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The influence of assembly friction stir weld location on wing panel static strength

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ABSTRACT

Finite Element simulations and mechanical tests are undertaken to assess the impact of weld joint location on stiffened panel static strength. An upper wing cover panel, with a manufacturing process of welding multiple near-net-shape multi-stiffener extrusions with a final net-shape machining phase is investigated. The 7000 series aluminium alloy extrusions and skin bay longitudinal friction stir butt welds are examined. Geometric imperfections exhibit the greatest influence on panel collapse, thus for static strength design the selection of weld joint location should minimise imperfection generation. Moreover the analysis demonstrates limited impact on panel collapse strength when an optimised welding process is employed.

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1. Introduction

Friction Stir Welding (FSW) is a joining method which holds great promise for the fabrication of structures incorporating heat-treatable aluminium alloys. The static strength of joints made using FSW appear favourable when compared with traditional mechanically fastened joints [1]. Moreover, welding offers the potential for faster fabrication times than mechanical fastener assembly and hence manufacturing cost reductions. For aerospace applications the change from mechanically fastened lap joints to welded butt joints enables the potential for simpler joint design, which offers the additional potential for reduced weight and reduced inspection requirements in-service [2–6].

FSW is typically a slower process than fusion welding techniques, such as arc or laser beam welding, but as FSW does not melt the local joint materials it applies a lower heat energy input. This leads to the main advantage of FSW for fabrication of aluminium structures, as a lower processing temperature results in the potential for lower levels of local joint material degradation and lower levels of induced residual stress in the final fabricated components.

To date FSW has being used in a limited number of flight vehicles on an ad hoc basis, due to limited experience of process industrialisation and limited knowledge on in-service performance. A number of detailed studies, examining space vehicle and aircraft structures, have been undertaken to understand the impact of local joint material degradation and induced residual stress on the static strength of final fabricated components [1–5]. These studies have examined the impact of FSW assembly for a single panel design, benchmarking the welded structures performance against an equivalent mechanically fastened assembly [1,2]. Or through detailed Finite Element (FE) simulations have examined varying levels of welding induced material degradation and residual stress and benchmarked these against structures free of welding process residual effects [3–5]. The work available in the public domain does not examine directly the impact of panel weld location on strength, nor is there experimental analysis of representative welded wing panel structure.

Thus this paper presents the results of a study undertaken to assess the impact of assembly weld joint location on the collapse behaviour of stiffened panels. The studied panel structure is designed to be representative of that found within an aircraft upper wing cover. In particular to represent a panel with an ultimate design load of 2500 N/mm, and to be manufactured by welding multiple near-net-shape multi-stiffener panel extrusions before a final net-shape machining process. A combined experimental and simulation study is undertaken, with the experimental results used to validate a simulation procedure, and a series of simulations then used to expand the knowledge on the impact of weld location and the magnitude of welding process residual effects.

The paper is organised as follows: Section 2 briefly introduces the FSW process and reviews the state-of-the-art in the static strength verification of FSW in aerospace stiffened panel assembly.

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Sections 3 and 4 present respectively the experimental and simulation components of the study, and Section 5 presents the combined results and discussion. Section 6 concludes the article with a summary of the key findings.

2. Background

2.1. Friction stir welding

FSW is a solid phase welding process in which a non-consumable, rotating tool transverses the joint. The tool comprises a shoulder, and a protruding probe, which typically features a thread. In the FSW butt joining process the rotating tool is driven axially into two abutted panel edges until the tool shoulder is in contact with the top surfaces, and the bottom of the probe reaches to within a small distance of the panel bottom surfaces. The tool then transverses along the interface. The rotating motion of the tool and the applied tool pressure generates significant frictional heating, sufficient to plasticise the material within the local zone of the tool. As the probe moves along the abutted panels, it stirs the plasticised material from in front of the probe around itself into its wake. The forging pressure applied by the tool shoulder then presses the intermixed plasticised material behind the probe producing a butt joint.

Assembling aircraft stiffened panels using FSW offers opportunity to reduce fabrication time and cost in comparison to current mechanical fastener assembly. FSW can achieve joining speeds of the order of 0.60 m per minute in comparison to the 0.25 m per minute achieved by traditional auto-riveting. Moreover, welding enables complex mechanically fastened lap joints to be replaced by simpler butt joints. Removing lap joints reduces potential sites for crevice corrosion and the removal of mechanical fasteners has the potential to reduce panel mass and reduce external surface irregularities, improving the aerodynamic characteristics of the assembled structure.

However, FSW assembly has a number of disadvantages when considering the thin-walled nature of aerospace structures and the heat-treatable aluminium alloys they typically incorporate:

- *Local material property degradation* – the local heat applied during welding can alter the microstructure and degrade the local material properties around the joint line.
- *Residual stresses* – the weld heating and consequent joining and cooling introduces residual stresses, potentially detrimental to panel fatigue and damage tolerance. Moreover the induced residual stresses can cause panel geometric distortions, and these again can be detrimental to panel stability.
- *Design for durability* – mechanical fastened joints can act as crack arresters but a welded structure will behave as a single integral component, thus an initiated crack may propagate through the entire fabricated structure with no natural crack arresting features.

A significant number of studies have examined the impact of these residual process effects on panel static strength, fatigue and damage tolerance behaviour, considering basic joint coupons [7–14]. There is less literature available which focuses on larger panel assemblies under representative in-service loading. As this paper focuses on wing panel static strength the following section summarises those studies which concentrate on static strength behaviour of larger panel assemblies.

2.2. Large stiffened panel studies

Work examining spacecraft launch vehicles considered FSW as a rivet replacement technology for panel construction [1,2], benchmarking the static strength of welded joints and compression panels against equivalent mechanically fastened assemblies. The test results demonstrated the potential for FSW joints to exceed the lap shear strength of traditional riveted joints, and the compression tests demonstrated the potential of FSW assembly lap joints to effectively function throughout panel local skin buckling, post-buckling and ultimate panel failure behaviour. The work considers the direct replacement of a riveted skin-stiffener lap joint with an identically located welded skin-stiffener lap joint, with no direct examination of the impact of weld joint location on static strength.

FSW has also been investigated as a rivet replacement technology for the manufacture of aircraft fuselage panels [3,4]. In this work no equivalent riveted specimens were tested but an attempt was made to quantify the impact of welding process effects on static strength performance via computational studies modelling the experimentally tested specimens. Again, like the launch vehicle studies no direct examination of the impact of weld joint location on panel static strength was considered. However, based on these fuselage studies modifications to conventional aircraft panel static strength design methods have been proposed [5]. The experimental results established that standard panel buckling analysis procedures must be altered to account for the weld joint geometry and process altered material properties.

Considering aircraft wing structures Yoon et al. [6] examines FSW as a rivet replacement technology for the assembly of wing cover panels. The study does not present experimental test data but focuses on detailed Finite Element simulations, demonstrating the potential impact of weld joint material property degradation on the maximum buckling load of the assembled wing structure.

Beyond aerospace significant work has also been undertaken on marine stiffened panels. Aalberg et al. [15] experimentally examined FSW for the assembly of passenger deck floors for high-speed catamaran ferries. The tests again demonstrate the potential for FSW joints to function throughout panel local skin buckling, post-buckling and ultimate panel failure behaviour. Paik [16] also undertook significant experimental work on FSW for the assembly of marine stiffened panels, comparing performance against previously tested fusion-welded specimens [17]. Paik's experimental studies demonstrated the potential for improved panel strength, due to the smaller initial imperfections and material degradation possible with FSW assembly.

To date significant work is available on the impact of FSW as a direct replacement technology for panel skin-stiffener riveted lap joints, with significant experimental and simulation studies beyond simple coupon structures, examining large panel assemblies. There is less equivalent experimental and simulation work published on the use of FSW in the assembly of aircraft wing panel structures. However, the available computational studies on wing panel assembly with FSW highlight the potential for the residual process effects to impact static strength. Overall the published work tends to focus on a single design with very limited work directly examining the impact of panel weld location on strength, the main aim of this paper.

3. Validation

3.1. Specimen design

In order to fill the identified gap in knowledge, a test programme was developed to assess the impact of assembly weld joint location on stiffened panel static strength. To represent realistic aircraft structure a conventional upper wing cover panel design was created based on generic design requirements for a single aisle civil transport aircraft. The generic wing panel was

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