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On the detection threshold for fatigue cracks in welded steel beams using vibration analysis

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ABSTRACT

In this paper the influence of a surface fatigue crack on vibration behaviour of tee-welded plates was studied and results compared to the influence of machined through-thickness cuts on the dynamic response of cantilever beams. Comparison of experimental data with two and three dimension finite element modelling results was also carried out and discussed. Detection threshold using natural frequencies shift was found and compared to literature.

The influence of naturally grown fatigue cracks on the oscillation frequencies was analysed and compared to two and three-dimensional numerical modelling results. An experimental detection threshold was found using the variation of the first mode natural frequencies.

The power density spectra of the acceleration signals were analysed. Crack shape was found important for the detection threshold of the method. It was found that small size semicircular fatigue cracks do not noticeably modify the beam natural frequency but generate integer harmonics of the vibration modes that provoked stresses at the samples surface affected by the crack. The harmonics found were found to be generated by the breathing behaviour of the fatigue crack. A detection threshold using this spectral analysis was found to be lower than those found by using frequency shifts. The results obtained showed the ability of the experimental technique to detect cracks from a size of 0.6% of the cross section area, at 55% of the fatigue lifespan, 35% earlier than the other method studied.

1. Introduction

It is widely known that the dynamic characteristics of intact structures change when they are somehow damaged. The natural vibration frequencies and mode shapes of a structure are both affected when a crack exists because the stiffness is lowered. Both effects can be used to identify cracks. Three main methods are found in literature for crack detection and measurement: (a) modal testing (by studying the eigenmodes of eigenfrequencies changes, vibrational response), (b) vibration-based methods (using the time-based signal or modelling), and (c) non-traditional methods, such as fuzzy logic, neural networks, etc. Among the first group there is a study carried out by Cawley and Adams [1] who found out that stress distribution through a vibrating structure was different for each natural frequency mode and that a crack would alter these stress distributions in a different way for each of them. This led to modal vibration analysis for identification of cracks. Dimarogonas [2] combined rotor dynamics with fracture mechanics to analyse the influence of cracks in rotating shafts. The author observed coupled vibrational modes and non-linear effects due to the existence of a breathing crack. Chondros et al. [3] used the energy method based on the earlier analytical expressions for stress fields of Christides and Barr [4] and the fracture mechanics equations for the analysis of vibrations of cracked beams. A large amount of work has been published in the field of cracked rotating shafts analysis [5–8]. On the other hand, it was found in literature that most of the vibration analyses of cracked prismatic beams were based on inverse methods [10–14] by means of solving the vibrational mode shapes and frequencies for Euler–Bernoulli or Timoshenko beam models with cracks and comparing their results with experimental data. Real fatigue grown cracks are of the breathing type, opened by tensile surface stresses and closed by compressive stresses. Most analyses found in literature used models that represented these cracks with the same influence on the beam stiffness in both opening and closing conditions, without the breathing behaviour. These cracks have a half-elliptical shape and are characterised by their aspect ratio $a/c > 0$, being 'a' crack depth and 'c' crack width. Two-dimensional Euler–Bernoulli of Timoshenko beam models imply through-thickness cracks. These rectangular shaped cracks can be assumed to have an aspect ratio $a/c = 0$, considering that 'c' equals to infinity, regardless of the crack depth 'a'. This leads to significant differences between modelling

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and experimental results with naturally grown cracks, i.e. cracks that start from a material or geometric discontinuity and grow due to oscillating (fatigue) loads. Silva and Gomez [15] found that cracks of small depth resulted in twice the change in frequency as slots of the same depth. This fact was confirmed also by Dimarogonas [2]. Kisa and Brandon [6] stated the difficulty of modelling the vibration response of a beam with a breathing crack when using finite element methods due to the bilinear behaviour of the bending stiffness of the cracked section. Such behaviour of the cracked cantilever response can be modelled as a weakly bilinear oscillator, studied by Zhang and Billings [16] and Bayly [17]. The bilinear behaviour of cracked sections in bending can be understood as a linear spring with a given stiffness constant for compression response and a lower value stiffness constant for tension response. Regardless of the theoretical model, most authors studying the influence of cracks in vibrations of structures often used test cracks with depth-to-thickness ratio (a/h) greater than 0.1. Owolabi et al. [18] found a decrease of less than 1% of the first mode natural frequency for cracks of $a/h = 0.1$. Bamnios et al. [19] performed anti-resonance slope analysis of mode shapes to detect cracks in beams but stated that the method lacks sensibility for depths ratios lower than 0.1. Cracks with low depth ratio are difficult to identify when using natural frequency shift or modal analysis but are more detectable when analysing their non-linear effects in the frequency spectrum. These non-linear effects can be detected in the response spectrum as additional peaks at multiples of a natural frequency. Bovsunovsky and Matveev [14] used fatigue cracks of depth ratio greater than 0.1 and stated that the non-linear effects are much more sensitive to the presence of a crack than the change of natural frequencies and mode shapes. Faverjon and Sinou [20] used frequency response functions for the detection of more than one crack in a beam and the minimum crack depth ratio that they used was 0.1. Ruotolo and Surace [8] analysed the longitudinal vibration of bars with multiple cut through cracks and compared their theoretical results with experimental data from Chondros et al. [9]. They found zero frequency shift for a minimum experimental crack depth ratio $a/c = 0.06$. In addition, it has been found that in literature most of the experimental research was done using long and slender bar test samples. High slenderness of prismatic bars gives lower natural frequencies when compared to thicker sample pieces. Therefore, there is a significant difference between real components and testing sample behaviour. Most authors used test pieces with high slenderness (length/height > 20) made of various materials [5–7,10]. Authors who used test pieces with lower slenderness ($10 < L/h < 20$) selected materials with lower Young Modulus, such as Aluminium, plexiglas of polymer composite for making their test samples [11,18,21,22]. In the present work the threshold of detection of cracks was studied through the analysis of impact test responses of steel prismatic cantilever bars with slenderness relatively small ($L/h = 12$) since these characteristics are closer to many real applications in service, such as connecting rods, crankshafts and turbine blades. Impact tests on cantilever samples were performed at equal intervals throughout the crack growth process to acquire vibration data. The extent of applicability of a frequency measurement technique for the early detection of naturally grown cracks was studied.

2. Experimental and numerical analysis procedure

2.1. Experimental tests, materials and methods

The difference between the impact responses of samples with naturally grown cracks and with through-thickness cracks was analysed using tee shaped samples cut from two tee-welded plates. The samples base plate thickness was 25.4 mm while the samples cantilever part thickness was 12.7 mm. The mean sample width was 48 ± 0.4 mm. The material used was A36 steel and the welding was done using MIG equipment with the following parameters: 310 A current, 30 V voltage, and a speed of 0.4 m/min. The samples were tightly fixed by the base plate. The defects on the samples were produced at the weld toe by two techniques: mechanical saw cuts and by fatigue. In Fig. 1i a diagram of the cutting technique for the making of the cracks with aspect ratio $a/c = 0$ and a sample cut with this technique is shown in Fig. 1iii. The fatigue cracks were grown upon the application of an alternating bending stress to the cantilever part, as shown in Fig. 1ii. A post mortem sample fatigue fracture surface is shown below in Fig. 1iv. In the latter case an alternating force at a frequency of 10 Hz was applied vertically onto the cantilever part of the sample. The force amplitude was 4.5 KN, with ratio $R = 0.2$, which led to fatigue nucleation and growth, as detected by strain gages. The nominal maximum tensile stress at the surface was 275 MPa. The alternating forces on samples were provoked by a walking beam type fatigue test machine, shown in Fig. 3. The tensile stresses on the samples surface at the weld toe were measured by strain gages, as explained in Section 2.2. In Fig. 2i and ii the experimental set ups for impact testing for each type of sample are shown. The samples were fixed by the base plate for impact testing onto the cantilever part. The driving points for impact tests can be observed at the lower right corner of each picture in the figure. Driving points number one and three were located at each corner of the cantilever, while driving point number two was located at the centre of the test sample end. Impact tests were carried out

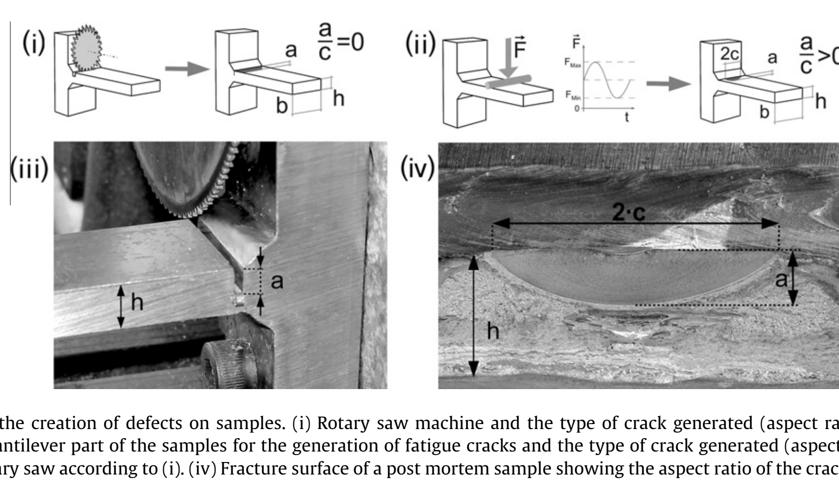

Fig. 1. Experimental set up for the creation of defects on samples. (i) Rotary saw machine and the type of crack generated (aspect ratio $a/c = 0$). (ii) Alternating vertical bending forces schema on the cantilever part of the samples for the generation of fatigue cracks and the type of crack generated (aspect ratio $a/c > 0$). (iii) Sample showing through-thickness crack and rotary saw according to (i). (iv) Fracture surface of a post mortem sample showing the aspect ratio of the crack produced by the technique shown in (ii).