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Fatigue crack deflection in cruciform specimens subjected to biaxial loading conditions

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ABSTRACT

Crack deflection is studied for the aluminum alloys AA2024-T351 and AA5028-H116 under biaxial fatigue loading. With cruciform specimens that have a testing area of about 420 × 420 mm^2 a fatigue crack was subjected to nominal biaxiality ratios between 1.0 and 3.0. Consequently, the crack is subjected to different magnitudes of T-stress. Finite element simulations of the growing crack revealed that the crack path is not significantly influenced by the T-stress but the T-stress predicts whether the crack path remains stable. If at least two crack paths are basically possible the crack will kink for positive T-stresses and remain stable for negative T-stresses. Furthermore, small spikes with strain concentrations along the crack path are identified with digital image correlation which might cause crack deflection in this case.

1. Introduction

For commercial aircrafts the damage tolerance design and design against fatigue are necessary for safety reasons but they cause also economic problems in terms of cost-efficiency [1]. Such lightweight structures are subjected to loadings close to their limits for an optimal exploitation of their mechanical capabilities. Due to non-constant service loads during the service life fatigue cracks will arise and need to be considered in the design process. Consequently, not only the crack propagation rate but also the crack path needs to be predictable. In this context crack turning has been identified as an approach to enhance the damage tolerance behavior [2]. Dependent on the external stress state a turning crack can significantly enhanced the residual strength of fuselage structures with a 2-bay-crack, as the crack tip loadings are reduced [3,4].

Under linear-elastic conditions the stress state near the crack tip can be analytically described with the Williams series expansion [5]. In linear-elastic fracture mechanics usually only the first term is used because the fracture behavior is dominated by the near-tip stress field. The coefficients are the well-known stress intensity factors K_I and K_{II} with the $1/\sqrt{r}$ singularity [6]. Taking into account the following non-singular coefficient leads to a stress component acting parallel to the crack growth direction. This constant stress term is known as the *T*-stress. Fig. 1 illustrates the local stress components at the crack tip which lead to K_I, K_{II} and the *T*-stress. It has to be mentioned that there is no equivalent term in the perpendicular direction because the related term in the Williams series is zero.

Over time, it was found out that more accurate approaches including higher order terms are required to sufficiently capture local effects on the crack tip [7]. There are concepts that use up to three parameters in linear-elastic as well as in elastic-plastic fracture mechanics [8]. The *T*-stress has been identified as a parameter that can be used to predict the crack path stability under biaxial loadings. Under negative *T*-stress ($T < 0$) the crack path will remain stable while under positive *T*-stress ($T > 0$) the initial crack path becomes unstable [7], [9]. In linear-elastic fracture mechanics it is assumed that a crack grows straight under pure mode I loading conditions, i.e. in absence of mode II and III loadings. One criteria to predict the crack path taking into account the *T*-stress uses the maximum average tangential stress (MATS)). Here it is assumed that the crack will grow perpendicular to the direction where the tangential stress is maximum [10,11]. Considering a straight crack orientated to one of the principal axis in a biaxially loaded sheet (like the skin of the fuselage structure of an aircraft), an evaluation of this loading situation only based on the concept of stress intensity factors will not account for any crack deviation effects, i.e. the crack will not change its direction within this kind of analysis. But taking into account the *T*-stress would allow the prediction of crack kinking starting at a certain stress level. Furthermore, the effects of *T*-stress are also clearly reflected in the shape of the plastic zone at the crack tip. While positive *T*-stress reduces the size of the plastic zone, negative *T*-stress increases its size [12]. The characteristics of the plastic zone again are very important as they significantly influence the

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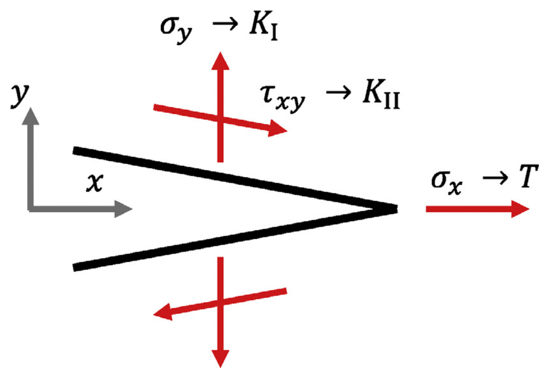

Fig. 1. Illustration of stress components at the crack causing K_I, K_II and T.

crack behavior and can also be used to predict the crack path [13,14]. In this paper the crack deflection under biaxial fatigue loading conditions is studied. Numerical analyses as well as local DIC investigations are carried out to investigate the crack propagation behavior of the aluminum alloys AA2024-T351 and AA5028-H116. Both alloys are used in the aviation industry, and here biaxial loading significantly influences the damage tolerance capability of the aircraft structures.

2. Experimental program & Numerical studies

In the experimental program crack deflection was studied for the aluminum alloys AA2024-T351 and AA5028-H116. While the former had a thickness of $t = 1.8$ mm the latter had a thickness of $t = 3.3$ mm. The experiments were supported by crack propagation simulations within a linear-elastic finite element model. The design of the specimen is shown in Fig. 2. This kind of specimen has been used for decades at the German Aerospace Center with different modifications [15]. The gauge area of the specimen is in its center (blue part). With the dimension of 380 mm × 380 mm it covers the area of about three stringers as found in a fuselage structure. This (blue) sheet is joined to in total eight loading arms (grey – four on the front and four on the rear) that are fixed to the clamping tools of the testing machine. Finally, the

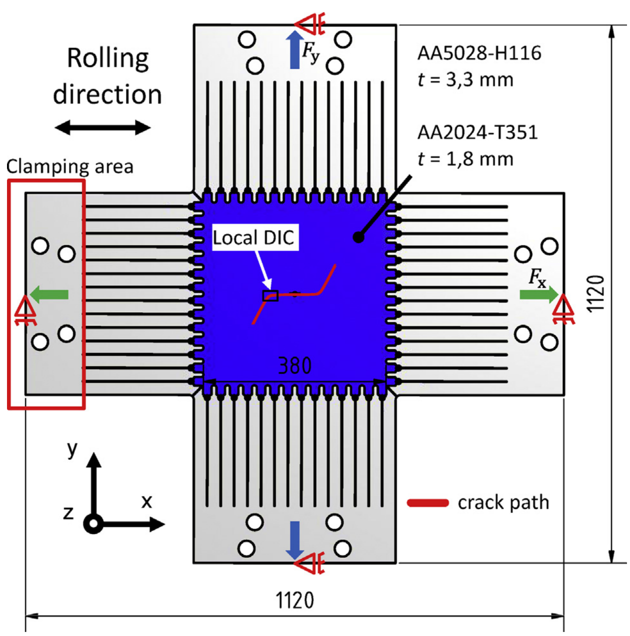

Fig. 2. Details of the biaxial specimens with boundary conditions. The crack path of the fatigue crack experiment is illustrated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cruciform specimen has overall dimensions of 1120 mm × 1120 mm. The fatigue crack will grow inside this testing area in the center (blue) as illustrated by the red line in Fig. 2. To promote the initial crack growth direction being parallel to one of the principal loading axis a starter notch was induced. Therefore, an 8 mm hole was drilled in the center of the specimen and 10 mm long saw cuts were introduced in the x direction on two opposite sides of this hole.

The biaxial stress conditions are characterized by Eq. (1) using the biaxiality ratio λ. It is defined by the stress parallel to the crack $\sigma_=$ divided by the stress perpendicular to the crack $\sigma_\perp$.

$$\lambda = \frac{\sigma_=}{\sigma_\perp} = \frac{\sigma_\mathrm{x}}{\sigma_\mathrm{y}} \tag{1}$$

In detail the following investigations were conducted in this paper:

(1) Finite element simulations of different angels of a kinking crack to analyze the relationship of K_I, K_II and T-stress.
(2) Crack propagation simulations in cruciform specimens with different biaxiality ratios λ ranging from 1.0 to 3.0.
(3) Experimental investigations of the biaxiality ratios λ ranging from 1.0 to 3.0 in specimens made of the aluminum alloys AA2024-T351 ($t = 1.8$ mm) and AA5028-H116 ($t = 3.3$ mm) under fatigue loadings with a load ratio R of 0.1.
   a. Introducing a $2a = 80$ mm long fatigue crack with $\Delta K_\mathrm{I} = 10$ MPa√m and λ = 0.0.
   b. Crack propagation of $\Delta a = 2$–3 mm with λ = 1.0.
   c. Crack propagation of $\Delta a = 2$–3 mm with λ = 1.5 (only AA5028-H116 specimen).
   d. Crack propagation of $\Delta a = 2$–3 mm with λ = 2.0.
   e. Crack propagation of $\Delta a = 2$–3 mm with λ = 3.0.
   f. Continuing with crack propagation with last biaxiality ratio after the crack kinked.

With regards to aircraft structures the case of λ = 1.0 can basically be attributed to parts of the upper fuselage section where hoop stresses and longitudinal stresses are nearly equal. A biaxiality ratio of λ = 2.0 is a typical case for a circumferential crack if the stresses are estimated by Barlow's formula for a closed (thin walled) pipe-like structure with internal pressure. The stresses in hoop direction are twice as much as that in longitudinal direction. Complex load spectra representing realistic flight scenarios are neglected in these fundamental analyses as their consideration would clearly complicate the interpretation of the experimental findings. The experiments were conducted with two different initial stress states for both specimens which are $\sigma_\mathrm{y} = 40$ MPa for the AA2024-T351 and $\sigma_\mathrm{y} = 29$ MPa the AA5028-H116 specimen. For both experiments the corresponding stresses are finally summarized in Fig. 8.

2.1. Finite element simulations

All simulations were conducted with ANSYS Classic controlled by APDL scripts. The FE model of the cruciform specimen is derived from the geometry shown in Fig. 2. Here the gauge area in the middle (blue section) is modelled with 2D plane stress elements. With thicknesses of 1.8 mm and 3.3 mm this sheet is thin compared to its overall dimensions (Fig. 2) which supports this assumption of prevailing plane stress conditions. Because of the symmetry of the specimen out-of-plane effects like bending or buckling are limited to the very final stage of the experiments, and are consequently neglected in the simulations. Furthermore, 2d elements have the advantage in fracture mechanical analyzes that only a unique value for the stress intensity factor is obtained instead of a through thickness distribution along the crack front for a 3d model (which would require additional assumptions for the computation of a single representative stress intensity factor). The loading arms are modelled with 3d solid elements because this element type facilitates the model generation as the loading arms can directly be

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