MECHANICS OF THE COLD HOLE EXPANSION OF AEROSPACE COMPONENTS

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ABSTRACT

Cold hole expansion is a commonly adopted cold working method for fatigue life improvement of aerospace structures containing fastener holes. This method involves the insertion of an oversized mandrel through the hole, which induces inhomogeneous plastic deformation in the surrounding regions. The unloading residual stresses resulting from this cold-working operation determine the fatigue life improvement of the structure. It is therefore the purpose of this investigation to conduct comprehensive three-dimensional elasto-plastic finite element analysis to evaluate the development and growth of the plastic zone and unloading residual stress resulting from the cold expansion of two adjacent holes. The contact between the mandrel and the hole was modelled using special contact elements, which employ the combined penalty-Lagrange multipliers formulation. Both simultaneous and sequential expansions of the two holes are considered.

INTRODUCTION

Fatigue is undoubtedly the most prevalent mode of failure in aircraft structures (Fig. 1). The consequence of failure of a primary load-carrying component in an airframe or engine is usually catastrophic, often resulting in loss of life and hardware. The designers of such systems are constantly faced with the challenge of establishing stress levels in these parts that will allow the use of suitable high strength materials to provide lightweight, high-performance structures. These structures should be sufficiently resistant to fatigue failure.

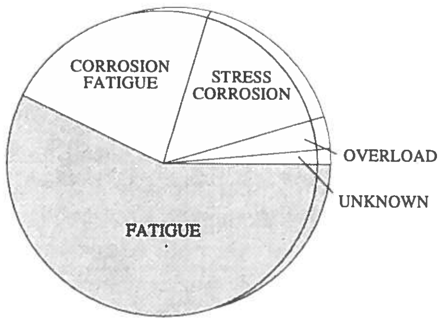
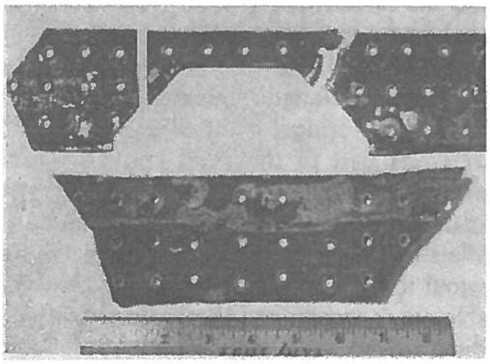


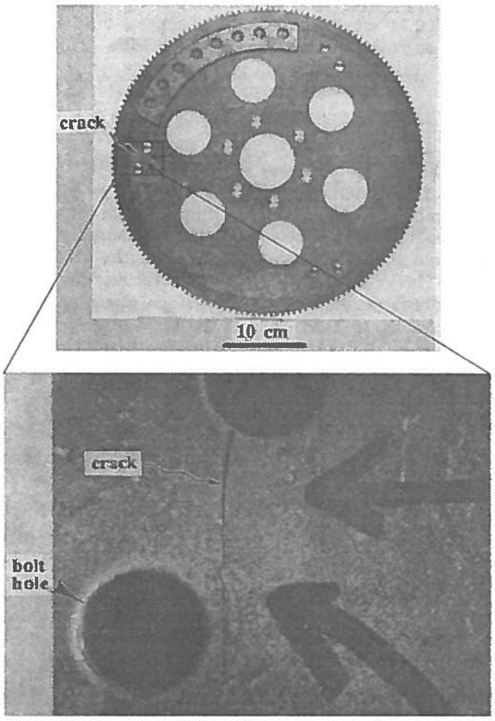
Fig. 1 Modes of failure in aircraft (after [1]).

Fatigue failure almost invariably begins at the root of geometrical discontinuities in highly stressed components, such as those depicted in Fig. 2. For example, the presence of interacting fastener holes in the upper skin assembly of a F-105 fuselage, depicted in Fig. 2(a), resulted in the fatigue failure and the ultimate fracture of the assembly. Fig. 2(b) shows the fatigue failure of a flywheel plate of a Station Wagon which was caused by excessive vibrations.

At this stage, it is important to identify the pertinent parameters which influence the fatigue strength of critical load bearing components/ assemblies. These include: (i) the presence of and the interaction between stress concentration features, (ii) the externally applied load, (iii) the induced residual stress field, and (iv) the toughness of the material selected. The importance of these parameters is evident in providing guidelines for: (i) the selection of the different geometrical features in newly designed/developed aircraft, (ii) the life assessment of aging aircraft, (iii) the introduction of beneficial residual stresses in airframe and engine components, and (iv) the selection of materials, such as Al-Zn alloys. The current literature indicates that these issues have not been given their due attention. It is the



(a)



(b)

Fig. 2 Examples of failures involving interacting holes: (a) aeronautical (after[2]), and (b) automotive industries (after[3]).

objective of this article to examine the mechanics of the cold expansion of fastener holes and to evaluate the development and growth of the plastic zone and unloading residual stresses resulting from the cold expansion of adjacent holes.

Cold expansion of fastener holes has been used for over forty years in the aerospace industry. It is a very efficient approach which results in the extending fatigue life of the treated part without any weight penalty. Until recently, particularly for civil aircraft, the technique was only applied to critical holes in highly loaded zones of the structure, such as landing gears and engine mounting regions. In modern aircraft, however, one may find over a thousand cold expanded holes in the wing alone. The requirement of increasing structural efficiency combined with a reduction in manufacturing costs has demanded a closer study of the cold expansion process.

Cold hole expansion is typically conducted using an oversized mandrel which results in inducing inhomogeneous plastic deformation around the hole. Upon unloading, a compressive residual stress field develops at and near the hole boundaries. This is equilibrated by tensile residual stresses away from the hole.

A major impediment to the use of ball or mandrel in the cold hole expansion of fasteners is the surface damage introduced at the interface during the cold expansion process. To overcome this difficulty, the split sleeve method has been developed. In this method (Fig. 3) a thin, dry lubricated sleeve is placed over the stem of the mandrel and is pushed into the hole creating an interference fit. The mandrel is then drawn back through the split sleeve. Aircraft holes commonly treated by this method range from 5mm to over 40mm in diameter, with expansions between 2% and 6% depending on the material and application (see Champoux [4]).

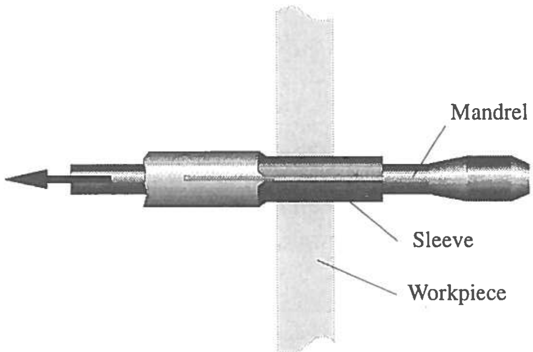


Fig. 3 Schematic of the split sleeve method.

The parameters that influence the residual stress field due to the expansion of an open hole and, therefore, the effectiveness of the process include process, geometrical, material and loading parameters [5].

One of the major process parameters is the hole expansion level. The optimum expansion level should be established for each material, loading and geometry. Another important parameter is the surface upsetting or part thickening which is inherent in the hole expansion process. This out-of-plane displacement occurs at both the entrance and exit sides of the hole and is always greater at the exit side (lip formation). This results in a non-uniform residual stress field throughout the thickness of the component, with greater values of compressive residual stresses at the exit side. Fig. 4 shows the fatigue fracture surfaces of two identical specimens which contain (a) an untreated hole and (b) a cold expanded hole. The figure indicates that for the untreated hole, the fatigue crack growth is the same on both sides of the specimen, resulting in a uniform crack profile. On the other hand, hole expansion leads to the introduction of a non-uniform residual stress field which results in a non-uniform crack profile. Subsequent reaming of the cold worked hole will also influence the effectiveness of the expansion process.

Entry Face

Fig. 4 Fatigue crack growth of (a) untreated hole, and (b) cold expanded hole (after [5]).

The geometrical parameters include the sequence of cold working, hole depth, hole surface finish prior to expansion, hole straightness, bellmouthing, barrelling, ovality and expansion levels for multi-hole patterns. The applied stress level and the material of the component constitute two other important parameters influencing the residual stress field before and during fatigue crack growth.

The result of the compressive residual stresses introduced by the cold hole expansion is the vast improvement in the fatigue life of airframe components. For commercial applications, the hole expansion is typically between 2% and 6%, depending on the material and the desired residual stress field. It has been reported in [5] that depending on the treated materials, hole expansion levels and loading conditions, the fatigue life improvement factor (LIF), defined as the ratio of the fatigue life of the treated hole to that of the untreated hole, ranges from 2 to 20. It has been shown in [6] that larger amounts of coldworking reduces the initiation life of fatigue cracks due to damage at the hole edge. Therefore, an optimum level of hole expansion has to be found for each material, loading conditions and hole geometry.

Analytical solution of the cold expansion of a single hole has been developed by Nadai [7] for ideally plastic material. Nadai's model was extended by Hsu and Forman [8] for a strain hardening material. Isotropic linear hardening and reverse yielding were considered in the solution of Rich and Impellizzeri [9] and Jongebreur and Koning [10]. Recently, Wanlin [11] extended the solution of Hsu and Forman to account for the finite width of the plate. In view of the limitations of the developed analytical solutions, the finite element method was adopted by Priest et al. [12]. Priest et al. also conducted X-ray diffraction to measure the radial hoop residual stresses around the expanded fastener hole in 2024-T351 alloy. Link and Sanford [13] also obtained the residual strain field surrounding a split-sleeve cold expanded hole in aluminum plates using moiré interferometry. Recently, a two-dimensional finite element analysis [14] was conducted by the authors to examine the effect of the presence of two adjacent holes upon the field variables. It is the objective of the current study to investigate the interaction effects resulting from the cold expansion of two adjacent holes using three-dimensional elasto-plastic finite element analysis. Both simultaneous and sequential expansions of the two holes are considered.

FINITE ELEMENT MODELLING

The situation envisaged is that of a plate containing two holes each of radius a with a centre distance c between the holes, as shown in Fig. 5. The dimensions of the plate were: width w=c+12a, height h=12a and thickness t=1.2a. These dimensions were determined carefully so as to avoid the effect of the boundary. The results were obtained for a=2.5mm. For the case of simultaneous hole expansion, only one quarter of the plate was discretized. For the case of simultaneous expansion, one half of the plate was modelled. Twenty-noded hexahedral elements were used in the neighborhood of the mandrel to capture the large stress variation in that region. The remaining region of the plate was conveniently discretized using ten-noded tetrahedral elements. A number of convergence runs were conducted using different discretized geometries. Fig. 6 shows a typical mesh for the case of sequential expansion. The material properties used for the workpiece were that of aluminum alloy 7075-T651 with E=72 GPa, ν=0.32 and an initial yield stress of σ_0=506 MPa. The material of the mandrel was that of high strength hardened steel. Throughout this work, the authors utilized the ANSYS finite element code.

The interface between the mandrel and the hole surface was modelled using contact elements. The three-dimensional contact element used adopts a contact node-target segment approach in conjunction with the penalty function method. Elastic Coulomb's friction with a coefficient of friction μ=0.15 was used. Numerous convergence tests were conducted to evaluate the appropriate values of the normal and tangential stiffnesses. As a result the following values of K_n and K_t were selected: 10^{12} and 10^8 (N/m) respectively.

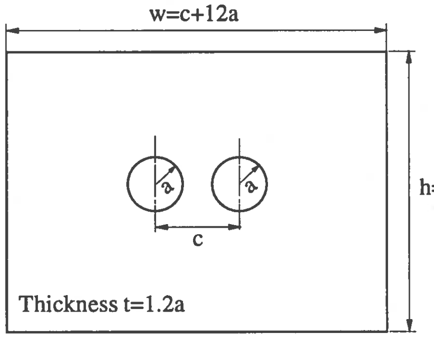


Fig. 5 Schematic of examined geometry.

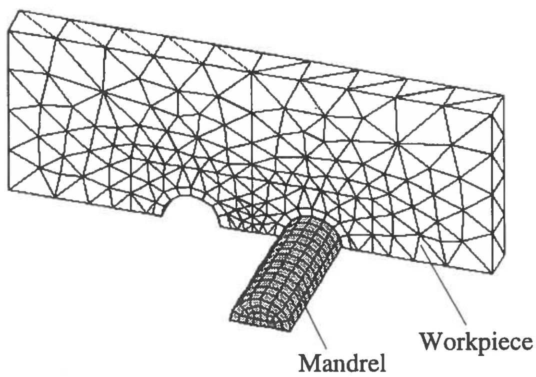


Fig. 6 Typical finite element mesh.

RESULTS AND DISCUSSION

To investigate the effect of the geometry, the centre distance between the two holes was varied from 3a to 10a. The outer boundary of the plate which was rigidly fixed was selected such that it does not affect the results in the regions surrounding the expanded holes. The total mandrel displacement (16mm) was simulated using a 20-step displacement history.

The von Mises stress contours for a centre distance of 4a at four different mandrel positions is shown in Figs. 7 and 8 for the case of sequential expansion of 2%. Both the entry and the exit views are provided. Consider first the expansion of the first hole, as shown in Fig. 7. At the initial entry stage (Fig. 7(a)), the mandrel is in contact with a small fraction of the fastener hole. In this case, the equivalent stress trajectories at the entry surface reveal the limited contact between the mandrel and the plate. When the mandrel is pushed further into the plate (Fig. 7(b)), both surfaces experience comparable levels of stresses. However, with the additional travel of the mandrel into the hole (Fig. 7(c)), the equivalent stress field at exit surface is dramatically increased. Fig. 7(d) shows the exit stage of the mandrel. The figure reveals the remarkable difference between the equivalent stress at exit and entry surfaces. This shows clearly the inability of two-dimensional modelling to accurately capture the plastic zone development and unloading residual stresses resulting from the cold expansion of two adjacent holes.

The same observations can be made for the sequential expansion of the second hole. It is clear from Fig. 8 that the expansion of the second hole changes the residual stress field around the first hole. Fig. 8(d) shows the final exit stage of the mandrel. Again, the figure reveals the remarkable difference between the equivalent stress at exit and entry surfaces. It also shows that the residual stress field around the first hole has been changed due to the expansion of the second hole.

Fig. 9 shows the variation of the tangential residual stress contours across the thickness of the plate at points B and B′ for a centre distance of 4a and an expansion of 4%. For comparison, the results of the simultaneous expansion analysis are also provided. It is clear that the sequential expansion leads to lower compressive residual stresses at the exit face of the workpiece, as compared with the simultaneous expansion.

Fig. 10 shows the variation of the tangential residual stress field in the region between the two holes for a centre distance of 4a and an expansion level of 4%. Regarding the stress field of the first hole, the figure indicates that the sequential expansion results in lower compressive residual stresses than the simultaneous expansion at the exit face of the workpiece. The figure also reveals that in the region between the two holes at the entry face, the residual stress changes rapidly from compressive close to the hole edges to highly tensile at the central point A. These high tensile residual stress combined with any tensile stresses resulting from the applied service load could lead to premature failure under conditions of cyclic loading.

CONCLUSIONS

Comprehensive three-dimensional elasto-plastic finite element analysis was conducted to evaluate the residual stress fields due to the cold hole expansion process of two adjacent holes. The contact between the mandrel and the hole was modelled using special contact elements. The work examined the effect of the geometry of two adjacent cold expanded holes upon the resulting

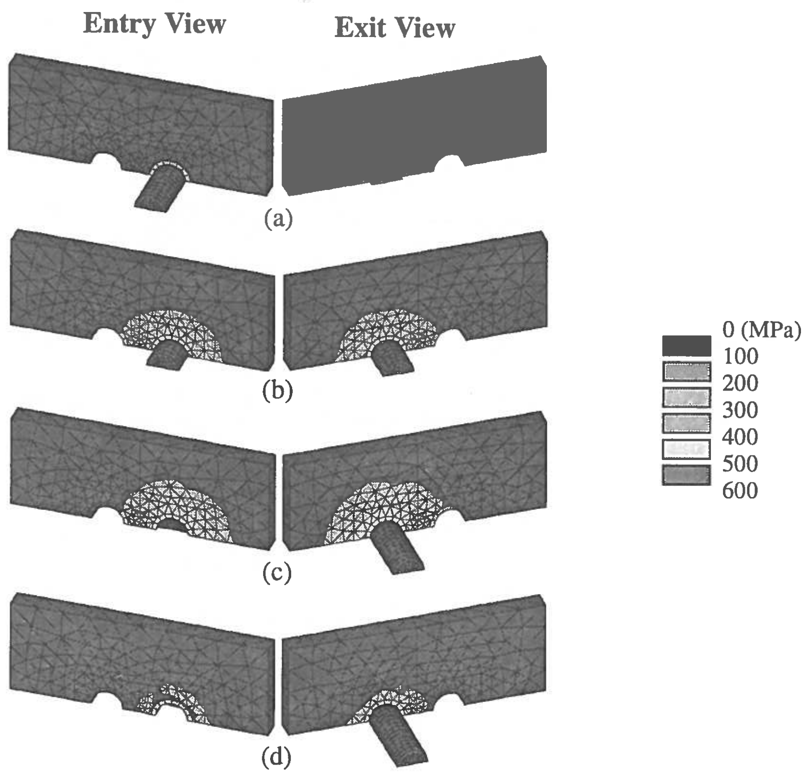


Fig. 7 Equivalent stress contours at entry and exit during the sequential expansion of the first hole for different mandrel strokes: (a) 10%, (b) 25%, (c) 60%, and (d) 100%.

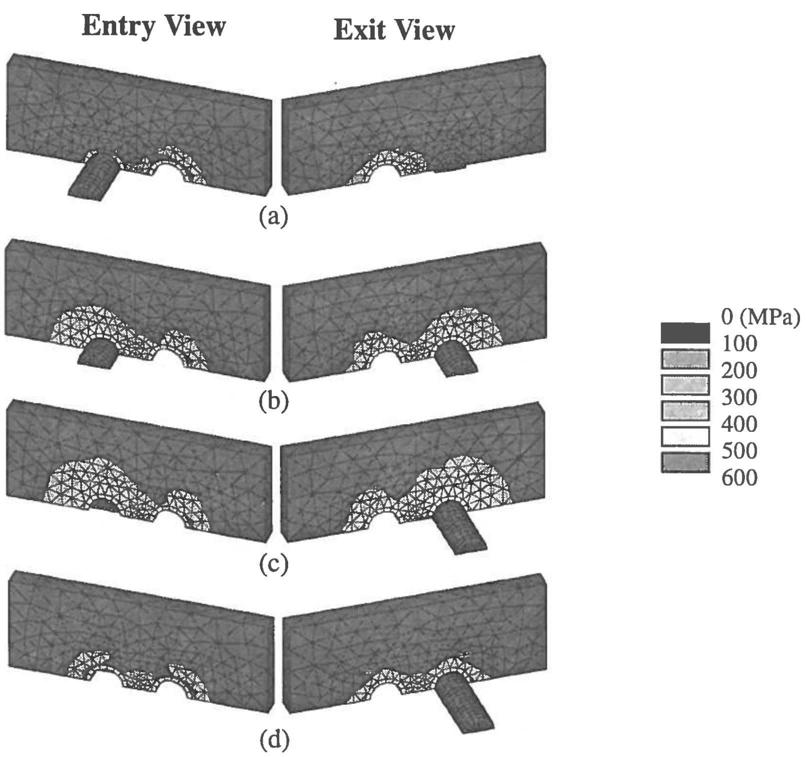


Fig. 8 Equivalent stress contours at entry and exit during the sequential expansion of the second hole for different mandrel strokes: (a) 10%, (b) 25%, (c) 60%, and (d) 100%.

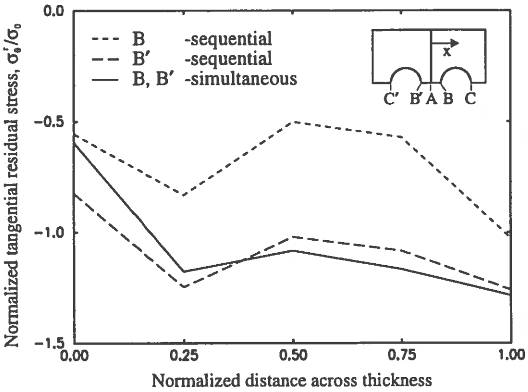


Fig. 9 Variation of normalized tangential residual stress $\sigma_\theta^r / \sigma_0$ through thickness at points B and B′.

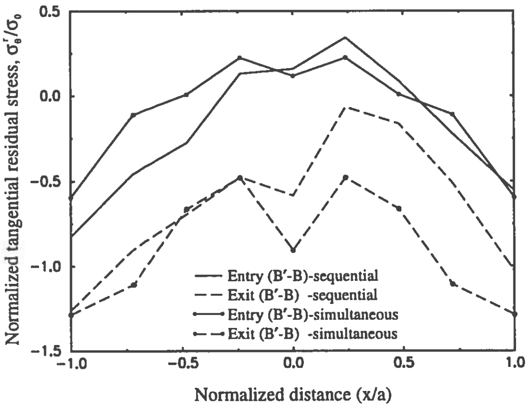


Fig. 10 Variation of normalized tangential residual stress $\sigma_\theta^r / \sigma_0$ along length BB′.

three-dimensional residual stress field. Both simultaneous and sequential expansions of the two holes are considered. The work reveals the following:

(i) two-dimensional finite element models are incapable of accurately predicting the residual stresses resulting from the cold expansion process,
(ii) improper cold expansion of adjacent holes can lead to high tensile residual stresses, and
(iii) sequential hole expansion results in lower compressive residual stresses at the exit face of the workpiece.

Acknowledgments

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