Cold Expansion of Elongated Hole: A Realistic Finite Element Simulation

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ABSTRACT

The aircraft wing pivot fitting components contain numerous elongated shaped holes for the purpose of functional requirements. Under operational loads, large stress concentrations are developed around elongated holes thereby leading to frequent in-service fatigue cracking problems. To overcome the fatigue cracking problems around elongated holes, different approaches such as shape reworking, shape optimization and cold expansion combined with interference fitting approaches are currently used as a repair/life extension options. In practice, application of these approaches for repairing or extending the fatigue life of elongated holes leads to either addition of material or modification of geometry. To economically repair or enhance the fatigue life of elongated hole without adding material and modifying hole geometries, a novel method derived from renowned hole cold expansion process is proposed in the literature. In order to investigate the benefit of implementing proposed novel cold expansion method for elongated hole, a simplified three-dimensional non-linear Finite Element (FE) simulation is carried out in this work. From the FE simulation of novel cold expansion method, induced beneficial residual stress distributions around and along the thickness direction of elongated hole is predicted. The predicted results indicate that significant beneficial residual stresses are induced throughout the thickness surface of elongated hole. Also, the induced beneficial residual stresses are found to significantly vary along the thickness direction of elongated hole. These beneficial residual stress predictions can be further used to quantify the fatigue life enhancement benefit around elongated hole.

Keywords: Elongated hole, Cold expansion, Beneficial residual stresses, Fatigue life enhancement

1. INTRODUCTION

Aircraft industries are continuously facing challenges in developing the light weight structures with increased durability and damage tolerance. One such example is the frequent in-service fatigue cracking problems around fuel flow vent holes of wing pivot fittings in F-111 aircrafts [1-3]. These fuel flow vent holes are machined elongated holes with semi-circular ends (i.e. non-circular holes) in wing pivot fitting components for the purpose of allowing fuel flow in the wings. Among several such functional elongated holes in wing pivot fittings, some of the elongated holes are extremely vulnerable for pre-mature fatigue cracking owing to flight operational loads [4-6]. To repair the fatigue damaged elongated holes, different life extension approaches viz. shape reworking, shape optimization and cold expansion combined with interference fitting approaches are used in practice [1-6].

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In shape reworking approach, the material layers on the elongated hole boundaries are progressively machined to slightly higher sizes so that the material layers containing fatigue cracks are completely eliminated [1,4]. Although shape reworking eliminates fatigue cracking problem during repair stage, it is not possible to avoid fatigue cracking problems which arise during later stages of service-life of component. The shape optimization approach involves optimizing fatigue damaged elongated hole shapes with an objective of minimizing stress concentrations and maximizing fatigue life/damage tolerance by employing optimization algorithms [1, 6]. Although optimization of elongated hole shapes significantly reduces the peak stresses at stress concentration locations, the production of optimized hole shapes often poses difficulties due to complexities in hole geometries. Hence, to overcome the limitations of shape reworking and shape optimization approaches, cold expansion combined with interference fitting approach is developed. In this approach, a specially designed oversized mandrel/sleeve combination made of hardened material is permanently inserted into elongated hole opening causing cold expansion combined with interference fitting. As a result, compressive residual stresses are developed around damaged elongated hole impeding the fatigue crack initiation/propagation under in-service operational loads [1-6]. Though the cold expansion combined with interference fitting approach is found to be capable of enhancing the fatigue life of elongated holes to larger extents, it leads to addition of extra material on the wing pivot fitting assemblies. Application of proceeding approaches in repairing fatigue-damaged elongated holes lead to either shape modification or material addition thereby posing a difficulty in meeting one of the mandatory air-force durability and damage tolerance certification requirements. This requirement insists to prevent or repair fatigue damaged structural holes without adding extra material and imposing costly structural replacements [7-8].

To overcome the aforementioned limitations of different life extension approaches, a novel cold expansion method which is derived from renowned hole cold expansion process is proposed in Ref. [9] for enhancing the fatigue life of elongated holes. Although, the novel method of cold expansion for elongated holes is proposed, none of the researchers have previously attempted to investigate the method in-detail and quantify resulting fatigue life enhancement benefits. Hence, an attempt is made in the present work to realistically simulate the novel cold expansion method for typical elongated hole in Al 7075-T651 plate and adequately predict the cold expansion-induced beneficial residual around the elongated hole and its thickness directions by developing a simplified FE framework.
2. A NOVEL COLD EXPANSION METHOD FOR ELONGATED HOLE

The proposed novel cold expansion method can be implemented on fatigue-damaged elongated hole in two steps as schematically illustrated in Fig.1. In first step, a specially designed hard metal insert is tightly fitted into elongated hole opening in such a way that circular hole region is obtained at one of the ends as shown in Fig.1. Further, a hardened and tapered mandrel of size greater than the diameter of hole region is gradually forced into hole region from one (entry) side and subsequently removed from the other (exit) side. As an effect, the material surrounding semi-circular end region of the elongated hole is cold expanded similar to regular cold expansion process [9-11].

![Figure 1. Schematic of steps involved in cold expansion of elongated hole](image)

In second step, the hard insert is reversed and again fitted into elongated hole opening so as to obtain circular hole region at other end of the elongated hole. The obtained circular hole region is further cold expanded by gradually passing the oversized mandrel and the operation is completed by removing the insert. This novel method of cold expansion process can be applied to critical elongated holes either during manufacturing stage or repair stage. As a result of cold expansion, permanent compressive residual stresses are induced around stress concentration locations such as semi-circular ends of elongated hole. The extent of compressive residual stresses induced around semi-circular ends of elongated hole depends on the diametrical interference between maximum diameter of the mandrel and diameter of the circular hole region. Although, the compressive residual stresses are induced in all three-dimensions such as radial, tangential and transverse (thickness) directions, the residual stresses induced in tangential directions are effective in preventing fatigue crack.
initiations/propagations. Hence, these tangential residual stresses ($\sigma_{\theta}$) are termed as beneficial residual stresses which actually lead to fatigue life enhancement of cold expanded elongated holes.

3. THREE-DIMENSIONAL FINITE ELEMENT SIMULATION OF COLD EXPANSION OF ELONGATED HOLE

To investigate the benefit of implementing proposed cold expansion method to elongated hole, a three-dimensional non-linear FE simulation is carried out. For the purpose of simulation, a typical elongated hole configuration made of aircraft grade Al 7075-T651 material as shown in Fig.2 is considered. Owing to the symmetry of the geometry considered (Fig.2), only quarter symmetry FE model is created in FEA tool (ANSYS) as shown in Fig.3. In this model, 9,568 numbers of 8-noded solid 185 element type are used after ensuring mesh convergence through number of trial runs. The material properties for present FE simulation is obtained from the true stress-strain curve reported in Ref. [12]. These properties include elastic modulus=72 GPa, Poisson’s ratio=0.3 and yield strength ($\sigma_y$) = 506 MPa. The elastic-plastic behavior of the material is modeled using tangent modulus of 1000 MPa under Mises plasticity option with isotropic hardening rule.

The situation of implementing proposed cold expansion method to elongated holes can be considered as equivalent to sequential cold expansion of two closely spaced adjacent circular holes (Fig.1). Taking this consideration into account, the mechanics of cold expansion process around closely spaced adjacent holes have been reviewed from the published literature [12-16]. It is identified that either simultaneous or sequential cold expansion of closely spaced adjacent holes (hole centre-to-centre spacing is equal to two times the hole diameter) induces approximately same level of compressive residual stresses around the holes. Hence, during simulation of cold expansion for elongated hole, it can be considered that both circular hole regions (at either semi-circular ends) are simultaneously cold expanded for the purpose of simplifying FE modelling and reducing computational time.

The complete cold expansion method for elongated hole is simulated in two stages viz. gradual expansion of the material layer by layer on semi-circular end during first stage and release of expanded material layer by layer in the same sequence during second stage. For accounting the effects of layer by layer material expansion and relaxation, the total thickness (3 mm) of the plate is divided into 8 equal elemental divisions as shown in Fig.3. These 8 divisions are further grouped as three layers having 3 elemental divisions in each layer. This
grouping of layers is only for the purpose of studying through thickness effects, whereas, in the actual plate, the material along the thickness is continuous. In the first stage of simulation, each layer along the thickness direction is sequentially expanded one after the other starting from mandrel entry side (top plane) and moving towards the exit side (bottom plane) of the plate. The expansion of each layer is simulated by applying the displacements that causes circular hole region to expand by 2 % of its diameter (expansion level). This indicates the gradual engagement of mandrel into circular hole region from the entry side (top plane), expansion of material along hole thickness direction and removal of mandrel from the exit side (bottom plane).

![Figure 2. Dimensions (mm) of the plate with elongated hole](image)

(R- Radius of the semi-circular end, C- Spacing between semi-circular ends)

In the second stage of simulation, all the displacements which are applied in first stage of simulation are successively removed layer by layer starting from mandrel entry side towards the exit side of the plate. This indicates the gradual elastic-plastic recovery (spring-back) of expanded material on the circular hole region starting from mandrel entry side to exit side. Throughout the simulation, the effect of insert in elongated hole slot is considered by constraining the displacements on straight edge portion of elongated hole boundary. Whereas, in actual cold expansion situations, after cold expansion of circular hole regions at either ends of elongated hole, the insert is permanently ejected-out thereby leaving the semi-circular ends

![Figure 3. Quarter symmetry FE model of the plate with elongated hole](image)
in cold expanded state. Thus, after the complete FE simulation, the semi-circular ends of elongated hole are in cold expanded state.

4. RESULTS AND DISCUSSIONS

4.1 Validation of Finite Element Simulation Framework

To validate the FE simulation framework developed for simulating the cold expansion of elongated hole in the present work, either experimental or numerical results are not available in literature. Hence, for validating the present FE simulation framework, the case of two adjacent circular holes whose radius equal to end radii of elongated hole is considered in the configuration identical to elongated hole configuration shown in Fig.2. For this case having two adjacent circular holes in the plate of dimensions shown in Fig.2, the results of sequential cold expansion process is available [16]. Therefore, for the purpose of validation, a separate half-symmetry FE model having two adjacent circular holes is developed as shown in Fig.4 using 14,896 numbers of 8-noded solid 185 element type after testing mesh convergence.

![Figure 4. Quarter symmetry FE model of the plate with two adjacent circular holes](image)

To capture through thickness variation effects, the thickness (3 mm) of the plate is discretized into 8 equal elemental divisions as shown in Fig.4. The complete simulation of cold expansion around adjacent circular holes is carried out through several loading steps by following the FE simulation framework employed for elongated hole. From the FE simulation on cold expansion of adjacent circular holes for 2 % expansion level, the beneficial residual stress distribution is predicted and presented in Fig.5. It is evident from Fig.5 that cold expansion-induced beneficial residual stresses vary throughout the thickness of holes starting from a minimum magnitude of 228 MPa (compressive) to maximum magnitude of 606 MPa (compressive). Also, the beneficial residual stress variations on top and bottom planes of two adjacent holes are predicted and validated with published results [16] as shown in Fig.6. This validation study shows that present simplified FE simulation
framework is capable of realistically predicting through thickness variations of cold expansion – induced beneficial residual stresses. Hence, the developed simplified FE simulation framework is reliably extended to simulate the cold expansion of elongated hole.

![Image](image1.png)

**Figure 5.** Beneficial residual stress distribution around adjacent circular holes

![Image](image2.png)

**Figure 6.** Variation of normalized beneficial residual stresses over the normalized distance on hole center line section

### 4.2 Beneficial Residual Stresses around Cold Expanded Elongated Hole

The beneficial residual stress distributions predicted around cold expanded elongated hole is as shown in Fig.7. It is clear from Fig.7 that significant beneficial residual stresses are induced around the hole and along the thickness direction of critical locations viz. semi-circular ends of elongated hole. These beneficial residual stresses are found to significantly vary throughout the thickness of elongated hole starting from top plane to bottom plane. Under remote fluctuating loads, sections HH¹ and VV¹ shown in Fig.2 are found to be critical for fatigue failures around elongated hole. Hence, the variations of beneficial residual stresses
on different planes (top, mid-thickness and bottom) of critical sections (HH'1 and VV'1) are predicted and presented in Figures.8 and 9. Also, the through thickness variations of beneficial residual stress at two critical locations (H and V) on elongated hole boundary is predicted as shown in Fig.10.

![Figure 7. Beneficial residual stress distribution around elongated hole](image)

Along the thickness of location ‘H’, the beneficial residual stresses vary from a minimum magnitude of 171 MPa (compressive) on bottom plane to 613 MPa (compressive) on a plane which is at a distance of 2.25 mm from top plane (Fig.10). Similarly, along the thickness of location ‘V’, the beneficial residual stresses vary from a minimum magnitude of 444 MPa (compressive) on bottom plane to 633 MPa (compressive) on a plane which is at a distance of 0.75 mm from top plane (Fig.10). In the region between elongated hole edge and edge of the plate, the magnitudes of beneficial residual stresses are found to be maximum at semi-circular end and gradually decays over the distance away from the semi-circular ends as observed from Fig.8 and Fig.9. On top, mid-thickness and bottom planes, the beneficial residual stresses remain compressive up to 1.25 mm distance from the elongated hole edge (H and V) as shown in Fig.8 and Fig.9. Beyond this region, equilibrating tensile residual stresses of small magnitudes are induced up to certain distance and further decays to negligible magnitude as observed in Fig.7 and Fig. 8. Similar trend is observed for all the planes along the thickness direction. Due to the minimum magnitude of beneficial residual stress on bottom plane (Fig.10), the locations on this bottom plane are the most probable locations for fatigue crack initiation/propagation. As observed from Figures.7 to 10, the through thickness variation of cold expansion – induced beneficial residual stresses are due to non-uniform expansion/recovery of the material and difference in material support conditions along the thickness direction.
Figure 8. Variation of normalized beneficial residual stresses over the normalized distance on center line section HH of elongated hole

Figure 9. Variation of normalized beneficial residual stresses over the normalized distance on section VV of elongated hole

Figure 10. Variation of beneficial residual stresses through the thickness of critical locations H and V of elongated hole
Thus, the developed FE simulation framework is simple to implement and capable to adequately predict the cold expansion-induced beneficial residual stresses around the hole and along the thickness of elongated holes. The present predictions confirm the presence of significant beneficial residual stresses around the semi-circular ends and its thickness directions. As a result, the possibility of fatigue crack initiation/propagation around the semi-circular end locations are reduced thereby leading to appreciable fatigue life enhancement of elongated hole without adding extra material and modifying hole geometry.

5. CONCLUSIONS

- The simplified three-dimensional non-linear FE simulation frame work for realistically simulating the novel cold expansion method for elongated hole is developed
- The through thickness variations of cold expansion-induced beneficial residual stresses around the elongated hole and along the thickness directions are predicted
- Induced beneficial residual stresses are found to significantly vary throughout the thickness of elongated hole owing to very nature of cold expansion process
- Induced beneficial residual stresses reduces the tendency of fatigue crack initiation/propagation at the stress concentration locations (semi-circular ends) of elongated hole thereby leading to significant fatigue life enhancement
- The beneficial residual stress predictions from the present FE simulation can be further used to quantify the exact fatigue life enhancement benefit which can be achieved due to cold expansion

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REFERENCES