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Study of different DIC approaches to measure crack opening/closing levels in a biaxial crack growth trial with combined HCF/LCF loads

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Abstract – Crack closing forces are important to determine effective cyclic stress intensity factors ΔK_{eff} in fatigue crack growth trials. By digital image correlation (DIC), the change of stiffness between the open and closed crack can be measured in different ways evaluating stress-strain curves either globally using integral strain perpendicular to crack growth direction or locally measured by virtual extensometers distributed along the crack. Crack opening and crack closing forces obtained by compliance of integral strain and of crack opening profiles measured by virtual extensometers are compared for a biaxial crack growth trial applying HCF and LCF cycles.

Keywords – DIC; Fatigue crack growth; Uni- and biaxial loading; Compliance method

Precise determination of the remaining service life of technical components requires sufficient knowledge of fatigue crack growth behavior and the growth rate of defects. Cracks in real components often experience multiaxial far-field stresses due to their complex geometry and composite loadings acting on it. This paper shows results from a GPU-based high-performance DIC system specifically designed for a planar biaxial test-rig to carry out multiaxial fatigue crack-growth experiments. It provides comprehensive strain data comprising biaxial integral strain on a measurement rate of 850 Hz, like mechanical extensometers, and fast full-field evaluations in selected images selected from the data stream in real-time [1, 2]. Figure 1 shows on the left the DIC measurement head in front of a biaxial testing machine equipped with a cruciform specimen. As can be seen in the camera image on the right, the microstructure of the specimen is used as correlation pattern without need for speckle paint.

To investigate crack closure behavior, the resulting DIC data can be used in three different ways: calibration of fracture mechanical FE models to simulate the influence of T-stress or crack-closure effects like plasticity-induced crack closure [3] or evaluating the strain data directly for the change of specimen stiffness when the crack opens or closes. The latter can be done either in integral strain signal by the compliance method as defined by ASTM E647 [4] or, similarly, by evaluating stress-strain curves from virtual extensometers placed in full-field DIC along the crack [5].

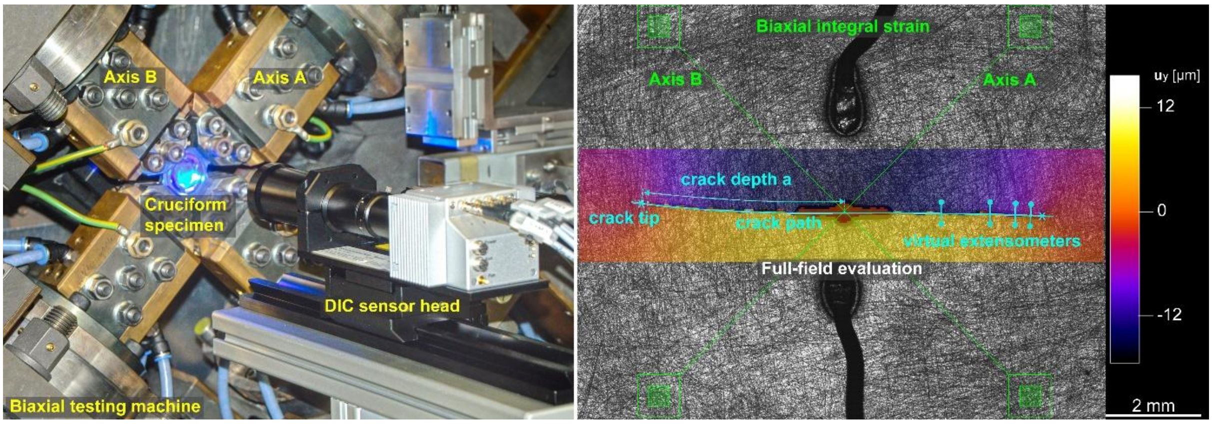

Figure 1: Left: DIC sensor head in front of the biaxial testing machine equipped with a cruciform specimen. Right: camera image of specimen surface superimposed by the four subsets for measuring integral strain or elongation Δl (green) and by the full-field evaluation area with vertical displacement u_y (color scale), i.e., in force direction. Crack evaluation (cyan): crack opening Δu_I in mode I direction is measured by virtual extensometers positioned 0.2, 0.5, 1.0, and 2.0 mm behind the crack tip. Crack tip positions are marked by 'x'. Crack depth a is defined as half crack path length between the tips.

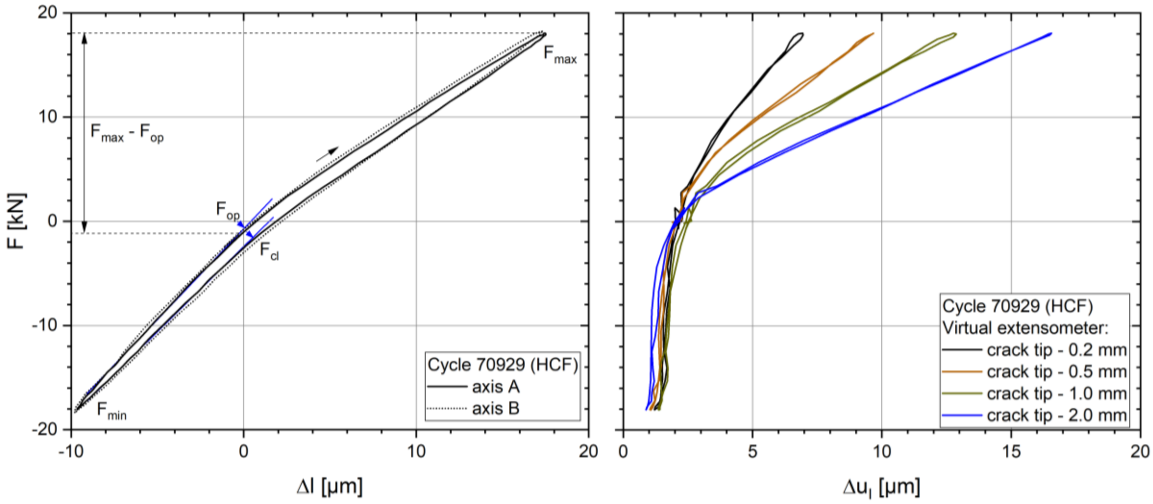

Figure 2: Left: Opening and closing forces F_{op} and F_{cl} from integral strain for an HCF cycle at a crack depth a of 4.164 mm. Right: corresponding curves from virtual extensometers depicted in Figure 1. The load is symmetric to axes A and B, therefore total force is perpendicular to the crack. As the crack appears as a discontinuity in displacement, the elongation Δl and, correspondingly, the crack opening Δu_I in mode I direction are drawn instead of strain values.

The crack opening/closing curves from figure 2 were taken from trial mAARTdf5 [2] using a titanium alloy Ti6246 for aero engine applications like blisks. A component near load-collective is mimicked by a fixed sequence where 20 HCF-amplitudes of 18 kN are applied symmetrically to both axes for 20 consecutive cycles, followed by an overload LCF-amplitude of 35.5 kN.

Generally, crack growth rates da/dN in Paris diagrams are often drawn against the effective cyclic stress intensity factor ΔK_{eff} which is calculated from the force range $F_{max} - F_{op}$ instead of $F_{max} - F_{min}$. In that effective range, the crack is open and growing. A common method to measure opening and closing levels, F_{op} and F_{cl}, is based on the offset of the compliance du_I/dF [4 - 6]. On the left in figure 2 it is demonstrated that the stiffness of the specimen changes when the crack opens or closes. On the right of figure 2, similar stiffness curves from the virtual extensometers depicted in figure 1 are drawn which were placed 0.2, 0.5, 1.0, and 2.0 mm behind the crack tip, respectively. This paper studies the consistency of the crack opening/closing levels obtained from these curves under HCF an LCF loading situations.

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