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SEQUENTIAL COLD EXPANSION AND RESULTING BENEFICIAL RESIDUAL STRESS PREDICTION AROUND ADJACENT FASTENER HOLES

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Abstract. Fatigue life of aircraft structure fastener holes are enhanced through cold expansion process, which creates an annular zone of compressive residual stresses around the hole. Durability and damage tolerance analysis of structures containing cold expanded adjacent holes require quantification of cold expansion-induced compressive residual stresses. Three-dimensional non-linear FE simulation of sequential cold expansion of two closely spaced adjacent holes in Al 7075-T651 plate is carried out to predict the beneficial residual stresses completely. Further, an experimental investigation on sequential cold expansion of adjacent holes is carried out using cold expansion tooling system developed in-house and the retained expansion levels are measured. Comparison of FE simulation results and results of experimental investigations indicate that developed simplified FE simulation approach is capable of adequately predicting cold expansion-induced beneficial residual stresses around the hole, including through thickness variations.

Keywords: fatigue life; adjacent fastener holes; cold expansion; compressive residual stress.

1. Introduction

Aircraft and aero-engine structures are often connected through mechanical fastener joints such as riveting, bolting etc. It is inevitable to drill series of holes in these structural components to achieve the fastener joints. Under operational fluctuating loads, large stress concentrations are developed around the fastener holes often leading to fatigue failures [1, 2].The fatigue strength of critical fastener holes is often enhanced through cold expansion process either during manufacturing stage or repair stage [1 - 3]. Typically, the cold expansion process for circular holes is carried out by forcing an oversized hardened mandrel into hole surface from one end of the plate (entry plane) and removing the mandrel from the other end of the plate (exit plane) as schematically illustrated in Fig.1. As a consequence of pulling the mandrel through the hole, the material surrounding the hole periphery is plastically expanded at the expense of diametrical interference between mandrel major diameter and hole diameter. Upon removal of the mandrel from exit plane, the expanded material on the hole surface is recovered (spring-back effect) starting from the entry plane and moving towards exit plane thereby creating an annular permanent compressive residual stress zone on the entire thickness of hole. These compressive residual stresses, particularly, tangential compressive residual stresses tend to reduce the stress concentration effects and impede fatigue crack initiations/propagations around hole regions, leading to fatigue life enhancements without any material additions and shape modifications [4]. Hence, the cold

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expansion–induced tangential compressive residual stresses are termed as beneficial residual stresses. The extent of induced beneficial residual stresses around hole region is controlled by the process parameter, namely level of applied expansion (I_a) as defined in Equation (1).

$$I_a = \frac{D_m - D}{D} \times 100, \tag{1}$$

where, D_m is the major diameter of mandrel and D is the initial hole diameter [5, 6]. In aircraft industry, from 2% to 6% expansion levels (I_a) are commonly used for the fastener holes, which range from 5 mm to 40 mm in diameters [7, 8]. After complete cold expansion of holes, certain level of expansion is permanently retained around the hole and it is known as retained expansion (I_r). This retained expansion level (I_r) around cold expanded holes is expressed as

$$I_r = \frac{D_{CE} - D}{D} \times 100, \tag{2}$$

where, D_{CE} is the diameter of cold expanded hole [6].

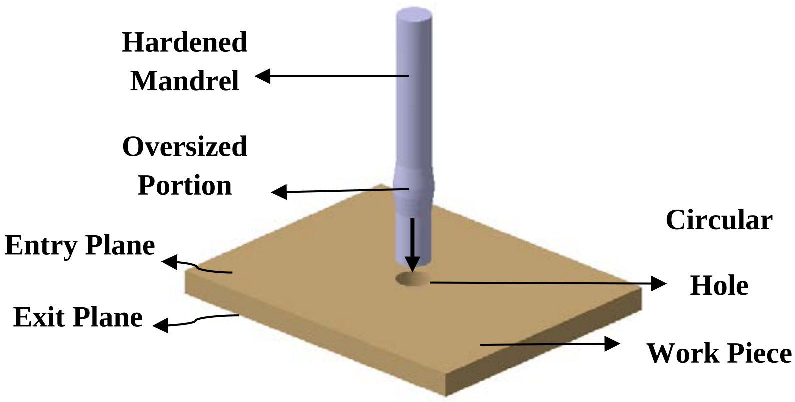

Fig. 1. Schematic of cold expansion process for circular holes.

To assure the durability and damage tolerance of aircraft structures having critical holes, it is required to exactly quantify the fatigue life enhancements, which can be derived from cold expansion process [4]. The fatigue life enhancement benefit can be precisely quantified by adequately measuring the cold expansion – induced compressive residual stresses around the holes and along the thickness directions. Although few experimental techniques such as X-Ray Diffraction, Neutron Diffraction, Sach's boring-out technique etc. can be employed for cold expansion – induced residual stress measurements, it is not possible to capture through thickness residual stress variations on holes due to the inherent limitations associated with each experimental technique [3]. Owing to such difficulties with experimental measurement techniques, many researchers have previously employed FE method to predict beneficial residual stresses around single hole, which is free from the influence of adjacent holes [2, 3].

The actual aircraft structures contain numerous fastener holes, which are separated by certain distances. In practice, these fastener holes are sequentially cold expanded one after the other. Although, the very nature and deformation mechanics of cold expansion process for single hole which is free from the influence of adjacent holes is very well reported in the literature, very limited studies [7 – 12] have attempted to study the efficacy of cold expansion process by considering the influence of adjacent holes. It is identified that cold expansion-induced beneficial residual stresses around one hole is influenced by the presence of adjacent hole, if holes are closely spaced (center-to center distance between the holes is less than four times the hole diameter) [10, 12]. In all the previous studies, complicated and time consuming FE modeling procedures i.e. by defining contacts between mandrel and hole thickness surfaces are employed for simulating cold expansion process for closely spaced adjacent holes [7 – 12]. Whereas, in the present work, a simplified and computationally less complicated FE procedure is developed for realistically simulating sequential cold expansion process for closely spaced adjacent holes and adequately predict resulting beneficial residual stresses. Owing to the favorable effects observed from FE simulation results, an experimental investigation on sequential cold expansion of adjacent holes is carried out by in-house developed cold expansion tooling system. As a consequence, the retained displacements around cold expanded hole peripheries are measured using high resolution profile projector. These retained displacement measurements and FE simulation predictions are compared for validation.

2. Sequential cold expansion of two adjacent holes: Three-dimensional finite element simulation

To thoroughly understand the very nature and the mechanics of sequential cold expansion process for closely spaced adjacent holes, a three dimensional, non-linear FE simulation is carried out for nominal level of expansion (I_a = 4 %). For the purpose of simulation, two closely spaced adjacent circular holes of 6 mm diameter (*D*) each separated by a center-to-center spacing (*C*) of three times the hole diameter (*D*) is considered in 6.35 mm thick plate (84.5 mm × 60 mm) specimen made of aircraft grade aluminum alloy (Al 7075-T651) as shown in Fig. 2. Owing to the symmetry of specimen geometry considered (Fig. 2), only half-symmetry FE model is developed using FE tool (ANSYS) as shown in Fig. 3. For developing the half-symmetry FE model (Fig. 3), 84,888 numbers of 8-noded brick 185 (solid 185) element type are used after testing grid independence through a series of trial simulations.

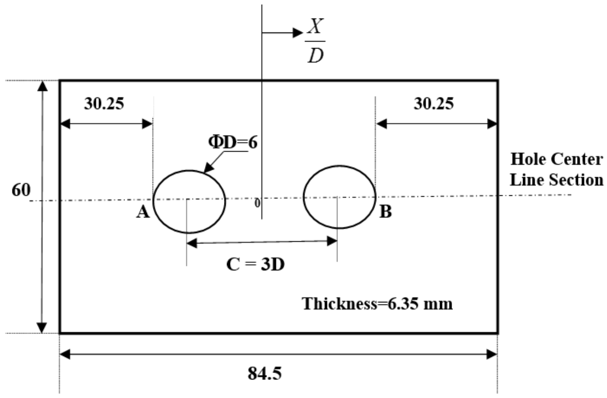

Fig. 2. Dimensions (mm) of the plate specimen.

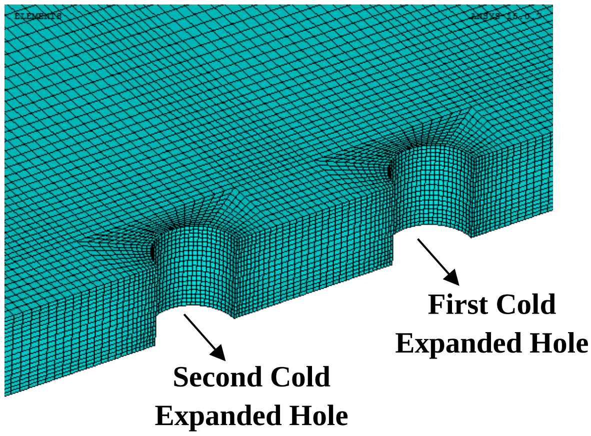

Fig. 3. FE model of the plate specimen with two adjacent circular holes.

In order to precisely capture the through thickness variation of beneficial residual stresses the total thickness (6.35 mm) of the plate is divided into 18 elemental divisions. These 18 elemental divisions are further grouped into three layers for the purpose of layer-by-layer cold expansion process simulation as per the realistic FE simulation approach suggested in Ref. [3]. Among the three layers, first and last layer consists of 4 elemental divisions each and these are located near the entry/exit plane of the plate. Whereas, the second layer consists of 8 elemental divisions and these are located near the mid-thickness plane. This layer-by-layer grouping of elemental divisions is only for the convenience of simulation. Otherwise, the material on the actual hole thickness surface is continuous. The true stress-strain curve of

Al7075-T651 material for the present FE simulation is obtained from Ref. [11]. The true stress-strain behavior is modeled using bilinear isotropic hardening model with Mises plasticity rule. For modelling isotropic hardening behavior, the elastic-plastic material properties such as elastic modulus = 72000 MPa, Poison's ratio = 0.32, yield strength = 506 MPa and tangent modulus =1000 MPa are employed.

In the actual sequential cold expansion simulation, initially, first (right side) hole is cold expanded followed by the second (left side) hole for same level of expansion. Each hole cold expansion simulation is carried out in two stages, namely gradual expansion of hole layer-by-layer in the first stage and elastic-plastic recovery of expanded layers in the second stage. In first stage of simulation, the displacements causing 4 % expansion of hole is sequentially applied to one layer at a time starting from entry plane and moving towards exit plane simulating the gradual expansion of material layer-by-layer as happens in actual cold expansion process. Further, in the second stage of simulation, the applied displacements on the layers are removed sequentially one at a time in the same sequence simulating the elastic-plastic recovery of expanded material layer by layer as happens in actual cold expansion process. After complete sequential cold expansion simulation, retained expansions and induced beneficial residual stresses around two adjacent hole regions are captured.

3. Experimental procedure

Set-Up for cold expansion process. To carry out the experimental investigations on sequential cold expansion process for two adjacent holes, the direct mandrel cold expansion tooling system is developed in-house. The developed tooling system consists of tapered mandrel assembly (combination of tapered mandrel, drill chuck and threaded rod) and fixtures for supporting specimen.

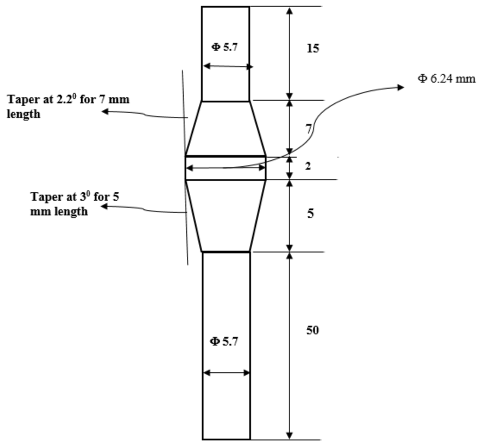

Fig. 4. Dimensions (mm) of the mandrel.

The mandrel is initially machined from high carbon high chromium steel to the dimensions shown in Fig. 4 and further hardened up to 60 HRC. The cold expansion operation was carried out using BISS make Universal Testing Machine (UTM) of 150 kN capacity. For cold expansion operation, the mandrel is pre-lubricated and the complete mandrel assembly is tightened to the end of hydraulic actuator unit as illustrated in Fig. 5. The specimen required for sequential cold expansion operation are prepared to the dimensions shown in Fig. 2 using 'as-received' Al 7075-T651 plate and supported firmly on the worktable through specially designed fixtures. During operation, the actual cold expansion process for two adjacent holes is carried out sequentially one after the other. In each hole cold expansion process, the hardened mandrel (6.24 mm major diameter) is initially forced into a hole (6 mm diameter) from the top of plate specimen (entry plane) causing 4% (I_a) expansion.

Measurement of retained expansions. As a consequence of sequential cold expansion of two adjacent holes, significant amount of beneficial residual stresses is permanently retained throughout the thickness of holes. In practice, the direct measurement of these cold expansion-induced beneficial residual stresses is very costly. However, the cold expansion-induced beneficial residual stresses can be qualitatively determined rapidly by measuring retained expansion (I_r) levels around cold expanded holes [6]. In the present work, the diameters of the adjacent holes are measured at entry and exit planes before and after cold expansion process using Profile Projector (Mitutoyo PJ-A3000). Using the measured diameters, the retained expansion (I_r) levels at entry and exit planes of both first and second cold expanded holes are determined using Equation (2).

4. Results and discussions

Retained expansion ratio. The retained expansion ratios (I_r/I_a) on entry and exit planes of both cold expanded holes as an average of measurements on three specimens are presented in Table 1.

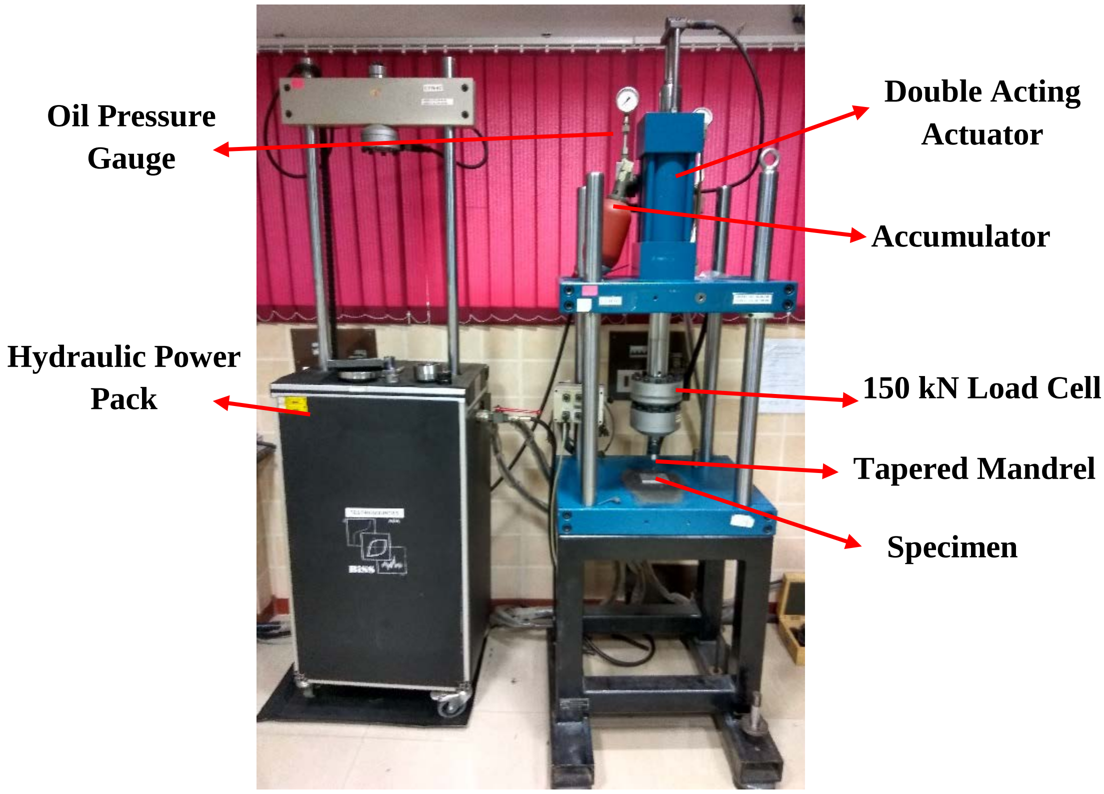

Fig. 5. Cold expansion tooling set-up.

In addition, the retained expansion ratios (I_r/I_a), obtained from FE simulation predictions are presented in Table 1 for comparison. The close agreements between experimental measurements and FE simulation predictions indicate that present FE simulation approach is capable of realistically simulating actual sequential cold expansion process for adjacent holes. From the FE simulation, the retained displacements after sequential cold expansion of two adjacent holes is predicted in the form of contour plot as shown in Fig. 6. It is evident from Fig. 6 that retained displacements vary significantly throughout the thickness surfaces of both holes starting from entry plane and moving towards exit plane. The deformations on entry and exit planes (due to mandrel engage/pull-out from entry/exit plane) are found to be higher than the deformations on intermediate layers between entry and exit planes. This indicates that deformations are non-uniform throughout the thickness surfaces of holes. The reason for such non-uniform deformations may be attributed to the difference in material support conditions along the thickness surface of the holes.

Table 1. Retained expansion ratios (I_r/I_a) around cold expanded holes.

Location	Retained Expansion Ratio (I_r/I_a)			
	Second Hole		First Hole	
	Experiment	FE Prediction	Experiment	FE Prediction
Entry Plane	0.92	1	0.94	1
Exit Plane	0.91	1	0.78	1

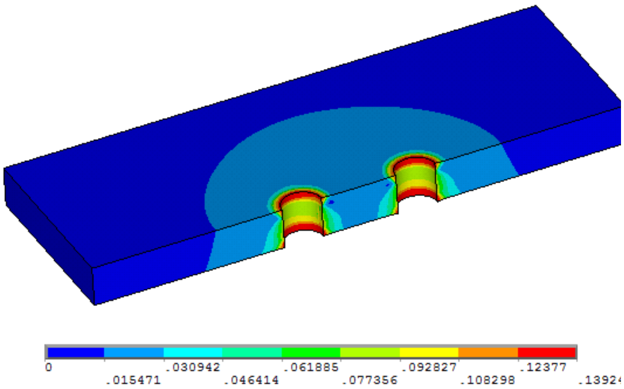

Fig. 6. Retained displacements after sequential cold expansion of adjacent holes.

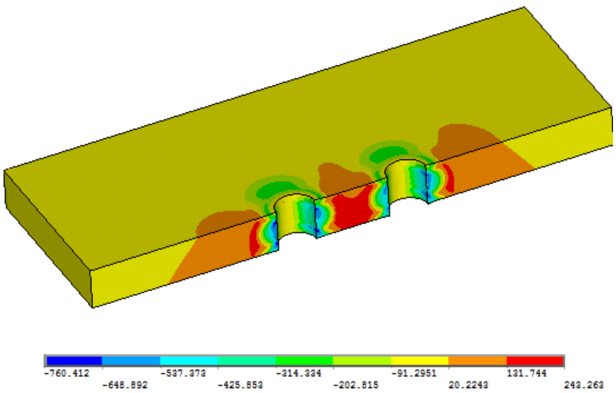

Fig. 7. Beneficial residual stress distributions around cold expanded holes.

Beneficial residual stress predictions. The beneficial residual stress distributions due to sequential cold expansion of two adjacent holes are shown in Fig. 7. It can be observed from Fig. 7 that induced beneficial residual stresses vary significantly along the thickness directions of holes starting from entry plane to exit plane. Under remote fluctuating loads, the locations A and B on hole center line section are found to be critical for fatigue failures. Considering the criticality of hole center line section, the through thickness variations of induced beneficial residual stresses at two critical locations (A and B) and along the hole center line section as a function of normalized distance from the center of plate are present in Fig. 8 and Fig.9, respectively. The magnitude of beneficial residual stress vary significantly from entry plane to exit plane by reaching the maximum value at a distance of 5.1 mm from entry plane as observed from Fig.7 and Fig.8. On different planes (entry, mid-thickness and exit) of hole center line section, the beneficial residual stresses are found to be compressive up to 2.1 mm away from the hole edges as indicated in Fig. 8. In the region between the holes, the magnitude of beneficial residual stresses vary from 249 MPa (compressive) to 128 MPa (tensile) on entry plane and 518 MPa (compressive) to 180 MPa (tensile) on exit plane as observed from Fig. 9. In the region between edge of the hole and edge of the plate, the magnitude of beneficial residual stresses vary from 252 MPa (compressive) to 105 MPa (tensile) on entry plane and 518 MPa (compressive) to 180 MPa (tensile) on exit plane. From these results, it is evident that significant amount of tensile residual stresses are developed in the regions, which are away from the hole edges.

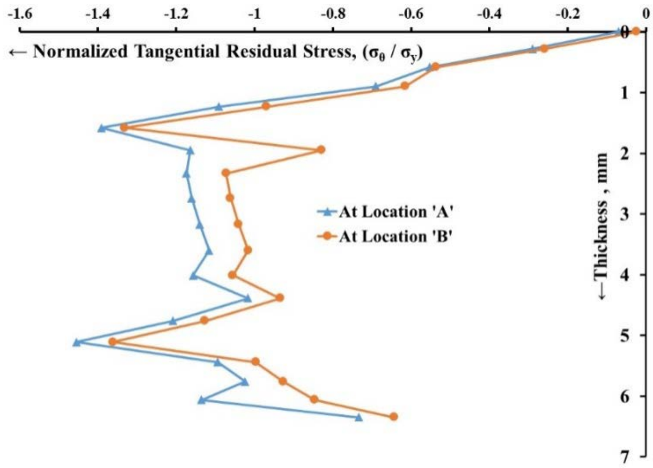

Fig. 8. Variation of residual stresses through the thickness at critical locations on hole center line section.

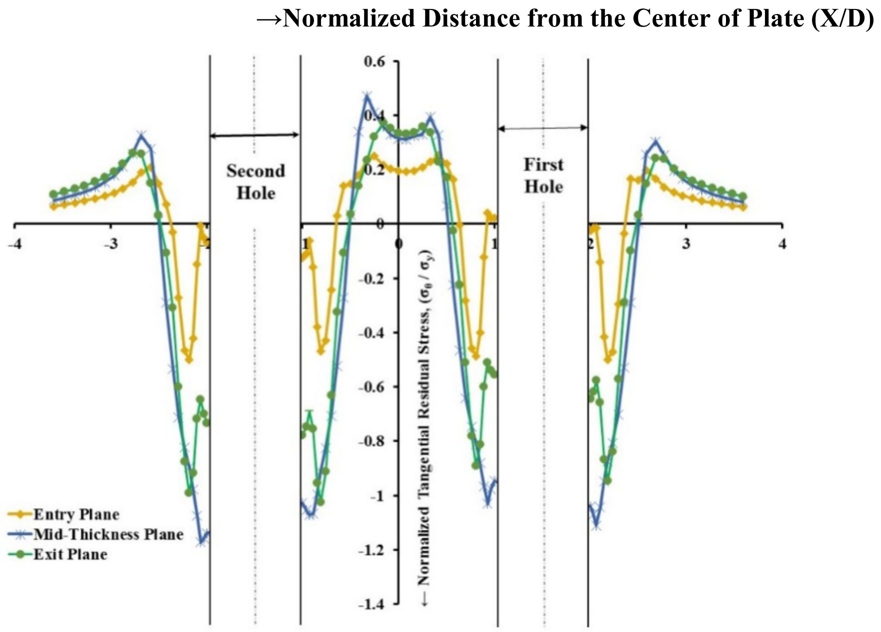

Fig. 9. Through thickness variation of beneficial residual stresses over the normalized distance on hole center line section.

The reason for developing tensile residual stresses between the holes are close proximity of two adjacent holes. Moreover, it is evident that induced beneficial residual stresses vary significantly throughout the thickness of holes as observed in Fig. 7 and Fig. 8. The reason for such through thickness beneficial residual stress variation may be due to the difference in material support conditions along the thickness surface of the holes and dynamic nature of cold expansion process. From these predictions, it is clear that the present FE simulation approach is capable of realistically capturing through thickness residual stress variations due to sequential cold expansion of adjacent holes. The developed approach is simple to implement, computationally less complicated and provides realistic predictions. Using the predicted beneficial residual stresses, the extent of fatigue life enhancement benefit around closely spaced adjacent holes can be quantified.

5. Conclusions

The sequential cold expansion process for closely spaced adjacent holes in Al 7075-T651 plate is realistically simulated by employing a simplified, three-dimensional non-linear FE simulation approach.

Through the developed FE approach, cold expansion-induced beneficial residual stresses around the hole and their variation along the thickness direction of closely spaced holes are predicted.

The beneficial residual stresses and retained expansions are found to vary significantly along the thickness directions of cold expanded holes. These variations are due to the very nature of cold expansion process and difference in material support conditions between entry/exit planes and intermediate layers of the plate.

Experimental investigation on sequential cold expansion of two adjacent holes also revealed that significant expansions are retained around hole peripheries.

Comparison of results obtained from FE simulation and experimental investigations prove that the developed FE approach is capable of predicting the effects of cold expansion accurately.

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