Testing of fatigue cracks under biaxial loading conditions to represent conditions of a metallic aircraft fuselage section

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ABSTRACT

Shortage of resources has led to a situation where lightweight structures become tremendously significant nowadays. Generally, lightweight design means that parts and structures are subjected to loadings close to their limits for an optimal exploitation of their mechanical capabilities. If such structures are subjected to non-constant services loads during their operational life fatigue cracks will surely occur. A typical example for this situation is the fuselage section of commercial aircrafts, as wall thickness of about 1.2 mm to 2.5 mm together with fatigue stresses of more than 100 MPa are usual values here. The dominating concept used in aviation industries to face these unavoidable fatigue phenomena is called “damage tolerance design”. In short it means that cracks are basically allowed but must not lead to catastrophic failure during scheduled service operations. Thus, cracks have to be considered already in the design process of new aircrafts, and their behavior needs to be fundamentally studied to reliably predict lifetimes and associated failure probabilities, respectively, or service intervals. To fulfill these requirements excessive mechanical testing of full-scale and barrel tests as well as panel tests is needed while associated with enormous testing costs.

During the preliminary design stage more basic questions concerning the individual fatigue behavior of different materials or structural designs is on focus. Therefore, in this work an enhanced testing procedure has been developed to map fatigue cracks of an aircraft fuselage to cruciform specimens that can be tested under close-to-reality biaxial loading conditions [1]. For this purpose, at first the mechanical loadings and the fatigue crack behavior of a full-scale panel test specimen, a so called IMA-panel test, has been analyzed with finite element simulations providing detailed information about the local crack tip loadings. The crack propagation scenarios here are mainly distinguished into circumferential (I) and longitudinal (II) cracks. With further simulations of the cruciform specimens these crack tip loadings were mapped onto them. Finally, this procedure led to two different specimen designs which allow realistic tests of two-bay-cracks of primary aircraft structures. For the circumferential crack the cruciform specimen has overall dimensions (i.e. including clamping zone) of 1120 x 1120 mm² and a testing area of 380 x 380 mm². Three stringers are attached to reproduce a crack behavior close to reality. The scenario of the longitudinal crack requires a much larger specimen with a testing area of 923 x 559 mm² and an overall size of 2098 x 1734 mm². Figure 1 illustrates this specimen together with the experimental setup. The large biaxial testing machine with the crosswise arranged hydraulic actuators has a maximum static loading capacity of 1000 kN and cylinder strokes of 100 mm. With specimen thicknesses of 1.60 and 1.75 mm maximum loadings of about 177 kN were needed. For the investigations of fatigue cracks artificial saw cuts acting as starter notches have been cut in the center of the specimens. Due to the biaxial sinusoidal loadings during the

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tests the cracks propagated symmetrically in the specimens and the crack growth rates were captured at certain intervals. All experiments were conducted using a GOM Aramis 12M 3D digital image correlation (DIC) system to obtain the deformation and displacement fields of the specimen's surface during testing. Based on these data the fracture mechanical parameters J, K_I and K_{II} were calculated with a special post-processor which uses the J and interaction integral as line integrals surrounding the crack tip [2]. Two different aluminum alloys, namely AA2024-T351 and AA5028-H116, were tested simulating the two cracking scenarios. While AA2024 is a standard alloy which has been used for decades in aviation industries, the comparably new AA5028 has similar mechanical properties but an about 4 % lower density which offers the opportunity for further weight reductions.

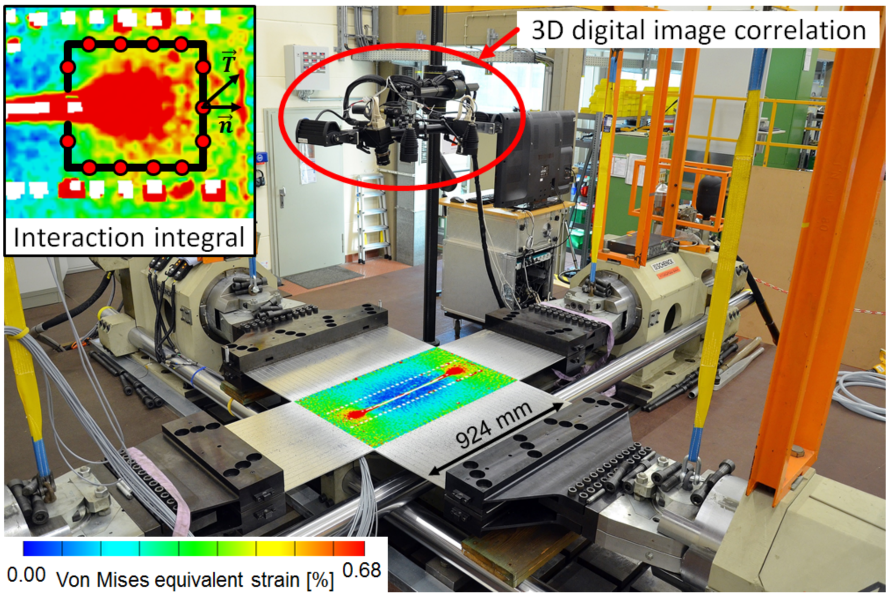

Figure 1: Biaxial testing of cruciform specimen supported by 3D digital image correlation

The obtained results led to very valuable conclusions. Because of the large specimen dimensions stress intensity factors up to 160 MPa√m together with stable crack propagation rates of more than 1 mm per cycle could be achieved. The enhanced DIC post-processing allowed for precise computation of the locally acting stress intensity factors and J integrals. By conducting such computations at maximum and minimum loading conditions even crack closure effects can be captured. Therefore, with this procedure it is possible to even take the complex effects of the plastic zone into account [3]. The crack propagation data in terms of da/dN-ΔK diagrams show that the evaluations based on linear-elastic finite element analysis and the DIC post-processor reveal a slightly different behavior. Taking into account crack closure with the DIC evaluations the curves of the different experiments move closer together. Summarized, this procedure offers the opportunity for close-to-reality testing using comparably small specimen sizes but still being able to study crack propagation behavior under very high biaxial loadings as found in actual fuselage structures under service conditions.

References

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