IDENTIFICATION OF CRACK PARAMETERS AND STRESS INTENSITY FACTORS USING THE BODY FORCE TECHNIQUE

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Summary We present a method for crack detection and stress intensity factor measurement in plate structures by using strain gauges and applying the Body Force Method (BFM). The BFM is based on elastic solutions for concentrated loads and the principle of linear superposition allowing e.g. the calculation of the strain field in a cracked body. The inverse problem is solved applying the PSO (particle swarm optimization). Experiments are carried out under cyclic loading using pre-cracked plates made of aluminum alloy.

INTRODUCTION

Engineering structures are in general exposed to cyclic or stochastic mechanical loading. Exhibiting incipient cracks, particularly light-weight shell and plate structures suffer from fatigue crack growth, limiting the life time of the structure and supplying the risk of a fatal failure. Due to the uncertainty of loading boundary conditions and the geometrical complexity of many engineering structures, numerical predictions of fatigue crack growth rates and residual strength are not reliable. Most experimental monitoring techniques, nowadays, are based on the principle of wave scattering at the free surfaces of cracks. Many of them are working well, supplying information about the position of cracks. One disadvantage is, that those methods do not yield any information on the loading of the crack tip. On the other hand, there are techniques to measure the stress intensity factors e.g. applying a strain gauge in front of the crack tip. However, this method does not allow for crack growth. Goal of our work is the development of a monitoring concept supplying both the information on the actual crack position and the stress intensity factors. This enables a more comprehensive and reliable survey of structures, based on both the knowledge of the actual crack position and a numerical prediction of further crack development from crack tip loading parameters. In [1] this goal is pursued interpreting electric signals from a piezoelectric foil fixed to the surface of the structure. There, the crack tip *near* field is used for crack parameter identification. In this work, we use strain gauges to measure the *remote* strain field at different positions on the surface of a shell-like structure. The fields are controlled by both external loads and the crack growth. Representing external loads by equivalent crack surface tractions and an additional parameter not depending on the crack configuration, the crack length and stress intensity factors can be calculated based on crack weight functions solving the inverse boundary value problem. The approach presented in this paper is based on the weighted superposition of elastic Green's functions representing the strain field due to the presence of a crack, the weights again being identified by inverse problem solution [2].

FUNDAMENTAL CONCEPTS OF THE BODY FORCE METHOD

Considering that linear elastic fields can be super imposed, we express the elastic field under investigation by superposing some specific known elastic fields, which can be written in a closed form, multiplied with some unknown weight-magnitudes as follows [3]:

$$\boxed{\begin{array}{c}\text{elastic field}\\ \text{under}\\ \text{investigation}\end{array}} = \sum \boxed{\begin{array}{c}\text{specific known}\\ \text{solutions of}\\ \text{elastic field}\end{array}}_i \times \boxed{\begin{array}{c}\text{unknown}\\ \text{weight}\\ \text{magnitudes}\end{array}}_i \tag{1}$$

Calculation of strain at an arbitrary point

According to the body force method, the strain field due to cracks can be replaced by the strain field due to body force doublets distributed continuously along the prospective boundaries of the cracks in a homogeneous infinite plate [4]

$$\varepsilon_{ij}(P) = \int_\Gamma \varepsilon^*_{ij}(P, Q_x)\phi_x(Q)d\Gamma + \int_\Gamma \varepsilon^*_{ij}(P, Q_y)\phi_y(Q)d\Gamma + \sum_{kl=yy,xy} \tilde{\varepsilon}_{ij}(P)\sigma^\infty_{kl}. \tag{2}$$

Here, $\tilde{\varepsilon}_{ij}(P)$ is the strain at a point P caused by uniform stress σ^∞_{kl} applied at infinity, while $\varepsilon^*_{ij}(P, Q_x)$ and $\varepsilon^*_{ij}(P, Q_y)$ are, respectively, the strains at a point P due to the tensile and shearing sets of point force doublets acting at a point Q. Within the framework of linear elasticity the latter are also known as fundamental solution. The unknown densities of body forces are denoted by $\phi_x(Q)$ and $\phi_y(Q)$. These densities are defined by the following equations:

$$dF_x(Q) = \phi_x(Q)d\Gamma, \;\; dF_y(Q) = \phi_y(Q)d\Gamma, \tag{3}$$

where F_x and F_y are concentrated body force doublets.

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SOLVING THE INVERSE PROBLEM

The solution of the inverse problem is carried out using the PSO algorithm by minimizing a fitness function, defined as

$$fitness = \sum_{m=1}^{M} \sum_{ij=xx,yy,xy} \{\bar{\varepsilon}_{ij}(P_m) - \varepsilon_{ij}(P_m)\}^2. \tag{4}$$

The fitness function is defined by a square sum of residuals between measured $\bar{\varepsilon}_{ij}(P_m)$ and computed $\varepsilon_{ij}(P_m)$ strain distributions for an assumed crack.

EXPERIMENTAL RESULTS

Besides numerical experiments based on Finite Element calculations we perform real hardware experiments. We consider a fatigue edge crack located at the middle of a plate created by a cyclic load as shown in Fig. 1. The strain $\bar{\varepsilon}_{ij}(P_m)$ is measured using strain gauges at points P_m (m=1,...,7), the crack length ranges from $a = 16$ mm up to $a = 39,5$ mm, and the loading stresses from $\sigma_{yy}^{\infty} = 2$ MPa to $\sigma_{yy}^{\infty} = 24$ MPa. The crack opening displacement was electronically controlled. Figure 1. shows the obtained results.

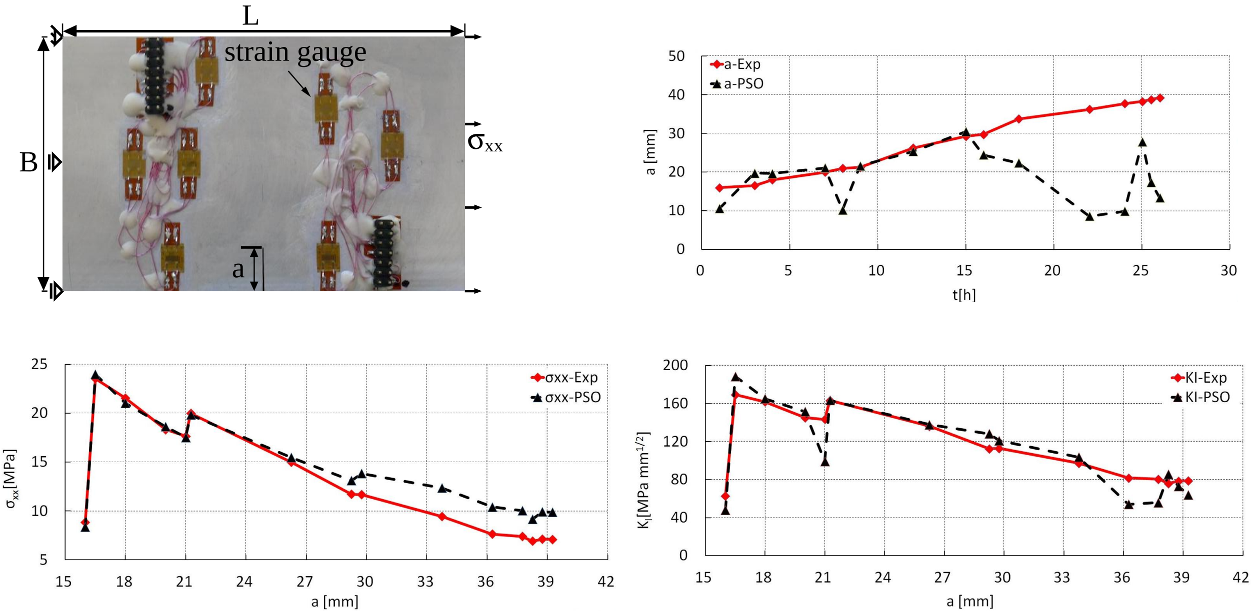

Figure 1: Plate with incipient edge crack and strain gauges (B = 70 mm, L = 150 mm). Plots show calculated (PSO) and observed (Exp) results of the crack lengths a, stress intensity factors K_I-and external loads σ_{xx}

CONCLUSIONS

In this work, the concept of body forces is used for the detection of cracks and the calculation of SIFs by monitoring fatigue crack growth in a plate. We verified this method experimentelly for an edge crack exposed to external cyclic loads. The solution of the inverse problem is in a good agreement with the model data within a wide range of parameters. The method introduced in the present work can be extended to determine cracks with random orientations.

References

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