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Numerical simulations of the fatigue damage evolution at a fastener hole treated by cold expansion or with interference fit pin

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ABSTRACT

Numerical simulations of the fatigue damage evolution at a hole in a plate treated by cold expansion or with interference fit pin is performed based on continuum damage mechanics and the finite element method. The damage-coupled Chaboche plasticity constitutive model is used to model the mechanical behavior of material. Plastic-strain-based and stress-based equations are used to calculate damage accumulation. The process of the hole cold expansion or pin interference fit and the subsequent fatigue damage evolution are simulated. The predicted results agree well with the experimental data available in the literature. Result shows that the beneficial effect of cold expansion and interference fit on the fatigue life improvement of a fastener hole is not only due to the reduction in maximum stress or stress amplitude, but also to the change in the fatigue damage evolution at the critical location.

1. Introduction

For many mechanical joints subjected to cyclic loads, fatigue cracks typically develop at fastener hole stress concentrations. In order to increase fatigue resistance of mechanical joints such as rivet and bolt joints, hole cold expansion or interference fit fasteners are widely used in aeronautical industry. In the cold expansion process, a significant amount of plastic deformation is produced around the hole by pulling an oversized tapered mandrel through the fastener hole. This process creates compressive residual stresses around the hole due to the recovery of the elastic deformation in the material. The compressive residual stresses reduce the maximum tensile stresses at critical locations when the component is subjected to tensile cyclic loading [1]. In the interference fit process, an oversized pin or bolt is inserted into the fastener hole during component assembly. This process creates mainly tensile residual stresses around the hole due to the hole being expanded by the oversized pin or bolt. Although the tensile residual stresses increase the mean stress when subjected to cyclic loading, the stress amplitude is significantly reduced due to the 'support effect' of the pin or bolt [2] and leads to fatigue life improvement. Either cold expansion or interference fit improves the fatigue resistance of the fastener hole by changing the stress and strain distributions around the hole.

Studies [3,4] has demonstrated that the cold expansion can improve the fatigue life of a fastener hole by a factor of 3–10. The beneficial effect of cold expansion is attributed to the compressive residual stress, which has the effect of extending both the crack nucleation and crack propagation periods by large proportions [1]. Experimental and finite element methods [5] were used to calculate the residual stress field. It is known that the fatigue striation crack lengths and the crack growth rates of cold expanded specimens are smaller than for those with untreated open hole [6–8]. There are scatter studies that have investigated the effect of interference fit on fatigue life of bolted or pinned joints [9–11]. It is supposed that the reduction in stress amplitude is the primary reason for the fatigue life improvement. However, the studies of hole cold expansion and holes with interference fit rely upon experimental tests, and the knowledge for fatigue life improvement is limited to date and the explanations remain largely qualitative [10,12,13]. It is difficult to quantitatively analyze the effects of hole cold expansion or holes with interference fit on the resultant fatigue life improvement.

To estimate the residual stress effect on the fatigue life improvement of a fastener hole, life prediction methods require the inclusion of the analysis of residual stress and strain distributions around the hole. Chakherlou et al. [14,15] used the finite element method combined with different critical plane criteria (e.g., Glinka [16], Smith–Watson–Topper [17], Fatemi-Socie [18], etc.) to estimate the fatigue lives of specimens with cold expanded holes and holes with interference fit fasteners and showed that none of the criteria gave accurate results for all of the specimens tested. Matos et al. [19] used an analytical fracture mechanics

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approach to assess the effects of cold expansion on the fatigue life of a rivet hole. However, the approach simplified the cold expanded specimen into a 2D problem, and therefore failed to describe the fatigue crack location accurately. To predict the fatigue damage in cold expanded holes and those with interference fit fasteners, the conventional analytical methods only consider the effect of residual stress; plasticity damage and the subsequent fatigue damage evolution is not fully understood. Continuum damage mechanics provide a new method for describing the damage evolution in the material.

Continuum damage mechanics (CDM) [20] introduces a continuous damage variable to describe the degradation of materials. Based on thermodynamic and corresponding damage mechanisms, damage evolution laws combined with damage-coupled elasto-plastic or visco-plastic constitutive models can be used to model the evolution of ductile plastic damage, fatigue, creep and creep-fatigue interaction. The fundamental concepts of CDM can be found in publications by Kachanov [21], Lemaitre [22], as well as Lemaitre and Chaboche [23]. CDM has been widely used in engineering applications and research, which can also be used to simulate complicated mechanical behavior such as ratcheting-fatigue interaction [24] and fretting fatigue [25,26]. For accurate applications and when the coupling between strains and damage is strong, a coupled CDM approach is necessary. The constitutive models need to be implemented within a finite element code, and the damage accumulate cycle by cycle to take account of the material degradation and stress redistributions [27].

In this paper, the continuum damage mechanics approach combined with the finite element method are used to simulate the fatigue damage evolution in a fastener hole treated by cold expansion or with interference fit pin. Firstly, the process of cold expansion or interference fit is simulated to obtain the residual stress and strain field and the plasticity damage in the hole caused by those processes. Then the fatigue damage is simulated with consideration of residual stress, and elasticity and plasticity damage. The damage-coupled Chaboche plasticity constitutive model [23] is used to represent the material behavior, and plastic-strain-based and stress-based equations are used to calculate damage accumulation, which is implemented by a user material subroutine (UMAT in ABAQUS). The critical-plane SWT approach is used for comparison purposes. The performance of the proposed approach is verified by comparison with experimental results available in the literature, and to show to be superior to the SWT approach. The effects of cold expansion and interference fit pin on fatigue damage of a fastener hole are investigated.

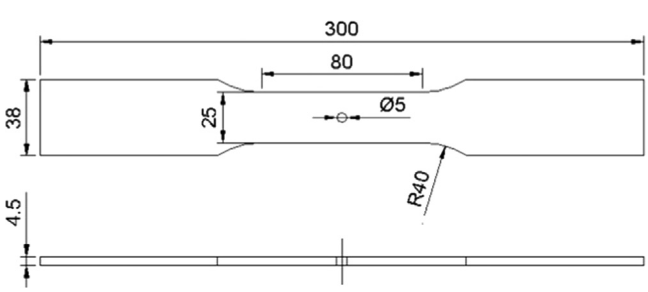

Fig. 1. Dimensions of the open hole specimens (mm) [28].

2. Fatigue experiments

The experiments of specimens with cold expanded hole and holes with interference fit pins performed by Chakherlou et al. [2,28] are simulated in this study. A brief overview of the experiments is presented here.

In the fatigue test of specimens with cold expanded holes [28], two groups of specimens (open hole and cold expanded) made of Al alloy 7075-T6 were tested. Fig. 1 shows the dimensions of the open hole specimen, in which the diameter of the central hole is 5 mm. The hole cold expanded specimen was produced by pulling an oversized tapered pin through the hole. The schematic of the process is shown in Fig. 2(a). The pin was made of En 24 grade steel and has an outer diameter of 5.2 mm, which will be used to produce a cold expansion of 4%. The dimensions of the pin are shown in Fig. 2(b). Fatigue tests were performed under the pulsating cyclic loading (loading ratio is zero). The applied cyclic loading P_{max} and the maximum remote stress in the cross-sectional area are shown in Table 1, and the fatigue test results are shown in Fig. 4(a).

To investigate the effect of pin interference fit on fastener hole fatigue life improvement, four groups of interference fitted specimens and one group of open hole specimens were tested in the literature [2]. The pin interference fitted specimen (Fig. 3(a)) was obtained by inserting an oversized steel pin into the hole of an open hole specimen. The material of the pin was made of AISI-D2 steel. The interference fit level is defined as $I = (d_2 - d_1)/d_1 \times 100\%$, where d_1 is the diameter of the hole and d_2 is the large diameter of the pin. Fig. 3(b) shows the dimensions of the pin causing an interference fit of 2%. Fatigue tests were performed at seven different maximum

Table 1
Maximum cyclic loading for the specimens with cold expanded hole.

P_{max} (kN)	14.63	16.88	19.13	21.38	23.65	25	27	29.03
Maximum remote stress (MPa)	130	150	170	190	210	222	240	258

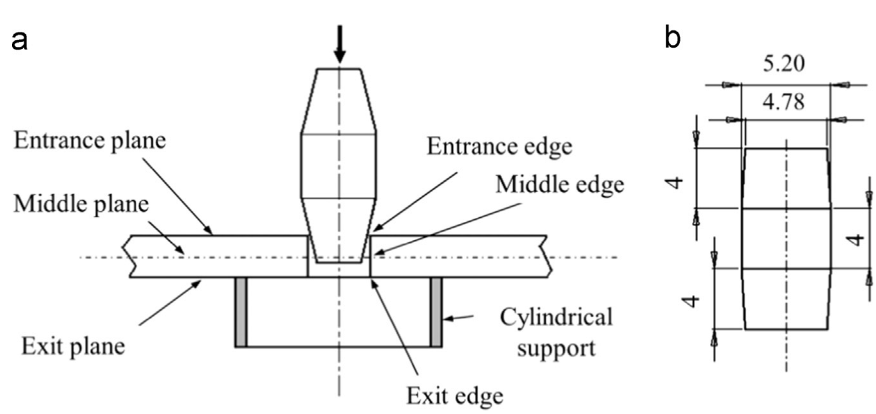

Fig. 2. (a) Schematic of the hole cold expansion process, (b) dimensions of the pin (mm) [28].