Experimental Analysis of Linear Friction Welded Components Under Complex Loading

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Abstract. Experimental studies using a bespoke Arcan test fixture characterise the structural performance of Linear Friction Welded (LFW) wing rib foot joints under combined tension and shear loading. Under tension dominated loading the LFW specimens demonstrated equivalent static strength to their integrally machined counterparts, but as loading becomes more shear dominated then LFW specimens demonstrate performance reductions. Residual strength tests on pre-damaged specimens however shows that LFW joints were more sensitive to tension dominated loading than shear dominated loading, with crack-opening fracture perpendicular to the weld line proving critical.

Introduction.

Linear Friction Welding (LFW) is an advanced joining technique with the potential to produce joined components of equivalent strength to traditional integrally machined components [1-2]. While force and oscilliatory speed requirements currently limit the scale of application, it is ideally suited for joining relatively short features such as the multiple flange elements on the circumference of a typical aircraft wing rib. The loading on such a component is complex, typically combined tension and shear in differing ratios. This paper describes the experimental studies undertaken to assess the performance of LFW rib foot components under these loading conditions. Additionally, considering the increased susceptibility of welded joints to premature failure due to localised damage, a further objective of this study is to analyse the sensitivity of LFW rib foot joint performance to the presence of weld critical flaws.

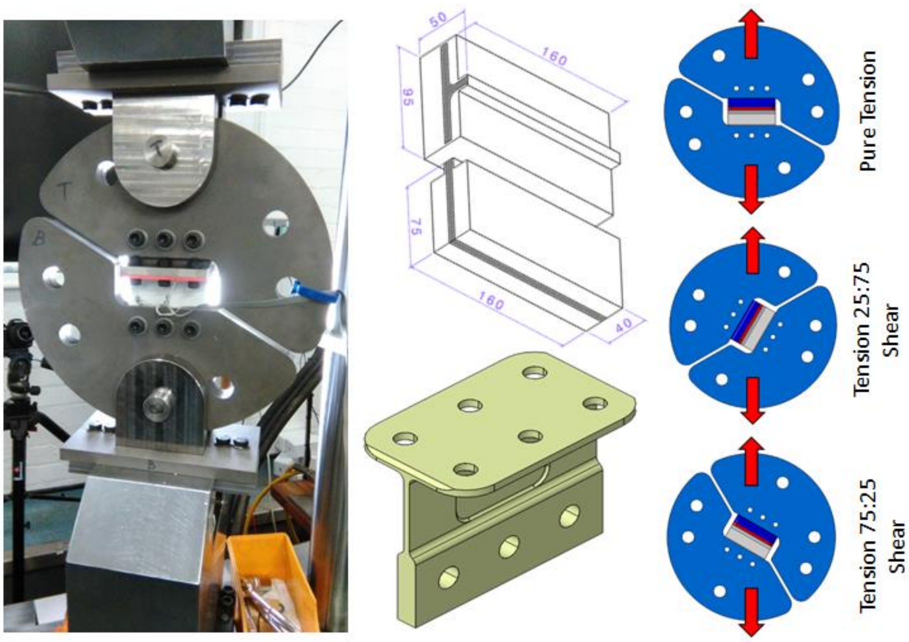

Figure 1. Experimental setup demonstrating the Arcan test fixture, initial weldment pieces, final test specimen geometry and the three test configurations for variable loading.

Methodology.

Specimen geometry is designed to be representative of a complete in-service wing rib shear-tie unit, incorporating free edge mouse-hole boundary conditions and in-service foot flange fastening mechanisms (Fig. 1). Baseline reference specimens are integrally machined from AL7050-T7451 plates. LFW specimens are also manufactured from AL7050 plates. Prior to welding the net foot flange and shear tie web components are extracted independently (Fig. 1). These components are welded together with the weldline running laterally across the vertical rib foot shear tie. Figure 1 presents the final specimen, though final dimensions have been omitted for proprietary reasons. For the residual strength experiments a series of specimens are pre-damaged prior to testing, with an initial crack located directly on the weld line at the edge of the specimen.

Arcan Fixture Design. The test fixture was designed to facilitate combined loading with variable ratios of tension, which assumed perpendicular to the weld line, and shear which is assumed parallel to the weld line (100% Tension, Tension 75%:25% Shear and Tension 25%:75% Shear). Based on background literature an “Arcan” test fixture has been identified as the most suitable fixture type to enable the application of combined tension and shear loading [3]. While more typically used for small scale specimens, the concept has been revised and redesigned for use with larger scale specimens being tested in this work (Fig. 1).

Test Setup and Procedure. Strain gauges are primarily located to acquire and compare local strain data in the vicinity of the LFW weld-line. A digital image correlation (DIC) system is used to measure in-plane and out-of-plane displacement and strain in the central test section pocket. The specimen is loaded in displacement control at a uniform rate a specified in ASTM tensile testing standards until specimen failure occurs.

Table 1: Average percentage variation of AL7050 LFW specimens compared to equivalent baseline machined specimens.

Performance	Tension: 100% Shear: 0%	Tension: 75% Shear: 25%	Tension: 25% Shear: 75%
Yield Strength	+1.8%	-5.4%	-27.5%
Ultimate Strength	+19.2%	+6.0%	-3.4%

Results and Discussion

Static Structural Performance. Rib foot performance demonstrated significant sensitivity to the type of loading applied. In general, under pure tension loading there is no reduction in ultimate strength, with minimal, if any, reduction in yield strength (Table 1). However, under combined loading conditions the relative performance of the LFW components decreases as the level of shear loading increases. The reduction in yield strength is typically greater than the reduction in ultimate strength. When shear loading is applied there are localised regions of high strain detected along the weld-line HAZ (Fig. 2). Consequently, material yielding occurs in this area at a lower load, therefore reducing the structural performance of the rib foot. Under pure tension loading these localised regions of increased strain along the weld-line are less pronounced.

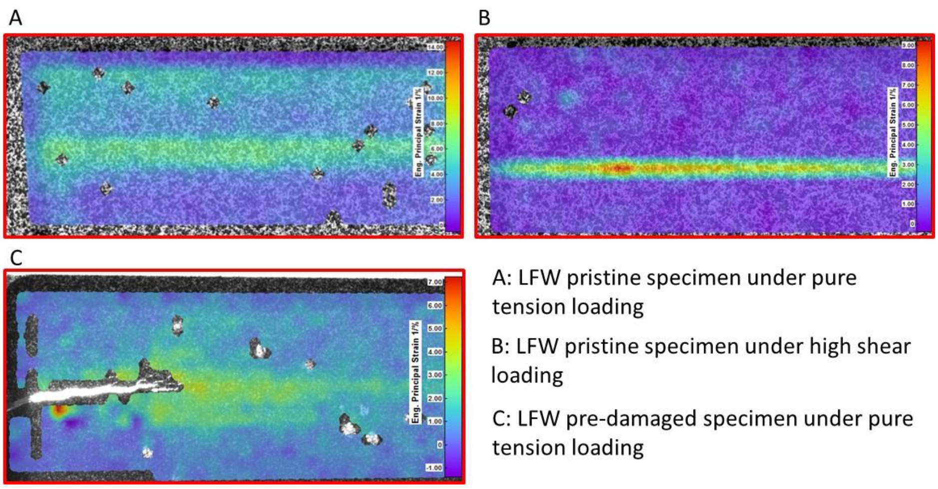

Figure 2: Principle strain in the central shear tie pocket, captured immediately prior to failure using Digital Image Correlation, for pristine and pre-damaged specimens under different loading.

Residual Strength Performance. Testing to failure of pre-damaged specimens was performed under both Tension 75%:25% Shear and Tension 25%:75% Shear loading configurations. LFW specimens demonstrated constistently lower residual strength, with greater performance reductions evident under tension dominated loading. For both baseline and LFW specimens there was relatively 'stable' crack growth until the crack front reached approximately 40-50% of the specimen width, after which crack growth to complete fracture was instantaneous. On the LFW components the "opening mode" fracture acts perpendicular to the weld plane, effectively pulling the weld apart. This may be a potentially critical crack growth mode for this type of weld, contributing to the reduced residual strength performance under tension dominated loads.

Conclusions

The design and manufacture of a bespoke Arcan test fixture enabled the testing of representative linear friction welded wing rib feet under combined tension and shear loading. While LFW specimens demonstrated equivalent static strength performance of their integrally machined counterparts under pure tension loading, as shear component of loading is increased the LFW specimens exhibiting increasing performance knock-downs. In contrast, tests on pre-damaged specimens indicate that the residual strength of LFW rib feet is more sensitive to pure tension loading where the crack opening mode perpendicular to the weld line is potentially more critical.

References

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