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Security Challenges of Sophisticated Simulation towards Construction Materials Fatigue Phenomena Elimination

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Abstract:

Modern societies have become highly dependent on modern technology. Without its tools, their economies can no longer be run and their infrastructure would collapse. Thus technology has offered a high and sophisticated standard of living to societies, but at the same time it has introduced an inherent vulnerability. The efficient Automatic Dynamic Incremental Nonlinear Analysis (ADINA) is a Finite Element Method (FEM) based system, very suitable for solving large variety of personnel security problems; observing construction material processing and growth of fatigue damage, crack propagation and the distribution of stress fields. Leveraged by simulated fracture and damage of material models, it is the catalyst of the problem-solution roadmap towards substantial material cracks elimination.

Keywords:

Modelling and simulation, construction material fatigue, experiments, cracks and degradation process, reliability and personnel security, sophisticated numerical tools, propagation direction.

1. Introduction

The fatigue of construction materials is a degradation process of irreversible changes in material properties caused by cyclic loading. The importance of fatigue is tied foremost to safety of persons whose life depends on the reliability of given device

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operation and an economic viewpoint (new material development cost, device testing, methodology of testing prototypes and final products etc.). Lowering costs and, to a great extent, also increasing efficiency allow progress in computer technology usability and in application of numerical techniques onto large amount of problems in mechanical engineering. Nowadays a large number of commercial computational programs are at the disposal, which allows analyzing fatigue crack propagation. The analysis of cracks within structures is an important application, if the damage tolerance and durability of structures and components are to be predicted. As part of the engineering design process, engineers have to assess not only how well the design satisfies the performance requirements, but also how durable the product will be over its life cycle. Often, cracks cannot be avoided in structures; however the fatigue life of the structure depends on the localization and size of these cracks. In order to predict the fatigue life for any component, a fatigue life and crack growth study needs to be performed [1-3].

Technology has a range of implications for national governments: the impact that scientific and technological developments have on the society, economy and environment; what the latest trends are; what the future might hold; and how this all affects both internal and external security. Therefore, technology, research and development have to be taken into consideration and included among the factors determining security strategy. Additionally, the fast development of technology could have in some nations an internal aspect, as it is not sure that all top managers and their political masters are well aware of what is going on. This remark is not made to blame them, but to stress that the technical complexity is now so high that it has become very difficult for specialists to inform the decision makers thoroughly and clearly about the possibilities and consequences of every technical progress. This leaves the door open to a lot of deleterious lobbying and potentially dangerous strategic orientations and operational choices.

2. Crack Growth Rate

The application of fracture mechanics principles to fatigue permits separate considerations of a crack initiation stage, crack propagation and final failure stages. In many engineering applications, cracks like defects exist when the component is put into service, eliminating the initiation part of the fatigue life. Crack propagation behaviour then becomes the most important damage regime in developing fatigue life predictions. In a fatigue (crack growth) test, the crack length (a) and the associated number of cycles (N) are recorded. The crack growth rate is defined as the crack increment per cycle da/dN. It was found out that da/dN could be correlated by the stress intensity factor K. This means that different geometries show about the same da/dN when the same ΔK ($\Delta K = K_{\max} - K_{\min}$) is applied. In other words, cycle with the same ΔK will always produce the same crack growth rate da/dN (da/dN = $f(\Delta K)$) (Fig. 1).

Paris found a linear relation between da/dN and ΔK on a log-log scale for intermediate crack growth rates which implies:

$$\mathrm{d}a/\mathrm{d}N = c\Delta K^m \qquad (1)$$

The equation is referred to as Paris law. ΔK can be considered as the crack driving force. This driving force has to overcome the resistance of the material against cracking. If a crack grows, it is a consequence of a variation in K. The Paris law is a simplification, because other influences are not explicitly considered. These influences were thought to be secondary to the ΔK effect and as a consequence they were neglected. The stress ratio effect (effect of R, $R = \sigma_{\mathrm{min}}/\sigma_{\mathrm{max}}$) was also supposed to be a secondary effect, but later experiments have shown that R-effect is significant for many materials.

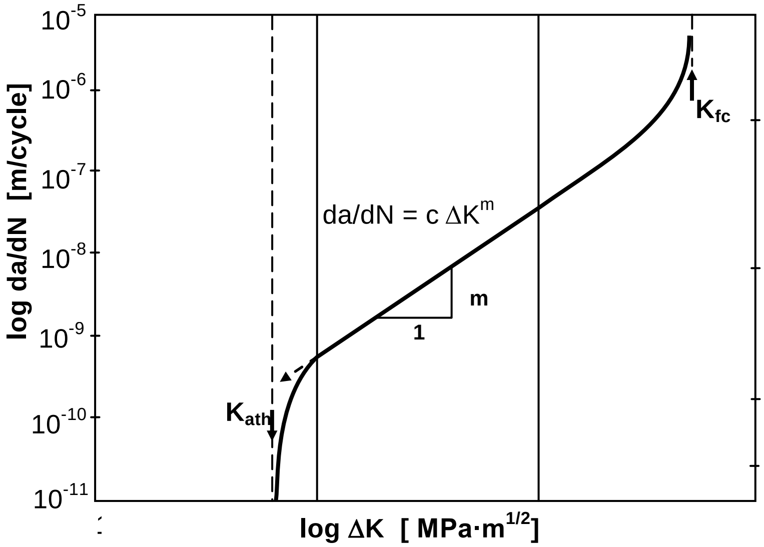

Fig. 1 Fatigue crack growth as a function of ΔK

One of the problems encountered with the similitude approach is the relation of da/dN to the stress ration. A solution for this problem was found by Elber. He discovered that fatigue cracks are closed for significant portion of a tensile load cycle, due to residual plastic deformation left in the wake of a growing crack (Fig. 2). He introduced an effective ΔK, which is the K variation during which the crack is fully open. By using a relation, experimentally found, between ΔK_{eff} and the stress ratio R, he was able to fit da/dN – ΔK curves at various R values into a narrow scatter-band. The similitude concept could be restored by using da/dN and ΔK_{eff} instead of da/dN and ΔK.

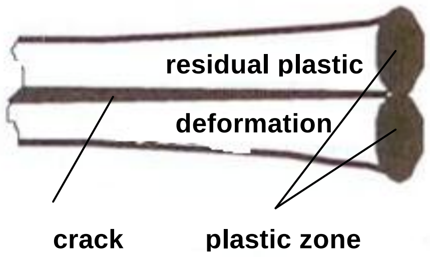

Fig. 2 Principle of plasticity inducted crack closure

3. Methodology of Modelling and Simulation

In this case, the virtual crack extension method was applied using the virtual material shift. The crack was defined as a line because 2D analysis was carried out. Input of the analysis was the static tensile test of the particular material which the relation stress – strain ($\sigma - \varepsilon$) was obtained from. So plotted material curve was used for calculation of stress intensity factor range ΔK along crack growth which purveyed data about crack propagation, potentially crack stopping.

Subsequently, a model was created in finite-element software ADINA which was identical with bar used for experimental tests. The test specimen shows double symmetry, and this knowledge was effectively used to reduce the model when only one quarter of the specimen together with boundary conditions for symmetry was modelled. Boundary conditions for symmetry were defined not to allow note shifting in the direction perpendicular to the crack growth. Cyclic load was applied on the boundaries.

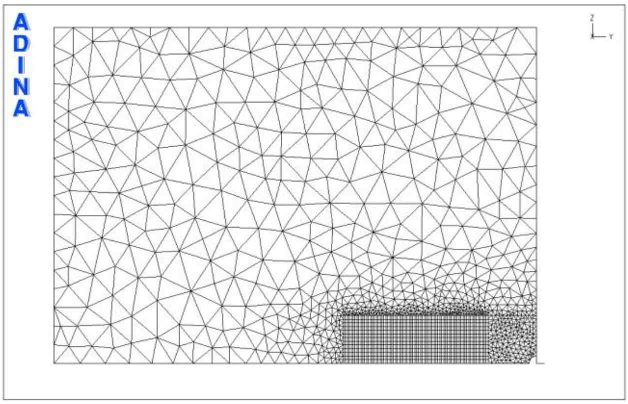

Fig. 3 Meshed model

The material is modelled as an ideal elastic-plastic material with no defects or imperfections, except for the defined initial crack. The structure of the meshed model (Fig. 3) consisted of finite elements with triangle shape with six nodes. In the area of crack propagation and in the vicinity, finer mesh was produced in order to achieve higher accuracy. It has turned out that the quality of the mesh has significant influence on the accuracy of the results. The structure was created by 6 239 nodes and 2 540 finite elements. There were used 400 crack increments.

The resistance curve (Fig. 4) was created in MATLAB by inverse analysis from one experimental curve $2a - N$ and from relation of J-integral on crack length obtained from finite-element software ADINA for particular geometry. The relation of the resistance curve on crack increment was found out by analysis and directly put into module for the calculation of crack growth as a material characteristic.

Subsequently, remaining curves $2a - N$ were obtained for different asymmetry coefficient. Crack growth was assigned by virtual material shift moving with the crack tip during the propagation (Fig. 5) using “node shift/release” technique (Fig. 6).

The crack propagation surface, which typically corresponds to the ligament in a fracture mechanics test specimen, is defined in ADINA as the set of nodes which may possibly be released when the crack opens. The crack propagation surface must be planar. In 2D models, the crack propagation surface reduces to a line, though it is still called a surface. The crack propagation surface must always lie either in the *X*-*Y* plane of the global Cartesian coordinate system or in the a-b plane of a skew system common to all the nodes on the crack propagation surface. When the crack growth control parameter (energy release rate or any other parameter available in ADINA) indicates a crack increase, the crack tip node is automatically shifted to a new position (Fig. 6 – step 2). When the advance of the crack tip node becomes larger than the width of the element ahead of the crack tip node in the propagation direction (and connected to the crack propagation surface), the crack tip node is released and the next node on the crack propagation surface begins to shift (Fig. 6 – step 3). Mid-side nodes are shifted accordingly, to remain halfway between the corresponding corner nodes, and they are released when the preceding corner node on the crack propagation surface is released. This procedure does not require any specific element size or mesh refinement, apart from general considerations on the accuracy of the analysis results.

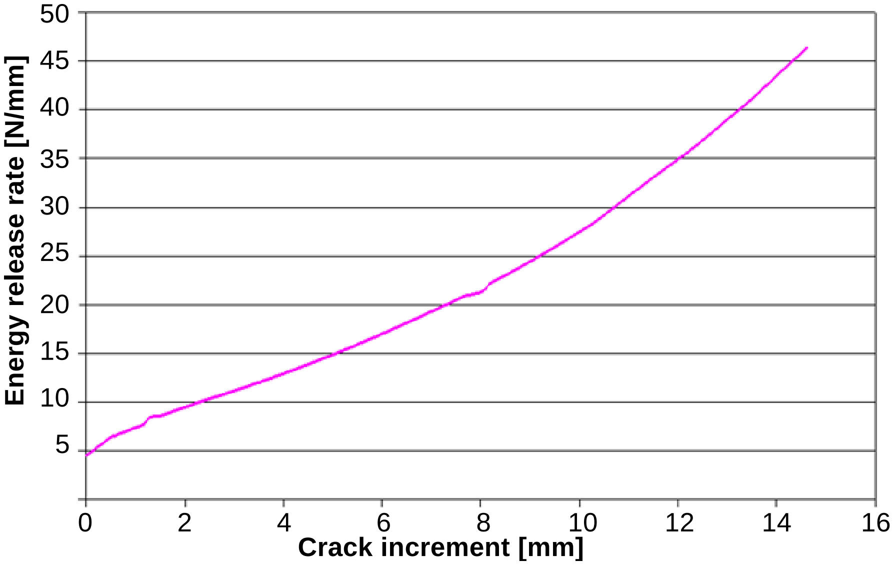

Fig. 4 Resistance curve

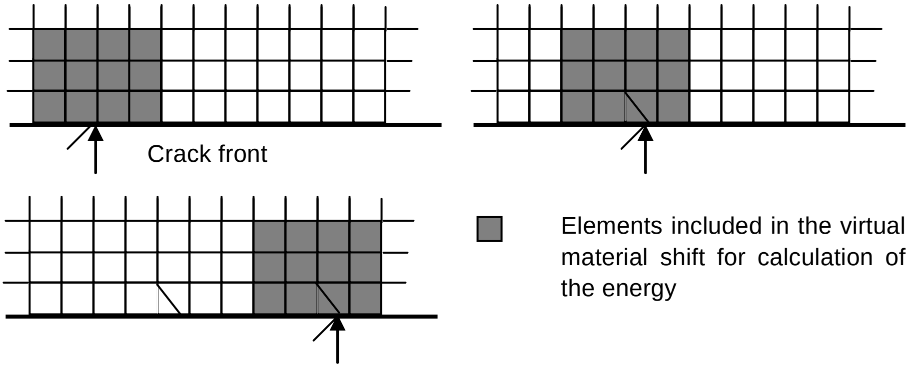

Fig. 5 Virtual material shift which moves with the crack tip during propagation

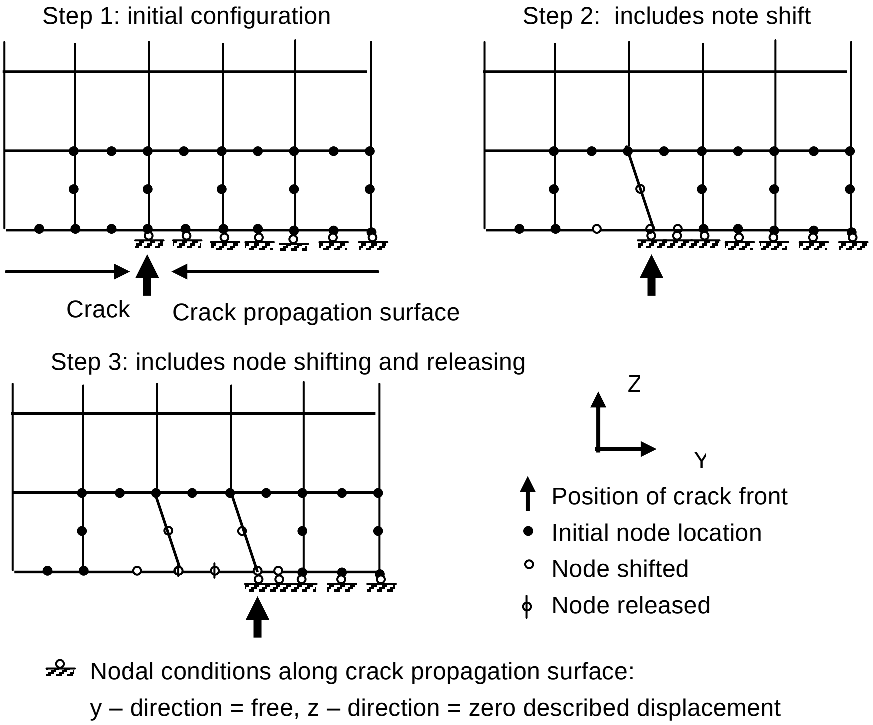

Fig. 6 The node shifting and releasing procedure for crack propagation

In regular time intervals the surface crack length $2a$ and number of loading cycles were measured. For processing of the experimental results, as well as for numerical results (Fig. 7), the starting point was the relation of crack length $2a$ on the number of cycles N. From the relation $2a – N$, the relation of fatigue crack propagation velocity da/dN on the crack length $2a$ was numerically obtained, as well as the relation of fatigue crack propagation velocity da/dN on the applied value of stress intensity factor range ΔK_{apl} [4].

4. Numerical Part

The simulations were carried out on material which is widespread in the construction in the railway transport. Construction steel S235JRG1 is weldable, low-carbon, soft steel used for building transport machinery and devices, for chosen mechanical parts, parts of constructions, frames and suspension of rail vehicles and other transport vehicles. Chemical composition and chosen mechanical properties of low-carbon steel are shown in Tabs. 1 and 2.

Table 1 Chemical composition (mass%), S235JRG1

C	Mn	Si	P	S
0.15	0.93	0.44	0.01	0.009

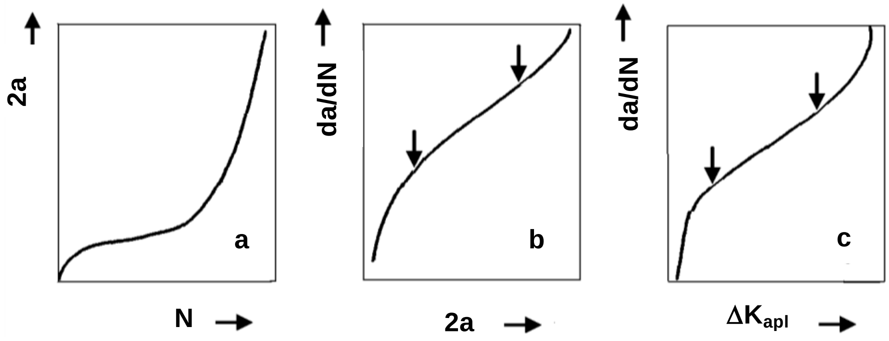

Fig. 7 Method of results processing

Table 2 Mechanical properties, S235JRG1

R_e [MPa]	R_m [MPa]	A [%]	Z [%]	E [MPa]	HV
235	372	24	57	2.06×10^5	132

In accordance with presented process, there were acquired $2a - N$, shown in Fig. 7 for testing specimens by frequency $f = 10$ Hz with maximal strength of constant value $F_{\max} = 100$ kN at asymmetry loading cycle $R = 0.35$; 0.5 and also numerical results in ADINA and both results – experiment and simulation were compared (Fig. 8).

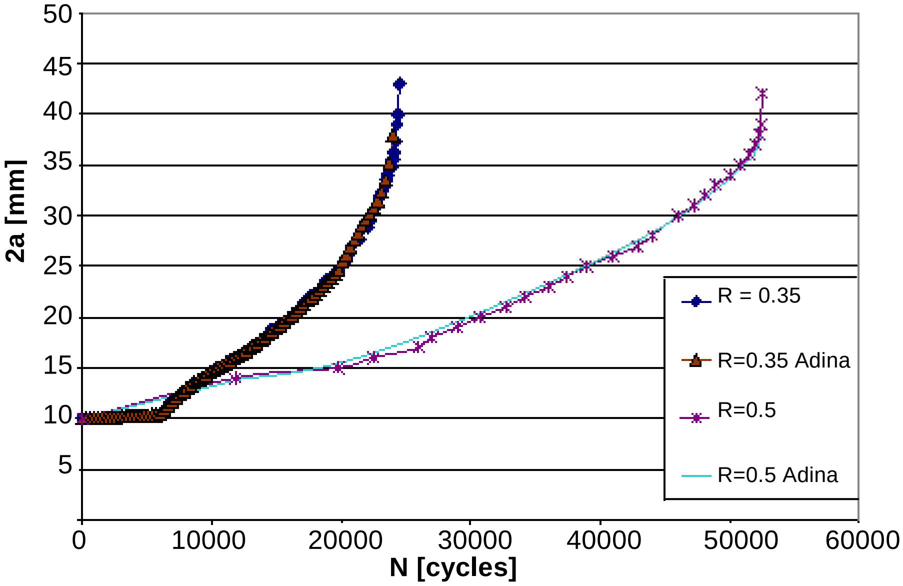

Fig. 8 Comparison of the relation 2a – N for R = 0.35; 0.5

Fatigue crack growth in the range of 20 mm $\leq 2a \leq$ 35 mm (validity of the Paris law) is considered to be stable. Relations of fatigue crack growth on the applied value of the stress intensity factor range for steel S235JRG1 using the finite element software ADINA in the area of Paris law for different asymmetry coefficients R are depicted in Fig. 9. Results obtained numerically are compared to the experimentally obtained relations. To calculate the applied value of the stress intensity factor range ΔK_{apl} we use the equation:

$$\Delta K = \Delta K_{apl} = \frac{F_{\max} - F_{\min}}{B \cdot W} \sqrt{W \cdot \tan \frac{\pi a}{W}} \qquad (2)$$

where B – test specimen thickness, W – test specimen width, a – half size of crack length.

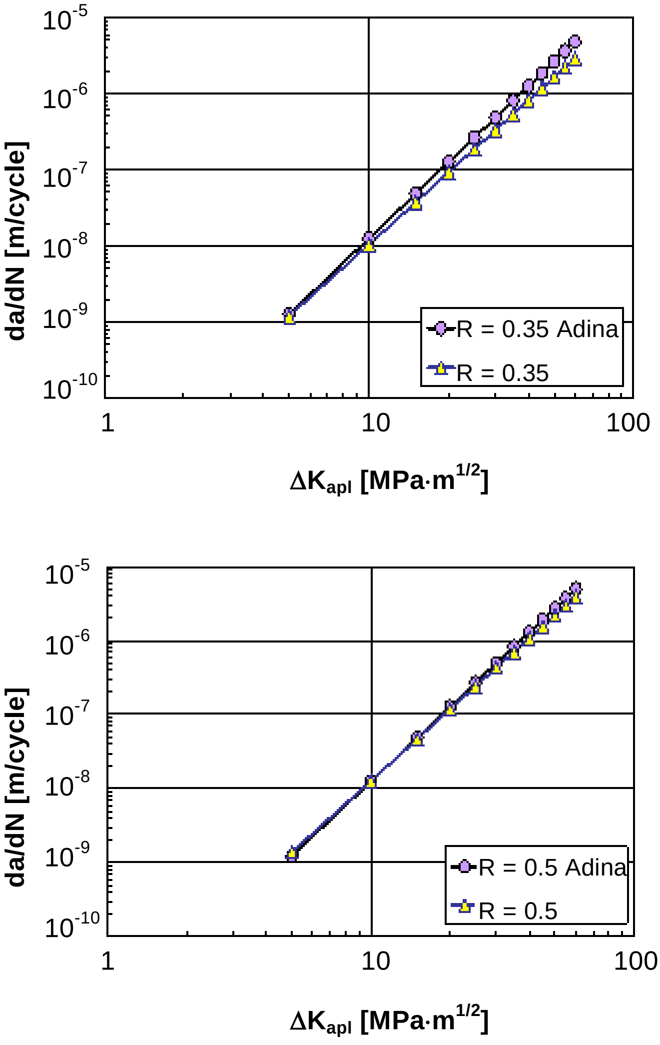

Fig. 9 Relation da/dN – ΔK_{apl} for R = 0.35 and 0.5

5. Conclusion

Based on the experimental measurements as well as numerical simulations, we can consider that fatigue crack length is increasing with the increasing number of cycles and loading cycle asymmetry *R*. The results obtained by experimental measurement as well as by numerical simulation are shown in the Fig. 9. If we compare the simulation and experiment, we can consider the difference between two results as negligible. It is possible to state a good correlation between the experimental measurement and numerical simulation. The difference was caused by some factors influencing experimental tests, for instance more defects and impurities in comparison to simulation. In the case of simulation, results are strongly dependent on fineness of the mesh in the crack propagation area and also on material model. We have come to the conclusion that finite element software ADINA is able to solve the problem of fatigue crack propagation and its results are fully comparable to experimental results.

A useful feature of the simulation is the ability to determine and evaluate fatigue resistance and to predict the results of experimental tests subjected to cyclic loading with a reasonable accuracy [5, 6]. Scientific and technological expertise permits a nation to exploit its resources and produce more and better goods and services, including those of a military nature. Accordingly, differences in technological capacity among nations give rise to differences in the main traditional dimensions of security, i.e. social, economic and military.

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