EFECT OF VARIATIONS OF RIVETING PROCESS ON THE QUALITY OF RIVETED JOINTS

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Bijay Bajracharya

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I have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial Engineering.

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Dr. Hossein Cheraghi, Committee Chair

We have read this thesis and recommend its acceptance:

____
Dr. Krishna Krishnan, Committee Member

____
Dr. Roy Myose, Committee Member

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ABSTRACT

This thesis presents a study of the effect of controllable riveting parameters, mainly squeeze force, rivet length, rivet diameter tolerance, hole countersunk depth and hole diameter tolerance, on the quality of formed rivet. The quality of a formed rivet is determined by the geometry of its head formation and the extent to which the hole is filled. The study determines maximum allowable tolerance on drilled hole in a 0.064” thick aluminum sheet for a 1/8” rivet. The study is performed using finite element simulation of the riveting process. Theoretical relations between squeeze force and formed rivet head geometry derived in this study is used to validate the finite element model. Statistical design of experiment is employed to analyze the simulation data of riveting and determine the effect of individual factors, their interactions and relationship with the quality of formed rivet head.

The results demonstrate that the correct formation of rivet head geometry depends upon all the factors studied. However, correct geometry of rivet head is not enough to determine the quality of a riveted joint, because the countersunk rivet head does not expand enough to fill up the hole completely, thereby creating a gap and leading to a loose rivet. The gap increases with the increase in tolerances in drilled hole, limiting its allowable tolerances to 0.006”. The length of rivet has no significant effect on the gap formation. To ensure the elimination of gap formation, an alternate procedure with reduced countersunk depth is studied, which allows for increased allowable tolerance in drilled hole. Results show that with as little as 0.01” reduced countersunk depth, the allowable tolerances on drilled hole could be increased to 0.03”, without compromising on the quality of the joint.

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LIST OF ABBREVIATIONS / NOMENCLATURE

DOE	Design of Experiment
FEM	Finite Element Modeling

LIST OF SYMBOLS

^{o}	Degree
ϵ	True Strain
σ_{sq}	Squeeze Stress
F_{sq}	Squeeze Force
”	Inches
lbf	Pound Force
D	Diameter of Formed Rivet Head / Buck-tail Diameter
H	Height of Formed Rivet Head / Buck-tail Height
V	Volume of Deformed / Bucked Rivet Head
D_o	Nominal Rivet Diameter
H_o	Rivet Shank Height that Protrudes out of the Sheet
l	Rivet Length
t	Sheet Thickness
n	Strain Hardening Exponent
K	Strength Coefficient of Material

CHAPTER 1

INTRODUCTION

Sheet metal parts are very common in aircraft industries. Most sheet metal parts used in aircraft assembly are joined using rivets. Stresses induced during manufacture cause premature failure of rivets which in turn may lead to assembly failures with severe consequences. For example, the 1988 Aloha Airlines flight 243 disaster, in which a portion of the passenger compartment disintegrated and resulted in one civilian casualty and several passengers sustained life threatening injuries. The fatal misfortune was attributed to a failure at and around one of the rivet holes, which propagated to the whole assembly (Szolwinski, 2000).

Rivet failure in aircrafts is a combination of three factors: induced stresses during manufacture, thermal fatigue and vibration. Of these, thermal fatigue and vibration are difficult to control. Hence, reducing induced stresses during the riveting process is essential to prevent rivet failures. Several factors in the riveting process contribute to the induced stress. Tolerance stack-ups in sheet metal, riveting sequence, and other process parameters such as squeeze force, rivet geometry, edge margin and pitch, can all contribute to increased residual stress concentrations in the assembly, leading to failure of the joint. These factors and its influence on stresses induced during manufacture depend on manufacturing procedures. The best procedures for reducing the induced stresses and ensuring the best rivet quality have to be identified to prevent failures.

In addition to the above factors, stress is induced when sheets are not formed to the correct dimensions. Before riveting the sheets are forced together and clamped. When sheet geometry does not conform, gaps in between sheets exist, leading to hole misalignments. Clamps are used to hold sheets together during the riveting process. When the sheets are clamped, they contribute to residual stresses on the rivet.

The stress concentrations arise also when the drilled hole is not of correct size. Rivets require that holes have enough clearance, and that these holes must be aligned perpendicular to the surface of the sheet. It is very common to have misalignment of holes when the sheets to be joined are assembled. Although rivets can be used in any orientation, enough clearance must exist to set them properly. The clearance between the manually drilled rivet hole and rivet is difficult to control. The acceptable range of tolerance limit depends on the geometry of rivet, material properties and the squeeze force.

There are no standard riveting practices in aircraft manufacturing with respect to squeeze force applied in the rivet gun, method of aligning holes, or the sequence of riveting. These factors are often selected based on the riveter's experience. Due to the high volume of riveting, there is variability in the process even when the same riveter is performing the tasks.

The variation in the rivet installation process and the quality of the resulting riveted joint is directly linked. The quality of a formed rivet is determined by the geometry of its driven head formation and the extent to which the hole is filled, without any cracks on the rivet and sheet periphery. The shop driven head (buck tail) that results from driving or squeezing the rivet must meet certain criteria. The acceptable dimensions of formed rivet head diameter and height for various sizes of rivets can be found in Military Standard Handbook (MIL-HDBK-5G, 1994) and Standard Handbook of Riveting (1994). A properly driven rivet will have a shop head of approximately 1 ½ times the diameter of the rivet shank in width and about 1/2 times the diameter in height (MIL-HDBK-5G, 1994). It is important to ensure correct rivet buck tail dimensions for enough clamping force in the joint. Similarly, a hole completely filled by rivet will have high interference between rivet and sheets, leading to stronger joint. Incomplete filling of rivet in hole leads to loose rivet with sealing issues and premature failure of rivet.

Since riveting is performed in high volume, it is difficult to measure the correctly driven buck tail dimensions individually; hence best method is to ensure good manufacturing practices. It is very important to identify the best procedures of riveting for limiting the stresses in order to ensure the best rivet quality. A study to determine the parameters that significantly affect the quality of riveted joints and the amount of variations allowed during the riveting process will be very beneficial to the aircraft industries that use riveted joints considerably.

Hence we need to study the manufacturing process parameters that can be controlled to reduce the stresses on the rivets. The controllable parameters of the process include squeeze force, correct selection of rivet length, tolerances in rivet geometry and hole, and correct countersunk depth. These parameters determine the final geometry of the rivet buck tail and stresses induced on the joint. The best combination of these parameters that induce less residual stress, with the existence of manufacturing variability during riveting process need to be determined.

The objective of the thesis is to find a relation between the geometrical parameters of a rivet driven head (buck-tail) and the applied squeeze force under various manufacturing variability that are likely to exist, such as sheet hole tolerance, rivet geometry tolerance, countersunk depth and length of rivet. With this relation, it will be possible to assess and ensure riveting quality. The aim is to determine maximum allowable tolerances on drilled hole with a range of force values under variability in rivet diameter, rivet length and countersunk depth.

With the intention of limiting the cost of experimental procedures necessary to obtain data, a numerical procedure based on accurate finite element modeling is used. Finite element modeling of a riveting process is simulated using experimental data collected by Szolwinski and Farris (2000). The use of finite element model is appropriate in studying this process not only because it shows the stress and strain fields in a continuous way, but also offers a model from which one can predict the final shape and dimension of the part and the possible failure zones. This numerical tool allows a user to vary the concerned parameters such as the specimen geometry, loading and time very easily. Experiments are carried out by changing parameters of interest to simulate real world riveting conditions, for instance, by changing tolerances on rivet, hole and forces for a given rivet length. The formed rivet head geometries, and induced stresses are measured from the finite element simulation. The finite element model is validated using theoretical relationships between the squeeze force and the rivet driven head (buck-tail) geometries.

Statistical analysis of numerical simulation data is performed using Design of Experiment analysis of variance to determine the parameters that affect the final quality of rivet head in terms of the dimension of the rivet driven head (buck tail) geometry. A statistical analysis of the two-level fractional factorial design is used to find the significant factors and their interactions on the formation of rivet head (buck tail) dimensions.

This thesis focuses on the riveting procedures and standards used in aircraft industries. The rivet that is being studied is 1/8” nominal diameter 100° countersunk flat head of aluminum 2117-T4 alloy. The sheet metal is 0.064” thick aluminum 2024-T3 alloy.

CHAPTER 2

LITERATURE REVIEW

Even though riveted joints are widely used, there has been little research work on the quality of rivet formation taking manufacturing variations of riveting procedures into account. Published literature on riveted lap joints lack detailed link between rivet installation process and the life of the joint. Most of the research works are in prediction of fatigue life, crack initiation and propagation, residual stress analysis and load distribution in and around riveted joints. There is limited research on the effect of variation in rivet installation process, such as variation in drilled hole size, diameter of rivet, length and squeeze force, on the quality of rivet formation.

The literature related to riveting process may be classified into following categories:

1) Load distribution in a riveted joint
2) Fretting damage in a riveted joint
3) Residual stress in a riveted joint
4) Factors that affect the life of riveted joints
5) Effect of squeeze force on rivet formation and fatigue life

2.1 Load Distribution in a Riveted Joint

In the application of a lap joint, loads are transferred by rivet shear and through friction between the sheets. All the edges, such as a countersunk rivet hole, act as stress concentration site (Silva et al., 2000). The uneven load transfer through friction, combined with the stress concentration due to holes and the secondary bending of the sheet gives a complex three dimensional stress distribution (Silva et al., 2000). Estaugh et al. (1995) reported that stress distributions are caused by the combination of the following loadings:

1) Biaxial tension in the sheet

1) Pin loading at the hole due to load transfer through rivet shear

2) Clamping load applied by the rivet

3) Surface shear within the clamping zone of the rivet due to load transfer through friction

4) Internal pressure in the hole due to expansion of the rivet, possibly causing yielding

5) Out of plane bending

The above sources of residual stresses and the stress concentration due to hole raise the stress above yield strength under normal conditions, resulting in rivet failure and sheet metal crack propagation (Silva, 2000). When the riveted joints are subjected to repeated cyclical loads, the stress concentration effect will produce fatigue crack and finally the riveted joints will fail by tearing of the sheets, or shearing of the rivet shank. It is, therefore, very important to study residual stresses and determine ways to control it during the assembly process of sheet metal itself, to avoid catastrophic failure in the application.

2.2 Fretting Damage in a Riveted Joint

Fretting is a surface damage process which occurs due to repeated loading in a structure. Fretting fatigue causes small sliding movement at contact surfaces, which is one of the major causes of initiation of fatigue cracks in riveted joints. Some of the important parameters that promote fretting damage according to Collins (1993) are:

1) Magnitude of relative motion between fretting surfaces

2) Magnitude and distribution of normal pressure between fretting surfaces

3) The state of stress in the region of fretting surfaces

4) Number of fretting cycles

5) Temperature in fretting surfaces

6) Atmospheric environment surrounding fretting surfaces

7) The material of the members being fretted

Collins (1993) pointed out the interaction among these variables, making them dependent on each other on their effects. There is no general technique to quantitatively predict the effect of each variable and its interactions on the fretting damage. Collins (1993) supported the fact that local compressive stresses are beneficial in minimizing fretting fatigue damage. Fretting damage can be reduced by increasing normal pressure, which helps in eliminating the relative motion between the sheets (Collins, 1993).

2.3 Residual Stress in a Riveted Joint

Fitzgerald et al. (1994) claim to provide the first data to measure residual stress in and around rivet and sheet due to riveting. They proposed a new method of measuring residual stresses using X-ray diffraction technique. When a force is applied to rivet, the rivet's diameter expands against the hole developing a barrel like shape inside the hole. A head on the protruding end of the rivet is formed, producing a clamping force. If the hole is loaded elastically, the material nearby will be in tension, whereas if plastic deformation occurs, the residual stresses are compressive. The radial stresses increase with increasing riveting force. In all riveting forces, there is compressive stress at the rivet's center, decreasing towards the rivet's edge.

Fitzgerald et al. (1994) found that at low rivet forces, the rivet is in compression and the tangential hoop stress is nearly constant across the rivet head. At the sheet in the rivet sheet interface the stresses are tensile. This is expected for an elastically loaded hole wall. At high rivet forces, there is compression on the sheet rivet interface, all hole walls are being stressed plastically, and there is highest level of compression in the rivet head and sheet metal.

The tangential hoop stresses on the buck-tail and surrounding material area have lower stresses than near the rivet head. However, the hoop stresses are not constant. As the riveting force increases, the slope of the stress from the buck-tail center to its edge goes from negative to positive, as the loading of the hole wall goes from elastic to plastic.

Edwards and Ozdemir (1992) used the neutron diffraction method to provide information about the three dimensional residual stress distributions after a cold working process of drilling and reaming a hole for the rivet. The technique involved plastically deforming a hole to increase its diameter permanently. It was accomplished by inserting a hard tool that is bigger than the initial diameter of the hole. Once the tool was removed from the hole, and the sheet allowed spring-back, it was found that the area around the hole consisted of compressive residual stresses. This proved that a plastically deformed area consisted of compressive residual stresses. The plastically deformed hole with compressive radial and hoop stresses lead to improvement in fatigue life either by reducing or suppressing crack initiation as well as by reducing fatigue crack growth rate.

The use of cold expansion process of drilling a rivet hole introduces compressive residual stresses in the material surrounding the hole, which enhances service life of joint (Muller, 1995, Hertzberg, 1993). A standard practice used in the United States is a cold expansion technique developed by the Boeing Company and marketed by Fatigue Technology Inc. (FTI, 1991). Kang et al. (2002) developed two and three dimensional finite element model of the cold expansion process in two aluminum alloys, 2024-T351 and 7050-T7451, used in aircraft industries. The cold expansion process included hole expansion, elastic recovery and reaming simulations. The results obtained were compared with experimental results from Edwards and Ozdemir (1992), which were in agreement. In addition to conclusions from Edwards and Ozdemir, their results suggested that there is a significant difference in residual stresses at different sections along the thickness of the sheet, different plastic hardening models of the sheet had no impact on the residual stress distribution, and so did the reaming of the material around the hole. Their analysis also concluded that the industry practice of spacing rivet holes at four hole distances apart resulted in a high tensile stress of approximately 100MPa. There was also no significant difference between the 2D and 3D models.

2.4 Factors that Affect the Life of a Riveted Joint

The riveted joint parameters such as number of rivets, edge margin distance, distance between rivets (pitch), etc. are designed to ensure mechanical strength. The parameters depend on the mechanical and geometrical properties of the sheet metal and rivet. Standard rules exist on the proportions of riveted joints that give maximum and minimum pitch and edge distance depending on the size and shape of rivet and sheet thicknesses (Reithmaier, 1991). Failure to comply with these rules may lead to defects during the riveting process.

Smith (1957) did an experimental study on the factors that affect life of a riveted joint. The results showed that load per rivet can be reduced by riveting using smaller pitch. Frost et al. (1974) also mentioned that increasing the number of rows of rivets increases the fatigue strength of the joint, and that the optimum fatigue strength was achieved by changing rivet spacing and position. Seliger (1943) investigated the effect rivet pitch has on the fatigue strength of one-row riveted lap joint. The results agree with Smith (1957), that greater fatigue strength can be achieved with a smaller pitch.

Andrews and Holt (1945) suggested that depth of countersink was very important. The difference in depth of countersink as small as 0.01” or 0.02” could make a difference in strength of sheets as thick as 0.125”. Heywood (1962) analyzed several factors that affect the strength of riveted joints, mainly type of aluminum alloy, dimensional parameters, mean stress on the joint, and rivet arrangements on the assembly. He discovered that the significant dimensional parameters that are important are the rivet diameter, sheet thickness and pitch. Engineering Sciences Data Unit (Data Sheet 79031, 1979) analyzed fatigue test result from the joints made of aluminum alloy and countersunk rivet head. The fatigue test data concluded that for the same loading stresses, the rivets with larger diameter to sheet thickness ratio had longer fatigue life.

Frost et al (1974) proposed several methods of increasing the fatigue strength of riveted joints - by using interference fit, inserting anti-fretting compound between rivet shank and hole wall, overloading the joint statically, and increasing axial tensile stress in the rivet. Overloading the joint by applying high force on rivet induces high compressive residual stresses which retards the crack growth. Increasing tensile load on rivet enables most of the load in the joint to be transmitted to the contacting surfaces of sheets through friction, instead of shear in rivet. Out of all these methods, Frost et al. (1974) proposed the most effective method to be increasing axial tensile strength on the rivet. This will be effective especially when the axial tensile load is sufficient to guarantee that total load is carried by frictional forces between the sheets.

However, no numerical analysis has been performed on any of the above mentioned studies. They relied only on the fatigue strengths from the experimental data. With the use of powerful computers, it has become possible to simulate real life situations and analyze stress, strains and failure modes of joints using finite element methods. Ekvall (1986) developed a simple finite element model for the stress analysis of joint and determined local stress, strain and critical fatigue locations on riveted joint. In this simple model, the rivets were modeled as three spring constants corresponding to the stiffness due to an axial load, a shear load and bending moment applied to rivet. No contact between sheet and rivet was assumed.

Fung and Smart (1996) did a numerical parametric study of snap and countersunk riveted lap joints using finite element models and fatigue tests. The stresses around the rivet hole and sheet were presented along with the effects of varying clamping force, interference fit of rivet, coefficient of friction between sheets and the geometry (length, width and thickness of sheets). It was found that with increased clamping force, interference fit in the rivet hole and friction coefficient between sheets, and decreased width and thickness of the sheet, the total effective stress was reduced. This increased fatigue life of the joint.

Iyer et al. (1999) examined the effect of countersinking a rivet head, its material, and friction between sheets using finite element modeling of riveted joint. Their work showed that all these factors were related and increased with severity of the countersink. The stress concentration factor of the joint could be reduced by decreasing the thickness of the lower sheet, and compensating this thickness to the upper countersunk sheet.

Silva et al. (2000) also performed finite element simulation which was verified by experimental data to predict multiple site damage. They mentioned that fatigue cracks usually start in the upper rivet row in the outer sheet. However, depending on the sheet thickness, clamping pressure and type of rivet, cracking can also occur in the inner sheet. It is typically found that rivet hole corners, surface discontinuities such as dents and burrs, abraded and fretted surfaces were high stress concentration sites, where cracks initiate. This could be also due to a poor drilling technique, which gives rise to small initial surface damage.

2.5 Effect of Squeeze Force on Rivet Formation and Fatigue

Most recent works related to the fatigue life associated with rivet installation process is in the study of squeeze force that is used to drive the rivet. Researchers have found a correlation between a larger driven head size (buck-tail diameter and height) and increased fatigue life using high squeeze force. The effect of squeeze force on the fatigue life of rivet was first studied using finite element method by Muller (1995). Muller (1995) indicated that riveting using high squeeze force could have positive effect on the life of a joint. The studies showed that a high squeeze force in a rivet filled up the hole properly, and a larger driven rivet head increased clamping between the two sheets. When a rivet fills the hole, a uniform bearing pressure distribution exists in the thickness direction of the sheet. The increased clamping is beneficial with respect to improving load transfer by friction between contacting surfaces of sheets.

Muller's work was extended by Szolwinski and Farris (2000) to analyze quasistatic squeeze force controlled riveting process with the use of finite element modeling. They used a two dimensional axisymmetric model of the riveting process, which was verified with actual experimental data. They used 0.1875" diameter rivet (2117 T4 Aluminum) with 0.09" thick (2024 T3 aluminum) sheets and applied squeeze forces in the range of 2500lbf to 5000lbf. They found that as the squeeze force increased, the magnitude of the compressive residual stress (at the radial interference between plate and rivet) increased also, with expansion of the rivet against the hole wall. This compressive hoop stress counteracts the crack opening stress, retarding the crack growth.

Like Szolwinski, Li et al. (2004) 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 the riveting process. They used 0.08" thick (2024 T3 aluminum) sheets with 0.25" diameter rivet (2117 T4 Aluminum), and applied 12000lbf to 14000lbf squeeze force. They concluded that squeeze force was the most important factor in the riveting process. A model was developed which can be used to find out driven rivet head diameter and height with a known squeeze force. Numerical simulation showed that the connection between the outer sheet and the rivet was weaker than the inner sheet. Due to this, fatigue cracks usually start at the mating surface and the hole edge, and propagate into the outer sheet.

The studies on the effect of squeeze forces in the above literatures conclude that high squeeze force is beneficial for fatigue life. However, high squeeze force increases rivet deformation, hence creating an overdriven rivet with buck-tail geometry out of conformity. In addition, the amount of squeeze force to apply depends on rivet material, type and geometry of rivet and hole, and the variations associated with rivet installation process. Very high squeeze force will also not be practical in terms of manual riveting. Thus, a correct amount of squeeze force that conforms to the acceptable buck-tail geometry, along with variations that are likely to exist during rivet installation, needs to be determined.

CHAPTER 3

METHODOLOGY

The variation in riveting process is studied using finite element simulations. Finite element simulations data are used because it is easy to see the contours of stresses and strains and see the effect of each parameter individually while keeping the others constant. The simulations for experiments are designed using factorial design of experiment method, after parameters of interest to study are decided. Finite element model data from simulations are compared with theoretical equations derived for validation. The data from simulations are analyzed statistically using analysis of variance technique to find out the individual effects of riveting process parameters. Two models are studied – Model I, without changing countersunk depth, and Model II with reduced countersunk depth.

3.1 Modeling

In order to study the variation in riveting process parameters finite element model of riveting process is developed. Finite element model is used to study the effect of variations in rivet length, tolerances in rivet diameter and hole, riveting upset squeeze force and countersunk depth. In finite element modeling, the contours of stresses and strains and the effect of each parameter can be studied individually while keeping the others constant. Finite element model data from simulations are compared with theoretical equations derived for validation.

3.1.1 Model Development

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

- Geometric nonlinearity due to large displacement effect
- Boundary nonlinearity due to contact between tool and rivet, rivet and sheet, and in between sheets
- Material nonlinearity due to plastic deformation

The modeling technique used is followed from Szolwinski and Farris (2000), since their finite element model is experimentally verified. Msc. Patran is used as preprocessor to model the parts, apply appropriate boundary conditions, mesh and generate input file (*.key file) for LS-Dyna (Solver). LS-Post (Post processor) is then used to analyze the results from the output of LS-Dyna in binary plot formats. The simulation output from LSPost is used to measure the rivet driven head deformation, stress and strain.

3.1.1.1 Model Geometry

The configuration chosen for modeling is of a standard 2017 T4 aluminum alloy 100 degree flat countersunk head rivet of 1/8” nominal diameter, and two 0.064” thick 2024 T3 aluminum alloy sheets, most widely used in aircraft industries as shown in Table 1 (Standard Aircraft Handbook, 1991). Only a quarter two dimensional model of the rivet and sheet is modeled by utilizing symmetry conditions to reduce computing cost. The length of the sheets extended 12 rivet diameters from the axis of symmetry. Cross section of a three dimensional model of rivet, sheets, and tools to form the rivet is shown in Figure 1. A quarter two dimensional model used in the study is shown in Figure 2.

TABLE 1

GEOMETRIC PARAMETERS USED IN MODELING

Nominal rivet diameter, D_o (inch)	1/8 = 0.125
Rivet length, l (inch)	0.25, 0.32
Hole diameter, D_{hole} (inch)	0.1285
Countersunk hole diameter (inch)	0.2285
Sheet thickness, t (inch)	0.064

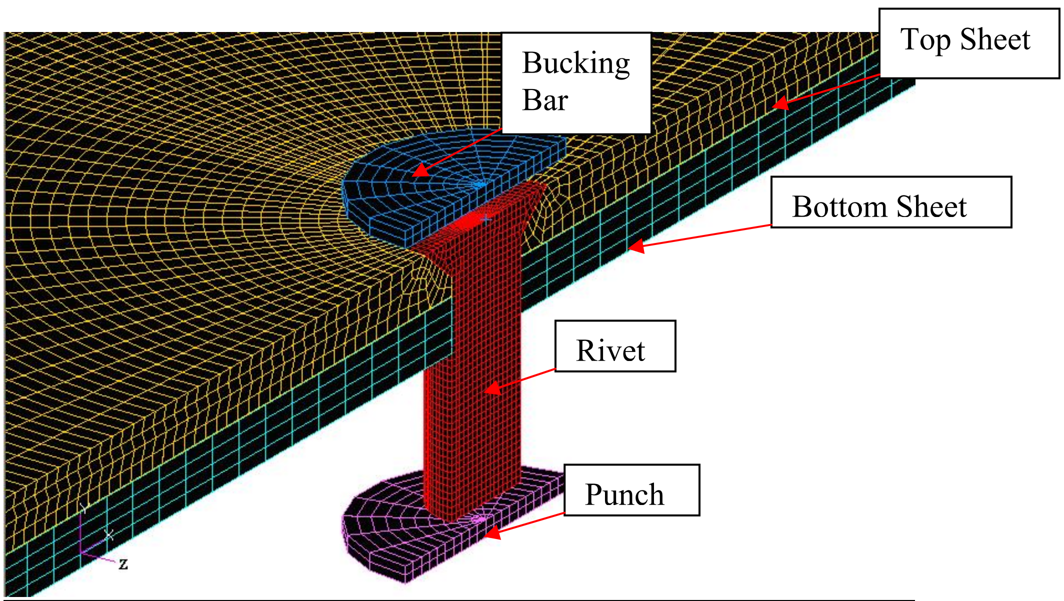


Figure 1. 3D Cross Section Model of Rivet and Sheets

3.1.1.2 Element Selection

By using axisymmetric 2D elements, the need for 3D modeling can be avoided. Four node axisymmetric shell elements with reduced integration of three points are used to represent sheets and rivet. 2D shell elements are used with 0.001inch thickness. A typical mesh and schematic of the axisymmetric model are shown in Figure 2.

3.1.1.3 Mesh Selection

Simulations of riveting allows for large plastic deformations of rivet, which results in distorted elements in rivet. When elements become distorted the calculation time increases and can even be terminated. To minimize the distortion of elements in rivet, adaptive mesh is used. Adaptive meshing makes it possible to maintain a high-quality mesh throughout an analysis, even when large deformations occur, by allowing the mesh to move independently of the material and rebuilding the mesh in a defined area during the simulation. A mesh size of 0.002" adaptive mesh is used for rivet. 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. The mesh in Figure 2 was finally chosen, with enough elements to provide adequate precision in the calculations. Mesh size for top sheet was 0.005" and bottom sheet 0.006" with total number of elements of 2629 for bottom sheet, 3700 for top sheet and 983 for rivet.

3.1.1.4 Boundary Condition

The edges of the sheet are constrained along x and z axis displacement and rotation, and allowed to move only in the y-direction (axis convention is shown in Figure 2). Rivet axis is constrained on all degrees of freedom along x and z, but allowed displacement along y-direction. The riveting tools are modeled as rigid bodies with no rotational degrees of freedom. The punch and bucking bar are constrained on all degrees of freedom, except for the y-direction displacement. The finite element model and its boundary conditions are shown in Figure 2.

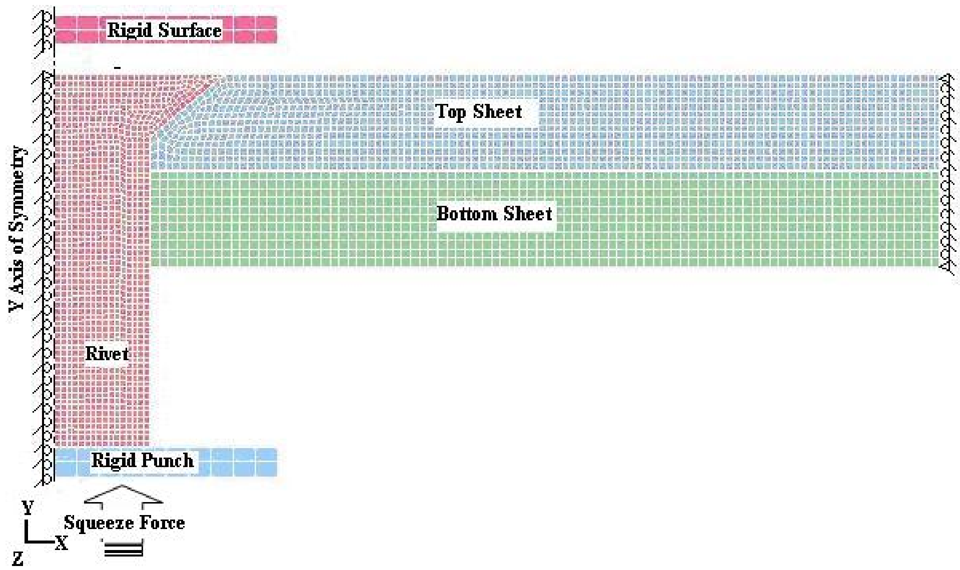


Figure 2. Boundary Conditions and Mesh Size

3.1.1.5 Material Modeling

The material of the rivet and sheet is isotropic plasticity model with rate effects, which uses power hardening rule, with the following equation, $\sigma = K\epsilon^n$, where σ is true stress, ϵ is true strain, K is the strength hardening coefficient and n is the strength hardening exponent. The material properties used in the simulations are from Szolwinski and Farris (2000) as shown in Table 2.

TABLE 2

MATERIAL PROPERTIES USED IN MODELING

	Rivet (2117 T4)	**Sheets (2024 T3)**
Young's Modulus (psi)	10.4 E6	10.5 E6
Poisson ratio	0.33	0.33
Yield Strength (Ksi)	24	45
Hardening parameter	K = 80 Ksi, n = 0.15	K = 105.88 Ksi, n = 0.1571
Density (lb/in^3)	0.101	0.101

3.1.1.6 Contact Condition

The model includes contacts between rivet and sheets and in the interface between the upper and lower sheets, and in between the riveting gun or squeezer and rivet. The contact analysis was conducted using LS Dyna automatic surface to surface contact with penalty and penetration check. With this approach, explicit definition of point to point contact was eliminated; user could define master and slave pair surfaces (slave being the rivet), allowing to generate internal contact elements as needed. Coulomb friction at the interface with exponential interpolation between static and dynamic friction coefficients was specified. The frictional value of 0.2 recommended by Szolwinski (2000) was used for all contacts.

3.1.2 Model Validation

The finite element model is validated by comparing the rivet formed driven head geometry – formed rivet head diameter and height, from finite element model with those of theoretical calculations. Theoretical calculations of the relationship between formed rivet head geometries and riveting upset squeeze force is derived under ideal conditions in the following section.

3.1.2.1 Theoretical Relation between Driven Rivet Head and Squeeze Force

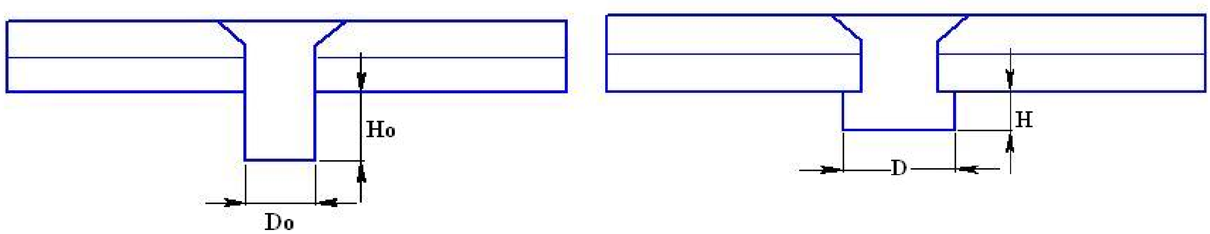
Obtaining an empirical relation between squeeze force and driven rivet head dimensions is a difficult task, because riveting process is a highly nonlinear forming process and there exists variations in the process itself. However, a theoretical relationship can be derived based on the assumption that no rivet material gets filled inside the hole after riveting, and all rivet volume that protrudes out of the sheet gets squeezed to form the driven rivet head (buck-tail). This assumption will hold if there is no initial clearance between rivet and hole.

As shown in Figure 3 (a) before impact, the initial volume, V_o, of the rivet shank that protrudes from the sheet is given by,

$$V_o = \frac{1}{4} \Pi D_o^2 H_o \qquad (3.1)$$

Similarly, as shown in Figure 3 (b) after impact, the final volume, V, of the driven head, assuming that the driven head has cylindrical shape, may be written as,

$$V = \frac{1}{4} \Pi D^2 H \qquad (3.2)$$



(a) Before Impact (b) After Impact

Figure 3. Geometry of Rivet Head Formation

Thus, for an ideal condition, neglecting the change of volume inside the hole, $V/V_o = 1$. So, from equations (3.1) and (3.2),

$$\frac{1}{4} \Pi D^2 H / \frac{1}{4} \Pi D_o^2 H_o = 1$$

$$\text{Or, } H/H_o = (D_o/D)^2 \qquad (3.3)$$

Squeeze stress, σ_{sq}, is true stress, which is the stress associated with the actual deformed area, is given by,

$$\sigma_{sq} = F_{sq} / \frac{1}{4} \Pi D^2 \qquad (3.4)$$

For an ideal forming of the protruding rivet head, assuming a cylindrical shape of the rivet driven head at the end of the formation, and constant volume before and after riveting, following equation is valid for the total strain in x, y and z direction,

$$\epsilon_x + \epsilon_y + \epsilon_z = 0 \tag{3.5}$$

For uniform compression, the true strain in the y direction (vertical), $\epsilon_{y,}$ is,

$$\epsilon_y = \ln (H/H_o) = \ln (D_o/D)^2 \tag{3.6}$$

The true stress for forming of rivet using power law plasticity material model is given by,

$$\sigma_{sq} = K (\epsilon_y)^n \tag{3.7}$$

Where, K is the strength coefficient and n is the strain hardening exponent of the rivet material.

Therefore, from (3.4) and (3.7),

$$\sigma_{sq} = K (\epsilon_y)^n = F_{sq} / \tfrac{1}{4} \Pi D^2 \tag{3.8}$$

From (3.6) and (3.8),

$$\sigma_{sq} = K [\ln (H/H_o)]^n = K [\ln (D_o/D)^2]^n = F_{sq} / \tfrac{1}{4} \Pi D^2 \tag{3.9}$$

$$\text{Or, } F_{sq} = \tfrac{1}{4} \Pi D^2 K [\ln (D_o/D)^2]^n \tag{3.10}$$

$$\text{Or, } F_{sq} = \tfrac{1}{4} \Pi D^2 K [\ln(H/H_o)]^n \tag{3.11}$$

Equations (3.10) and (3.11) provide a relation between applied squeeze force and the deformed rivet head diameter (D) and height (H) under ideal condition in riveting when no rivet material flows into the hole. Equations (3.10) and (3.11) can be used to verify the simulation results from finite element method. Simulations are run under such an ideal condition with minimal clearance between rivet and hole, with a known squeeze force. The corresponding formed diameter and height of rivet head found out from simulation results are compared with equations (3.10) and (3.11).

3.1.2.2 Results of Model Validation

The finite element model is validated against the theoretical equations (3.10) and (3.11) for squeeze force in terms of D and H values. While deriving theoretical equations, it is assumed that there is no initial clearance between rivet and hole. To minimize the clearance between rivet and hole, 0.128” diameter rivet with 0.1285” diameter hole is modeled for validation purpose.

Theoretical D and H values are calculated at forces 1500 lbf to 3000 lbf with an increment of 150 lbf using equations (3.10) and (3.11), i.e. at 1650, 1800, 1950,…,3000. The result from the model is compared with theoretical result at the same force values. The Force versus D and H values for theoretical and model are plotted as shown in Figures 4 and 5. It is seen that D increases with force and H decreases with force, almost linearly.

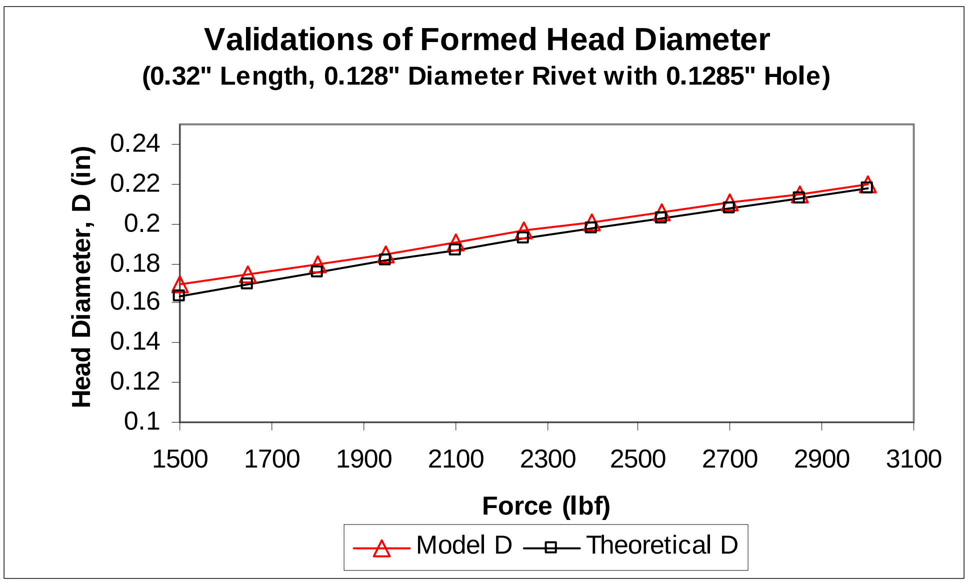


Figure 4. Validation of Formed Head Diameter

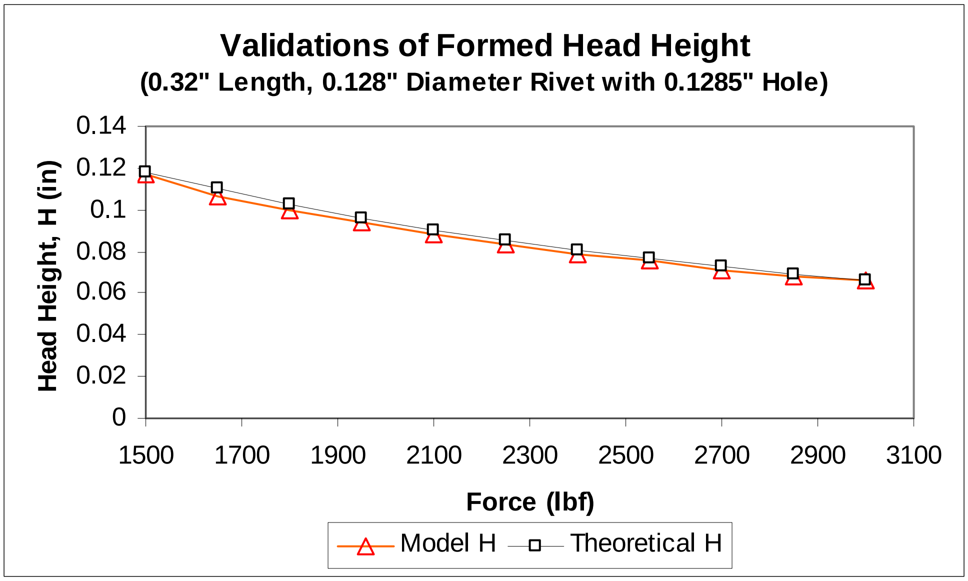


Figure 5. Validation of Formed Head Height

The average difference between D and H values of theoretical and model values are shown in Table 3. The difference for formed head diameter is higher because when the rivet head forms, it forms a barrel like shape, rather than a cylindrical shape as assumed when the theoretical equations are derived.

TABLE 3

COMPARISON OF THEORETICAL AND MODEL D AND H

	Average Difference: Model versus Theory
Diameter, D (in)	0.003649”
Height, H (in)	0.001727”

The difference between the mean values of theoretical and model are tested at 5% significant level (95% confidence interval). Assuming both the populations are normally distributed, estimation of the difference between the two means (model and theoretical) is found to be not significant. Since the difference between theoretical and model D and H values are not significant, we can conclude that the finite element model is valid.

3.2 Experimental Design

Experiments are devised using statistical design of experiment method in order to study the effect of variations in riveting process parameters on the formation of rivet. The parameters of study are: rivet length, tolerances in rivet diameter and hole, countersunk depth and squeeze force. Experiments are run with all the possible combinations of these parameters. The geometry of rivet driven head (buck tail diameter and height) and the extent to which the hole is filled (gap) are measured at the end of the rivet formation. Statistical design of experiment is used to find out the significant factors and their interactions on the formation and quality of rivet. Results from design of experiment also provide relationship among these parameters. The objective is to find a relation between the geometrical parameters of a rivet driven head (buck-tail) and riveting parameters such as force, rivet length, countersunk depth and tolerances in drilled hole and rivet diameter. The relation can then be used to determine maximum acceptable tolerances on drilled hole and the amount of force to apply under variability in rivet diameter, rivet length and countersunk depth.

Two experimental models are studied – Model I with standard 0.042” countersunk depth, and Model II with reduced countersunk depth of 0.032”. In each model, four factors – hole tolerance, rivet diameter tolerance, rivet length and squeeze force are taken into consideration. Each of four factors has two levels – low and high. Experiments are run as fractional factorial of 2^4, i.e. 16 runs. The design is analyzed using the Design Expert software.

Since in reality there are many more factors than studied here, the factors that are taken into consideration are only those factors that can be controlled in real life. Because there are only two levels (low and high), it is assumed that the response is approximately linear over the range of the factor levels chosen. Also, the results generated from the designed experiments are valid only within the range tested.

3.2.1 Levels and Ranges of Parameters of Experiment

Squeeze Force: The magnitude of squeeze force is directly proportional to the rivet deformation. Squeeze forces vary depending upon different pneumatic squeezers. The value of applied force will be known from the specifications of squeezer itself. The maximum and minimum values of forces can be found out from different rivet squeezers specifications. For 1/8" rivet, the low and high forces used are 1500 lbf and 3000 lbf.

Hole Diameter Tolerance: The nominal hole diameter in the sheet for a 1/8" rivet is 0.1285" (Standard Aircraft Handbook, 1991). In real life, there will be variation in drilled holes and the maximum acceptable tolerance value for the hole need to be determined. A tolerance value of +0.008" is shown in Figure 6. However, tolerances can be as high as +0.03" on manually drilled holes.

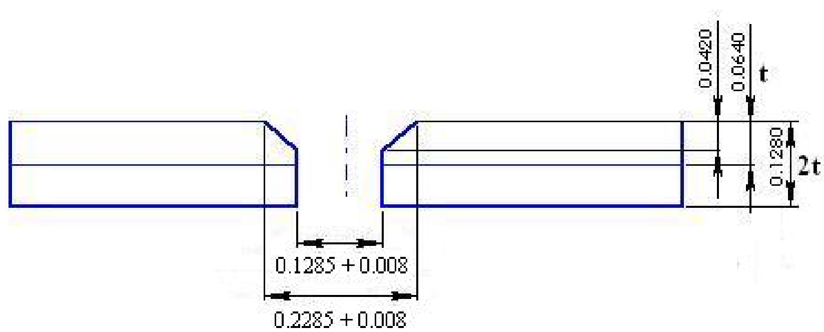


Figure 6. Sheet Hole and Thickness Dimensions

Rivet Diameter Tolerance: Rivet shank diameter tolerance controls the clearance between sheet hole and rivet. Smaller clearance allows for better chances of getting the hole filled by the formed rivet. Rivet diameter tolerance can be found in rivet manufacturer's handbooks. ASME small solid rivet handbook (1965) gives a tolerance of (+0.002 and -0.004) for rivets of nominal diameters between 3/32" to 5/32". For a 1/8" rivet, the nominal diameter should be in the range of (0.127" to 0.121") (ASME handbook, 1965). In the simulations, +/-0.003 is used for the rivet head and shank diameter tolerance. The dimensions are as shown in Figure 7.

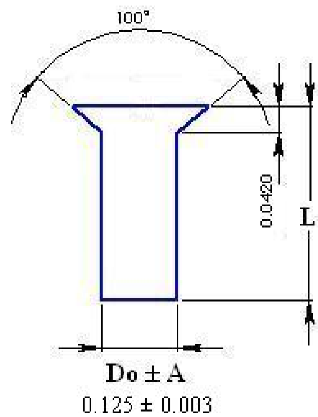


Figure 7. Rivet Dimensions

Rivet Length: Rivet length is selected based upon the rivet nominal diameter and sheet thickness. Standard Aircraft Handbook (1991) mentions that the length of the rivet that extends beyond the sheets (H_o in Figure 8) to be riveted should be 1 to 1.5 times the nominal diameter (D_o) of the rivet. So, for a 1/8" rivet on two 0.064" thick sheets, proper rivet length would be between 0.253" (with $H_o = D_o$), and 0.3155" (with $H_o = 1.5D_o$). Two rivet lengths of 0.25" and 0.32" are compared to see whether longer or smaller length makes any significant difference on the formation of upset rivet head and on the quality of riveted joint.

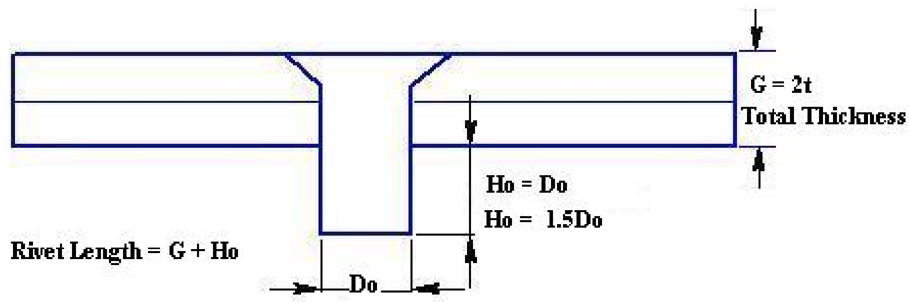


Figure 8. Selection of Length of Rivet

3.2.2 Held Constant Factors

Only 1/8” nominal diameter countersunk rivet is used in experiments. The sheet thickness is 0.064”, rivet length tolerance is zero, rate of application of force is same for all the riveting simulation and there is no tolerance in rivet countersunk angle (100°). The material for rivet is 2117 T4 and sheet is 2024 T3 aluminum.

3.2.3 Experimental Models

Two sets of experimental models are studied – Model I and Model II. Model I experiments are conducted with standard countersunk depth of 0.042” for 1/8” rivet. The effect of decreasing the countersunk depth is studied as second set of experiment in Model II. Model II experiments are conducted with reduced countersunk depth of 0.032”, without changing the countersunk angle of 100° as shown in Figure 9. With 0.032” countersunk depth, the rivet head elevates 0.01” higher than the surface of sheet as shown in Figure 10. Decrease in the countersunk depth by 0.01” guarantees proper filling of rivet material inside the hole.

The number of factors and factor levels selected for both the models are as indicated in Table 4. The design limits for Models I and II are same, except for the range of hole tolerance studied. The hole tolerance for Model I is studied up to 0.008”, while it is increased to 0.03” for

Model II. Model II has increased allowable hole tolerances because of the reduction in countersunk depth, which ensures proper filling of rivet material in the hole.

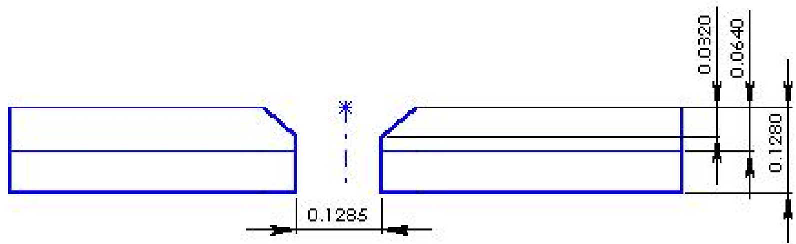


Figure 9. Countersunk Depth of 0.032" for Model II

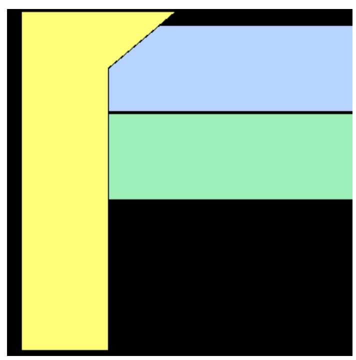


Figure 10. Rivet Head Protruding Higher with Countersunk Depth of 0.032"

TABLE 4

FACTORS AND THEIR CORRESPONDING LEVELS FOR MODELS I AND II

Factor	**Name**	**Units**	**Low**	**High**
A	Sheet Hole Tolerance	in	0.00	Model I: +0.008 Model II: +0.03
B	Rivet Diameter Tolerance	in	-0.003	+0.003
C	Rivet Length	in	0.250	0.320
D_F	Force	lbf	1500	3000

With a hole tolerance of +0.008”, hole diameter ranges from (0.1285 – 0.1365)” and hole countersunk diameter ranges from (0.2285–0.2365)”. With a hole tolerance of +0.03”, hole diameter ranges from (0.1285 – 0.1585)” and hole countersunk diameter ranges from (0.20477–0.23477)”. Similarly, with a ±0.003”, rivet diameter tolerance, rivet shank diameter ranges from (0.122 – 0.128)”.

The design matrix with the factors of interest and their levels for Model I are shown in Table 5 below. Design matrix for Model II is the same as Model I, except that the hole tolerance values of 0.008” in Model I are replaced by 0.03” for Model II.

TABLE 5

DOE DESIGN MATRIX FOR MODEL I

No.	Hole Tolerance (in)	Rivet Diameter Tolerance (in)	Rivet Length (in)	Force (lbf)
1	0	-0.003	0.25	1500
2	0.008	-0.003	0.25	1500
3	0	0.003	0.25	1500
4	0.008	0.003	0.25	1500
5	0	-0.003	0.32	1500
6	0.008	-0.003	0.32	1500
7	0	0.003	0.32	1500
8	0.008	0.003	0.32	1500
9	0	-0.003	0.25	3000
10	0.008	-0.003	0.25	3000
11	0	0.003	0.25	3000
12	0.008	0.003	0.25	3000
13	0	-0.003	0.32	3000
14	0.008	-0.003	0.32	3000
15	0	0.003	0.32	3000
16	0.008	0.003	0.32	3000

3.2.4 Response Variables: Factors that determine Quality of Rivet for the Models

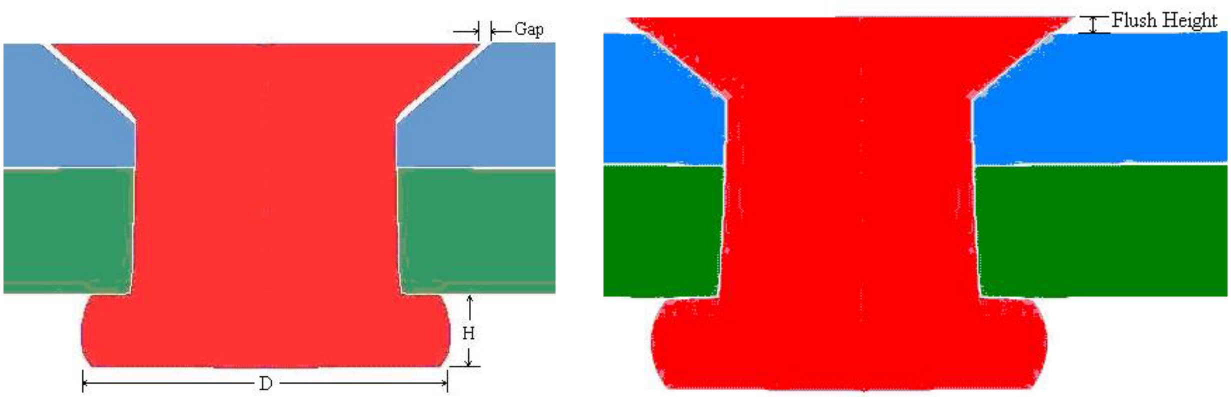
The factors that are of interest at the end of the rivet formation are – the formed buck-tail diameter (D), height (H), gap in between sheet and rivet, and the flush head height of the rivet on the surface of sheet, as shown in Figure 11 (a) and (b). The geometries of these parameters determine the quality of rivet formation. From the Aircraft Standard Handbook (1991), the maximum and minimum values of D and H that are acceptable for a 1/8" rivet, at the end of the rivet head formation, are as follows:

H: (0.046875 – 0.078125)"

D: (0.171875 – 0.21875)"

Gap/clearance in between sheets and rivet after the formation of rivet should be zero. Any clearance in between sheet and rivet leads to a loose rivet.

Flush height/Rivet head height: Minimum protrusion (less than 0.01") of rivet head height from the sheet to maintain flushed surface.



(a). Diameter, Height and Gap after Rivet Formation (b). Flush Height after Rivet Formation

Figure 11. Factors that determine Quality of Rivet Formation

CHAPTER 4

RESULTS AND DISCUSSION

Two sets of experiments are studied – Model I with countersunk depth of 0.042" and Model II with countersunk depth of 0.032", under variability in rivet diameter, length, drilled hole, and squeeze force. The objective of the experiments is to determine a relationship between these parameters by determining significant factors that contribute to the formation of rivet. With this relationship, the allowable variations among the parameters can be determined. The aim is to find a combination of force, length and diameter of rivet that gives maximum allowable tolerance on the sheet hole. The resulting combination must conform to the conditions for a good quality of rivet formation – (a) a rivet joint without any gap in between rivet and sheet, (b) diameter and height of the buck-head that fall within the acceptable range, and (c) rivet head flushed less than 0.01" from the surface of the sheet.

From the results of Model I, it is found that the allowable tolerance on sheet hole is limited by the presence of gap in between countersunk rivet head and countersunk hole. This problem is solved by raising the rivet 0.01" higher by reducing the countersunk depth as presented in Model II. Hence it is proposed that while riveting, decreasing the depth of countersink up to 0.01" is favorable, as it increases the allowable hole tolerances, without compromising on the other parameters that determine the quality of rivet formation.

4.1 Model I

The experimental runs and the corresponding values of formed head (buck-tail) diameter (D), height (H) and gap in between sheet hole and rivet are shown in Table 6. Design Expert software is used to analyze the data in Table 6 to find out the significant factors that affect the formation of response variables D, H and gap. Based upon the data from Table 6, the Design Expert also provides relationship between the significant factors.

TABLE 6

MODEL I EXPERIMENTAL DATA

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response 1**	**Response 2**	**Response 3**
Expts.	**A:Hole Tolerance**	**B:Rivet Dia. Tolerance**	**C:Rivet Length**	**D_F:Force**	**D**	**H**	**Gap**
1	0.000	-0.003	0.250	1500	0.15535	0.07187	0.00152
2	0.008	-0.003	0.250	1500	**0.15108**	0.0645	**0.0047**
3	0.000	0.003	0.250	1500	0.15892	0.08443	0
4	0.008	0.003	0.250	1500	0.15179	0.0796	0.00153
5	0.000	-0.003	0.320	1500	0.17123	0.100304	0.0016
6	0.008	-0.003	0.320	1500	0.167306	0.09498	**0.00336**
7	0.000	0.003	0.320	1500	0.172257	**0.11701**	0
8	0.008	0.003	0.320	1500	0.17223	0.1055	0.00157
9	0.000	-0.003	0.250	3000	0.200378	0.038887	0
10	0.008	-0.003	0.250	3000	0.195672	**0.033269**	0.000416
11	0.000	0.003	0.250	3000	0.205856	0.045	0
12	0.008	0.003	0.250	3000	0.199534	0.04118	0
13	0.000	-0.003	0.320	3000	0.21744	0.058356	0
14	0.008	-0.003	0.320	3000	0.2137	0.055078	0.00164
15	0.000	0.003	0.320	3000	**0.22**	0.066012	0
16	0.008	0.003	0.320	3000	0.219	0.061738	0.00033

Notes: Low and high values for D, H and Gap are shown in bold.

Based on the statistical analysis of data from Table 6, the significant factors that affect the formation of buck-tail diameter (D), height (H) and gap, is explained in section 4.1.1. The relationships between D, H and gap with their significant factors are also presented. This relationship can be used to predict the values of D, H and gap when the values of factors A, B, C and D_F are known.

The practical application of these relationships is illustrated graphically in section 4.1.2. Section 4.1.2 is graphical depiction of results to determine maximum variation in factors A, B, C and D_F, while remaining within the boundaries of acceptable values of D, H and gap. The objective is to determine maximum allowable drilled hole tolerances with variation in squeeze force, rivet length and rivet diameter.

4.1.1 Significant Factors for the Formation of D, H and Gap from Design Expert Analysis

Buck-tail Diameter, D: For the formation of buck-tail diameter, the important factors that emerged from the analysis were the main effects hole tolerance (A), rivet diameter tolerance (B), rivet length (C) and squeeze force (D_F). Diameter (D) decreased with increase in hole tolerance. D increased with an increase in force, length, and rivet diameter tolerance. As seen in Table 6, the maximum D (0.22”) is when rivet diameter tolerance is high (+0.003”), high force (3000lbf), bigger rivet length (0.32”) and zero tolerance on drilled hole. On the contrary, the minimum D (0.15108”) is when rivet diameter tolerance is low (-0.003”), low squeeze force (1500lbf), smaller length rivet (0.25”) and high hole tolerance (0.008”). Based on the statistical analysis, the relationship between the formed rivet head diameter (D) and the factors A, B, C and D_F from Design Expert analysis is shown in equation (4.1).

$$D = 0.049545 - (0.48623*A) + (0.57148*B) + (0.24033*C) + (3.0951E\text{-}*D_F) \qquad (4.1)$$

The percentage contribution of each factor for the formation of D from Design Expert analysis is given in Table 7. As seen in Table 7, the dominant factor is the squeeze force (D_F), and the least dominant is rivet diameter tolerance (B).

TABLE 7

MODEL I: PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR FORMATION OF "D"

Factors	% Contribution
A	0.61
B	0.48
C	11.45
D_F	87.21

Buck-tail Height, H: For the formation of proper buck-tail height, the important factors that emerged from the analysis were the main effect of hole tolerance (A), and interactions of rivet diameter tolerance and force (BD_F), and rivet length and force (CD_F). As seen in Table 6, head height (H) and hole tolerance (A) are inversely proportional. From Table 6, H is lowest with high squeeze force (3000lbf), high hole tolerance (+0.008), low rivet diameter tolerance (-0.003) and smaller rivet length (0.25"). On the contrary, H is highest with low squeeze force (1500lbf), zero hole tolerance, high rivet diameter tolerance (+0.003) and bigger rivet length (0.32"). Based on the statistical analysis, the relationship between the formed rivet head height (H) and the factors A, B, C and D_F from Design Expert analysis is given in equation (4.2).

$$H = -0.022169 - (0.71911*A) + (3.39304*B) + (0.54265*C) - (3.1136E\text{-}6* D_F) - (7.3741E\text{-}4*B*D_F) - (8.2255E\text{-}5*C*D_F) \quad (4.2)$$

The percentage contribution of each factor for the formation of H from Design Expert analysis is given in Table 8. As seen in Table 8, the dominant factor is the squeeze force (D_F), and the least dominant is the interaction between rivet diameter tolerance and squeeze force (BD_F).

TABLE 8

MODEL I: PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR FORMATION OF "H"

Factors	% Contribution
A	1.38
B	4.53
C	26.21
D_F	66.38
BD_F	0.46
CD_F	0.78

Gap: For high tolerances on hole, the rivet countersunk head does not expand enough to fill up the countersunk part of the sheet hole, thus creating a gap. The gap existed only in the countersunk area, and existed regardless of acceptable buck-tail dimensions.

The formation of gap occurred due to the main effects of hole tolerance (A), rivet diameter tolerance (B) and squeeze force (D_F). The effects were only individual effects with no interactions. As seen in Table 6, the higher the hole tolerance, the bigger the hole, hence increasing the gap. High squeeze force (3000lbf) filled up the gap. High tolerance on rivet diameter (+0.003, leading to bigger diameter rivet), decreased the clearance in the hole, which reduced the gap. The length of rivet (factor C) had no effect on the elimination of gap, i.e. gap existed regardless of whether smaller length (0.25") or bigger length (0.32") of rivet was used. From Table 6, it is seen that the maximum gap of 0.0047" and 0.00336" resulted with high tolerance on hole (+0.008"), low squeeze force (1500lbf) and low tolerance on rivet diameter (-

0.003”), regardless of rivet length. Based on the statistical analysis, the relationship between the gap and the factors A, B, and D_F from Design Expert analysis is given in equation (4.3).

$$Gap = 2.62013E\text{-}3 + (0.16291*A) - (0.20429*B) - (9.91167E\text{-}7*D_F) \qquad (4.3)$$

The percentage contribution of each factor for the formation of Gap from Design Expert analysis is given in Table 9. As seen in Table 9, the dominant factor is the squeeze force (D_F), and the least dominant is rivet diameter tolerance (B).

TABLE 9

MODEL I: PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR FORMATION OF “Gap”

Factors	**% Contribution**
A	30.70
B	27.96
D_F	37.84

4.1.2 Graphical Analysis of Results

In order to visually observe the amount of variations allowed for the factors (A, B, C and D_F), equations (4.1), (4.2) and (4.3), are plotted, with known acceptable range of D and H, and gap value of zero. Graphs to determine allowable tolerances on drilled hole at various force values, rivet lengths, and rivet diameter are plotted. The plotted graphs consist of force on the Y-axis and hole tolerances on the X-axis. On the graphs, the lines of maximum and minimum acceptable D and H values and gap of zero line are plotted. The feasible area is shaded, which is the area where the values of D and H are acceptable and no gap exists in between rivet and hole. The plot in Figure 10 shows that there is no feasible area for rivet diameter tolerance less than -

0.001” (rivet diameter 0.124”) for rivet length of 0.25”. Rivet diameter less than 0.124” fails to fill up hole with existence of gap in between rivet head and countersunk hole.

4.1.2.1 Rivet Diameter Tolerance of -0.001” (D_o = 0.124”)

The feasible region is governed by the gap of zero line as seen in Figures 12 and 13. As rivet diameter decreases, the clearance between rivet and hole increases, creating higher amount of void to be filled by the rivet. The bigger the clearance, the more difficult it becomes to fill the hole. The following results can be summarized from Figures 12 and 13 below:

- Allowable tolerance is limited by zero gap in between rivet head and sheet hole. Gap does not depend on the lengths, since the slope of gap line on the graphs are same for 0.25” and 0.32” lengths.
- There is only one feasible point for 0.25” length (Figure 12). Compared to 0.32” length, for the same amount of force, the H value for 0.25” length decreases, making the feasible area smaller. The values of D and H are higher for 0.32” length rivet than for 0.25” length rivet. Thus, D and H increases with length for same amount of force.
- For 0.25” length, the only feasible point is with zero tolerance hole and 2775 lbf. For 0.32” length, the maximum allowable tolerance on hole is +0.0015” with 3000 lbf. With +0.0015” tolerance in hole, and -0.001” tolerance on rivet diameter (0.124”diameter rivet), the initial clearance between rivet shank and sheet hole is 0.006”. So, the maximum clearance allowed is 0.006” for 0.32” length rivet.
- Minimum allowable tolerances on rivet diameter is -0.001” (diameter of 0.124”) for 0.25” rivet and -0.002” (diameter of 0.123”) for 0.32” rivet, limited by existence of gap.

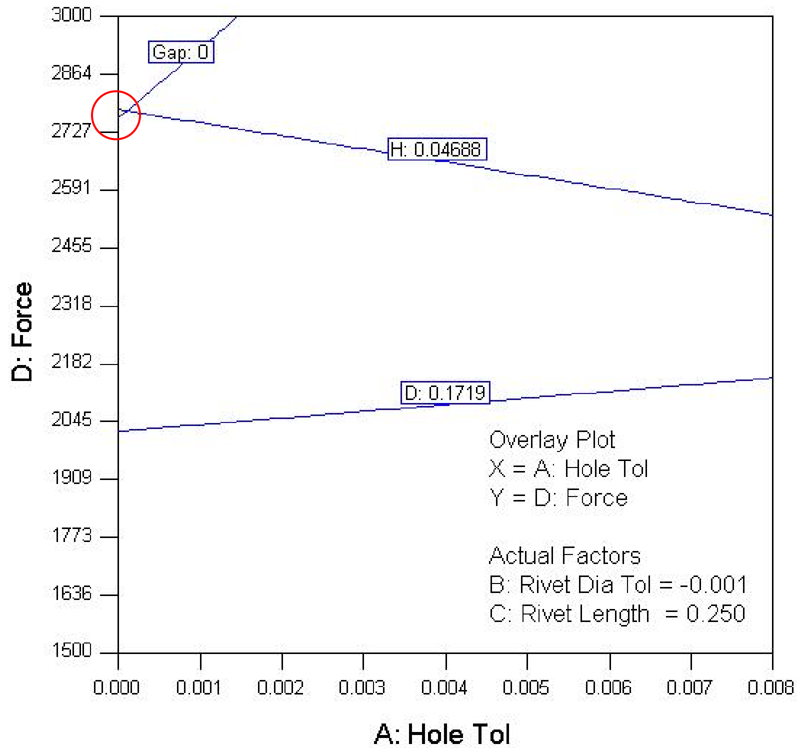


Figure 12. Model I: Feasible Region for 0.25" Length, 0.124" Rivet Diameter (-0.001" Tolerance)

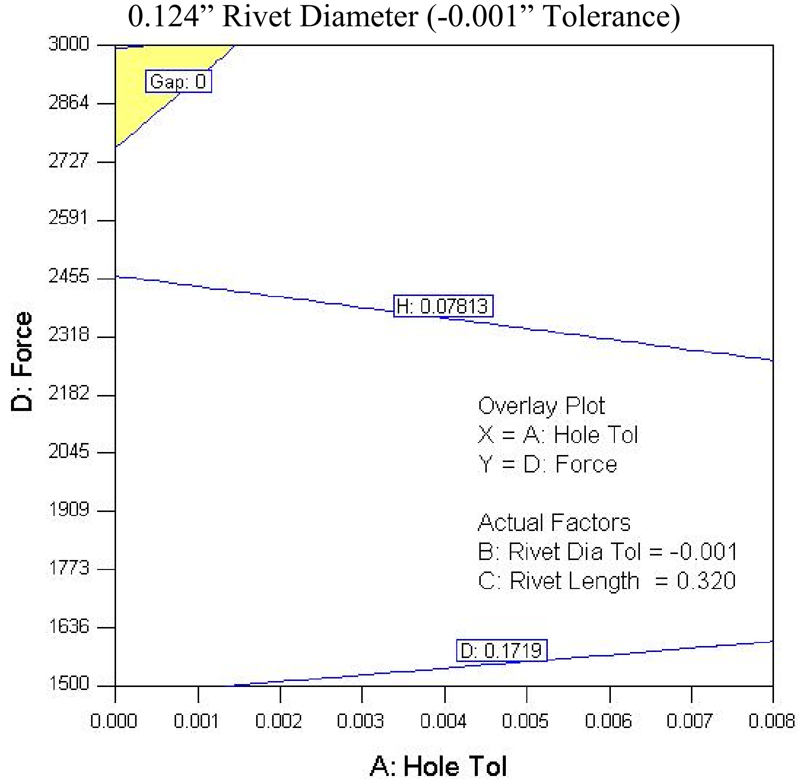


Figure 13. Model I: Feasible Region for 0.32" Length, 0.124" Diameter Rivet (-0.001" Tolerance)

4.1.2.2 Rivet Diameter Tolerance of 0.00” (D_o = 0.125”)

The following results can be summarized from Figures 14 and 15 below:

- The feasible area is smaller for 0.25” length than for 0.32” length. Compared to 0.32” length, for the same amount of force, the H value for 0.25” length decreases, making the feasible area smaller. The values of D and H are higher for 0.32” length rivet than for 0.25” length rivet. Thus, D and H increases with length for same amount of force.
- Allowable tolerance is limited by zero gap in between rivet head and sheet hole. Gap does not depend on the lengths. It is seen that the slope of gap line on the graphs are same for 0.25” and 0.32” lengths.
- For 0.25” length, the allowable hole tolerance is approximately +0.001” with 2790 lbf. With +0.001” tolerance in hole, and 0.125” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.0045”.
- For 0.32” length, the allowable hole tolerance is approximately +0.0025” with 3000 lbf. With +0.0025” tolerance in hole, and 0.125” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.006”.

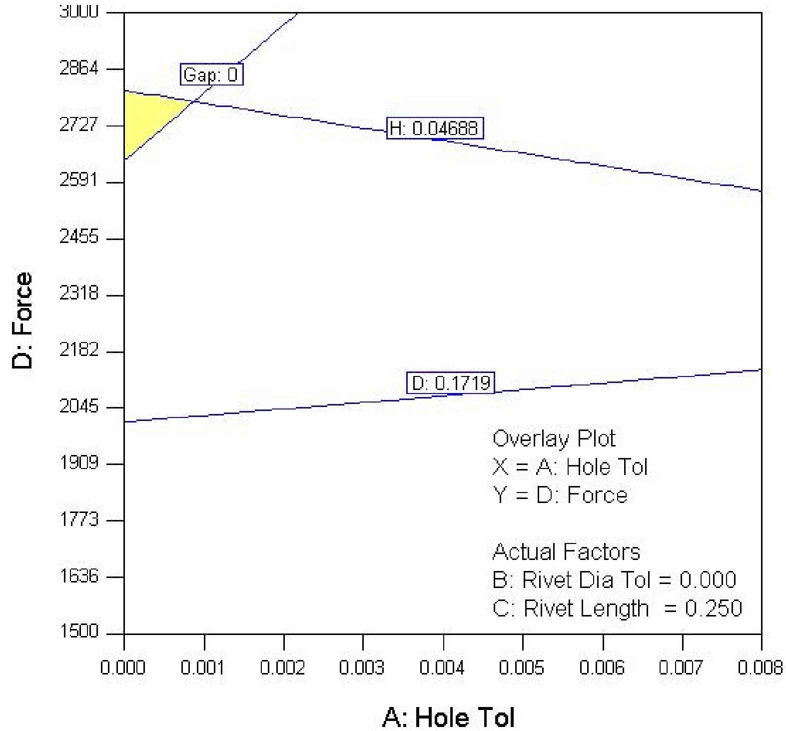


Figure 14. Model I: Feasible Region for 0.25” length, 0.125” Diameter Rivet (0.00” Tolerance)

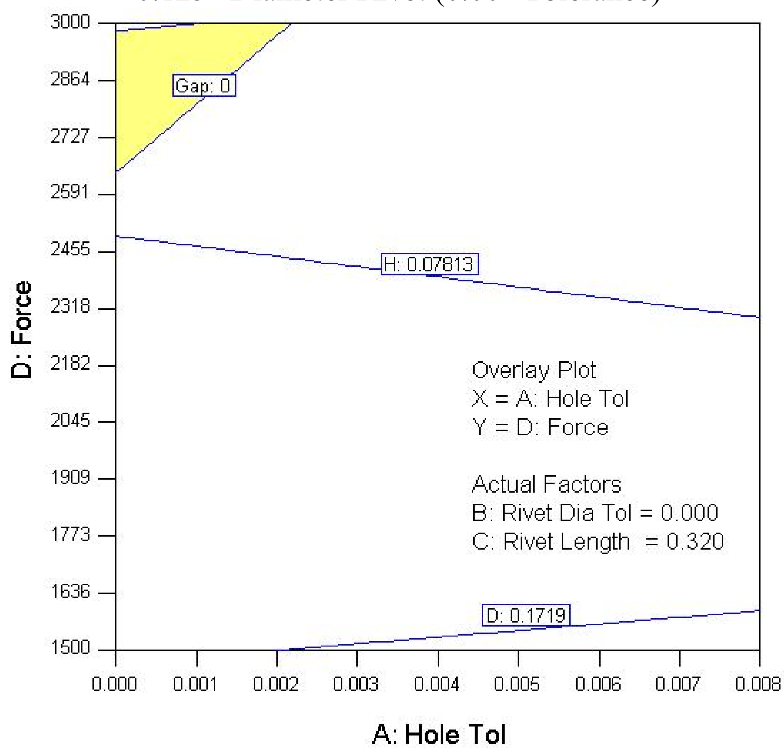


Figure 15. Model I: Feasible Region for 0.32” length, 0.125” Diameter Rivet (0.00” Tolerance)

4.1.2.3 Rivet Diameter Tolerance of +0.003” (D_o = 0.128”)

Compared with the results from 0.125” and 0.124” diameter rivet, rivet with 0.128” diameter has the biggest feasible area. The following results can be summarized from Figures 16 and 17:

- Allowable tolerance is limited by zero gap in between rivet head and sheet hole. Gap does not depend on the lengths, as the slopes of gap line on the graphs are same for 0.25” and 0.32” lengths.
- The values of D and H are higher for 0.32” length rivet than for 0.25” length rivet. Thus, D and H increases with length for same amount of force.
- For 0.32” length, the maximum allowable hole tolerance is +0.006” with 3000lbf. With +0.006” tolerance in hole, and 0.128” diameter rivet, the initial clearance between rivet shank and sheet hole is 0.0065”. So, the maximum clearance allowed is 0.0065”.
- For 0.25” length, the maximum allowable hole tolerance is +0.005” with 2827lbf. With +0.005” tolerance in hole, and 0.128” diameter rivet, the initial clearance between rivet shank and sheet hole is 0.0055”. So, the maximum clearance allowed is 0.0055”. The allowable tolerance is smaller due to smaller value of H for the same amount of force compared to 0.32” length rivet.

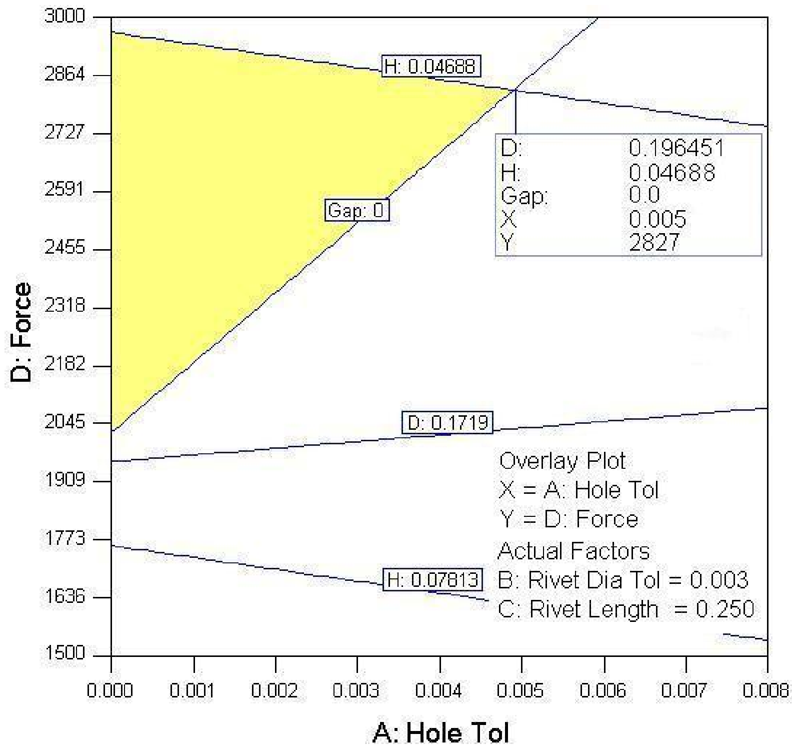


Figure 16. Model I: Feasible Region for 0.25" length, 0.128" Diameter Rivet (+0.003" Tolerance)

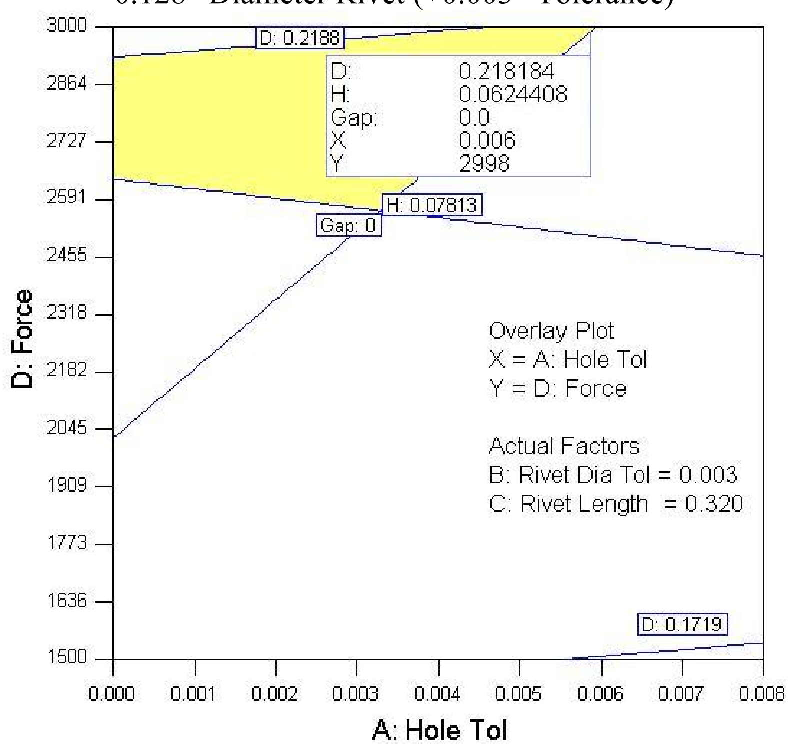


Figure 17. Model I: Feasible Region for 0.32" length, 0.128" Diameter Rivet (+0.003" Tolerance)

4.2 Model II

The experimental runs and the corresponding values of formed head (buck-tail) diameter (D), height (H) and gap in between sheet hole and rivet are shown in Table 10. Design Expert software is used to analyze the data in Table 10 to find out the significant factors that affect the formation of response variables D, H and gap. Based upon the data from Table 10, the Design Expert also provides relationship between the significant factors.

TABLE 10

MODEL II EXPERIMENTAL DATA

	Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response 1**	**Response 2**	**Response 3**	**Response 4**
Expts.	**A:Hole Tol.**	**B:Rivet Dia. Tol.**	**C:Rivet Length**	**D_F:Force**	**D**	**H**	**Flush Ht**	**Gap**
1	0.000	-0.003	0.250	1500	0.1490	0.0723	0.0075	0.0000
2	0.030	-0.003	0.250	1500	**0.1474**	0.0379	**0.0000**	0.0000
3	0.000	0.003	0.250	1500	0.1623	0.0714	**0.0100**	0.0000
4	0.030	0.003	0.250	1500	0.1583	0.0453	0.0010	0.0000
5	0.000	-0.003	0.320	1500	0.1720	0.0954	0.0075	0.0000
6	0.030	-0.003	0.320	1500	0.1629	0.0718	0.0003	0.0000
7	0.000	0.003	0.320	1500	0.1731	**0.1123**	**0.0100**	0.0000
8	0.030	0.003	0.320	1500	0.1596	0.0957	0.0015	0.0000
9	0.000	-0.003	0.250	3000	0.1951	0.0374	0.0064	0.0000
10	0.030	-0.003	0.250	3000	0.1630	**0.0173**	0.0008	0.0000
11	0.000	0.003	0.250	3000	0.2069	0.0418	0.0085	0.0000
12	0.030	0.003	0.250	3000	0.1844	0.0265	0.0012	0.0000
13	0.000	-0.003	0.320	3000	0.2183	0.0555	0.0066	0.0000
14	0.030	-0.003	0.320	3000	0.1996	0.0427	0.0002	0.0000
15	0.000	0.003	0.320	3000	**0.2237**	0.0619	0.0081	0.0000
16	0.030	0.003	0.320	3000	0.2094	0.0506	0.0011	0.0000

Notes: Low and high values for D, H and Gap are shown in bold.

Based on the statistical analysis of data from Table 10, the significant factors that affect the formation of buck-tail diameter (D), height (H) and gap, is explained in section 4.2.1. The relationships between D, H and gap with their significant factors are also presented. This relationship can be used to predict the values of D, H and gap when the values of factors A, B, C and D_F are known.

The practical application of these relationships is illustrated graphically in section 4.2.2. Section 4.2.2 is graphical depiction of results to determine maximum variation in factors A, B, C and D_F, while remaining within the boundaries of acceptable values of D, H and gap. The objective is to determine maximum allowable drilled hole tolerances with variation in squeeze force, rivet length and rivet diameter.

4.2.1 Significant Factors for the Formation of D, H and Gap from Design Expert Analysis

Buck-tail Diameter, D: Similar to Model I, for the formation of buck-tail diameter, the important factors that emerged from the analysis were the main effects hole tolerance (A), rivet diameter tolerance (B), rivet length (C) and squeeze force (D_F). Diameter (D) decreased with increase in hole tolerance. D increased with an increase in force, length, and rivet diameter tolerance. Resembling Model I, as seen in Table 10, the maximum D (0.2237”) is when rivet diameter tolerance is high (+0.003”), high force (3000lbf), bigger rivet length (0.32”) and no tolerance on hole. Similarly, the minimum D (0.1474”) is when rivet diameter tolerance is low (-0.003”), low squeeze force (1500lbf), smaller length rivet (0.25”) and high hole tolerance (0.008”). Based on the statistical analysis, the relationship between the formed rivet head diameter (D) and the factors A, B, C and D_F from Design Expert analysis is shown in equation (4.4).

$$D = 0.050857 - (0.48242*A) + (1.46367*B) + (0.27189*C) + (2.63101E\text{-}5*D_F) \quad (4.4)$$

The percentage contribution of each factor for the formation of D from Design Expert analysis is given in Table 11. As seen in Table 11, the dominant factor is the squeeze force (D_F), and the least dominant is rivet diameter tolerance (B).

TABLE 11

MODEL II: PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR FORMATION OF "D"

Factors	**% Contribution**
A	9.81
B	3.25
C	16.24
D_F	68.54

<u>Buck-tail Height, H</u>: For the formation of buck-tail height, the important factors that emerged from the analysis were the main effect of hole tolerance (A), rivet diameter tolerance (B) and interaction of rivet length and force (CD_F). As seen in Table 10, head height (H) and hole tolerance (A) are inversely proportional. As in Model I, H is lowest with high squeeze force (3000lbf), high hole tolerance (+0.008), low rivet diameter tolerance (-0.003) and smaller rivet length (0.25") (Table 10). Similarly, H is highest with low squeeze force (1500lbf), zero hole tolerance, high rivet diameter tolerance (+0.003) and bigger rivet length (0.32") (Table 10). Based on the statistical analysis, the relationship between the formed rivet head height (H) and the factors A, B, C and D_F from Design Expert analysis is shown in equation (4.5).

$$H = - 0.093808 – (0.66779*A) + (1.56995*B) + (0.74616*C) + (1.87446E\text{-}5*D_F)$$
$$– (1.44287E\text{-}004*C* D_F) \quad (4.5)$$

The percentage contribution of each factor for the formation of H from Design Expert analysis is given in Table 12. As seen in Table 12, the dominant factor is the squeeze force (D_F), and the least dominant is rivet diameter tolerance (B).

TABLE 12

MODEL II: PERCENTAGE CONTRIBUTION OF EACH FACTOR
FOR FORMATION OF "H"

Factors	**% Contribution**
A	16.20
B	3.36
C	32.98
D_F	42.68
CD_F	4.17

Flush Height: The height between countersunk rivet head and sheet surface is influenced by interactions of hole tolerance and force (AD_F), and hole tolerance and rivet diameter tolerance (AB). The length of rivet (factor C) had no effect on the flush height. The flush height was at its maximum value of 0.01" when there was minimum clearance between rivet and hole. The rivet head flushed with the surface as the clearance increased.

Based on the statistical analysis, the relationship between the gap and the factors A, B, and D_F from Design Expert analysis is shown in equation (4.6).

$$\text{Flush Ht} = 0.010083 - (0.31569*A) + (0.35792*B) - (8.9400E\text{-}7*D_F) - (7.0666*A*B) + (3.20333E\text{-}5*A*D_F) \qquad (4.6)$$

The percentage contribution of each factor for the formation of H from Design Expert analysis is given in Table 13. As seen in Table 13, the dominant factor is the tolerance on hole (A), and the least dominant is squeeze force (D_F).

TABLE 13

MODEL II: PERCENTAGE CONTRIBUTION OF EACH FACTOR FOR FORMATION OF "FLUSH HEIGHT"

Factors	**% Contribution**
A	93.36
B	3.99
D_F	0.67
AB	0.71
AD_F	0.91

Gap: No gap existed in between the countersunk rivet head and countersunk hole; the hole was always filled.

4.2.2 Graphical Analysis of Results

As in Model I, results are graphically illustrated in order to visually observe the amount of variations allowed for the factors (A, B, C and D_F). Equations (4.4), (4.5) and (4.6) are plotted with known acceptable range of D and H, and flush height. Graphs to determine allowable tolerances on drilled hole at various force values, rivet lengths, and rivet diameter are plotted. The plotted graphs consist of force on the Y-axis and hole tolerances on the X-axis. On the graphs, the lines of maximum and minimum acceptable D and H values and the line of Flushed height are plotted. The feasible area is shaded, which is the area where the values of D and H are acceptable, with flush height within 0.01" and no gap exists in between rivet and hole. Results are graphically illustrated for rivet diameter tolerances of -0.003" (diameter 0.122"), 0.00" (diameter 0.125") and +0.003" (diameter 0.128").

4.2.2.1 Rivet Diameter Tolerance -0.003” (D_o = 0.122”)

The following results can be summarized from Figures 18 and 19 below:

- The feasible area is smaller for 0.25” length than for 0.32” length, because the values of D and H are higher for 0.32” length rivet than for 0.25” length rivet. Thus, D and H increases with length for same amount of force.
- For 0.25” length, the allowable hole tolerance is approximately +0.003” with 2250lbf. With +0.003” tolerance in hole, and 0.122” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.0095”.
- For 0.32” length, the allowable hole tolerance is +0.03” with (2300-2700) lbf. With +0.03” tolerance in hole, and 0.122” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.0365”.

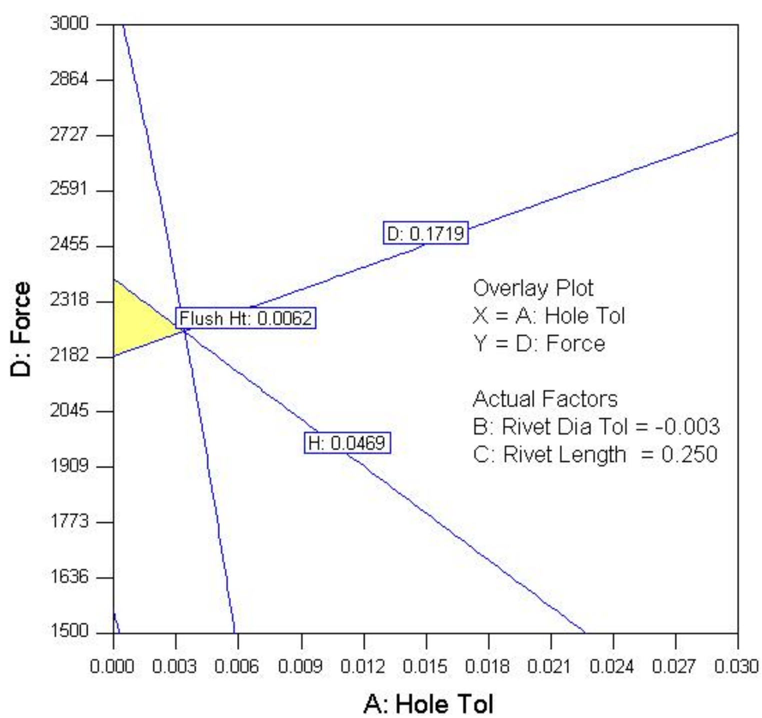


Figure 18. Model II: Feasible Region for 0.25” length, 0.122” Diameter Rivet (Tolerance -0.003”)

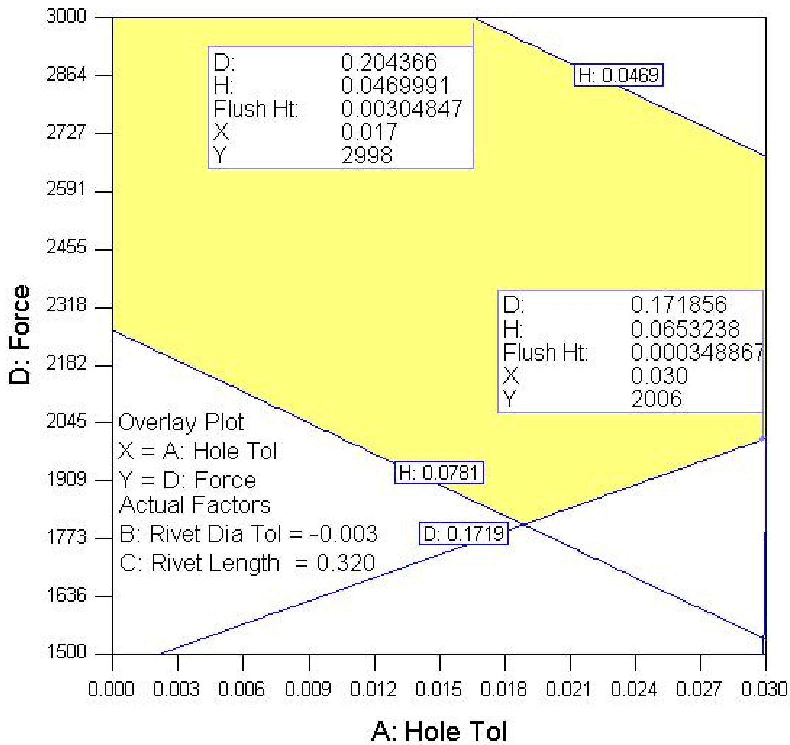


Figure 19. Model II: Feasible Region for 0.32” length, 0.122” Diameter Rivet (Tolerance -0.003”)

Figures 18 and 19 above can be used to estimate the force and allowable hole tolerances for lengths in between 0.25” and 0.32”. Figure 20 is a combination of the graphs of 0.25” and 0.32”, which gives the combined feasible area. The maximum and minimum values of D and H for lengths 0.25” and 0.32” are indicated in the figure. The feasible area for rivet length of 0.285” is shown in figure 20.

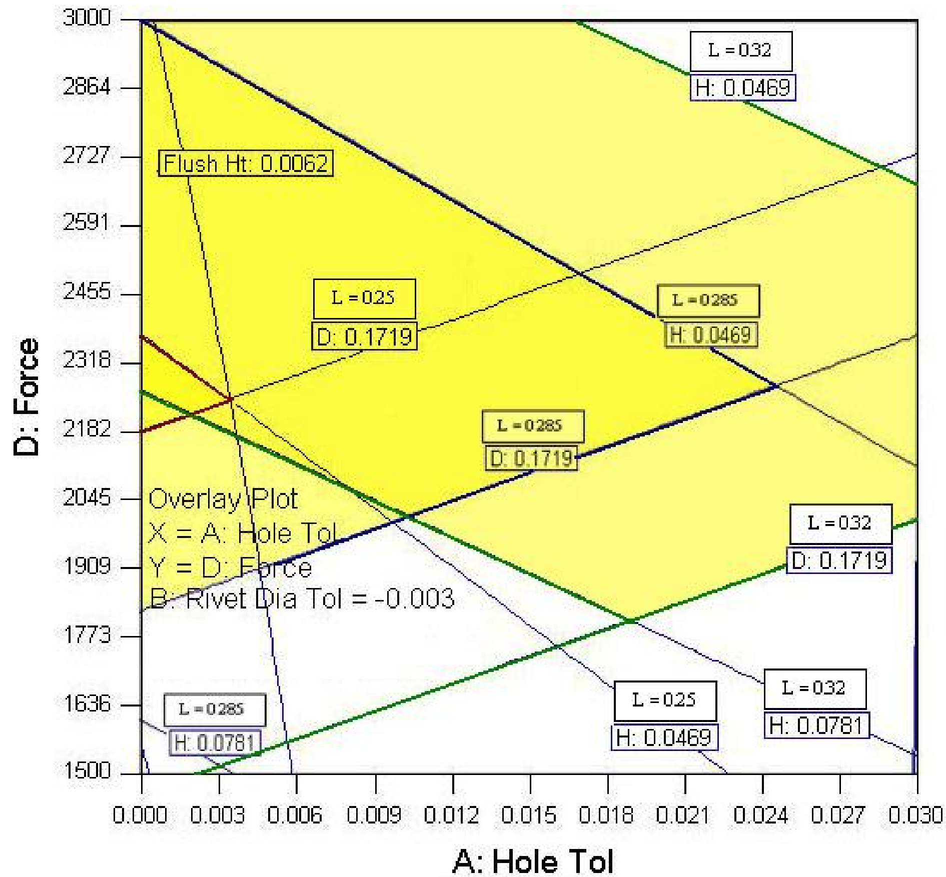


Figure 20. Model II: Combined Feasible Region
for 0.122” Diameter Rivet (Tolerance -0.003”)

4.2.2.2 Rivet Diameter Tolerance 0.00” (D_o = 0.125”)

The following results can be summarized from Figures 21 and 22 below:

- For 0.25” length, the allowable hole tolerance is approximately +0.012” with 2250 lbf. With +0.012” tolerance in hole, and 0.125” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.0095”.
- For 0.32” length, the allowable hole tolerance is +0.03” with (2400-2800) lbf. With +0.03” tolerance in hole, and 0.122” diameter rivet, the initial allowable clearance between rivet shank and sheet hole is 0.0365”.

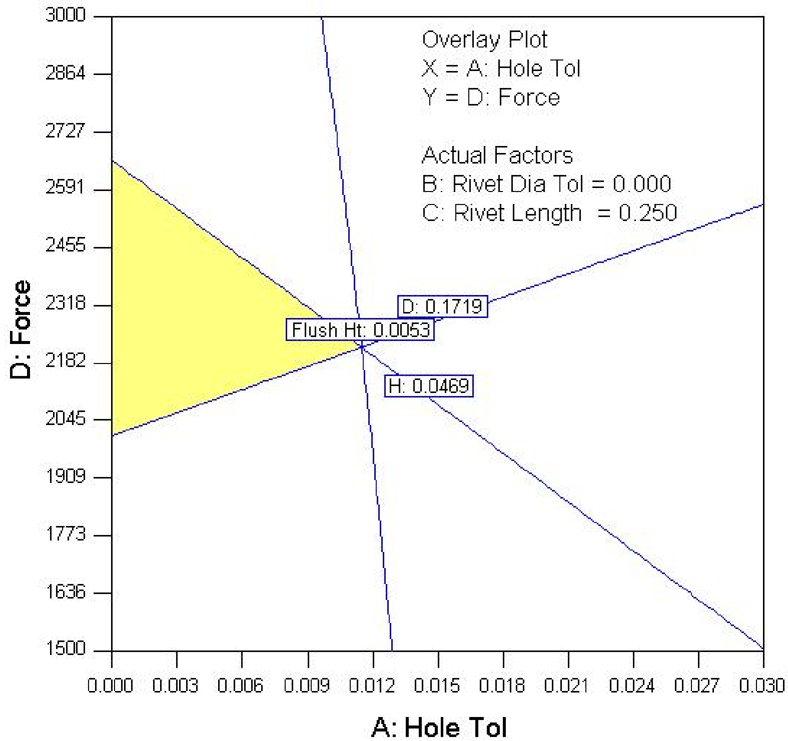


Figure 21. Model II: Feasible Region for 0.25" length, 0.125" Diameter Rivet (Tolerance 0.00")

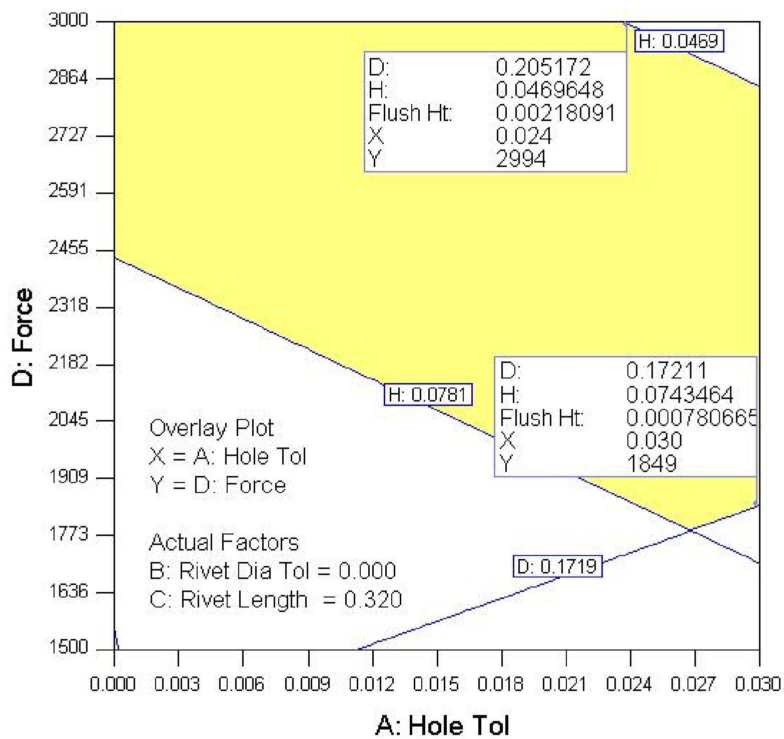


Figure 22. Model II: Feasible Region for 0.32" length, 0.125" Diameter Rivet (Tolerance 0.00")

Figures 21 and 22 above can be used to estimate the force and allowable hole tolerances for lengths in between 0.25” and 0.32”. Figure 23 is a combination of the graphs of 0.25” and 0.32”, which gives the combined feasible area. The maximum and minimum values of D and H for lengths 0.25” and 0.32” are indicated in the figure. The feasible area for rivet length of 0.285” is shown in figure 23.

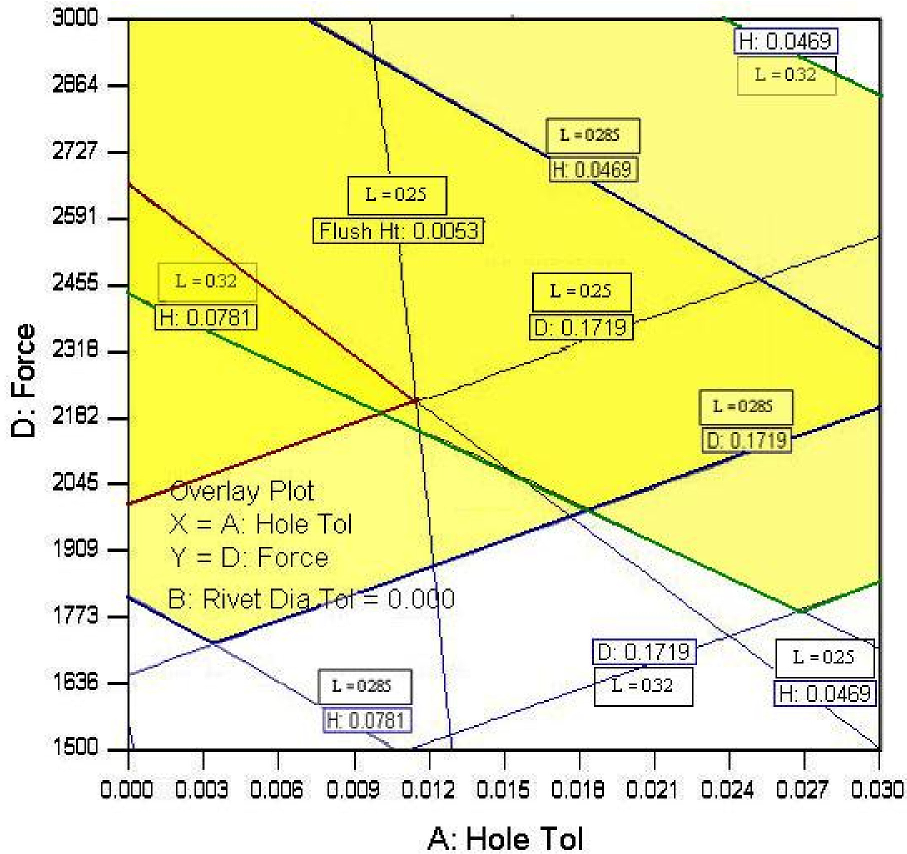


Figure 23. Model II: Combined Feasible Region
for 0.125” Diameter Rivet (Tolerance 0.00”)

4.2.2.3 Rivet Diameter Tolerance +0.003" (D_o = 0.128")

Compared with the results from 0.125" and 0.122" diameter rivet, rivet with 0.128" diameter has the biggest feasible area. The following results can be summarized from Figures 24 and 25 below:

- For 0.25" length, the maximum allowable hole tolerance is +0.019" with 2250lbf. With +0.019" tolerance in hole, and 0.128" diameter rivet, the initial clearance between rivet shank and sheet hole is 0.0195". So, the maximum clearance allowed is 0.0195".
- For 0.32" length, the maximum allowable hole tolerance is +0.03" with (2600-3000) lbf. With +0.03" tolerance in hole, and 0.128" diameter rivet, the initial clearance between rivet shank and sheet hole is 0.0305". So, the maximum clearance allowed is 0.0305".

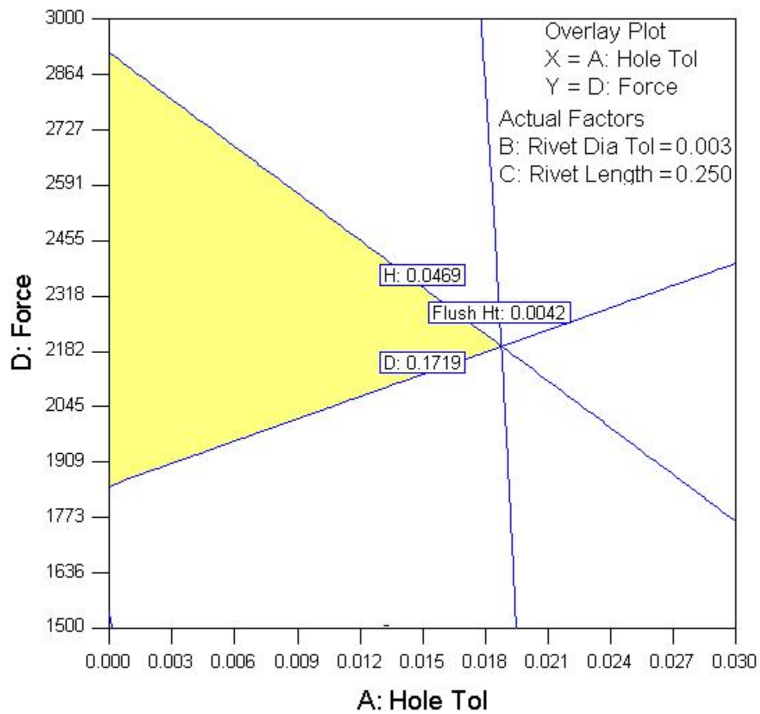


Figure 24. Model II: Feasible Region for 0.25" length, 0.128" Diameter Rivet (Tolerance +0.003")

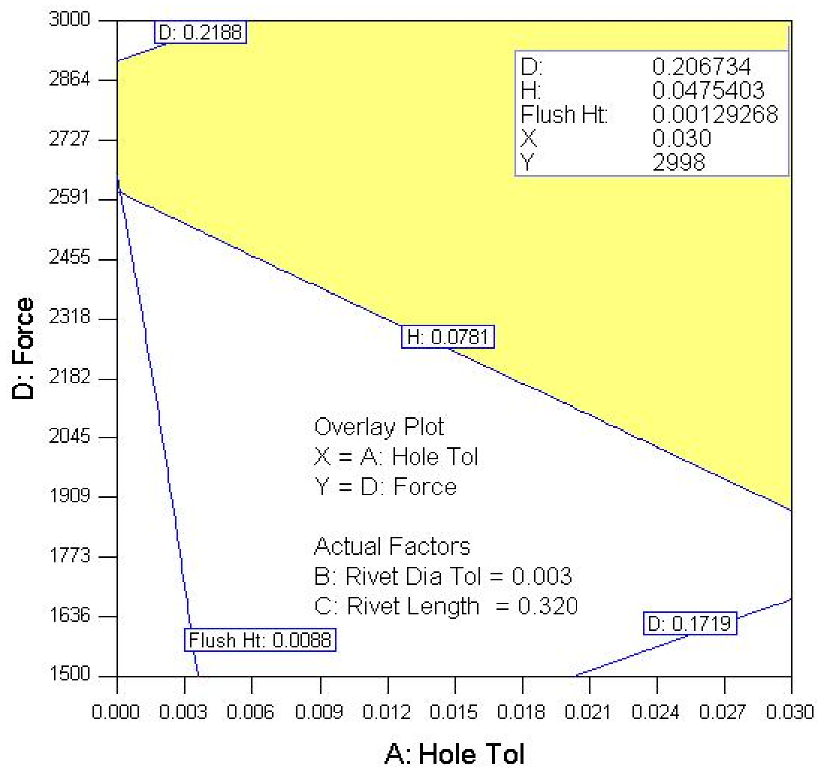


Figure 25. Model II: Feasible Region for 0.32” length, 0.128” Diameter Rivet (Tolerance +0.003”)

Figures 24 and 25 above can be used to estimate the force and allowable hole tolerances for lengths in between 0.25” and 0.32”. Figure 26 is a combination of the graphs of 0.25” and 0.32”, which gives the combined feasible area. The maximum and minimum values of D and H for lengths 0.25” and 0.32” are indicated in the figure. The feasible area for rivet length of 0.285” is shown in figure 26.

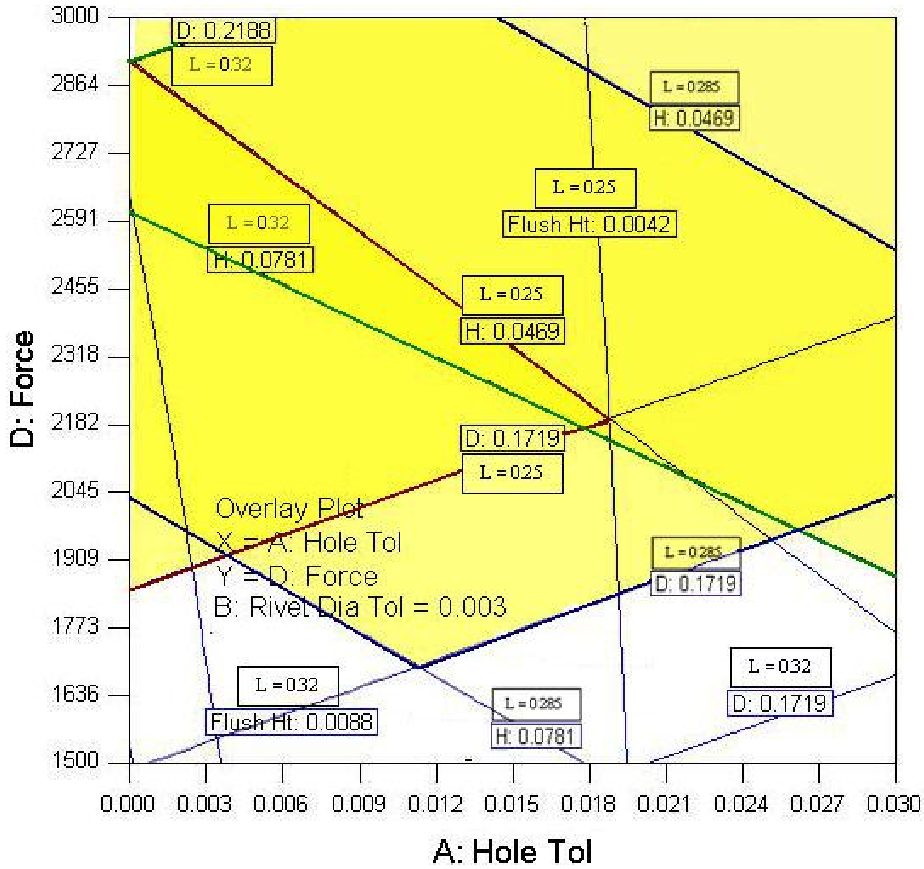


Figure 26. Model II: Combined Feasible Region
for 0.128” Diameter Rivet (Tolerance +0.003”)

4.3 Comparison of Results of Model I and II

As seen in the plots of previous section, the feasible area is greater for all conditions of Model II than for Model I. The summary of results for Model I and II are shown in Table 14 and 15 below. It is seen that allowable variation in drilled hole increases with rivet length, rivet diameter and squeeze force.

For both models, it is seen that as length increases, allowable tolerance on drilled hole increases as well, suggesting that 0.32” length rivet is beneficial when compared to 0.25” length. The amount of squeeze force required to form a rivet also increases with length. Similarly, both the models suggest that high squeeze force increases allowable tolerances in hole by completely filling rivet material in the hole, thereby decreasing the gap.

In both models, high tolerance in rivet diameter (+0.003”) resulting in bigger diameter rivet (0.128”), increases the allowable tolerance on the drilled hole. In Model I, the minimum allowable tolerance on rivet diameter is (-0.001”), limiting the diameter to only 0.124”. A rivet diameter tolerance less than -0.001” will result in a rivet joint with gap in between countersunk rivet head and hole. However, in Model II, since the gap is always filled, the allowable tolerance on rivet diameter can be (-0.003”) with diameter of 0.122”.

In Model I, even with maximum force of 3000lbf and maximum length of 0.32”, the allowable tolerance is only in the range of (0.0015” - 0.0065”). In contrast, Model II increases the allowable hole tolerance to as high as 0.03” with as little force as 2300lbf. This suggests that Model II with reduced countersunk depth of 0.032” is beneficial as opposed to standard countersunk depth of 0.042”.

TABLE 14

RESULTS SUMMARY FOR MODEL I (0.042” COUNTERSUNK DEPTH)

Rivet Diameter	**Length = 0.25”**	**Length = 0.32”**
0.125 - 0.003 = 0.122”	Not Feasible	Not Feasible
0.125 - 0.001 = 0.124”	F_{sq} = 2775 lbf Hole Tolerance = 0.0” Clearance = 0.0045”	F_{sq} = 3000 lbf Hole Tolerance = 0.0015” Clearance = 0.006”
0.125 + 0.000 = 0.125”	F_{sq} = 2790 lbf Hole Tolerance = 0.001” Clearance = 0.0045”	F_{sq} = 3000 lbf Hole Tolerance = 0.0025” Clearance = 0.006”
0.125 + 0.003 = 0.128”	F_{sq} = 2827 lbf Hole Tolerance = 0.005” Clearance = 0.0055”	F_{sq} = 3000 lbf Hole Tolerance = 0.006” Clearance = 0.0065”

TABLE 15

RESULTS SUMMARY FOR MODEL II (0.032” COUNTERSUNK DEPTH)

Rivet Diameter	**Length = 0.25”**	**Length = 0.32”**
0.125 - 0.003 = 0.122”	F_{sq} = 2250 lbf Hole Tolerance = 0.003” Clearance = 0.0095”	F_{sq} = (2300 - 2700) lbf Hole Tolerance = 0.03” Clearance = 0.0365”
0.125 + 0.000 = 0.125”	F_{sq} = 2250 lbf Hole Tolerance = 0.012” Clearance = 0.0155”	F_{sq} = (2400 - 2800) lbf Hole Tolerance = 0.03” Clearance = 0.0335”
0.125 + 0.003 = 0.128”	F_{sq} = 2250 lbf Hole Tolerance = 0.019” Clearance = 0.0195”	F_{sq} = (2600 – 3000) lbf Hole Tolerance = 0.03” Clearance = 0.0305”

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Sheet metal parts are widely used in the assembly of aircraft. The most common method of assembling sheet metal parts is through riveting. Failure of a rivet could have severe consequences in terms of loss of human lives and financial loss. There are many parameters associated with a riveting process that directly affect the quality and health of the produced rivets. Some of the parameters can be controlled while others are difficult to control. The controllable parameters include rivet length, geometric and dimensional tolerances on rivets and drilled holes, and squeeze force. Incorrect selection or extreme variation in these parameters could not only induce excessive residual stresses that result in stress concentration sites and initiate cracks, but also result in improper rivet head deformation leading to loose rivet.

This thesis presented a numerical and statistical study of the effect of various riveting process parameters on the quality of the rivet formation. The thesis studied the effect of controllable riveting parameters - squeeze force, rivet length, rivet diameter tolerance, hole countersunk depth and hole diameter tolerance, on the quality of formed rivet. The quality of a correctly formed rivet is determined by the geometry of its head formation and perfectly filled hole. The thesis determined relationship between the resulting geometrical parameters of a rivet driven head (buck-tail) and the applied squeeze force under various manufacturing variability that are likely to exist, such as sheet hole tolerance, rivet geometry tolerance, countersunk depth and length of rivet. With this relation, it is possible to assess the riveting quality, and thus the joint quality with respect to fatigue life. It was found that in order to check quality of rivet, correct dimension of buck-tail formation is not enough. Buck-tail forms with/without gap in between sheet and rivet countersunk head, leading to loose rivet.

This thesis also determined maximum allowable variation in drilled hole for a 1/8" rivet on a 0.064" thick aluminum sheets, with a given amount of force, rivet length and countersunk depth. It is found that variation in drilled hole is limited by gap formation in between rivet head and countersunk hole. This problem of gap formation is solved by reducing the countersunk depth from 0.042" to 0.032", which ensured proper filling of rivet head into the countersunk hole. Hence, it can be concluded that reduction in countersunk depth by 0.01", even though elevates the rivet 0.01" higher than the surface of the sheet, is an acceptable practice.

5.1 Recommendations and the Amount of Variation Allowed for the Parameters

Countersunk Depth: Countersunk depth should be reduced by 0.01" from the standard depth. Countersunk depth of 0.032" allowed more variations among the parameters than standard depth of 0.042" by filling up the gap between rivet and hole. Countersinking 0.032" elevates the rivet 0.01" higher than the surface of the sheet before driving the rivet. The elevation of 0.01" is reduced and the rivet is flushed with the surface after the rivet is driven and formed. Hence, countersinking 0.01" less than the standard depth is recommended, since it allows for maximum variation among all the parameters studied.

Rivet Length: When selecting rivet length, longer rivet length (0.32") is beneficial, because it increases allowable tolerances in drilled hole. Hence, the length of the rivet that extends beyond the sheets to be riveted should be 1.5 times the nominal diameter (D_o) of the rivet, as opposed to 1 times nominal diameter (D_o).

Rivet Diameter Tolerance: Rivet diameter tolerance is limited to (-0.001 to +0.003)" for 0.042" countersunk depth. The range is higher (+/-0.003") for the countersunk depth of 0.032".

Drilled Hole Tolerance: The maximum drilled hole tolerance is only (+0.006”) for the countersunk depth of 0.042”. The tolerance limit is increased considerably to (+0.03”) with reduced countersunk depth of 0.032”.

Squeeze Force: High squeeze force is beneficial, because it not only provides higher compressive residual hoop and tangential stress in and around the rivet and hole, resulting in higher strength of the joint, but also ensures complete filling of rivet material in the hole. However, high squeeze force may overdrive the rivet buck-tail; overdriven rivet do not conform to the acceptable diameter and height of rivet buck tail as specified in Standard Aircraft Handbook (1994), and may fail prematurely. Also, in manual riveting, high squeeze force will not be practical. The amount of squeeze force needed to drive a rivet increases with rivet length and rivet diameter. With 0.042” countersunk depth, recommended force is 3000lbf, while the force can be decreased to 2300lbf with 0.032” countersunk depth.

5.2 Future Works

The study was limited to controllable parameters only. Parameters that may be difficult to control, such as riveting velocity, friction in between riveting tools and rivet and coefficient of friction in between the sheets could be studied as future work. The study was also limited to 1/8” countersunk rivet with constant sheet thickness of 0.064”. The thesis could be extended to study the effect of various rivet diameters and sheet thickness. The joint strength on the top sheet can be increased by increasing its thickness while compensating this thickness by decreasing the thickness of the lower sheet. The effect of two different sheet thicknesses on the resulting joint could be studied.

The results in this thesis are based on numerical finite element simulation of riveting process. Even though the finite element model is validated by theoretical results, data from practical experiments of actual riveting can be collected to verify the results derived in this thesis. Hence, the future work could be to conduct experiments in Table 6 and 7 for Models I and II and compare with the results derived.

The thesis did not study residual stresses after the formation of rivet. It is assumed in this thesis that since the variations among the parameters studied were within the actual range, the stresses would be inevitable. However, since the fatigue strength of rivet is higher with high compressive residual stresses in and around the rivet periphery, a method of riveting to increase such residual stresses can be studied in future.

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REFERENCES

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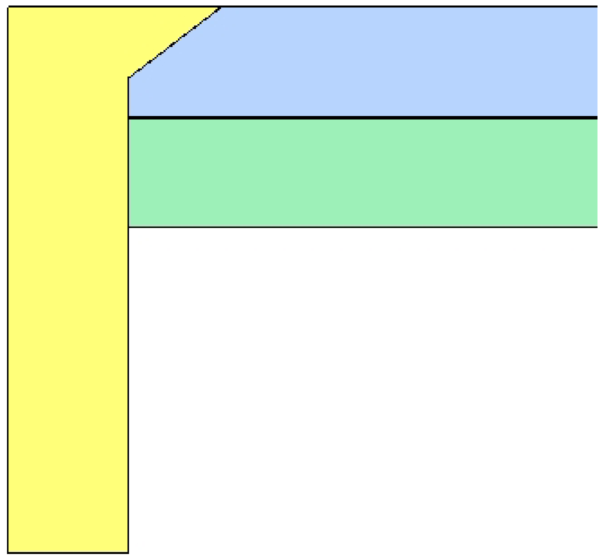
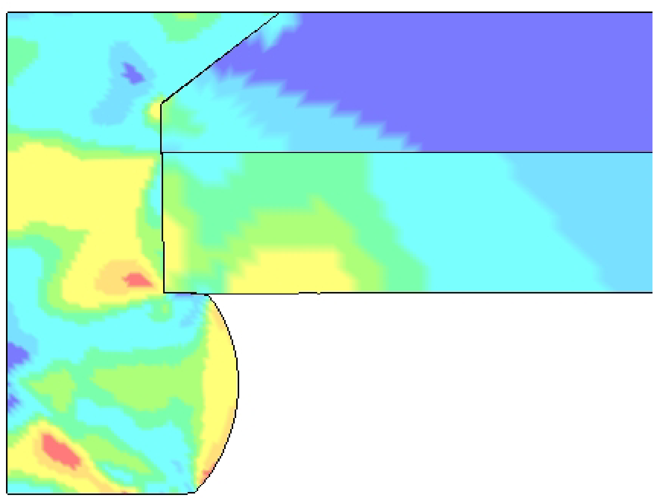
APPENDICES

APPENDIX A

MODEL I: 0.042" COUNTERSUNK DEPTH WITH 0.32" LENGTH RIVET
TOLERANCES: +0.003" RIVET DIAMETER, 0.00" HOLE



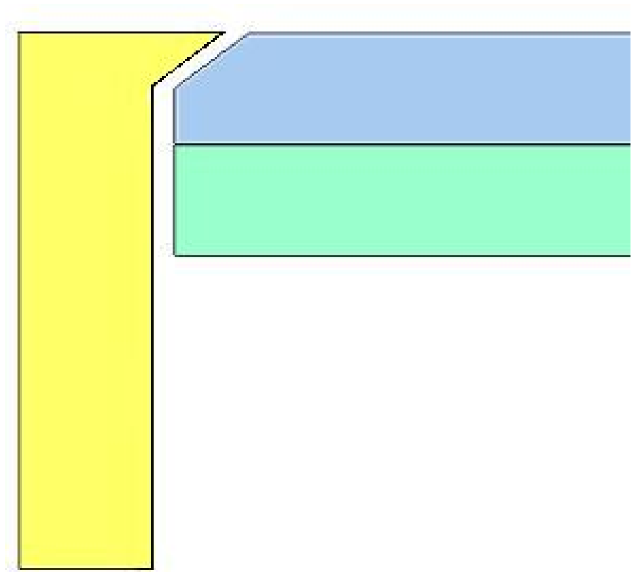
Before Riveting



After Riveting

APPENDIX B

MODEL I: 0.042" COUNTERSUNK DEPTH WITH 0.32" LENGTH RIVET
TOLERANCES: +0.003" RIVET DIAMETER, +0.008" HOLE



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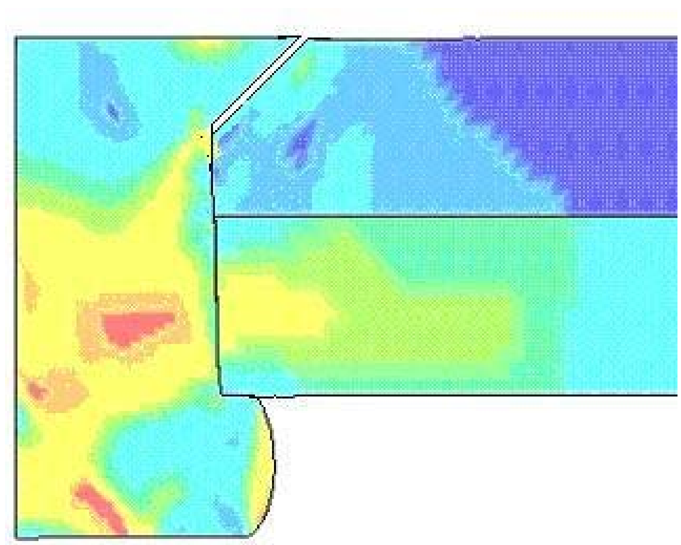
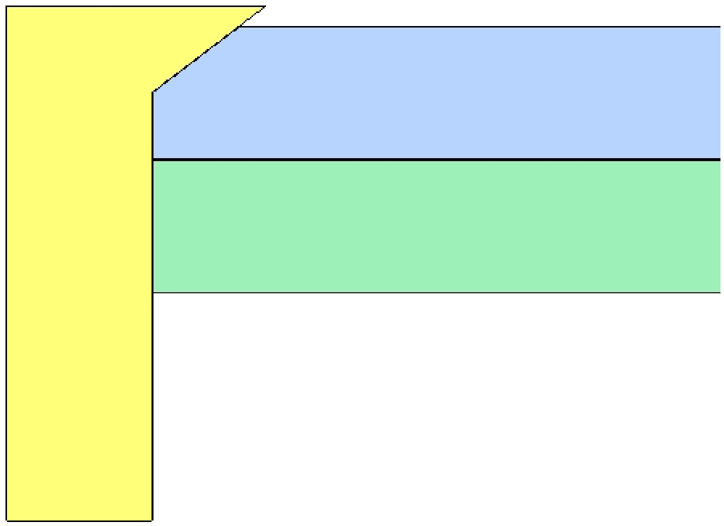


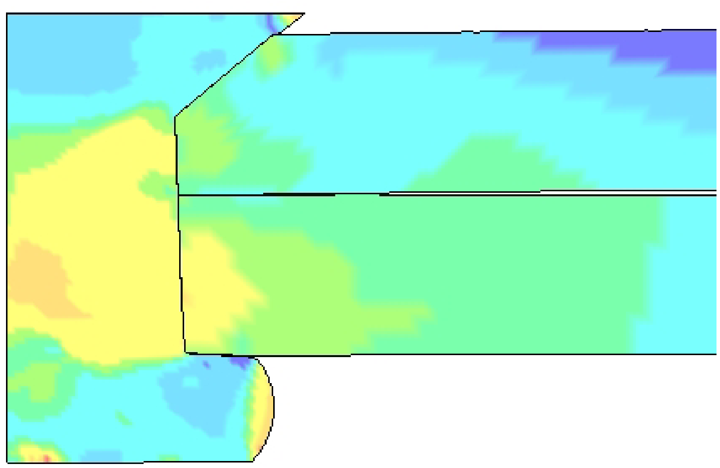
After Riveting: Gap Formation under Countersunk Rivet Head and Hole

APPENDIX C

MODEL II: 0.032” COUNTERSUNK DEPTH WITH 0.25” LENGTH RIVET
TOLERANCES: +0.003” RIVET DIAMETER, 0.00” HOLE



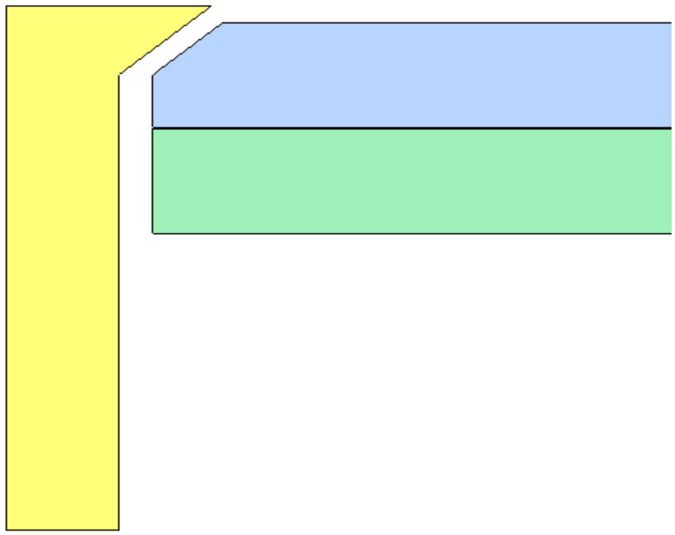
Before Riveting: Rivet Head 0.01” Higher than the Sheet Surface



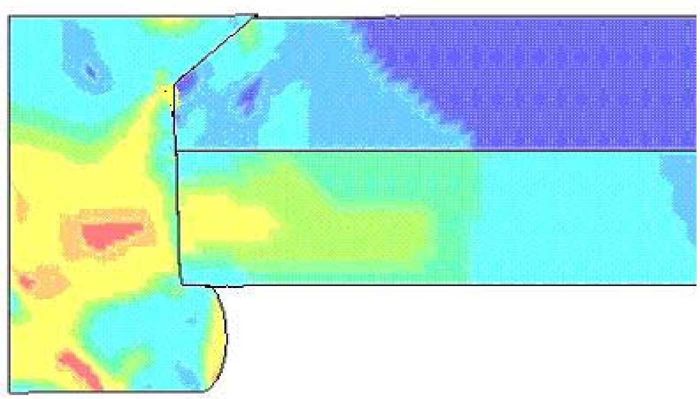
After Riveting: Rivet Head Not Flushed with the Sheet Surface

APPENDIX D

MODEL II: 0.032” COUNTERSUNK DEPTH WITH 0.25” LENGTH RIVET
TOLERANCES: +0.003” RIVET DIAMETER, +0.03” HOLE



Before Riveting: Rivet 0.01” Higher than the Sheet Surface



After Riveting: Rivet Head Flushed with the Sheet Surface