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**An Experimental Investigation into the Fatigue Behaviour of Dimple
Countersunk GLARE Riveted Lap Joints**

By

Calvin Rans, B.Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of

Master of Applied Science

Department of Mechanical and Aerospace Engineering
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Mechanical and Aerospace Engineering

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ABSTRACT

GLARE (GLAss REinforced) laminates are part of a family of metal-composite hybrid materials being used for airframe applications. One critical design element in such an application is the riveted lap joint. Machine countersinking, necessitated by the use of flush-head rivets, produces a knife-edge in some of the GLARE plies. The resulting stress concentrations likely accelerate crack nucleation in such joints, diminishing fatigue performance. Furthermore, the superior fatigue performance of GLARE relative to monolithic aluminum permits reductions in skin thickness, increasing the risk of a through-thickness knife-edge.

This thesis examines the potential of dimple countersinking as an alternative method to machine countersinking in thin GLARE laminates. Using simple coupons, the dimpling process and crack initiation behaviour of dimpled GLARE is investigated. Additionally, wide lap joint fatigue specimens were tested to compare the relative performance of machine countersunk and dimpled GLARE lap joints. Initial results showed that dimpled GLARE joints have an inferior fatigue performance; however, these results are based on dimpling tools and processes optimized for aluminum. Delamination damage was observed during the dimpling process which may be responsible for the poor fatigue performance. Through optimization of the dimpling tool geometry, such damage may be avoidable, allowing the true potential of dimpling to be investigated.

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NOMENCLATURE

D	Upset rivet head diameter [in]
D _o	Rivet shank diameter [in]
h	Countersink depth [in]
p	Row pitch [in]
R	Stress Ratio [dimensionless]
s	Rivet pitch [in]
t	Fuselage skin thickness [in]
ARALL	Aramid Reinforced ALuminum Laminates
CIS-A	Crack Initiation Specimen type A
CIS-B	Crack Initiation Specimen type B
CSK	Countersink
FEM	Finite Element Method
FML	Fibre Metal Laminates
GLARE	GLAss REinforced laminates
IAR	Institute for Aerospace Research
LS	Lower Sheet
MSD	Multiple Site Damage
NDI	Non-Destructive Inspection
NRC	National Research Council (Canada)
US	Upper Sheet

UNITS

This thesis uses English units to keep with the North American aerospace industry practice. The following conversion factors are provided to convert to S.I. units:

English Unit	Conversion Factor to S.I. Unit
in.	25.40 mm
lb.	4.45 N
ksi	6.89 MPa

Chapter 1: INTRODUCTION

Fibre metal laminates (FMLs) are a new family of fatigue resistant materials consisting of alternating metallic and fibre-reinforced polymer layers (Figure 1.1). One promising application of FMLs is the use of GLARE (GLASS REinforced aluminum) laminates as a replacement for monolithic aluminum skins of pressurized aircraft fuselages. In addition to fatigue life improvements, the fatigue performance of GLARE would allow the use of smaller skin thicknesses, resulting in structural weight savings.

Figure 1.1: Typical fibre metal laminate layup.

A critical aspect of fuselage design is the fatigue life of riveted joints. Individual skin panels are spliced together using rivets to form the fuselage skin, which in turn is riveted to the underlying fuselage structure. These joints are primarily loaded by membrane stresses in the fuselage skin resulting from cabin pressurization and depressurization cycles during successive flights. This loading produces large stress concentrations around the fastener holes, which limit the fatigue life of the overall structure.

A major factor contributing to the magnitude of the stress concentration around rivet holes is the depth of the rivet countersink. The aerodynamic requirements of modern jet aircraft demand the use of countersunk fasteners on most external aircraft surfaces, including the fuselage. Countersinking is typically performed by machining away material from the material being joined (skin panels) around the fastener hole. This machined countersink increases the elastic stress concentration associated with the fastener hole by a factor proportional to the countersink depth as a percentage of the skin thickness (Young and Lee, 1993). Furthermore, machine countersinking reduces the bearing surface of the countersunk sheet, increasing the stress concentration due to rivet bearing.

The effect of the rivet countersink on the stress state around the rivet hole is more pronounced in narrow body aircraft. The pressurization loads in the relatively small diameter of a narrow-body aircraft permit the use of small skin thicknesses. In such skins, countersink depths of 70-90% of the skin thickness are commonly encountered. With the application of thinner GLARE laminates as a skin material in narrow-body aircraft, countersink depths could easily exceed the skin thickness, leading to a “knife-edge” condition (Figure 1.2a). The stress concentration associated with such a condition is detrimental to fatigue performance. Furthermore, machine countersinking GLARE will produce a knife-edge in at least one of the thin aluminum layers, depending on the GLARE layup and countersink depth. Given the negative influence of machine countersinking on the fatigue performance of GLARE skins in narrow-body aircraft, an alternative form of countersinking is desirable. One alternative is press countersinking

(dimpling), in which the sheet material around the rivet hole is plastically deformed, forming a dimpled countersink (Figure 1.2b).

Figure 1.2: Types of countersinks; (a) machine countersunk rivet with knife-edge; (b) dimple countersunk rivet.

This thesis presents an experimental investigation into the potential of dimpling as an alternative method for countersinking GLARE in narrow-body aircraft applications. A portion of this work was completed as part of a collaborative project between the Institute of Aerospace Research (IAR-SMPL) of the National Research Council Canada (NRC), Bombardier Aerospace, and Carleton University to understand the behaviour of GLARE in narrow-body scale aircraft structures. The thesis organization is as follows:

Chapter 2 – review of fuselage construction and loading.

Chapter 3 – review of the fatigue mechanism in riveted lap joints.

Chapter 4 – review of the properties of GLARE and issues associated with the application of GLARE as a skin material in narrow-body aircraft.

Chapter 5 – definition of thesis objectives and scope.

Chapter 6 – results of an experimental study into dimple forming in GLARE.

Chapter 7 – results of fatigue crack initiation tests in dimpled and machine countersunk GLARE.

Chapter 8 – results of wide lap joint fatigue tests in GLARE, including the four lap joint specimens tested as part of the collaboration with Bombardier Aerospace and NRC-IAR-SMPL.

Chapter 9 – discussion of results.

Chapter 10 – conclusions from the project.

Chapter 11 – recommendations for future work.

Chapter 2: STRUCTURAL JOINTS IN AIRFRAMES

Mechanically fastened joints are an essential part of airframe construction. Their need arises from limitations in available sizes of stock material, as well as manufacturing, assembly, and logistical requirements in airframe construction. Mechanical joints serve to transmit load between two components; however, the discontinuous nature of this load transfer creates stress risers that limit the overall structural capabilities of the airframe. Thus the design of mechanically fastened joints is critical in airframe construction.

2.1 Fuselage Construction

The fuselage of modern pressurized aircraft consists of a thin metallic skin supported longitudinally by stringers and circumferentially by frames and bulkheads (Table 2.1). This type of construction, referred to as *semi-monocoque* construction (Figure 2.1), results in an efficient structure with high strength-to-weight ratio.

Table 2.1: Explanation of main fuselage structural components (Cook, 2001).

Structure	Function	Comments
Frames	Maintain fuselage shape and reduce stringer column length providing compressive stability	Spacing: 18-20 in. (typical) Materials used: 7075-T6, 7150-T77
Bulkheads	Transfer localised loads to surrounding fuselage structure. Typically located at wing, empennage, and landing gear attachment points	Materials used: 7050, 7075-T6 Sometimes forgings are used in cases of very high loads
Stringers	Support the fuselage skin, and carry axial fuselage loads due to bending and pressure	Spacing: 6-10 in. (typical) Materials used: 2024-T3, 2524-T3, 7150-T77
Skin	Supports shear loads and fuselage pressurization loads, and to a lesser extent, tensile and compressive loads due to fuselage bending and torsion.	Sheet thickness: 0.036-0.087 in. depending on aircraft. Materials used: 2024-T3, 2524-T3

Figure 2.1: Typical semi-monocoque fuselage structure illustrating key components (Niu, 1995).

Fuselage skin panels are typically made of high strength, fatigue resistant aluminum alloys, such as 2024-T3, rolled into 8 ft by 12 ft sheets. The limited available size of the rolled aluminum sheets requires multiple skin panels be joined longitudinally and circumferentially to form the entire skin of the fuselage. Mechanically fastened joints utilizing deformable shank fasteners (solid rivets) are most commonly used for this application.

2.1.1 Fuselage Loading

During a typical flight, aircraft fuselages are subjected to various torsional, bending, shear, and pressure loads encountered during ground operations (taxiing, take-off, and landing), in-flight manoeuvres, and cabin pressurization. A major factor in the design of fuselage splices is loading due to cabin pressurization.

Flying at typical altitudes of 35,000 to 45,000 ft, commercial transport aircraft require a pressurized cabin to protect the crew and passengers from the effects of high altitude hypoxia. Federal Aviation Regulations Part 25 Section 841 (FAR 25.841) dictates a maximum cabin pressure altitude of 8,000 ft. Thus a positive pressure differential (Δp) is created between the aircraft cabin and external environment, generating longitudinal (axial) and circumferential (“hoop” or tangential) stresses within the fuselage structure. Idealizing the fuselage as a monocoque pressure vessel, the equations for hoop stress (σ_θ) and longitudinal stress (σ_l) are:

$$\sigma_\theta = \frac{\Delta p \cdot R}{t} \quad (1.1)$$

$$\sigma_l = \frac{\Delta p \cdot R}{2t} \quad (1.2)$$

where R is the fuselage radius and t is the skin thickness. For design purposes, the hoop and axial loads are typically expressed in terms of running loads (stress component multiplied by skin thickness). Since the hoop stress component has twice the magnitude as the axial stress component, it represents a major design load for fuselage joints.

Real fuselage structures are stiffened semi-monocoque structures. The presence of the stiffening members (frames and stringers) reduces the overall hoop and axial

stresses encountered in the fuselage skin to 75-90% of their monocoque values (Miller *et al.*, 1992). Furthermore, these stiffening members provide a local reduction in hoop and axial stress, resulting in a stress distribution similar to Figure 2.2.

Figure 2.2: Mid-plane hoop and axial stress distributions in a Boeing wide-body skin panel (Miller *et al.*, 1992).

2.1.2 Types of Joints used for Fuselage Skin Splices

There are three major types of joints used for fuselage skin splices; single shear butt, double shear butt, and single shear lap (Figure 2.3). Loading across such splices is predominately tensile (due to fuselage pressurization); however, shear loads and transverse loads will inevitably be present.

Figure 2.3: Types of tension loaded riveted joints.

Drag considerations govern joint type selection for circumferential fuselage splices. The overlap in single shear lap joints and outer splice strap in double shear butt joints create forward (or rearward) facing steps relative to air flow over the fuselage. Tight tolerances can be imposed on the gap size in single shear butt joints, producing an aerodynamically smooth outer surface that minimizes drag. As a result, circumferential fuselage splices typically take the form of single shear butt joints.

Longitudinal fuselage splices typically take the form of single shear lap joint due to its relative simplicity. Fewer fasteners and a lack of splice straps help reduce the weight and manufacturing costs of this joint type. The presence of a load path eccentricity, however, generates bending which lowers the fatigue life of the joint.

Double shear butt joints do not contain a load path eccentricity, and are generally seen as having a higher fatigue life. For this reason, in the past some aircraft manufacturers, such as Douglas, have used variations of the double shear butt joint as longitudinal fuselage splices. It is generally agreed, however, that sufficient fatigue life is obtainable through optimization of a lap joint design, making the added weight and

complexity of the double shear butt joint unnecessary for fuselage splice applications. As such, the present investigation will be limited to the longitudinal fuselage lap joint.

2.1.3 Solid Rivets

A large variety of rivets and other fasteners can be applied in fuselage joints; however, only solid rivets will be considered here. Solid rivets are a form of deformable shank fastener that is installed by compressing (driving) one end of the fastener, plastically forming the rivet into the sheet. As the rivet is installed, it expands to fill the rivet hole, producing an interference fit, and is cold worked, producing a strong fastener. Solid rivets are widely used in the aerospace industry due to their low cost and relatively good fatigue performance.

Fuselage joints typically use countersunk rivets due aerodynamic performance requirements. Although several styles of countersunk rivets head styles exist, the most commonly used are MS20426 and NAS1097. Both rivet head styles have a head angle of 100°. MS20426 rivets have a deeper countersunk head than NAS1097 (Table 2.2). In addition to rivet head style, rivets are available in a wide range of diameters, lengths, and rivet materials, which are defined by a code added to the rivet head style. The code breakdown is as follows:

Table 2.2: Rivet countersink depths according to MIL-HDBK-5H (DoD, 1998).

D _o (in)	h (in)	
	MS20426	NAS1097
1/16	0.022	-
3/32	0.036	0.021
1/8	0.042	0.027
5/32	0.055	0.036

The diagram illustrates the geometry of a rivet countersink. It shows a cross-section of a hole in a material with a countersink. The countersink has a conical shape with a 100-degree angle. The depth of the countersink is labeled 'h' and the diameter of the hole is labeled 'D_o'.

Table 2.3: Rivet alloy designations.

Material Designation	Rivet Alloy
A	1100
B	5056-H32
AD	2117-T4
D	2017-T4
DD	2024-T4
E	7050-T73

Rivet Installation

Rivets are installed using either a hammering or squeezing process. Hammering is typical of hand riveting practices where pneumatic riveting guns are used to progressively deform the rivet shank to the desired dimensions. Hand riveting is highly dependent on the skill of the workers, resulting in a wide variation in the quality of individual driven rivets. Automated riveting machines typically use a squeezing process to upset the rivet shank, and produce a more consistent rivet than hand riveting.

The quality of a driven rivet is typically determined by the geometry of the upset rivet head. Standard riveting practices state that:

- The upset rivet head diameter (D) should nominally be 1.3-1.5 times the original rivet shank diameter (D_o). The acceptable D/D_o range varies from 1.25 – 1.8.
- The upset rivet head height should nominally be 0.5 times D_o .

These constraints were developed based on past experience with hand riveted structures. The increasing use of automatic rivet squeezers allows an alternative measure to be used to assess the quality of a driven rivet: the rivet squeeze force. It is argued that such force controlled riveting practices result in a more consistent control over the rivet hole filling. As such, the beneficial residual compressive stresses resulting from this process can be controlled and optimized to maximize fatigue life. Müller (1995a) presents a detailed discussion on the benefits of force controlled riveting.

2.2 Lap Joint Nomenclature

The major geometric variables of a lap joint are shown in Figure 2.4, namely rivet pitch, row pitch, rivet diameter, sheet thickness, and number of rivet rows. Furthermore, the naming convention used in this thesis for joint sheets, sheet surfaces, and rivet rows is illustrated in Figure 2.4. Collectively, the top and bottom rivet rows are also referred to as the outer rivet rows in joints with three or more rivet rows.

Figure 2.4: Naming convention of rivet lap joint features and variables.

2.3 Longitudinal Fuselage Lap Joint Loading

As previously discussed, the primary load applied to longitudinal fuselage joints is the hoop load due to fuselage pressurization. Important to the design of such joints is an understanding of the mechanism by which riveted lap joints transmit this load, and its interaction with the joint eccentricity.

2.3.1 Load Transfer

Load transfer in riveted lap joints occurs through two mechanisms. The majority of the load is transferred through bearing between the rivets and sheet material. The remainder of the load is transferred through friction between the faying joint surfaces.

Figure 2.5: Schematic representation of load transfer in a riveted lap joint.

Figure 2.5 shows a schematic representation of this load transfer. In joints with multiple rivet rows, a portion of the load is transferred from the upper to the lower sheet by each rivet row, while the remainder (referred to as the bypass load) remains in the upper sheet.

Frictional load transfer comprises a small portion of the overall load transfer in riveted joints. Solid rivets provide low clamping forces, minimizing friction between the faying sheet surfaces. Furthermore, an interfaying sealant is often applied to the faying surfaces of riveted joints to prevent corrosive attack. This sealant acts as a lubricant, further reducing frictional forces. Although it is generally agreed that friction comprises a small portion of the load transfer in riveted joints, determining its magnitude is difficult due to uncertainties in friction factors and rivet clamping forces.

In joints containing more than two rivet rows, load is unevenly distributed across the rivet rows. Neglecting load transfer through friction, the relative bearing load transferred by each rivet row can be related to the relative flexibilities of the rivets and

sheets being joined by imposing displacement compatibility. For a 3-row riveted lap joint, it can be shown that (Müller, 1995a):

$$T_1 + T_2 + T_3 = P \quad (1.1)$$

$$T_1 = T_3 \quad (1.2)$$

$$\frac{T_2}{T_1} = \frac{f_{rivet}}{f_{rivet} + f_{sheet}} \quad (1.3)$$

where:

T_n	Load per unit width transferred by the n^{th} row of the splice
P	Applied running load
f_{rivet}	Rivet flexibility (empirically determined (Huth, 1986, Tate and Rosenfield, 1946, Swift, 1971))
f_{sheet}	Sheet flexibility ($= \frac{p}{E \cdot t \cdot s}$)
p	Rivet pitch
t	Sheet thickness
s	Row pitch
E	Young's modulus of sheet material

Equation 1.3 shows the relationship between load distribution and rivet and sheet flexibilities. For the case of a rigid rivet ($f_{rivet} = 0$), the entire load is transferred evenly by the outer rivet rows ($T_2 = 0$). If some rivet flexibility exists, then T_2 will be non-zero; however the load transferred by the middle rivet row will always be less than the load transferred by each of the outer rivet rows.

Under high loads, plastic deformation of the rivet holes allows the rivets to rotate, increasing rivet flexibility. As the load is increased, the rivet flexibility in Equation 1.3 becomes dominant, and the load becomes evenly distributed across all rivet rows. This is commonly taken into account in determining the ultimate strength of a riveted joint.

2.3.2 Secondary Bending

Bearing loads at individual rivets produce bending due to the eccentric load path of riveted lap joints. This bending, referred to as *secondary bending*, produces out-of-plane deformation of the sheets and increases the peak stress encountered by the faying joint surfaces. The additional stress concentration generated by secondary bending plays a significant role in the fatigue life of riveted lap joints, particularly in the fatigue crack initiation life.

A model for predicting the effects of secondary bending in two-row riveted lap joints by modelling a joint by its neutral axis was developed by Schijve (Homan *et al.*, 2001), and later extended to joints with three or more rows by Müller (1995). A neutral line, stepped at each rivet row, is used to represent the eccentric load path of the lap joint (Figure 2.6). The load transmission through the individual rivet rows is used to calculate the different eccentricities.

Figure 2.6: Neutral line representation of a three-row riveted lap joint (Homan *et al.*, 2001).

Under an applied load F, the deflection (w) of the neutral line can be represented by the following differential equation:

$$M_x = P \cdot w = E_i I_i \cdot \frac{d^2 w}{dx^2} \Rightarrow \frac{d^2 w}{dx^2} - \alpha_i^2 \cdot w = 0 \quad \text{with } \alpha_i^2 = \frac{P}{E_i I_i} \quad (1.4)$$

which has the following solutions:

$$w_i = A_i \cdot \sinh(\alpha_i \cdot x) + B_i \cdot \cosh(\alpha_i \cdot x) \quad (1.5)$$

where:

- M_x Secondary bending moment
- $E_i I_i$ Flexural rigidity of part i (Figure 2.6)
- A_i, B_i Constants related to joint boundary conditions

By applying the boundary conditions for joint displacement (assuming pinned connection at point of load application) and equating the slopes of the deflection curves on both sides of the rivet row, the constants A_i and B_i can be obtained. Bending stresses can be obtained by:

$$\sigma_{bending} = \frac{M_x \cdot z}{I} = \frac{P \cdot w(x) \cdot z}{I} = w(x)'' \cdot E \cdot z \quad (1.6)$$

where z is the distance from the neutral axis.

Schijve's neutral line model physically represents a lap joint with infinitely thin bond lines located at the rivet row locations. As such, it is not capable of predicting the changes in secondary bending between rivets in the same rivet row. Furthermore, since

the rivets are dimensionless in the model, the effect of rivet geometry on the location of peak bending stress is not accurately predicted.

The severity of secondary bending is typically quantified by the secondary bending factor (K_b). This bending factor is defined as a ratio of the bending stress and the remotely applied stress:

$$K_b = \frac{\sigma_{bending}}{\sigma_{remote_applied}} \quad (1.7)$$

Results from a two-row riveted lap joint¹ modelled with the neutral line model (Müller, 1995a) show that a non-linear relationship between K_b and applied load exist (Figure 2.7). As the applied load is decreased, K_b increases exponentially, highlighting the importance of secondary bending to high cycle fatigue life of riveted joints.

Figure 2.7: Secondary bending stress ($\sigma_{bending}$) and secondary bending ratio (K_b) at critical location as a function of applied load (P) (Müller, 1995a).

¹ Secondary bending factors based on a 2-row 2024-T3 lap joint with 1.0 mm thick sheets, 40 mm row pitch, and a range of applied loads from 5 MPa – 100 MPa, modelled using Schijve's neutral line model

Chapter 3: FATIGUE OF RIVETED LAP JOINTS

The importance of fatigue to pressurized airframes became clear after unstable fatigue crack growth lead to the catastrophic failure of two DeHavilland Comets after 1,286 and 954 flights respectively. In both cases, a fatigue crack initiated in the fuselage skin at the corner of a window where a high stress concentration existed due to insufficient rounding of the corner. Fatigue testing of the airframe design prior to the accidents indicated a life of 16,000 flights was obtainable; however, these results were tainted by a static test to a high load which plastically deformed the skin around the window corner, generating residual compressive stresses that prolonged crack initiation. Although these failures did not occur along the longitudinal riveted joints of the airframe, they do highlight the importance of stress concentrations and residual stresses to fatigue.

Longitudinal fuselage lap joints transmit hoop loads due to pressurization from the upper to lower skin panels at discrete fastener locations. As a result, significant stress concentrations exist at the fastener holes. Generally, one pressurization-depressurization cycle occurs every flight. In light of the large number of pressurization cycles an airframe will endure in its lifetime, and the large stress concentrations inherent in lap joints, fatigue appears to be a critical design issue for these joints. The remainder of this section explores the fatigue behaviour of 2024-T3 longitudinal fuselage joints. Subsequent sections will discuss the fatigue behaviour of GLARE, a damage tolerant alternative to 2024-T3 for fuselage skin applications.

3.1 Crack Initiation

Fatigue cracks initiate in *slip bands*, local regions of a material weakened by persistent material slip under cyclic loading. The rate at which a slip band is formed is dependent on the stress level within the material. Thus crack initiation is likely to occur in the region of highest stress concentration. Major sources of stress concentrations in riveted lap joints include:

- Bearing due to load transfer between the rivets and surrounding sheet material,
- Bypass loads around the rivet holes resulting from load transfer being distributed between multiple rivet rows,
- Secondary bending resulting from joint eccentricity, and
- Wear between the two connected sheets due to friction (fretting) and corrosion.

The location of crack initiation is dependent upon the relative contributions of each of these stress concentrations. Bearing and bypass loads promote cracking at the perimeter of the fastener hole along the joint minimum section. Bearing loads produce a hoop stress along the fastener hole nearly equivalent to the average bearing stress on the hole (Figure 3.1). The fastener hole also acts as a stress riser to the bypass load in the sheet, further increasing the stress concentration along the perimeter of the fastener hole. Figure 3.2 shows a typical crack initiation site dominated by bearing and bypass stress concentrations.

Figure 3.1: Stress concentrations at a fastener hole (a) due to bearing load on fastener hole (Hart-Smith, 1995), (b) due to bypass load around fastener hole.

Figure 3.2: Fatigue crack nucleation at the rivet hole in a countersunk riveted lap joint (Müller, 1995a).

In contrast, secondary bending and fretting wear promote cracking away from the rivet hole, under the rivet head in the so called “shadow” of the rivet head. When loaded, the rivet tends to tilt, exerting a large pressure on the loaded side of the joint sheet, producing fretting damage in that region (Figure 3.3). The increase in surface roughness resulting from this fretting wear promotes fatigue crack initiation (Andrews and Sehitoglu, 2000). Fatigue crack initiation is further promoted in this region by secondary bending. Clamping provided by the rivet head causes the zone of maximum secondary bending to flow around the rivet hole, rather than through it (Figure 3.4). Figure 3.5 shows a typical crack initiation site dominated by fretting and secondary bending.

Figure 3.3: Typical fretting wear pattern at a countersunk rivet hole in a fuselage lap joint (Wakeman, 1996).

Figure 3.4: Location of maximum secondary bending resulting from rivet head clamping (Müller, 1995a).

Figure 3.5: Fatigue crack nucleation in the "shadow" of the rivet head in a protruding head riveted joint (Müller, 1995a).

3.1.1 Critical Rivet Row

Although stress concentrations due to bearing, bypass, secondary bending, and fretting corrosion exist at each rivet location, not all rivets are equally critical. The majority of load transfer is accomplished by the outer rivet rows (Section 2.3.1). As such, bearing and bypass loads are highest in these rows, resulting in two critical cracking locations: in the upper sheet at the top rivet row, and in the lower sheet at the bottom rivet row (Figure 3.6). In joints containing countersunk rivets, the top rivet row is typically more fatigue critical due to the added stress concentration produced in the upper sheet by the machined countersink.

Figure 3.6: Possible fatigue crack initiation sites in a 3-row riveted lap joint.

3.2 Crack Growth

Due to secondary bending and fretting wear, stresses are typically higher at the faying joint surfaces compared to the outer joint surfaces. As a result, crack initiation occurs as a part-through crack at the joint faying surface beneath the rivet head. An

uneven rate of growth is experienced along this crack front due to the variation in through-thickness stress resulting from secondary bending. After the crack penetrates the outer joint surface, it becomes a through-crack; however, variations in crack growth rate still exist along the crack front due to secondary bending.

This early crack growth occurs beneath the rivet head, complicating the detection of fatigue cracks through Non-Destructive Inspection (NDI). Current NDI techniques (eddy current, ultrasonic, and x-ray) are incapable of accurately detecting flaws hidden beneath a rivet head. Cracks can only be accurately detected once they have grown beyond the rivet head, after a significant portion of their growth life has passed.

Once cracks grow beyond the rivet head, the influence of the rivet hole on the growth rate decreases and the crack growth resistance of the sheet material as a bulk property becomes dominant. 2024-T3 has long been the aluminum alloy of choice for fuselage construction due to its superior fatigue performance compared with other aluminum alloys. Although 2024-T3 is considered to have a high fatigue resistance, the detectable crack growth life has been observed to comprise only 10%-25% of the total fatigue life of riveted lap joints (Eastaugh, 1993, Krizan, 1999, Müller, 1995a). Therefore, improving the ability to detect fatigue damage often supersedes overall fatigue life in lap joint design. Hart-Smith (1995) highlights the prevalence of this trade-off in typical fuselage lap joint designs where a large rivet pitch, resulting in higher bearing stresses and an overall shorter fatigue life, is used to improve the detectability of fatigue cracks.

3.2.1 Multiple Site Damage (MSD)

Multiple Site Damage (MSD) is a form of widespread fatigue damage in which multiple fatigue cracks initiate in a repeating structural element. The presence of MSD can greatly reduce the structural integrity of the part. The critical crack length in a structure containing MSD can be significantly lower than in a structure containing a single crack. Furthermore, MSD cracks in close proximity can influence each other's growth rates, and can link-up to form large unstable cracks.

Longitudinal riveted lap joints are particularly prone to MSD due to the large number of fatigue critical rivet locations and relatively uniform stresses along the length of the joints. By the time the first crack grows beyond the rivet head, making its detection possible, numerous fatigue cracks may have formed at other rivet locations, significantly reducing the residual strength of the joint. Furthermore, cracks within the same rivet pitch can quickly link-up, forming a longer dominant lead crack, ultimately leading to unstable fracture. This became tragically apparent after the explosive decompression of an Aloha Airlines Boeing 737 aircraft on April 28, 1988, where a 15 ft section of the upper fuselage was peeled open after several MSD cracks had linked-up to form a critical crack. It is important to note that corrosion played an important role in accelerating crack growth rates in this accident. Indeed, the combined effects of corrosion and MSD are a serious issue in ageing aircraft.

MSD shortens the time from fatigue crack initiation to unstable fracture in fuselage lap joints, making early detection of fatigue damage essential. Furthermore, MSD afflicts the entire joint, requiring fatigue damage to be assessed beyond the scope of a single rivet hole. In order to aid in detecting and assessing MSD damage in aircraft, researchers have developed programs to simulate MSD behaviour (Singh *et al.*, 1994,

Moukawsher *et al.*, 1996, Pidaparti *et al.*, 2000). The development of fibre metal laminates as a damage tolerant alternative to 2024-T3, however, may alleviate issues of inspectability of MSD in future aircraft. This will be discussed thoroughly in subsequent chapters.

Chapter 4: GLARE

4.1 History of Fibre Metal Laminates

Fibre Metal Laminates (FMLs) originated from the development of built-up structures pioneered by Fokker Aircraft in the late 1940's. Originally, laminated metallic materials were produced by bonding thin aluminum sheets together. It was found that such a laminated structure impeded crack propagation through the thickness of the material. Crack growth was confined to a single lamina, allowing the remaining undamaged laminae to bridge the load around the crack. These properties resulted in increased fatigue lives and a decrease in sensitivity to microstructural defects over monolithic aluminum structures.

The first FMLs were produced when high strength fibres in the form of sheets of epoxy pre-impregnated aramid fibres (aramid-epoxy prepreg) were added into the layup to create ARALL (Aramid Reinforced ALuminum Laminates). Extensive research was conducted at Technical University Delft to determine an optimum combination of adhesive and metallic laminae to accompany the aramid-epoxy prepreg. ARALL, however, only provided a 3-fold increase in fatigue strength over monolithic aluminum, and was found to have a low blunt notch strength and low buckling strength. This combined with the high cost of ARALL limited its commercial application.

In the 1980's, GLARE (GLAss REinforced), was created when the aramid-epoxy prepreg layers in ARALL were replaced by glass-epoxy prepreg. The glass fibres did not break as easily around crack regions as aramid fibres in ARALL. This solved the low blunt notch strength issues with ARALL, making GLARE a viable fatigue resistant material for aerospace applications.

4.2 GLARE Variants

GLARE consists of a lay-up of multiple metallic and fibre layers bonded together in an autoclave. Each fibre layer is manufactured using unidirectional prepreg layers consisting of S2-glass fibres embedded with FM 94 adhesive. By altering the number and orientation of the prepreg layers in each fibre layer of GLARE, a limitless number of GLARE variants is possible. Currently, 6 standard grades are available. These grades are summarized in Table 4.1.

Table 4.1: Standard grades of GLARE (Roebroeks, 2001).

GLARE grade	Sub	Metal sheet thickness [mm] & alloy	Prepreg orientation* in each fibre layer**	Main beneficial characteristic
GLARE 1	-	0.3-0.4 7475-T761	0/0	fatigue, strength, yield stress
GLARE 2	GLARE 2A	0.2-0.5 2024-T3	0/0	fatigue, strength
	GLARE 2B	0.2-0.5 2024-T3	90/90	fatigue, strength
GLARE 3	-	0.2-0.5 2024-T3	0/90	fatigue, strength
GLARE 4	GLARE 4A	0.2-0.5 2024-T3	0/90/0	fatigue, strength in 0° direction
	GLARE 4B	0.2-0.5 2024-T3	90/0/90	fatigue, strength in 90° direction
GLARE 5	-	0.2-0.5 2024-T3	0/90/90/0	Impact
GLARE 6	GLARE 6A	0.2-0.5 2024-T3	+45/-45	shear, off-axis properties
	GLARE 6B	0.2-0.5 2024-T3	-45/+45	shear, off-axis properties

* All aluminum rolling directions in standard laminates are in the same orientation; the rolling direction is defined as 0°, the transverse rolling direction is defined as 90°.

** The number of orientations in this column is equal to the number of prepregs (each nominally 0.127 mm thick) in each fibre layer

Along with the 6 standard grades, a standard coding system is used to fully define a GLARE laminate. The code format consists of the grade of GLARE, ratio of metallic-to-fibre layers, and metallic layer thickness in mm separated by hyphens. For example:

GLARE3-2/1-0.3

would be defined as:

- a GLARE laminate consisting of fibre and aluminum layers conforming to grade GLARE 3 in Table 4.1,
- 2 aluminum layers and 1 fibre layer, and
- each aluminum layer is 0.3 mm thick.

In some instances, laminates consist of metallic layers with different thicknesses.

In such cases, all metallic layer thicknesses are reported in the order of the lay-up. When all metallic layers are the same thickness, the layer thickness is often omitted.

4.3 Fatigue Behaviour

GLARE was developed as a damage tolerant alternative to monolithic aluminum alloys for aerospace structures. Although the aluminum layers in GLARE exhibit similar fatigue behaviour as monolithic aluminum, the presence of the fibre layers significantly improves the fatigue performance of GLARE. Specifically, rapid extension of fatigue cracks is prevented due to the bridging of loads around cracks by the fibre layers.

4.3.1 Crack Initiation

Fatigue crack initiation mainly affects the aluminum layers in GLARE due to the superior fatigue performance of the fibre layers. Furthermore, the fibre layers do not provide any mechanism to prevent fatigue crack initiation in the aluminum layers. Therefore, the fatigue crack initiation process in GLARE is analogous to that of monolithic aluminum; namely, monolithic aluminum panels and aluminum layers in GLARE with similar stresses will have a similar crack initiation life.

Compared to monolithic aluminum, the stresses in the aluminum layers of an equally thick GLARE panel are higher due to:

- The Young's modulus mismatch between the aluminum and fibre layers in GLARE, causing stress levels in the stiffer aluminum layers to exceed the gross applied stress,
- The lower bending stiffness of GLARE, which increases the effects of secondary bending, and
- Residual tensile stresses in the aluminum layers resulting from thermal expansion during the autoclave curing cycle.

As a result of these higher stress levels, crack initiation occurs earlier in GLARE than in monolithic aluminum. The superior crack growth behaviour of GLARE, however, results in an overall longer fatigue life.

4.3.2 Crack Growth

After a fatigue crack develops within the aluminum layers of GLARE, a significant portion of the load is transferred over the crack by the intact fibre layers (Figure 4.1). This mechanism is known as fibre bridging. The reduction in stress intensity factor at the crack tip generated by fibre bridging results in lower crack growth rates in GLARE compared to monolithic aluminum, despite the higher stresses in the aluminum layers of GLARE.

Figure 4.1: Bridging of load around cracked aluminum layers in GLARE (Müller, 1995a).

The degree of crack opening during loading is constrained by the intact prepreg layers and dictated by the shear deformation produced in the adhesive layer due to fibre bridging (Alderliesten, 2001). This constraint in crack opening reduces the stress intensity factor at the crack tip. As the crack grows, delamination between the aluminum and prepreg layers occurs in the vicinity of maximum crack opening due to the large cyclic shear stresses produced in the adhesive. This delamination releases the fibres in the prepreg layer, lowering the fibre stresses and redistributing the load over the length of the delamination. As such, this delamination prevents fibre fracture, prolonging the life of the material.

Improvements in through-thickness crack growth are also present in GLARE due to its laminated structure. Delamination of the adhesive between layers prevents the growth of the crack through the thickness of the laminate. As a result, each aluminum layer must undergo crack initiation for a crack to propagate through the entire laminate thickness, improving material damage tolerance. Furthermore, a plane stress state occurs around the crack tip in laminated structures due to the small thickness of the individual

lamina. Such benefits were first observed in bonded metal laminate structures pioneered by Fokker in their F-27 aircraft (Krishnakumar, 1994).

4.4 Application of GLARE to Narrow-Body Fuselage Skins

Narrow-body aircraft typically fly shorter-haul flights compared to wide-body aircraft; thus their design life comprises of a larger number of flights. For instance, the design life in flights for the Boeing 747 (wide-body) and Boeing 737 (narrow-body) is 20,000 flights and 75,000 flights respectively. This longer design life in terms of flights results in higher fatigue life requirements for the fuselage skin panels and joints, making GLARE an attractive option for narrow-body aircraft.

The skin thickness in a typical narrow-body aircraft is on the order of 0.040". When working with such skin thicknesses, care must be taken to ensure that the machined rivet countersink depth does not exceed the skin thickness, producing a *knife-edge* (Figure 4.2). The presence of a knife-edge generates a 72% increase in the elastic stress concentration of the rivet hole over that of a plain hole (Young and Lee, 1993). Furthermore, the reduced bearing surface increases the bearing stress concentration in the countersunk sheet. As a result, the knife-edge condition is detrimental to fatigue life.

Figure 4.2: Typical machine countersunk rivet installation showing a “knife-edge” condition (Cook, 2001).

Replacing monolithic aluminum with GLARE typically implies a reduction in skin thickness. The superior fatigue performance of GLARE allows thinner sheets to be used, resulting in substantial weight savings. Savings in direct aircraft operating costs resulting from the weight savings would be used to justify the high cost of GLARE compared to monolithic aluminum. It follows that knife-edge considerations will become a prominent issue in the application of GLARE to narrow-body aircraft.

4.4.1 Dimpling (Press-countersinking)

An alternate method to machine countersinking is press-countersinking or, dimpling. In this form of countersinking, the upper and lower joint sheets are countersunk by plastically deforming the sheet material under high pressure using a set of dimpling dies. Dimpling is typically used in monolithic aluminum sheets to avoid the formation of a knife-edge in sheet thicknesses below 0.040" (Bonacci, 1987).

The use of dimpling in riveted joints alters the load transfer mechanism (Figure 4.3). Bearing and frictional load transfer will occur between the dimple cones in the joint

sheets as long as the sheets are held together by the rivet. Bearing load transfer through the rivet will also occur to some degree. The reduction of bearing stress in mechanically fastened joints has been linked to improved fatigue life (Hart-Smith, 1995); however, whether this is applicable to dimpled joints could not be verified, as no detailed fatigue data on dimpled joints was available in the literature. Fretting could also be significant in dimpled joints if insufficient clamping is provided by the rivet.

Figure 4.3: Primary load transfer mechanism in (a) machine countersunk riveted joints and (b) dimple countersunk riveted joints.

Due to plastic deformation during dimpling, a residual stress distribution will be present in the dimple cone; however, the distribution of these residual stresses is unknown. Residual compressive stresses due to rivet forming have been linked to longer crack initiation lives in both monolithic aluminum and GLARE. Dimpling may also introduce such beneficial residual stresses, providing a method for improving the crack initiation life of riveted GLARE joints.

No evidence of the use of dimpling as a countersinking method in GLARE was found in the literature. Potentially, dimpling could be a viable method for preventing the

formation of a knife edge in narrow-body aircraft skins. In monolithic materials, dimpling is limited in its application due to the formation of radial cracks in thicker sheet materials. Bruhn (1973) reports an upper thickness limit of 0.064" when dimpling monolithic aluminum. Due to the thin individual layers in GLARE, such radial cracking may not be an issue; however, delamination, fibre fracture, and other forming related issues may limit the potential of dimpling in GLARE.

4.5 Additional Issues with GLARE Riveted Joints

The superior crack growth performance of GLARE can result in a 10-fold increase in the fatigue life of riveted lap joints over 2024-T3 joints of equal thickness (Müller, 1995a). This fatigue life is dominated by the crack growth phase, allowing for increased inspection intervals and a higher reliability in detecting fatigue damage during the life of the joint. In contrast, the crack initiation in GLARE occurs more rapidly than in 2024-T3. Two potential issues arise from large crack growth life in GLARE:

- GLARE fuselages must be certified to operate with fatigue cracks for the majority of their design life to obtain the full fatigue benefits of GLARE.
- The full effects of simultaneous corrosion and fatigue crack growth are not known, and could potentially reduce the crack growth benefits of GLARE.

With regards to the second issue, GLARE is generally considered to have a higher corrosion resistance than monolithic aluminum since the fibre layers provide a corrosion barrier, preventing the through-thickness propagation of corrosion damage. Corrosion rates in exposed aluminum layers have also been observed to be slower in the thin aluminum layers of GLARE compared to thicker monolithic aluminum sheets. The rapid

quenching rate of the thinner sheets minimizes the diffusion of alloying elements to the grain boundaries, improving corrosion behaviour (Borgonje *et al.*, 2001).

The above benefits apply to undamaged GLARE. In light of the relatively long crack growth life of GLARE, corrosion fatigue of damaged GLARE would seem more important. The slow crack growth rates could allow sufficient time for corrosion products to form at the crack tip, influencing its rate of growth. Furthermore, the adhesive layer becomes exposed to the environment once fatigue cracks are formed. Corrosion could cause local disbonding, reducing the effectiveness of crack bridging. Fatigue damage of the prepreg layer could also permit corrosive attack of the hidden aluminum layers.

Relatively little research has been conducted into the simultaneous corrosion fatigue performance of GLARE. In the literature, only one paper covering this topic was found. Müller *et al.* (1995b) fatigue tested 2024-T3 and GLARE3-3/2 specimens submerged in a 5 wt.% NaCl salt water solution at loading frequencies of 1 Hz and 10 Hz. One 2024-T3 and one GLARE3-3/2 specimens were tested at each of the loading frequencies. The 2024-T3 specimens were cycled to failure, while testing of the GLARE specimens was halted after 200,000 cycles. These tests found that by changing the load frequency from 10 Hz to 1 Hz, the fatigue life of 2024-T3 panels reduced by 25%, while the level of fatigue damage¹ increased by 66% in GLARE3-3/2. Indeed, the low frequency of applied pressurization loads in service combined with long term exposure to the environment could significantly reduce the fatigue life benefits of GLARE.

¹ The level of fatigue damage in GLARE3-3/2 was measured as a percentage of the aluminum layers cracked in the net section.

Chapter 5: PROJECT DEFINITION

The objective of this thesis is to investigate the potential of dimple countersinking as an alternative to machine countersinking in GLARE. Motivation for this project is two-fold. First, dimpling may provide a means of countersinking rivets in narrow-body GLARE fuselage skins without producing a through-thickness knife-edge. Second, variations in residual stress distribution and load transfer mechanism in dimpled joints may improve the crack initiation performance of GLARE, alleviating potential certification and corrosion fatigue issues. Work related to this project was broken down into three main topics:

- Dimple Formation in GLARE: Variations in dimple process parameters are investigated using forensic analysis to identify suitable parameters for subsequent fatigue tests, and identify potential damage due to dimpling. In addition, finite element modeling (FEM) is used to quantify the residual stress field due to dimpling.
- Crack Initiation Coupon Testing: The crack initiation life of dimpled GLARE is investigated through fatigue tests. Efforts are made to isolate the influence of the alternate load transfer mechanism and the elimination of the knife-edge in dimpled GLARE on crack initiation.
- Wide Lap Joint Fatigue Testing: The influence of dimpling on overall fatigue performance is studied through fatigue tests on wide lap joint specimens. Particular attention is placed on crack growth rates and the formation of MSD.

5.1 Project Scope

To limit the scope of this investigation and provide a focused investigation into the potential of dimple countersinking GLARE, some constraints and limitations were imposed. These constraints and limitations are detailed below.

5.1.1 Material Grade and Thickness

Only GLARE3-2/1 is considered in this investigation. GLARE3 has an equal number of fibres in the 0° and 90° directions, making it well suited to the biaxial stress state in fuselage skin panels. A 2/1 layup was chosen due to its thickness. Typical monolithic aluminum narrow-body fuselages have a nominal skin thickness of 0.040". When replacing with GLARE, a reduction in skin thickness is often considered to trade off excess fatigue life for added weight savings. GLARE3-2/1 has a nominal thickness of 0.034", making it an ideal candidate for narrow-body aircraft. In instances where GLARE is compared to aluminum, 0.040" thick 2024-T3 will be considered.

5.1.2 Fibre Orientation and Layer Nomenclature

Since GLARE3-2/1 is an unsymmetric laminate, a standard sheet orientation was used (Figure 5.1), where the 0° layer has fibres running in the direction of load application and 90° layer has fibres running perpendicular to the loading direction. Additionally, a layer naming convention used in the presentation of results is defined in Figure 5.1.

Figure 5.1: Orientation of fibre layers and layer naming convention used for riveted lap joints.

5.1.3 Rivet Type

Two countersunk rivet types are considered: MS20426, and NAS1097. MS20426 is the standard 100° countersunk rivet used in most aerospace applications. NAS1097 rivets have the same 100° countersink angle, but have a reduced countersink depth for use in thinner sheet material (Table 5.1).

Table 5.1: Rivet countersink depths according to MIL-HDBK-5H (DoD, 1998).

D_o (in)	h (in)	
	MS20426	NAS1097
1/16	0.022	-
3/32	0.036	0.021
1/8	0.042	0.027
5/32	0.055	0.036

Standard design practice dictates that $D_o \geq 3t$ (Müller, 1995a). Using this rule, for GLARE3-2/1, the minimum acceptable rivet diameter from Table 5.1 is 1/8". At this diameter, MS20426 rivets would produce complete through-thickness knife-edge in GLARE3-2/1, which is not acceptable standard practice (Figure 5.2). For this reason,

1/8" diameter NAS1097 rivets are used in machine countersunk GLARE. As dimpling tools are only commercially available for the MS20426 style rivet head, 1/8" diameter MS20426 rivets are used in dimple countersunk GLARE.

Figure 5.2: Comparison of knife-edges in GLARE3-2/1 from 1/8" MS20426 and NAS1097 rivets.

5.1.4 Joint Geometry

A reference joint geometry based on a fatigue specimen designed by Eastaugh (1994) was adopted for this investigation. A summary of the reference joint geometry is presented in Table 5.2. MS20426 and NAS1097 rivets are used as described above.

Table 5.2: Summary of reference joint geometry.

Variable	Value	Unit
Number of rows	3	-
Rivet pitch (s)	1	in
Row pitch (p)	1	in

5.1.5 Loading

Selection of load was made to replicate conditions that would be experienced by the skin of a narrow-body aircraft due to pressurization. Researchers (Eastaugh, 1994; Krizan, 1999; Cook, 2001) have used 13.6 ksi as a nominal hoop stress for 0.040" 2024-T3 skins, which translates into a running load of 544 lbf/in. This running load was adopted for this investigation.

Chapter 6: DIMPLE FORMING IN GLARE

6.1 Overview of Dimple Forming Techniques

Dimpling is a forming process involving a set of dimpling tools (a punch and die) and the application of large squeeze forces. Dimpling is performed after the rivet holes have been drilled and deburred. In instances where the material being dimpled is too thick or brittle to dimple at room temperature (cold dimpling), heat can be applied to the dimpling tools (hot dimpling) to form the dimple without the formation of radial cracks. 2024-T3 can be safely cold dimpled up to a thickness of 0.064" (Bruhn, 1973); thus hot dimpling will not be considered in this thesis, and term dimpling will be used to refer to cold dimpling.

Figure 6.1 shows two variations of the dimpling process: coin dimpling and radius dimpling. Coin dimpling involves the formation of a dimple in a single sheet at a time; thus upper and lower joint sheets are dimpled independently. Identical dimples are formed in the upper and lower joint sheets, necessitating a reduction in sheet thickness at the dimple cone to allow the dimples to fit together or nest properly (Figure 6.2). For a 100° dimple angle, a 23% reduction in sheet thickness is required. The plastic flow of material due to this local thickness reduction causes the edge of the rivet hole to be formed against the mandrel of the punch, resulting in a more cylindrical rivet hole.

Figure 6.1: Differences between coin and radius dimpling.

Figure 6.2: Reduction of dimple wall thickness for proper nesting of coin dimpled sheets.

Conversely, radius dimpling involves the simultaneous formation of dimples in all sheets being joined. The simultaneous forming of the dimples ensures that the dimples will properly nest. Variations in dimple angle occur between the upper and lower joint sheets, and between the outer and faying surfaces of joint sheets, depending on the geometry of the dimpling tools, the thickness of the sheets being dimpled and the dimpling pressure. Additionally, the degree of hole stretch in each sheet varies with radius dimpling, resulting in a less cylindrical rivet hole than produced with coin dimpling. Optimization of the dimpling tools can result in proper nesting of radius dimpled sheets with minimal reduction in sheet thickness along the dimple wall.

The basic geometry of a set of dimpling tools is shown in Figure 6.3. These geometric variables can be optimized to over-form the sheet material during dimpling, resulting in a nominal dimple geometry after elastic springback of the sheet material. Thus optimal geometric values are dependent on the nominal rivet dimensions, dimpling process, and the type and thickness of sheet material. Generic dimpling tools designed to perform acceptably over a wide range of aluminum alloys and sheet thicknesses are available for MS20426 style rivets. These dimpling tools typically have no springback angles in the die or punch.

Figure 6.3: Basic dimple tool geometry (adapted from Templin and Fogwell, 1942).

6.2 Dimpling Trials in GLARE

In order to evaluate the potential for coin and radius dimpling in GLARE, a series of dimple and rivet forming tests on GLARE3-2/1 coupons were performed. Visual inspection of the formed dimples and rivets, and inspections of cross-sections taken through the rivet hole centre line were used to evaluate dimple nesting and to determine if any damage occurs during dimple formation in GLARE. Details on the test setup and results are presented in the following.

6.2.1 Test Setup

Riveting and dimpling was done under load control using a 100kN capacity MTS 810 hydraulic test frame with a Teststar IIsTM digital controller (Figure 6.4). Custom steel fittings that could accept standard riveting and dimpling tools were machined to fit into the hydraulic grips of the test frame. The width of the test frame limited its use to dimpling/riveting joints up to a maximum width of 12 inches.

Figure 6.4: MTS 810 test rig adapted for force controlled dimpling/riveting.

Dimpling/riveting trials were conducted on 6.0"x1.5" GLARE3-2/1 strips containing a pattern of three 0.1285" diameter (#30 drill) rivet holes centred on the strip, with a pitch of 1.0" (Figure 6.5). Only the middle hole was dimpled and riveted, while temporary sheet metal fasteners, called "clecos", were placed in the outer two holes to hold the two strips of GLARE in place. Clecos were not necessary during coin dimpling as this process is performed on a single sheet (strip) at a time. Dimpling and riveting

were done dry (without the use of lubricant or sealant) using a set of commercially available dimpling tools (US Industrial Tools Co. part # TP4264) and riveting tools (US Industrial Tools Co. part # SM212). MS20426AD4-4 rivets were used for all riveted coupons.

Figure 6.5: Dimpling/riveting trial coupon.

Dimpling and riveting was done under load control. A five second closed loop ramp function was used to apply the forming load. Dimple forming loads of 4,000, 5,000, and 6,000lbf and rivet forming loads of 2,000, 2,500, and 3,000lbf were used in this investigation.

6.2.2 Coin Dimpled Holes

This section presents the results from coin dimpling trials in GLARE3-2/1. Results for all forming loads were similar and will be treated together. The following observations were made for all coin dimpling trials:

1. Coin dimpled holes did not nest neatly together, indicating that an insufficient reduction in dimple wall thickness was obtained.
2. Glass fibres were visible within the dimpled hole (Figure 6.6), indicating that fibre layer was delaminating and was being squeezed out of the laminate.
3. As the dimple forming load was increased, dimple nesting improved; however, the amount of fibre layer squeezed out into the rivet hole increased as well.

Figure 6.6: Coin dimpled GLARE3 coupon showing delaminated fibre layer squeezed out into rivet hole.

Overall, it appears that insufficient thinning of the aluminum layers in GLARE3-2/1 is produced to achieve the 23% reduction in dimple wall thickness required for proper nesting of 100° coined dimples. The 0.012" thick aluminum layers are very thin, requiring higher forming loads to produce local thinning than thicker monolithic aluminum sheets. Rather, thinning of the dimple wall was being achieved primarily through the fibre layer (which constitutes 29% of the laminate thickness) being squeezed

out of the dimple wall. Conceivably, proper nesting of the coin dimpled holes could have been obtained by increasing the forming load and squeezing out more of the fibre layer; however, it was decided that this damage would be too detrimental to the fatigue life to warrant further investigation.

6.2.3 Radius Dimpled Holes

This section presents the results from radius dimpling trials in GLARE3-2/1. The following observations were made during the radius dimpling trials:

1. Radius dimpled holes nested neatly together for all dimple forming loads investigated.
2. No immediately visible evidence of delamination damage was present, unlike in the coin dimpling trials.
3. A slight curvature was left in the coupon after dimpling, suggesting that the dimple was underformed (Figure 6.7). This curvature was slightly reduced by increasing the forming load from 4,000lbf to 5,000lbf; however, negligible improvement was obtained when increasing the forming load from 5000lbf to 6,000lbf.
4. Delamination damage, local thinning of the aluminum layers, and tight bending radii were observed in cross-sections taken through radius dimpled holes (Figure 6.8)

Figure 6.7: Checking degree of dimple forming.

Figure 6.8: Cross-section of radius dimpled hole showing delamination between the fibre layers. Hole was dimpled using a 5,000lbf forming load.

Results from the radius dimpling trials showed more promise than coin dimpling. Proper nesting between dimples was achieved, and although delamination damage was detected, the fibre layer was not squeezed out of the dimple wall as in coin dimpling. Two possible contributing factors to the delamination are the tight bending radii produced by the dimpling tool set used in the trials, and the local thinning of the aluminum layers. Small bending radii produce a larger deformation gradient through the thickness of the laminate, resulting in large interlaminar shear stresses. Similarly, large interlaminar shear

stresses are produced as the fibre layers resist the elongation of the aluminum layers due to local thinning.

The specimen curvature observed due to radius dimpling GLARE is typically an indication of an insufficient forming load; however, no improvement in curvature was observed for forming loads above 5,000lbf. The larger springback typically observed in GLARE compared to monolithic aluminum (de Jong *et. al*, 2001), combined with the lack of any punch or die springback angle in the dimpling tools are likely responsible for the curvature observed with forming loads above 5,000lbf.

As a result of the coin and radius dimpling trials, it was decided to limit the remaining investigation to radius dimpling using a 5,000lbf forming load. It should be noted that the curvature and delamination observed in these trials could possibly be reduced or even eliminated through optimization of the dimpling tool geometry; however, this is beyond the scope of this investigation. The standard dimpling tool set described in Section 6.2.1 is used throughout this investigation.

6.2.4 Dimpled-Riveted Holes

This section presents the results from riveting trials in radius dimpled GLARE3-2/1. A 5,000lbf dimple forming load was used for all trials. Rivet forming loads (squeeze force) of 2,000, 2,500, and 3,000lbf, corresponding to D/D_o ratios of 1.3, 1.4, and 1.5 respectively, were investigated. These correspond to the D/D_o ratio range of 1.3-1.5 deemed acceptable in standard riveting practice (Bonacci, 1987). Cross-sections of the dimpled/riveted holes are shown in Figure 6.9.

Figure 6.9: Cross-sections of dimpled/riveted holes (a) 2,000lbf rivet forming load; (b) 2,500lbf rivet forming load; (c) 3,000lbf rivet forming load.

Riveting was observed to influence the delamination formed during dimpling. Radial pressure due to rivet expansion caused the outer surface of the lower sheet (Al-4) to buckle. The degree of buckling was dependent upon the rivet squeeze force, with practically no buckling at a squeeze force of 2,000lbf to severe buckling at a squeeze force of 3,000lbf (Figure 6.9). Peeling stresses resulting from the buckling deformation could contribute to the size of the delamination; however, the extent of delamination and the relative contributions from dimpling and riveting could not be determined visually.

Once the delamination is formed, the load bridging capabilities of GLARE are reduced. Depending on the growth of this delamination under fatigue loading, the load bridging action may not re-establish itself – a potentially serious problem because the fatigue life advantage disappears.

6.3 Numerical Modelling of Residual Stresses due to Dimpling

To assess the effects of dimple formation on the residual stress field and related fatigue performance of dimpled joints, a finite element analysis of the dimple forming process was done using the commercial code LS-DYNA. This code uses an explicit time integration solution methodology, making it well suited to non-linear problems, such as problems involving large deformations. LS-DYNA was initially developed for simulating explosives and crashworthiness at the Livermore National Laboratory; however, it is currently applied in a wider range of applications, including metal forming.

It was initially intended to simulate the dimple forming process in monolithic aluminum and GLARE. Results from dimple trials in GLARE (see Section 6.2.3) meant a delamination model was necessary for GLARE model. Initial trial simulations proved that accurately simulating this delamination using existing models in LS-DYNA was problematic. Thus, due to time constraints, efforts were focused on modelling dimpling in monolithic aluminum, to gain some insight into dimpling.

6.3.1 Model Details

The dimpling process was broken up into two stages for modelling purposes. Forming of the dimple was simulated using an explicit solver, while an implicit solver was used to capture the effects of elastic springback in the sheet material once the forming load was removed. Axisymmetric models were used for both simulations and run using LS-DYNA version 950d. The configuration of the model was composed of a set of standard dimpling tools conforming to the geometry used in the dimpling trials

(Section 6.2.1), and two 0.040" thick 2024-T3 sheets with a 0.1285" diameter hole (#30 drill). A 5,000lbf forming load applied over 1 second was investigated.

All simulation entities were meshed using a 2-D axisymmetric area weighted solid element (ELFORM 15). The dimple tools were modelled as rigid entities (material type 20) while a power law plasticity formulation (material type 18) was used for the aluminum sheets. Construction and initial meshing of the model was done using FEMB, a third party pre- and post-processor. Figure 6.10 shows a typical mesh generated in FEMB. An adaptive remeshing option in LS-DYNA was used to automatically remesh the aluminum sheets, preventing excessive distortions in the elements during dimple forming. A remeshing frequency of 0.1 Hz was used for all simulations. The mesh of the sheets extended 0.50" from the axis of symmetry, with a cantilever support at the edge. Ideally, a roller constraint with the corner sheet nodes constrained from movement in the sheet thickness direction (to prevent rigid body motion) would be applied (Figure 6.11); however, during remeshing, all nodal constraints are lost. To overcome this, a global constraint plane can be defined that will apply nodal constraints on any node created on the plane during remeshing. Only one type of constraint can be specified for this plane, necessitating fully constraining the sheet ends to prevent rigid body motion.

Figure 6.10: Typical mesh as generated in FEMB.

Figure 6.11: Ideal sheet boundary conditions compared to those obtained using a global constraint plane.

Contact surfaces were defined between the faying sheet surfaces, and between the tool and sheet surfaces using the 2D_AUTOMATIC_SURFACE_TO_SURFACE contact definition available in LS-DYNA. This contact definition allows the user to define a master and slave surface rather than defining point-to-point contact, ensuring that the

contact definition is not lost during remeshing steps. Frictional contact was defined using frictional coefficients reported by Ryan and Monaghan (2000): $\mu=0.173$ aluminum/steel, $\mu=0.178$ aluminum/aluminum.

6.3.2 Material Properties

The material properties for 2024-T3 used in this simulation were obtained from MIL-HDBK-5H (DoD, 1998) and are summarized in Table 6.1. Stress-strain data was given in the form of Ramberg-Osgood parameters. Since material plasticity cannot be represented with Ramberg-Osgood parameters for axisymmetric simulations in LS-DYNA, the stress-strain curve was plotted and the strength coefficient (k) and hardening exponent (n) for the power law ($\sigma = k\varepsilon^n$) were obtained by curve fitting (see Figure 6.12 and Table 6.2).

Table 6.1: Summary of 2024-T3 material properties.

Property	Value	Unit
Young's Modulus	10500	ksi
Yield Stress	47	ksi
Density	0.1	lb/in ³
Poisson's Ratio	0.33	-

Figure 6.12: Stress strain curve for 2024-T3 obtained using Ramberg-Osgood parameters from MIL-HDBK-5H.

Table 6.2: Power law plasticity factors obtained from curve fitting 2024-T3 stress-strain curve.

Constant	Value	Unit
Strength coefficient (k)	77	ksi
Hardening exponent (n)	0.10	-

6.3.3 Mesh Sensitivity

Mesh size was defined by a characteristic element length; the average length of one side of the 4-node axisymmetric solid elements. Three mesh densities, with characteristic element sizes of 0.0067", 0.0050", and 0.0040" were simulated. For all mesh densities, adaptive remeshing at a frequency of 0.1 Hz was included. Table 6.3 shows a comparison of some of the indicators used to assess solution convergence.

Table 6.3: Maximum and minimum stress components from dimple forming simulations with various mesh sizes.

Characteristic Element Length (in)	Number of Elements	Max Von Mises (psi)	Hoop Stress		Radial Stress		Transverse Stress	
			Max (psi)	Min (psi)	Max (psi)	Min (psi)	Max (psi)	Min (psi)
0.0067	780	69195	53732	-94232	26140	-90594	8876	-110109
0.005	1392	70236	40973	-91318	38459	-71574	11518	-117620
0.004	2180	67947	52399	-97900	38630	-76834	20555	-118760

Due to the large deformations involved in this simulation, care needed to be taken in assessing the convergence of the results. Typically, as the mesh size is decreased, the solution accuracy increases; however, for simulations with large deformations, distortion of the elements must be considered. As the element size is decreased, the amount of deformation required to severely distort the element is reduced. This was observed in the simulation containing a 0.004" characteristic element length where severe element distortion was responsible for a divergence in maximum hoop stresses and maximum transverse stresses shown in Table 6.3. Based on these results, a characteristic element length of 0.005" was used for the final simulation.

6.3.4 Model Verification

Experimental verification of the residual stresses due to dimpling is not a trivial matter. Common experimental stress analysis techniques, such as strain gauges and photoelastic coatings, can not be applied as the gauge or film placed around the rivet hole would be ruined during the dimple forming process. Instead, the load-displacement behaviour of the dimple punch was used as an indication of the validity of the model. Experimental load-displacement data was obtained using the force controlled

dimpler/riveter described in Section 6.2.1 and is plotted together with data from the simulation in Figure 6.13.

Figure 6.13: Comparison of experimental and FEM punch load-displacement curves.

The load-displacement curves obtained from experiments and FEM simulation agreed well. Only a slight deviation of the results was observed beyond 4,000lbf, after which the FEM simulation indicated little displacement of the dimple punch. Further displacements indicated by the experimental results were small and nearly linear, indicating they may be the result of elastic deformation of the dimpling tools and test frame.

6.3.5 Simulation Results

The residual hoop, radial, and transverse (Figure 6.14) stress distributions resulting from the dimple forming and elastic springback models are shown in Figure

6.15, Figure 6.16, and Figure 6.17 respectively. Results showed that residual compressive radial and hoop stress fields were generated along the faying surfaces of the dimpled cones, while residual tensile radial and hoop stress fields were generated at the outer surfaces. Fatigue crack initiation is typically critical at the joint faying surfaces due to secondary bending. The observed residual compressive stresses at the faying surface will serve to prolong this crack initiation. Depending on the magnitude of secondary bending, crack initiation at the outer sheet surface in the region of residual tensile stresses may become critical.

Figure 6.14: Axisymmetric element stresses.

Differences were observed in the relative magnitudes of residual stresses in the upper and lower dimpled sheets. The lower dimpled sheet experienced higher residual tensile stresses and lower residual compressive stresses compared to the upper dimpled sheet. This may result in the lower dimpled sheet (corresponding to the lower joint sheet) being more fatigue critical.

Figure 6.15: Residual hoop stress distribution in dimpled 2024-T3 sheets (psi).

Figure 6.16: Residual radial stress distribution in dimpled 2024-T3 sheets (psi).

Figure 6.17: Residual transverse stress distribution in dimpled 2024-T3 sheets (psi).

Chapter 7: CRACK INITIATION COUPON TESTING

This chapter presents a summary of the results of several fatigue tests that were performed to investigate the relative crack initiation behaviours of dimpled and machined countersunk GLARE. The test matrix employed for this investigation is shown in Table

7.1. Two specimen configurations, shown in Figure 7.1, were investigated;

1. Specimens containing a single unfilled rivet hole, designated CIS-A (a).
2. Narrow three-row riveted lap joints, designated CIS-B (b).

Figure 7.1: Crack initiation specimens (a) CIS-A, (b) CIS-B.

Table 7.1: Test matrix for crack initiation specimens.

CIS-A			CIS-B		
Specimen	Material	CSK Method	Specimen	Material	CSK Method
CIS-A-01	GLARE3-2/1	-	CIS-B-01	GLARE3-2/1	Dimpled
CIS-A-02	GLARE3-2/1	-	CIS-B-02	GLARE3-2/1	Dimpled
CIS-A-03	GLARE3-2/1	-	CIS-B-03	GLARE3-2/1	Dimpled
CIS-A-04	GLARE3-2/1	-	CIS-B-04	GLARE3-2/1	Machined
CIS-A-05	GLARE3-2/1	Machined	CIS-B-05	GLARE3-2/1	Machined
CIS-A-06	GLARE3-2/1	Machined	CIS-B-06	GLARE3-2/1	Dimpled
CIS-A-07	GLARE3-2/1	Machined			
CIS-A-09	GLARE3-2/1	Dimpled (US)*			
CIS-A-10	GLARE3-2/1	Dimpled (LS)**			
CIS-A-11	GLARE3-2/1	Dimpled (US)			
CIS-A-12	GLARE3-2/1	Dimpled (LS)			
CIS-A-13	GLARE3-2/1	Dimpled (US)			
CIS-A-14	GLARE3-2/1	Dimpled (LS)			
CIS-A-15	GLARE3-2/1	Dimpled (US)			
CIS-A-16	GLARE3-2/1	Dimpled (LS)			

* Upper sheet during dimpling process

** Lower sheet during dimpling process

The first specimen is used to study the effect of dimpling on the crack initiation life of GLARE in the absence of load transmission and residual stresses due to riveting. Furthermore, this specimen permits dimpling to be studied without the effects of riveting damage observed in Section 6.2.4. Non-countersunk, machine countersunk, and dimple countersunk holes are considered.

The second specimen is used to study the crack initiation life of dimpled GLARE lap joints. Only dimpled and machined countersunk GLARE joints are considered.

7.1 Test Set-up

7.1.1 Loading and Test Frame

Loading of the crack initiation specimens was applied using an MTS 810 hydraulic load frame controlled with a Teststar IIs™ controller and MultiPurpose

TestWare® testing software version 2.4C (Figure 7.2). A 4Hz sinusoidal load varying between 544 lbf and 16 lbf ($R=0.03$) was used for both specimen configurations. These parameters were selected to match the reference running load of 544lbf/in detailed in Section 5.1.5 and to ensure that compression of the specimen was avoided.

Figure 7.2: Crack initiation test set-up.

The specimens were attached through a set of standard hydraulic grips. A 1"x 3"x 2" machined block was used during specimen installation to centre the specimen in the 3" wide hydraulic grips, and ensure the specimen was parallel to the loading direction (Figure 7.3). The upper hydraulic grip was connected to a movable cross-head, allowing the test frame to easily accommodate the different lengths of the two specimen configurations.

Figure 7.3: Installation of crack initiation specimen.

7.1.2 Crack Detection

Visual inspections with a 20X microscope were performed to detect crack initiation. Crack initiation was defined as the presence of a 0.03" long visible crack. This crack length was based on the average length of cracks at detection from previous testing. In CIS-A, crack length was defined as the distance from the crack tip to the edge of the rivet hole (Figure 7.4). Vertical lines were marked at the 0.03" crack length positions to facilitate in determining the crack initiation point. As cracks are not visible under the rivet head, the definition of crack length in CIS-B specimens was changed to the length of crack visible beyond the rivet head.

Figure 7.4: Crack length definition for (a) CIS-A, and (b) CIS-B specimens.

7.2 Results

A summary of the overall results and observations from the crack initiation test series is given below. Further details on individual specimens can be found in Appendix A.

7.2.1 CIS-A

Figure 7.5 shows the average crack initiation life for the four types of CIS-A specimens: plain hole, machine countersunk hole, dimpled hole US (upper sheet), and dimpled hole LS (lower sheet). Both types of dimpled hole coupons exhibited a crack initiation life greater than that of the machine countersunk coupons. The dimpled upper sheet coupons exhibited ~90% improvement in crack initiation life. Three of the four dimpled lower sheet coupons were stopped at 1,000,000 cycles, with no detectable cracks, representing a 14 fold increase in crack initiation life over the machine

countersunk coupons. The other coupon failed due to unstable crack growth at 710,301 cycles. Crack initiation was not detected in this coupon prior to failure.

Figure 7.5: Average crack initiation life with scatter bands for CIS-A coupons (average of 3 coupons).

In the straight hole coupons, cracks initiated at the edge of the rivet hole along the minimum section of the coupon. This corresponds to the region of highest elastic stress concentration due to the rivet hole. Cracks were typically found in the aluminum layer adjacent to the 90° fibre layer (Al-1), although some coupons exhibited cracks in both aluminum layers. The unsymmetrical lay-up of GLARE3-2/1 generates bending stresses that increase the average stress in Al-1 by ~9% compared to the aluminum layer adjacent to the 0° fibre layer (Al-2). Thus it is expected that crack initiation would favour Al-1.

Similarly, cracks initiated at the edge of the rivet hole along the minimum section in the machine countersunk coupons. Furthermore, crack initiation always occurred in

AL-1 as a result of the combination of higher average stress levels and the presence of a knife-edge due to countersinking.

Cracking also occurred along the minimum section of the dimpled upper sheet coupons; however, cracks initiated at the maximum diameter of the dimple cone rather than at the edge of the rivet hole. Initiation occurred in AL-1, which corresponds to the sheet surface that comes in contact with the dimple punch. This initiation location and layer are consistent with the region of residual tensile stress observed in the 2024-T3 dimpling simulations in Section 6.3.

No initiation location data was obtained for the dimpled lower sheet coupons.

7.2.2 CIS-B

During testing of the CIS-B coupons, two different initiation events could be observed. First, evidence of cracks within one of the faying joint surface (layers Al-2 and Al-3) was detected. These are deemed *hidden* cracks, as the faying joint surfaces are not visible during testing. The second initiation event was the detection of a *visible* crack within one of the outer joint surfaces (layers Al-1 and Al-4). Details on these two initiation events are presented below. Additionally, issues with the validity of the visual crack detection lives are discussed.

Detection of Hidden Cracks

Evidence of hidden cracks in AL-3, in the form of a surface depression, was observed along the bottom rivet row of all CIS-B specimens. This depression is a result of a step in the neutral axis formed around a crack due to fibre bridging (Figure 7.6). The resulting bending moment from this step in neutral axis produces the depression.

Additionally, the bending stiffness of the sheet material around the crack is determined by the intact layers. Thus the local reduction in bending stiffness resulting from a hidden crack further contributes to the visible depression.

Figure 7.6: Visual detection of cracks in hidden aluminum layers in GLARE3-2/1: (a) step in neutral line around crack producing bending moment; (b) formation of depression due to bending moment; (c) Visually detected surface depressions (image colours inverted for clarity).

On average, detection of hidden cracks occurred after 80,000 (± 0) and 315,000 ($\pm 5,000$) cycles in the dimpled and machine countersunk CIS-B coupons respectively. These initiation lives are limited in accuracy, as many variables will influence the visibility of the surface depression formed by the hidden crack. Specifically, slight variations in lighting conditions were found to greatly influence the ability to detect such depressions. Furthermore, difference between the clamping restraint provided by the upset rivet head, and the bending stiffness of the machine countersunk and dimpled

sheets (due to presence of delamination and dimple cone) in the dimpled and machine countersunk coupons could also influence detection of the surface depression.

Detection of Visible Cracks

The average visible crack detection lives for the dimpled and machine countersunk CIS-B coupons were 205,000 ($\pm 5,000$) and 800,000 ($\pm 120,000$) cycles respectively. In all coupons, visible cracks were first detected along the bottom rivet row in AL-4. This corresponds to the region in which hidden cracks were first discovered. Although there is no data to compare the dimpled coupon results to, studies conducted by Müller (1995a) on wider machine countersunk lap joints indicate that visible crack initiation should occur in the upper sheet along the top rivet row in the machined countersunk coupons. Cracking in this location is expected mainly due to the added stress concentration the machined countersink generates in the upper sheet. This crack location was not observed in any of the machine countersunk coupons in the current study.

Prior to visual crack detection, it was observed that the surface depression, indicating the presence of a hidden crack, had grown across the entire coupon width in all machine countersunk coupons. The presence of a “full-width” hidden crack was confirmed visually from the edge of the specimen (Figure 7.7). This full-width hidden crack locally reduced the bending stiffness along the bottom rivet row, concentrating secondary bending deformation to this area, and relieving the secondary bending stresses along the top rivet row. Indeed, the stress distribution along the width of the coupon is no longer representative of a real lap joint once a full-width crack has developed.

Figure 7.7: Side view of bottom row in CIS-B-05 showing excessive bending deformation due to full-width hidden crack.

A full-width hidden crack was not formed in the dimpled CIS-B coupons; however, dismantling of these coupons after testing revealed that the hidden cracks did span over 75% of the coupon width. Given the results of the machine countersunk CIS-B coupons, the confidence in these results was low. Therefore, it was decided to obtain visual crack initiation results from the wider lap joint specimens covered in the following chapter.

Chapter 8: WIDE LAP JOINT FATIGUE TESTING

To assess the overall fatigue performance of dimpled GLARE joints, a series of wide lap joint fatigue tests were performed. A portion of this work was done in collaboration with Bombardier Aerospace and the Institute for Aerospace Research (IAR-SMPL) of the National Research Council Canada (NRC) on GLARE durability. Particular attention was paid to the MSD behaviour and crack growth rates of the dimpled GLARE joints. First, a review of issues associated with the testing of wide lap joint specimens is presented, followed by a description of the test series and a summary of the results.

8.1 Review of Issues Concerning the Testing of Wide Specimens

Ideally, a specimen used to study the fatigue life and formation of MSD in a riveted lap joint requires a uniform rivet load distribution across the width of the specimen. Furthermore, a wide specimen is desirable (15"-20") in order to conform to the width of fuselage panels between frames. This review will discuss two issues that influence the rivet load distribution in wide fatigue test specimens and present two specimen designs that have been applied to overcome them. A more elaborate discussion is presented by Müller (1995a).

The boundary conditions at the loaded ends of a lap joint specimen can influence the rivet load distribution. Typically, load is applied through a set of stiff clamps. Without sufficient distance between the clamped edges and outer rivet rows, lateral contraction of the specimen will be restrained by the clamped edges. Furthermore, secondary bending along the rivet rows can be influenced by the clamped edges in short

specimens. Using simple FEM models, Müller (1995a) found that these influences of the clamped specimen edges could be avoided if a length-to-width ratio greater than 2 is used.

Lateral contraction due to the finite width of fatigue specimens is also influenced by the overlap region of the specimen. Outside the overlap, the nominal stress in the sheet is equal to the nominal specimen stress, producing a theoretical lateral contraction strain of $-\nu\sigma/E$. Within the overlap, the nominal stress is lower due to the added thickness, and varies between the upper and lower sheets due to load transfer. As a result, differences between lateral contraction strains in the upper and lower sheets produce additional shear loads on the rivets; particularly the rivets surrounding the edge of the specimen. This so called “edge effect” results in premature crack initiation at the edge rivets. These cracks grow to the edge of the specimen and lead to specimen failure before significant MSD can develop at other rivet locations.

Two solutions developed to prevent the formation of edge cracks are described. Eastaugh (1994) adopted a specimen configuration reinforced with various doublers along the free edges and clamped edges of the specimen. This arrangement mimicked the structure of a single frame bay of a fuselage, where the frames (represented by the edge doublers) locally reduce the stress in the skin panel. This specimen successfully produced MSD and has been utilized extensively by the Institute for Aerospace Research at the National Research Council of Canada. A simpler solution was used by Müller (1995a). By applying additional “zero-load transfer” rivets in the edge rivet columns (Figure 8.1), a local reduction in secondary bending around the edge rivets is achieved.

The reduction in secondary bending stress postpones crack initiation at the edge rivets, allowing the formation of MSD.

Figure 8.1: Zero-load transfer rivets near specimen free edge (Müller, 1995a).

8.2 The Wide Lap Joint Fatigue Test Series

8.2.1 The Test Specimen

For the present investigation, a specimen based on Müller's (1995a) zero-load transfer specimen was used. The overall dimensions are shown in Figure 8.2. Complete drawings of the specimen can be found in Appendix B.

Figure 8.2: Wide lap joint specimen with major dimensions and GLARE sheet orientation.

In order to validate the effectiveness of the zero-load transfer rivet concept, two proof-of-concept specimens were produced and tested (MSD-AL-001 and MSD-AL-002). Complete results of these tests can be found in reports R-MSD-AL-001 and R-MSD-AL-002 in Appendix C. MSD was not obtained in MSD-AL-001; however, failure of this specimen was later attributed to a manufacturing fault. Strain readings taken during this test indicated that the zero-load transfer rivets were effective. Subsequent testing of MSD-AL-002 proved the validity of the specimen design.

8.2.2 Test Matrix

The test matrix employed in this investigation is shown in Table 8.1. Machine countersunk 2024-T3 and GLARE3-2/1 specimens were tested as a reference to compare the results of the dimpled GLARE3-2/1 specimens to.

Table 8.1: Test matrix for wide lap joint test series.

Specimen	Material	Countersink Type	Rivet Type	Description
MSD-AL-001	2024-T3	none	MS20470AD5-5	proof-of-concept specimen
MSD-AL-002	2024-T3	machined	MS20426AD5-5	proof-of-concept specimen
MSD-AL-003*	2024-T3	machined	NAS1097AD4-4	aluminum reference
MSD-AL-004*	2024-T3	machined	NAS1097AD4-4	aluminum reference
MSD-GL-001*	GLARE3-2/1	machined	NAS1097AD4-4	machine csk GLARE joint
MSD-GL-002*	GLARE3-2/1	machined	NAS1097AD4-4	machine csk GLARE joint
MSD-GL-003	GLARE3-2/1	dimpled	MS20426AD4-4	dimpled GLARE joint
MSD-GL-004	GLARE3-2/1	dimpled	MS20426AD4-4	dimpled GLARE joint

* Tested as part of the collaboration agreement with Bombardier Aerospace and IAR-SMPL of the NRC

In addition to these specimens, two addition GLARE3-3/2 specimens were tested as part of the collaborative agreement between Carleton University, Bombardier Aerospace, and the IAR. No details on the results of these tests will be presented as they do not directly pertain to this study.

8.2.3 Test Procedure

Cycling of the specimens was performed using a 4 Hz sinusoidal waveform with a peak load of 10,880 lbf and stress ratio (R) of 0.03. These loading parameters were selected to match the 544 lbf/in running load discussed in Section 5.1.5. All tests were operated under load control.

Load was applied using an MTS 244.21 hydraulic actuator controlled by an MTS 407 digital controller. The hydraulic actuator was connected to a large self-reacting steel

test frame through a universal joint (Figure 8.3). A similar universal joint was present opposite the hydraulic actuator to ensure proper alignment of the test piece.

Figure 8.3: Image of test frame with installed specimen.

Load was transferred from the test frame to the specimen through two 1.5" diameter pins. These pins were inserted through steel clevis connected to the test frame, and through 0.50" thick steel plates bolted to the specimens. The pinned connection would allow the specimen to self align, ensuring a uniform distribution of load across the specimen width. Detailed drawings of the specimen mounting hardware are available in Appendix B.

During initial tests, excessive oscillations occurred in the specimen due to the number of degrees of freedom introduced by the pin-clevis arrangement and universal joints. To remedy this problem, a steel beam was added to the test frame to eliminate the

degrees of freedom introduced by the universal joint connection between the test frame and actuator (Figure 8.4).

Figure 8.4: General test set-up (a) and MTS 407 controller (b).

8.2.4 Strain Gauges

Each specimen had 16 or more strain gauges distributed along its width on both sides of the upper joint sheet (Figure 8.5). The strain gauges were located 1" above the top rivet row, and gauges on the faying and outer sheet surface were aligned such that secondary bending and membrane stresses could be measured in the sheet. Strain readings were obtained using an Instronet data acquisition system containing two iNet-100 network devices, an iNet-200 PCI controller, and a Pentium class personal computer.

Data acquisition was controlled using the “instruNet World” software included with the system. Readings were taken at the beginning of the test to ensure a uniform and repeatable stress distribution in the specimens. Additional strain readings taken throughout the test were used to monitor changes in the stress distribution due to fatigue cracking.

Figure 8.5: Typical strain gauge placement.

8.2.5 Crack Detection and Measurement

Regular visual inspections were performed during testing to detect fatigue cracks. A wide range of magnifiers, including a 10X portable magnifier and a 20X travelling microscope, were used to aid in crack detection. No other means of non-destructive inspection (NDI) were used.

Crack measurements were taken using a 20X travelling microscope custom designed and built for this experiment (Figure 8.6). The travelling microscope was designed with a 24" travel, allowing a common datum to be used for all crack measurements within the 20" wide specimen. The digital scale has a measuring accuracy of $\pm 0.001"$; however, human error in locating the crack tip reduces this accuracy to $\pm 0.005"$. Crack tip locations were measured with respect to the left edge of the specimen (denoted as coordinate X in Figure 8.5). This edge was also used as a datum during specimen manufacturing.

Figure 8.6: Travelling microscope.

Crack lengths were calculated from the crack tip positions. Crack length was defined as the distance between the crack tip measured with the travelling microscope and edge of the 0.1285" diameter (#30 drill) rivet hole (Figure 8.7). Locations of the rivet hole edges were based on nominal specimen geometry, not on measurements from the travelling microscope (as the rivet hole is hidden once the rivets are installed). As the rivet holes were made using a precision milling machine, this should introduce negligible errors.

Figure 8.7: Crack length definition.

A rivet numbering scheme was adopted to aid in recording and referencing crack initiation and growth data (Figure 8.8). Cracks were identified by the number of the rivet they emanated from, and a “left” or “right” designation, where “left” corresponds to the side of the rivet closest to $X = 0''$, and right corresponds to the side of the rivet closest to $X = 20''$.

Figure 8.8: Rivet numbering scheme.

8.3 Results

A summary of the fatigue life and failure mode results is shown in Table 8.2. Details on the results of a machine countersunk and dimpled GLARE specimens will be

presented below. Complete details on each of the specimens can be found in their corresponding testing report in Appendix C.

Table 8.2: Summary of wide lap joint specimen results.

Specimen	Description	Failure Mode	Failure Location	Fatigue Life
MSD-AL-001	Proof-of-concept	edge crack*	top row	363,523 *
MSD-AL-002	Proof-of-concept	MSD	top row	61,176
MSD-AL-003	Csk aluminum reference	MSD	bottom row	387,109
MSD-AL-004	Csk aluminum reference	MSD	top row	178,699
MSD-GL-001	Csk GLARE3-2/1	clamping failure**	clamp	691,050 **
MSD-GL-002	Csk GLARE3-2/1	MSD	top row	1,101,153
MSD-GL-003	Dimpled GLARE3-2/1	MSD	bottom row	280,000
MSD-GL-004	Dimpled GLARE3-2/1	not tested	-	-

* Test was stopped after a single fatigue crack had grown to the specimen edge

** Test was stopped after fatigue cracking was discovered along the clamped specimen edge

8.3.1 MSD-GL-001

Crack Detection

Evidence of hidden cracks, in the form of depressions along the outer sheet surface, was first detected in the lower sheet of MSD-GL-001 along the bottom rivet row after 90,000 cycles. These surface depressions resembled those observed during the CIS-B test series (Section 7.2.2), which were attributed to the presence of cracks in the faying aluminum layer. Qualitative growth and link-up data for the hidden cracks was obtained through observations of these surface depressions (Figure 8.9). As the “tip” of the surface depression was not easily distinguishable, measurements of the length of the surface depressions could not be made.

MSD-GL-001 failed along the clamped edge at 691,050 cycles. As a result, visible crack initiation and growth data could not be obtained.

Figure 8.9: Visible detection, growth, and link-up of surface depressions along the bottom row of the lower sheet in MSD-GL-001.

8.3.2 MSD-GL-002

Crack Detection

Hidden cracks were first detected in MSD-GL-002 at 250,000 cycles. The qualitative growth and link-up data for the hidden cracks is shown in Figure 8.10. Detection of the surface depressions was more difficult in MSD-GL-002 than in MSD-GL-001. MSD-GL-001 was manufactured using aluminum clad GLARE3-2/1. The high reflectivity of the clad layer increased the visibility of the shadows cast by the surface depressions (Figure 8.11). Furthermore, plastic deformation in the cladding produced a permanently visible outline of the surface depression, allowing it to be viewed with no load applied to the specimen. All other wide lap joint GLARE specimens were made

with anodized GLARE3-2/1, rather than clad GLARE3-2/1, which had a matte surface that produced a less visible shadow. These results partially explain why hidden cracks were detected earlier in MSD-GL-001 than in MSD-GL-002, and emphasize the qualitative nature of the data obtained from observing the surface depressions.

Figure 8.10: Visible detection, growth, and link-up of surface depressions along the bottom row of the lower sheet in MSD-GL-002.

Figure 8.11: Differences in visibility of surface depressions in (a) clad GLARE3-2/1 (MSD-GL-001) and (b) anodized GLARE3-2/1 (MSD-GL-002).

Visible cracks were first detected along the top rivet row in Al-1 after 420,000 cycles. No visual evidence of hidden cracks along the top rivet row preceded this visual crack detection; however, the likelihood of hidden cracks preceding the formation of visual cracks is high due to secondary bending. The inability to detect these hidden cracks is likely due to the orientation and lay-up of the GLARE3-2/1 sheets used in the specimens (Figure 5.1). In this configuration, the presence of a crack in the faying aluminum layer along the top rivet row will produce a much smaller step in the neutral axis than in the bottom rivet row (Figure 8.12). As a result, less bending deformation occurs, reducing the visibility of the depression. Differences in bending restraint provided by the countersunk rivet head (top row) and upset rivet head (bottom row) may also influence the visibility of the surface depressions.

Figure 8.12: Differences in neutral line step due to relative placement of 0° prepreg ply and cracked aluminum layer in GLARE3-2/1.

Crack Initiation Sites

Two crack initiation sites were prevalent within Al-2 of MSD-GL-002. First, cracking along the joint minimum section was observed at several rivets (Figure 8.13a). This crack initiation location is associated with a high bearing stresses as discussed in Section 3.1. The second initiation site observed was along the perimeter of the rivet hole (Figure 8.13b). This location is associated with high secondary bending stresses and high rivet squeeze forces. Neither initiation location seemed to be favoured in MSD-GL-002.

Figure 8.13: Two typical cracking locations observed in MSD-GL-002 (facing faying joint surface after specimen failure): (a) cracking near joint minimum section at rivet # 15; (b) cracking around rivet hole at rivet #7.

Crack initiation locations within A1-1 were influenced by the presence of the hidden cracks in A1-2. In instances where hidden cracks occurred along the joint minimum section, visible cracks in A1-1 also occurred along the joint minimum section. Conversely, when hidden crack initiated along the perimeter of the rivet hole, visible cracks initiated below the joint minimum section.

Visible Crack Growth and Link-up

The growth period of the visible cracks in MSD-GL-002 lasted 681,153 cycles, with specimen failure occurring at 1,101,153 cycles due to unstable crack growth. The hidden crack detection life and visual crack detection life consisted of 23% and 38% of the total life of the specimen respectively. Crack growth curves for the entire specimen width are plotted in Figure 8.14.

Figure 8.14: Crack growth curves for visible cracks in top rivet row of MSD-GL-002.

A typical crack link-up observed in MSD-GL-002 is shown in Figure 8.15. Link-up, in the form of overlapping crack tips, is commonly observed in aluminum lap joint fatigue tests (Cook, 2001; Müller, 1995a; Eastaugh, 1994; Krizan, 1999); however growth of the individual cracks after overlapping is limited. In MSD-GL-002, significant growth of the cracks continued subsequent to overlapping of cracks. Furthermore, little change in direction in this crack growth was observed, as is common in aluminum joints.

Figure 8.15: Typical link-up in MSD-GL-002.

Rivet Head Fracture

Rivet fracture along the base of the countersunk rivet head was observed at several rivet locations in MSD-GL-002. This severe rivet damage occurred within the last 10% of the life of the specimen. Damage was first observed in the form of a plastic hinge along the countersunk rivet head (Figure 8.16a). A through-crack then developed along the plastic hinge leading to complete fracture of the countersunk rivet head (Figure 8.16b and c).

Figure 8.16: Development of rivet head fracture at rivet 14 in MSD-GL-002: (a) plastic deformation; (b) partial fracture; (c) complete fracture.

8.3.3 MSD-GL-003

Crack Detection

As with MSD-GL-002, first evidence of cracking in MSD-GL-003 came in the form of surface depressions along the bottom row of the lower joint sheet, detected at 140,000 cycles (Figure 8.17). The surface depressions were more difficult to detect in MSD-GL-003 compared to MSD-GL-002. This is likely due to the added bending stiffness provided by the dimple cone in the sheet material. Visual cracks in A1-4 along the bottom rivet row were detected soon after at 180,000 cycles. No evidence of hidden or visible cracks was observed along the top rivet row in MSD-GL-003.

Figure 8.17: Visible detection, growth, and link-up of surface depressions along the bottom row of the lower sheet in MSD-GL-003.

Crack Initiation Sites

Visible crack initiation occurred in the maximum dimple cone diameter in A1-4 in the region of high residual tensile stress in the lower sheet observed in Section 6.3.5 (Figure 8.18). This also corresponds to the layer most severely damaged during riveting after dimpling. Dismantling of the specimen after testing revealed that a hidden crack in A1-3 appeared to initiate in a similar region (Figure 8.19). Large deposits of fretting product were visible in this region, indicating that fretting may have played a significant role in crack initiation. The cracking location observed in MSD-GL-003 (lower sheet, bottom row) is undesirable, as it corresponds to the interior surface of the aircraft, which is not readily accessible for inspection.

Figure 8.18: Region of visible crack initiation in MSD-GL-003.

Figure 8.19: Typical cracking location in MSD-GL-003 (a) outer aluminum layer (Al-4) at rivet 43; (b) hidden aluminum layer (Al-3) at rivet 43.

Visible Crack Growth and Link-up

The growth period of the visible cracks in MSD-GL-002 lasted 100,000 cycles, with the test being stopped at 280,000 cycles due to the pending growth of a fatigue crack to the edge of the specimen. The hidden crack detection life and visual crack detection

life consisted of 50% and 64% of the total life of the specimen respectively. This dimpled joint represented a 75% reduction in overall fatigue life compared to the machine countersunk MSD-GL-002. Crack growth curves for the entire specimen width are plotted in Figure 8.20.

Figure 8.20: Crack growth curves for visible cracks in bottom rivet row of MSD-GL-003.

Figure 8.21 shows a typical link-up observed in MSD-GL-003. Subsequent to overlapping of the cracks, crack growth was limited, and curvature of the crack growth path was observed. This matches the behaviour observed in the aluminum references specimens (MSD-AL-003 and MSD-AL-004), indicating that the fibre-bridging mechanism which prevented this behaviour in MSD-GL-002 was not effective in MSD-GL-003.

Figure 8.21: Typical link-up in MSD-GL-003.

8.3.4 MSD-GL-004

Due to the apparent lack of fibre bridging in MSD-GL-003, likely resulting from the delamination damage due to dimpling/riveting GLARE with standard dimpling tools, it was decided to postpone testing of MSD-GL-004 until these issues could be resolved.

Chapter 9: DISCUSSION

9.1 Dimple Forming

Two dimpling processes were considered in this investigation: coin dimpling and radius dimpling. Coin dimpling trials on GLARE3-2/1 showed that the thin aluminum layers did not adequately deform in the transverse direction to provide the reduction in dimple wall thickness required for proper nesting of coin dimpled holes. Rather, delamination and expulsion of the fibre layer occurred to produce the required thickness reduction. The severity of this damage would be detrimental to the fatigue performance of a riveted joint. As the thickness reduction causing the expulsion of the fibre layer is necessary for coin dimpling, this process was deemed unacceptable for practical application to GLARE.

Radius dimpling trials were also conducted, and showed that delamination between the 0° and 90° fibre layers occurred; however, the fibre layer was not expelled from the laminate as with coin dimpling. The delamination is likely the result of the sharp bending radius of the commercial dimpling dies used in this investigation. GLARE is known to have lower forming limits compared to 2024-T3 as a result of elastic strain limits in the fibre layers and shear stress limits of the adhesive between layers (de Jong *et al.*, 2001). Thus it is plausible that the geometry of the dimpling tools could be optimized to limit the extent of such delaminations, or eliminate them all together. Such optimization, however, was beyond the scope of this investigation, and only the performance of radius dimpled GLARE using commercially available dimpling tools was studied.

Subsequent riveting of radius dimpled holes in GLARE3-2/1 was observed to exacerbate this delamination damage. Radial pressure produced during riveting caused the thin outer aluminum layer in the lower sheet to buckle. This buckling deformation may introduce peeling stresses that increase the delamination damage during riveting, or promote delamination growth under applied load. In addition, the buckled aluminum layer will not contribute substantially to the load carrying capacity of the lower sheet in the region of the buckle. Therefore, the fatigue resistance of the undamaged aluminum layer would be reduced. To minimize the effects of this damage on fatigue test results, a rivet squeeze force of 2,500 lbf ($D/D_o = 1.4$) was adopted, falling within the range of acceptable riveting practice, and producing minimal visible buckling damage.

9.1.1 Numerical Modelling

In order to assess the influence of residual stresses generated during dimple formation on crack initiation, the dimpling process was simulated using LS-DYNA. An axisymmetric model simulating dimpling in monolithic 2024-T3 sheets was developed. Adaptive remeshing was included to limit severe distortions in elements due to the large deformation inherent in the problem. A mesh refinement study showed that accurate results were dependent on both the mesh size, and degree of element distortion. Smaller mesh sizes distorted more quickly, requiring a shorter adaptive remeshing step. As only a remeshing frequency of 1 Hz was used, further investigation into the influence of this variable on the results is needed.

Results from this model indicated that dimpling produces a favourable residual compressive stress field along the faying surfaces of the dimple cones. As secondary bending stresses are highest along the joint faying surfaces, this is expected to delay

crack initiation. Furthermore, larger residual tensile stresses were predicted in the lower sheet compared to the upper sheet, indicating that the lower sheet may be fatigue critical. This contradicts results from coupon testing of unfilled dimpled holes in GLARE3-2/1, indicating that the residual stress distribution in dimpled GLARE is significantly different than that predicted in the 2024-T3 simulations. Indeed, the anisotropy of material properties in the thickness direction in GLARE combined with the delaminations observed in dimpling trials will influence the residual stress distribution in GLARE.

9.2 Crack Initiation

9.2.1 Unfilled Dimpled Holes

Results from the CIS-A coupon test series demonstrated a positive improvement in fatigue crack initiation life in unfilled dimpled holes over unfilled machine countersunk holes in GLARE3-2/1. A nearly 2-fold improvement was observed for the dimpled upper sheet coupons. This demonstrated the potential benefits obtainable through elimination of the lamina knife-edge in machine countersunk GLARE.

Results from this test series also revealed a significant difference in crack initiation between an upper dimpled sheet (sheet which contacts dimple punch) and lower dimpled sheet (sheet which contacts dimple die). Fatigue crack initiation was not obtained in the lower dimpled sheets over a 1,000,000 fatigue cycle block, compared to the 135,000 cycle crack initiation life observed for the upper dimpled sheets. Differences in the degree of delamination damage and the residual stress distribution between the upper and lower dimpled sheets may be responsible for higher fatigue life observed in the

lower dimpled sheet; however, further investigation is needed to substantiate this explanation.

9.2.2 Dimpled Lap Joints

Two initiation events were observed in the dimpled and machine countersunk GLARE lap joints: nucleation of “hidden” cracks and nucleation of “visible” cracks. Hidden cracks were detected by the formation of a surface depression on the joint surface resulting from load bridging around the hidden crack.

Initiation of hidden cracks along the bottom rivet row was observed in all of the GLARE CIS-B and wide lap joint specimens. The initiation of these cracks preceded the initiation of cracks in the visible aluminum layers. Furthermore, the hidden cracks were observed to grow and link-up (or grow to the specimen edge in the case of CIS-B specimens) prior to the initiation of cracks in the visible aluminum layers. Although similar results were observed by Müller (1995a), little is known about the effects of such hidden damage on the residual strength and corrosion resistance of riveted joints.

Differences in the visible crack initiation data were observed between the CIS-B and wide lap joint specimens. In the CIS-B specimens, nucleation and growth of cracks across the entire width of the hidden aluminum layer occurred before the formation of a visible crack. The stress distribution in the coupons with a full-width hidden crack was no longer representative of a true lap joint, resulting in unreliable visible crack initiation data. Therefore this discussion is limited to the visible crack initiation results obtained from the wide lap joint specimens.

Unlike the unfilled dimple holes, the dimpled GLARE lap joint exhibited a shorter visible crack initiation life compared to machine countersunk joints. This implies

that either the load transfer mechanism, damage due to riveting, or both have a negative impact on the crack initiation life of dimpled GLARE lap joints. Given that cracks initiated along the lower sheet, it is likely that the buckling damage caused by riveting influenced the crack initiation life. As discussed above, this damage would result in higher stresses in the undamaged portion of the lower sheet, causing the decrease in crack initiation life. The role of the altered load transfer mechanism in GLARE, however, cannot be dismissed as a cause as the complete details of this mechanism are unknown.

9.3 Crack Growth

The dimpled GLARE lap joint specimen exhibited crack growth rates similar to monolithic aluminum joints (Figure 9.1), indicating that the fibre bridging mechanism crucial to the crack growth properties of GLARE was ineffective. Further evidence of the ineffectiveness of fibre bridging was observed in the link-up behaviour of the dimpled GLARE joints (Figure 9.2). Fibre bridging failed to limit the influence of the overlapping cracks on each other as observed in machine countersunk GLARE joints. The ineffectiveness of the fibre bridging mechanism in dimpled GLARE was likely caused by the delamination, formed during the dimpling/riveting process, growing in advance of the fatigue crack tip.

Figure 9.1: Aggregate crack growth curves normalized to time of visual crack detection.

Figure 9.2: Comparison of typical link-ups observed in (a) machine countersunk aluminum joints; (b) machine countersunk GLARE joints; (c) dimpled GLARE joints.

Formation and growth of a delamination is an integral part of the fibre bridging mechanism in GLARE. Without delamination growth, the fibre stresses due to the fibre bridging load would increase as the crack grew until fibre failure occurred. Instead, delamination growth increases the length over which the fibres are elongated, resulting in a reduction in fibre stresses (Alderliesten, 2001). Therefore, a balance between delamination growth and bridging load (crack length) is necessary. If the delamination formed during dimpling/riveting grew in advance of the crack, this balance would be altered. Crack tip opening would be insufficiently constrained by the fibre layer, resulting in the rapid crack growth rates observed in this investigation.

These results highlight the vulnerability of GLARE to delamination damage. Similar damage could be introduced into GLARE by other means, most notably by riveting at high squeeze forces. Although Müller (1995a) demonstrated that the fatigue life of GLARE joints could be increased by increasing residual compressive hoop stresses around the rivet hole by using larger rivet squeeze forces, the limit on this behaviour is unknown. Ryan and Monaghan (2000) conducted FEM simulations of riveting in GLARE, using standard riveting guidelines, and found possible regions where delaminations could occur. Such delaminations could be equally as detrimental to the fatigue performance as those observed in the present investigation.

9.4 Rivet Head Fracture

A rivet failure mode, by which the countersunk rivet head fractured along the rivet shank, was observed in the machine countersunk GLARE3-2/1 wide lap joint fatigue tests. These specimens contained the reduced countersink depth NAS1097 rivets.

The early stages of this failure mode were characterized by large plastic deformations in the countersunk rivet head. Fatigue cracks initiated in this region, eventually leading to fragmentation of the rivet head. Although this failure mode resulted in the fragmentation of several rivets, final failure of the specimens was still a result of unstable crack growth in the sheet material.

The presence of this failure mode reinforces the potential for dimple countersinking (as dimpling would allow rivets with larger countersink depths to be used), and the need for new riveting guidelines specific to GLARE. The specimens in which the rivet head fracture was observed were manufactured according to the standard riveting guidelines developed from experience with monolithic aluminum. The observed failure of rivet heads, however, is unacceptable in practice. Such a failure would significantly affect the residual strength of the joint, limiting its life. Furthermore, crevice corrosion and rivet tilting would be promoted by the gap that forms between the deformed rivet head and sheet material in the early stages of this failure mode (Figure 9.3). Further, the joint would be susceptible to corrosive attack after fragmentation of the rivet head occurred.

Figure 9.3: Gap formation due to plastic deformation stage of rivet head fracture.

Chapter 10: CONCLUSIONS

The main objective of this thesis was to investigate the potential of press-countersinking (dimpling) as an alternative to machine countersinking in thin GLARE lap joints. A series of fatigue tests was completed to investigate the crack initiation and growth behaviour of dimpled GLARE joints. Additionally, dimpled coupons and numerical modelling were used to investigate the effects of the dimpling and riveting process on GLARE. Conclusions drawn from this project are as follows:

1. Coin dimpling GLARE3-2/1 using commercially available dimpling tools results in severe delamination damage and causes the fibre layer to be expelled from the laminate within the dimple cone. This damage was deemed too severe for further investigation.
2. Radius dimpling GLARE3-2/1 using commercially available dimpling tools results in delamination damage within the formed dimple cone. The severity of this damage is lower than that produced by coin dimpling. Subsequent riveting of radius dimpled holes exacerbates the delamination damage.
3. Numerical simulations of the dimpling process in 2024-T3 indicate a favourable residual compressive stress distribution along the faying sheet surfaces.
4. The dimpling simulations showed that higher residual tensile stresses are present in the lower sheet, indicating it may be fatigue critical.

5. The CIS-A coupons employed in this investigation indicated that unfilled dimpled holes exhibit a longer crack initiation life than unfilled machine countersunk holes in GLARE3-2/1.
6. An unfilled dimpled lower sheet had a significantly higher crack initiation life than an unfilled dimpled upper sheet in GLARE. This contradicts results from the FEM simulations of dimpling in 2024-T3, indicating a need for simulating the dimpling process in GLARE.
7. In dimpled and machine countersunk joints, hidden cracks initiate, grow, and link-up extensively prior to initiation of visible cracks.
8. The formation of a full-width hidden crack in the CIS-B specimens altered the stress state in the specimen, producing non-realistic visible crack initiation data.

Based on the results of the wide lap joint fatigue test series, the following observations were made. These observations must be considered in view of the high scatter inherent in fatigue testing and the small number of specimens they are based on.

1. The dimpled GLARE3-2/1 lap joint exhibited a shorter crack initiation life than the similar machine countersunk joints. Damage due to riveting, the alternate load transfer mechanism in dimpled joints, or both are likely responsible.

2. Crack growth rates in dimpled GLARE3-2/1 joint were similar to rates observed in monolithic 2024-T3 joints, indicating that fibre bridging is not effective in dimpled GLARE joints.

The expected performance of dimpled GLARE joints was not met; however, this may have been caused by a number of issues identified in this work. It is felt that further research is needed to establish the performance potential of this type of joint. With this recommendation in mind, a number of studies have been outlined in the next chapter.

Chapter 11: FUTURE WORK

The following sections provide some suggested topics for further research into the area of dimple forming in GLARE.

11.1 Numerical Simulation of Dimple Forming in GLARE

A numerical model for simulating the dimpling process in GLARE should be developed. A 3-dimensional model is required to capture the anisotropic properties of the fibre layers. Furthermore, a delamination model is required to simulate the delamination damage observed in the present investigation. This would allow the extent of delamination damage produced during dimpling to be studied. Optimization of dimpling tools could be performed to minimize or perhaps eliminate such damage. Additionally, the residual stress distributions obtained from this model may provide insight into the differences in crack initiation life between the upper and lower dimpled sheets observed in the present investigation, and could be used to further optimize the tool geometry.

This model could be further extended to include the rivet forming process, thereby allowing an investigation of the buckling damage due to rivet forming in dimpled holes. The final residual stress distribution in a dimpled/riveted lap joint could also be obtained.

11.2 Analysis of Load Transfer in Dimpled Joints

The load transfer mechanism in dimpled joints is not well understood. The relative contributions of friction, bearing between the dimple cones in the upper and lower sheet, and bearing between the rivet and sheets on load transfer are unknown. A

firm understanding of this mechanism is required to optimize the design of future dimpled joints. Specifically, the dimple cone angle (and rivet countersink angle), countersink depth, and rivet clamping force typical of machine countersunk joints may not be optimized for dimpled joints. Additionally, without detailed knowledge of the load transfer mechanism, and consequently stress distribution, in dimpled joints, accurate fatigue life predictions will not be possible.

11.3 Influence of Process Variations

In this investigation, a drill-dimple process was considered, where the rivet hole was first drilled, and then dimpled. Varying that process may be beneficial to the fatigue life of the joint. By dimpling the sheet material first, tensile plastic strain would be formed in the sheet. Subsequent drilling of the rivet hole would generate a region of residual compressive stress. Shewchuk (1974) used a similar process to introduce residual compressive stresses around holes in 2024-T3, improving their fatigue performance. This process could be beneficial to both monolithic materials as well as FML's.

11.4 Prevention of Buckling Damage due to Riveting

The buckling damage produced during riveting in dimpled GLARE may be preventable by supporting the dimple cone in the sheet during riveting. By designing a rivet squeezer that would support the dimple cone during riveting, fatigue tests could be undertaken to investigate the relative contribution of damage incurred during riveting to the poor fatigue performance observed in this investigation.

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APPENDIX A: SUPPLEMENTARY CIS-A AND CIS-B TESTING DATA

Table A.1: Detection lives for CIS-A specimens.

Number	Material	CSK Method	Visual Crack Detection (cycles)	Cracked Layer
CIS-A-01	GLARE3-2/1	-	225,000*	AL-1
CIS-A-02	GLARE3-2/1	-	110,000	AL-1
CIS-A-03	GLARE3-2/1	-	255,000	AL-1
CIS-A-04	GLARE3-2/1	-	110,000	AL-1
CIS-A-05	GLARE3-2/1	Machined	58,000	AL-1
CIS-A-06	GLARE3-2/1	Machined	89,500	AL-1
CIS-A-07	GLARE3-2/1	Machined	65,000	AL-1
CIS-A-09	GLARE3-2/1	Dimpled (US)	105,000	AL-1
CIS-A-10	GLARE3-2/1	Dimpled (LS)	>1,000,000	AL-1
CIS-A-11	GLARE3-2/1	Dimpled (US)	-**	-
CIS-A-12	GLARE3-2/1	Dimpled (LS)	>1,000,000	AL-1
CIS-A-13	GLARE3-2/1	Dimpled (US)	135,000	AL-1
CIS-A-14	GLARE3-2/1	Dimpled (LS)	-***	-
CIS-A-15	GLARE3-2/1	Dimpled (US)	165,000	AL-1
CIS-A-16	GLARE3-2/1	Dimpled (LS)	>1,000,000	AL-1

* Length of crack at detection exceeded the defined initiation length of 0.03".

** Specimen failed as a result of overload

*** Specimen failed due to unstable crack growth. Crack initiation was not detected.

Table A.2: Detection Lives for CIS-B specimens.

Number	Material	CSK Method	Hidden Crack Detection (cycles)	Visual Crack Detection (cycles)	Cracked Layer	Rivet Row
CIS-B-01	GLARE3-2/1	Dimpled	not tested	not tested	-	-
CIS-B-02	GLARE3-2/1	Dimpled	80,000	210,000	AI-3, AL-4	Bottom
CIS-B-03	GLARE3-2/1	Dimpled	80,000	203,334	AI-3, AL-4	Bottom
CIS-B-04	GLARE3-2/1	Machined	310,000	920,000	AI-3, AL-4	Bottom
CIS-B-05	GLARE3-2/1	Machined	320,000	680,000	AI-3, AL-4	Bottom
CIS-B-06	GLARE3-2/1	Dimpled*	-	380,000	AI-3, AL-4	Bottom**

* Coupon had rivet in bottom row reversed to force initiation in dimpled US

** Initiation occurred in bottom row, but dimpled US

APPENDIX B: WIDE LAP JOINT SPECIMEN DRAWINGS

APPENDIX C: WIDE LAP JOINT SPECIMEN TESTING REPORTS

Specimen	Page
MSD-AL-001	120
MSD-AL-002	134
MSD-AL-003	147
MSD-AL-004	165
MSD-GL-001	181
MSD-GL-002	197
MSD-GL-003	227

This appendix consists of individual testing reports for each of the wide lap joint fatigue specimens tested as part of this thesis. Each report is a self-contained testing report including its own set of appendices.

1. Scope

The results of the 20 inch wide proof-of-concept MSD specimen tested at Carleton University are detailed. General loading, specimen, and instrumentation properties of the experiment are documented, and testing goals and results are presented.

2. References

1. Mueller, R.P.G., *An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3*, Delft University of Technology, Delft, The Netherlands, 1995
2. Eastaugh, G.F., *Multiple site fatigue damage in fuselage skin splices*, Carleton University, Ottawa, Ontario, 1993
3. Rans, C.D., *Proposal for zero-load transfer rivet validation experiment*, Report 01-01, June 2001

3. Test Setup

The proof-of-concept specimen consisted of a 20 inch wide panel consisting of two 0.040 inch thick 2024-T3 aluminum sheets riveted together. The joint consisted of three rows of MS20479AD5-5 rivets with a 1 inch rivet and row pitch. Four zero-load transfer rivets were installed on the specimen to prevent edge cracking from occurring. Refer to the appendix for a detailed drawing of the specimen configuration.

30 strain gauges were installed on the specimen (refer to Figure 2 in the Appendix). Strain gauges were located on both sides of the aluminum sheet to obtain bending and nominal stresses in the joint. One bank (strain gauge bank 1) of gauges was located 1 inch above the top rivet row to obtain a nominal sheet stress distribution. Since the zero-load transfer rivet reduces the load on the edge rivets locally by redistributing the bending stress within the joint overlap, not by altering the nominal sheet stress distribution, strain gauges were also located around the edge rivets of the bottom rivet row (strain gauge bank 2). This required milling slots into the aluminum to allow strain gauges to be placed underneath the joint overlap.

The specimen was fatigue loaded at 4Hz with a peak load of 48.4kN to achieve a remote stress of 13.6ksi. $R = 0.03$ was used to prevent buckling of the specimen. A MTS 442 controller and MTS 244.21 hydraulic actuator and load cell were used for load application (Figure 3 in the Appendix). The load cell was last calibrated on October 1, 2001.

4. Testing Goals

The goals of testing the proof-of-concept specimen were as follows:

- Validate the effectiveness of the zero-load transfer rivets in reducing the nominal stress at edge rivets at peak load
- Monitor any degradation of the effectiveness of zero-load transfer rivets during fatigue
- Validate the effectiveness of the zero-load transfer rivets in preventing edge cracking and producing MSD
- Determine nominal stress distribution of the test specimen
- Gain experience in visual crack detection methods
- Obtain crack growth data

The success of meeting each goal is discussed in the Recommendations section.

5. Results

5.1 Nominal Stress Distribution

A strain survey was performed to determine the nominal stress distribution in the specimen (without the zero-load transfer rivets). This was done to validate the design of the specimen and specimen mounting clamps. Ideally a uniform stress distribution across the specimen width to promote the formation of MSD, and lower stress at the panel edges to prevent edge cracking and simulate the presence of frames is desired. However, due to the Poisson effect, a relatively uniform stress distribution with slightly higher stresses at the specimen edges was expected and found (see Figure 5.1).

Figure 5.1: Nominal and bending stress distribution of strain gauge bank 1. $\sigma_{\text{applied}} = 13.6\text{ksi}$

Figure 5.1 also includes the stress distribution with the zero-load transfer rivets installed. The zero-load transfer rivets redistribute bending stress in the joint overlap, reducing the local bending stress at the edge rivets. As a result, the remote location of strain gauge bank 1 relative to the critical edge rivets does not accurately reflect the stress distribution of the critical rivet row. It is, however, important to note that the zero-load transfer rivets do affect the bending stress distribution in this strain gauge bank, which can be used to evaluate their performance qualitatively.

5.2 Effectiveness of the Zero-Load Transfer Rivets

A second bank of strain gauges located in line with the bottom rivet row was utilized to observe the local nominal and bending stresses around these rivets with and without the zero-load transfer rivets.

Figure 5.2: Nominal and bending stress distribution of strain gauge bank 2. $\sigma_{\text{applied}} = 13.6\text{ksi}$

Figure 5.2 shows that the nominal stress without the zero-load transfer rivets is uniform across the specimen width until the specimen edge is reached where it is 7% higher. Installation of the zero-load transfer rivets reduced the stress of at the edge rivet by 13% while maintaining the uniform nominal stress distribution across the rest of the specimen width. Such a stress distribution should prevent edge cracking and promote MSD.

This effect of fatigue on the nominal stress distribution local to the rivets was also monitored to determine if the effectiveness of the zero-load transfer rivets was degraded with fatigue. Obscure stress distribution cycles can be attributed to s were detected at approximately 10000 cycles and 340000 cycles. The distribution a 10000 was caused by improper calibration of the strain gauges. This problem was discovered and remedied quickly. The distribution at 340000 cycles was caused due to rotation of the specimen which occurred as the crack approached the specimen edge. Other then these two regions, it was observed that the nominal stress distribution was not altered by fatigue (Figure 5.3).

Printed on: 27 May 2002 | Converted Excel Data

Figure 5.3: Nominal stress at strain gauge bank 2 vs number of fatigue cycles

5.3 Crack Formation and Growth

The proof-of-concept specimen was not successful in producing MSD; however, failure was not due to edge cracking, indicating that the zero-load transfer rivets were successful. Initial cracking occurred at rivet 18 (refer to Figure 4 in the Appendix for the rivet numbering scheme) and grew towards the centre of the specimen. This crack was not detected until 297000 cycles at which time it had a length of 0.298 inches (measured from centre of rivet) and an additional crack of 0.160 inches had formed at the opposite side of rivet 18. Complete failure of the specimen occurred at 363523 cycles when the crack grew through the edge of the specimen (refer to Figure 5.4).

Figure 5.4: Crack initiation and growth

Initial cracking of the specimen occurred earlier than expected. This indicates that initial cracking could have occurred due to a material or manufacturing defect in the joint. This is further supported by the fact that additional cracks did not form in the specimen during the growth of the initial crack. After failure of the specimen, the rivets were removed, taking care not to damage the rivet hole, and the faying joint surfaces were inspected visually. There did not appear to be any visible defects in rivet hole 18 in the cracked sheet that would have caused premature cracking; however a large burr was present at rivet hole 18 on the faying side of the mating sheet. A fretting pattern left on that sheet during crack growth allowed the crack initiation point to be traced back directly to that burr. As a result, the premature formation of that crack is attributed to poor manufacturing of the specimen.

6. Conclusions and Recommendations

From the results of this test, it can be concluded that:

- The zero-load transfer rivet effectively reduced the nominal stress of the edge rivets, thus preventing edge cracking
- The effectiveness of the zero-load transfer rivet did not appear to degrade with fatigue over the 360000 cycles that the specimen was tested to
- The test setup produces an adequate stress distribution in the test specimen that should allow for MSD formation

In addition, it is recommended that subsequent specimens undergo a much more controlled and quality inspected manufacturing process. New drill and deburring bits have already been ordered to ensure the best possible quality of hole for each specimen. In addition, it is recommended that each hole be visually inspected with a magnifier to ensure there are no burrs or swarf present in the holes before rivet installation.

For the next 2 specimens, it is proposed that the same rivet pattern be used, however the MS20470 rivets be replaced with MS20426 countersunk rivets. It is also proposed that a smaller diameter rivet (1/8 in dia) be used so that direct comparison between the next specimen and future GLARE 2 specimens can be made.

Appendix A: Drawings and Supplementary Pictures

Figure 1a: Detailed specimen drawing page 1 of 2

Figure 1b: Detailed specimen drawing page 2 of 2

Figure 2: Strain gauge numbering and placement

Figure 3: MTS controller and test rig setup

Figure 4: Rivet numbering scheme

Appendix B: Raw Data Tables

Strain Gauge Data (Static):

Young's Modulus of 2024-T3: 10500 ksi

Without Zero-Load Transfer Rivets	With Zero-Load Transfer Rivets	% Difference
--------------------------------------	-----------------------------------	-----------------

Load Scale (kN):	50 kN	50 kN	
Load (V):	9.681 V	9.681 V	0.0%
Load (kN):	48.405	48.405	0.0%

Strain Gauge Number	Strain Readings				
	(micro strain)	(ksi)	(micro strain)	(ksi)	
1	1275	13.39	1088	11.42	-14.7%
2	1201	12.61	1190	12.50	-0.9%
3	1143	12.00	1205	12.65	5.4%
4	1118	11.74	1184	12.43	5.9%
5	1131	11.88	1176	12.35	4.0%
6	1150	12.08	1178	12.37	2.4%
7	1144	12.01	1160	12.18	1.4%
8	1111	11.67	1158	12.16	4.2%
9	1112	11.68	1118	11.74	0.5%
10	1243	13.05	1239	13.01	-0.3%
11	1360	14.28	1193	12.53	-12.3%
12	1720	18.06	719	7.55	-58.2%
13	1574	16.53	1257	13.20	-20.1%
14	1641	17.23	1495	15.70	-8.9%
15	-6120	19.74	-6198	18.92	-4.1%
16	1524	16.00	1579	16.58	3.6%
17	1470	15.44	1376	14.45	-6.4%
18	1474	15.48	1374	14.43	-6.8%
19	1480	15.54	1395	14.65	-5.7%
20	1527	16.03	1461	15.34	-4.3%
21	1537	16.14	1478	15.52	-3.8%
22	1501	15.76	1469	15.42	-2.1%
23	1475	15.49	1444	15.16	-2.1%
24	1498	15.73	1466	15.39	-2.1%
25	1427	14.98	1389	14.58	-2.7%
26	1467	15.40	1515	15.91	3.3%
27	838	8.80	1507	15.82	79.8%
28	829	8.70	1075	11.29	29.7%
29	751	7.89	861	9.04	14.6%
30	538	5.65	583	6.12	8.4%

Calvin Rans:
Gauge 15: Initial zero was -8000

Table 1: Static strain gauge data for specimen with and without zero-load transfer rivets

Strain Data (Fatigue)

Loading Frequency: 4 Hz
Load Scale: 50 kN

	Max		Average	
	Max Load:	9.81 V (49.1 kN)	9.70 V (48.5 kN)	
	Min Load:	0.19 V (0.9 kN)	0.28 V (1.4 kN)	

CalVin Rans:
Gauge 15:
Initial zero was -8000

Number of Cycles	Max Load		Min Load (V)	Strain Gauge Reading (micro strains)															
	(V)	(V)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
1	9.681	0.196		1088	1190	1205	1184	1176	1178	1160	1160	1158	1118	1239	1193	719	1257	1495	-6198
1000	9.682	0.189		1117	1211	1224	1204	1199	1198	1180	1180	1143	1138	1256	1204	759	1416	1565	-5961
2000	9.694	0.199		1133	1208	1222	1206	1189	1189	1179	1179	1145	1138	1271	1216	761	1206	1399	-6298
3000	9.694	0.299		1138	1213	1225	1205	1191	1196	1182	1182	1146	1141	1263	1214	774	1213	1402	-6302
4000	9.687	0.281		1142	1215	1227	1211	1193	1197	1183	1183	1148	1140	1262	1217	785	1217	1407	-6299
5000	9.689	0.300		1140	1214	1226	1210	1193	1198	1184	1184	1149	1141	1263	1217	788	1217	1403	-6293
6000	9.695	0.277		1137	1209	1221	1203	1192	1190	1176	1176	1141	1139	1257	1228	755	1232	1374	-6244
7000	9.687	0.303		1135	1210	1221	1204	1193	1190	1175	1175	1141	1134	1254	1230	751	1231	1372	-6235
8000	9.697	0.302		1146	1219	1230	1214	1201	1199	1186	1186	1152	1149	1280	1231	754	1235	1378	-6231
9000	9.691	0.297		1146	1219	1231	1213	1202	1200	1186	1186	1153	1185	1276	1230	755	1234	1380	-6232
10000	9.714	0.299		1146	1220	1231	1213	1201	1200	1185	1185	1151	1183	1273	1230	756	1235	1382	-6231
11000	9.685	0.262		1147	1220	1231	1213	1200	1199	1184	1184	1150	1141	1264	1230	757	1236	1376	-6227
12000	9.812	0.256		1143	1218	1230	1211	1194	1197	1184	1184	1151	1169	1270	1229	756	1235	1382	-6231
13000	9.688	0.303		1142	1217	1229	1209	1194	1196	1183	1183	1150	1141	1262	1230	756	1236	1372	-6240
14000	9.764	0.300		1146	1222	1232	1215	1198	1201	1187	1187	1151	1142	1269	1216	782	1237	1397	-6331
15000	9.689	0.293		1145	1221	1229	1212	1195	1199	1184	1184	1148	1145	1296	1214	780	1237	1393	-6336
16000	9.711	0.300		1141	1216	1226	1207	1189	1191	1175	1175	1140	1131	1253	1215	778	1236	1393	-6335
17000	9.811	0.297		1133	1212	1222	1204	1189	1191	1176	1176	1142	1133	1252	1214	783	1239	1391	-6338
18000	9.685	0.299		1137	1213	1221	1205	1191	1192	1176	1176	1141	1132	1253	1214	782	1240	1391	-6315
19000	9.691	0.300		1141	1218	1226	1209	1194	1195	1179	1179	1144	1134	1252	1212	785	1245	1394	-6315
20000	9.745	0.297		1130	1205	1216	1198	1184	1185	1169	1169	1132	1121	1245	1212	786	1247	1391	-6318
21000	9.691	0.299		1133	1209	1218	1200	1186	1188	1172	1172	1137	1127	1247	1211	785	1248	1390	-6319
22000	9.685	0.299		1132	1207	1217	1200	1186	1186	1173	1173	1135	1124	1243	1214	787	1250	1390	-6318
23000	9.685	0.295		1134	1207	1216	1199	1184	1186	1169	1169	1134	1123	1244	1214	788	1252	1390	-6318
24000	9.697	0.297		1134	1208	1217	1199	1184	1184	1169	1169	1134	1123	1256	1219	793	1262	1398	-6314
25000	9.694	0.302		1132	1207	1217	1199	1184	1182	1167	1167	1132	1121	1247	1219	793	1262	1398	-6313
26000	9.685	0.297		1133	1207	1217	1199	1184	1182	1168	1168	1133	1122	1265	1221	796	1264	1401	-6311
27000	9.682	0.300		1142	1217	1226	1208	1194	1194	1177	1177	1141	1131	1252	1219	797	1264	1396	-6323
28000	9.685	0.306		1137	1212	1221	1204	1189	1191	1173	1173	1138	1128	1256	1221	796	1262	1388	-6334
29000	9.679	0.297		1132	1206	1214	1200	1184	1184	1165	1165	1133	1122	1244	1223	799	1264	1384	-6342
297000	9.679	0.220		1136	1210	1220	1202	1186	1188	1170	1170	1135	1130	1245	1238	797	1268	1397	-6289
300000	9.691	0.297		1134	1208	1219	1201	1186	1186	1169	1169	1134	1124	1246	1234	797	1268	1394	-6300
310000	9.679	0.297		1135	1211	1222	1204	1188	1188	1160	1160	1138	1127	1247	1253	803	1273	1402	-6284
320000	9.697	0.297		1131	1204	1218	1203	1185	1188	1174	1174	1143	1127	1255	1275	782	1245	1386	-6340
330000	9.703	0.299		1128	1202	1218	1202	1185	1188	1174	1174	1142	1131	1261	1304	783	1245	1388	-6308
340000	9.706	0.284		1127	1202	1218	1204	1186	1189	1174	1174	1144	1129	1275	1358	785	1246	1391	-6300
350000	9.689	0.280		1120	1195	1214	1201	1183	1187	1173	1173	1144	1130	1305	1468	781	1244	1390	-6290
360000	9.688	0.287		1088	1172	1198	1188	1177	1182	1171	1171	1146	1140	1398	1618	746	1211	1360	-6291
362500	9.688	0.303		1076	1160	1190	1183	1173	1180	1171	1171	1148	1141	1431	1312	734	1200	1351	-6285
363523	9.691	0.189		812	954	1032	1063	1087	1126	1137	1137	1147	1171	1890	-295	559	1008	1196	-6194

Number of Cycles	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1579	1376	1374	1395	1461	1478	1469	1444	1466	1389	1515	1507	1075	861	583
10000	1590	1388	1381	1407	1492	1474	1470	1439	1465	1381	1473	1474	1048	830	541
20000	1546	1362	1352	1369	1431	1458	1462	1443	1460	1372	1485	1478	1069	925	646
30000	1553	1368	1357	1374	1435	1461	1463	1440	1457	1374	1485	1480	1077	931	651
40000	1555	1372	1360	1376	1437	1462	1463	1450	1460	1385	1492	1486	1081	937	645
50000	1555	1373	1362	1377	1438	1465	1468	1443	1465	1382	1490	1484	1077	925	643
60000	1569	1385	1371	1389	1451	1458	1458	1436	1459	1377	1484	1478	1074	924	643
70000	1573	1387	1372	1392	1454	1443	1441	1418	1437	1367	1474	1475	1066	913	630
80000	1574	1387	1373	1392	1454	1464	1465	1438	1452	1383	1495	1490	1082	928	647
90000	1573	1386	1372	1392	1453	1465	1468	1442	1461	1396	1501	1500	1096	939	664
100000	1573	1387	1372	1392	1454	1483	1481	1453	1468	1402	1508	1508	1099	947	662
110000	1572	1386	1371	1390	1452	1479	1479	1455	1470	1401	1506	1502	1095	943	658
120000	1572	1385	1370	1391	1452	1478	1481	1452	1468	1396	1502	1500	1092	937	654
130000	1573	1385	1371	1391	1452	1505	1505	1478	1492	1425	1537	1524	1122	965	685
140000	1563	1386	1374	1387	1443	1472	1475	1453	1480	1388	1491	1504	1093	977	716
150000	1563	1384	1373	1386	1442	1439	1435	1418	1437	1348	1449	1457	1046	926	650
160000	1565	1387	1374	1388	1444	1451	1456	1431	1446	1408	1474	1477	1067	956	680
170000	1564	1386	1374	1388	1443	1453	1452	1432	1446	1409	1472	1481	1070	943	671
180000	1564	1386	1375	1388	1444	1454	1452	1432	1448	1408	1466	1475	1075	951	667
190000	1569	1390	1377	1391	1446	1449	1450	1429	1444	1405	1464	1482	1072	950	641
200000	1567	1389	1377	1390	1446	1460	1453	1434	1447	1408	1471	1485	1079	954	650
210000	1567	1388	1376	1390	1446	1454	1451	1431	1446	1407	1465	1480	1075	950	642
220000	1567	1390	1377	1390	1446	1450	1448	1429	1447	1404	1463	1474	1074	962	658
230000	1567	1389	1377	1390	1446	1451	1451	1427	1447	1403	1469	1478	1075	950	646
240000	1571	1392	1378	1391	1448	1446	1452	1435	1444	1410	1480	1480	1080	956	645
250000	1570	1390	1377	1391	1447	1447	1448	1426	1443	1406	1467	1490	1078	941	642
260000	1573	1393	1379	1393	1449	1450	1450	1428	1442	1403	1474	1483	1083	950	641
270000	1572	1393	1378	1393	1448	1447	1446	1428	1438	1401	1469	1478	1082	943	636
280000	1569	1389	1376	1391	1446	1457	1449	1426	1440	1400	1471	1477	1083	946	633
290000	1566	1385	1373	1387	1443	1447	1448	1422	1440	1400	1471	1476	1078	947	633
297000	1573	1392	1378	1393	1449	1450	1442	1419	1435	1397	1476	1469	1080	934	623
300000	1572	1391	1377	1392	1448	1438	1437	1413	1429	1394	1466	1463	1081	927	625
310000	1577	1395	1380	1397	1450	1441	1438	1417	1431	1396	1488	1471	1088	933	622
320000	1550	1375	1365	1382	1440	1438	1444	1419	1444	1404	1512	1461	1086	950	639
330000	1548	1371	1363	1382	1439	1435	1437	1420	1443	1410	1535	1455	1086	951	642
340000	1545	1369	1363	1382	1440	1438	1438	1421	1445	1423	1588	1450	1085	953	644
350000	1535	1358	1357	1378	1437	1436	1437	1419	1447	1455	1705	1443	1086	936	646
360000	1488	1319	1325	1353	1414	1434	1441	1425	1455	1540	1813	1419	1073	925	658
362500	1474	1307	1318	1347	1410	1436	1437	1427	1461	1575	1457	1398	1068	918	669
363523	1199	1114	1170	1238	1332	1381	1411	1427	1488	2018	110	1142	904	812	745

Crack Growth Data:

Number of Cycles	18		19		20	
	L	R	L	R	L	R
297000	0.298	0.160				
300000	0.307	0.170				
310000	0.360	0.202				
320000	0.410	0.270				
330000	0.498	0.342				
340000	0.605	0.442				
345000	0.678	0.525				
350000	0.790	0.650				
355000				0.142		
360000				0.398		
362500				0.625		
363300				0.942		
363523				Failure		

Table 3: Crack growth data. Rivets with no cracking are excluded

1. Scope

This report details results of the MSD-AL-002-40 specimen tested at Carleton University as well as the validation of manufacturing techniques. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. Rans, C., *R-MSD-AL-001-40*, Carleton University, 2002
2. Eastaugh, G.F., *Multiple site fatigue damage in fuselage skin splices*, Carleton University, Ottawa, Ontario, 1993
3. Mueller, R.P.G., *An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3*, Delft University of Technology, Delft, The Netherlands, 1995

3. Test Set-up

Specimen Properties

- Material: 2024-T3

Dimensional Properties

- Width: 20"
- Thickness: 0.040"
- Drawing: D1-MSD-AL-002-40 (see Appendix)

Joint Properties

- Rivet Type: MS20426-AD-5-5
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets installed on specimen to prevent edge cracking

Strain Gauges

- Number Installed: 20
- Location of Banks: Refer to Figure 3.1

Testing Characteristics

- Load Frequency: 4Hz
- Peak Load: 48.5 kN
- Remote Stress: 13.6 ksi
- R: 0.03
- Controller Type: MTS 442
- Hydraulic Actuator Type: MTS 244.21

4. Testing Goals

The goals of the MSD-AL-002-40 specimen were as follows:

- Validate manufacturing technique changes recommended in R-MSD-AL-001-40
- Validate countersinking methods
- Prove specimens ability to produce MSD
- Obtain crack initiation and growth data

5. Results

5.1 Specimen Manufacturing

Results from MSD-AL-001-40 [1] prompted changes to the quality of specimen manufacturing. As recommended, new tools for drilling, deburring and countersinking were acquired and used in the manufacturing of specimen MSD-AL-002-40. MSD was obtained in this specimen, indicating these manufacturing changes were sufficient.

In contrast to specimen MSD-AL-001-40, MSD-AL-002-40 required the rivet holes to be machine countersunk. This process was completed using a microstop countersink on a drill press. The countersunk depth required for the MS20426-AD-5-5 rivet was found to be larger than the sheet thickness. This produced a knife edge in the countersunk sheet of the riveted joint that was detrimental to the crack initiation life. Selection of MS20426-AD-5-5 rivets was made based on the MSD specimens tested by Eastaugh [2]. Review of Eastaugh's thesis confirmed that the MS20426-AD-5-5 rivets were used, and testing proceeded.

5.2 Crack Initiation

Cracking, in the form of advanced MSD, was first detected at 57402 cycles. 14 cracks were observed, with lengths as large as 0.35 inches (Figure 5.1). Using the results of Eastaugh's work, crack initiation was not expected until over 250000 cycles [2]; thus, not much attention was being directed at searching for cracks below 100000 cycles. Testing conducted by Muller [3] on similar joint configurations, but using NAS1097 rivets, were found to produce results similar to that reported by Eastaugh. Other researchers have obtained similar results. The NAS1097 rivets have a shallower countersink, and do not produce a knife-edge in 0.040 inch thick sheet material. This suggests that the joints tested by Eastaugh did not contain a knife-edge, and the short crack initiation life obtained for MSD-AL-002-40 is valid.

Crack initiation was expected near the centre of a riveted panel where the remote stress is slightly higher (Figure 5.2); however crack initiation and growth only occurred on one half of the specimen between rivets 11 and 19 (Figure 5.1). This behaviour was a result of poor countersinking. During riveting, it was found that the countersink depth became progressively deeper from one end of the specimen to another, causing the countersink to be too deep on one half of the specimen. This variance in countersink depth was a result of the countersinking process. During countersinking, the joint was fixed to a drill press, while the drilling head was moved. This caused the drill press operator to have to reach

over the specimen while countersinking the far side of it. This need to reach created a variance in drill press pressure during countersinking which led to the deeper countersinks in one half of the specimen.

5.3 Crack Growth and Link-up

Crack growth measurements were made using a travelling microscope. Due to the late detection of cracking, limited crack growth data was obtained (Figure 5.3).

Four crack link-ups were observed before specimen failure. Link up was observed (but did not necessarily occur) at 61100 cycles between rivets 15 & 16, at 61160 between 13 & 14 and 16 & 17, and at 61170 between 14 & 15 (figure 5.4). The link-up between rivets 14 & 15 was preceded by significant crack tip overlap which caused the crack tips to curve in on each other, and produced several secondary cracks (Figure 5.5).

Final failure of the specimen occurred at 61176 cycles. Failure was observed to be caused by unstable fracture of the specimen. Post failure inspection of the fracture surface found that hidden cracks were present at rivets 8 and 9 prior to specimen failure.

6. Conclusions and Recommendations

This experiment has shown that the current manufacturing procedures and specimen design will pro MSD. The location of the MSD cracks indicated a deficiency in the uniformity of rivet hole countersinks that needs to be addressed. It is recommended that changes to the countersinking procedure be made in order to improve this deficiency and manufacturing quality be documented. Specifically, data on the maximum countersink diameter, driven rivet head diameter, and driven rivet head height should be recorded.

MS20426 rivets should be replaced with NAS1097 for future specimens in order to prevent the formation of a knife-edge during countersinking.

Lastly, more attention will be placed on crack inspection to prevent the late detection of cracks. Photographs of the rivets in the critical rivet row should be taken prior to testing and used during inspection to distinguish between scratches formed during manufacturing and installation of the specimen and fatigue cracks.

Figure 3.1: Strain Gauge Numbering And Placement

Figure 5.1: Crack Initiation And Growth

Figure 5.2: Comparison of uncracked stress distribution 1 inch above critical rivet row in specimens MSD-AL-001-40 and MSD-AL-002-40

Figure 5.3: Crack growth curves

Between rivets 13 and 14
(detected at 61160 cycles)

Between rivets 14 and 15
(detected at 61170 cycles)

Between rivets 15 and 16
(detected at 61100 cycles)

Between rivets 15 and 16
(detected at 61160 cycles)

Figure 5.4: MSD linkups

61160 cycles - unloaded

61160 cycles

61167 cycles - unloaded

61168 cycles

61169 cycles - unloaded

61170 cycles - linkup

Figure 5.5: Progression of link-up between rivets 14 and 15

Appendix A: Drawings and Supplementary Pictures

Figure A. 1: Rivet numbering scheme

Figure A. 2: MTS controller and test rig setup

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Date: July 25, 2002

Testing Summary Report
For Specimen:
MSD-AL-002-40

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Appendix B: Manufacturing Documentation

Specimen Number: MSD-AL-002-40	Drawing Numbers: D1-MSD-AL-002-40
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Joint Configuration:

Rivet Type: MS20-426-AD-5-5	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/machine csk
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: 2024-T3	Sheet Thickness: 0.040"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	15-May-02	Micheal, Calvin
Drill mounting bolt holes	9-Jun-02	Alex
Center drill/drill/debur rivet holes	10-Jun-02	Micheal, Calvin
Countersink holes	10-Jun-02	Micheal, Calvin
Rivet installation	13-Jun-02	Flight Research Lab

Quality Control:

All measurements are conducted on the critical rivet row and with an accuracy of $\pm 0.005"$. Rivets numbered from left to right on critical rivet row.

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #.		Rivet #.		Rivet #.		Rivet #.		Rivet #.		Rivet #.	
1		11		1		11		1		11	
2		12		2		12		2		12	
3		13		3		13		3		13	
4		14		4		14		4		14	
5		15		5		15		5		15	
6		16		6		16		6		16	
7		17		7		17		7		17	
8		18		8		18		8		18	
9		19		9		19		9		19	
10		20		10		20		10		20	
Nom.		Avg.	#DIV/0!	Nom.		Avg.	#DIV/0!	Nom.		Avg.	#DIV/0!

Comments:

Countersinking on large milling machine produced deeper countersinks on right side of specimen. These countersinks were too deep, causing csk rivet head to be resseded in csk sheet.

Specified rivets required csk larger then the sheet thickness. Knife edge produced in csk sheet.

Table 1: Raw strain gauge data

Strain Gauge Data (Fatigue):

	Max	Average
Max Load:	9.97 V (49.9 kN)	9.75 V (48.8 kN)
Min Load:	0.23 V (1.2 kN)	0.27 V (1.4 kN)

Strain Gauge Reading

Number of Cycles	Max Load (V)		Strain Gauge Reading (micro strains)											
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
20000	9.694	0.290	1122	1078	1103	1178	1173	1159	1216	531	1783	1418	1495	1626
40000	9.697	0.294	1123	1080	1117	1186	1190	1174	1236	521	1795	1409	1501	1630
57399	9.829	0.234	1130	1084	1123	1204	1206	1186	1264	531	1804	1416	1508	1629
57402			1141	1094	1147	1254	1217	1183	1315	579	1802	1409	1512	1645
59000	9.732	0.287	1106	1115	1171	1274	1238	1204	1340	616	1823	1405	1532	1656
61000	9.689	0.236	1078	1097	1150	1266	1221	1184	1336	604	1799	1362	1510	1638
61100	9.691	0.280	1189	1121	1207	1446	1422	618	1679	750	1781	1348	1518	1666
61160	9.694	0.278	1161	1130	1227	1511	1276	579	1756	772	1793	1424	1550	1676
61170			1172	1183	1347	1940	692	344	2185	1069	1702	1408	1550	1714
61176	9.974	0.294	1175	1195	1379	2040	694	324	1920	1187	1681	1403	1553	1725

Table 2: Raw crack growth data

Crack Growth Data:

Legend:

Link-up observed

Crack growth too small to measure

Crack length measured from right edge of riveted joint in inches

Number of Cycles	12		13		14		15		16		17		18		19	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
1																
20000																
40000																
57399																
57402	-8.6815	-7.7810	-7.7965	-7.2650	-6.8110	-6.1690	-5.8575	-5.1540	-4.7880	-4.2300	-3.7555	-3.2985	-2.7110	-2.3175	-1.3235	
59000	-8.6930	-7.7965	-7.2480	-7.2480	-6.8300	-6.1375	-5.8830	-5.1240	-4.8080	-4.2145	-3.7680	-3.2885	-2.7230	-2.3020	-1.3155	
61000	-8.7115	-7.8185	-7.2080	-7.2080	-6.9040	-5.9600	-6.0605	-4.9375	-4.9375	-4.1525	-3.8085	-3.2615	-2.7485	-2.2760	-1.3090	
61100	-8.7125	-7.8290	-7.1870	-7.1870	-6.9675	-5.9530	-6.0750	-4.9375	-4.9375	-4.0985	-3.8280	-3.2490	-2.7505	-2.2695	-1.3040	
61160		-7.8500				-5.9360	-6.0790					-3.1790	-2.7665	-2.2600	-1.6680	-1.2990
61162						-5.9335						-3.1695	-2.7680			
61163												-3.1575				
61164												-3.1505				
61170		-8.3670				-5.9255						-3.1090	-2.7830			
61173												-3.0725	-2.8045			
61176		-8.3510										-3.0355	-2.8245	-2.2365	-1.6770	-1.2905

1. Scope

This report details the test results of specimen MSD-AL-003 tested at Carleton University. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. Mueller, R.P.G., An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3, Delft University of Technology, Delft, The Netherlands, 1995

3. Test Set-up

Specimen Properties

- Material: 2024-T3

Dimensional Properties

- Width: 20"
- Thickness: 0.040"
- Drawing: D1-MSD-AL-003-40 (see Appendix)

Joint Properties

- Rivet Type: NAS1097-AD-4-4
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets installed on specimen to prevent edge cracking

Strain Gauges

- Number Installed: 26
- Location of Banks: Refer to Figure A. 1

Testing Characteristics

- Load Frequency: 4Hz
- Peak Load: 48.5 kN
- Remote Stress: 13.6 ksi
- R: 0.03
- Controller Type: MTS 442
- Hydraulic Actuator Type: MTS 244.21

4. Test Goals

Specimen MSD-AL-003 is the first of 2 aluminum reference specimens in a collaborative between Carleton University and the National Research Council of Canada into the MSD behaviour of GLARE riveted lap joints. As required by the needs of this collaboration, the goals for testing specimen MSD-AL-003 are:

1. Produce MSD under a known, repeatable remote stress distribution
2. Obtain crack nucleation and growth data for 2024-T3
3. Validate the effectiveness of the zero-load transfer rivets for an untested joint configuration

5. Results

5.1 Stress Distribution

20 strain gauges were used to obtain a remote stress distribution along the width of the test specimen (gauges 1-20 in Figure A. 1). These gauges were to be located 1 inch above the critical rivet row; however, they were installed 0.5 inch to high. This does not affect the remote stress distribution results, but in order to facilitate crack detection and allow the comparison of secondary bending based on a consistent strain gauge location, 6 more strain gauges were installed (gauges 21-26 in Figure A. 1).

Figure 5.1: Comparison of stress distribution in specimens MSD-AL-002 and MSD-AL-003

The remote stress distribution agreed well with that obtained with specimen MSD-AL-002 (Figure 5.1). Secondary bending stresses were significantly different in MSD-AL-003 compared to MSD-AL-002. This is a result of the use of NAS1097 rivets, which have a smaller countersunk rivet head diameter. Since the rivet head acts like a clamp, the smaller rivet head diameter increases the distance from the strain gauge to the edge of the rivet head, thus decreasing the bending moment (Figure 5.2). The stresses obtained in MSD-AL-003 also appear to be more uniform than for specimen MSD-AL-002. The high bending stress gradient in the rivet row direction causes any inaccuracies in strain gauge placement to be magnified. Since the bending stresses observed for MSD-AL-003 were much smaller than MSD-AL-002, this effect is minimized and reading appear more uniform.

Figure 5.2: Variation in moment arm at strain gauge for different rivet head diameters

5.2 Clamping Failure

The specimen failed at 341135 cycles due to the formation of an edge crack at the clamped edge of the specimen. Inspection of the failed clamped edge revealed a large amount of fretting damage, which was caused by the edge of the clamping plate (Figure 5.3). This edge had been radius cut during the manufacturing of the clamping plates; however, the transition from the flat plate surface to the radius cut was not perfectly smooth. This problem has been remedied for future tests by smoothing the transition in the clamping plates with a fine file.

Figure 5.3: Specimen failure due to fretting at clamped edge

Due to the large size of the specimen, it was decided that removing the damaged clamped edge and reinstalling the specimen to complete testing could be done. This resulted in an overall reduction in specimen length of 6 inches (an 11% reduction in specimen length). To accommodate the available travel in the test rig actuator, the specimen's mounting was also modified. Only 2 rows of bolts were used in either clamping plate, resulting in only a 3.2 inch reduction in specimen length between clamped edges (Figure 5.4). Testing was resumed, and the specimen failed after an additional 45974 cycles were applied.

Figure 5.4: Comparison of original specimen geometry (above) to modified geometry after failed clamped edge is removed

5.3 Crack Detection

Due to secondary bending, higher stresses exist at the faying surfaces of a riveted joint; thus cracks initiate at this surface have to grow through the sheet thickness. This through-thickness growth typically occurs while the crack is under the rivet head and cannot be detected visually; however this was not the case with MSD-AL-003. Such sub-surface cracks were detected beyond the rivet head by a depression they formed on the joint surface when loaded (Figure 5.5). Although these depressions could be seen visually by the shadow they cast on the joint surface, they proved difficult to photograph or measure.

Figure 5.5: Progression of crack from (a) first detection of depression, (b) growth of depression and plastic yielding of joint surface around depression, (c) through crack formation and growth

The time between detection of a depression and penetration of the joint surface by the crack was not consistent. Times varied greatly from less than 5000 cycles to more than 30000 cycles, and in some cases, through cracks did not form at depression locations. Regardless, this precursor to through-crack formation proved valuable in early crack detection.

5.4 Crack Initiation and Growth

5.4.1 Critical Rivet Row

Through-cracks were first detected at 290000 cycles on the bottom rivet row at rivet 52 (see Figure A. 1 for rivet numbering scheme). Several other cracks nucleated and grew along the bottom rivet row, generating MSD and causing failure at 387109 cycles (Figure 5.6). Limited cracking was also observed in the top rivet row; however the growth and nucleation of these cracks were limited due to the presence of the cracks in the bottom rivet row.

Figure 5.6: Crack growth curves for bottom row of MSD-AL-003

Cracking and the formation of MSD typically occurs at the top rivet row (countersunk sheet) rather than the bottom rivet row (non-countersunk sheet). The machined countersink creates a larger stress concentration in the countersunk sheet. Additionally, better hole filling is achieved on the shop head side of the riveted joint, thus increasing the amount of compressive residual stresses in the non-countersunk sheet. Both these factors tend to make the top rivet row more critical for fatigue. MSD-AL-003 did not agree with this generality. Although limited cracking did occur in the top rivet row, the bottom row was critical.

Mueller [1] found that countersunk joints often cracked in the bottom rivet row when the manufactured rivet head diameter was smaller than the final shop head diameter, and the manufactured head protruded above the sheet in the joint. Both of these phenomena together produce a permanent curvature in the joint. This curvature expands the rivet hole in the non-countersunk sheet, reducing the residual tensile stresses due to rivet squeezing, and increases the bending stress at the bottom row, resulting in the bottom row being more fatigue critical.

Both of these phenomena existed in MSD-AL-003. The NAS1097AD5-5 rivets used in the specimen have a shallow countersink depth; thus the machined rivet head diameter is small. A standard shop-head-diameter-to-shank-diameter ratio of 1.5 was used during riveting, causing the shop head to be around 4% larger than the machined head. As well, the rivets were proud of the joint surface; however they were under the acceptable height of 0.010". These factors combined produced a visible curvature in the joint that is likely responsible for the bottom row being critical in the joint.

5.4.2 Multiple Crack Initiation Sites

Several rivets exhibited multiple crack initiation sites on a single side of the rivet (Figure 5.7). In such cases, either the cracks grew into one another, or one crack became dominant and the other crack was arrested.

Figure 5.7: Multiple cracks formed at rivets

6. Conclusions and Recommendations

All testing goals were met by MSD-AL-003. A repeatable stress distribution and MSD was achieved, crack nucleation and growth data was obtained, and the zero-load transfer rivets were again successful in preventing edge cracking. Cracking occurred primarily on the bottom rivet row, but can be attributed to the rivet squeeze imperfection as detailed by Muller [1].

To minimize the causes for cracking in the bottom rivet row in future specimens, care should be taken to minimize how much the countersunk rivet head protrudes above the joint surface. Visual inspection for joint curvature should be performed and recorded to aid in interpreting future testing results. Specimen MSD-AL-004 was manufactured prior this test, so changes can not be implemented in its manufacturing. Inspection of this manufactured specimen indicates a curvature is present in the joint. As such, cracking in the bottom rivet may occur in this specimen.

Appendix A: Drawings and Supplementary Pictures

Figure A. 1: Strain gauge placement for specimen MSD-AL-003

Figure A. 2: Rivet numbering scheme

Figure A. 3: MTS controller and test rig setup

Figure A. 4: Variation in remote stress along specimen width

Figure A. 5: Crack growth curves for bottom rivet row of MSD-AL-003

Figure A. 6: Crack growth curves for top rivet row of MSD-AL-003

CYCLES	
367000
381000
385000
386605
386627
386948
387000

Figure A. 7: Crack propagation and linkup in bottom rivet row

Appendix B: Manufacturing Documentation

Specimen Number: MSD-AL-003	Drawing Numbers: D1-MSD-AL-003
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Joint Configuration:

Rivet Type: NAS1097-AD-4-5	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/machine csk
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: 2024-T3	Sheet Thickness: 0.040"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	15-May-02	Micheal, Calvin
Drill mounting bolt holes	09-Jun-02	Alex
Center drill/drill/debur rivet holes	17-Jun-02	Micheal, Calvin
Countersink holes	18-Jul-02	Micheal, Calvin
Rivet installation	22-Jul-02	Flight Research Lab

Quality Control:

Measurements below are conducted on the critical rivet row and with an accuracy of $\pm 0.005"$, $0.001"$, and $0.001"$ from left to right respectively. Rivets numbered from left to right on critical rivet row.

Csk max dia. (inches)				Shop head max dia. (inches)				Shop head depth (inches)			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
1	0.195	11	0.190	1	0.187	11	0.186	1	0.068	11	0.075
2	0.195	12	0.195	2	0.187	12	0.182	2	0.074	12	0.076
3	0.190	13	0.190	3	0.187	13	0.189	3	0.074	13	0.078
4	0.190	14	0.195	4	0.189	14	0.187	4	0.073	14	0.076
5	0.195	15	0.185	5	0.189	15	0.186	5	0.075	15	0.075
6	0.195	16	0.190	6	0.188	16	0.184	6	0.070	16	0.075
7	0.190	17	0.190	7	0.189	17	0.186	7	0.073	17	0.075
8	0.190	18	0.190	8	0.186	18	0.187	8	0.075	18	0.075
9	0.190	19	0.190	9	0.186	19	0.188	9	0.077	19	0.078
10	0.190	20	0.190	10	0.188	20	0.188	10	0.076	20	0.074
Nom.	0.193	Avg.	0.191	Nom.	0.188	Avg.	0.187	Nom.	0.063	Avg.	0.075

Comments:

During drilling, portion of milling machine fell and gouged the non-csk sheet. The gouge is located away from any critical crack initiation locations.

Strain gauges were mistaken installed 0.5" too far from the critical rivet row. 6 extra strain gauges were installed the proper distance from the rivet row in order to facilitate comparison of results between past and future specimens not possible with the improperly installed gauges

Appendix C: Raw Data Tables

Link-Up Data:

Link-up between rivets (cycles)									
1 & 2	2 & 3	3 & 4	4 & 5	5 & 6	6 & 7	7 & 8	8 & 9	9 & 10	10 & 11
11 & 12	12 & 13	13 & 14	14 & 15	15 & 16	16 & 17	17 & 18	18 & 19	19 & 20	

Link-up between rivets (cycles)									
41 & 42	42 & 43	43 & 44	44 & 45	45 & 46	46 & 47	47 & 48	48 & 49	49 & 50	50 & 51
									387010
51 & 52	52 & 53	53 & 54	54 & 55	55 & 56	56 & 57	57 & 58	58 & 59	59 & 60	
386627	380109		386611	386947	386999	387018			

	Max	Average
Max Load:	10.19 V (50.9 kN)	9.73 V (48.6 kN)
Min Load:	0.25 V (1.3 kN)	0.29 V (1.4 kN)

Appendix C

Legend
Link-up
Dimming visible
Crack length change < 0.05mm

Crack Growth Data: Bottom Row

Appendix C

1. Scope

This report details the test results of specimen MSD-AL-004 tested at Carleton University. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. C. Rans, *Testing summary report for MSD-AL-003*, Report No. R-MSD-AL-003, Aug 23, 2002
2. Müller, R.P.G., *An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3*, Delft University of Technology, Delft, The Netherlands, 1995
3. Eastaugh, G.F., *Multiple site fatigue damage in fuselage skin splices*, Carleton University, Ottawa, Ontario, 1993

3. Test Setup

Specimen Properties

- Material: 2024-T3

Dimensional Properties

- Width: 20"
- Thickness: 0.040"
- Drawing: MSD-001

Joint Properties

- Rivet Type: NAS1097-AD-4-4
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets installed on specimen to prevent edge cracking

Strain Gauges

- Number Installed: 20
- Location of Banks: Refer to Figure A. 1

Testing Characteristics

- Load Frequency: 4Hz
- Peak Load: 48.5 kN
- Remote Stress: 13.6 ksi
- R: 0.03

Testing Equipment

- Controller Type: MTS 442 (Figure A. 3)
- Hydraulic Actuator Type: MTS 244.21
- Test rig calibration date: Oct. 1, 2001
- Travelling Microscope: Refer to Figure A. 4a
- Data acquisition system: INET 200 controller card, 2 INET 100 HC boxes (Figure A. 4b)

4. Testing Goals

Specimen MSD-AL-004 is the second of 2 aluminum reference specimens in a collaborative project between Carleton University and the National Research Council of Canada into the MSD behaviour of GLARE riveted lap joints. As required by the needs of this collaboration, the goals for testing specimen MSD-AL-004 are:

1. Produce MSD under a known, repeatable remote stress distribution
2. Obtain crack nucleation and growth data for 2024-T3

In addition, the following goal also pertains to this test.

1. Integrate new Instronet data acquisition system into test setup and evaluate its performance compared to the Measurements Group P-3500 portable strain indicator and SB-10 switch and balance units used in previous tests.

5. Results

5.1 Stress Distribution

The experimental test set-up for this specimen included an Instronet data acquisition system to help reduce the time required in recording strain gauge readings. This system can record readings from 16 strain gauges simultaneously, eliminating the gauge-by-gauge recording necessary with the Measurements Group P-3500 portable strain indicator and SB-10 switch and balance unit used in previous tests. To accommodate the 16 gauge capacity of the Instronet data acquisition system, measurements from 4 strain gauges installed on MSD-AL-004 could not be made throughout the test. As a result, readings from gauges 1, 10, 11, and 20 were not made throughout the test (Figure A. 1).

The strain readings obtained from the Instronet system were observed to drift within a ± 30 microstrain range. Multi-channel data acquisition systems are more susceptible to noise; thus the Instronet data acquisition system was expected to have a larger drift than the portable strain indicator and switch and balance unit used in previous tests. This drift was found to have a negligible effect on the remote stress distribution; however it did reduce the uniformity of the secondary bending ratio across the panel width (see Figure 5.1). This non-uniformity is exaggerated by the small bending ratios expected at the strain gauge locations.

To confirm that the variances between strain readings in MSD-AL-003 and MSD-AL-004 were a result of the different data acquisition systems, strain readings were taken with the Measurements Group P-3500 portable strain indicator and SB-10 switch and balance unit at the 4 strain gauges not connected to the Instronet system (gauges 1, 10, 11, and 20). Readings at these gauges (not plotted in Figure 5.1) agreed within 0.5%, indicating that the observed variances were a result of the drift in the Instronet data acquisition system.

Figure 5.1: Comparison of stress distribution in specimens MSD-AL-003 and MSD-AL-004 (readings for MSD-AL-004 made with Instrunet data acquisition system)

Overall, the Instrunet data acquisition system will provide acceptable accuracy for monitoring the change in remote stress distribution within MSD specimens and for ensuring a consistent remote stress distribution is obtained between different MSD specimens.

5.2 Crack Initiation and Growth

Cracking was first detected after 110000 cycles at rivet 16 and 18 (see Figure A. 2 for rivet numbering scheme). At this time, both cracks were less than 0.03 in long (see Figure 5.2). No cracking occurred in the bottom rivet row; however most cracks and MSD formation/linkup was limited to the right half of the specimen (rivets 9-19).

Detection of subsurface cracking proved more difficult in MSD-AL-004 than was found in MSD-AL-003. The presence of surface scratches and scuffs from the countersinking and riveting processes made the detection of region of plastic deformation created by a subsurface crack difficult. Greater success was obtained with MSD-AL-003 since cracking occurred primarily on the bottom row, where the sheet was relatively free of scratches and scuffs from manufacturing. Despite this, careful crack inspections proved successful in detecting most cracks before they exceeded a length of 0.03 in.

Figure 5.2: First detected cracks on MSD-AL-004. Detected at 110000 cycles.

Crack growth curves for MSD-AL-004 are plotted in Figure A. 5. The period of crack growth lasted 68699 cycles from first crack detection to unstable fracture of the panel.

The growth rates of the lead cracks in specimens MSD-AL-004 and MSD-AL-003 are plotted in Figure 5.3. Since 2 cracks were present in MSD-AL-004 at the time of first detection, the growth rates for both cracks are plotted. A jog in the crack growth rate is clearly visible for the lead crack in MSD-AL-003 at 50000 cycles after crack detection. This correlates with the nucleation of another crack on the opposite side of the rivet head. Similar jogs are less clearly seen in MSD-AL-004 for cracks 16R and 18R at 60000 and 36000 cycles respectively.

Figure 5.3: Crack growth rates of lead cracks in MSD-AL-003 and MSD-AL-004

5.2.1 Location of Cracking

Cracking was limited to the right half of the specimen (rivets 9-19), although one crack did form at rivet number 1, but did not grow. This trend has also been observed for specimens MSD-AL-001, MSD-AL-002, and MSD-AL-003. Strain surveys performed on all specimens have not indicated any significant imbalance in the system. Although cracking has been limited to a single side of the specimen, full MDS has been produced and failures have been due to unstable crack growth, and not the formation of an edge crack.

One hypothesis to explain why cracking has been limited to the right half of the specimen relates to the specimen manufacturing procedure. During manufacturing, one edge of the aluminum panels is consistently used as a reference. All mounting and rivet holes are drilled relative to this edge. As a result, if the width of the aluminum panels is above or below its nominal value, the specimen mounting bolt pattern will not be centred on the specimen. Since the grips are joined to the test rig through a pin, the specimen would have a non-uniform stress distribution to balance rotational moments around the pin, causing the specimen to favour cracking on one side (Figure 5.4).

Figure 5.4: Simplified representation of change in panel stress distribution due to off-nominal panel width

The widths of the aluminum panels were measured to investigate this hypothesis. Specimens MSD-AL-003 and MSD-AL-004 had widths of 20.023" and 20.014" respectively (nominally 20.00"). Isolation of cracking to the right side of the panel could be a result of this higher than nominal panel width. Specimen MSD-AL-002 was found to be slightly narrower than nominal; however cracking on the right side of this specimen was attributed to variations in countersink depth along the width of the specimen (noted during fabrication and corrected in subsequent specimens).

5.2.2 Specimen Rotation during Testing

The MSD specimen test setup uses a pin joint to attach the specimen to the test rig. This pin joint allows the specimen to self-align as load is applied, ensuring a uniform stress distribution across the panel. However, the pin joint allows the specimen to rotate as the specimen cracks, causing a redistribution of stress that does not occur in actual airframes. This rotation poses less of a problem in the IAR MSD specimen design [3] due to the presence of the edge doublers and the smaller width of the specimen.

Rotation of the specimen during testing could contribute to the isolation of cracking to one half of the panel. The presence of a crack reduces the stiffness of the joint locally around the crack. This imbalance in stiffness causes the pinned joint to rotate, reducing the load on the uncracked half of the specimen. Müller included stops in his test setup to prevent the rotation of the specimen during testing [2]. The stops were identified by Müller as being necessary for residual strength testing edge crack investigations; however it is unknown if the stops were used for all tests. These stops were adjustable so that the alignment problems inherent to a fully-fixed grip were eliminated. Improper adjustment of the grips, however, could potentially introduce an imbalance. Müller was able to achieve MSD across the entire width of his specimen using this setup.

6. Additional Notes

Inspection of the MSD specimen mounting assembly was conducted. The setup has been subjected to more than 1000000 cycles. No evidence of cracking was observed; however some wear was identified. In one set of the clamping plates, 3 distinct scrape marks were observed inside the 1.5 in diameter pin hole. These marks match up with similar ones found on the clevis and are a result of debris getting caught between the pin and clevis during pin removal/insertion. Better care should be taken to ensure that the pin and hole surfaces are clean and well lubricated before pin insertion/removal. Additionally some rust formation was observed. This was removed with fine sand paper. To prevent further rust formation, the surfaces of the clamping plates will be coated with WD-40 and gloves will be used when handling the plates.

7. Conclusions

Valuable crack initiation and growth data has been obtained with MSD-AL-004. Unlike MSD-AL-003, MSD formation occurred in the top rivet row; however cracking was still limited to one half of the specimen.

Several factors that could be contributing to the localized cracking in the specimens have been identified. The larger width and reduced stiffness of this MSD specimen design could amplify the effects of dimensional tolerances in specimen manufacturing and specimen rotation due to a pin joined specimen mounting over what has been previously experienced with IAR MSD specimen design. It is recommended that future specimens be milled to a closer tolerance width to minimize these effects. The addition of stops is not recommended due to the potential for introducing imbalances associated with fixed grips into the test specimen. Furthermore, it is recommended that 1 additional aluminum specimen be tested to allow comparison of results from these modifications.

Appendix A: Drawings and Supplementary Pictures

Figure A. 1: Strain gauge placement for specimen MSD-AL-004

Figure A. 2: Rivet numbering scheme

Figure A. 3: MTS controller and test rig setup

Figure A. 4: Test equipment. (a) Travelling microscope (b) Instrunet data acquisition system

Figure A. 5: Crack growth curves for top rivet row of MSD-AL-004

Figure A. 6: Crack growth and linkup between rivets 16 and 17

Figure A. 7: Crack growth and linkup between rivets 17 and 18

Figure A. 8: Crack growth and linkup between rivets 18 and 19

Appendix B: Manufacturing Documentation

Specimen Number: MSD-AL-004-40	Drawing Numbers: D1-MSD-AL-004-40
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Joint Configuration:

Rivet Type: NAS1097-AD-4-5	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/machine csk
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: 2024-T3	Sheet Thickness: 0.040"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	15-May-02	Micheal, Calvin
Drill mounting bolt holes	09-Jun-02	Alex
Center drill/drill/debur rivet holes	17-Jun-02	Micheal, Calvin
Countersink holes	18-Jul-02	Micheal, Calvin
Rivet installation	22-Jul-02	Flight Research Lab

Quality Control:

Measurements below are conducted on the critical rivet row and with an accuracy of $\pm 0.005"$, $0.001"$, and $0.001"$ from left to right respectively. Rivets numbered from left to right on critical rivet row.

Csk max dia. (inches)				Shop head max dia. (inches)				Shop head depth (inches)			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
1	0.185	11	0.190	1	0.183	11	0.185	1	0.075	11	0.077
2	0.185	12	0.185	2	0.187	12	0.197	2	0.076	12	0.076
3	0.190	13	0.190	3	0.185	13	0.187	3	0.073	13	0.072
4	0.185	14	0.185	4	0.184	14	0.186	4	0.078	14	0.072
5	0.190	15	0.190	5	0.186	15	0.190	5	0.075	15	0.074
6	0.180	16	0.185	6	0.186	16	0.183	6	0.075	16	0.075
7	0.185	17	0.185	7	0.186	17	0.185	7	0.076	17	0.071
8	0.190	18	0.190	8	0.185	18	0.187	8	0.077	18	0.074
9	0.185	19	0.190	9	0.187	19	0.188	9	0.075	19	0.073
10	0.185	20	0.190	10	0.187	20	0.188	10	0.072	20	0.071
Nom.	0.193	Avg.	0.187	Nom.	0.188	Avg.	0.186	Nom.	0.063	Avg.	0.074

Comments:

Appendix C: Raw Data Tables

Table C. 1: Strain gauge data for MSD-AL-004

Number of Cycles		Strain Gauge Reading (micro strain)																		
1	2	3	4	5	6	7	8	9	10*	11*	12	13	14	15	16	17	18	19	20*	
1	1366	1256	1275	1235	1254	1307	1338	1332	1364	1226	1279	1298	1306	1296	1271	1220	1309	1263	1259	
1000		1273	1273	1255	1274	1326	1344	1321	1351		1260	1303	1320	1287	1287	1223	1307	1280		
2000		1263	1265	1262	1278	1327	1329	1328	1350		1268	1307	1303	1309	1284	1246	1310	1272		
3000		1259	1263	1259	1258	1319	1328	1327	1350		1251	1279	1312	1307	1290	1245	1307	1267		
4000		1247	1273	1241	1258	1320	1327	1317	1341		1268	1289	1306	1301	1287	1241	1307	1269		
5000		1265	1259	1243	1263	1317	1336	1321	1351		1266	1295	1307	1297	1283	1222	1320	1269		
6000		1259	1271	1252	1254	1327	1337	1332	1346		1269	1286	1311	1300	1291	1229	1324	1289		
7000		1258	1260	1264	1252	1320	1334	1338	1358		1264	1297	1303	1292	1281	1236	1311	1276		
8000		1267	1273	1258	1264	1326	1325	1327	1343		1264	1296	1312	1303	1289	1223	1322	1274		
9000		1262	1267	1258	1269	1314	1329	1340	1359		1263	1290	1315	1298	1285	1220	1318	1277		
10000		1265	1262	1255	1269	1301	1317	1343	1350		1270	1285	1309	1301	1293	1219	1323	1278		
11000		1263	1271	1260	1272	1315	1332	1348	1355		1260	1300	1312	1311	1278	1236	1318	1273		
12000		1250	1274	1259	1274	1331	1344	1340	1367		1276	1291	1324	1305	1282	1245	1335	1281		
13000		1260	1288	1262	1270	1320	1346	1355	1366		1262	1315	1322	1309	1286	1256	1336	1290		
14000		1271	1285	1274	1264	1314	1340	1339	1371		1266	1311	1311	1296	1287	1241	1330	1285		
15000		1271	1263	1270	1276	1323	1346	1351	1373		1274	1296	1315	1302	1292	1243	1333	1280		
16000		1269	1282	1263	1272	1317	1344	1351	1379		1280	1307	1330	1294	1302	1226	1328	1288		
17000		1264	1280	1273	1275	1326	1351	1354	1381		1268	1304	1312	1292	1287	1232	1339	1284		
18000		1269	1286	1264	1282	1323	1356	1361	1404		1270	1312	1309	1289	1302	1233	1340	1298		
19000		1270	1288	1268	1272	1331	1351	1369	1399		1274	1319	1314	1296	1297	1236	1339	1309		
20000		1263	1288	1268	1271	1339	1348	1387	1416		1275	1310	1319	1298	1294	1241	1338	1299		
21000		1273	1288	1273	1276	1344	1358	1378	1420		1272	1299	1332	1307	1286	1247	1359	1317		
22000		1269	1284	1278	1276	1338	1358	1393	1434		1275	1305	1335	1295	1297	1241	1357	1328		
23000		1261	1285	1276	1286	1342	1353	1423	1453		1268	1309	1321	1305	1295	1253	1365	1345		
24000		1265	1285	1276	1292	1324	1365	1410	1482		1268	1307	1322	1307	1290	1246	1364	1349		
25000		1262	1273	1265	1287	1346	1376	1415	1490		1270	1316	1327	1309	1303	1250	1388	1371		
26000		1270	1283	1291	1281	1344	1365	1443	1519		1258	1308	1322	1308	1305	1272	1389	1399		
27000		1250	1281	1287	1288	1354	1381	1466	1569		1268	1301	1338	1309	1307	1262	1411	1483		
28000		1258	1274	1291	1287	1345	1382	1465	1602		1262	1306	1335	1312	1304	1260	1430	1471		
29000		1254	1288	1284	1288	1356	1382	1471	1615		1261	1307	1326	1321	1309	1265	1431	1494		
30000		1258	1275	1283	1286	1354	1393	1491	1635		1263	1308	1340	1305	1319	1263	1446	1503		
31000		1256	1269	1296	1288	1373	1404	1551	1692		1258	1308	1328	1320	1318	1278	1484	1577		
32000		1252	1299	1283	1284	1380	1394	1581	1723		1230	1299	1330	1304	1311	1313	1507	1593		
33000		1234	1308	1284	1294	1379	1411	1621	1783		1245	1308	1345	1317	1322	1323	1543	1619		
34000		1241	1290	1289	1299	1392	1418	1622	1785		1233	1308	1331	1313	1324	1317	1552	1599		
35000		1243	1284	1291	1301	1394	1437	1634	1776		1236	1313	1337	1321	1343	1324	1593	1580		
36000		1235	1287	1300	1296	1402	1446	1697	1899		1233	1302	1343	1314	1349	1342	1648	1500		
37000		1229	1287	1298	1297	1417	1458	1789	1572		1223	1300	1345	1365	1379	1701	1350	1350		
38000		1222	1295	1304	1321	1441	1509	1854	1424		1229	1290	1337	1337	1381	1394	1794	1177		
39000		1218	1270	1302	1339	1466	1540	2041	1100		1211	1292	1356	1336	1412	1435	1970	761		
40000		1200	1280	1309	1360	1496	1591	2195	845		1213	1299	1371	1337	1435	1485	2117	280		
41000		1188	1277	1319	1354	1525	1643	2349	839		1191	1301	1368	1367	1463	1539	2250	207		
42000		1180	1269	1332	1382	1557	1691	2433	851		1181	1277	1370	1374	1498	1575	2347	176		
43000		1167	1264	1343	1392	1627	1785	2638	858		1158	1275	1389	1410	1547	1662	2541	111		
44000		1141	1266	1352	1415	1651	1832	2727	797		1142	1287	1395	1419	1595	1704	2639	39		
45000																				

Measured with strain indicator boxes

*Measured with strain indicator boxes

Table C. 2a: Crack growth data for MSD-AL-004

Legend:		Link-up
	Dimple visible
	Crack length change 0.005in

Number of Cycles	Crack Length Measurement									
	Crack length measured from left edge of riveted joint in inches									
	L	R	L	R	L	R	L	R	L	R
11000										
119000										
126600										
131500										
136500										
146000										
156000										
160000										
165000										
170000										
172500										
174000										
176500										
177000										
177500										
178050										
178150										
178261										
178382										
178387										
178388										
178418										
178479										
178598										
178639										
178660										
178671										
178672										
178683										
178686										
178687										
178698										
178699										

Table C.2b: Crack growth data for MSD-AL-004 (cont.)

Number of Cycles	11		12		13		14		15		16		17		18		19		20	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
11000											15.6235				17.6210					
119000			11.6130								15.6290				17.6545					
126000			11.6210								15.6385				17.6805			18.6430		
131500	10.5920										15.6475				17.6975			18.6575		
136500	10.6010		11.6300								15.6525				17.7145			18.6730		
146000	10.6225		11.6365								15.6685				17.7475			18.7045		
156000	10.6415		11.6540								15.6925				17.7935			18.7405		
160000	10.6485		11.6565								15.7045				17.8185			18.7565		
165000	10.6560		11.6670								15.7195				17.8525			18.7810		
170000	10.6670		11.6820								15.7395				17.8985			18.8155		
172500	10.6790		11.6910								15.7590				17.9240			18.8295		
174000	10.6815		11.3735								15.3470				17.9450			18.8440		
176500	10.6745		11.3590								15.3305				17.9940			18.8790		
177000			11.3500								15.3195				18.0170					
177500			11.6995								15.7850				18.0410			18.2120		
178050											15.7915				18.0700			18.1815		
178150	10.6845		11.7060								15.7915				18.1100			18.9285		
178261											15.7915				18.1555			18.1000		
178382											15.7915				18.1690			18.9395		
178387											15.7915				18.1740			18.0950		
178388											15.7915				18.1845			18.0845		
178418											15.7915				18.1965			18.0805		
178479											15.7915				18.2000			18.0700		
178598											15.7915				18.2085			18.0630		
178639											15.7915				18.2120			18.0575		
178660											15.7915				18.2120			18.0575		
178671											15.7915				18.2120			18.0575		
178672											15.7915				18.2120			18.0575		
178683											15.7915				18.2120			18.0575		
178686											15.7915				18.2120			18.0575		
178687	10.7025		11.3550								15.7915				18.2120			18.0575		
178698			11.3420								15.7915				18.2120			18.0575		
178699											15.7915				18.2120			18.0575		

1. Scope

This report details the test results of specimen MSD-GL-001 tested at Carleton University. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. C. Rans, *Testing summary report for MSD-AL-003*, Report No. R-MSD-AL-003, Aug 23, 2002
2. C. Rans, *Testing summary report for MSD-AL-004*, Report No. R-MSD-AL-004, Oct 7, 2002
3. Müller, R.P.G., *An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3*, Delft University of Technology, Delft, The Netherlands, 1995
4. Eastaugh, G.F., *Multiple site fatigue damage in fuselage skin splices*, Carleton University, Ottawa, Ontario, 1993
5. C. Rans, *Testing summary report for MSD-GL-002*, Report No. R-MSD-GL-002, May 6, 2003

3. Test Setup

Specimen Properties

- Material: GLARE3-2/1

Dimensional Properties

- Width: 20"
- Thickness: 0.034"
- Drawing: MSD-001

Joint Properties

- Rivet Type: NAS1097-AD-4-4
- Countersink Type: Machined
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets installed on specimen to prevent edge cracking

Strain Gauges

- Number Installed: 15
- Location of Banks: Refer to Figure A. 1

Testing Characteristics

- Load Frequency: 4Hz
- Peak Load: 48.5 kN
- R: 0.03

Testing Equipment

- Controller Type: MTS 407 (Figure A. 3)
- Hydraulic Actuator Type: MTS 244.21
- Test rig calibration date: Jan. 31, 2003
- Travelling Microscope: Refer to Figure A. 4a
- Data acquisition system: INET 200 controller card, 2 INET 100 HC boxes (Figure A. 4b)

4. Testing Goals

Specimen MSD-GL-001 is the first of four GLARE splices being tested in collaboration with the National Research Council of Canada. For this purpose, the goals for this specimen are:

1. Produce MSD under the same running load of 544 lbf/in applied to the two aluminum reference specimens MSD-AL-003 and MSD-AL-004
2. Obtain visible crack nucleation and growth data for GLARE3-2/1
3. Observe the fatigue cracking behaviour of GLARE3-2/1, making qualitative observations of the presence of subsurface cracks, and documenting major differences in the behaviour of GLARE3-2/1 compared to 2024-T3

In addition, the following goal also pertains to this specimen.

1. Evaluate if imposing a tighter tolerance on the specimen width is effective at producing initial cracking in the centre of the specimen [2].

5. Results

5.1 Stress Distribution

5.1.1 Strain Gauge Difficulties

Several difficulties were encountered with strain gauges throughout testing of MSD-GL-001. During strain gauge installation, several strain gauges were not adhering to the specimen. Such gauges were removed, and replaced; however adhesion problems persisted at strain gauge location 3 (Figure A. 1). As a result, this gauge location was left empty.

During testing, strain gauge 13 generated inconsistent readings and did not zero correctly upon removal of load from the specimen. Strain gauge 3 experienced similar inconsistencies after 380000 cycles had been applied to the specimen. Due to the inability of these gauges to zero upon load removal, it is concluded that the irregular strain readings were due to problems with the gauge rather than anomalies such as cracks or delaminations in the specimen.

5.1.2 Experimental Values

Figure 1 shows the experimental stress distribution across the specimen width. The theoretical stress values were obtained using a running load of 544 lbf/in and neglecting secondary bending. Secondary bending as well as the ± 30 microstrain accuracy of the strain data acquisition system account for the discrepancies between the experimental and theoretical values. The 2024-T3 specimens MSD-AL-003 and MSD-AL-004 (0.040" TH) experienced a 13.6 ksi nominal stress under the same running load. The higher stresses observed in GLARE3-2/1 were expected due to its smaller overall thickness (0.034" TH) and the lower stiffness of the prepreg layers.

Figure 1: Stress distribution across MSD-GL-001 width. Theoretical values based on running load of 544 lbf/in (neglecting secondary bending in splice)

5.2 Crack initiation and Growth

The laminated nature of GLARE cause cracks to initiate and grow in the individual aluminum layers. As a result, cracks could potentially nucleate and grow in aluminum layers that are not directly visible in the joint. Early on in the test program, it was decided that the expertise and equipment necessary for performing non-destructive inspections (NDI) of the MSD panels to find such cracks was not available at Carleton, and it was not feasible to suspend testing and transport the specimen for regular NDI at other facilities. Thus crack initiation and growth data was to be collected for visually detectable cracks.

First evidence of cracking occurred at 90000 cycles at the bottom rivet row on the back side of the panel. Although a crack was not visible, a small depression in the sheet material was observed. These depressions resembled similar ones observed in MSD-AL-003 [1], which signified the presence of a sub surface crack that had not grown through the entire sheet thickness (Figure 2). Growth and link-up of these depressions were observed in MSD-GL-001, indicating that they were formed due to the initiation and growth of crack in the non-visible aluminum layer at the faying surface of the joint.

Figure 2: Plastic deformation of joint surface forming a depression due to (a) presence of crack in faying aluminum layer of GLARE3-2/1 specimen MSD-GL-001; (b) presence of subsurface crack in 2024-T3 specimen MSD-AL-003.

Qualitative crack growth lives for the hidden cracks were obtained by observing the formation and link-up of the surface depressions (Figure A. 6). Initiation and link-up followed similar trends as observed in the 2024-T3 specimens MSD-AL-003 and MSD-AL-004. Growth rates were not obtainable, as the tips of the depressions were not easily deciphered through the travelling microscope. As the depressions grew, zones of plastic deformation formed. Figure 3 shows that these zones were visible even when the specimen was unloaded.

Figure 3: Zones of plastic deformation, created by cracks in the faying aluminum layer of MSD-GL-001, visible in the unloaded condition.

Visual cracks did not form at the lower outer layer along the bottom rivet row over the duration of the test; however a single visible crack did form at rivet number 2 on upper outer layer of the specimen. Signs of depressions in the top rivet row were not easily distinguishable from the intricate pillowing pattern surrounding the countersunk rivet heads. No signs of the plastic zone detected in the bottom rivet row were observed for the top rivet row.

5.3 Clamping Failures

During testing, failure of the specimen at the clamped edge occurred twice at 620000 cycles and 691050 cycles (Figure 4, Figure 5). A similar failure was experienced during the testing of MSD-AL-003, and was attributed to fretting damage along the clamped edge. As with MSD-AL-003 [1],

the failed end of MSD-GL-001 was sheared off, and new mounting bolt holes were drilled to permit continuation of the test. The clamping plates were also cleaned and polished to remove any debris that could promote fretting damage. Refer to [1] for details on changes to specimen length and mounting resulting from shearing off the failed clamped edge. Testing was resumed until the second clamping failure occurred.

Figure 4: Location and extent of clamping failure discovered in MSD-GL-001 at 620000 cycles

The second clamping failure was discovered at 691050 cycles, although audible fibre breakage was detected at 690000 cycles. Cracks in the second failure occurred along the first row of mounting bolt holes (which were unloaded after the specimen was modified due to the first clamping failure [1]), and along the original clamped edge (Figure 5). The presence of cracking along this edge indicates that microcracks were likely present along this edge at the time of the first clamping failure. Testing was halted after the second clamping failure.

Figure 5: Location and extent of 2nd clamping failure discovered in MSD-GL-001 at 691050 cycles

After the second clamping failure, means for preventing such failures in future specimens were reviewed. Consultations with Ron Gould at the National Research Council indicated that the highly polished surface on the clamping plates may promote fretting. By lightly sandblasting the clamping plates, slippage between the specimen and clamping plates could be prevented. In addition, the use of bonded tabs to locally thicken the specimen at the clamped edges was also discussed. As a result, the clamping plates were sandblasted with 220 grit aluminum oxide. The next specimen will be tested without tabs, and will be carefully monitored for evidence of cracking at the clamped edge. If cracking at the clamped edge is discovered, the specimen will be removed and tabs will be installed, and all future GLARE specimens will include bonded tabs.

5.4 Rivet Head Cracking

Inspection of the rivet heads after testing after testing was stopped revealed that rivets 2, 3, 4, and 5 all contained some plastic deformation (Figure 6). This deformation was later observed in MSD-GL-002 and was the precursor to rivet head cracking and complete fracture. Such deformation is believed to be caused by increased bending deformation resulting from cracks locally reducing the bending stiffness of the joint [5]. Since only 1 small crack was visible in MSD-GL-001, it is likely that several hidden cracks are present around rivets 2-5 in the upper faying layer of the joint. Disassembly of MSD-GL-001 could confirm the presence of such cracks.

Figure 6: Plastic deformation of rivet head 5 at 691050 cycles

6. Conclusions

From data collected and observations made during the testing of MSD-GL-001, the following conclusions can be made:

1. The presence of hidden cracks in the lower sheet along the bottom rivet row were visually detectable by the formation of a surface depression
2. Such surface depressions were not observed in the upper sheet along the top rivet row
3. Deformation of rivet heads along the top rivet row was observed within the lifetime of the GLARE specimen

In addition, the following recommendations are made:

1. The MSD specimen clamping plates should be sandblasted to prevent premature fretting failures at the clamps in future MSD specimens
2. Disassembly of MSD-GL-001 should be conducted to investigate the extent of cracking in the faying joint surfaces and correlate this to the observed surface depressions and rivet head deformations

Appendix A: Drawings and Supplementary Pictures

Figure A. 1: Strain gauge placement for specimen MSD-GL-001

Figure A. 2: Rivet numbering scheme

Figure A. 3: Test rig with installed specimen and travelling microscope (left). MTS 407 controller (right).

Figure A. 4: Test equipment. (a) Travelling microscope (b) Instrunet data acquisition system

Figure A. 5: Orientation of GLARE3-2/1 layers in MSD-GL-001

Figure A. 6: Initiation and growth lives of cracks in faying aluminum layer of MSD-GL-001. Cracking occurred along the bottom rivet row on the back side of the specimen.

Figure A. 7: Growth and linkup of hidden cracks between rivets 57, 56, and 55 in MSD-GL-001

Figure A. 8: Plastic zone due to hidden cracks in the bottom row of MSD-GL-001 (across entire specimen width).

Appendix B: Manufacturing Documentation

Specimen Number: MSD-GL-001	Drawing Numbers: MSD-001
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Joint Configuration:

Rivet Type: NAS1097-AD-4-4	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/machine csk
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: GLARE3-2/1	Sheet Thickness: 0.034"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	October 29, 2002	Calvin Rans
Mill Sheet Edges	October 29, 2002	Alex Proctor
Drill mounting bolt holes	November 8, 2002	Alex Proctor
Center drill/drill/debur rivet holes	November 11, 2002	Calvin Rans
Countersink holes	November 12, 2002	Calvin Rans
Rivet installation	November 18, 2002	FRL

Quality Control:

All measurements are conducted on the critical rivet row and with an accuracy of $\pm 0.002"$. Rivets numbered from left to right on critical rivet row.

Top Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
1	196	11	196	1	200	11	200	1	67	11	68
2	197	12	193	2	201	12	200	2	67	12	68
3	198	13	193	3	200	13	201	3	67	13	67
4	198	14	195	4	200	14	199	4	68	14	68
5	198	15	196	5	200	15	201	5	70	15	69
6	196	16	193	6	201	16	201	6	68	16	69
7	194	17	196	7	200	17	199	7	67	17	69
8	194	18	195	8	201	18	201	8	69	18	69
9	193	19	194	9	201	19	201	9	66	19	67
10	195	20	195	10	201	20	200	10	66	20	67
Nom.	193	Avg.	195.25	Nom.	188	Avg.	200.4	Nom.	63	Avg.	67.8

Bottom Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
41	199	51	201	41	200	51	199	41	70	51	67
42	200	52	202	42	200	52	200	42	71	52	68
43	199	53	202	43	201	53	200	43	70	53	69
44	201	54	202	44	199	54	199	44	68	54	68
45	202	55	195	45	199	55	200	45	70	55	70
46	201	56	198	46	201	56	200	46	68	56	69
47	203	57	195	47	198	57	199	47	69	57	69
48	200	58	196	48	199	58	202	48	71	58	67
49	200	59	195	49	200	59	202	49	69	59	68
50	201	60	196	50	201	60	201	50	68	60	68
Nom.	193	Avg.	199.4	Nom.	188	Avg.	200	Nom.	0.063	Avg.	68.85

Comments:

*During milling, delamination occurred on one side of the sheet. This is attributed to excessive wear of high speed bit caused during milling of non-delaminated side of sheet.
*Drilling of mounting bolt holes caused flaring of one hole. Hole was flattened in a press and enlarged with a reamer to facilitate installation.
*Rivet hole pattern is 0.127 degrees off square from reference edge.

Appendix C: Raw Data Tables

Table C. 1: Strain gauge data for MSD-AL-004

Number of Cycles	Strain Gauge Reading (micro strains)															
	1	2	3*	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1756	1737	-55	1780	1754	1758	1768	1790	1830	1846	1892	1844	1840	1813	1794	1804
10000	1755	1714	-65	1773	1747	1760	1775	1795	1811	1845	1889	1852	1500	1825	1819	1815
20000	1761	1719	-77	1774	1740	1761	1783	1798	1812	1833	1889	1844	1479	1821	1818	1819
30000	1753	1720	-66	1775	1751	1773	1787	1793	1811	1834	1898	1860	1474	1821	1812	1811
40000	1756	1722	-57	1777	1746	1770	1783	1790	1819	1841	1889	1849	1421	1826	1811	1827
50000	1761	1718	-66	1774	1743	1765	1777	1801	1808	1840	1883	1848	1424	1820	1813	1818
60000	1747	1730	-73	1777	1742	1777	1788	1810	1805	1805	1895	1826	1533	1830	1837	1817
70000	1751	1733	-73	1780	1749	1772	1797	1814	1798	1826	1891	1849	1470	1838	1831	1812
80000	1738	1731	-71	1778	1748	1770	1783	1822	1796	1825	1896	1836	1442	1827	1836	1840
90000	1741	1726	-71	1776	1736	1775	1790	1812	1805	1817	1891	1832	1408	1833	1824	1825
100000	1745	1710	-73	1786	1741	1778	1778	1820	1794	1822	1891	1860	1396	1839	1833	1824
110000	1737	1726	-74	1783	1745	1780	1769	1821	1797	1823	1889	1833	1378	1816	1826	1821
120000	1739	1722	-83	1797	1732	1779	1777	1805	1790	1808	1903	1829	1396	1812	1836	1817
130000	1728	1751	-83	1780	1749	1773	1785	1811	1787	1811	1895	1836	1365	1826	1823	1832
140000	1731	1737	-66	1790	1739	1769	1771	1808	1792	1831	1898	1848	1481	1825	1835	1813
150000	1741	1731	-66	1790	1767	1767	1790	1804	1791	1819	1883	1849	1417	1830	1825	1818
160000	1743	1720	-64	1784	1753	1768	1786	1807	1806	1823	1871	1842	1419	1832	1816	1830
170000	1742	1733	-64	1789	1743	1777	1778	1795	1794	1809	1886	1844	1390	1812	1831	1830
180000	1733	1740	-82	1781	1751	1772	1785	1805	1792	1811	1898	1851	1377	1827	1826	1821
190000	1732	1728	-71	1786	1756	1775	1787	1806	1792	1820	1908	1843	1370	1829	1827	1825
200000	1745	1717	-72	1791	1754	1781	1776	1812	1779	1822	1896	1858	1355	1824	1830	1818
210000	1743	1740	-73	1800	1741	1784	1784	1805	1796	1812	1916	1836	1350	1826	1828	1824
220000	1746	1730	-73	1781	1756	1763	1793	1805	1789	1826	1897	1839	1466	1831	1814	1816
230000	1734	1739	-74	1786	1745	1761	1786	1804	1798	1815	1898	1836	1428	1822	1831	1820
240000	1754	1729	-83	1782	1746	1760	1780	1805	1792	1834	1891	1848	1355	1828	1826	1817
250000	1755	1735	-82	1792	1739	1775	1772	1805	1790	1818	1906	1843	1363	1809	1837	1814
260000	1747	1728	-83	1793	1746	1769	1792	1796	1790	1822	1900	1854	1322	1832	1815	1822
270000	1754	1736	-77	1790	1753	1764	1775	1801	1786	1830	1888	1853	1301	1842	1820	1817
280000	1762	1731	-58	1799	1754	1770	1783	1807	1796	1819	1887	1843	1417	1823	1817	1805
290000	1750	1746	-56	1781	1752	1769	1785	1806	1786	1822	1886	1840	1396	1811	1825	1816
300000	1752	1738	-78	1801	1756	1766	1779	1801	1776	1821	1890	1843	1500	1825	1830	1815
320000	1808	1731	-73	1797	1751	1758	1781	1804	1778	1821	1895	1841	1421	1826	1824	1815
330000	2161	1733	-70	1798	1752	1774	1779	1796	1785	1822	1899	1842	1399	1818	1818	1826
340000	2342	1746	-68	1785	1746	1768	1780	1799	1785	1816	1890	1842	1398	1822	1814	1807
350000	2492	1743	-64	1782	1742	1782	1773	1813	1779	1822	1901	1835	1360	1810	1831	1818
360000	2571	1742	-67	1794	1747	1775	1780	1800	1772	1823	1908	1836	1343	1813	1816	1814
370000	2681	1741	-92	1799	1749	1778	1786	1808	1792	1826	1895	1852	1470	1829	1831	1808
380000	9067	1724	-64	1790	1756	1768	1785	1811	1766	1837	1879	1847	1403	1823	1818	1804
390000	21563	1738	-65	1793	1750	1777	1786	1810	1777	1812	1904	1831	1378	1821	1829	1805
400000	22209	1750	-71	1790	1753	1783	1792	1791	1780	1825	1904	1845	1363	1817	1817	1814

Table C. 2: Strain gauge data for MSD-AL-004 (cont.)

Cycles	Number of Strain Gauge Reading (micro strains)															
	1	2	3*	4	5	6	7	8	9	10	11	12	13	14	15	16
410000	4294	1743	-97	1792	1757	1772	1774	1801	1780	1825	1910	1839	1443	1831	1813	1800
420000	23131	1741	-77	1790	1757	1772	1786	1790	1778	1828	1902	1836	1407	1823	1806	1806
430000	39328	1750	-71	1800	1759	1782	1778	1809	1767	1830	1897	1837	1336	1832	1821	1806
440000	26536	1753	-54	1795	1751	1789	1771	1803	1770	1830	1900	1841	1332	1828	1809	1811
450000	22918	1751	-57	1786	1755	1790	1785	1812	1773	1840	1896	1848	1325	1843	1807	1817
460000	29804	1732	-53	1782	1763	1789	1787	1810	1779	1849	1895	1861	1318	1827	1819	1799
470000	33290	1742	-55	1782	1765	1781	1768	1817	1767	1848	1894	1861	1294	1833	1808	1800
480000	10643	1732	-94	1791	1758	1785	1778	1802	1783	1819	1903	1842	1443	1824	1832	1794
490000	15506	1744	-84	1786	1746	1796	1770	1815	1771	1834	1890	1844	1398	1821	1836	1796
500000	20647	1737	-58	1765	1772	1780	1775	1815	1759	1844	1877	1867	1345	1834	1810	1807
510000	42176	1766	-57	1789	1762	1797	1779	1804	1769	1831	1895	1840	1337	1822	1817	1808
520000	13959	1746	-60	1788	1766	1790	1777	1808	1764	1827	1902	1829	1335	1831	1816	1798
530000	27702	1769	-48	1790	1760	1788	1779	1816	1758	1828	1903	1826	1329	1828	1813	1810
540000	48520	1745	-55	1782	1761	1796	1776	1811	1798	1832	1898	1830	1337	1812	1825	1787
550000	38321	1753	-68	1773	1772	1787	1778	1805	1805	1832	1901	1831	1313	1835	1816	1807
560000	55326	1746	-57	1788	1750	1813	1777	1816	1796	1833	1893	1840	1309	1830	1831	1796
570000	5387	1750	-93	1784	1765	1777	1783	1804	1811	1842	1893	1842	1400	1837	1819	1798
580000	37487	1755	-104	1789	1759	1793	1776	1816	1888	1837	1905	1849	1341	1821	1822	1797
590000	39221	1749	-105	1781	1751	1800	1792	1810	1874	1837	1905	1849	1325	1833	1813	1799
600000	32872	1737	-109	1793	1750	1795	1785	1807	1873	1865	1895	1856	1315	1829	1824	1777
610000	32730	1755	-105	1795	1756	1782	1788	1818	1866	1848	1904	1855	1309	1835	1815	1800
620000	65063	1755	-108	1812	1757	1797	1771	1818	1829	1834	1910	1848	1315	1826	1822	1790
620335	1623	1798	18	1828	1760	1871	1812	1830	1829	1780	1864	1786	1625	1771	1740	1760
631000	5666	1807	7	1843	1760	1876	1823	1818	1882	1767	1878	1772	1557	1751	1766	1727
640000	40427	1808	7	1837	1766	1874	1839	1828	2047	1766	1896	1770	1529	1766	1764	1721
650000	34139	1801	-5	1831	1766	1857	1822	1826	1962	1764	1875	1793	1516	1774	1752	1743
660000	39620	1803	1	1851	1773	1869	1829	1829	1957	1776	1872	1777	1502	1778	1756	1743
670000	28952	1808	2	1841	1779	1872	1831	1812	1939	1772	1869	1791	1493	1763	1739	1750
680000	27172	1799	3	1842	1754	1873	1823	1826	1884	1779	1876	1799	1483	1756	1741	1749
690000	5121	1807	-25	1858	1773	1877	1817	1809	1844	1765	1875	1813	1577	1773	1744	1732

1. Scope

This report details the test results of specimen MSD-GL-002 tested at Carleton University. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. C. Rans, *Draft Testing summary report for MSD-GL-001*, Report No. R-MSD-GL-001, March 24, 2003
2. C. Rans, *Testing summary report for MSD-AL-003*, Report No. R-MSD-AL-003, Aug 23, 2002
3. C. Rans, *Testing summary report for MSD-AL-004*, Report No. R-MSD-AL-004, Oct 7, 2002
4. Müller, R.P.G., *An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints: the significance of the rivet squeeze force and a comparison of 2024-T3 and Glare 3*, Delft University of Technology, Delft, The Netherlands, 1995
5. Eastaugh, G.F., *Multiple site fatigue damage in fuselage skin splices*, Carleton University, Ottawa, Ontario, 1993

3. Test Setup

Specimen Properties

- Material: GLARE3-2/1

Dimensional Properties

- Width: 20"
- Thickness: 0.034"
- Drawing: MSD-001

Joint Properties

- Rivet Type: NAS1097-AD-4-4
- Countersink Type: Machined
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets installed on specimen to prevent edge cracking

Strain Gauges

- Number Installed: 16
- Location of Banks: Refer to Figure A. 1

Testing Characteristics

- Load Frequency: 4Hz
- Peak Load: 48.5 kN
- R: 0.03

Testing Equipment

- Controller Type: MTS 407 (Figure A. 3)
- Hydraulic Actuator Type: MTS 244.21
- Test rig calibration date: Jan. 31, 2003
- Travelling Microscope: Refer to Figure A. 4a
- Data acquisition system: INET 200 controller card, 2 INET 100 HC boxes (Figure A. 4b)

4. Testing Goals

Specimen MSD-GL-002 is the second of four GLARE splices being tested in collaboration with the National Research Council of Canada. For this purpose, the goals for this specimen are:

1. Produce MSD under the same running load of 544 lbf/in applied to the two aluminum reference specimens MSD-AL-003 and MSD-AL-004, and MSD-GL-001
2. Obtain visible crack nucleation and growth data for GLARE3-2/1
3. Observe the fatigue cracking behaviour of GLARE3-2/1, making qualitative observations of the presence of subsurface cracks, and documenting major differences in the behaviour of GLARE3-2/1 compared to 2024-T3

In addition, the following goal also pertains to this specimen.

1. Evaluate effectiveness of sandblasting specimen clamping plates for prevention of premature fretting failure of the specimen

5. Manufacturing Faults

During the rivet hole drilling process, an error was made in establishing the references that were used to locate all rivet holes. As a result, all the rivet holes are 0.010" off centre along the axis of the rivet row (ie: Rivet 1 is centred at $X = 0.510$ " rather than 0.500", where X is measured from the left side of the specimen as is shown in Figure A. 1). This fault is small and did not prevent the formation of MSD in the specimen; however, this fault needs to be considered when calculating crack lengths from the raw crack tip position data in Table C. 2.

6. Results

6.1 Stress Distribution

Figure 1 ,shows the experimental stress distribution across the specimen width. The theoretical stress values were obtained using a running load of 544 lbf/in and neglecting secondary bending. Secondary bending as well as the ± 30 microstrain accuracy of the strain data acquisition system account for the discrepancies between the experimental and theoretical values. The average stress distribution in MSD-GL-002 agreed with values obtained in MSD-GL-001 within $\pm 5\%$.

Figure 1: Stress distribution across MSD-GL-002 width. Theoretical values based on running load of 544 lbf/in (neglecting secondary bending in splice)

6.2 Initiation and Growth of Cracks in Hidden Aluminum Layers

First evidence of cracking was found at 250000 cycles in the form of a surface depression in the back side of the specimen at rivet 48 along the bottom rivet row. This indicated the presence of a crack within the hidden aluminum layer. Growth of these surface depressions was observed during the life of the specimen; however, none of the hidden cracks responsible for the formation of the depressions developed into through-thickness cracks.

6.2.1 Detection of Cracks in Hidden Layers

As was found with specimen MSD-GL-001 [1], evidence of subsurface cracking in the form of a surface depression was observed in the bottom rivet row. This depression is formed as a result of a step in the neutral axis around the crack formed due to fibre bridging in GLARE (Figure 2). The presence of the crack in the aluminum layer causes load to be bypassed around the crack by the remaining intact layers. As such, the neutral axis shifts with respect to the remaining intact layers in the vicinity of the crack. The resulting bending moment from this step in neutral axis produces the depression. Additionally, the bending stiffness of the sheet material around the crack is determined by the intact layers. Thus a crack locally reduces the bending stiffness of the sheet, causing secondary bending moments from the eccentricity in the lap joint to produce larger bending deformations, contributing to the formation of the depression.

Figure 2: Visual detection of cracks in hidden aluminum layers in GLARE3-2/1: (a) step in neutral line around crack producing bending moment; (b) formation of depression due to bending moment; (c) Visually detected surface depressions in MSD-GL-002 (image inverted for clarity)

In both the top and bottom rivet rows, cracks are expected to initiate in the hidden aluminum layer at the faying surface in the lap joint due to higher secondary bending stresses and fretting damage; although the top rivet row is typically critical due to the presence of countersinks and poorer rivet hole filling. The formation of surface depressions, however, was only observed in the bottom rivet row. Initially it was believed that the surface depressions in the top rivet row were masked by the complex pillowing pattern formed around the countersunk rivet heads; however the asymmetry of the GLARE3-2/1 laminate provides a better explanation. Due to the orientation of the GLARE3-2/1 laminates within the MSD-GL-002 splice (Figure 3), the presence of a crack in the faying aluminum layer along the top rivet row will produce a much smaller step in the neutral axis than in the bottom rivet row (Figure 3). The relative positioning of the 0° and 90° prepreg plies and the cracked aluminum layer will influence the degree to which the laminate neutral axis is stepped around the crack. Since the 0° ply is directly adjacent to the faying aluminum surface for the critical sheet along the top rivet row, less bending deformation will occur in the presence of a hidden crack, making detection of a surface depression difficult. The extent of such sub-surface cracking and how it relates to the formation of surface depressions could be further investigated by disassembling MSD-GL-001, which failed prematurely at the clamps.

Figure 3: Differences in neutral line step due to relative placement of 0° prepreg ply and cracked aluminum layer in GLARE3-2/1

Detection of the surface depressions in MSD-GL-002 was more difficult than in the previous specimen, MSD-GL-001. This is attributed to the presence of the anodized coating in MSD-GL-002 (MSD-GL-001 was constructed out of GLARE3-2/1 that had an aluminum clad layer rather than an anodized coating). The matte surface of the anodized coating minimized the shadow cast on the specimen by the surface depressions.

6.2.2 Growth of Hidden Cracks in the Bottom Rivet Row

During testing, the growth and link-up of hidden cracks along the bottom row could be qualitatively observed through the growth and link-up of surface depressions generated by the hidden cracks. Only initiation and link-up data was obtainable, as the "tip" of the depression was not easily distinguishable, preventing growth data from being obtained. Initiation and link-up of the surface depressions is plotted in Figure A. 5.

The average growth period for the surface depressions was 200000 cycles. Longer lives were observed at the extreme edges of the specimen, and no surface depression formation was observed at the two outermost rivets; however this is likely due to the presence of the zero-load transfer rivet. The zero-load transfer rivets reduce secondary bending at the outer rivet row locations along the end of the specimen by clamping the free edge of the splice overlap, increasing the bending stiffness of the splice at its edges. As a result, less bending is expected at the bottom rivet row at the specimen edges, making the detection of surface depressions more difficult.

6.3 Initiation and Growth of Visible Cracks

First detection of cracking within the outer GLARE aluminum layers was observed in the countersunk sheet at 420000 cycles along the top rivet row. Initiation, growth, and link-up of cracks along the top rivet row continued until unstable crack growth lead to specimen failure at 1101153 cycles. No cracks initiated in the outer aluminum layer of the lower sheet.

6.3.1 Detection of Visible Cracks

Regular inspections of the specimen for fatigue cracks were conducted with a 10X travelling microscope. At 420000 cycles, 2 cracks, located on the left side of rivet 7 (7L) and the right side of rivet 16 (16R), were discovered. At the time of detection, the cracks were 0.060" and 0.022" respectively. These hairline cracks were difficult to detect with the microscope as crack opening

was limited by the prepreg layers in the GLARE sheet material (Figure 4). To assess whether a higher powered microscope would aid in crack detection and measurement, a 20X inspection microscope was used to inspect each rivet location at 425000 cycles. With the higher powered inspection microscope, 3 additional cracks not visible with the travelling microscope were detected. As a result, a new eyepiece was purchased for the travelling microscope which upgraded its magnification to 20X. This new upgraded microscope was used for all inspections and measurements from 425000 cycles onwards.

Figure 4: Hairline crack as detected at location 7L of MSD-GL-002 after 420000 cycles

6.3.2 Crack Initiation Sites

All visible cracks initiated at the edge of rivet holes. Most initiated slightly above the rivet row minimum section where rotation of the rivet during loading generates large secondary bending stresses; however some cracks initiated below the minimum section where secondary bending stresses are much lower (Figure 5). Cracking below the rivet row minimum section is not typically expected.

Figure 5: Two crack initiation sites observed during testing: (a) above the rivet row minimum section where secondary bending stresses are highest; (b) below rivet row minimum section

Upon failure of the specimen, the locations of cracks within the hidden aluminum layer (faying surface) were visible. It was found that a correlation between the locations of the cracks in the visible and hidden aluminum layers could be made. At rivets where cracks in the visible aluminum layer initiated below the rivet minimum section, cracks within the hidden aluminum layer were located above the rivet hole in the "shadow" of the rivet head [4]. For all other rivet locations, cracks initiated at approximately the same location along the perimeter of the rivet hole within the hidden and visible aluminum layers (Figure 6).

Figure 6: Differences in relative initiation sites of hidden and visible cracks (facing faying joint surface): (a) visible crack located above joint minimum section; (b) visible crack located below joint minimum section

6.3.3 Secondary Cracking

The formation of a secondary fatigue crack was observed at several rivets already containing fatigue cracks (Figure 7). Typically, the secondary fatigue cracks formed at rivets where the initial crack initiated below the rivet row minimum section (visible crack location in Figure 6b). Growth of the primary crack often slowed down or even stopped in the presence of a secondary crack, causing the secondary crack to become dominant and eventually link-up with cracks at adjacent rivets (refer to back of Appendix A for photographs of rivet link-up sequences).

Figure 7: Formation of a secondary crack at rivet 12 in MSD-GL-002

6.3.4 Crack Growth

The growth period of the visible cracks in MSD-GL-002 lasted 681153 cycles (Figure 8). This represents a 10-fold increase in crack growth life of 2024-T3 observed in specimen MSD-AL-004, and agrees with similar trends found by Müller [4]. Crack growth curves for individual cracks are plotted in Figure A. 6 and Figure A. 7 in Appendix A.

Figure 8: Comparison of aggregate crack growth lives in 2024-T3 and GLARE3-2/1 MSD specimens

Crack growth rates did not show a strong dependency on crack length, with growth rates remaining nearly constant for the majority of the growth life of cracks. Constraints on crack opening produced by the fibre bridging mechanism in GLARE prevent large changes in crack tip stress intensity factors with crack length. Only in the presence of nearby cracks and pending link-ups were accelerated crack growth rates observed.

Delaminations form and grow behind the tip of a crack in GLARE to prevent the local failure in the prepreg layers due to excess fibre strain at the maximum opening of the crack. As the tips of adjacent cracks approach, so too do the delaminations trailing these crack tips. The approaching delaminations reduce the area of intact adhesion between the cracked aluminum and prepreg layers, reducing the effectiveness of the fibre bridging mechanisms. As such, as crack tips approach, the crack tip stress intensity factors for both cracks begin to increase as the effectiveness of the fibre bridging mechanism is reduced and the crack growth behaviour begins to resemble that of monolithic aluminum. Formation and growth of such delaminations were clearly visible during testing (Figure 9).

Figure 9: Visible delaminations observed during testing of MSD-GL-002

6.4 Rivet Head Cracking

Varying degrees of failure of the countersunk head of rivets, including plastic deformation, cracking, and complete fracture, were observed along the top row of rivets during testing (Figure 10). Prior to failure of the specimen, 9 rivets of the 20 rivets along the top row were missing fragments due to rivet head fracture, while 5 other rivets exhibit some degree of cracking ()

Figure 10: Progression of various degrees of rivet damage

Progression of failure observed in the rivet heads predominantly followed Mode II fracture. Shearing of the rivet head in a plane perpendicular to the plane of the joint was clearly visible in the deformation of fracturing rivets (Figure 11). This shear plane is generated by differences in bending stiffness on either side of the rivet as cracking progresses through the joint. As mentioned earlier, the presence of a crack locally reduces the bending stiffness of the joint. This can cause heavily cracked regions in a lap splice to undergo large out-of-plane deformation upon loading. This deformation, in turn, is resisted by the rivet heads, creating a state of shear stress perpendicular to the loading plane. The slow crack growth in GLARE allows such large out-of-plane deformations to be sustained long enough before failure of the splice to allow the initiation and growth of cracks in the thin countersunk rivet heads.

Figure 11: Shear deformation of rivet head 5

6.5 Clamping Failure

In response to multiple failures at the clamped edges of MSD-GL-001, the clamping plates for the MSD test rig were sandblasted with a 220 aluminum oxide grit [1]. Upon failure of MSD-GL-002, inspection of the clamped edges of the specimen revealed very little evidence of fretting damage, even though the specimen had undergone nearly twice as many fatigue cycles as MSD-GL-001. This demonstrates the effectiveness of sandblasting the plates in preventing clamping failures.

6.6 Specimen Buckling

During testing of MSD-GL-002, the hydraulic interlock on the test rig was tripped due to a power surge at 636599 cycles. This removed hydraulic pressure from the test rig, causing the specimen to buckle under the weight of the clamping plates as the hydraulic cylinder fully extended. Due to the large length of the specimen, buckling was likely elastic under the limited travel of the hydraulic cylinder. Only minor amounts of plastic deformation of the right bottom corner of the specimen at the clamped edge was found.

To prevent future incidences of the specimen buckling if hydraulic pressure is suddenly cut from the test rig, the upper specimen clamping plate was tied to a cross-beam in the test rig with nylon rope. This rope will carry the weight of the clamping plate if hydraulic pressure is lost, but is flexible enough to permit tensile deformations of the specimen during loading.

7. Conclusions

From data collected and observations made during the testing of MSD-GL-002, the following conclusions can be made:

1. The effectiveness of the zero-load transfer rivet specimen design in producing MSD in GLARE3-2/1 specimens has been demonstrated.
2. The formation of surface depressions under the presence of hidden cracks was observed in the bottom rivet row of MSD-GL-002. These depressions are likely formed due to the step in neutral axis formed around a crack.
3. Surface depressions were not observed in the top rivet row of MSD-GL-002. The orientation of prepreg layers in the splice causes a smaller step in the neutral axis of the sheet material around hidden cracks in the top row, preventing a visible depression from forming.
4. Crack growth rates in GLARE3-2/1 are not heavily dependant on crack length. Increases in crack growth rates observed in MSD-GL-002 are likely due to a reduction in fibre bridging due to approaching delaminations in adjacent cracks.
5. Large out of plane deformations in heavily damaged regions of the splice sustained by the slow crack growth rate of GLARE lead to Mode II fracture of the countersunk rivet heads.

Additionally, with respect to fretting failures experienced in previous specimens at the clamping plates, sandblasting of the clamping plates was successful in preventing fretting failure at the clamps.

Appendix A: Drawings and Supplementary Pictures

Figure A. 1: Strain gauge placement for specimen MSD-GL-002

Figure A. 2: Rivet numbering scheme

Figure A. 3: Test rig with installed specimen and travelling microscope (left). MTS 407 controller (right).

Figure A. 4: Test equipment. (a) Travelling microscope (b) Instrunet data acquisition system

Figure A. 5: Growth lives of surface depressions along the bottom rivet row of MSD-GL-002

Figure A. 6: Crack growth curves for top rivet row of MSD-GL-002: entire specimen width

Figure A. 7a: Crack growth curves for top rivet row of MSD-GL-002: growth between rivets 1 - 5

Figure A. 8b: Crack growth curves for top rivet row of MSD-GL-002: growth between rivets 5 - 9

Figure A. 8c: Crack growth curves for top rivet row of MSD-GL-002: growth between rivets 9 - 13

Figure A. 8d: Crack growth curves for top rivet row of MSD-GL-002: growth between rivets 13 - 17

Figure A. 8e: Crack growth curves for top rivet row of MSD-GL-002: growth between rivets 17 - 20

Figure A. 8: Cracking along entire top row of MSD-GL-002 at 1097500 cycles

Figure A. 9: Growth and link-up of cracks between rivets 10 and 11 in MSD-GL-002

Figure A. 10: Growth and link-up of cracks between rivets 11 and 12 in MSD-GL-002

Appendix B: Manufacturing Documentation

Specimen Number: MSD-GL-002	Drawing Numbers: MSD-001
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Joint Configuration:

Rivet Type: NAS1097-AD-4-4	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/machine csk
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: GLARE3-2/1	Sheet Thickness: 0.034"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	October 29, 2002	Calvin Rans
Mill Sheet Edges	January 21, 2003	Alex Proctor
Drill mounting bolt holes	February 19, 2003	Alex Proctor
Center drill/drill/debur rivet holes	February 27, 2003	Calvin Rans
Countersink holes	February 28, 2003	Calvin Rans
Rivet installation	March 3, 2003	FRL

Quality Control:

All measurements are conducted on the critical rivet row and with an accuracy of $\pm 0.002"$. Rivets numbered from left to right on critical rivet row.

Top Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
1	200	11	195	1	196	11	198	1	71	11	70
2	199	12	195	2	196	12	197	2	70	12	71
3	198	13	200	3	196	13	193	3	71	13	71
4	192	14	195	4	197	14	196	4	69	14	70
5	197	15	198	5	197	15	195	5	68	15	66
6	195	16	199	6	196	16	197	6	70	16	72
7	200	17	194	7	191	17	196	7	70	17	69
8	199	18	200	8	195	18	195	8	69	18	73
9	200	19	197	9	196	19	196	9	70	19	74
10	198	20	198	10	195	20	195	10	70	20	70
Nom.	193	Avg.	197	Nom.	188	Avg.	196	Nom.	63	Avg.	70

Bottom Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
41	202	51	197	41	194	51	195	41	76	51	70
42	201	52	194	42	195	52	198	42	75	52	68
43	204	53	196	43	195	53	196	43	70	53	70
44	203	54	200	44	194	54	196	44	69	54	72
45	205	55	193	45	191	55	197	45	71	55	66
46	201	56	195	46	196	56	195	46	73	56	74
47	194	57	195	47	197	57	197	47	70	57	71
48	195	58	196	48	197	58	196	48	71	58	72
49	194	59	192	49	195	59	194	49	65	59	70
50	196	60	199	50	195	60	194	50	72	60	73
Nom.	193	Avg.	198	Nom.	188	Avg.	195	Nom.	63	Avg.	71

Comments:

During drilling the rivet holes, the radius of the edge finder was improperly accounted for in zeroing the digital readout of the mill, resulting in all of the rivet holes being offset 0.010" to the right (in the x direction)

Appendix C: Raw Data Tables

Table C. 1: Strain gauge data for MSD-GL-002

Number of Strain Gauge Reading (micro strains)																
Cycles	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1724	1699	1680	1691	1685	1682	1682	1748	1922	1970	1947	1941	1944	1923	1910	1891
10000	1712	1707	1670	1691	1682	1674	1700	1747	1924	1970	1964	1929	1932	1920	1907	1883
20000	1710	1708	1660	1695	1690	1669	1689	1746	1908	1965	1955	1944	1917	1921	1901	1886
30000	1705	1705	1662	1692	1693	1677	1679	1748	1906	1968	1961	1948	1932	1932	1919	1871
40000	1696	1707	1668	1684	1681	1671	1690	1736	1921	1965	1948	1929	1916	1922	1904	1858
50000	1705	1698	1667	1695	1691	1674	1685	1758	1915	1971	1956	1944	1938	1922	1901	1864
60000	1704	1707	1673	1686	1695	1673	1691	1752	1914	1967	1945	1936	1944	1927	1909	1869
70000	1717	1706	1674	1694	1690	1663	1697	1753	1931	1966	1968	1917	1941	1913	1924	1868
80000	1719	1701	1684	1691	1696	1667	1682	1756	1922	1968	1950	1937	1937	1923	1906	1877
90000	1716	1706	1670	1693	1685	1679	1694	1752	1917	1975	1941	1946	1935	1923	1921	1861
100000	1712	1695	1678	1699	1697	1671	1694	1748	1917	1980	1940	1958	1916	1919	1918	1874
110000	1710	1707	1659	1698	1682	1683	1680	1745	1915	1971	1944	1935	1937	1922	1907	1865
120000	1713	1710	1674	1682	1688	1656	1686	1745	1941	1958	1965	1928	1938	1914	1912	1856
130000	1705	1710	1668	1689	1705	1658	1687	1754	1941	1960	1945	1921	1928	1917	1910	1869
140000	1694	1705	1666	1696	1685	1680	1686	1758	1921	1959	1954	1922	1947	1908	1910	1849
150000	1715	1692	1664	1686	1673	1669	1683	1764	1923	1971	1965	1922	1943	1915	1915	1850
160000	1709	1702	1675	1682	1690	1673	1686	1749	1926	1966	1960	1941	1933	1925	1929	1860
170000	1714	1699	1673	1684	1679	1667	1682	1753	1912	1980	1955	1935	1934	1917	1926	1848
180000	1709	1704	1670	1690	1675	1670	1677	1740	1920	1977	1973	1923	1936	1926	1919	1855
190000	1717	1694	1673	1689	1683	1665	1682	1766	1906	1986	1959	1937	1920	1920	1927	1844
200000	1722	1705	1665	1685	1681	1666	1673	1733	1928	1986	1968	1932	1926	1913	1927	1834
210000	1708	1696	1674	1694	1683	1667	1671	1743	1930	1979	1949	1924	1939	1913	1915	1837
220000	1724	1705	1667	1680	1682	1669	1676	1741	1920	1988	1949	1945	1924	1919	1926	1833
230000	1720	1699	1674	1685	1690	1661	1681	1764	1915	1986	1958	1943	1923	1925	1925	1838
240000	1719	1708	1654	1702	1695	1662	1675	1746	1932	1986	1973	1932	1939	1922	1928	1845
250000	1710	1700	1672	1687	1681	1660	1679	1744	1924	1975	1970	1938	1932	1918	1921	1838
260000	1715	1705	1672	1692	1666	1652	1662	1743	1929	1993	1965	1940	1928	1912	1921	1842
270000	1722	1705	1670	1694	1688	1667	1663	1748	1935	1989	1963	1934	1930	1917	1915	1850
280000	1731	1707	1672	1688	1681	1645	1680	1744	1927	1982	1954	1929	1921	1923	1906	1845
290000	1727	1704	1663	1689	1688	1669	1669	1748	1916	1983	1957	1935	1923	1918	1914	1853
300000	1720	1706	1670	1688	1679	1662	1681	1739	1915	1973	1959	1930	1928	1905	1916	1835
310000	1717	1715	1666	1680	1686	1662	1693	1762	1922	1982	1972	1927	1941	1898	1903	1853
320000	1705	1699	1678	1690	1692	1668	1690	1753	1925	1988	1960	1919	1938	1901	1916	1849
330000	1714	1705	1678	1672	1687	1667	1678	1747	1922	1988	1951	1928	1935	1894	1905	1853
340000	1711	1703	1676	1671	1682	1654	1685	1751	1936	1994	1953	1930	1944	1899	1897	1863

Table C. 1: Strain gauge data for MSD-GL-002 (cont)

Number of Strain Gauge Reading (micro strains)																
Cycles	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
350000	1716	1700	1679	1681	1688	1665	1681	1756	1931	1997	1946	1940	1939	1894	1908	1858
360000	1711	1699	1665	1679	1684	1671	1680	1763	1931	1999	1951	1928	1935	1893	1896	1863
370000	1717	1693	1670	1679	1678	1667	1689	1754	1932	2001	1960	1932	1946	1900	1908	1855
380000	1714	1701	1674	1682	1680	1662	1691	1752	1951	1997	1946	1932	1948	1900	1908	1858
390000	1728	1720	1664	1672	1690	1670	1678	1746	1935	1989	1963	1929	1925	1912	1912	1856
400000	1722	1724	1675	1671	1682	1666	1670	1740	1934	1978	1956	1926	1941	1907	1916	1837
410000	1714	1697	1663	1672	1689	1659	1666	1751	1934	1984	1952	1928	1924	1898	1966	1849
420000	1713	1710	1669	1678	1676	1663	1663	1744	1935	1980	1947	1924	1922	1912	2040	1855
425000	1729	1707	1673	1687	1679	1660	1676	1747	1931	1983	1956	1917	1934	1900	2090	1850
440000	1708	1721	1660	1679	1673	1668	1682	1751	1937	1992	1956	1903	1939	1901	1927	1851
450000	1721	1701	1662	1686	1669	1678	1678	1757	1932	1999	1945	1928	1931	1908	1926	1846
460000	1724	1722	1663	1667	1675	1656	1684	1750	1943	1993	1962	1915	1930	1910	1936	1854
470000	1719	1719	1657	1678	1680	1685	1682	1752	1940	1992	1956	1903	1937	1888	1969	1849
480000	1729	1719	1659	1682	1676	1658	1676	1751	1935	1986	1944	1920	1923	1915	1996	1843
490000	1728	1721	1653	1680	1685	1664	1669	1756	1926	2011	1946	1917	1922	1918	2124	1849
500000	1724	1737	1659	1688	1678	1663	1680	1749	1943	1986	1952	1885	1931	1908	2463	1850
520000	1717	1725	1655	1672	1686	1659	1663	1756	1931	1986	1938	1915	1917	1914	3006	1861
540000	1720	1713	1665	1692	1680	1651	1678	1736	1924	1986	1956	1927	1930	1905	6159	1844
560000	1726	1712	1673	1686	1690	1657	1658	1750	1922	1993	1937	1930	1923	1904	5328	1830
580000	1718	1710	1663	1692	1689	1662	1665	1731	1933	1994	1947	1919	1924	1906	4873	1847
600000	1713	1714	1655	1691	1694	1657	1684	1752	1951	1998	1951	1907	1948	1884	1936	1833
620000	1715	1702	1657	1685	1697	1667	1685	1748	1944	2002	1948	1900	1952	1895	1922	1852
640000	1706	1707	1656	1689	1698	1657	1684	1741	1961	1997	1946	1899	1953	1883	1940	1835
660000	1708	1707	1657	1679	1704	1661	1686	1740	1948	2012	1944	1901	1966	1870	1936	1844
680000	1705	1706	1667	1682	1705	1646	1691	1743	1942	2012	1950	1893	1950	1877	1924	1862
700000	1710	1705	1670	1674	1703	1654	1691	1749	1960	2003	1948	1899	1963	1867	1937	1854
720000	1715	1703	1665	1673	1714	1652	1694	1749	1942	2014	1944	1900	1970	1871	1932	1862
740000	1708	1731	1658	1693	1712	1648	1680	1744	1943	1991	1944	1889	1967	1863	2029	1848
760000	1702	1727	1666	1678	1723	1628	1693	1734	1931	1992	1942	1897	1968	1865	2015	1843
780000	1702	1724	1662	1675	1723	1643	1700	1749	1929	2007	1933	1888	1958	1868	2281	1851
800000	1707	1741	1660	1669	1730	1623	1691	1741	1930	2005	1934	1878	1950	1862	2317	1835
820000	1713	1728	1678	1676	1736	1622	1685	1747	1937	2001	1929	1883	1956	1933	3285	1853
840000	1695	1730	1659	1667	1747	1604	1695	1743	1935	2000	1922	1861	1972	2020	2354	1837
860000	1709	1783	1649	1673	1748	1607	1700	1749	1918	2006	1925	1871	1985	3013	2897	1843

Table C. 1: Strain gauge data for MSD-GL-002 (cont)

Cycles	Strain Gauge Reading (micro strains)															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
880000	1711	1788	1663	1673	1750	1611	1696	1750	1931	2022	1923	1851	1988	2675	2602	1864
900000	1715	1799	1655	1651	1751	1603	1692	1738	1923	2016	1911	1845	1991	2575	2369	1857
920000	1726	1855	1655	1631	1758	1584	1698	1757	1939	2033	1900	1827	1999	2381	2279	1855
940000	1727	1822	1646	1605	1773	1574	1708	1760	1940	2029	1886	1769	2016	2230	2220	1868
960000	1732	1846	1638	1554	1803	1574	1722	1756	1964	2051	1885	1714	2036	2789	2040	1864
980000	1734	1836	1603	1534	1820	1525	1734	1768	1970	2061	1839	1689	2073	2041	2033	1865
1000000	1758	1842	1517	1525	1856	1490	1746	1794	1979	2110	1702	1665	2116	2317	2049	1882
1010000	1758	1921	1496	1513	1893	1457	1753	1797	1982	2125	1675	1633	2134	3970	2106	1890
1020000	1752	2052	1492	1499	1940	1416	1767	1794	1978	2142	1666	1654	2143	4230	2255	1902
1027461	1783	1927	1477	1508	1968	1407	1787	1799	1994	2171	1672	1658	2192	1933	2137	1914
1030000	1787	2006	1484	1499	1980	1410	1780	1813	1993	2181	1674	1667	2197	2487	2382	1921
1032500	1792	1983	1495	1523	1998	1395	1799	1811	2015	2199	1679	1661	2213	2258	2355	1923
1035000	1779	2015	1483	1514	2016	1397	1804	1809	1997	2204	1675	1653	2226	2063	2349	1906
1037500	1799	2021	1478	1500	2028	1408	1797	1811	2008	2214	1669	1641	2245	2099	2446	1919
1040000	1802	2030	1475	1485	2044	1400	1796	1822	2017	2232	1658	1652	2254	1974	2417	1934
1042500	1793	2045	1467	1482	2061	1399	1814	1836	2036	2250	1660	1635	2289	2237	2359	1924
1045000	1796	2042	1463	1477	2072	1417	1834	1840	2025	2251	1646	1638	2292	2010	2422	1949
1047500	1805	2071	1472	1468	2083	1409	1836	1843	2032	2285	1655	1657	2290	1999	2685	1946
1050000	1822	2063	1455	1458	2080	1417	1865	1857	2035	2300	1649	1635	2297	1945	2711	1947
1052500	1833	2077	1455	1444	2084	1412	1880	1865	2036	2311	1638	1625	2273	1912	2377	1972
1055000	1830	2104	1455	1442	2018	1441	1881	1871	2058	2321	1641	1611	2252	1887	2451	1986
1057500	1853	2133	1447	1438	1939	1452	1913	1898	2063	2364	1641	1617	2149	1862	2384	2000
1060000	1865	2129	1452	1450	1781	1468	1926	1915	2077	2382	1642	1630	1967	1906	2389	2009
1065000	1900	2189	1446	1459	1637	1471	1976	1956	2104	2416	1650	1635	1826	1868	2391	2054
1070000	1911	2245	1450	1439	1577	1449	1977	2002	2124	2461	1653	1638	1771	1887	2394	2086
1075000	1951	2253	1453	1425	1503	1425	1971	2050	2157	2495	1661	1613	1694	1802	2301	2135
1080000	1991	2271	1447	1411	1477	1404	1840	2151	2199	2518	1660	1622	1678	1834	2212	2224
1085000	2032	2274	1422	1415	1420	1360	1733	2251	2251	2501	1659	1622	1599	1803	2110	2336
1087500	2081	2204	1422	1425	1413	1346	1699	2306	2293	2453	1688	1611	1603	1661	1910	2390
1090000	2131	2045	1441	1406	1423	1315	1689	2356	2347	2283	1693	1606	1592	1602	1901	2439
1092500	2242	1867	1428	1418	1409	1275	1666	2444	2461	2070	1731	1609	1604	1598	1893	2531
1095000	2312	1806	1431	1430	1416	1226	1651	2535	2515	2007	1745	1650	1595	1693	2507	2651
1097500	2399	1788	1441	1401	1467	1116	1671	2518	2604	2004	1774	1678	1681	1368	1977	2587
1100000	2542	1832	1514	1420	1424	1076	1705	2127	2768	2024	1898	1871	1714	1214	2093	2207
1101153																

Legend:

Link-up
Dimple visible
Crack length not measured

Appendix C

Table C. 3: Crack growth data for secondary cracks in MSD-GL-002

Number of Cycles	Secondary Crack											
	5L bottom	6R top	7L top	7R middle	7R top top	9R Top	12L top	12R top	14R Top	16L Top	16R Top	18R Top
740000	4.3755											
760000	4.3770											
780000	4.3690											
800000	4.3650											
820000	4.3615					8.6540						
840000	4.3465					8.6620						
860000	4.3395					8.6510						
880000	4.3380					8.6550						
900000	4.3315					8.6545						
920000	4.3215					8.6550						
940000	4.3115					8.6615						
960000	4.2975					8.6710						
980000	4.2875					8.6730						
1000000	4.2710					8.6855						
1010000	4.2640					8.6980						
1011661												
1011735												
1020000	4.2550			6.6190		8.7065			13.6045			
1027461	4.2500			6.6290		8.7110			13.6245			
1030000									13.6315			
1032500									13.6350			
1035000	4.2455			6.6395	6.6225	8.7220			13.6400			
1037500												
1040000												
1041918												
1042323												
1042500	4.2360			6.6440	6.6255	8.7320			13.6530			
1045000												
1045156												
1047500	4.2295			6.6495	6.6360	8.7425			13.6665			
1050000												
1051507												
1051512												
1052500									13.6815			
1055000												
1057500							11.3520	11.6290	13.7005			
1060000	4.2160	5.6210	6.3800	6.6610	6.6425	8.7700	11.3250	11.6450	13.7065			
1065000						8.7855	11.2830	11.6840	13.7315			
1068624							11.2690					
1070000	4.2005	5.6430	6.3640	6.6685	6.6550	8.8035	11.2590	11.7015	13.7620			
1073253												
1075000		5.6555	6.3610		6.6640	8.8210		11.7105	13.7920			
1077509												
1080000	4.1790	5.6675			6.6790	8.8355			13.8410	15.3715	15.6370	17.6000
1085000		5.6825			6.7115	8.8475			13.8745	15.3550	15.6575	
1087500	4.1570	5.6940			6.7185	8.8535			13.8935	15.3510	15.6720	17.6175
1089103												
1090000	4.1390					8.8540			13.9045	15.3405	15.6810	
1090230												
1090781												
1092500	4.1100											
1093102												17.6285
1094112												
1095000	4.0655	5.7170			6.7285	8.8695			13.9315		15.7000	
1097500	4.0110											
1097965												
1100000	3.9225	5.7295							13.9415		15.7155	

Table C. 4: Rivet head cracking/fracture detection times

Rivet	1	2	3	4	5	6	7	8	9	10
Crack Detected	1010000	1010000	1085000	1092500	1060000	1045000	1010000			
Fracture Detected		1060000			1087500	1080000		1010000	1010000	1010000
Rivet	11	12	13	14	15	16	17	18	19	20
Crack Detected	1010000			1010000				1060000	1010000	
Fracture Detected	1045000			1070000					1095000	

Table C. 5: Link-up detection times

Link-up of visual cracks between rivets (cycles)										
1 & 2	2 & 3	3 & 4	4 & 5	5 & 6	6 & 7	7 & 8	8 & 9	9 & 10	10 & 11	
					1045156		1027461		1070000	
11 & 12	12 & 13	13 & 14	14 & 15	15 & 16	16 & 17	17 & 18	18 & 19	19 & 20		
1073253	1077509	1011735	1051512		1097500					
Link-up of surface depressions between rivets (cycles)										
41 & 42	42 & 43	43 & 44	44 & 45	45 & 46	46 & 47	47 & 48	48 & 49	49 & 50	50 & 51	
	840000	720000	780000	660000	520000	460000	440000	400000	440000	
51 & 52	52 & 53	53 & 54	54 & 55	55 & 56	56 & 57	57 & 58	58 & 59	59 & 60		
400000	410000	480000	440000	460000	480000	520000	600000			

1. Scope

This report details the test results of the dimpled GLARE 3-2/1 riveted joint specimen MSD-GL-003 tested at Carleton University. Experiment characteristics including joint properties and testing characteristics are presented followed by the testing goals and results.

2. References

1. C. Rans, *Testing Summary Report for MSD-GL-002*, Report No. R-MSD-GL-002, May 6, 2003
2. C. Rans, *Testing Summary Report for MSD-GL-001*, Report No. R-MSD-GL-001, March 24, 2003
3. C. Rans, *Testing Summary Report for MSD-AL-004*, Report No. R-MSD-AL-004, October 7, 2002
4. C. Rans, *Testing Summary Report for MSD-AL-003*, Report No. R-MSD-AL-003, August 23, 2002

3. Test Setup

Specimen Properties

- Material: GLARE 3-2/1

Dimensional Properties

- Width: 20"
- Thickness: 0.034"
- Drawing: MSD-001

Joint Properties

- Rivet Type: MS20426-AD-4-4
- Countersink Type: Dimpled
- Number of Rivet Rows: 3
- Rivet Pitch: 1"
- Row Pitch: 1"
- Additional Notes: 4 zero-load transfer rivets were installed to prevent edge cracking

Strain Gauges

- Number Installed: 16
- Location of Banks: Refer to Figure A 2

Testing Characteristics

- Load Frequency: 4 Hz
- Peak Load: 48.5 kN
- R: 0.03

Testing Equipment

- Controller Type: MTS 407 (Figure C 1)

- Hydraulic Actuator Type: MTS 244.21
- Testing Rig Calibration Date: Jan. 31, 2003
- Traveling Microscope: Refer to Figure C 2a
- Data Acquisition System: INET 200 controller card, 2 INET 100 HC boxes (see Figure C 2b)

4. Testing Goals

The MSD-GL-003 specimen was the third GLARE splice tested for the investigation into fatigue optimization of GLARE mechanical splices. The purpose of this test is to produce Multiple Site Damage (MSD) under the same running load (544 lb/in) applied to the reference specimens MSD-AL-003, MSD-AL-004 and MSD-GL-002 [1,3,4] in order to obtain crack nucleation and crack growth data for a dimpled GLARE 3-2/1 riveted joint undergoing fatigue loading. Data and qualitative observations will be used to evaluate the behaviour of a dimpled GLARE 3-2/1 riveted joint when compared to the behaviour of Al 2024-T3 and machine countersunk GLARE 3-2/1 riveted joints.

5. Results

5.1 Stress Distribution

Figure 1 shows the experimental stress distribution across the specimen width. The theoretical values assume a 544 lb/in running load with no secondary bending. These assumptions and the accuracy of the strain reading apparatus account for the discrepancy observed.

Figure 1: Stress Distribution Across the Specimen Width

5.2 Crack Nucleation and Crack Growth in the Faying Surface Aluminum Layer

Evidence of subsurface cracking on the back face of the specimen in the bottom rivet row, was observed at 140000 cycles. The progress of the faying surface cracks can be qualitatively observed through the visible surface depression caused by the underlaying crack [1]. The subsurface cracks were found to propagate rapidly throughout the back side bottom rivet row as can be seen in Figure 2. As these observations were only quantitative, only initial detection of the surface depression and link-up of depressions are given. These subsurface cracks then developed into through the thickness cracks.

Qualitative Subsurface Crack Detection and Link-up

Figure 2: Qualitative Representation of Subsurface Crack Detection and Link-Up

5.3 *Crack Nucleation and Crack Growth in the Outer Surface Aluminum Layer*

The first detection of cracking in the outer aluminum layer of the lower aluminum sheet occurred at 180000 cycles. Nucleation and crack growth continued along the bottom row of rivets on the back side of the specimen until a crack on an outer rivet reached the edge of the specimen. As an edge crack would have change the loading configuration of the specimen, the test was stopped and the specimen was considered to have attained failure at 280000 cycles.

5.3.1 Detection of Visible Cracks

Regular inspections of the specimen for fatigue cracks were conducted on the top rivet row of the front surface with a 20X traveling microscope. The bottom row of rivets was inspected for cracks at irregular intervals with a 9X magnifying eyepiece, as the specimen was not expected to fail at that location. Hence, cracks were not detected immediately and the average crack size at detection was 0.096". Upon detection, the traveling microscope setup was moved to the rear of the specimen for accurate crack detection and measurement. The cracks proved easy to detect, as significant fretting product was pushed through the cracks. This can be seen in Figure 3.

Figure 3: Cracks as detected at rivet 42 at 180000 cycles

5.3.2 Crack Initiation Sites

The cracks on the outer surface of the specimen were found to initiate at the base of the dimple cone. Most cracks initiated slightly below the minimum rivet row section as shown in Figure 4, where rotation of the rivet during loading generates large secondary bending

stresses. As the specimen was not taken to complete failure, the faying surface crack initiation sites are not known.

Figure 4: Typical Location of Crack Nucleation for Outer Back Aluminum Sheet

Secondary cracks were found at several rivet locations already containing fatigue cracks. The secondary crack was observed to quickly linkup to the primary crack.

5.3.3 Crack Growth

The growth period of the outer layer fatigue cracks was of 100000 cycles. This represents a crack growth life similar to that of specimens MSD-AL-003 and MSD-AL-004, as shown in Figure 5. The crack penetration rate through the different layers of aluminum was also high (approximately 50000 cycles). The exhibited rates indicate the fiber bridging properties inherent to GLARE material did not function properly. Hence, the material behaved similarly to a thin sheet of aluminum. A possible explanation is that the dimpling process causes delamination damage in the lower sheet. This damage would move ahead of the crack tip during fatigue loading, thereby inhibiting fibre bridging.

It was found that the cracks size did not have a strong impact on the crack growth rates as the crack growth rates remained constant for most of the growth life of the crack (Figure 6).

Aggregate Crack Growth Curves

Figure 5: Aggregate Crack Growth Curve of MSD Specimens Tested

Figure 6: Crack Growth Curves for Bottom Rivet Row of MSD-GL-003

5.3.4 Fretting

A large amount of fretting product was observed being pushed out of the cracks when compared to tests on specimens MSD-GL-001 and MSD-GL-002. This indicated that an unusual amount of fretting was occurring in the material ahead of the crack. As the crack advanced, the fretting product gathered was released. This was not observed in other GLARE specimens.

Figure 7: Fretting Product Released by Cracks (277500 cycles)

5.4 Specimen Buckling

During the testing of specimen MSD-GL-003, a power surge caused the load frame controller to shut down and reboot at 277500 cycles. This adversely caused the load frame's hydraulic system to depressurize, lowering the actuator piston and buckling the specimen. However due to the large size of the specimen and the limited travel of the actuator piston, no plastic deformation was observed.

6. Conclusions

The following conclusions were made following the data analysis and observations made during the testing of the MSD-GL-003 specimen:

1. Sub-surface cracking in the back sheet can be observed quantitatively by the presence of surface depressions.
2. The crack growth rates observed are similar to that of monolithic aluminum, indicating that fibre bridging did not occur.
3. The dimpling process is detrimental to the fatigue life of the bottom rivet row.
4. A high amount of friction and fretting occurred in the joint.

7. Recommendations

In an attempt to improve the fatigue life of dimpled GLARE 3-2/1 riveted joints the following recommendations were made:

1. Investigate the possibility of modifying the dimpling dies in order to reduce the damage imparted to the GLARE material during the dimpling process.
2. Provide an edge support plate to support the specimen adequately during the riveting process.
3. Investigate the possible use of sealants as lubricants to reduce fretting in the joint.

Appendix A: Specimen Drawings

Figure A 1: Test Specimen Drawing

Figure A 2: Strain Gauge Placement for Specimen MSD-GL-003

Figure A 3: Rivet Numbering Scheme

Figure A 4: Orientation of GLARE 3-2/1 layers in MSD GL-003

Appendix B: Manufacturing Data Sheet

Specimen Number: MSD-GL-003	Drawing Numbers: MSD-001
---------------------------------------	------------------------------------

Joint Configuration:

Rivet Type: MS20-420-AD-4-4	# Rivet Rows: 3	Rivet Pitch: 1.00"	Row Pitch: 1.00"	Hole Preparation: center drilled/drilled/ debured/dimpled
Zero-load Transfer Rivet Type: MS20-470-AD-5-5	Sheet Material: GLARE3-2/1	Sheet Thickness: 0.034"	Joint Width: 20.0"	

Manufacturing Dates:

Process	Date	Completed by
Cut sheet material	October 29, 2002	Calvin Rans
Mill Sheet Edges	January 21, 2003	Alex Proctor
Drill mounting bolt holes	November 8, 2002	Alex Proctor
Center drill/drill/debur rivet holes	May 7, 2003	Calvin Rans/Magali Duval
Countersink holes	May 9, 2003	FRL
Rivet installation	May 9, 2003	FRL

Quality Control:

All measurements are conducted on the critical rivet row and with an accuracy of $\pm 0.002"$. Rivets numbered from left to right on critical rivet row.

Top Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
1		11		1	194	11	196	1	80	11	77
2		12		2	197	12	194	2	82	12	80
3		13		3	195	13	197	3	79	13	80
4		14		4	195	14	196	4	77	14	80
5		15		5	195	15	195	5	82	15	82
6		16		6	196	16	194	6	81	16	80
7		17		7	196	17	197	7	82	17	79
8		18		8	196	18	197	8	80	18	84
9		19		9	195	19	195	9	80	19	79
10		20		10	196	20	197	10	81	20	80
Nom.		Avg.		Nom.	190	Avg.	196	Nom.	87	Avg.	80

Bottom Rivet Row:

Csk max dia. (0.001")				Shop head max dia. (0.001")				Shop head depth (0.001")			
Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:		Rivet #:	
41		51		41	197	51	195	41	82	51	80
42		52		42	197	52	198	42	78	52	82
43		53		43	194	53	197	43	81	53	80
44		54		44	193	54	196	44	79	54	82
45		55		45	195	55	197	45	82	55	82
46		56		46	194	56	197	46	79	56	79
47		57		47	196	57	195	47	80	57	80
48		58		48	196	58	197	48	82	58	80
49		59		49	194	59	196	49	80	59	79
50		60		50	194	60	196	50	82	60	77
Nom.		Avg.		Nom.	190	Avg.	196	Nom.	87	Avg.	80

Comments:

Measurements of rivet hole positions after drilling revealed that the two sheets were out of square alignment by approximately 0.143° ($0.050"$ over specimen width) when the rivet holes were being drilled.

Appendix C: Test Setup Photos

(a)

(b)

Figure C 1: Test Load Frame with Mounted Specimen (a) and MTS 407 Controller(b)

(a)

(b)

Figure C 2: Travelling Microscope (a) and Instronet Data Acquisition System Used During Testing

Appendix D: Crack Growth Curves

Figure D 1: Crack Growth Curves for Cracks between Bottom Row Rivets 41 to 44

Figure D 2: Crack Growth Curves for Cracks between Bottom Row Rivets 44 to 48

Figure D 3: Crack Growth Curves for Cracks between Bottom Row Rivets 48 to 52

Figure D 4: Crack Growth Curves for Cracks between Bottom Row Rivets 52 to 56

Figure D 5: Crack Growth Curves for Cracks between Bottom Row Rivets 56 to 60

Appendix E: Raw Data Tables

Table E 1: Strain Gauge Data for MSD-GL-003

Number of Cycles	Strain Gauge Reading (micro strains)															
	1	2**	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1593	59	1537	1616	1625	1641	1612	1653	1973	2025	2020	2010	1934	1965	1921	1985
20000	1610	41	1536	1623	1626	1642	1610	1594	1992	2043	2032	2019	1947	1967	1920	1974
40000	1619	38	1545	1631	1628	1638	1601	1598	1973	2040	2014	2014	1945	1968	1913	1978
60000	1614	54	1534	1626	1626	1640	1613	1608	1999	2042	2018	2013	1941	1961	1905	1983
80000	1607	62	1548	1634	1640	1642	1629	1609	1999	2025	2019	2011	1948	1962	1915	1976
100000	1626	71	1540	1631	1627	1645	1616	1594	1994	2035	2011	2022	1951	1961	1899	1973
120000	1618	35	1543	1635	1613	1634	1611	1607	1996	2037	2012	2012	1938	1956	1921	1980
140000	1604	56	1551	1631	1630	1635	1612	1611	1986	2041	2024	2023	1959	1951	1910	1976
160000	1608	81	1539	1641	1614	1642	1607	1597	1994	2021	2024	2018	1963	1947	1923	1970
180000	1606	74	1543	1628	1622	1638	1606	1594	1986	2024	2040	2004	1971	1941	1938	1948
200000	1598	4	1557	1629	1628	1649	1614	1594	1993	2048	2023	2025	1973	1913	1894	1964
220000	1599	8	1551	1624	1630	1653	1604	1596	1979	2048	2021	2027	1980	1922	1894	1975
240000	1599	5	1558	1631	1643	1649	1611	1602	1964	2040	2023	2017	1973	1927	1900	1967
260000	1575	27	1570	1646	1637	1645	1620	1592	1940	2043	2028	2045	1973	1941	1897	1951
265000	1539	8	1581	1642	1642	1650	1637	1575	1910	2044	2037	2059	1970	1932	1879	1965
277500	1514	75	1628	1691	1666	1655	1619	1575	1891	2021	2076	2109	2008	1955	1874	1953
280000	1500	82	1628	1712	1672	1664	1618	1547	1882	2014	2101	2138	2006	1957	1877	1950

Legend:

Link-up
Dimple visible
Crack length change < 0.005 in

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Table E 3: Crack Growth Data for Rivets 49 to 56

Legend:	Link-up
	Dimple visible
	Crack length change <0.005in

Number of Cycles	Crack Length Measurement											
	Crack length measured from left edge of riveted joint in inches											
	49	50	51	52	53	54	55	56				
	L	R	L	R	L	R	L	R	L	R	L	R
140000												
180000												
185000												
190000												
195000												
200000												
210000												
220000												
230000												
240000												
250000												
255000												
260000												
262500												
265000												
267500												
270000												
275000												
277500												
278513												
280000												

Table E 4: Table E 5: Crack Growth Data for Rivets 57 to 60

Legend:
	Crack length change <0.005in

Crack Length Measurement

Number of Cycles	Crack length measured from left edge of riveted joint in inches					
	57		58		59	
	L	R	L	R	L	R
140000						
180000	16.3565	16.6655	17.3245	17.6410	18.3165	
185000	16.3495	16.6732	17.3282	17.6480	18.3167	
190000	16.3345	16.6725	17.3078	17.6418	18.3015	18.6308
195000	16.3350	16.6815	17.3095	17.6537	18.3012	18.6317
200000	16.3223	16.6810	17.2995	17.6578	18.2930	18.6358
210000	16.3015	16.6968	17.2805	17.6730	18.2727	18.6492
220000	16.2790	16.7025	17.2520	17.6797	18.2493	18.6423
230000	16.2662	16.7192	17.2387	17.6910	18.2365	18.6637
240000	16.2445	16.7350	17.2148	17.7160	18.2115	18.6785
250000	16.2192	16.7580	17.1792	17.7292	18.1795	18.6847
255000	16.1975	16.7695	17.1575	17.7443	18.1683	
260000	16.1750	16.7835	17.1375	17.7570	18.1437	18.6947
262500						
265000	16.1662	16.8065	17.1230	17.7785	18.1272	18.7110
267500						
270000	16.1365	16.8332	17.0925	17.8022	18.1007	18.7130
275000	16.1100	16.8603	17.0563	17.8335	18.0743	18.7255
277500	16.1020	16.8845	17.0465	17.8480		18.7320
278513					18.0430	
280000	16.0765	16.9005	17.0085	17.8670	18.0255	18.7285
						19.6215
						19.6300
						19.6215

Table E 6 Crack Growth Data for Secondary Cracks in MSD-GL-003

Legend:		Link-up
	Dimple visible
	Crack length change <0.005in

Number of Cycles	Secondary Cracks				
	50L upper	44L upper	46R upper	49L upper	53R upper
140000					
180000					
185000	9.3755				
190000	9.373				
195000	9.377				
200000					
210000	9.3745	3.3857			
220000	9.36				
230000	9.375	3.3855	5.6257		12.621
240000					
250000		3.3855		8.3837	12.62
255000				8.38	
260000					
262500					
265000					
267500					
270000					
275000					
277500					
278513					
280000					