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Investigation of the fatigue life and crack growth in torque tightened bolted joints

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ABSTRACT

The fatigue crack initiation and fatigue crack growth life estimations have been numerically investigated and the total estimated fatigue lives have been compared with available experimental fatigue test results for a single plate of aluminum 7075-T6 bolted with different applied torques. To do so, pre-stresses around the hole due to the torque tightened bolt and stress concentration factor of the combined longitudinally applied load and bolt clamping force were determined using 3D finite element simulations results. The calculated pre-stresses and stress concentration factors for different bolt clamping forces were employed in AFGROW computer package to predict fatigue crack initiation and fatigue crack growth lives. The results show that there is good agreement between the numerically predicted total fatigue lives and available experimental fatigue test results. The numerical results also show that bolt clamping force increases both fatigue crack initiation and fatigue crack growth lives individually.

1. Introduction

Design of structures and the optimum selection of materials, in industries such as the aerospace industry have always been considered of critical importance if they are to be efficient and safe, and thus resistant to the effects of dynamic loads as occurs during flights. Because safety is of paramount importance, there have been continuing efforts in design and testing of material properties ever since the invention of the first airplane up to the design of today's advanced aerospace vehicles.

Among the most important elements in aerospace structures are mechanical joints, especially bolted joints. They are used in very large numbers on modern aircraft, and because of the nature of changing geometrical shape and load transfer it is well known that they are a potential source of fatigue crack initiation (FCI). It is therefore essential that nut and bolt clamp parts together well and have good resistance to alternating loads [36]. According to results of previous researches [19,36], bolted joints have higher tensile and fatigue strengths than welded, riveted and also pinned joints.

Comparison between fatigue test results for steel members that have been joined together using rivets and those joined using both rivets and bolts in old railway bridges in Ref. [36] indicates a considerable increase in fatigue life of specimens which had more bolts instead of rivets.

However, drilling holes in members in order to create fastener joints inherently causes a stress concentration near the hole and reduces the load carrying cross sectional area. Also, drilling a hole may cause a rough surface finish which is prone to fatigue crack initiation (FCI) and fatigue crack growth (FCG) under dynamic loads, and there were a lot of attempts to alleviate this defection using cold expansion method [3,9,10,24–27,37,38,41], and interference fit [5,7,28] or using lubricant material between hole and fastener [6].

When a nut and bolt are used to join mechanical members together the nut is tightened by applying torque, thus causing the bolt to axially stretch. As the bolt head and nut (usually with a washer) clamp the joint members together, the bolt is left in tension (called a preload) and the mechanical members are compressed together [8,32]. Previous researches have demonstrated that the bolt clamping effect can decrease the stress concentration at the bolted hole region and thus increase the tensile and fatigue strengths of the joint [8,39]. Also, it was illustrated practically and numerically that an increase in the amount of clamping force can enhance the fracture strength by decreasing the stress intensity factor of a cracked holed plate including a fastener via closing the crack mouth [4]. However, it was also found experimentally that an increase in the amount of clamping force can cause the phenomenon of fretting on the surfaces of mating bolted plates and this has a negative effect on fatigue life under cyclic loading. This especially happens when a higher torque is applied to the nut in order to tighten the joint [30,31]. Furthermore, it was depicted that the fatigue life of a joint much depends on the tightness of the bolt, and if the fastener becomes loose the fatigue life can be extremely short. This is because, in such a case, the load is transferred by bearing pressure (which tends to open the hole)

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Nomenclature

3D	Three-dimensional
a	Crack length (in $\underline{A}$ direction, see Fig. 16)
a_0	Intrinsic crack length (0.0381 mm)
a_i	Initial flaw size for the AFGROW computer program in $\underline{A}$ direction
$\underline{A}$	Crack propagation direction (see Fig. 16)
A_k	Fit parameter of NASGRO equation
b	Fatigue strength exponent
B_k	Fit parameter of NASGRO equation
c	Crack length (in $\underline{C}$ direction, see Fig. 16)
c'	Fatigue ductility exponent
c_i	Initial flaw size for the AFGROW computer program in $\underline{C}$ direction
$\underline{C}$	Crack propagation direction
C_{th}	Threshold coefficient
E	Elastic modulus
K_{Ic}	Plane strain fracture toughness (Mode I)
K_σ	Stress concentration factor
N_f	Number of cycles to crack nucleation under a certain stress and strain level
N_g	Number of cycles to crack growth under a certain stress and strain level
N_t	Total number of cycles to specimen fatigue fracture
P	Applied axial remote load to specimen
$R = P_{\min}/P_{\max}$	Load ratio
S_a	Remote stress amplitude
$S_{\max}$	Maximum applied remote stress
SIF	Stress Intensity Factor
SWT	Smith–Watson–Topper
t	Plate thickness
t_0	Reference thickness (plane strain condition)
T	Applied torque
α	Plane stress/strain constraint factor
$\Delta\varepsilon/2$	Maximum principal strain amplitude (local)
ΔK	Stress intensity range
ΔK_0	Threshold stress intensity range at $R = 0$
ε	Strain (local)
ε'_f	Fatigue ductility coefficient
μ	Friction coefficient
ν	Poisson ratio
σ_0	Flow stress
σ'_f	Fatigue strength coefficient
$\sigma_{\max}$	Maximum tensile stress (local)

rather than predominantly by surface friction of the compressed mating plates in tighter fasteners [29,34].

In a research by Fawaz and Hill on the validation of stress intensity factors of diametrically opposed corner cracks in a hole, they declared that "although correlating fatigue life and flaw shape predictions are a more coarse validation technique, these two methods are preferred and recommended for stress intensity factors validation studies" [12]. They found that the best method for such validation efforts is using the fatigue life, crack history, and crack shape which can be obtained at 1/10th the cost of obtaining striation spacing measurements [12].

First study which published in FCG using AFGROW was accomplished by Harter in 1999 [17]. In many researches two popular crack growth life prediction codes FASTRAN and AFGROW have been extensively used in FCG life and are modified utilizing the enhanced partial crack closure model [2,13–15,20–22,40]. Most of the previously mentioned researches stated that the AFGROW model provided a reasonable prediction of the FCG rate behavior.

Zhang and Wang investigated and reported the effects of cold expansion on the fatigue life enhancement of the fastener's hole [41]. Then, they also estimated FCG life for such holes using existing closed-form residual stress models [38]. The fatigue life of riveted sheet metal of helicopter airframe joints has been studied by Urban [35]. Urban has studied and showed that the joint geometry, fastener type and materials affect the fatigue behavior of fastened joints. Zhang and Wang [38] and also Pasta [26] have used the AFGROW computer program to predict the life of fatigue crack propagation in cold worked specimens.

In this research, fatigue life prediction was carried out for single bolted plates for the case where experimental fatigue lives are available from the previous research which was carried out in order to investigate the isolated effect of bolt clamping on fatigue life improvement. The fatigue tests were carried out on simplified bolted joint specimen which includes a holed plate with a single bolt assembled in the hole and clamped using different tightening torques. In the numerical study, finite element models were used to find the stress and strain distributions around the hole due to the different bolt clamping force and subsequent applied longitudinal load at the plate ends. These stress and strain distributions around the hole were used to predict FCI life using SWT parameter and FCG life using NASGRO crack growth rate equation to predict the total fatigue life in AFGROW computer program.

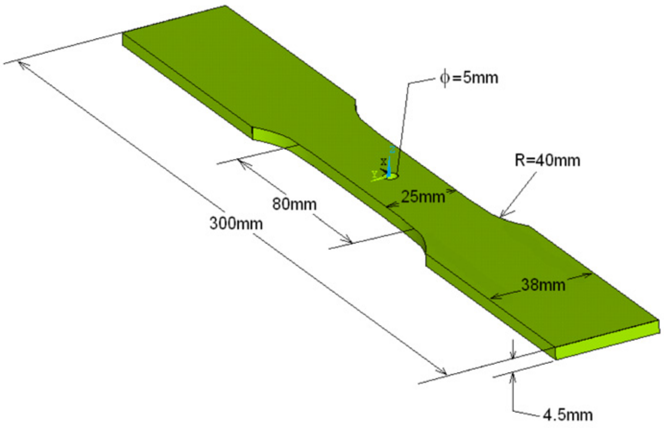

Fig. 1. The dimensions of fatigue specimen.

2. Experimental test brief

The details of the experimental fatigue test programme were previously reported in [8] and only briefly discussed here. Test specimens were made from 4.5 mm thick aluminum alloy 7075-T6 plate, and had a 5 mm diameter central hole drilled and reamed, as shown in Fig. 1. To clamp the specimens at their hole area a hexagon head steel bolt (M5 × 0.8 with material class of 8.8 and shape according to ASME B18.2.3.5M) was used.

To carry out fatigue tests, four batches of specimens were used: one batch with open hole (without using any bolt in the hole) and three batches using a bolt in the hole and tightened using selected torques of $T = 0.25$, 3.5 and 7 N m which created clamping forces equal to $F_{cl} = 244$, 3409 and 6818 N respectively. The relation between the applied torque and resultant pre-tension (or clamping force) was extensively explained in Ref. [8]. The fatigue tests were carried out at constant-amplitude sinusoidal loading at a load fre-