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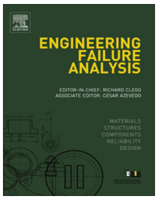

Structural overloading evaluation based on the identification of subcritical crack increments

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ABSTRACT

A complex approach using fractographic and FE analysis was used to assess the load level of a lower root spar assembly under conditions, which were close to the critical load of the structure.

A Damage Tolerance scheme of determining the conditions for subcritical crack increments was used. The stress state for the measured subcritical increments in an airplane structure was determined using a proposed iterative solution to match the material *R* curve to the *J*-integral solution. A structural stress analysis of the root of the wing structure assigned a load level to the crack state identified above. The numerical FE solutions of the *J*-integral along the identified crack fronts were generated using ABAQUS SW at the Strength of Structures Dpt., Aerospace Research and Test Establishment.

The analysis provides information regarding the near-critical loading condition of the wing structure.

1. Introduction

A fatal accident occurred on an all-metal two-seater trainer sailplane in Austria, Ferlach in 2010 [1,2]. The main spar of the right wing failed near the root due to a positive load while approaching an airfield after an aerobatic training flight. The right wing detached from the aircraft and the pilots lost control of the sailplane. Two people died as a consequence of this accident, and the entire fleet of sailplanes of this type was grounded by the EASA [1].

The wing span of the airplane is subjected to cyclic loading during its service. For this reason, the spar components experience fatigue, leading to initiation and propagation of cracks at highly stressed areas. Case histories in aerospace indicate that fatigue is the dominant mode of failure in aircraft components, accounting for nearly 55% of the total failures [3,4]. Failure of the wing is often fatal for the airplane and its crew, and there is a high priority to ensure the structural integrity of wings [5–7]. To return the fleet sailplanes to service and clarify the accident, an analysis of the wrecked parts was performed.

2. Failured parts

The preliminary investigation revealed that the failure was due to fatigue [8]. Fractographic features of fatigue were found on fracture surfaces, but was not stated whether the failure was caused by overloading due to restricted maneuvre

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or whether the construction was roughly serviced, which could accelerate a crack growth, e.g. by high number of training flights with winch starts or by high number of aerobatic flights inconsistent with sailplane design scope. The full service history was not obvious from records in flight book because of insufficient logs [8]. In order to find out more information about sailplane operation, fractographic analysis was performed on the wrecked parts [9].

The fracture occurred approximately 200 mm from the wing root through fastener holes in the wings main spar lower flange located in the area of the hinge (see Fig. 1). Fastener holes are drilled perpendicular to the flange base short transverse direction and are countersunked.

The fatigued part of the flange failure consists of initiation, crack growth and subsequent connection of 3 fatigue cracks, denoted *T*1–*T*3 in Fig. 2. Fatigue failure passes over 2 fastener holes (denoted as I and II in Fig. 2) through which the flange, fitting and splice are joined together.

Crack *T*1 grew from the outer fastener hole I to the edge in a plane perpendicular to the longitudinal axis of the flange with one-quarter of the penny-shape in a front. The rest of the crack surface with 60° to the flange basis was mechanically damaged; i.e. fracture micromorphology could not be described [9]. Crack *T*2 grew from the outer fastener hole I in an opposite direction to crack *T*1 in a similar way. The *T*2 crack front changed to a straight shape, perpendicular to the slightly curved growth direction, after propagating through the entire thickness of the flange. Simultaneously, the crack started to twist around the direction of propagation and finally reached an entire cross section between fastener holes *I* and *II*. Crack *T*3 propagated from fastener hole *II* in the same direction as crack *T*2. Two initially separated quarter penny-shaped cracks connected with each other and continued as one crack with a straight crack front non-perpendicular to the flange sites [9]. Two other cracks *T*4 and *T*5 were found in the flange. Crack *T*4 is positioned opposite to crack *T*3 and crack *T*5 is located at the edge of fastener hole *III*. They are short in comparison with dominant cracks *T*1, *T*2 and *T*3 and did not connect other cracks.

Fractographic analysis revealed, that cracks *T*1 and *T*2 initiated at approximately the same time. The first excessive overloading created tear bands denoted as *O*1. Crack *T*1 had at overloading event an approximate length of 1.5 mm and crack *T*2 of 1 mm. The subsequent excessive overloading created tear bands denoted as *O*2. The end of this tear band is unclear on crack *T*1 due to mechanical damage of fracture surface. The advance of the crack front may have been 1 mm or it may have reached the free edge and break a resting cross section between fastener hole I and the free edge of the flange. In that case, the crack extent would have been 4 mm. The second overloading caused a 1 mm thick tear band at crack *T*2, and a slightly curved crack front was created. Furthermore, two separate fatigue cracks in hole *II* were connected by this overloading, resulting in an approximately straight crack front of crack *T*3. This scenario assumes a continuous crack in the flange with a length of 12.5–16.5 mm (diameter of the fastener hole included) after the overloading *O*2. The presence of progression marks beyond tear bands *O*2 on fracture surfaces of cracks *T*2 and *T*3 provide evidence of repetitive cyclic loading after the tear bands formation (see Fig. 3). This implies that final failure of entire cross section of the flange did not occur next to the second excessive overloading, but later at longer crack lengths advanced by continuing cyclic loading on lower load levels.

Fractographic analysis confirmed the fact that the fracture mechanism of all cracks was fatigue [9]. The well-defined mechanism of striation formation through crack propagation was evident, which is consistent with the fatigue crack propagation mechanism [10–13]. On the fatigue fracture surfaces were found zones of ductile fracture with dimples at longer cracks as depicted in Fig. 3 [9]. Regions of striations are interrupted by bands which reveal ductile fracture. A similar surface feature has been reported on many fatigue fracture surfaces of aluminium alloy aircraft components, particularly for in-service failures [14–17]. Forming such zone of ductile fracture is mostly referred to stable tearing. However, other descriptive terms are used in the literature, such as brittle crack growth, tensile crack jumping, quasi-cleavage, tongue-shaped crack extension, ductile tearing rupture, and mixed fatigue–tensile crack growth [18].

Variable striation spacing and beach marks document crack propagation via variable amplitude loading. Very high overloading cycles may cause tear bands [14]. Sequences of flight loads and markings are usually related to reveal the relationships between the crack front progression markings and the loading history of the structure component. However, the boundaries between the regions of crack growth and final failure are not always fully clear due to excessive mechanical damage of crack surfaces at longer crack lengths. In the absence of knowledge of service loading, it is practically impossible to determine the crack growth curves and interaction among cracks using methods of reconstruction of crack growth based on

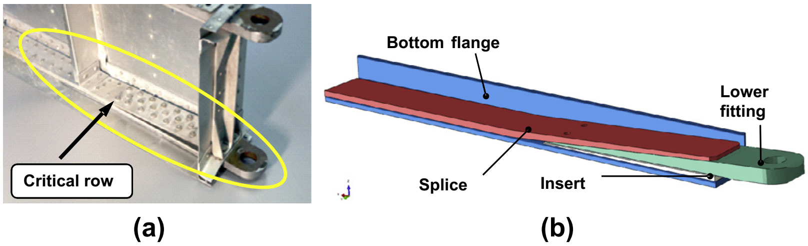

Fig. 1. (a) Root spar assembly view and (b) Lower root flange assembly – 3D model.