3D Finite Element Stress Analysis of Plate with Straight-Shank and Counter-Sunk Circular Riveted Hole with the ANSYS

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Abstract

Lightweight aerospace structures are the major research topic in material engineering. Nowadays, due to expense of experimental testing and greater demands to reduce product lead times, more use is made of numerical modeling using Finite Element Analysis (FEA) as a way of simulating and optimizing a design prior to model. This research proposes comment on the use of the FEA technique for modeling the dynamic behaviour of plate with straight-sunk and counter-sunk riveted hole of the type used in the aerospace industry today. The stress concentration at a hole edge is one of the main causes of the shortening of crack initiation life of a riveted plate when cyclic stress was applied. The corner of the root of the countersink was rounded, and stress concentration at that point was reduced. From an analysis by the finite element method, the value of stress concentration at the improved rivet hole is lower than that of a normal rivet hole. The analysis included a wide range of countersunk depths, plate thicknesses, countersunk angles and plate widths.

Keywords: Fatigue crack, aerospace structure, finite element analysis, dynamic failure.

1. Introduction

The greatest advantage of using riveted joints in a lightweight aerospace structure is that they are stronger and more durable than any other joints such as welded joints. The shapes of the countersunk and countersunk head rivet were improved to extend the fatigue life of a riveted plate which uses countersunk head rivets. Failure of riveted plates in service occurred due to crack initiation from rivet holes.
Mechanical joints used in riveted and bolted joints are common in metallic aircraft structures where they suggest a quick and convenient method of assembling large structures from smaller components. Mechanical joints are still widely used in the construction of current composite structures, especially when load transfer has to be achieved between composite and metallic components.

When two structural components are welded together, only the exterior of the components are joined together. Alternatively, using a rivet joints the two components from the inside. As a result, allowing for a stronger and more durable joint. This is extremely important for aircraft's joints. Riveted joints are also easier to inspect than welded joints. With a welded joint, a portable device must be utilized to inspect the joined components. On the other hand, it takes only a moment without any device a quick visual inspection of a riveted joint to ensure that the two connected components are secure protected.

Rivet joints have been used to connect plates or frames. In particular, countersunk head rivets have been used in airplanes. Failure of riveted plates in service occurred due to crack initiation from rivet holes. The stress concentration at a hole edge is one of main causes of the shortening of crack initiation life of a riveted plate when cyclic stress was applied. In aircraft construction, countersunk holes are widely used and they have a bearing on the fatigue life of structural components since fatigue strength is a direct function of the local stress concentrations associated with the countersunk hole. While stress concentrations around plain holes in structural members have been extensively investigated both theoritically and experimantally, there is little information available on stress concentrations associated with countersunk holes.

A survey of the literature revealed only three published works which relate directly to stress concentration in countersunk holes. The first was by Wharley [1] using birefringent coating on aluminum plates to measure the stresses on the surface of the plate with countersunk holes. Unfortunately, he found that the highest stress concentrations were at the root of the countersink and his experiments were not setup to measure the stresses there. The other piece of experimental work was carried out by Cheng [2] using stress freezing techniques to obtain the stresses through the thickness of the plate with a countersunk hole. His results showed conclusively that the highest stress concentration for loading in tension occurs at the root of countersunk and also provided a measure of its magnitude.

Other than these experimental findings, no analytical work on this subject has been reported so far. Design practice with regard to the use of countersunk holes had been established empirically by various aircraft companies through their own testing and experience. In 1993, Young and Lee [6] conducted an independent 3D FE analysis of plates with countersunk holes subjected to tension load and proposed a design equation by combining their FE results and British Aerospace's 2D design equation. Young and Lee's solutions were based on a very coarse FE model and their equation even did not reduce to 2D solution in literature. Young and Lee using finite element analysis modeling for Stress Concentration factors in countersunk holes. They showed that countersunk depth and edge distance have a strong influence on the K_t value while the t/d ratio has a lesser effect. Variation of countersunk angle between 90°and 110°was found to have a negligible influence on the maximum K_t values. They also shown that normalizing the stress concentration factors of a countersunk hole by dividing the K_t values at various countersunk depths by the K_t values for a plain hole of similar configuration, enable the stress concentration factors in a countersunk hole to be determined from values in a plain hole.

In the development of machinery designed in consideration of limited economic life, measures for fatigue life cycles development that wants to be caused by metal fatigue are worked out [3, 4]. In the overworked body, there is in particular the case that a multi-site crack occurs from the multiple rivet holes [4-7]. Therefore, it is effective for the fatigue life improvement of a structure used for planes to reduce stress concentration to occur in the rivet hole region. In this study, the enhancement of the fatigue life of plate form rivet and cover rivet materials by improving the shape of the rivet hole experimentally.

The objective of the present study is to conduct a comprehensive analysis of three-dimensional stress concentrations for circular straight-shank and counter-sunk rivet hole in a plate subjected to cyclic loading encountered in structural joints. Three-dimensional finite-element (FE) stress analyses of plate with straight-shank and counter-sunk circular hole was conducted with the ANSYS code.

2. Materials and Experimental Methods

2.1 Material

Material used was an aluminum alloy 2024-T351. The nominal chemical composition and mechanical properties of the alloy are shown in Table 1 and Table 2, respectively.

2.2 Finite element models for rivet hole specimen

In this study, 3D FE models were used to simulate stress distributions around the rivet hole. According to the value of fillet radius R = 1.0, 2.0 and 3.0 mm, three finite element models were developed. The ANSYS explicit dynamic finite element code was used to carry out the stress distributions around the rivet hole analysis. In the ANSYS element library, ANSYS structural, linear, elastic and Isotropic SOLID45 elements and 3-D structural solid element was used to the model. In the model, the rolling direction was set as uni-directionally whereas the width and thickness direction were arranged bi-directionally and as Z - directions, respectively. Total number of nodes are 3500 and finest division pattern was applied in the vicinity of the hole edge. However, in the present study, the purpose of calculation is find quantitative tendency of stress concentration. Detailed calculation will be added in the future.

Figure 1 shown the outline of the analysis model, and only a quarter of the plate and rivet was needed in this model due to the double symmetry with respect to X–Y and X–Z planes. In addition, the applied stress σ_0 set it in 100 MPa. The rivet and specimen were made of aluminum with Young's modulus of 68 GPa and Poisson's ratio of 0.33. Material was assumed to be linear and elastic. In addition to the boundary constraints along the planes of symmetry, the plate was constrained within the 3 directions at the fix face nodes.

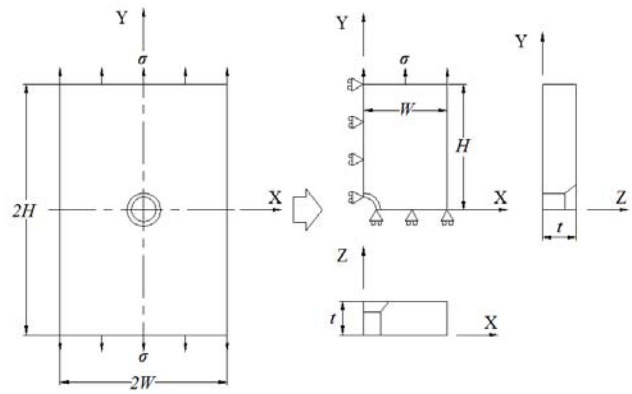

Fig. 1 Analysis model in calculation of stress distribution around the rivet hole (Boundary at X-axis and Y-axis are supported by roller in each direction).

Figure 2 is the example of division method of specimen with elements in the present calculation. The element type for vicinity of the hole is Hexagon and that of the rest is Tetragon. The FE mesh size 1/100 was used for finer in the high stress gradient regions or vicinity of the hole and 1/10 was used for coarser at the low or no stress gradient regions. There is a few number of numerical analysis which treat the stress concentration factor of rivet hole shaped with countersunk. According to study of Young and Lee [6], the stress concentration of countersunk has good correlation with deep of countersunk, distance between the specimen edge and hole center and angle of countersunk. The stress intensity factor in one of the countersunk shown in their study was calculated by the present paper's method. The unloaded countersunk hole had been modeled with the Lusas finite element package to determine the stress concentration factors when the plate is loaded in tension. Then, we evaluated the calculation accuracy by comparing the result of the present calculation with that of their study. Consequently, on the basis of their study about rivet hole of

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countersunk [6], less than 10% error in the present calculation was evaluated.

3. FEM Results and Discussion

According to the FEM analysis results, the fatigue life was improved by the improvement of hole shape of the riveted specimens. One of the reasons of the fatigue life extension is the reducing stress concentration could be achieved by the improving of fillet radius in the rivet hole.

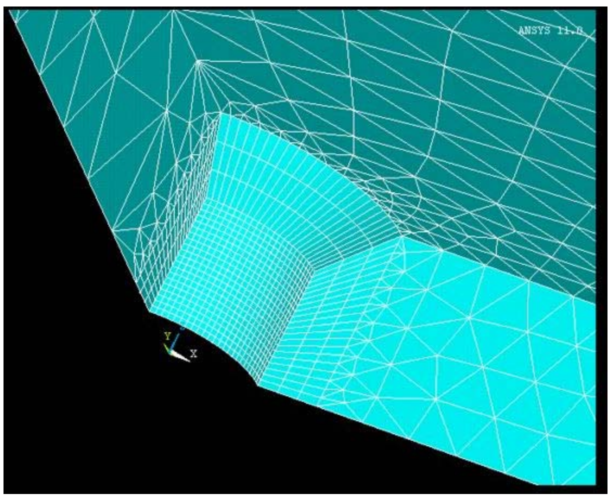
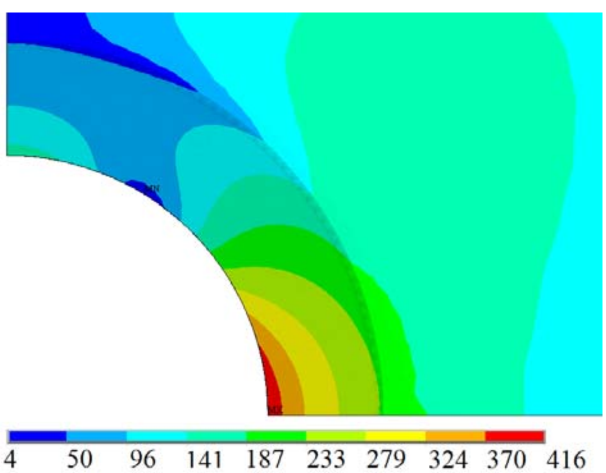
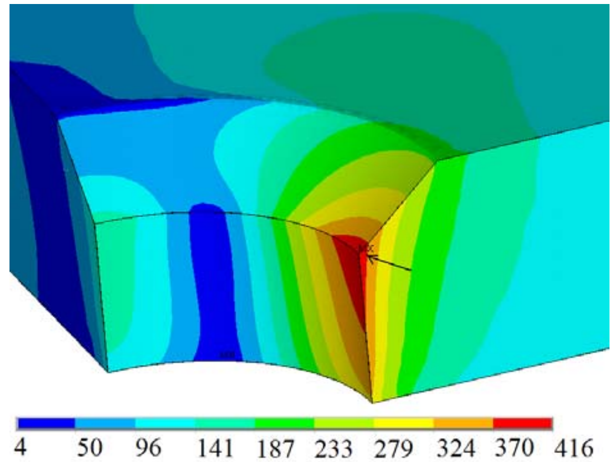


Fig. 2 Example of division method of calculated model by Finite Element Method

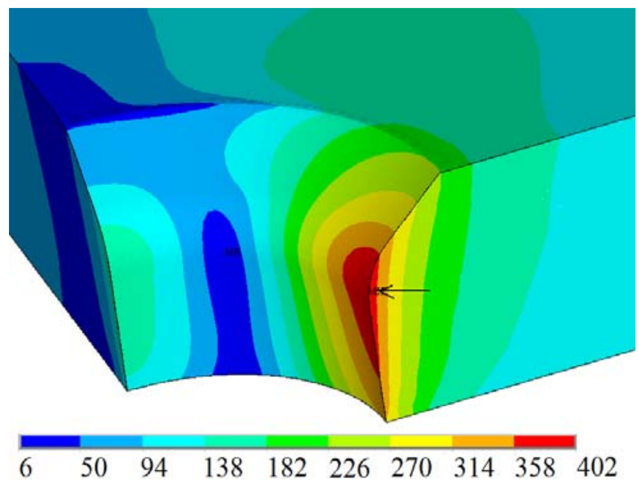


(a) On the specimen surface plane.

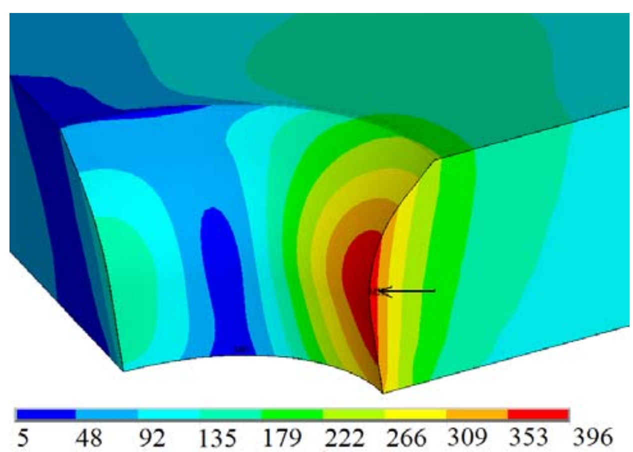


(b) Around the edge of rivet hole.

Fig. 3 Stress distribution for the normal rivet hole (distribution of the stress in loading direction was shown)



(a) R = 1.0 mm



(b) R = 2.0 mm

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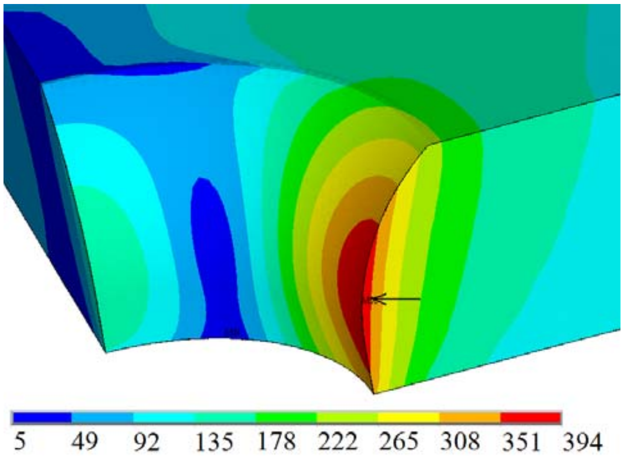

(c) R = 3.0 mm

Fig. 4 Stress distribution for the improved rivet hole, (a) R = 1.0 mm, (b) R = 2.0 mm and (c) R = 3.0 mm (the stress distribution around the hole was shown)

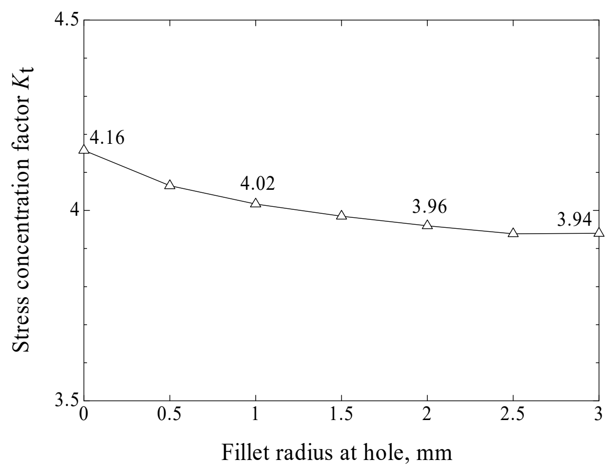

Fig. 5 Variation of stress concentration factor K_t which was evaluated by maximum equivalent stress

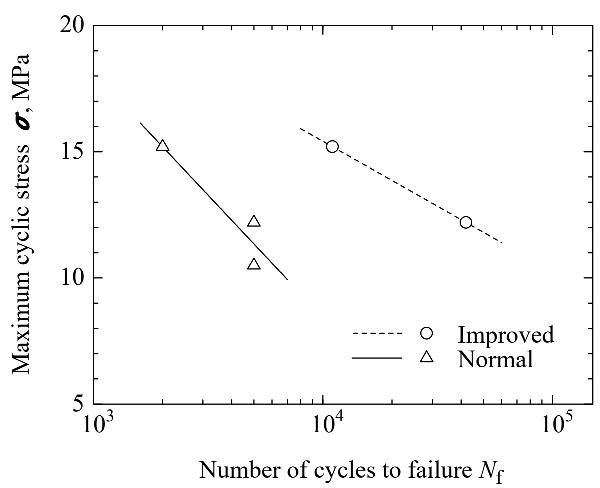

Fig. 6 S-N curves for polycarbonate specimen with rivet hole

Stress concentration factor becomes decreases by the increase of improved filler radius of rivet hole. Therefore, stress distribution around the rivet hole by finite element analysis show in Figs. 3 and 4. The experimental results show that the longest fatigue life was obtained in case of improved type rivet holes specimens.

Figure 3(a) showed stress distribution in the specimen plane, and Fig. 3(b) emphasizes the stress distribution around the hole circumference. The arrow shows a position of the greatest stress, and the strength of the stress separates it by color. From Fig. Figure 4 showed the stress distribution of the load direction in the hole circumference for improved type rivets.

In the case of fillet radius of curvature R is 1.0 mm, 2.0 mm and 3.0 mm maximum stress distributions at the rounded corner was 402 MPa, 396 MPa and 394 MPa in that order. In the case of improvement, the fillet center moved and the fillet radius became rounded. It is understood that the position of the radius of curvature R is large, maximum stress distributions around the rivet hole happen to smaller. The all in Fig. 3 and 4 shows the maximum stress distributions around the rivet hole in the loading direction.

The maximum longitudinal stress σ_{max} in the specimen was calculated to obtain the stress concentration factor $K_t = \sigma_{max} / \sigma_0$. Where σ_0 is the uniform longitudinal tensile stress. Figure 5 is expressed the calculated relation between fillet radius R at hole and stress concentration factor K_t. The stress concentration factor K_t varies inversely proportional to the fillet radius at hole, namely the smaller the value of the fillet radius R becomes, the larger the value of the stress concentration factor K_t becomes. From Fig. 2, The value of the stress concentration factor for fillet radius R = 0 at hole is approximately 4.158 that indicates the normal rivet hole specimen case, where as Fig. 3(b) shows that the maximum value of the longitudinal stress obtained by present FEM calculation is approximately 402 MPa.

Besides, as for the result of figs. 4 and 5, that there was qualitative connection with the experiment result was considered from the viewpoint of enhancement of the fatigue life of improved type rivet hole specimens. In addition, in this FEM analysis, the most suitable values for fillet radius of curvature R were not identified, because it depends on thickness and the hole dimensions of the specimens. From Fig. 5, the range of fillet radius R from 1 mm to 2 mm the change of the values of stress concentration factor K_t is not so large, in relation with this the fatigue life improvement was not so big.

In the case of improved the rivet hole specimen, rivet and shape of the corner region of the contact part of the rivet head and rounded corner, fatigue life was improved and, from the above mentioned results, it is understood that it was related to stress distribution around the rivet hole. In this study, single plate with rivet specimen was considered. The details mechanism about the effect of plastic deformation [8] for the multiple plates into the multiple rivet holes with rivet specimens will be discussed in future work.

Table 1: Chemical composition of aluminum alloy 2024-T351 (mass, %)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zn +Ti	Other	Al
0.07	0.18	4.48	0.55	1.51	0.03	0.08	0.02	0.03	0.01	bal.

Table 2: Mechanical properties of aluminum alloy 2024-T351 (MPa, %)

0.2% proof strength $\sigma_{0.2}$, MPa	Tensile strength σ_B, MPa	Elongation Φ, %
370	460	22.9

Figure 6 is an experimental result, used the polycarbonate resin material in comparison material of aluminum alloy 2024-T3. Experimental technique was same as previous. In this experiment, the fatigue life of improved type rivet hole specimen was used to compare with conventional type rivet specimen. From the experimental results, it is clear that the fatigue life of improved type rivet hole is longer than that of normal type rivet hole shown in Fig. 6. Therefore, the longer fatigue lives obtain when the stress concentration factor is reduced by improving the shape of the rivet hole.

4. Conclusions

The fatigue life of the specimen which processed a rivet hole was improved by improving a plate form rivet and the shape of the rivet hole. According to the FEM analysis whose code was ANSYS results, in the case of improved type rivet hole stress distribution acquire lower in compare with normal type rivet hole. As a result, the values of stress concentration factor become downward for the case of improved type rivet hole in comparison with conventional type rivet hole.

REFERENCES

[1] Wharley, R.E., Stress concentration factors for countersunk holes, Expt. Mech., August 1965, pp 257-261

[2] Cheng, Y.F., Stress-concentration factors for a countersunk hole in a flat bar in tension and transverse bending, J. Appl. Mech., December 1978, 45, pp 929-932.

[3] Nishida, S., Failure Analysis in Engineering Applications, (1986), Butterworth Heinemann.

[4] McEvily, A. J., Metal Failures, (2002), John Wiley & Sons, INC.

[5] Nishimura, T., Noguchi, Y. and Uchimoto, T., Damage Tolerance Analysis of Multiple-Site Cracks Emanating from Hole Array, *Journal of Testing and Evaluation*, Vol.18, No.6 (1990), pp.401-407.

[6] Young J. B. and Lee. K. K., Stress concentration factors in countersunk holes, *Aeronautical Journal*, 1993, 97, (968), pp. 267-276.

[7] Newman, J. C. Jr., Steadman, D. and Ramakrishnan, R., Fatigue-crack-growth analyses of cracks in riveted lap joint of a narrow-body aircraft, *9th International Fatigue Congress,* FT-408(2006), CD-Rom 10 pages, Atlanta, Georgia.

[8] Matos, P. F. P. de, McEvily, A.J., Moreira, P.M.G.P. and Castro P.M.S.T. de., Analysis of the effect of cold-working of rivet holes on the fatigue life of an aluminum alloy, *International Journal of Fatigue*, Vol. 29(2007), pp. 575–586.