Prediction of Fatigue Crack Growth at Cold Expanded Fastener Holes with ForceMate Bushings

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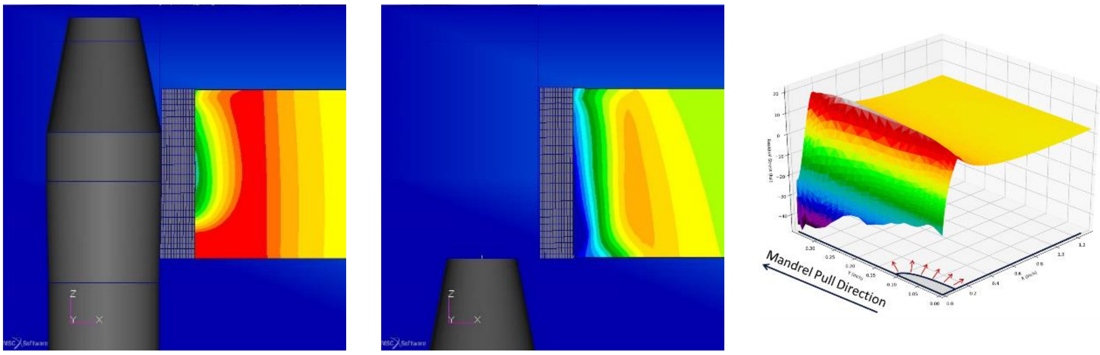
Two bulkheads of the Royal Canadian Air Force CF-188 aircraft have been prone to fatigue cracking at fastener holes attaching the main landing gear (MLG) uplock mechanism. Over the years, several modifications and special inspections have been implemented to the MLG uplock support attachment holes to prevent or address fatigue cracking. Most aircraft were modified with ForceMate bushings, made by Fatigue Technology Inc. (FTI), to prevent fatigue cracking. This modification procedure consisted of oversizing the holes, installing the bushings, and conducting repeated inspections after rework. Due to the lack of experimental data and methods for analysing the fatigue performance of ForceMate bushings, the inspection intervals were determined without considering the beneficial effect of residual stresses induced by the bushing installation, which is overly conservative considering the typical fatigue life benefit of this technique.

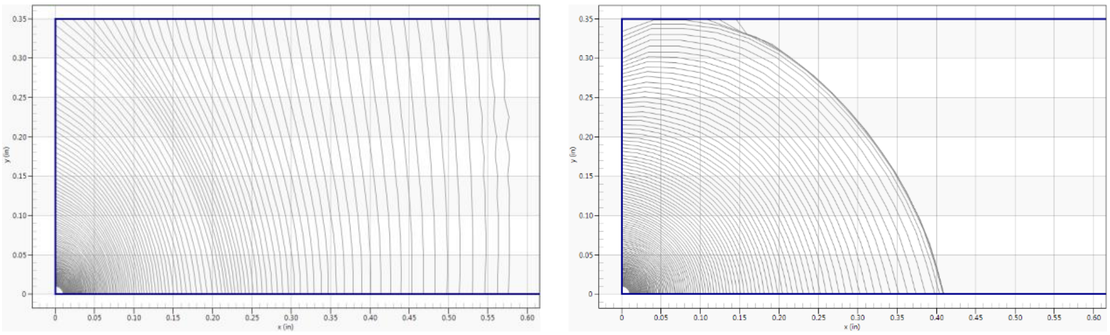
In order to evaluate the fatigue performance of ForceMate bushings, the National Research Council of Canada (NRC) developed a methodology to analytically determine the fatigue life improvement factor (LIF) resulting from the installation of ForceMate bushings. To achieve this, the residual stress field, resulting from the installation of a ForceMate bushing, was calculated by using non-linear finite element analyses (Figure 1), crack propagation was simulated to calculate the resulting crack shape and stress intensity factors (Figure 2), and AFGROW life prediction software was used to determine the crack growth life. The effect of the high interference cold expanded bushing was included in the crack growth life simulations. The analyses showed that the effect of the bushing could have significant impact on the crack growth life by shedding the load away from the crack tip. Based on finite element analyses, modelling the high interference bushing in the residual stress field reduced the hoop stress by up to 54% for an applied remote stress of 20,000 psi compared to an open-hole scenario with the same residual stress field. The hoop stress distributions, shown in Figure 3, also indicate that the effect of the high interference bushing decreases with the radial edge distance. However, significant LIF is expected as a large fraction of the total fatigue life is typically spent on crack nucleation and crack growth of small cracks. The hoop stress distribution was used to develop stress intensity correction factors as a function of crack length using a functionality available in AFGROW that scales the stress intensity factor solution of the open-hole solution according to the hoop stress distribution determined by NRC using finite element analyses. Based on these analyses, a LIF larger than 5 was analytically determined from the crack growth life ratios from an initial crack size of 0.010 inch to a final crack size of 0.4 inch between the model with residual stress and bushing effects and the open-hole baseline model without residual stresses.

Based on these initial results, NRC plans to: a) validate the modelling approach using other methods and tools, b) refine the analysis methodology by including the residual stress relaxation caused by crack growth and external loads, and c) compare experimental crack growth results against analytical crack growth predictions. There is also a joint effort between NRC and other organizations to measure and model the residual stresses induced by hole cold expansion. This effort will support the validation of the residual stress predictions using finite element methods.



a) Mandrel insertion b) Bushing reaming c) Residual stress field

Figure 1. Determination of the residual stresses induced by the installation of a ForceMate bushing using finite element analyses.



a) No residual stresses b) Within the calculated residual stress field

Figure 2. Propagation of a radial corner crack from an open hole.

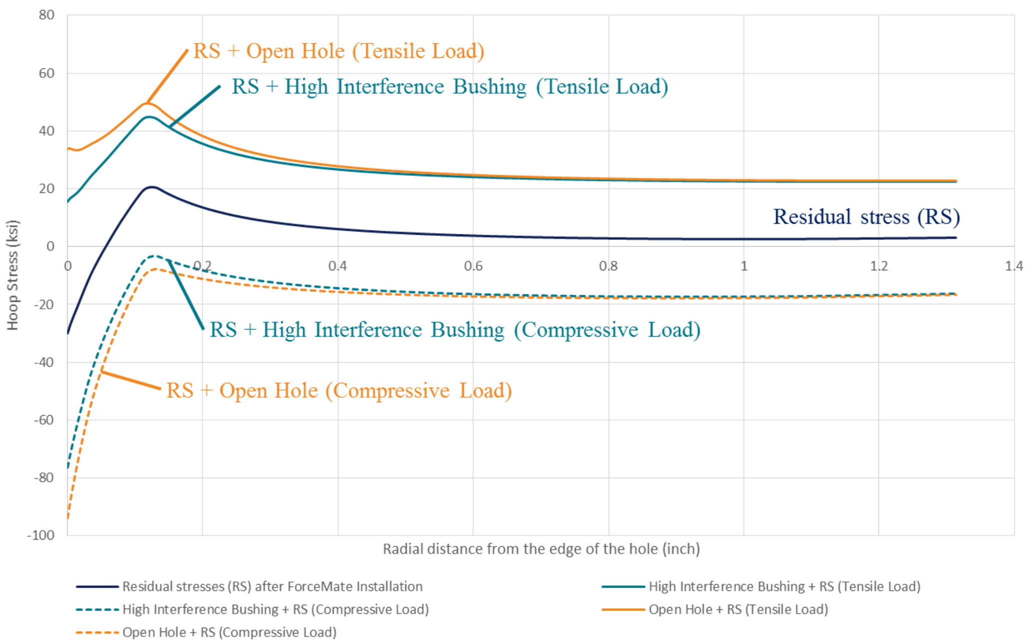


Figure 3. Effect of a high interference bushing on the hoop stress distribution around a cold expanded hole subjected to external tensile and compressive remote stresses of 20,000 psi.