SIMULATION OF FATIGUE CRACK GROWTH IN REAL STRUCTURES

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Introduction. Fracture of structures and components due to fatigue crack growth in many cases cannot solely be explained by fatigue or service strength investigations. Not only in those cases, but even more generally fracture mechanics provides valuable approaches and methods in order to predict and to prevent crack growth or at least in order to understand and investigate already occurred failures. In this contribution it will be shown, to what extent fatigue crack growth in real structures under complex loading situations can be predicted and simulated. Especially inspection intervals for safety relevant components can only reliably be defined by simulating fatigue crack growth.

Crack growth concepts for 3D-structures

The basis for most fatigue crack growth concepts in 3D-structures are the near field solutions for the stress distribution at the crack front:

$$\sigma_{ij}(t) = \frac{K_I(t)}{\sqrt{2\pi r}} f_{ij}^{I}(\varphi) + \frac{K_{II}(t)}{\sqrt{2\pi r}} f_{ij}^{II}(\varphi) + \frac{K_{III}(t)}{\sqrt{2\pi r}} f_{ij}^{III}(\varphi)$$

with the stress intensity factor K_I for Mode I-, K_{II} for Mode II- and K_{III} for Mode III-loading [1]. Those 3D-Mixed-Mode-loading situations often occur in real structures with complex geometry and loading conditions, which additionally might even change during the crack growth. An existing crack under just Mode I-loading conditions (which is charac-terised by the stress intensity factor K_I) will propagate within its original crack plane. Mode II-loading generally leads to a kinking of the crack, while Mode III causes a twisting of the crack front. But also the superposition of Modes I, II and III creates special crack surfaces, which often can be observed in practical cases (Fig. 1).

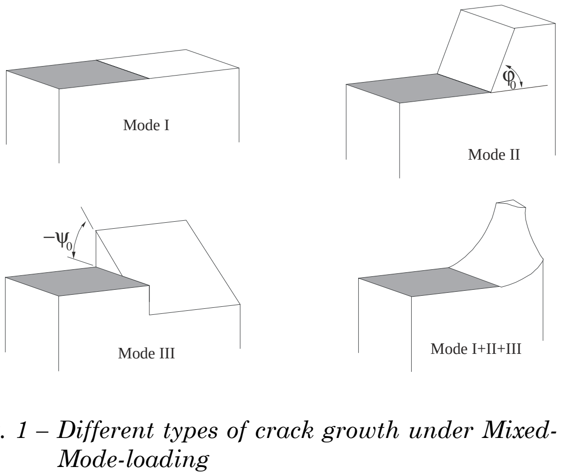

Fig. 1 – Different types of crack growth under Mixed-Mode-loading

A crack that is subjected to an arbitrary Mixed-Mode-loading is able to propagate under fatigue crack growth conditions, if the local crack front loading consisting of a weighted combination of Mode I, II and III is within the range of the fatigue threshold value $\Delta K_{I,th}$ and the cyclic fracture toughness value ΔK_{Ic}. That means that the crack will grow, if the cyclic equivalent stress intensity factor

$$\Delta K_{eq} = \frac{\Delta K_I}{2} + \frac{1}{2}\sqrt{\Delta K_I^2 + 4(\alpha_1 \Delta K_{II})^2 + 4(\alpha_2 \Delta K_{III})^2}$$

with α_1=1.155 and α_2=1.0 exceeds $\Delta K_{I,th}$. Unstable crack growth occurs for $\Delta K_{eq} = \Delta K_{Ic} = (1-R)K_{Ic}$ (Fig. 2, [2]).

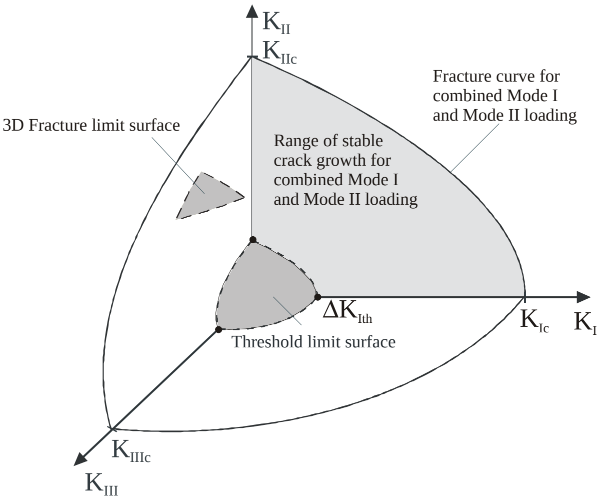

Fig. 2 – Fracture and Threshold limit surface for 3D-Mixed-Mode

The fracture surfaces, that will develop under stable as well as unstable 3D-crack propagation are described by a kinking angle φ_0 and a twisting angle ψ_0 (Fig. 1). They can be determined by following formulas [1,2]:

$$\varphi_0 = \mp\left[140^\circ \frac{|K_{II}|}{K_I + |K_{II}| + |K_{III}|} - 70^\circ\left(\frac{|K_{II}|}{K_I + |K_{II}| + |K_{III}|}\right)^2\right]$$

$$\psi_0 = \mp\left[78^\circ \frac{|K_{III}|}{K_I + |K_{II}| + |K_{III}|} - 33^\circ\left(\frac{|K_{III}|}{K_I + |K_{II}| + |K_{III}|}\right)^2\right]$$

Numerical and experimental simulations of fatigue crack growth

The simulation of fatigue crack growth i. a. can be carried out with the help of the Finite-Element-Method. The program system ADAPCRACK3D has turned out to be well suited for the investigation of real 3D-crack problems [3]. For a 3D-structure a Finite-Element-Model is generated, that takes into account the basic as well the crack geometry of the structure. Under consideration of the boundary conditions the problem is solved by a standard FE-solver with the help of the submodelling technique. From the nodal forces and displacement the energy release rate for the crack propagation and thus the stress intensity factors K_I, K_{II} and K_{III} (resp. ΔK_I, ΔK_{II} and ΔK_{III}) can be calculated along the 3D-crack front. After checking, whether the crack propagation criterion is fulfilled, the crack growth direction (in case of a growing crack) can be determined for every node of the crack front, and the simulation can be continued until $\Delta K_{eq} = \Delta K_{Ic}$. This approach has already successfully been applied for a large number of practical crack cases. Examples for this i.a. are a shutter ring of a hydraulic press [3] and the broken wheel tyre of the German ICE-high speed train, which in 1998 caused a catastrophic accident [Fig. 3, [4]). However, a necessary prerequisite for a good agreement between the numerical simulation and reality is the reliable experimental determination of fracture mechanical parameters such as the Threshold-value ΔK_{th} for fatigue crack growth and the crack growth rate curve $da/dN=f(\Delta K)$. For the purpose of calculating the lifetime of a structure under service load additionally the consideration of interaction effects is important [5].

Fig. 3 – Comparison of simulated crack front with the real fracture surface of the wheel tyre

Conclusions

Fracture mechanics enables to perform numerical and experimental simulations of fatigue crack growth processes in real structures. Many investigations of practical crack cases and comparison with experiments on components prove the high quality obtainable by such simulations.

References

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