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Case study

Fracture analysis of a low pressure steam turbine blade

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ABSTRACT

Cracks were analysed at the root of the third blade row of low-pressure steam turbine blades of different natural frequencies. The root cause of the fatigue crack initiation was pitting corrosion of the forged ferritic/martensitic X20Cr13 material. Metallographic investigations, finite element analysis and fracture mechanics analysis combined with experimental data from the literature are used to evaluate crack propagating stresses to discuss the operating conditions. The calculations show that corrosion pits at the root of the turbine blade increase the local stresses above yield strength. Excitation of natural frequencies by changing the rotor speed is not responsible for the crack propagation. The centrifugal load and superimposed bending load caused by unsteady steam forces are responsible for the crack propagation.

1. Introduction

Pitting corrosion at turbine blades in steam power plants is a frequent starting point of growing fatigue cracks [1–3]. In a recently conducted failure analysis [4], pitting corrosion has been detected at the first load bearing flank of a low pressure steam turbine blade during a major overhaul. Metallographic investigations as well as qualitative finite element analysis (FEA) of the cracks were carried out to determine the root cause of the failure. Questions about the crack propagating loads (important for operation), the excitation of natural frequencies (important within cyclic operating conditions) and the generation of a viable crack size (damage tolerant design) are important for operators and designers of steam power stations. For them it is important to determine inspection intervals; to calculate the operation time to the present (or a detectable) crack size. Inspection, maintenance and replacement cause downtimes are costly and therefore studied [5] to optimise intervals.

Linear elastic fracture mechanics (LEFM) and FEA are typically used for damage tolerance or fail-safe design concepts (e.g. the evaluation of the residual life-time with the Paris law or the leak-before-break design) as illustrated by [6, p. 378]. Here LEFM and FEA are used to evaluate stresses in order to suggest the crack initiation, propagation and finally the operating conditions. Results from failure analysis with literature data are used as an input for the fracture mechanics analysis. Knowing three of the parameters in Fig. 1a (e.g. Y, a, ΔK) the fourth ($\Delta\sigma$) can be calculated. FEA and determined input parameters (see Fig. 1b) are used as a proof and as an extension to the analysis. The cracks are illustrated in Fig. 2 to show the investigated turbine blade in top Fig. 2a and side Fig. 2b view. The red planes at the first load bearing flank mark the positions of the fatigue cracks. Crack 1 is the oldest fatigue crack and is therefore used for analysis.

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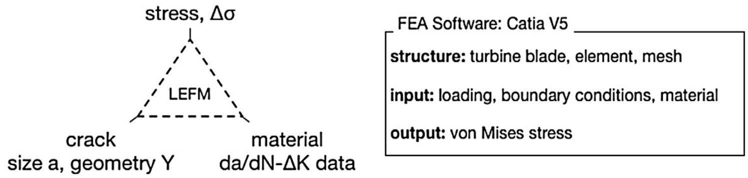
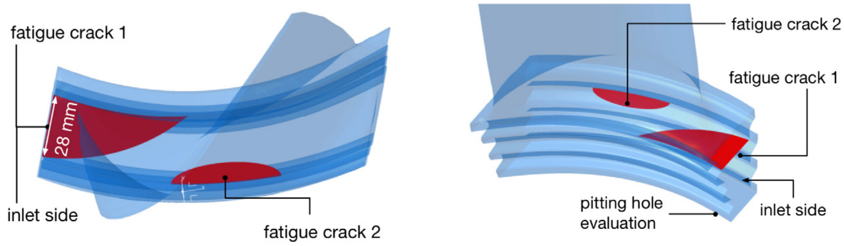


(a) Schematic input parameters for LEFM.
(b) Stress or strain as output parameters of the FEA.

Fig. 1. LEFM and FEA input and output to compare evaluated stresses from 2 independent results.



(a) top view
(b) inlet edge side

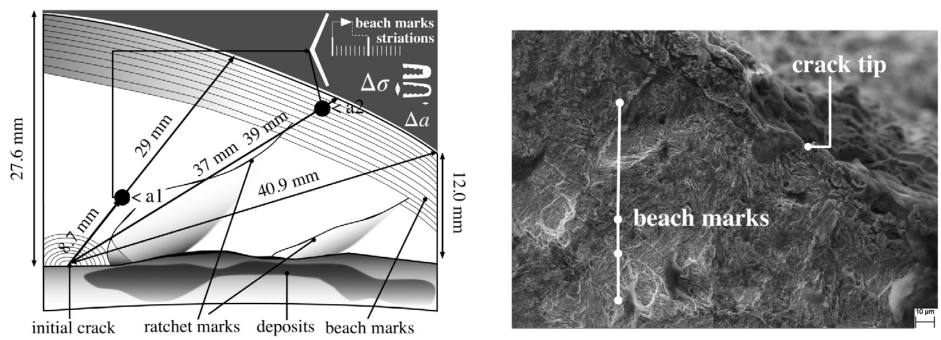
Fig. 2. The fatigue cracks are illustrated with red planes at the pressure (crack 1) and the suction side (crack 2) of the blade. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Crack growth can generally be divided into three stages [7,8] as to the crack propagation curve – though more detailed distinctions are possible [9]. Stage I is related to crack nucleation or crack initiation, stage II to constant fatigue crack growth and stage III is related to failure by fracture, instability or an other limiting factor. Crack initiation within stage I occurred by pitting corrosion at the first load bearing flank. To investigate the fracture surface in stage II, the apparent beach and ratchet marks of crack 1 were analysed and are illustrated in Fig. 3. The cyclic stress amplitude and/or load ratios relates to beach mark and striation formation [9, pp. 530], which is aka similitude hypothesis [10]. Fig. 3a shows the traced fracture surface image of crack 1 and displays the path of the crack like a roadmap, beginning from the pitting hole (initial crack) towards ratchet marks (local crack surfaces join each other) to the crack tip. The shape of the fracture surface is elliptical with a final relationship between the short arm a, and the long arm c (along the 1st load bearing flank), where $a = 27.6$ mm/ $c = 43.4$ mm = 0.64. The striations, separating different beach marks are not visible without the use of a scanning electron microscope (SEM). The positions for the evaluation of the striation distances are marked at the fracture surface with a_1 and a_2. The SEM image in Fig. 3b shows beach marks (indicating temporary crack arrest) at the crack tip and their distance is evaluated to be 23 ± 9 µm in average, although their distance is position dependent.

Stage III is related to fracture or failure and did not occur due to crack detection and replacement during the major overhaul.

1.1. Loads on a low pressure steam turbine blade

The loads acting on a turbine blade are the centrifugal forces, centrifugal bending, steady steam bending, unsteady centrifugal forces due to lateral shaft vibration and alternating bending [11]. These are created by the centrifugal load and



(a) Schematic illustration of crack 1 to provide information about the real fatigue crack surface.
(b) SEM image at the crack tip of crack 1.

Fig. 3. Traced fracture surface, providing information about the real fatigue crack surface.