International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

Failure Mode Prediction of Single Lap Bolted Joints

Babak Abazadeh
Department of Mechanical Engineering, University of Bonab, Bonab, Iran

***Abstract*— *In this paper, the failure mode of bolt clamped single lap joints of aluminum alloy 2024-T3 have been studied using numerical finite element method. To do so, a 3D model according to the available experimental fatigue test specimens has been created and the stress and strain analysis has been carried out using finite element based package. The stress distribution, contact details such as pressure and slip amplitudes have been employed to study the failure modes such as tensile failure or fretting fatigue. The results have been compared to the available experimental fatigue tests results. The numerical results show that in low applied clamping forces, the fatigue failure of the specimens occurs around the stress concentration location without wear but when the clamping force increases, the fatigue life increases and the cracks nucleate and propagate far from the hole edge because of fretting fatigue. Also, with the further increase of clamping force, the fatigue life reduces due to occurrence of the fretting fatigue in the critical location where the slip amplitude is within its critical region and the fretting failure occurs earlier than tensile failure.*

***Keywords*— *Bolted single lap joint, finite element method, fretting fatigue, torque tightening.*

I. Introduction

The advanced and complicated structures are a product of joining different simpler parts together. Therefore, the performance of the structures is a function of each parts design and selected joining method. The joints can be classified in two major categories. The permanent (inseparable) and the separable ones. The permanent joints such as welded and brazed ones are used mostly in structures subjected to static loading while the separable joints such as bolted ones can be used where the part is designed to work for a time or under cyclic loading for a pre-designed cycle numbers such as aerospace structures. The separable joints can be changed easily after the predicted service life to improve the safety and decrease the probable fault costs. There are a number of studies accomplished by researchers to find the important and effective parameters on the performance of the joints [1-3]. In bolted joints, the created hole acts as a discontinuity and creates a stress concentration site around the hole. Also it decreases the load tolerating capacity reducing net section and increasing maximum local stress. In contrary, while torque tightening a bolt in the joint, the reaction of clamping force of the bolt shank acts as a preload on the joined parts (around the hole) in the bolt longitudinal (part thickness) direction. In fact, the mentioned preload is transferred through contacted surfaces of parts and bolt head (or nut). The contact between different surfaces reduces the transferred load via bolt shank or plates net section. Consequently, torque tightening the bolt affects the stress distribution around the hole and reduces the maximum stress in the part [2, 4]. Besides, when a cyclic load is applied to the joined parts, the created oscillatory relative displacement and frictional force in contacted surfaces of bolt head and parts or between two joined parts may lead to fretting fatigue [1, 5]. The fretting fatigue is a function of normal pressure, slip amplitude (between two contacted surfaces), torsional stress in the contacted surfaces, surface quality, the parts material (physical and mechanical) properties and etc. [??]. Single lap joint is made of two joined parts using a pin, bolt or welding. In the bolted joints, the reaction of created clamping force in to the joined parts affect the static and dynamic performance when subjected to static or cyclic axial loading [2, 6]. In such joints, the amount of the assembly tightening torque is so important especially when the joint is encountered to cyclic loading. The bolted joint can increase the fatigue life by introducing compressive stress around the hole [4] or reduce it when causes fretting fatigue occurrence due to increasing the surface pressure or changing the slip amplitude [3].

In this study, using available experimental fatigue test results of single lap bolted joints made of aluminium alloys with different tightening torques and cyclic load amplitudes, the fretting fatigue behaviour and the effect of clamping force has been investigated. Thus, to have a more comprehensive view, the finite element models have been made using ANSYS finite element package and then after applying boundary conditions corresponding to the experimental tests, the results of stress analysis has been achieved. Finally, the finite element results were used to predict the fretting fatigue occurrence and situation. The predicted fretting fatigue occurrence and situation in different types of specimen has good agreement with the experimental tests results.

II. Experiments

The details of the experimental tests were illustrated broadly by Sanat Wagle and Hiroshi Kato [1]. However, to provide an overview, a brief but adequate discussion is given here. Specimens were created from a 4 mm thick aluminum alloy AL2024-T3 plate with nominal mechanical properties of 330 MPa in yield strength, 465 MPa in tensile strength and 20% in elongation to fracture in the rolling direction. Fig. 1 shows the configuration and dimensions of specimens used for experimental fatigue test. The specimen has a 6.03 mm diameter hole for bolt assembling. The bolted specimens were created by fastening two simple holed specimens with a bolt of 12.9 high grade chromium molybdenum steel (5.95 mm in shank diameter), stainless steel washers (1 mm in thickness, 6.6 mm in internal diameter, and 15.8 mm in outer diameter) and a nut with different tightening torques. The tightening torques were selected from 0 to 8 N.m with 1 N.m increments. To reduce the secondary bending moment in the fatigue testing (which was carried out using parallel grips), aluminum alloy plates of 4 mm in thickness were adhered at the grip sides of the bolted specimens [1].

International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

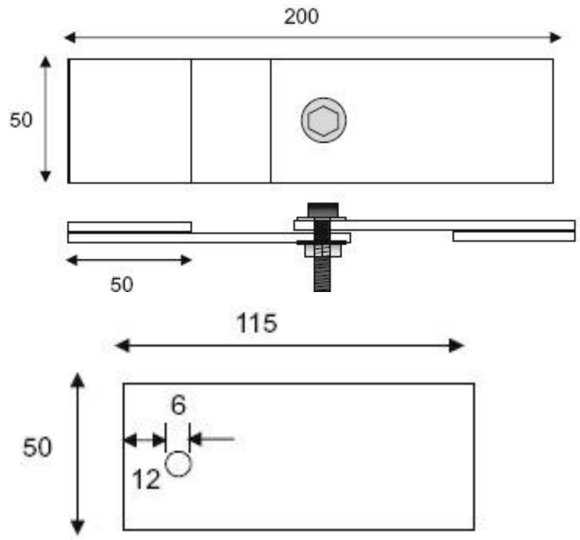


Fig. 1. Dimensions of the single lap joint (mm) [1].

After preparing the fatigue test specimens, the tests were carried out with a frequency of 10 Hz, the stress ratio of 0.05 (a tension–tension type) and various stress amplitudes of 15, 20, 25 and 30 MPa to obtain the S–N relation. The results of these fatigue tests until final fracture are shown in Fig.2.

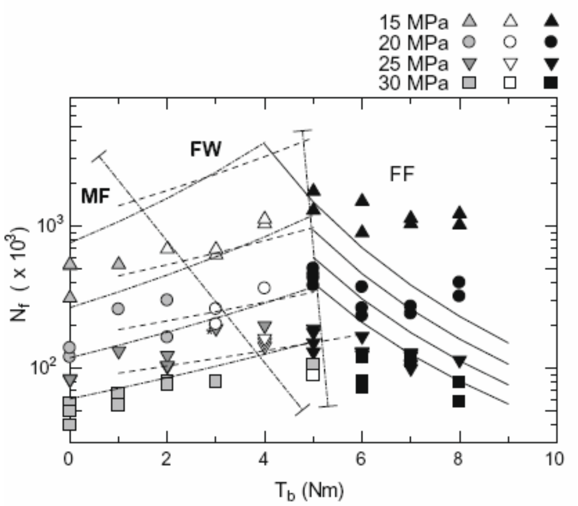


Fig. 2. Change in fatigue life N_f with tightening torque Tb.

III. Numerical Analysis

A. Geometry modeling

A 3D model was generated using ANSYS finite element package according to the dimensions of the parts of the experimental specimen (see Fig. 1). The model was used to simulate the experimental tests applying the clamping force of the bolt joint and subsequently implementing two cycles of longitudinal cyclic tensile load so as to find the stress and strain distribution around the hole and also contact factors (such as slip amplitude, pressure and torsional stress) between contacted surfaces.

The final used finite element model, as shown in Fig. 3 and in comparison with Fig. 1, consists of only a part of the plate's total length to avoid a big and unnecessary model. This optimization does not affect the accuracy of the analysis as effect of the stress concentration (due to the hole) diminishes at the selected distance and the longitudinal stress becomes uniform. Regarding the symmetry of the model, only a half of the model geometry was created using symmetry boundary condition. It is worth mentioning that, if there were not the bending effect of single lap joint, one fourth of model could be used.

An elastic-plastic multi-linear kinematic hardening model was used to define the aluminum alloy 2024-T3 stress-strain behavior which was attained from the experimental tests [1, 7]. Thus the elastic modulus and Poisson's ratio were defined as E=72 GPa and ν=0.33 respectively. However, for steel bolt a simple elastic material model was defined with E= 207 GPa and ν=0.3 as the loading of steel bolt and washer were within the materials elastic range.

To mesh the plates and bolt, 3D structural SOLID185 elements were used. The selected element is a linear isoperimetric cubic one defined by eight nodes (one node at each cube vertex). The nodes have three translation degrees of freedom in the x, y, and z directions. The Solid 185 was preferred to quadratic one because it provides the same accuracy in plasticity (2 × 2 × 2 integration points) and also it is well conjugated with contact elements [8]. In addition, different contact element sets using TARGE170 and CONTA174 elements were defined between the contacted surfaces of the bolt, washer and plates.

B. Applying Tightening Torque (clamping force)

Experimental tests were carried out using different tightening torques of 1, 2, …, 7 and 8 Nm selected to be applied to the bolted joint. Consequently, their corresponding clamping forces were to be applied to the plate in the numerical analysis. The corresponding clamping force were calculated using equation 1 where the K stands for the torque coefficient, $F_{Clamping}$ (N), T (N.m) and d (m) are the clamping force, applied torque and the bolt's nominal diameter, respectively [3].

$$F_{Clamping} = T \big/ K \times d$$
$$K = 0.25 \,\&\, d = 0.006 \rightarrow T = 1N.m, F_{Clamping} = 662.08N \qquad (1)$$

To simulate this process, a uniform temperature reduction in according with equation 2 has been applied to the shank of the bolt to get an axial reaction force equivalent to the joint assembly torque in the shank of the bolt.

$$\left.\begin{array}{l} \delta l = kl\delta\theta \rightarrow \dfrac{\delta l}{l} = k\delta\theta = \varepsilon \\ \varepsilon = \dfrac{F}{AE} \end{array}\right\} \rightarrow k\delta\theta = \frac{F}{AE}$$

$$F = 662.08N, A = \pi \times 0.003^2, E = 210 \times 10^9, \delta\theta = 1 \rightarrow k = 1.115 \times 10^{-4}$$

In this equation δl, l, k, θ and ε are bolt shank length variation, bolt shank length, thermal expansion coefficient,

Babak Abazadeh, "Failure mode prediction of single lap bolted joints," *International Research Journal of Advanced Engineering and Science*, Volume 1, Issue 4, pp. 95-99, 2016.

temperature variation and strain respectively. The thermal expansion coefficient was selected such that, unit temperature variation results in the corresponding clamping force equivalent to 1 N.m tightening torque in the bolt shank.

C. Applying Static Tensile Longitudinal Load

To simulate the experimental fatigue loading process (after applying clamping force, preparing the primary specimen), a tensile remote stress was applied to the finite element model as the tensile period of cyclic loading. In the next step, the applied tensile load was decreases to zero to simulate the unloading period of cyclic loading.

To ensure the mesh independency of the results, the mesh refining process were continued to attain an almost constant and mesh independent result. Fig. 4 shows the longitudinal stress distribution (S_X) attained from the finite element analysis in different steps of simulation. The results are presented and discussed in the next section.

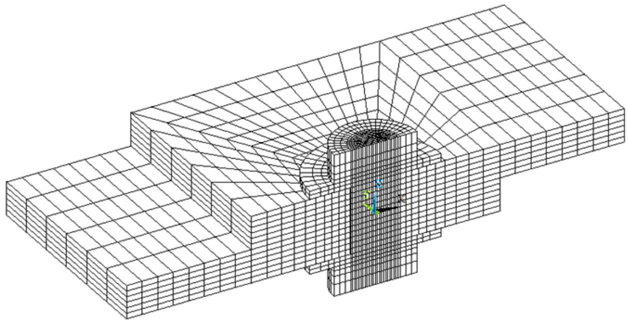
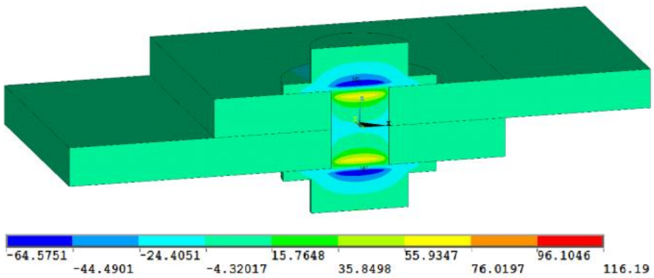
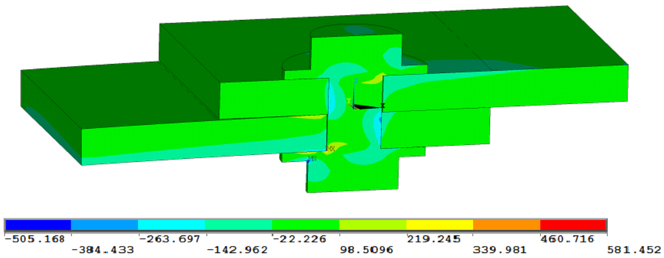


Fig. 3. Finite element model of single lap joint.



a. 8 N.m tightening torque (MPa).



b. 8 N.m tightening torque and 20 MPa longitudinal stress (MPa).
Fig. 4. Tangential stress in the specimen calculated using FEM.

IV. Discussion and Conclusion

Fig. 2 shows the experimental fatigue tests results representing the variation of the fatigue life in different bolt tightening torques and load amplitudes where T is the applied tightening torque to the joints' bolt and N is the attained fatigue life of the specimens in different specimen series subjected to different ranges of cyclic stress applied to the specimens. As the figure shows, the specimens failure occurs in three different failure modes. When low and middle torques (0-5 N.m) is applied, increasing the clamping force causes to enhancement of the fatigue life of the joint but when the applied tightening torque increases up to 5-8 N.m, higher resulted clamping forces of the bolt affects the fatigue life and decreases it.

The fatigue crack initiation location is a function of different variables such as material properties, surface conditions, stress state and etc. Herein the effect of the tightening torque of the bolted joint is studied. In the specimens with low clamping force, the initiation and growth of the fatigue cracks occurs at the edge of the fastening hole (Figs. 5, 6), but when the tightening torque increases, the fatigue cracks initiate and grow in a quite farther distance from the hole (Figs. 7, 8 and 9).

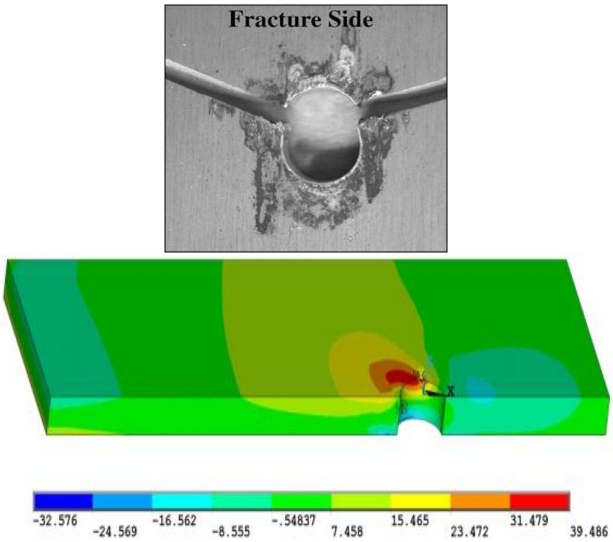
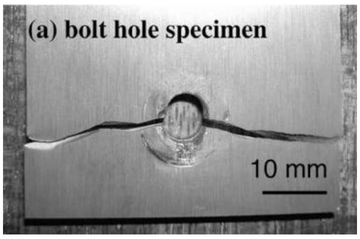
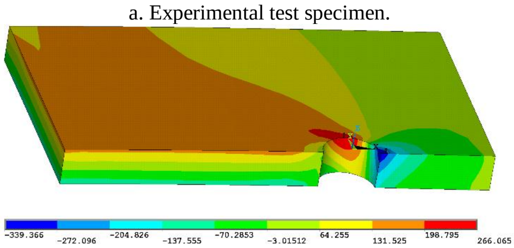


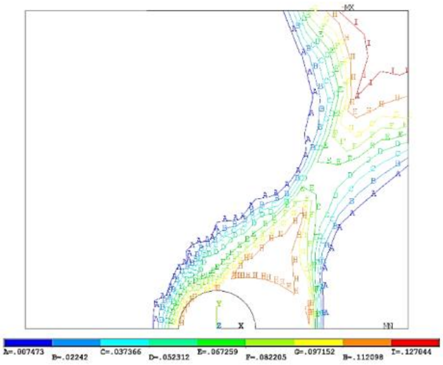
Fig. 5. The broken sample and axial stress (MPa) in a specimen with low value of tightening torque.



a. Experimental test specimen.



b. S_X distribution after loading perioid of cyclic loading.



c. Slip amplitude.
Fig. 6. Specimen with 6 N.m tightening torque and 20 MPa-cyclic load amplitude.

When torque tightening a bolt in the joint, the clamping force of the bolt is transferred to joined parts via contacted surfaces of the bolt head (or nut) and the parts as a normal load. Therefore, a pressure is presented in the contacted surfaces of the plate [2, 4, 7, 9]. When cyclic remote axial load is applied to the joint, an oscillatory slippage may occur between the contacted surfaces which can lead to fretting wear and fretting fatigue in the presence of normal pressure (see Figs. 7-9). Occurrence of the fretting wear and initiating and growing the cracks due to fretting fatigue reduces the final fatigue life of the specimens (see Fig. 2). As the finite element results show, in such specimens, the slippage amplitude can predict the crack nucleation and growth location and the maximum tensile stress has not the main role on the crack initiation. In other words, in such specimens, initial cracks are created due to fretting wear in contacted surfaces far from hole edge (where the critical slippage range of 5-50 µm occurs) prior to initiation of cracks in the hole edge because of the maximum tensile load range). As the figures show, finite element results can predict the fretting fatigue crack initiation location where the slip amplitude is within the critical 5-50 microns [10] in the contacted surfaces of the specimens (see Figs. 7, 8 and 9).

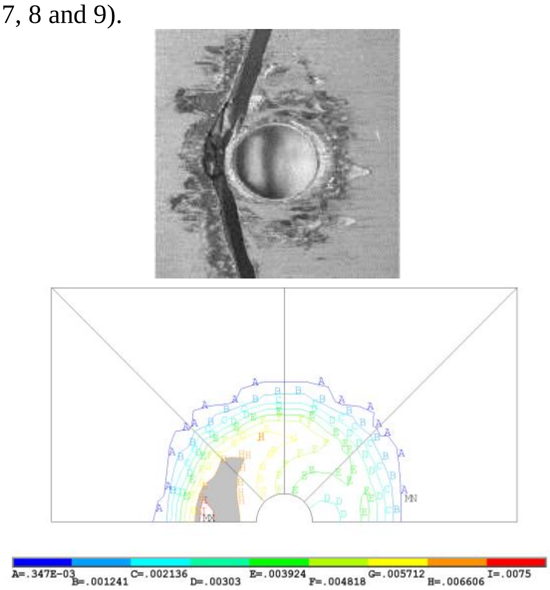
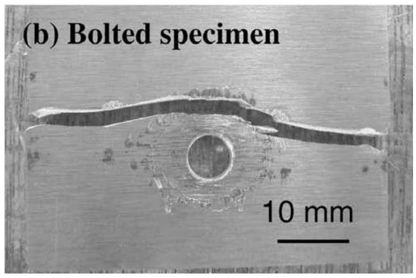
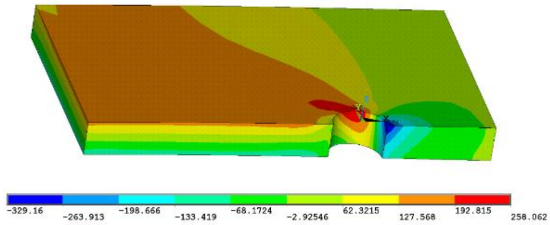


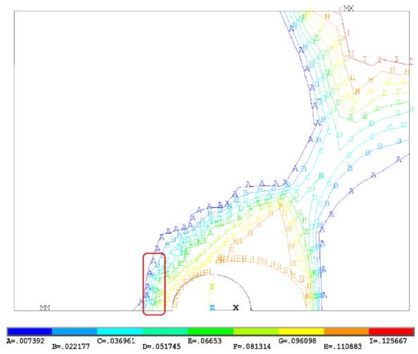
Fig. 7. The broken sample and the slip amplitude in samples with middle torque value.



a. Experimental test specimen.



b. S_X distribution after loading perioid of cyclic loading.



c. Slip amplitude
Fig. 8. Specimen with 8 N.m tightening torque and 20 MPa-cyclic load amplitude.

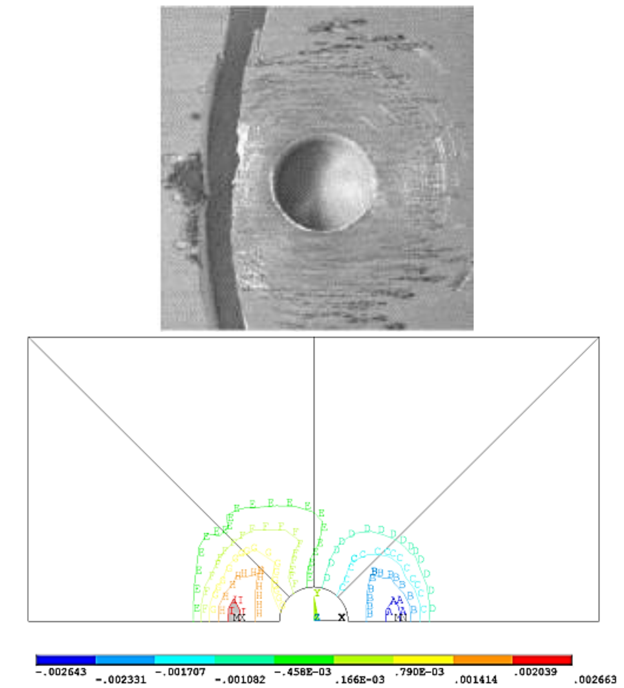


Fig. 9. The broken specimen and the slip amplitude in samples with high tightening torque.

REFERENCES

[1] S. Wagle and H. Kato, "Ultrasonic detection of fretting fatigue damage at bolt joints of aluminum alloy plates," International Journal of Fatigue, vol. 31, issue 8-9, pp. 1378-1385, 2009.

[2] T. N. Chakherlou, B. Abazadeh, and J. Vogwell, "The effect of bolt clamping force on the fracture strength and the stress intensity factor of a plate containing a fastener hole with edge cracks," *Engineering Failure Analysis*, vol. 16, issue 1, pp. 242–253, 2009.

[3] T. N. Chakherlou, M. J. Razavi, A. B. Aghdam, and B. Abazadeh, "An experimental investigation about the effect of clamping force and friction on the fatigue behaviour of bolted double shear lap joint," *Materials & Design*, vol. 32, issue 8-9, pp. 4641-4649, 2011.

[4] T. N. Chakherlou R. H. Oskouei, and J. Vogwell, "Experimental and numerical investigation of the effect of clamping force on the fatigue behaviour of bolted plates," *Engineering Failure Analysis*, vol. 15, issue 5, pp. 563–574, 2009.

[5] K. Shankar and R. Dhamari, "Fatigue behaviour of aluminium alloy 7075 bolted joints treated with oily film corrosion compounds," *Materials and Design*, vol. 23, issue 2, pp. 209-216, 2002.

[6] R. H. Oskouei and T. N. Chakherlou, "Reduction in clamping force due to applied longitudinal load to aerospace structural bolted plates," *Aerospace Science and Technology*, vol. 13, issue 6, pp. 325–330, 2009.

[7] B. Abazadeh, T. N. Chakherlou, and R. C. Alderliesten, "Effect of interference fitting and/or bolt clamping on the fatigue behavior of Al alloy 2024-T3 double shear lap joints in different cyclic load ranges," *International Journal of Mechanical Sciences*, vol. 72, pp. 2-12, 2013.

[8] Swanson Analysis Systems Inc. ANSYS, Release 15.0.

[9] T. N. Chakherlou and B Abazadeh, "Investigating clamping force variations in Al2024-T3 interference fitted bolted joints under static and cyclic loading," *Materials & Design*, vol. 37, pp. 128-136, 2012.

[10] D. Nowell, D. Dini, and D. A. Hills, "Recent developments in the understanding of fretting fatigue," *Engineering Fracture Mechanics*, vol. 73, issue 2, pp. 207-222, 2006.
.