plate is being a potential site of crack initiation. In order to know more things about stress distribution around bolt hole, numerous of studies has been carried out for the effects of different kinds of parameters on dynamic fatigue of bolted joint structures by researchers. For example, the stress around bolt hole of composite joints was examined by Stocchi et al. [4], and the non-uniform stress response along the thickness of composite laminates around the bolt hole was done by Iremana [5]. The use of advanced composite materials has grown up greatly in the aerospace industry. The countersunk bolted joints are also applied in the aircraft skin widespread where aerodynamic efficiency is required. Thus, lots of studies have been carried out in order to determine the failure load, stress distribution and damage of the single-lap countersunk composite joints by Gray et al. [6], Ekh et al. [7] and Liu et al. [8]. Results indicate that the effects of parameters, such as the coefficient of friction, dimension ratio of plate, clearance of bolt shank and hole, and pre-tighting force on the stress around bolt hole is very obvious.

In recent several decade years, through designing of composite structures containing bolt holes and open holes, Ireman [9] found that the bolted joints have higher tensile and fatigue strengths than that of the welded, riveted and also pinned joints. The strength of the riveted and bolted steel constructions was studied by Valtinat et al. [10]. Results display that a considerable increases in the fatigue strengths of bolted joint specimens instead of riveted joint specimens. However, stress concentration around bolt hole due to holes in plate is one of the problem. Meanwhile, a rough surface of plates which is prone to crack initiation and propagation under vibration force might be caused by drilling a hole. During the assembly of a bolted joint plate, the nut must be tightened by using different torque. Under the action of pre-tighting force, the bolt must be stretched axially. As the bolt head and the nut clamp the mechanical parts together under the pre-tighting force, the bolt is in a tension stress status, but the clamped mechanical parts is in a compression stress status [11]. Therefore, the effects of pre-tighting force on tensile strength of composite plates with a bolt hole were investigated by Giannopoulos et al. [12]. It is found that the stress concentration around bolt hole decreases and the tensile and fatigue strengths of the bolted joint plate increases when increases the pre-tighting force. However, an increase in the amounts of pre-tighting force causes the phenomenon of fretting on the surfaces of mating bolted plates which has a negative effects on the fatigue strength, especially when a higher torque is applied to the nut for tightening the bolted joint [13, 14]. Terada [15] and Zhao [16] investigated the effects of pre-tighting force on the bolted joint structure too. The results indicate that fatigue life can be extremely short if the fastener becomes loosen. It is because that the load is transferred by bearing pressure rather than by surface friction of the compressed mating plates.

Currently, although numerous of studies about stress distribution around bolt hole of bolted joint has been done by workers in field of engineering and academia. However, the mechanisms of the influences of bolt assembly on the mechanical behavior of bolted joint are still not revealed. For example, when a bolt is assembled misalignment, the stress around bolt hole under the pre-tighting and external force are not understood yet. Considering that bolt hole is the most probable site of crack initiation, thus studying of the stress concentration around plate hole is a important issue in the bolted joint design [17].

In the present study, in order to investigate the effects of bolt misalignment on the stress distribution around bolt hole subjected to pre-tighting force, a bolted joint structure having two plate and a bolt is employed. A parametrical three dimensional finite element model is built by using Python program and Abaqus package. The stress around plate hole under alignment and misalignment for the bolt and hole are analyzed in the end.

2 Model Description

2.1 Geometry of Specimen

A single lap bolted joint plate is designed in this study. The geometry and size is shown in Fig. 1. The specimen is composed of two plates, one bolt and one nut. Dimensions of each part are given in Table 1.

The diameter of bolt shank is designed as 6 mm. The diameter of bolt hole is designed as 6.6 mm, which is equal to 1.1 times of the diameter of bolt shank. Two main pates are assumed to be made of aluminium alloy with material density $\rho = 2740$ kg/m^3, Young's modulus $E = 71.7$ GPa and Poisson ratio $\nu = 0.33$. Bolt

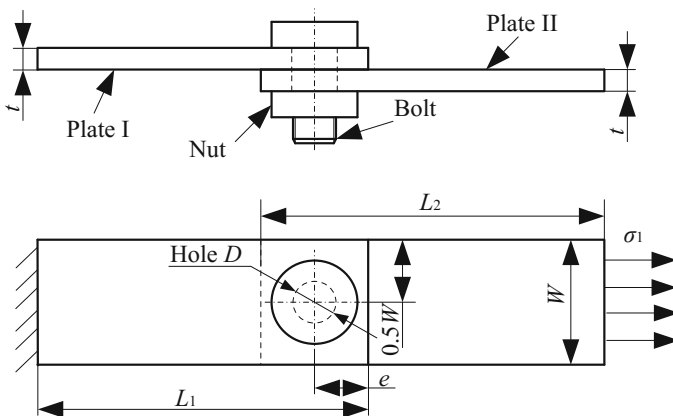**Fig. 1** Geometry of specimen

Table 1 Dimensions of specimen mm

| L_1	L_2	t	D	e	W
150	150	3	6.6	18	18

and nut are assumed to be made of steel with material density $\rho = 7850$ kg/m^3 and Young's modulus $E = 210$ GPa, Poisson ratio $\nu = 0.27$.

During analysis, one end of the single-lap bolted joint plate is assumed to be fixed and another end is assumed to be full free. An uniform force σ_1 with magnitude 0.1 MPa is applied to the free end.

2.2 Coordinate Model of Bolt Hole

It is assumed that there is no interference between the bolt shank and the bolt hole. In order to analysis the impacts of bolt misalignment on stress distribution around bolt hole, a cylindrical coordinate system is created as shown in Fig. 2. Assume that the hole center O_1 of the plate top surface is the original point of coordinate. The x axial is in line with the direction of force σ_1. The direction of force σ_1 is shown in Fig. 1. Suppose that the counterclockwise is the positive direction, and the center O_2 of the bolt could be modeled by a polar coordinate model (r, θ) as shown in Fig. 2. It is assumed that R is the radius of bolt hole. An arbitrary point A on the surface of the bolt hole could be modeled by the coordinate (α, R, h), and the stress

Fig. 2 Coordinate model of bolt hole
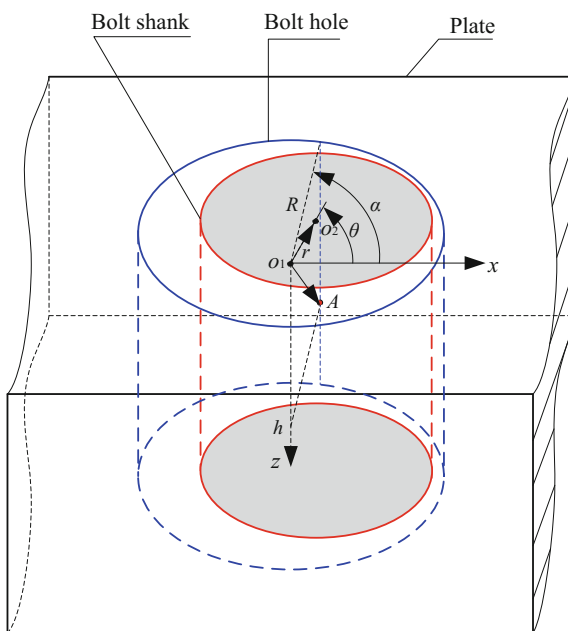
distribution around bolt hole can be modeled by the parameters of coordinate such as α, h, r and θ.

3 Finite Element Model

In order to analysis the stress around bolt hole under the fixed pre-tighting force and external force, a parametric finite element model of the bolted joint plate need to be developed first. Figure 3 is one of effective three dimensional finite element model of the single-lap bolted joint plate which is developed by using Abaqus package and Python program. In Fig. 3a, F is the pre-tighting force acted on the bolt. The dimensions of the bolted joint plate are given in the Table 1. The finite element model is parameterised to investigate the effects of bolt misalignment on the stress distribution around bolt hole when its geometry and finite mesh are sufficiently detailed to reflect the key features of bolts and plates.

The plates and the bolt are all meshed using elements C3D8R. Parameterised partition and seed are used so as to refine the mesh quality of the part near to the hole. Medial axial algorithm is used for mesh of the bolted joint model. A good

(a) bolt

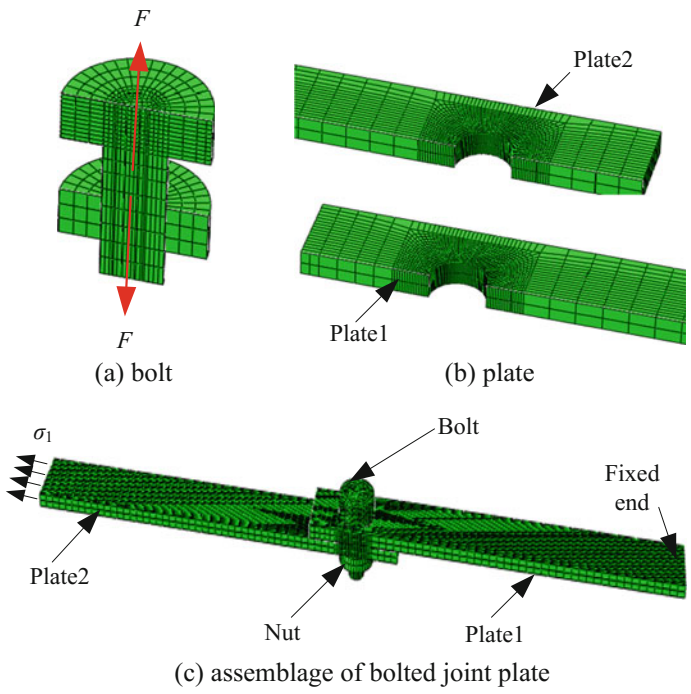(b) plate

(c) assemblage of bolted joint plate

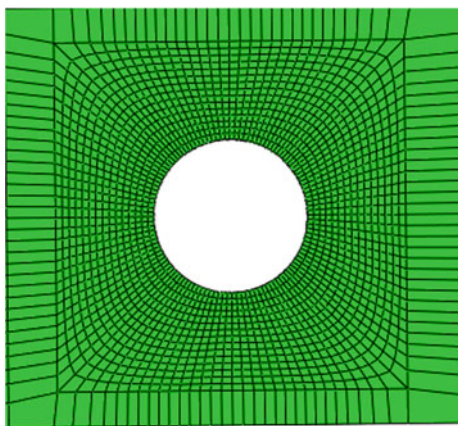Fig. 3 Finite element model of single-lap bolted joint plate

mesh precision has obtained for the FEM model of the bolted joint plate, and the partial view of refining mesh grid near the plate hole is shown as in Fig. 4.

In order to improve the analytical precision of stress around plate hole, the contact surfaces of plate and plate, plate and bolt head, plate and nut are defined as friction contact. And the penalty coefficient of them is defined as 0.15. Because the stresses of the bolt and nut are not the study goal in this article, the bolt and nut is assumed to be a tie connection in this FEM model to reduce computation time.

The typical methods of applying pre-tighting force to the bolt include cooling method, beam element method, bolt length controlling method, and so on. Based on the bolt loading method, the use of cross section and axial line is the sufficient term for applying pretighting force. This method can be easily achieved by using Abaqus software. In the present study, the cross section of bolt is assumed to be fixed, and the axial line position of bolt is assumed to be varied. Thus, the parametric method is used to define the cross section and axial coordinate so as to control the pre-tighting force on the bolt.

Figure 5 investigate the stress distribution of bolts when the bolt is assembled alignment and misalignment. Figure 5a indicates that under a fixed pre-tighting force, the stress of bolt shank is symmetry as the bolt is assembled alignment. But if the bolt and bolt hole is assembled misalignment status, the stress concentration area will be increased at the near part of bolt hole. On the contrary, the zone of stress concentration decreases for the far part of hole as shown in Fig. 5b, c. Results indicate that when the bolt is installed alignment, stress of the bolt is symmetry and it is in a good pretension status. However, when the bolt is assembled misalignment, the zone of stress concentration around bolt hole is increased. But the stress concentration zone on the side of the hole is decreased which has good function on the fatigue performance of the bolt. The fatigue properties of the bolts used in this study are better than those of the plates. Therefore, the effects of misalignment assemblage on the fatigue properties of the bolts are not considered in this paper.
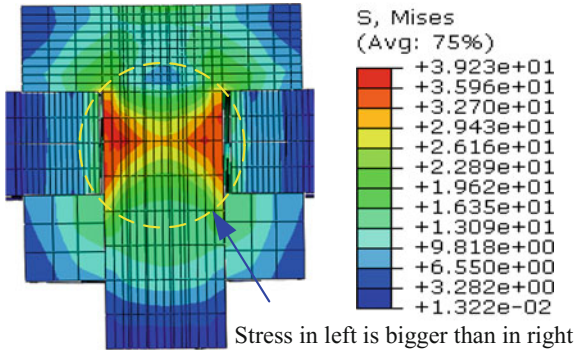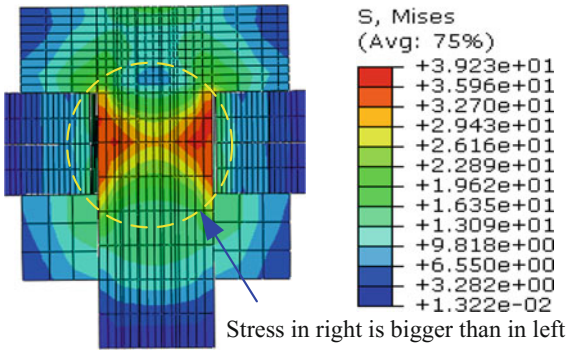

Fig. 4 Refining mesh near bolt hole

Fig. 5 Stress contour of bolt under fixed pre-tighting force

Stress symmetry

(a) $r=0$, $\theta=0$

Stress in left is bigger than in right

(b) $r=0.2$, $\theta=0$

Stress in right is bigger than in left
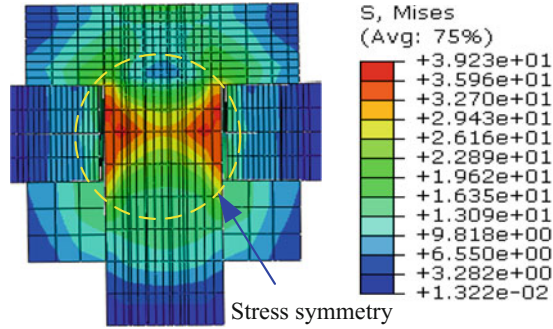
(c) $r=0.2$, $\theta=180$

4　Analytical Method

A parametric finite element model of the single-lap bolted joint plate is developed by using Python program based on the Abaqus package. Through Python transferring and organizing the kernel of Abaqus, the model function of the bolted joint plate with misalignment assemblage is set up to control solving module. And the goal of this job is to improve the analytical efficiency. The detailed analytical flowchart is shown in Fig. 6.

**Fig. 6** Flowchart of stress analysis
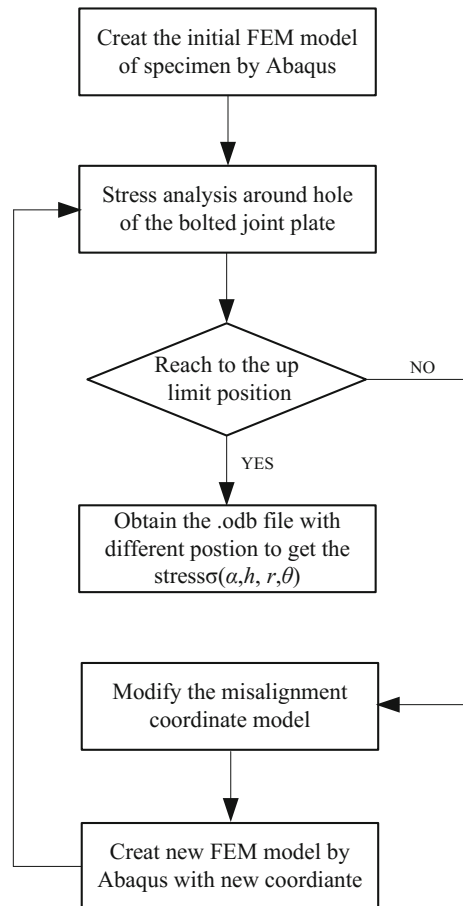
5 Result Analysis

5.1 Alignment of Bolt and Hole

When the bolt and the bolt hole is assembled alignment under the external force σ_1, the stress distribution around plate hole is shown in Fig. 7. The stress of hole reaches to a maximum value when the A is near to $\alpha = 0°$, $90°$, $180°$, $270°$. Figure 8 presented the contour of stress distribution at $\sigma(\alpha, 3.3, 0, 0)$. Results show that the stress distribution around bolt hole is symmetry. Under the action of force σ_1, the material around bolt hole is deformed, and the stress concentration is obviously.

Fig. 7 Stress of A point at the top surface of plate around hole
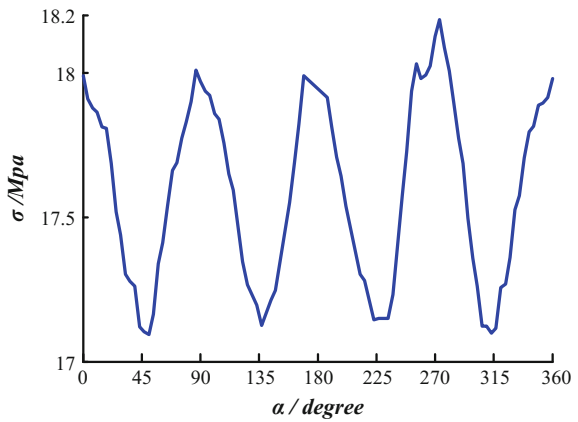
Fig. 8 Contour of stress around hole on the top surface of plate
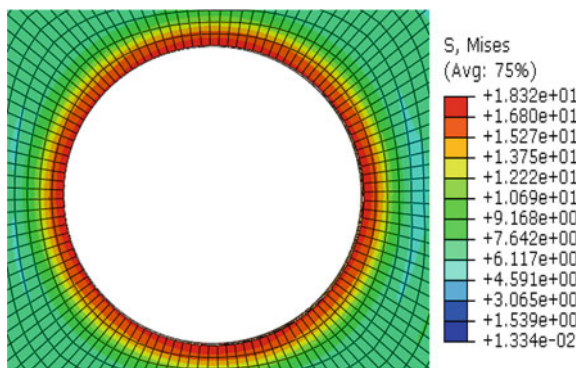
5.2 Misalignment of Bolt and Hole

It is assumed that the eccentric distance $r = 0.1$, 0.2 and 0.3. In order to reduce the calculation time, θ is assumed to be from 0° to 180°. The calculation step is defined as $\Delta\theta = 18°$. The stress around plate hole with position of hole depth equaled to 0, 1.5 and 3 mm is extracted respectively. The relation between the stress around plate hole with the parametric namely (α, r, θ) when $h = 0$ is examined in Fig. 9. And the relation between the stress around plate hole with the parametric namely (α, r, θ) when $h = 1.5$ mm showed in Fig. 10. The relation between the stress around plate hole with the parametric namely (α, r, θ) when $h = 3.0$ mm is studied in Fig. 11. Results indicate that the effects of misalignment of bolt on stress around bolt hole is similar along the depth of bolt hole. Increasing of the depth along hole will decrease the stress component. When $h = 0$, the stress around hole is the highest one. But when $h = 3$ mm, the stress around plate hole is the lowest one.

On the basis of further analysis, the place of stress concentration is not changed because of the misalignment of bolt and hole. The maximum stress were still staying at the position when $\alpha = 0°$, 90°, 180°, 270° for different install condition. But the peak value of stress is increased as the nearness of the center of bolt to the center of hole increase. The reason is because when the eccentric distance of bolt and hole decreases, the contact area of plate and bolt head increase. When the pre-tighting force is applied, the load during increases. But the relation is nonlinear according to the point view of numerical analysis. For example, to the periphery point around bolt hole, $\alpha = 0°$, $h = 0$.
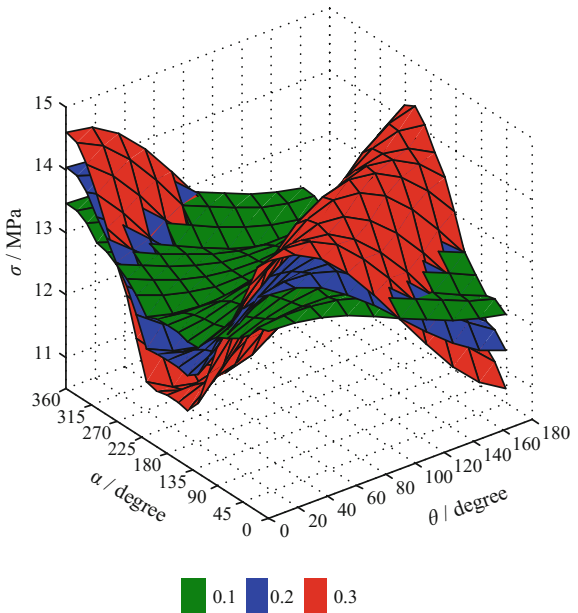

Fig. 9 Stress distribution around hole when $h = 0$
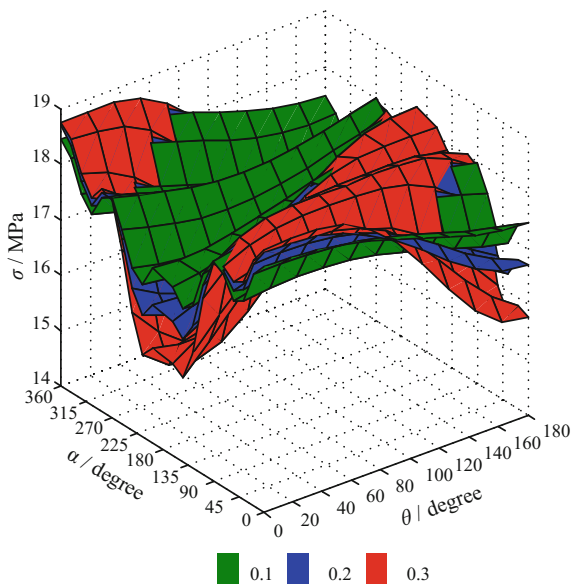
Fig. 10 Stress distribution around hole when $h = 1.5$ mm
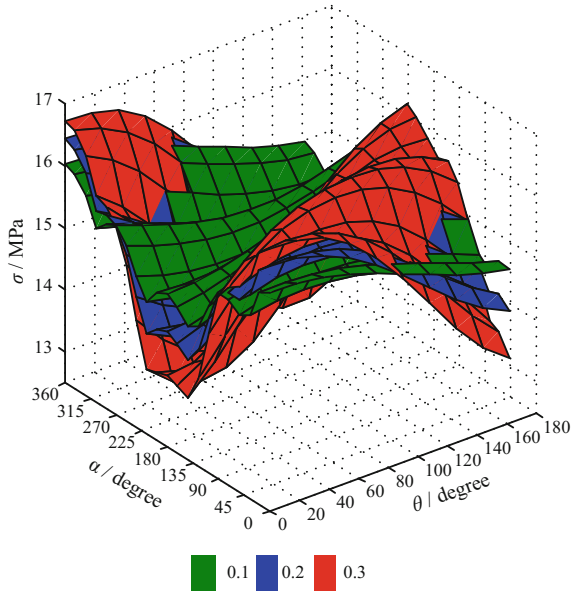
Fig. 11 Stress distribution around hole when $h = 3.0$ mm

When θ is smaller than 90°, then

$$\sigma(0, 0.3, \theta) > \sigma(0, 0.2, \theta) > \sigma(0, 0.1, \theta)$$

When θ is lie in 90°–180°, then

$$\sigma(0, 0.3, \theta) < \sigma(0, 0.2, \theta) < \sigma(0, 0.1, \theta)$$

The stress on the other periphery point is similar to the point as $\alpha = 0°$, but the demarcation point is different.

5.3   Relation of Stress Magnitude and Bolt Location

When external force is applied to the single-lap bolted joint plate, stress concentration is happened near the point as $\alpha = 0°$, 90°, 180°, 270°. But the point as $\alpha = 0°$ and 180° is in compression stress state, and the point as $\alpha = 90°$, 270° is in tensional state. Because tension state is prone to be fatigue, plus the stress distribution of the two point is symmetry, the stress at point $\alpha = 90°$ is extracted. The stress around plate hole varies with bolt center position is investigated in Fig. 12.

Results indicate that peak value of stress is positive related to the eccentric distance of bolt and hole. When θ is from 0° and 180°, the peak value of stress around hole is happened when $\alpha = 90°$. And when $\alpha = 0°$ and $\alpha = 180°$, the stress value is lowest. The stress $\sigma(90°, 3.3, 180°/0°)$ is the smallest that implied that the installation position of bolt at $(r, 0°/180°)$ is very helpful to reduce the stress peak at the peripheral point at $\alpha = 90°$. This discovery is very effective to improve the fatigue performance of the bolted joint plate. It is implied that using of bigger r will increase the fatigue life of the bolted joint plate.

Fig. 12 Relation of stress magnitude with bolt center position
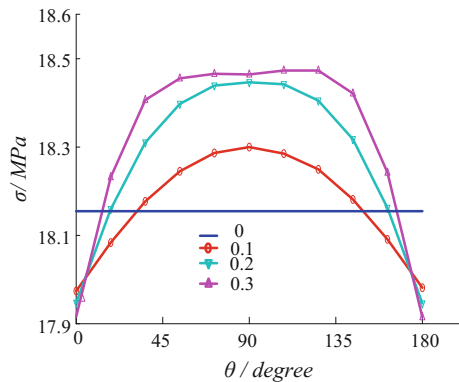
6 Conclusions

(1) When the bolt and bolt hole is alignment, the stress around plate hole is symmetry under fixed pre-tighting force. But if the bolt and bolt hole is misalignment, the zone of stress concentration increase for the edge of hole. But to the far parts of hole, the area of stress concentration is decreased.

(2) If the bolt and hole is alignment, the area of stress concentration around hole when $\alpha = 0°, 90°, 180°, 270°$ is big. And it is distributed symmetry along polar axial.

(3) The stress concentration zone is not varied with the changing of bolt position. And the stress peak value is still stay at the location when $\alpha = 0°, 90°, 180°, 270°$. The peak value of stress is positive relative to the eccentric distance of bolt and hole.

(4) The position of $(r, 0°/180°)$ is very sensitive to reduce the stress peak value when $\alpha = 90°$. This character is very helpful to improve the fatigue performance of the bolted joint plate.

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