INFLUENCE OF THE YIELD STRESS AND THE HARDENING OF THE MATERIAL ON THE FATIGUE CRACK GROWTH AFTER PEAK LOADS – A FINITE ELEMENT ANALYSIS

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ABSTRACT

Due to variable amplitude loading so-called interaction effects occur, which lead to retardations and accelerations of the fatigue crack growth. The finite element method is a useful tool in order to investigate the reasons for effecting the lifetime of a component or a structure. Within the scope of this paper numerical simulation results of the fatigue crack growth with interspersed overloads are presented taking the influence of the yield stress and the hardening of the material into account. The finite element simulations have been performed using ABAQUS. It can be shown that the initial yield stress as well as the type of hardening noticeably influence the numerical results. The effect of the modification of the rate and amount of the hardening is smaller.

1 INTRODUCTION

Fatigue crack growth under constant amplitude loading in the engineering practice is very rare, because machines or means of travel during the assembling, the transport or the use are exposed to variable amplitude loadings. In contrast to the constant amplitude loading the fatigue crack growth not only depends on the current loading, but also on the whole load history, i.e. the crack propagation is also influenced by the sequence of the loading. Due to this fact the crack growth is accelerated as well as retarded, which lead to lifetime reductions or lifetime extensions [1, 2]. The finite element method was used by numerous authors [e.g. 3-7] to investigate the reasons for the so-called interaction effects, for example cyclic plasticity at the crack tip, crack closure or residual stresses. Within the scope of this paper the influences of the constitutive behaviour of the material on the numerical results is investigated. Because many load spectra can be reduced to a constant amplitude loading, in which single overloads are interspersed, the focus of this investigations is upon these cases.

2 FINITE ELEMENT MODELLING

For the numerical investigations of the fatigue crack growth after single overloads the CTS-(Compact Tension Shear-) specimen developed by Richard [8] is used. In Fig. 1 the finite element mesh as well as the loading and bearing for the FE-model is illustrated. In the region of the crack growth in the middle part of the model (Fig. 1) quadratic 4-node elements with an element length of 25μm are chosen in order to realise the crack growth increment and to obtain the stress concentrations as well as the arising plastic zone at the crack tip [7].

The FE-model consists of three regions. In the regions ① and ③ an elastic stress-strain behaviour is assumed. The constitutive behaviour of the material in region ② is realized in the applied FE-code ABAQUS™ by using the Chaboche rate independent model [3, 9]. In order to investigate the influence of the initial yield stress σ_{YS0} and the material hardening both σ_{YS0} and the kinematic hardening parameters C and γ of the Chaboche model are varied (Table 1).

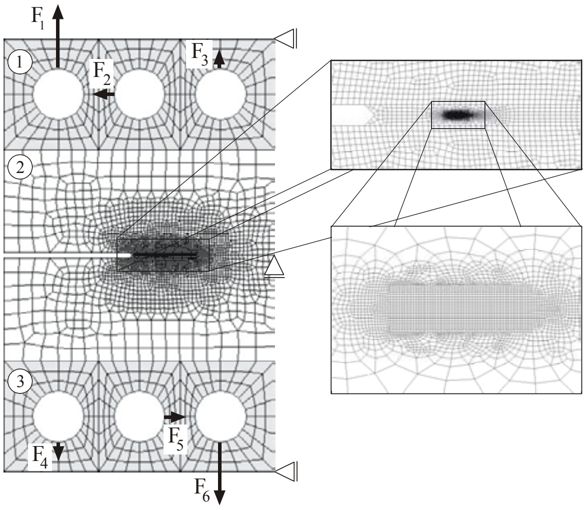

Figure 1: FE-model of the used CTS-specimen with a magnification of the interesting region

Also one simulation has been carried out with a nonlinear isotropic/kinematic hardening behaviour, whereby in addition to model 4 the isotropic hardening parameters are as follows: Q = 90 MPa and b = 2 [9]. The elastic properties of the material are: E = 213 GPa and ν = 0.33.

The simulation of the fatigue crack growth is realized by using the DEBOND technique of ABAQUS. Therefore at the beginning the nodes in the crack line are bonded and during the simulation the nodes are debonded over a distance of 0.1 mm in each debonding step. According to Newman´s release node concept [4, 5] the crack is extended at maximum applied load, but deviant from Newman between the crack growth five cycles are positioned in order to ensure stabilized cycles.

Table 1: Investigated parameters of the Chaboche model

Model	Initial yield stress	Kinematic hardening parameters		Behaviour
	σ_{YS0}	C [MPa]	γ	
1	340	3667	1	Linear kinematic
2	340	6974	1	Linear kinematic
3	440	3667	1	Linear kinematic
4	340	11000	28	Nonlinear kinematic
5	440	10	250	Ideally plastic

The plane stress FE-analyses are performed with a constant baseline level loading ΔK_{Bl} = 10 MPa(m)$^{1/2}$ and a constant stress ratio R_{Bl} = 0.1, i.e. after every crack growth step the forces F_1 to F_6 have to be adapted according to the current crack length [8, 10]. After the generation of an initial fatigue crack of 0.5 mm at 50.0 mm a single overload with an overload ratio $R_{ol} = K_{ol}/K_{max}$ = 2.0 is interspersed. Afterwards the baseline level loading is applied again.

3 NUMERICAL RESULTS

For numerical simulations with the steel L360 at first some basic analyses concerning the cyclic stress-strain curve have been performed. Therefore the influence of the used initial yield stress as well as of the type, rate and amount of hardening has been investigated.

3.1 Influence of the initial yield stress

Figure 2 shows the cyclic stress-strain curves of model 1 and 3. The slopes are identical, but the initial yield stresses σ_{ys0} have been varied.

In Figure 3a a comparison of the crack openings by means of y-displacements at a crack length of 50.5 mm is illustrated. It becomes apparent that due to an interspersing of an overload at a crack length of 50 mm strong plastic deformations along the crack wake, so-called humps, occur, which lead to a complete or partial crack closure. The amount of closure depends on the overload ratio as well as on the baseline level loading [2, 7]. As can be seen in Figure 3a the crack opening is also influenced by the initial yield stress. Due to an enhancement of σ_{ys0} a modification of the crack opening takes place. The smaller initial yield stress leads to a smaller crack opening. In literature many descriptions are given in order to determine the crack opening during a FE-simulation. For instance in [3] and [11] the crack opening is identified in a certain distance to the crack tip or just at that point, where the stresses change from compression to tension [12]. Within the scope of this work K_{op} is calculated for that particular point, where the crack is fully opened, i.e. it exists no surface contact along the wake of the whole fatigue crack any more. The crack opening stress intensity factors K_{op} in dependence of the crack length for both models are shown in Figure 3b. The absolute maximum value of K_{op} is not influenced very much, but the characteristics of K_{op} is slightly different. The maximum of K_{op} is reached 0.3 mm after the overload by a simulation with model 1, while the simulation with model 3 leads to a maximum at a crack length of 50.2 mm. Moreover the crack opening stress intensity factors at constant amplitude loading before applying the overload is higher for model 1 than for model 3.

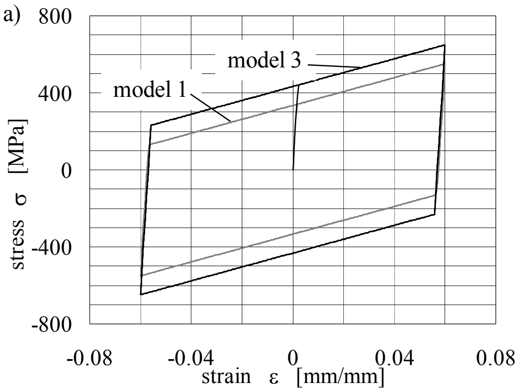

Figure 2: Cyclic stress strain curve of model 1 and 3

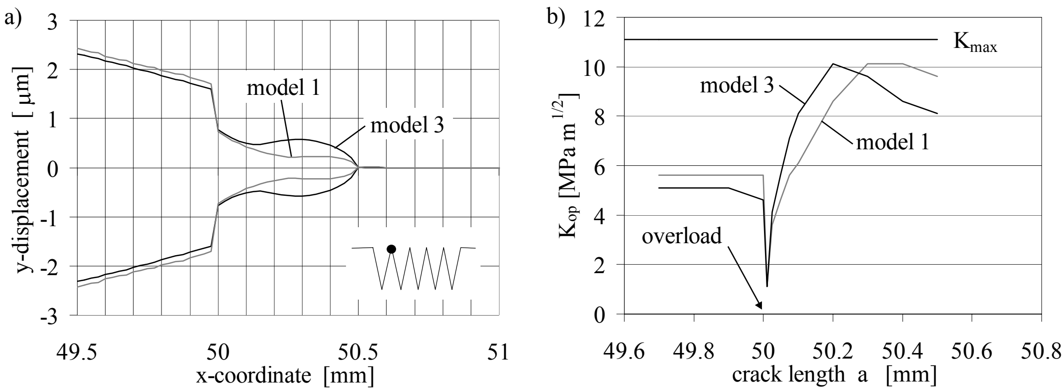

Figure 3: Influence of the initial yield stress
a) on the crack opening at a crack length of 50.5 mm and
b) on the opening stress intensity factor K_{op}

Furthermore the initial yield stress also has an influence on the stress distributions. Figure 4a illustrates the effect on the σ_y-stress distribution at the overload. At first it can be observed that due to the higher yield stress of model 3 also higher stresses are generated. Secondly, a smaller plastic zone ahead of the crack tip is created, which can be seen at the discontinuity of the stresses at 50.6 mm for model 3 and 51.2 mm for model 1 respectively.

Due to an overload not only the stresses in the ligament are disturbed during the crack growth in comparison to a constant amplitude loading, but also the stresses along the wake of the crack [7].

At the location of the overload tensile stresses are generated at maximum baseline level loading and high compressive stresses at minimum baseline level loading.

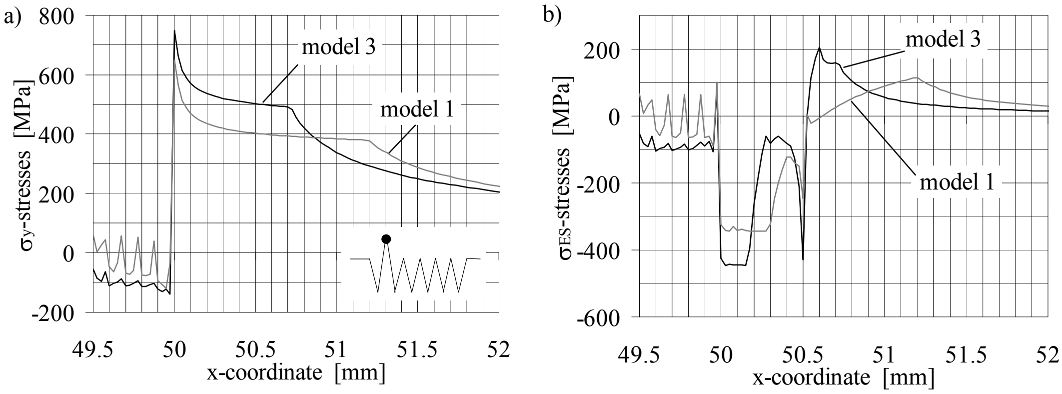

Figure 4: Influence of the initial yield stress
a) on the stress distribution $\sigma_y(x)$ at K_{ol} for a crack length of 50.0 mm and
b) on the residual stresses σ_{ES} at a crack length of 50.5 mm

In comparison of model 1 and 3 it becomes apparent that these stresses are affected over a longer crack increment by model 1. This effect can also be seen in Figure 4b, in which the influence on the residual stresses 0.5 mm after interspersing an overload is shown. As a result of the bigger plastic zone the compressive residual stresses along the wake of the crack are smaller with model 1, but reach over a longer distance, which in turn explains the different shape of the crack opening.

3.2 Influence of the type of hardening

In this section the influence of the type of hardening is illustrated. In Figure 5 at first the differences between an elastic-ideally plastic material behaviour with a yield stress of 440 MPa, which correspond to a mean value of $R_{p0.2}$ and the ultimate tensile strength for the investigated steel (model 5) [13], compared to model 3 with a linear kinematic behaviour and the same yield stress is outlined.

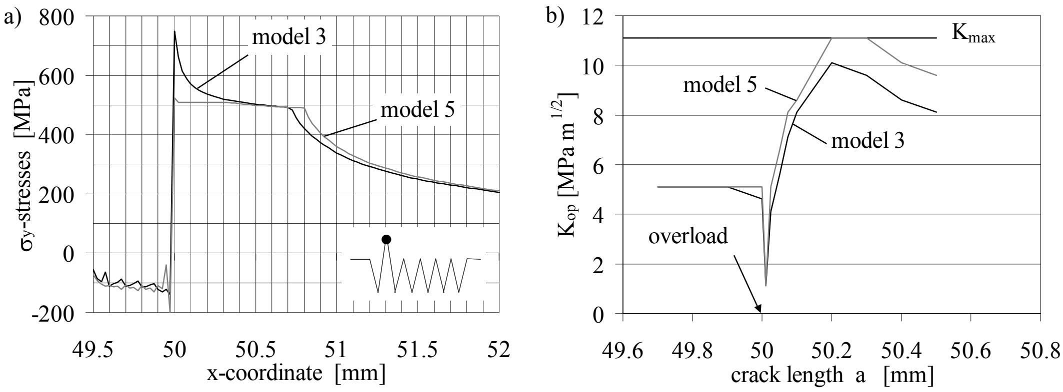

Figure 5: Comparison of the effects of bilinear and ideally plastic stress-strain behaviour
a) on the stress distribution $\sigma_y(x)$ at K_{ol} for a crack length of 50.0 mm and b) on the crack opening

The σ_y-stress distributions using model 5 or model 3 along the crack line during the overload and the following load sequence are very similar (Figure 5a). However, the crack opening stress intensity factor K_{op} after the interspersed overload is higher using the ideally plastic material behaviour (Figure 5b). K_{op} even reaches the maximum stress intensity factor, i.e. the effective cyclic stress intensity factor is zero and the crack is arrested.

3.3 Influence of hardening parameters

In order to investigate the effect of the amount and the rate of hardening the initial yield stress is kept constant, but the kinematic hardening parameters are varied (Table 1). The appropriate cyclic stress-strain curves are shown in Figure 6, whereby model 1 and 2 describe a linear (Figure 6a) and model 4 a non-linear behaviour (Figure 6b) fitted to the experimental stress-strain curve [13].

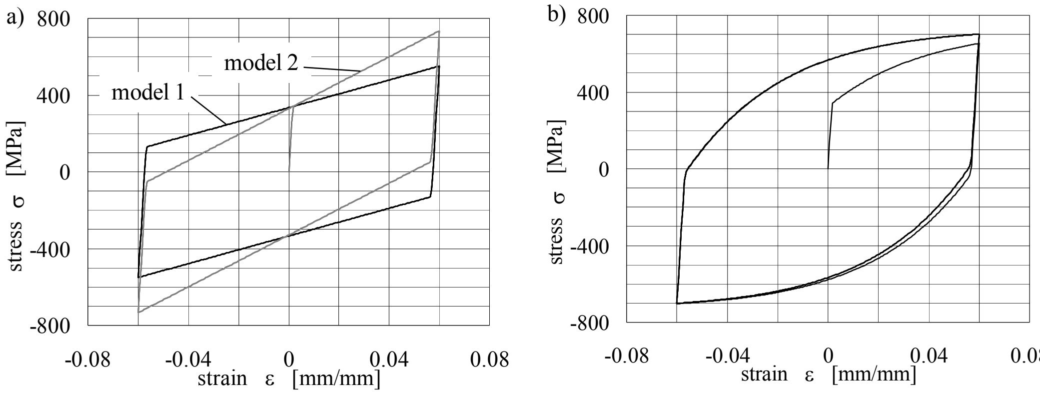

Figure 6: Cyclic stress-strain curve a) of model 1 and 2 and b) of model 4

Due to the variation of the kinematic hardening parameters the σ_y-stress distribution during the overload at K_{ol} as well as the stresses at minimum and maximum loading after a certain crack growth are nearly identical particularly between model 1 and 2. Only small differences can be observed using model 4 (Figure 7).

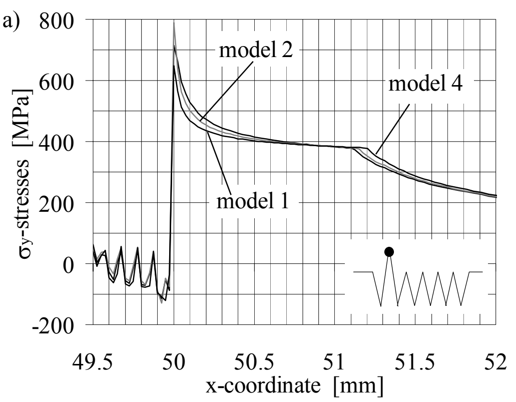

Figure 7: Influence of the investigated kinematic hardening parameters on the σ_y-stress distribution at K_{ol} at a = 50.0 mm

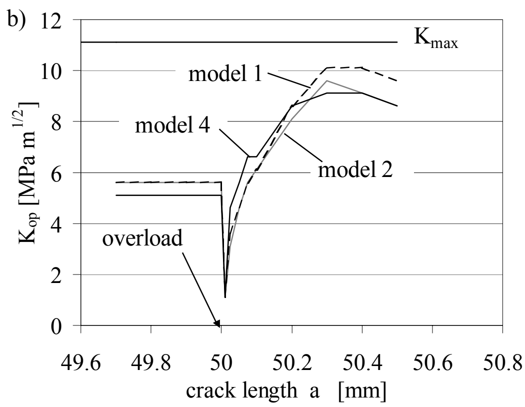

Figure 8: Crack opening stress intensity factors depending on the crack length for the models 1, 2 and 4

In addition the modifications of the kinematic hardening parameters only have a small influence on the crack opening stress intensity factor K_{op} computed after a single overload (Figure 8). But after 50.3 mm model 1 leads to larger K_{op}-values than model 2 and 4. Before the overload, i.e. under constant amplitude loading, the values determined with model 1 and 2 are higher than with model 4.

The simulation under consideration of nonlinear isotropic/kinematic hardening has been carried out with the kinematic parameters of model 4 and the isotropic hardening parameters Q = 90 MPa and b = 2. Neither at the stress distributions nor at the value of K_{op} differences to a simulation using model 4 can be observed.

4 CONCLUSIONS

For the simulations with the investigated constitutive behaviours of material it can be concluded that the yield stress is of great importance. The type of hardening has nearly no influence on the stress distributions, but has a noticeable effect on the crack opening stress intensity factor K_{op}, whereas the simulation results are nearly unaffected by the variation of the kinematic hardening parameters.

5 REFERENCES

[1] Skorupa, M.: Empirical trends and prediction models for fatigue crack growth under variable amplitude loading. ECN-R—96-007, Petten, 1996

[2] Sander, M.: Einfluss variabler Belastung auf das Ermüdungsrisswachstum in Bauteilen und Strukturen. VDI-Verlag, Düsseldorf, 2003

[3] Pommier, S. ; Bompard, Ph. : Bauschinger effect of alloys and plasticity-induced crack closure: a finite element analysis. In: Fatigue Fract. Engng. Mater. Struc., Vol. 23, 2000 pp. 129-139

[4] Newman, J.C. : A finite-element analysis of fatigue crack closure. In: Mechanics of crack growth, ASTM STP 590, ASTM, 1976, pp. 281-301

[5] Newman, J.C.: Advances in finite-element modelling of fatigue crack growth and fracture. In: Blom, A.F. (ed.): Fatigue 2002, Vol. 1, EMAS, Stockholm, 2002, pp. 55-70

[6] McClung, R.C.; Sehitoglu, H.: On the finite element analysis of fatigue crack closure. In: Engineering Fracture Mechanics, Vol. 33, No. 2, 1989, pp. 237-252

[7] Sander, M.; Richard, H.A.: Finite element analysis of fatigue crack growth with interspersed mode I and mixed mode overloads. Intern. J. of Fatigue, in press

[8] Richard, H.A.: Bruchvorhersagen bei überlagerter Normal- und Schubbeanspruchung von Rissen. VDI-Forschungsheft 631/85, VDI-Verlag, Düsseldorf, 1985

[9] Hibitt, Karlsson & Sorensen: ABAQUS/Standard Users's manual. Version 5.8, Pawtucket, Rhode Island, 1998

[10] Sander, M.; Richard, H.A.: Influence of the loading direction on fatigue crack growth. In: Conference proceedings of the 7th ICBMFF, Berlin, 2004

[11] Ogura, K.; Ohji, K.: FEM analysis of crack closure and delay effect in fatigue crack growth under variable amplitude loading. In: Engineering Fracture Mechanics, Vol. 9, 1977, pp. 471-480

[12] Anquez, L.: Contribution of numerical modelling to fatigue crack growth prediction. In: Petit, J. et al. (eds.): Fatigue crack growth under variable amplitude loading. Elsevier Applied Science, London, 1988, pp. 194-207

[13] Skorupa, M.; Machniewicz, T.: Private communication, 2004