Finite-element modeling of the semi-elliptical fatigue crack growth using damage accumulation approach

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Abstract

Simulation of surface fatigue crack growth for residual life assessment of structural elements is almost entirely based on the application of Linear Elastic Fracture Mechanics (LEFM). Thereby it is generally assumed that the crack front does not essentially change its shape, although it is not always confirmed by experiment. Furthermore, LEFM approach ignores plastic strain - one of the leading factors associated with the material degradation and fracture. Also, evaluation of stress intensity factors meets difficulties associated with changes in the stress state along the contour of the crack front.

Approach using Strain-life criterion and based on the finite element modeling of damage accumulation was proposed for simulation the evolution of surface cracks. It takes into account the crack closure effect, the nonlinear behavior of damage accumulation and material compliance increasing due to the damage advance. Suggested damage accumulation technique was applied to the semi-elliptical crack growth from the initial defect in the steel compact specimen. The simulation results are in good agreement with the experimental data.

1 Introduction

Structural elements in service may contain initial crack-like defects (e.g., in welded joints, localized corrosive damages, etc.) and fatigue cracks progress of which may result in onset of a critical condition.

Assessment of residual fatigue life is of special practical importance in case of providing safe life of aircraft fuselages, of pipelines, marine structures, etc. Fatigue crack growth evaluation addressed to estimation of residual life is based on the linear elastic fracture mechanics (LEFM) format [1, 2] and application of the finite element method (FEM). In the FEM-based simulation it is assumed that the crack has a regular elliptical shape, and with the crack progress its shape remains elliptic, although it is not always confirmed by the experiments [3]. According to the established methodology the initial defect presence is necessary; further, the stress intensity factor (SIF) values at certain points of the front are calculated. Then, for a given number of cycles the crack increments along the corresponding directions are defined by integrating Paris-Erdogan equation, and by this the new crack front is obtained. This procedure is performed until the stress field singularity remains ahead the crack tip. The crack closure effect is usually neglected due to the complexity of its evaluation.

Apart from that, some studies show that the Paris-Erdogan equation constants may differ depending on the integration direction, hence, the crack front estimation becomes incorrect and the life assessment barely correlates with the experimental data [4, 5]. The limitations of the LEFM format cause selection of the continuum damage mechanics as a feasible tool in modeling of surface fatigue cracks. Realistic crack front and growth rate predictions by means of damage accumulation modeling was confirmed by recent investigations [6, 7].

One of the important advantages of the damage accumulation approach is the possibility of modeling the damage process of the initially intact structural components, in the absence of initial crack-like defect which is required for evaluation of the stress intensity factor values. A feasible source of cracks may be, for example, the local heterogeneity of the material structure fatigue resistance. The idea of applying damage summation for fatigue cracks growth assessment has been formulated for a long time [8, 9], but it has been applied for the surface cracks propagation modeling only recently.

2 Approach description

One of the methods of the surface crack development simulation assumes artificial increase of the material elements compliance in the course of approaching the crack tip. These material elements are associated with the grain clusters characteristic by similar orientation of slip planes. Each material element is assigned a scalar damage variable D, having cumulative nature. Damage summation law may be accepted, for example, in nonlinear form proposed by Marco and Starkey [10]:

$$D = \sum_i (n_i/N_i)^{x_i} \tag{1}$$

where n_i is the number of load cycles prior the weakest element fracture at a certain stage of crack propagation, N_i is the number of cycles to failure of the element corresponding to the selected fracture criterion, x_i is the nonlinearity parameter. If $x_i = 1$, equation (1), obviously, corresponds to the linear damage accumulation. Quantitative estimation of the nonlinearity parameter for the analysis of crack growth in the compact specimen is described in the fourth section.

According to the present approach the elastic-plastic material cyclic behavior is described by the generalized cyclic curve obtained by standard testing [11]. The fatigue resistance of material elements is described by the strain-life Coffin - Manson criterion [12]:

$$\Delta\varepsilon = \Delta\varepsilon_p + \Delta\varepsilon_e = CN^{-\alpha} + BN^{-\beta} \tag{2}$$

where $\Delta\varepsilon$ is the total strain range, N is the number of cycles prior to failure, $C = 0.622$, $B = 0.006$, $\alpha = 0.618$, $\beta = 0.14$ — material parameters for steel BS 4360 50D [8].

Initiating the analysis, the number of cycles to failure of each element subjected to plastic strain is determined according to the criterion (2). As the first element with the minimal number of cycles fails, other elements are assumed acquired the damage corresponding to the past number of cycles. Then the computation is repeated for the new stress-strain state. When the damage value becomes equal to unity in the following affected element it has to be eliminated and the stress redistribution in the adjacent elements is calculated.

The elements ahead the crack tip resistance decrease is assumed caused by the two mechanisms, one of which is the damage accumulation, and another is the material degradation evaluated in decrease of its elastic properties, changes of the cyclic stress-strain slope curve. These changes were showed by testing samples at very low-cycle fatigue, and the elasticity modulus evolution was proposed [13]:

$$\tilde{E} = (1 - D)E \tag{3}$$

Increasing of the material compliance associated with its deterioration, apparently, may be characteristic only for conclusive phase of the crack tip advance to the element location. During this "agony" of the material element the damage accumulation may occur with increasing intensity. Certainly, modeling of the damage evolution in areas with varying strain intensity requires further experimental studies.

3 Modeling of the crack closure effect

Within a certain cycle part the crack remains closed even at the pulsating tension. This phenomenon was reported by Elber, who carried out testing of the crack growth in thin aluminum plates at different stress ratios [14]. The damage progress presumably can not occur during the cycle part when the crack is closed. Thereby some strain (stress) range portion may be "ineffective" for the damage evolution.

In the present study to describe the effect of the partial crack opening a closure parameter U was introduced, similarly to that proposed by Elber:

$$\Delta\varepsilon_{eff} = U\Delta\varepsilon \tag{4}$$

Experimental evaluation of the closure parameter U for semi-elliptical cracks is a barely soluble problem because the front interior points are difficult to access. Furthermore, certain factors such as front warping, surface roughness of the crack faces, the formation of oxidation products at the crack tip are difficult to describe and to model. These factors also influence the crack closure parameter.

It is generally assumed in FE-modeling of crack closure in the plane stress problem that crack opens when stress at the nodes of the opposite crack faces nearest to the crack tip becomes positive. However, as shown in [15] such approach is inaccurate, and it is sufficient to trace the change of nodal force sign at the crack tip to define the opening point, Fig. 1a. Numerical study of the crack faces contact allowed to show the applicability of this concept for description of the semi-elliptical crack closure, although the closure parameter values were slightly higher in comparison with the experimental ones [16].

When the surface crack tip is assumed blunted in modeling, it is possible to define the crack closure point by change of the mean stress sign in the eight nodes of element ahead of crack tip, Fig. 1b, or only in the four crack tip nodes, Fig. 1c. To verify this assumption the closure parameter calculation was carried out in two characteristic points of the two semi-elliptical cracks in a compact specimen and results were compared with the experimental data, Table 15. Dimensions "a" and "c" of semi-elliptical crack correspond to its depth and half of the length at the surface.

The results show that determination of the crack closure moment by change of the sign of the average stress at the crack tip nodes perpendicular to the front is preferable. Good agreement with the experimental data demonstrates the governing influence of plasticity on the incomplete crack opening. The resulting insignificant discrepancies about 6% may be referred to the complexity of closure mechanism and to the a lack of experimental data as well.

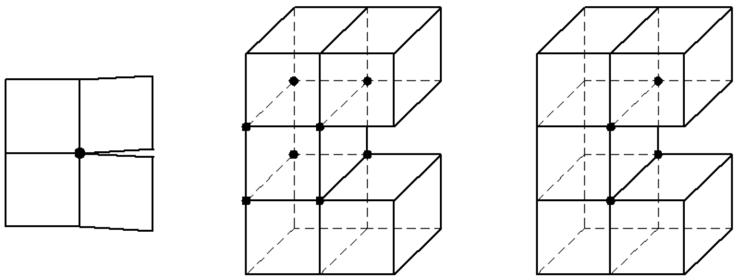

Figure 1: Governing nodes for calculation of the closure parameter

Table 15: Closure parameters validation.

Crack dimensions, mm	Experiment, [17]	Simulation	
		8 nodes	4 nodes
$a = 3.8$	0.83	0.92	0.88
$c = 4.0$	0.73	0.75	0.73
$a = 6.2$	0.87	0.90	0.86
$c = 8.0$	0.76	0.75	0.71

4 Results of crack evolution simulation

The proposed method based on FE-modeling of damage accumulation along with considering the effect of crack closure has been successfully applied to simulate the semi-elliptical crack propagation in a compact specimen, Fig. 2.

In experiment fatigue crack grew from the initial electro-erosion notch with dimensions $1.88{\times}2.6$ mm [17]. Specimen was subjected to constant cyclic loading close to the pulsating tension ($P_{max} = 1.3$ $kN, P_{min} = 25$ kN). When the fatigue crack reached half-length of 4 mm, single overload with double maximum load was applied. It is known that overload can induce significant residual stresses, which affect the further crack propagation. Due to the large residual compressive stress after overload crack opens less intensive, its growth rate decreases as shown in Fig. 6, full markers. The overload also has visible influence on the crack aspect ratio, Fig. 5, empty circlets. The paper [17] presented also prediction of crack the crack development in the absence of overload, Fig. 5 (dashed line).

In the present study the finite element model of the specimen tested in [17] was designed and the mesh was refined in the area of crack front to provide the necessary resolution of stress-strain field, Fig. 4. The sizes of the crack tip elements correspond to the thickness of the initial defect equal to 0.2 mm. Along with the crack extensions the stress-strain state of the elements at the crack tip was analyzed, and conclusion on consecutive failure of elements was based on evaluation of the effective strain range (4) and application of the strain-life criterion (2). The damage accumulation was assumed to be nonlinear described by relationship (1). The value of x was defined via equating the number of cycles obtained in the experiment and by FE - modeling just before the overload application. The crack propagation rate is in good agreement with the experimental data with the parameter value equal to 0.5, therefore this value was chosen for description of further damage accumulation in the absence of overload. In general, the nonlinearity parameter should be evaluated

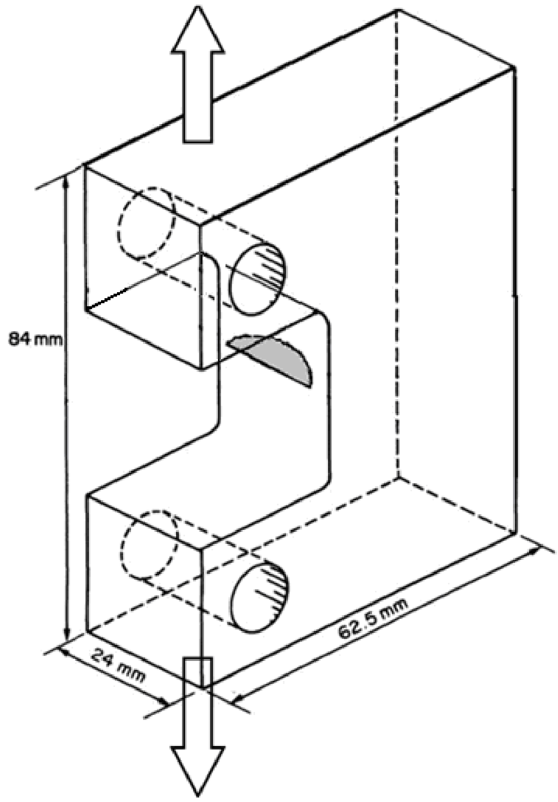

Figure 2: Semi-elliptical crack in a compact specimen [17]

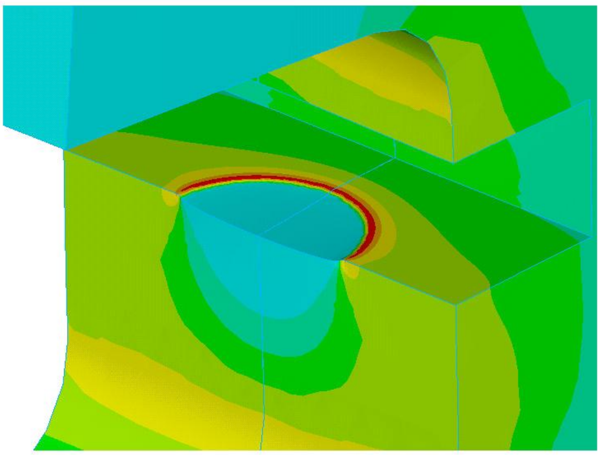

Figure 3: Distribution of the maximum principal stresses at the crack tip

from the experiment. Damage accumulation occurs with the increasing strain intensity in the each element, therefore the tests on the standard specimens in irregular loading with raising of the strain range have to be carried out. Presumably, it would let to define the nonlinearity character in the damage accumulation for the tested material and apply the nonlinearity parameter more soundly.

The resulting evolution of the front shape corresponds to experiment: at the early growth stage crack front demonstrates rapid widening with the tendency to preferred semi-elliptical shape, Fig. 4.

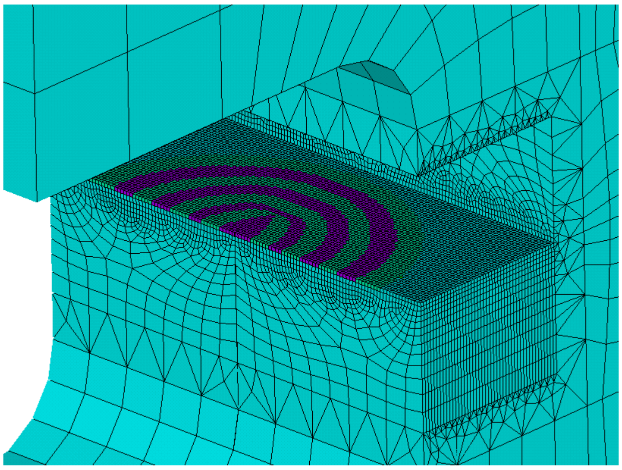

Figure 4: Crack increment sequences due to failure of elements

The crack growth estimated by using the FE-modeling in the absence of overload showed a monotonic character, Fig. 5 (solid symbols), and a reasonably good agreement with the predicted in [17], Fig. 5, dotted line.

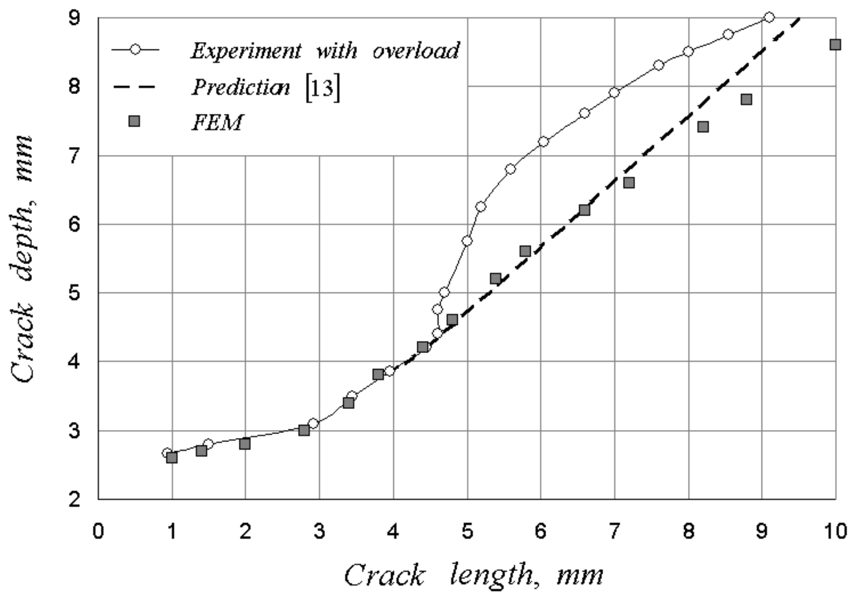

Figure 5: Advancement of crack dimensions

The slope of plotted relationships between the crack dimensions and number of cycles correspond to the crack growth rate in the depth and length directions, Fig. 5. Obviously, the overload decelerates crack advancement in both directions, so plot becomes close to horizontal. This retardation extends for about 300000 cycles, then the effect of residual stress decreases and growth gradient again begins to increase. Consequently, the relationship obtained by results of FE simulation without overloading does not contain retardation segment. It is evident that the application of single overload causes increase of the crack propagation time by 30%.

Experimental studies show that as the semi-elliptical crack grows its aspect ratio stabilizes after some initial stage [2, 18, 19]. Therefore, the configuration of the initial defect has

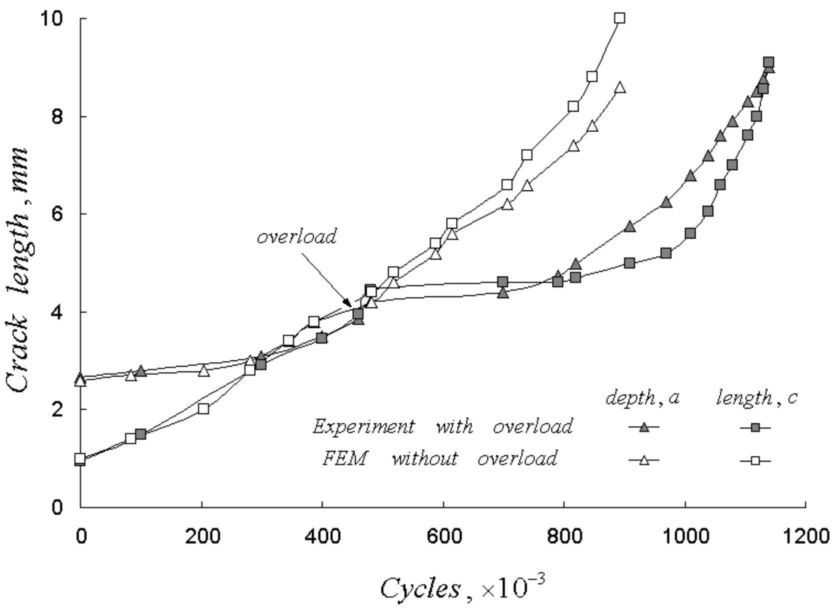

Figure 6: Crack growth in the two directions, at the surface and into the depth

insignificant influence on the crack front evolution, which rapidly becomes semi-elliptical. This effect is illustrated by the crack propagation modeling as initiated from two different defects, Fig. 6. Aspect ratio of cracks growing from various defects in the above compact specimen quickly reaches value ≈ 0.87 and later changes insignificantly, Fig. 7.

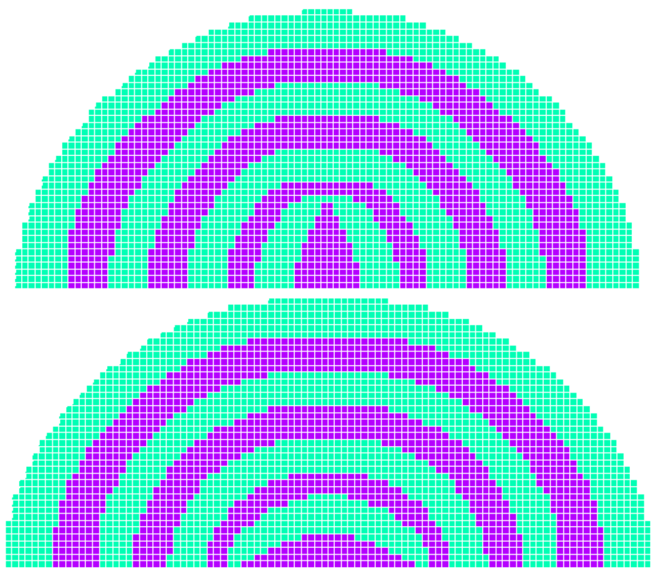

Figure 7: The crack front evolution

5 Conclusions

The simulation of semi-elliptical crack development from the initial defect in steel compact specimen was carried out by FE-modeling of damage accumulation. For the damage

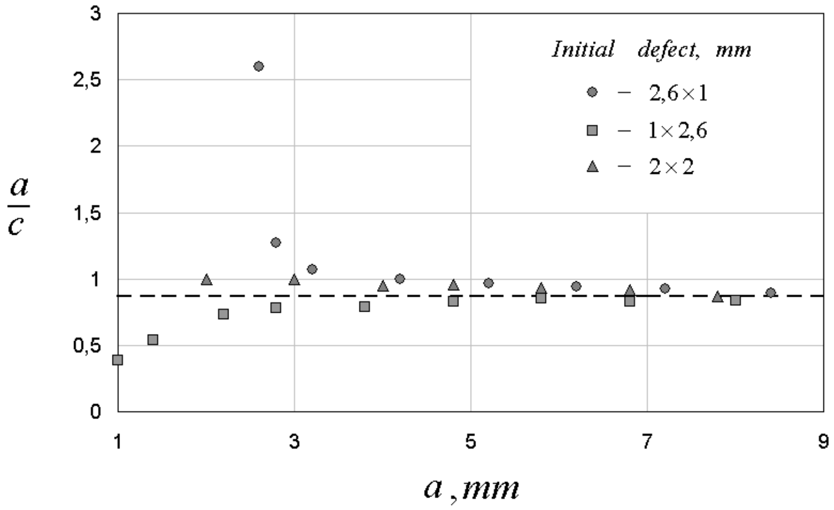

Figure 8: Stabilization of the crack aspect ratio

assessment the strain-life fatigue failure criterion was used. Crack closure effect, the non-linearity of the damage accumulation and change of the material stiffness at the crack tip were also considered. Simulation of crack growth confirmed rapid convergence of the crack front to semi-elliptical shape in the initial phase of its development which was revealed in the experiment.

It is shown that the cycle phase, during which the crack remains open, can be defined by fixing a moment when the average value of the stress perpendicular to front at the nodes of the crack tip changes its sign (as in the case of the plane stress). Crack closure parameters obtained on the basis of this assumption correlate reasonably well with the experimental data. Insignificant deviations can be explained by a lack of experimental values and the complex mechanism of crack closure. In addition to plasticity induced residual stresses the important factors as the formation of the oxidation products on the crack faces, varying surface roughness, and their influence on the crack closure have not been experimentally studied yet.

In the numerical analysis at the considered loading conditions, combined tension and bending, the initial defect configuration was found having insignificant effect on the further crack shape development. In the stable phase of crack growth its aspect ratio tends asymptotically to a constant value.

Further experimental studies are required for a more complete understanding of the damage accumulation behavior in areas with varying strain intensity as well as for assessment of the damage influence on the material compliance.

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