Numerical Analysis of Fretting Fatigue for Riveted Al 6XXX Components

R. Guo1*, J. X. Luo1, R. C. Duan2, G. Mesmacque2, A. Amrouche2

1 Kunming University of Science and Technology, Yunnan China
2 Laboratory of Mechanic of Lille UMR CNRS 8107 France

Email: guoran99@mails.tsinghua.edu.cn

Abstract Riveting is a procedure widely used for fitting together two or more elements of a structure, that could be of the same or different material. In these assemblies the stress field is complex and a number of parameters, including effect of the geometrical discontinuities, contact between elements, tightening, material properties and applied load must be considered. The current work focuses on the study of fretting fatigue crack formation in common 6XXX aluminum alloys, used in land transportation equipments, and the determination of the characteristic crack initiation sites by means of both experimental and numerical methods. 3D finite element models were validated by the experimental results obtained with strain gauges. The influence of the contact friction coefficient at the fretting surface, fastening forces and remote stresses applied in fretting fatigue experiments, on the initiation of cracks, are discussed by the comparison of the different numerical results.

Keywords: Fretting Fatigue, Riveted assembly, Finite Element Analysis, multi axial fatigue, crack initiation

BACKGROUND

One of the causes of structural deterioration and failure of land transportation equipment by aging can be attributed to the interfacial damage process that occurs in joint structures [1], also known as fretting. The role of fretting in the degradation of one particular class of complex systems—high speed train vehicles—has been highlighted recently during teardown analyses of riveted joint structures from both in-service vehicles and laboratory specimens. Fretting is the degradation of near-surface material that arises from a triple interaction among wear, corrosion and fatigue phenomena [2], often observed in nominally-clamped mechanical assemblies subjected to oscillatory loads or vibratory excitation. In contrast to interfacial damage associated with large-scale relative motion from either rolling or sliding displacements, fretting damage is a product of small-amplitude micro-slip, concentrated in regions near the edges of the contact area [3]. The absence of gross relative motion, often referred to as a condition of partial slip, usually results in a limited amount of interfacial wear and corrosion. On the contrary, the localized cyclic contact stresses induced by the applied oscillatory loads accelerate the nucleation of fatigue cracks in the near-surface material [2]. Some studies have derived useful results from finite element (FE) method analysis [4-10]. The current experimental and numerical efforts are focused on the study of fretting fatigue crack formation in riveted Al 6XXX components usually used in land transportation equipment. Characteristics of initial position of fretting, where the fatigue cracks appear, are determined from the evolution of stress field between the initial state and the crack initiation. 3D FE models of the contact configuration, in the same condition of tests of fretting fatigue, have been validated by the experimental results obtained with strain gauges. The comparison between the numerical and experimental results assess: (a) the influence of the
contact friction coefficient at the fretting surface, (b) the fastening forces and (c) the remote stress, on the crack initiation.

EXPERIMENTAL AND NUMERICAL MODEL

1. Experimental models
An experimental study, which involved over 80 tests up to failure and percentages of failure, was carried out to study fretting fatigue crack formation in common 6xxx aluminum alloys both in single-sample and single-bolt joints. The specimen geometry is shown in Fig. 1. The joint geometry has a fastener hole of 8 mm diameter, with a width of 60 mm, length of 230 mm and thickness of 6 mm. The strain gauges are arranged at: (a) two spots at 12 mm distance from the hole on the aluminum sample up-surface in the minimal section and (b) a spot at 9.6 mm distance from down intersect edge on the rivet tube used for calibrating the rivet fastening forces. The fixture, specially designed, includes steel bolts with a nominal diameter of 8 mm, two steel nuts, two steel washers and a rivet tube, which is used for fixing strain gauges more easily, in order to obtain and control the rivet fastening forces.

![Figure 1: Specimen and the fixture](image1)

![Figure 2: finite element model of 1/4 specimen geometry](image2)

2. Finite element analysis
A typical finite element model is meshed into eight parts: an aluminum specimen, a bolt, a rivet tube, two nuts, two washers and a clamp, as shown in Fig. 2. The aluminum specimen is meshed into a relatively high radial density of mesh near the hole and on the contacting surface under the washer, where high strain gradients exist. To decrease the model size by decreasing the number of elements and contact bodies, the fixture parts: bolt, rivet tube, nuts and washers, are meshed into a single element body, and then two contact relations between the down surface of the rivet tube and the aluminum up surface, the aluminum down surface and the up surface of down washer are considered. To simulate the bolt fastening process, the loads are applied at the two ends of the bolt in the first simulation step, without considering the contacts between the specimen and the rivets, in order to increase the distance between the down surface of the rivet tube and the up surface of down washer, which is less than the width of the aluminum specimen, when they are meshed. Sequentially, the loads are released gradually to fasten the specimen in the second step, while those contacts are considered.

DISCUSSION

1. Validation of the finite element model
Under a fastening force of 8 kN and an experimental tension load of 22.8 kN, the axial strains from the finite element model, paralleling the fatigue load, distribute along the vertical line of the fatigue load direction on the up-surface in the minimal section of the specimen, as shown in Fig. 3. The test results, obtained from gauges at the two spots located 12 mm from the hole, agree very well with the finite element results. In the same loading case, the numerical axial strains on the out surface of the rivet tube, paralleling the bolt, agree well with the experimental results obtained from gauges on such a
tube, as shown in Fig. 4. The good agreement between numerical and experimental results confirms the validity of the finite element model. We have obtained similar results with other specimens.

Figure 3: Axial strains versus distance from the hole on the up-surface in the minimal section of the specimen

Figure 4: Axial strains versus distance from the hole on the rivet tube

2. Effect of fastening force on fatigue life

A series of fretting fatigue experiments with different fastening forces and applied remote stresses, were carried out for the study of fretting fatigue, whereas a number of numerical models were also developed. From the good agreement between numerical and experimental results, it is possible to assess the effect of the contact friction coefficients, fastening forces and applied remote stresses on the location of the crack origin.

A group of fretting fatigue experiments with the maximum remote cyclic stress $\sigma_r=145$ MPa, $R=0.1$ and frequency $=25$Hz, were undertaken with 6 different fastening forces, including 0 kN, to study the influence of fastening force on the fretting fatigue life. In Fig. 5, it is obvious that the fretting fatigue lives change nonlinearly with the fastening forces, and the peak value occurs about at 8 KN in this loading case. This plot is interesting and provides the insight into the effect of the fastening loads on the fatigue life. The existence of the peak point results from the difference of crack origins, which will be discussed below.

3. Effect of fastening force on the location of the crack initiation sites

In Fig. 6(a), without fastening force, the crack is initiated at the edge of the hole, in the minimal section, as an ordinary fatigue crack. With
the increase of the fastening force, the crack does not originate in the minimal section [4,10], but at a certain
degree from the symmetrical axis of specimen, as shown in Fig. 6(b), as same as the results of Hiroyuki [1].
When fatigue crack is initiated from the edge of hole, the compress hoop stresses along the edge of hole,
induced by fastening axial pressure on the contacting area of the Al specimen, could reduce effectively the
maximal tensile hoop stress at maximal fatigue load, and then lead to effectively the increase of fatigue life.
Therefore, in this case fatigue life increases with fastening force, as the first stage shown in Fig. 5. In the
mean time, the fretting cracks are not easy initiated on the contact area, because the fastening forces are not
lower. When the fastening force exceeds the limit of 8kN, the fretting cracks originate at the outer edge of
the contact area under the rivet tube due to the fretting damage [3], as shown in Figs. 6(c) and (d). Increase of
the fastening force will accelerate the fretting fatigue damage at the outer edge of the contact area under the
rivet tube. Therefore, in that case fretting fatigue life will decrease with the increase of fastening force, like
the tendency of the second stage of life curve in Fig. 5. Therefore, the different trends of the fatigue life with
the deferent fastening forces result from the synergistic competition between the ordinary fatigue and the
fretting fatigue.

![Figure 5: Fretting fatigue life versus fastening force](image)

In the discussion of the fatigue crack initiation sites from the analysis of the numerical results of the stress
distribution, $\Delta \sigma$ represents the range of the hoop normal stress component, from the minimum to the
maximum load, in a steady constant fatigue loading cycle, which are defined in a polar coordinates from the
fasten hole center and $\sigma_m$ is the corresponding stress mean. Also, $\Delta \tau$ and $\tau_m$ represent the range and mean of
the corresponding shear stresses $\tau_r$ in polar coordinates in the specimen up surface, respectively. The angle
$\theta$ is defined in polar coordinates from the symmetrical axis of specimen. The loading direction is at $\theta = 0$.

Both $\Delta \sigma$ and $\sigma_m$ along the hole edge are shown in Fig. 7. $\Delta \sigma$ increases with the angle $\theta$, which induces the
ordinary fatigue crack formation at the edge and its maximum value is attained at $\theta = 90^\circ$, which leads to the
ordinary fatigue crack initiation generally at such an orientation. The decrease of $\Delta \sigma$ with increasing

![Figure 6: Crack origins with different fastening forces](image)
fastening force gives rise to an increase in fretting fatigue life. Therefore, when the fastening force is below a certain critical value, fretting fatigue cracks are initiated at the hole edge, as the ordinary fatigue crack location, and fretting fatigue life increases with fastening force, as the tendency of the first stage of the life curve in Fig. 5.

When the fastening force increases over a certain critical value, the fretting fatigue crack at the outer edge of the contact area under the rivet tube, is initiated more quickly than an ordinary fatigue crack initiated from the hole edge. In this case, the initiation of the fretting fatigue crack is affected by a number of factors, such as the shear stresses $\tau_{r\theta}$, contact normal force, contact friction, etc. However, the mechanisms of fretting fatigue damage are not clearly understood and represent a very active research field.

![Figure 7: $\Delta\sigma$ and $\sigma_m$ versus $\theta$ for different fastening forces $f$](image)

In relation to the shear stress $\tau_{r\theta}$, figure 8 illustrates that the maximum of the shear stress range $\Delta\tau$ occurs almost at an angle $\theta$ of 45°, which induces fretting fatigue crack initiation at these locations due to the fretting fatigue damage, as shown in Figures 6(c) and (d). The shear stress range $\Delta\tau$ near 45° decreases with the increase in the fastening force, as shown in Fig. 8, which should prolong the fretting fatigue life. However, such an increase in fretting fatigue life cannot be observed because fretting fatigue is also affected by the contacting pressure, which accelerates the surface damage of the material [2]. As far as the contact condition is concerned, the maximum micro-slip of the points under the rivet tube down out-edge, occurs at point “A”, almost at the angle 45°, as shown in Fig. 9. The maximum micro-slip induces the initiation of fretting cracks at these points, at 45°, in the same as before. However, the corresponding increase in contacting pressure due to the increase in fastening force will give rise to a decrease in fatigue life. The influence of the fastening force on fretting fatigue life in the second stage is not as clear as the first stage shown in Fig. 5.

![Figure 8: $\Delta\tau$ and $\tau_m$ versus $\theta$ for different fastening forces $f$](image)
4. Effect of fatigue load on fatigue life In Fig.10 the increase of $\Delta \sigma$ with the maximum remote fatigue stress $\sigma_r$ results in a decrease of the fretting fatigue life, when the crack initiates from the hole edge. In the mean time, the increase of $\Delta \tau$ with the maximum remote fatigue stress $\sigma_r$ results in a decrease of the fretting life.
fatigue life, as shown in Fig. 11, when the crack initiates from the contact outer edge. Therefore, the increase in the maximum remote fatigue stress $\sigma_r$ is harmful to the fatigue life of the riveted components.

5. Effect of friction on fatigue life In Fig. 12, the decrease in $\Delta \sigma$ with the increase of the friction coefficient $f$ results in an increase of the fretting fatigue life, when the crack is initiated from the hole edge. The decrease of $\Delta \tau$ with the increase of the friction coefficient $f$ results in an increase of the fretting fatigue life, as shown in Fig. 13, when the crack initiates from the contact outer edge. However, the phenomenon of fretting fatigue is much more complex when the crack is initiated from the contact area. From the numerical results, the decrease of $\Delta \tau$ with the increase of the friction coefficient $f$ results in an increase of the fretting fatigue life. On the other hand, the increase of the friction coefficients $f$ will induce an increase in the degree of the fretting damage on the contacting surface. Normally, the second factor is more important than the first. Therefore, the increase of the friction coefficient $f$ is also harmful to the fatigue life of the riveted components.

CONCLUSIONS

As suggested from the experimental and numerical results, the effect of an increase of the fastening force and
of the friction coefficient tend to delay the formation of a crack at the hole edge, at the minimal section. Above the certain critical fastening force, cracks are initiated at the outer edge of the contact area between the rivet tube and the specimen, close to an angle of 45°, due to the contact fretting damage, which is affected by the shear stress $\tau_{\theta}$, the maximum remote fatigue stress $\sigma_{r}$, the fastening force and the coefficient of friction.

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