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NUMERICAL ANALYSES OF MIXED MODE CRACK PROPAGATION USING VIRTUAL CRACK EXTENSION METHOD

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1. Introduction

For general, cracked structures it is necessary to consider the combined effects of mode I, II and III loading in linear elastic fracture investigations. In fact, mode III is largely separable and can be dealt with in an independent manner, but the combined effect of modes I and II, under tensile and shear loading, presents difficulties in analysis. Several mixed-mode fracture criteria exist, and they can be generally divided into two groups, depending on their scopes. Some criteria are concerned only with the local information at or around the crack tip (local approach) whereas others consider the global or total information about the whole body containing the crack (global approach). In the local approach, one needs to choose a parameter (or physical quantity) that measures the severity experienced by the local material particles at or around the crack tip. Widely used mixed-mode fracture criteria include:

1. The maximum tangential stress (MTS) criterion [Erdogan, et. al. 1963], where the direction of crack propagation depends on maximum tangential stress on a circle of sufficiently small radius around the crack tip,
2. The maximum energy release rate (G) criterion, where the direction of crack propagation depends on maximum energy release rate around the crack tip
3. The minimum strain energy density (SED) criterion [Sih 1974], where the direction of crack propagation depends on minimum energy density around the crack tip.

To determine crack propagation angle with MTS and SED criterion, stress intensity factors K_I and K_{II} should be known. They have been calculated with displacement correlation method (DCM) [Aliabadi et. al. 1992], energy release rate by using the complex *J* integral, *G(J)* [Hellen, et. al. 1975], and extrapolation of stresses (ES) [Ulbin, et. al. 2001].

Simulations of mixed mode crack propagation have been made in frame of the finite and boundary element methods. Virtual crack extension (VCE) method [Hellen 1975] is extensively used for fracture analysis with finite element method. It is based on calculation of strain energy release rate G which is energy difference for two crack positions, resulting in stress intensity factor K with no indication of influence of different fracture modes. A numerical analysis of crack propagation under MTS and SED criterion has been made using boundary element methods.

2. Computational analyses

Different crack propagation methods were evaluated for the CTS specimen [Richard, et. al. 1983] shown on Figure 1. A 2,5 mm fatigue crack is formed at the end of 52,5 mm long notch. The CTS specimen is loaded with a static load of 15 kN. In computational analysis this load is replaced with three equivalent nodal forces in x-y direction as it is shown in Figure 1 and 2.

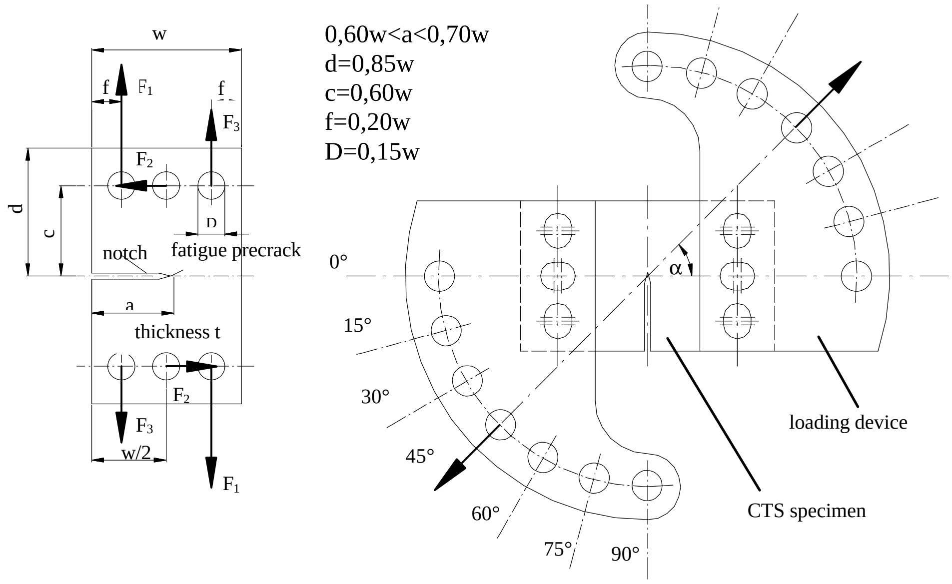

Figure 1. CTS specimen with the loading device

Different load cases for load angles between 0° and 90°, with a step of 15°, were used to simulate different fracture mode conditions. Pure Mode I condition was simulated with load angle of 0°, while pure Mode II was simulated with load angle of 90°. The mixed mode conditions are simulated using load angles between 15° and 75°. CTS specimen is restrained as shown in Figure 2.

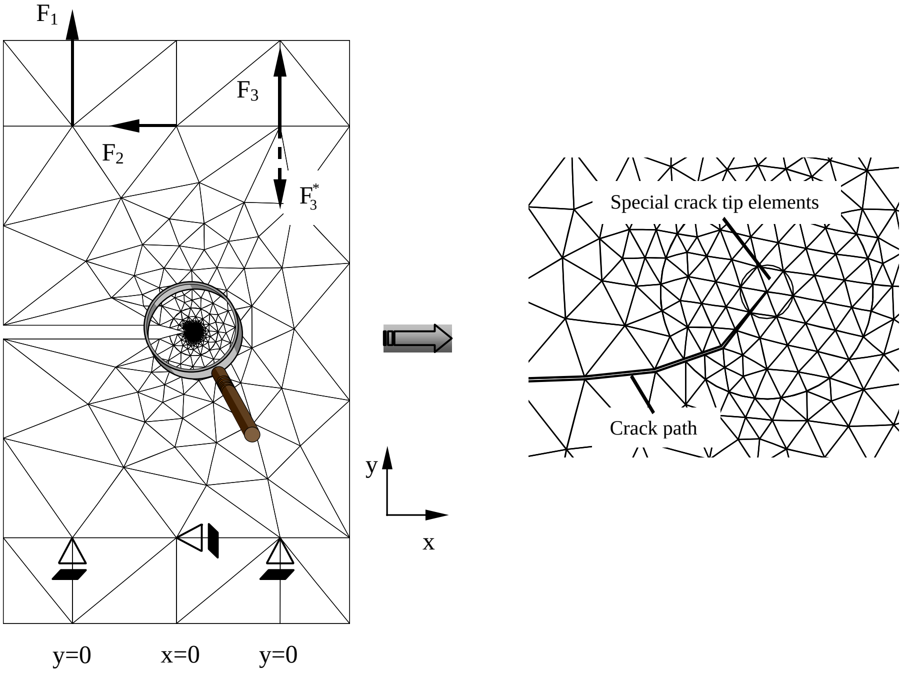

Figure 2. Discretised CTS specimen for finite element analysisand corresponding boundary conditions

The CTS specimen is made of alloy AlMgMn4,5-W32 with the Young´s modulus E = 72.400 MPa, tensile strength R_m = 314,5 MPa, 0.2% proof strength $R_{p0,2}$ = 164,7 MPa, Poisson´s ratio ν = 0,33 and plane strain fracture toughness K_{Ic} = 1297 N/mm$^{3/2}$.

For VCE method the finite element method was used. Special triangular crack tip finite elements with modified shape functions [Hellen 1975], have been used around the crack tip to simulate the stress singularity in this region.Figure 3 shows the boundary element mesh of CTS specimen, where the dual boundary elements [Portela 1992] have been used. Boundary conditions are the same as shown in Figure 2 for the FE model. Model with the boundary element was used for simulation of crack propagation based on the MTS criterion and SED criterion.

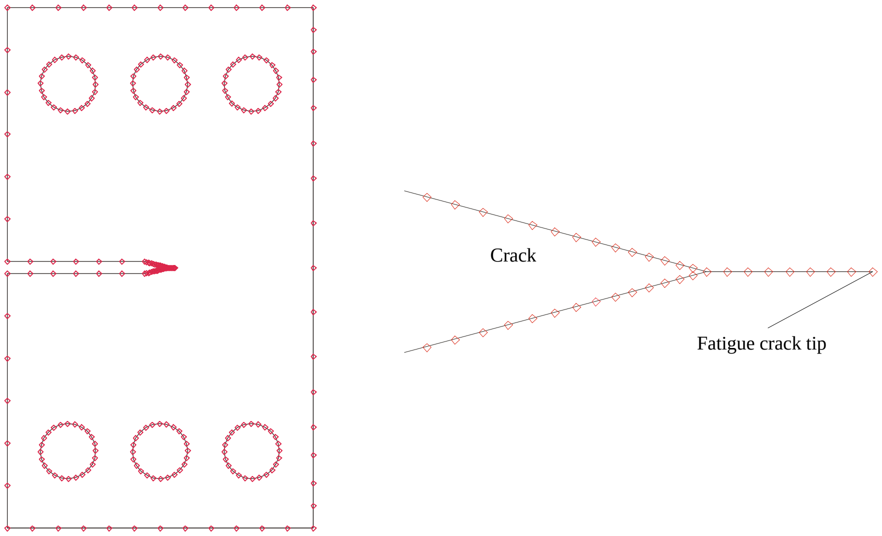

Figure 3. Boundary element discretisation of CTS specimen

3. Results

Figure 4 shows distribution of strain energy release rate *G* around the crack tip. The curve with sinusoidal shape, showing clearly that the directions of maximum *G* and minimum *G* are opposite. There are two directions of no energy release. Between them the energy release rate is negative, therefore crack extension is physically impossible in these directions. The value of *G* depends primary on K_I, resulting in highest value of *G* at pure Mode I, while *G* has the lowest value at pure Mode II.

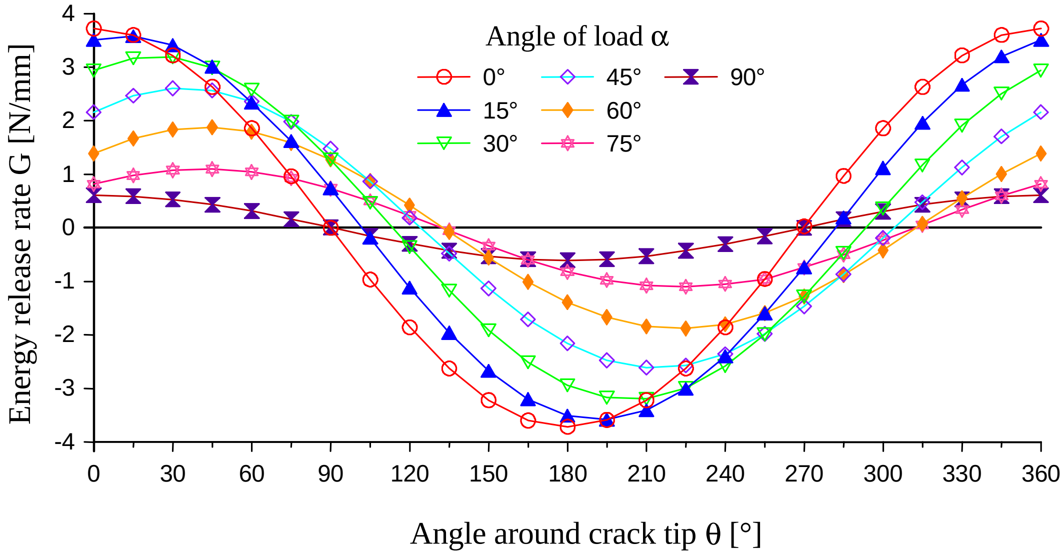

Figure 4. Plot of *G* against angle q

Calculated stress intensity factors K_I, $|K_{II}|$ are shown in Figure 4.

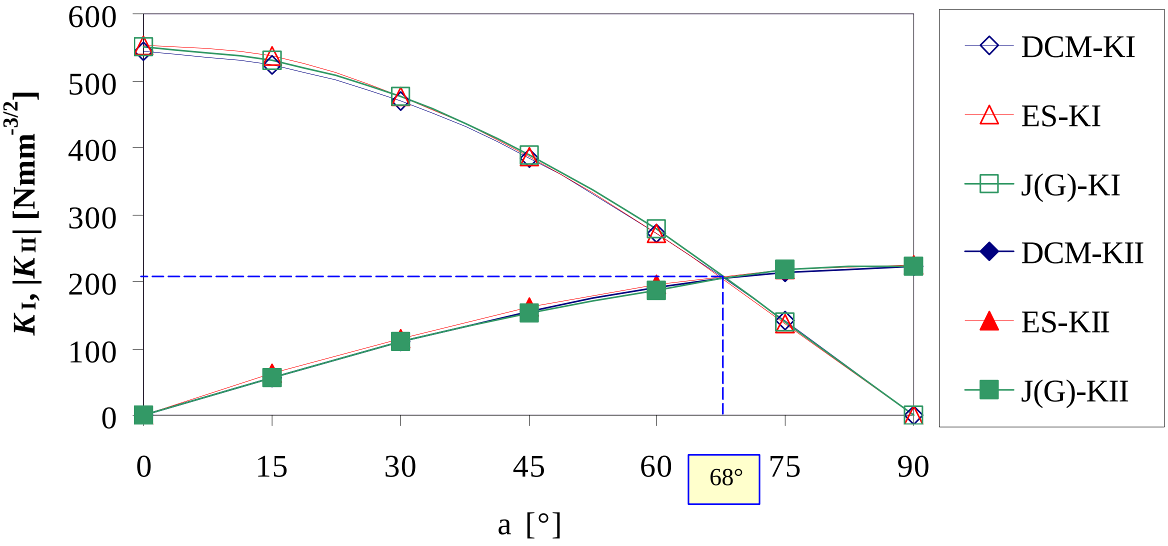

Figure 5. *KI* and |*KII*| for different load angles

At the start of crack propagation a kink in crack path is observed under mixed mode loading. The results in Figure 5 are therefore given for a loaded initial crack configuration. At load angle α ≈ 68° tensile and shear stresses around the tip of fatigue pre-crack are equivalent. Up to this value tensile stresses dominates and above it shear stresses dominates.

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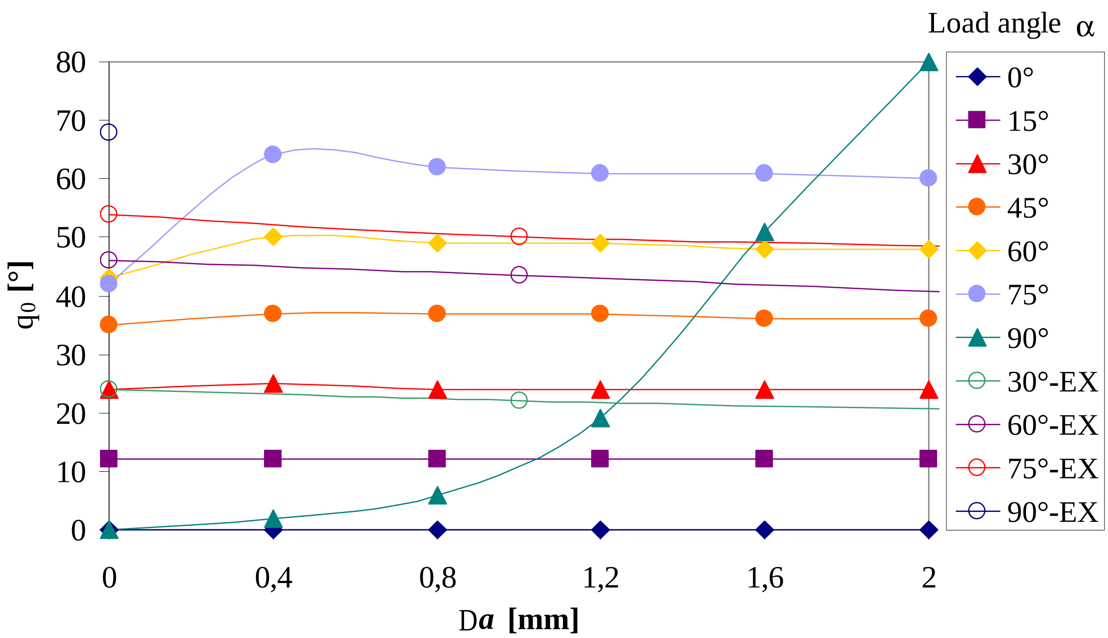

Figure 6. Crack propagation determined with VCE method

Results show a good agreement with experimental results for load angle α < 75°. The highest deviation between numerical and experimental results is observed at load angle α = 90° where a kink angle determined with VCE method is 0° while the angle determined with an experiment is ≈ 69°. After several crack extensions angle of crack propagation, determined with VCE method, approaches to this value.

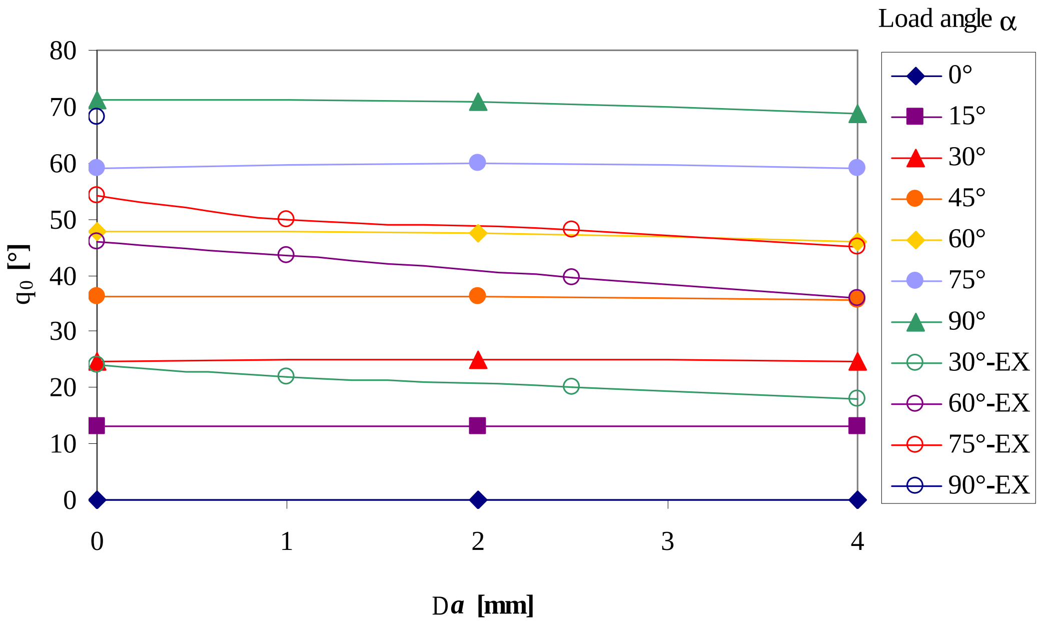

Figure 7. Crack propagation determined with MTS criterion

Results presented on figure 7 show a good agreement with experimental results for a kink angle, but for further crack extensions numerical results deviate from experimental results.

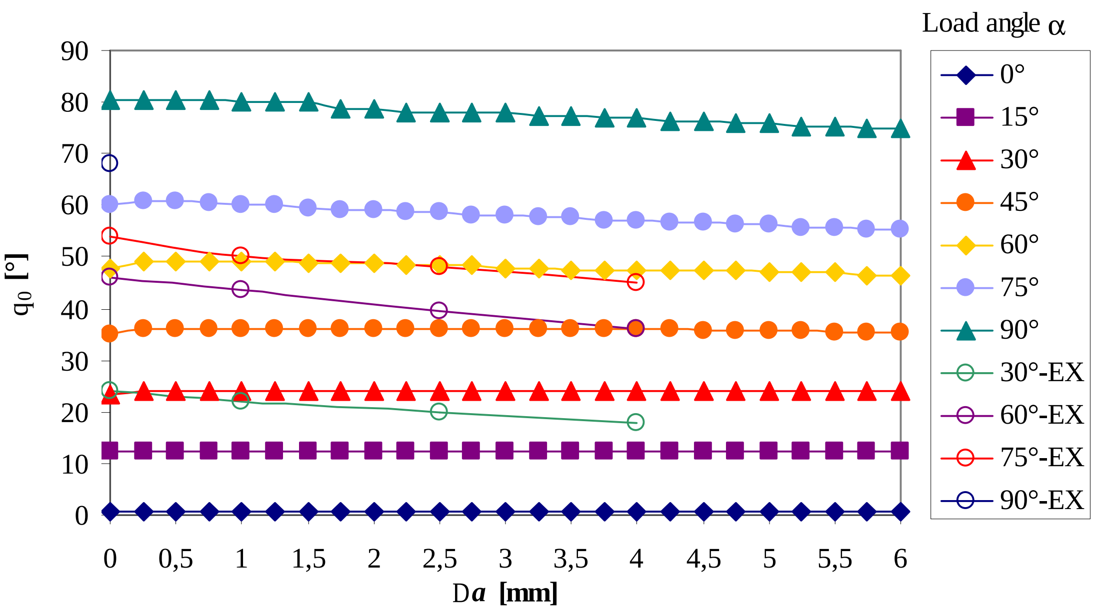

Figure 8. Crack propagation determined with SED criterion

Figure 8 shows that SED criterion is less accurate for determination of kink angle when shear stresses dominates around fatigue pre-crack similar to results obtained using VCE method.

4. Conclusions

Different methods for analyses of crack propagation on CTS specimen under mixed mode fracture were evaluated. All three methods, considered in this paper, give comparable results when a tensile stress around tip of fatigue precrack dominates. When shear stresses dominate MTS gives the most comparable results for kink angle to the experimental results. Under this loading condition the VCE method and SED criterion are less accurate.

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