International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 4 Issue 03, March-2015

Numerical Study of Knife Edge Effects in Flash Riveted Single Lap Joint

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Abstract— **The purpose of this work is to describe the effects of the countersink depth on the residual hoop stress in a flash riveted single lap joint. In this research instead of three dimensional finite elements, a force-controlled two-dimensional axisymmetric finite element analysis has been carried out to simulate the rivet installation. Results from this analysis show that with decrease in countersunk portion of the outer sheet, the rivet expansion is larger in the upper skin, leading to an increase in the compressive residual hoop stress near the hole edge. Furthermore the countersink depth must not exceed 60% of the skin thickness and anything beyond that will cause the skin to become knife edged. Using press countersinking instead of machine countersinking is highly recommended for sheet thickness less than 0.032 inch**

Keywords— ***Flash Rivet, Knife Edge, Residual Stress, Single Lap Joint, Press Countersinking, Finite Element***

I. INTRODUCTION

The fuselage of an aircraft consists of sheet panels, stringers, and stiffeners held together by riveted lap joints. Although different joining techniques exist, the skin panels are typically fastened together with rivets. Numerous rivets are required to join the skin completely. Flight cyclic loading is due to the pressurization and depressurization of the fuselage, which occurs once every flight. The concentrated stress state at the rivet/skin interface combined with a large number of loading cycles is a primary cause of crack initiation at and around the rivet/skin interface. The result of the 1988 Aloha Airlines flight243 incident, in which a portion of the passenger compartment disintegrated during a short flight, forced the aerospace community to refocus the procedure developed to ensure the structural integrity of aircraft, civilian and military alike. Expert review of the Aloha Airlines incident attributed the disaster to the sudden linking of multiple undetected cracks at and around rivet holes in the metallic panels comprising the skin of the pressurized fuselage [1].The fatigue and static strength of joints are strongly influenced by the residual stress and strain induced by the riveting process[2-3]. To understand joint integrity, it is necessary to study the localized conditions of residual stress and strain at and around the rivet/hole interface generated during the rivet installation process. Because of the complexity associated with the riveting process, it is difficult to develop a closed-form theoretical solution. Experimental testing and finite element methods have been used to determine the stress state present in lap joints. Riveting of fuselage lap joints using a quasi-static force controlled method have been carried out in the past to better control the rivet installation and, thus, the consistency of the conditions at and around the rivet/sheet hole interface [4-8].Review of the literature shows that both the experimental and numerical methods have been applied to study riveted joints since 1990s.

Langrand, et al [4] applied a strain gage method to measure radial sheet strains during and after riveting. The method was applied to circular and square-shaped panels. They observed more than 20% compressive strain levels near the crushing edge and lower than 1% strain levels away from the edge while riveting. After riveting, the residual strains were similar to maximum observed during the process. The x-ray technique was applied by Fitzgerald and Cohen [5] to determine residual stresses around rivets in clad aluminum alloy sheets. They assumed an in-plane stress state over the depth of penetration. This technique was limited such that the entire residual-stress state at and around the rivet/skin interface could not be measured. Only residual stresses close to the sheet surface could be calculated. Muller [6] used photo elasticity, rivet-sheet spring back, and micro hardness to determine residual stress at the panel-mating surface. The experiments were however unsuccessful, and it was concluded that experimental measurement of residual stresses was not a simple task. Based on the force-controlled two-dimensional axisymmetric model, he studied the residual stresses for a range of squeeze forces. He concluded that a force-controlled rivet installation provided a more accurate control for the process. A detailed investigation into the influence of rivet installation force completed by Muller demonstrated that the fatigue life of riveted joints could be increased tenfold by increasing the squeeze force. Muller’s work was extended by Szolwinski and Farris [7] to analyze quasi static squeeze force controlled riveting process with the use of finite element modeling. They used a two dimensional axisymmetric model of riveting process, which was verified with actual experimental data. They found that as squeeze force increased, the magnitude of the compressive residual stress also increased, with expansion of rivet against the hole wall. Like Szolwinski, Li et al. [8] studied rivet driven head deformation, induced residual stress, strain and interference in the joint sheets under different squeeze forces, using two dimensional axisymmetric finite element model developed to simulate riveting process. They concluded that squeeze force was the most important factor in the riveting process. Numerical simulation showed that the connection between the upper sheet and rivet was weaker than the lower sheet. Due to this, fatigue cracks usually start at the mating surface and the hole edge, and propagate into the upper sheet. Markiewicz et al. [9, 10] and Li et al. [11] were used both micro strain gauges and neutron diffraction to understand the strain variations in joints during and after the riveting process. Because micro strain gauges are capable of capturing the strain variations on a lap joint surface during the riveting process, the variation in the load history can be determined. Ryan and Monaghan [12] simulated rivet installation with an elasto-plastic axisymmetric model for fiber laminate and typical aluminum alloy countersunk panels. A large deformation, nonlinear quasi-static analysis was conducted since sheet materials, 2024-T3, fiber metal laminate (FML), rivet, 2117-T3 alloy are not strain rate sensitive at room temperature. They concluded from the models that the localized compressive hoop stress after the riveting process increases fatigue life of panels. Sundarraj, et al. [13] studied 3D effects in double-shear single rivet lap joints via axisymmetric FE models. However, the model was only applicable in the absence of frictional forces and for limited number of loads.

The main objective of this study is about knife edge phenomena in flash riveting process. Flush rivets are used, primarily, on external metal surfaces where good appearance and the elimination of unnecessary aerodynamic drag are important. In the flush type riveting process, countersinking is accomplished with a special cutting bit which carves out a cone shaped depression for a flush fastener. Countersinking is permitted only when the surface skin is thick enough to accommodate the cutout depression without enlarging the rivet hole. Otherwise knife edge is appeared. The concern about knife edge is due to stress cycles causing fatigue cracks. In the riveting process of machine countersunk, cracks mainly initiated around the rivet holes in the upper skin. In flush fasteners, the influence of rivet head in conjunction with the skin thickness on the stress distribution is still largely unknown. So it is necessary to develop a model that accurately characterizes the behavior of riveting process and implement the model to rivet head height variations respect to upper skin thickness. Results show the countersunk depth must not exceed 60% of the skin thickness and anything beyond that will cause the skin to become knife edge. At the end, press countersunk (dimpled skin) joint has been studied as an alternative of machine countersunk joint for thin sheet and its result compare with the knife edge condition.

II. Model Verification

The riveting process is similar to metal flow problem due to large plastic deformation of rivet and sheet material around the rivet. It is includes contact problems at interface between punch and rivet end, rivet shank and sheet, and between upper and lower sheets. The riveting process is very complex due to following nonlinearities: geometry nonlinearity due to large displacement effects, boundary condition nonlinearity due to contact between tool and rivet, rivet and sheet, and in between rivets, martial nonlinearity due to plastic deformation.

The Finite Element (FE) method is a powerful numerical tool to simulate complex forming problems. A force-controlled two-dimensional axisymmetric model consisting of two circular pieces of sheet metal connected by a single rivet was implemented to simulate the rivet installation in majority of prior research. By using axisymmetric 2D elements, the need for 3D modeling is avoided.

In this study a force-controlled two-dimensional axisymmetric model has implemented to simulate the rivet installation too. The specimen configuration is shown inFig.1. It consisted of two 3×3inch (76.2 mm X 76.2 mm) bare 2024-T3 Aluminum alloy sheets, each .079inch (2 mm) thick, and one 2117-T4 Aluminum alloy flash type rivet MS20426AD8-9.

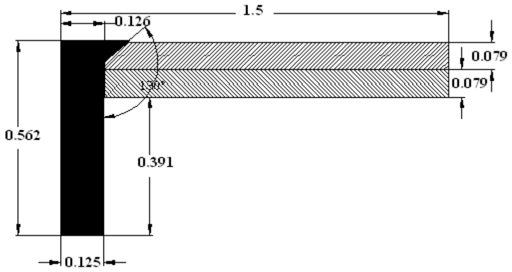


Figure.1 The specimen configuration for simulation

The material of the rivet and sheet is isotropic plasticity model with rate effect, which use power hardening rule, with following equation,

$$\sigma = C\,\varepsilon^{n} \qquad (1)$$

Where σ is true stress, ε is the true strain, C is a strength hardening coefficient and n is the strength hardening exponent. The material properties used in the simulations are from Szolwinski and Farris [7]. The elastic properties used for the bare sheets were E =10.5E6psi (72.4Gpa), ν =0.33, and initial yield stress, σy=40ksi (275Mpa), whereas these used for the 2117-T4 Aluminum alloy rivet were E =10.4E6 psi (71.7Gpa), ν =0.33, and σy=24ksi (165.4Mpa).The hardening parameters used for the sheets were C = 105.88ksi (730Mpa) and n=0.1571. The hardening parameters used for the rivet were C =79ksi (544.7Mpa) and n=0.23 when $0.02<\varepsilon \le 0.10$ and C =80ksi (551.6Mpa) and n=0.15 when $0.10<\varepsilon \le 1.0$.

A tabular listing of the stress and plastic strain values were put into a table provided by MSC.PATRAN interface, which used linear interpolation for values between the points to implement the hardening behavior of the model. For the boundary condition, the skin edge surfaces on one end were constrained in the x- direction, with the y- direction nodes constrained at top and bottom to prevent rigid-body motion. The rivet displacement was fixed at the head, while the squeeze force was applied at the rigid tool in contact with the rivet shank. The model includes contacts between rivet and sheets and in the interface between the upper and lower sheets, and between the riveting gun or squeezer and the rivet. The contact analysis was conducted using MSC.PATRAN automatic surface to surface contact. Coulomb friction at the interface was specified. A coefficient of friction of 0.20 was prescribed between all of the contact surfaces, reflecting data from friction tests with 2024-T351 aluminum alloy conducted in a separate study by Szolwinski[14]. Simulation of riveting allows for large plastic deformations of rivets which results in distorted elements in rivets. To minimize the distortion of elements in rivet, adaptive mesh is used. There is no need to have adaptive mesh in sheets because there is no excessive plastic deformation in sheets that lead to distortion of elements. Different mesh sizes were tested in the model to find an optimal mesh density. Mesh size for rivet was .004 inch and for upper and lower skin were .005 inch and .006 inch respectively. The process was simulated using MD.NASTRAN (SOL 400) in two steps: (1) a loading step in which the rivet was deformed by applied force and (2) an unloading step in which the rivet was allowed to spring back. Four squeeze forces were considered in this study: 6000lbf (26688N), 7995lbf (35561N), 10000lbf (44480N), and 12000lbf (53376 N). As previously studied the load-deflection behavior of the driven rivet head is used for verification of finite element model. The final deformed driven rivet head diameter and final deformed rivet head height predicted by the FE analysis was compared with experimental measurements for the range of squeeze forces. Table 1 shows this comparison.

Table 1: Comparison of Rivet Head Deformation as Predicted by the FE Method to Experiment Measurements [8]

	Rivet Head Diameter (in)		Rivet Head height	
Squeeze Force (lbf)	FE	Exp.	FE	Exp.
6000	.3341	0.336	0.227	0.228
7995	0.378	0.375	0.176	0.180
10000	0.397	0.4	0.158	0.157
12000	0.431	0.425	0.135	0.137

It can be seen the experimental results and the FE predictions agreed very well. Variations in the rivet driven head displacement vs. the 12000lbf squeeze force during the riveting process are presented in Fig.2.

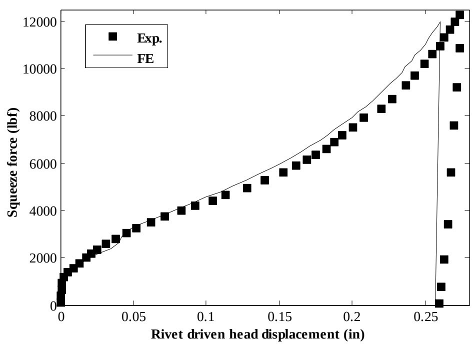


Figure 2: Comparison of rivet driven head displacement during entire riveting period

A slight discrepancy can be observed at unload and also at higher squeeze forces. The differences in the curves and the rivet deformation parameters can be attributed to geometry surfaces (which the FE model assumes perfect), numerical errors, and errors associated with experimental uncertainties. Taking into account these uncertainties, the FE predictions are observed to be in good agreement with the experiment. Fig.3 shows the deformed finite element mesh and contours of residual hoop stress after unloading step for 10000lbf squeeze force.

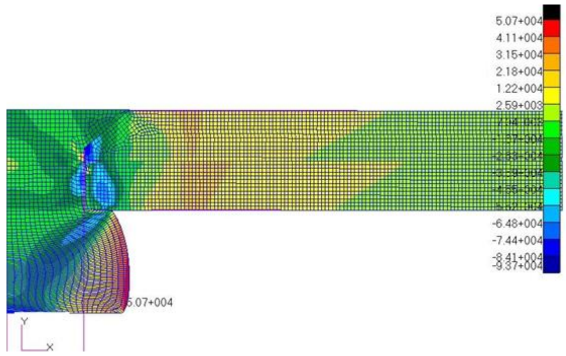


Figure 3: Residual hoop stress after unloading for 10000lbf

III. KNIFE EDGE EFFECT

As in the installation of conventional protruding head rivets, flush riveting starts with the drilling of the correct size hole for the rivet selected. The additional work generated by the use of flush rivets stems from the requirement to modify the drilled rivet hole to accept the cone shaped head of the flush rivet. This generally means that the drilled rivet hole will have to be either machine countersunk, or compression dimpled to provide the proper nest for the rivet head. With thin sheets, it has risked "knife edge" the countersunk hole. Knife edge, to the mechanic, means that there is no straight bore. A countersink and a straight bore hole are obtained by drilling a countersunk hole in a sheet or plate. If the countersink is too big, so there is no straight bore in the hole and then knife edge is appeared (Fig. 4).

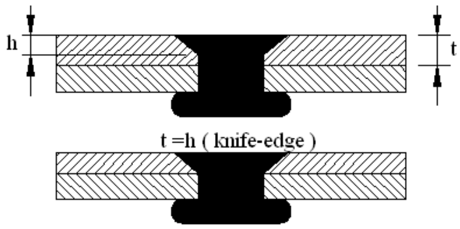


Figure 4: Knife-edge condition

Stress concentration in the outer sheet due to the presence of the knife edge reduces fatigue performance of countersunk rivet joints. Parametric studies were conducted to observe the effects of varying rivet head height respect to upper skin thickness on the Von-Mises and residual-stresses. Six upper skin thicknesses to rivet head height were considered in this study: 1.7, 1.5, 1.3, 1.2, 1.1 and 1(knife-edge) at 10000lbf squeeze force. Fig. 5 shows the contours of Von-Mises stress induce in the upper skin after unloading in the model for various skin thicknesses to rivet head height.

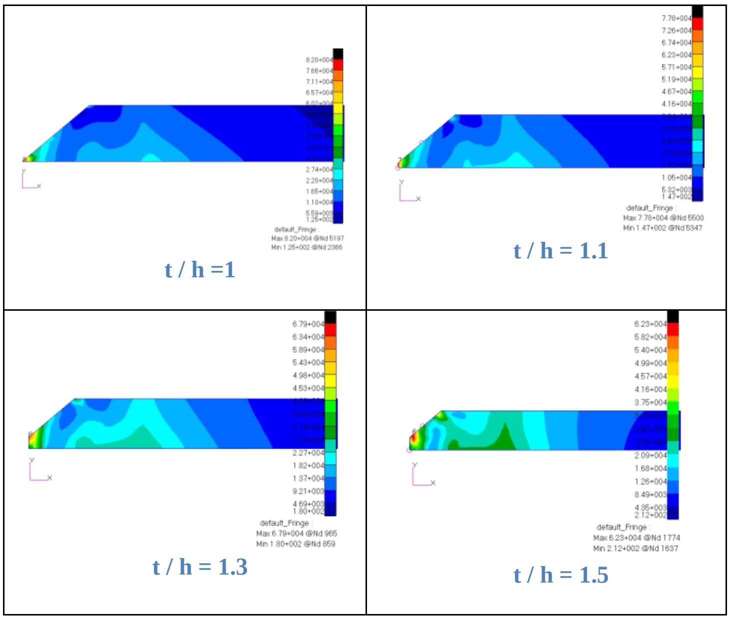


Figure 5: Von-Mises stress contour for upper skin at various t/h for 10000lbf squeeze force

As shown in Fig. 5 an increase in the rivet head height leads to a large Von-Mises stresses, consequently leading to fatigue crack initiation at or near rivet holes. Fig. 6 shows a plot of non-dimensional stress as a function of t/h at upper skin. The plot shows that for the ratio bigger than 1.5, stress variation is nearly constant. As a result, typical standard practice is to limit countersink depth to 2/3 thickness of the sheet. Anything greater, the skin is considered knife edge and a poor fatigue performance.

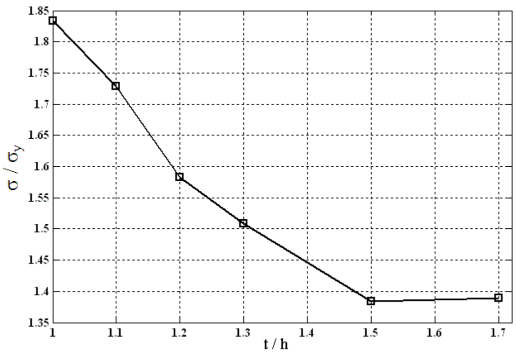
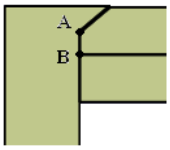


Figure 6: Non-dimensional stress as a function of t/h

Table 2 shows the rivet expansion for the several of t/h in the upper skin after unloading. During the process, the rivet expands against the hole and the contact pressure exceeds the yield point of the material ($\sigma_{xx}<\sigma_y$), the material deforms so that $\sigma_{zz}<0$. This compressive residual hoop stress is often induce around rivet holes prior to riveting by cold working the holes with an expanding mandrel to prevent fatigue cracks that might initiate around the holes. With a decrease rivet depth, the rivet expansion is larger in the upper skin leading to an increase in the compressive residual hoop stress near the hole edge.

Table 2: Rivet expansion at various t/h

Configuration (t /h)	Expansion at A (in)	Expansion at B (in)
1.1	0.00110	0.00143
1.2	0.00129	0.00153
1.3	0.00154	0.00169
1.5	0.00188	0.00212
1.7	0.002194	0.00255



As example of rivet deformation is shown in Fig. 7. As displayed in the contours of the residual hoop stress, the size and magnitude of compressive zone increase with decreasing rivet head height. The nature of this residual stress field plays an important role in the nucleation and growth of cracks in the vicinity of the rivet hole.

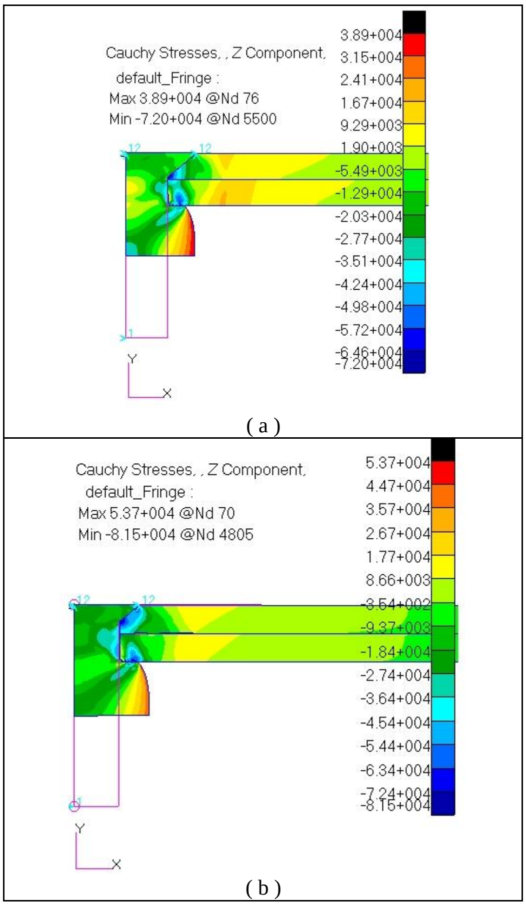


Figure 7: An example of residual hoop stress: a) t/h=1.1 b) t/h=1.7

IV. Dimpling

Generally 0.032inch (0.813 mm) is the minimum sheet thickness for countersinking. There are many airframe components with thickness smaller than the requirement. Mechanical attachment of these components with flush type rivets must be done using press countersinking (dimpling) instead of machine countersinking. Dimpling is the process of compressing the metal around a rivet hole, between a male and female die set, to create a nest for the rivet head (Fig. 8).

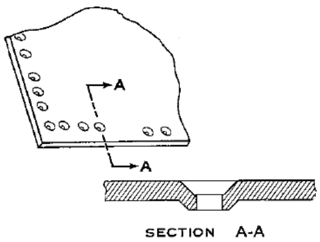


Figure 8: Press countersunk (dimpling)

Dimpling dies are made of heat treated steel and come in matched pairs. These dies, depending on their design, can be used with a rivet gun and a bucking bar, or with a rivet squeezer. Sometimes a hammer can be substituted for a rivet gun. With confidence established in the developed model to predict the stress state, the analysis was implemented to observe the effect of dimpled upper skin on the stress at the riveting process. The specimen consisted of two 2inch (50.8mm) × 2inch (50.8mm) bare 2024-T3 Aluminum alloy sheets with 0.03inch (0.76mm) and 0.04inch (1mm) thick for upper and lower skins respectively, and one 2117-T4 Aluminum alloy countersunk type rivet MS20426AD4-5. Fig.9 shows the deformed plot and contours of Von-Mises after unloading for 2600lbf (11565 N) squeeze force.

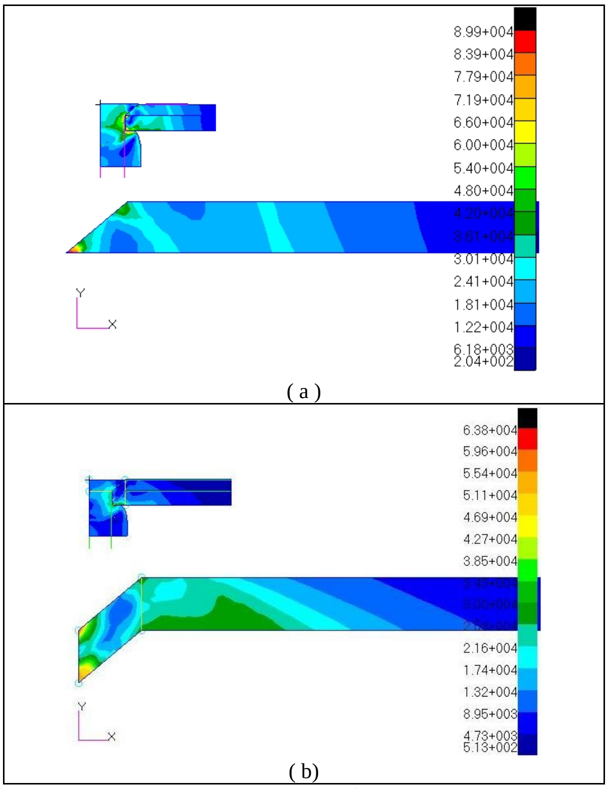


Figure 9: Von-Mises stress: (a) knife edge skin (b) dimpled skin

As shown in Fig. 9 dimpled skin decrease the Von-Mises stress near the hole edges. So the fatigue performance can be improved by retarding crack initiation around the hole. Residual stress distributions along the interface surfaces are important as making them a likely location for crack initiation. Fig. 10 compares the residual hoop stress distribution along these surfaces for knife edge and dimpled sheets under 2600lbf squeeze force.

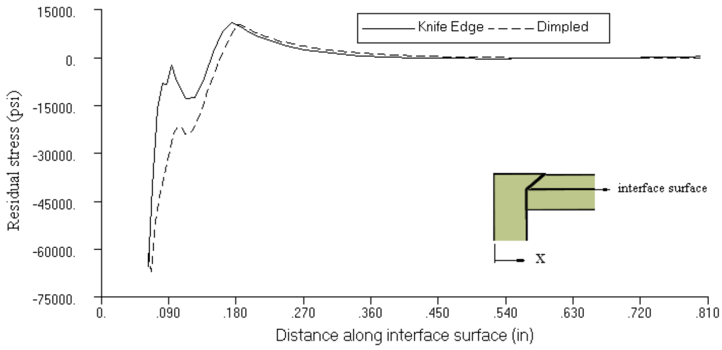


Figure 10: Hoop stress distribution along interface surface

Differences in the amount of radial expansion of the knife edge and dimpled sheet create a difference in residual tangential stress at the interface surfaces in the plastic region. Nearly identical residual stress distributions were observed for the both of them, while the wedge expansion mechanism in the knife edge rivet resulted in an improved residual stress distribution. These results suggest that other factor including stress concentration in the outer sheet due to the presence of the countersink should be considered as a critical factor for the reduced fatigue performance of knife edge rivet joints.

V. CONCLUTION

A force-controlled two-dimensional axisymmetric finite element analysis has been carried out to investigate the influence of upper skin thickness to rivet head height ratio. Results from this analysis show that:

- With decrease in countersunk portion of the outer sheet, the rivet expansion is larger in the upper skin, leading to an increase in the compressive residual hoop stress near the hole edge.
- Stress concentration in the outer sheet due to the presence of the knife edge is an important factor in the nucleation and growth of cracks in the vicinity of the rivet hole.
- The countersunk depth must not exceed 60% of the skin thickness and anything beyond that will cause the skin to become knife edged.
- Using press countersinking instead of machine countersinking is highly recommended for sheet thickness less than 0.032 inch.

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