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DYNAMIC FATIGUE CRACK PROPAGATION IN TUBULAR SPECIMENS

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Abstract. Gauging the fatigue performance of structures such as offshore jackets that are subject to cyclic loading is essential in the design and life extensions to ensure the suitability of the service. A novel fatigue rig that was developed at the Centre for Applied Dynamics Research in Aberdeen was recently modified to undertake experimental tests on tubular specimens with a range of sizes and various cross-sections while monitoring dynamic forces applied to the specimen using two new load-cells. The crack initiation and propagation on tubular specimens with pre-cut grooves were investigated using an alternating current potential difference (ACPD) method. Crack length time histories have also been constructed. The mathematical model describing the rig behaviour with cracked specimens was formulated, and the stiffness of the plastic components in contact with the specimens was refined in the mathematical model. The mathematical model of the rig was further refined to implement the stiffnesses of different components. The results of the mathematical model were compared against the measurements from experimental data acquisition. Following the calibration of the mathematical model, it was observed that the model response is very close to that from experimental measurement. The validated mathematical model can predict the response of the fatigue rig, which enables the calibration of the experimental parameters in advance to achieve the desired response from the system.

Keywords: Fatigue, crack propagation, experimental studies, mathematical modelling

1. INTRODUCTION

The design for fatigue performance of elements subject to cyclic loading is crucial in proving fitness for purpose and ensuring service life. The codes and standards used for fatigue checks are updated regularly in the light of new research and developments in this field. The jacket structures and wind turbines are designed for fatigue and in life extension projects. Demonstrating extra life can lead to extra years of service life and the best use of existing assets. The S-N curves in the design codes are normally conservative and can be generic. Some fatigue experiments aim to simulate the geometry and loading patterns experienced by the structural members in real life. Tubular sections are commonly used in the offshore industry in the structure subject to wave and wind loading, such as pipelines, caissons and risers. The cyclic loads on these elements from environmental loading cause fatigue damage, and the design for fatigue and life prediction is of paramount importance. Tubular specimens with pre-existing stress raisers, such as grooves, can be tested using the proposed experimental fatigue rig. Achieving higher fatigue life or improving the fatigue performance of metals is possible through a standard mechanical process in practice, such as peening or toe grinding in welds, or innovative methods like surface rolling treatment as studied by Carneiro *et al.* (2020). In the current study, the objective is to minimise uncertainties in fatigue experiments by monitoring loads, displacements and crack propagation to optimise a fatigue design. The use of aluminium alloys in structural engineering is more common nowadays due to the light weight and high corrosion resistance properties. Xiang *et al.* (2017) studied 6061-T6 aluminium alloy under ultra-low cycle fatigue scenarios, which is mainly practical in the use of aluminium in seismic prone regions. This study focuses on low and high cycle fatigue, which covers a wider range of industrial usage.

The fatigue phenomenon typically begins with the nucleation of microcracks, followed by coalescence and growth of microcracks. The final stages involve long crack growth and final fracture. Crack initiate at the location of high-stress concentration, which is usually in the region of geometry change, welding, connection points, inclusions, porosity, defects or discontinuities.

Novel fatigue rigs are being developed to perform fatigue experiments for practical purposes, such as the fatigue rig developed by Okeke *et al.* (2018) and Nagabhooshanam *et al.* (2018). Nevertheless, none of these rigs

enables direct measurement of forces applied on the specimens during the course of fatigue experiments. Many of such experiments use servohydraulic machines, such as the experiment carried out by Wei *et al.* (2020).

Foong *et al.* (2006) designed a novel fatigue rig at the University of Aberdeen. Subsequently, a parameter identification study was carried out on this rig. This rig was later used in further research on nonlinear vibration caused by fatigue and chaos caused by fatigue crack growth.

This fatigue rig enables fatigue experiments on specimens under bending. During this research, the fatigue rig underwent major modifications. The modifications allow the rig to carry out experiments on different section sizes while monitoring the exact dynamic force applied to the specimens using newly designed load cells. In this research, ACPD technology was used to monitor the initiation and propagation of the crack. This technique was also used in other fatigue experimental research. Mikulski *et al.* showed that the ACPD method is sensitive to early crack growth. Measuring the crack in the experiment without interruption during the test is one of the advantages of the ACPD method.

The dynamic fatigue testing rig quantifies crack propagation when external loads vary in amplitude with time. Parameter identification of mechanical system characteristics is important, especially in terms of its accuracy. Moreover, these characteristics are often nonlinear in nature and can be modelled accordingly in nonlinear mathematical equations so that the prediction of crack propagation rate can be as accurate as possible.

In particular, incorporating the stiffness characteristic in system governing equations to predict the system response accurately requires the ordinary differential equations to be updated and refined for experimental correlation.

2. EXPERIMENTAL FATIGUE RIG

The experimental rig facilitates experimentation on a single edge notched beam (SENB) such that an external forcing input comes from an electromechanical shaker, signal inputs to which were programmed in Labview software. Electrical signals from accelerometers were required to measure the accelerations of masses above and below the specimen. The kinematics of the electromechanical shaker was also quantified using the same type of transducer. The electrical signals were monitored in real-time on oscilloscopes to ensure that they were the same as what was recorded on a personal computer. An Eddy current probe, which is a form of proximity sensor, measured displacements from vibrations of a specimen. A schematic diagram of the experimental rig is shown in Figure 1.

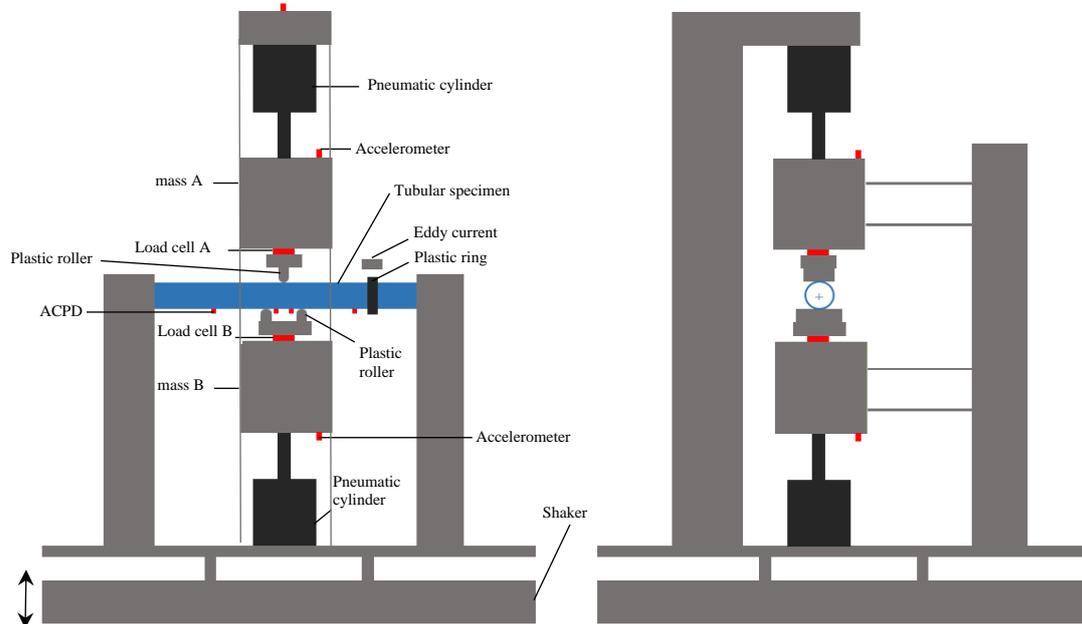


Figure 1: Schematic diagram of the modified experimental fatigue rig. The electromechanical shaker provides a base excitation to the experimental rig so that cyclic stresses in the tubular specimen initiate and propagate cracks. Two force sensors and three accelerometers combined with the proximity sensor (eddy current) and alternating current potential difference (ACPD) measurement setup are shown.

New flexible specimen jaws were designed to accommodate a range of specimen sizes and shapes. To apply the loads directly to the specimen, the rollers are made of high strength plastic to minimise the damping at the load interface. For this purpose, cast nylon 6 was used, which is of a hardness of 170 ball indentation, and is

resistant to abrasion. To ensure point contact with a 3-point bend specimen, the roller is shaped in a curve where it is in contact with the specimen. The photographs of the experimental rig are shown in Figure 2.

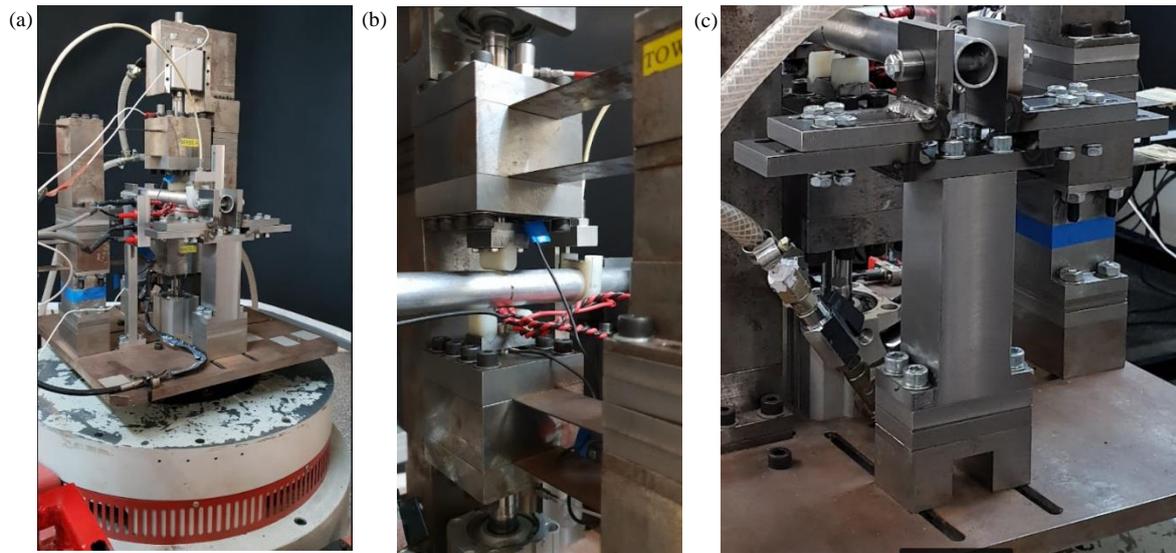


Figure 2: (a) Photograph of the experimental fatigue rig on an electromechanical shaker; (b) close-up photograph of Masses A and B at top and bottom of the tubular specimen, respectively, which are connected to a vertical tower fixture using leaf springs; plastic rollers were used to apply forces to the tubular specimen while the half circumference v-shaped groove guides the direction of formation of the initial crack. The ACPD cables are attached close to the sides of the groove to monitor crack length; (c) flexible jaws to facilitate experimentation on tubular specimens as well as arbitrary geometries.

The stiffness of leaf springs, as well as the damping ratio, were calculated by observing the damped, free vibration of masses A and B such that their accelerations were recorded in 40 seconds. The stiffness of leaf spring A turned out to be 14.181 kN/m, and that for leaf spring B was 14.392 kN/m. The damping ratios of leaf springs A and B were 0.00188 and 0.00141, respectively. Two force sensors located between the masses and specimens were calibrated using a 3kN Hounsfield load cell device in the materials laboratory at the University of Aberdeen. The propagation of a crack in the specimen is monitored using the ACPD method. A side experiment using pre-cut specimens, representing cracked specimens, showed that the ACPD reading and crack length measurement have a linear relationship. The finding is demonstrated in Figure 3.

Calibrations of the sensors were necessary to post-process the signals. A Labview programme was created for the modified fatigue rig, which collected the signals from the seven sensors and post-process to convert them into acceleration, force and displacement. The data were collected at the sample rate of 2000 per second. However, due to the very large amount of data, recording of the data was done in an optimised manner with spacing where the response of the system was harmonic. Full recording of the data was automatically triggered by crack initiation from the reading of the ACPD machine.

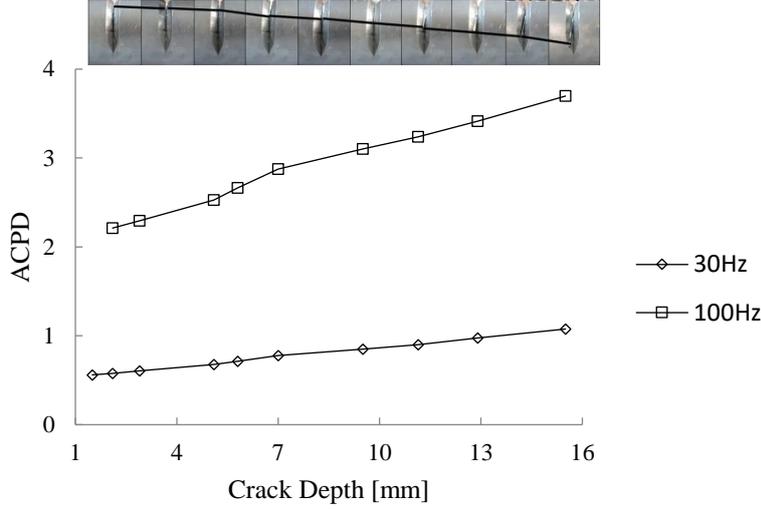


Figure 3: ACPD voltage readings were plotted against crack depth in 10 experimental tests for current passing through the crack at 30 Hz (diamond symbols) as well as 100 Hz (square symbols). Cracks were initiated and propagated in each of the 10 tests. The photographs from the 10 experiments are shown above the graph. The crack tips in the 10 photographs are connected with lines to show the trend of crack propagation

3. MATHEMATICAL MODELLING

A mathematical model to describe the response of the system was developed by Foong *et al.* (2006). This mathematical model is refined to account for the stiffness of the subcomponents, which were calculated by performing finite element analysis. In the current research, the two masses are in full contact with the specimen. A Heaviside function can be introduced to the mathematical model to account for crack opening and crack closing phases. The mathematical model is shown in equation (1). A parametric study was also performed to calibrate the system parameters and investigate the rig sensitivity to the input variables.

$$\begin{aligned}
m_1 \ddot{z}_{m1} + (c_{Ls1} + c_{p1}) \dot{z}_{m1} + (k_{Ls1} + k_{p1} + k_{sc1}) z_{m1} - k_{sc1} z_s &= m_1 A_b \Omega^2 \sin(\Omega t) \\
c_s \dot{z}_s + (k_s + k_{sc1} + k_{sc2}) z_s - k_{sc1} z_{m1} - k_{sc2} z_{m2} &= 0 \\
m_2 \ddot{z}_{m2} + (c_{Ls2} + c_{p2}) \dot{z}_{m2} + (k_{Ls2} + k_{p2} + k_{sc2}) z_{m2} - k_{sc2} z_s &= m_2 A_b \Omega^2 \sin(\Omega t)
\end{aligned} \tag{1}$$

The schematic of the fatigue rig and the parameters used in describing the dynamic behaviour is shown in Figure 4. The specimen is in contact with a single plastic roller at the top, which is represented as one spring. At the bottom, the force is applied on the specimen from a combined three-spring setup, representing two plastic rollers and a supporting steel part.

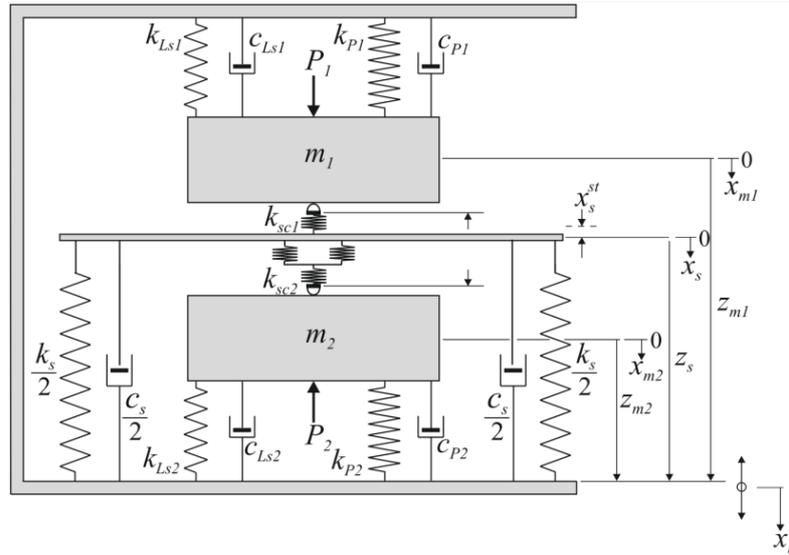


Figure 4: Schematic of the physical model where the system is based excited. The main system parameters including masse, springs and viscous dampers are depicted. Two static forces from pneumatic cylinders are denoted as P1 and P2.

Such a geometrical arrangement results in a localised physical subsystem with the stiffness of k_{sc2} . The stiffness of plastic is denoted by k_1 and the stiffness of the metal part is denoted by k_2 . An overall is stiffness quantity k_{sc2} is defined as follows, and it is part of system governing equations.

$$k_{sc1} = k_1, \quad k_{sc2} = \frac{k_1 k_2}{k_1 + 2k_2} \quad (2)$$

The nonlinear stiffness of the cracked specimen can be described as following equation in which the Heaviside function alternates between the cracked k_s^{op} and uncracked k_s^{cl} phase. The nonlinear bending stiffness of the cracked specimens for the crack closing case is very similar to an uncracked specimen. However, the cracked specimen bending stiffness is nonlinear and decreases with the growth in crack depth.

To implement a crack propagation on loading of the notched 3 point bend specimen, the variation of a specimen mechanical stiffness due to a time-dependent extension of crack length needs to be described by a mathematical function. The responses of the system in the time domain for an uncracked phase was compared against the predictions from the mathematical model and is shown in Figure 5.

$$k_s = k_s^{op} H(z_s) + k_s^{cl} H(-z_s) \quad (3)$$

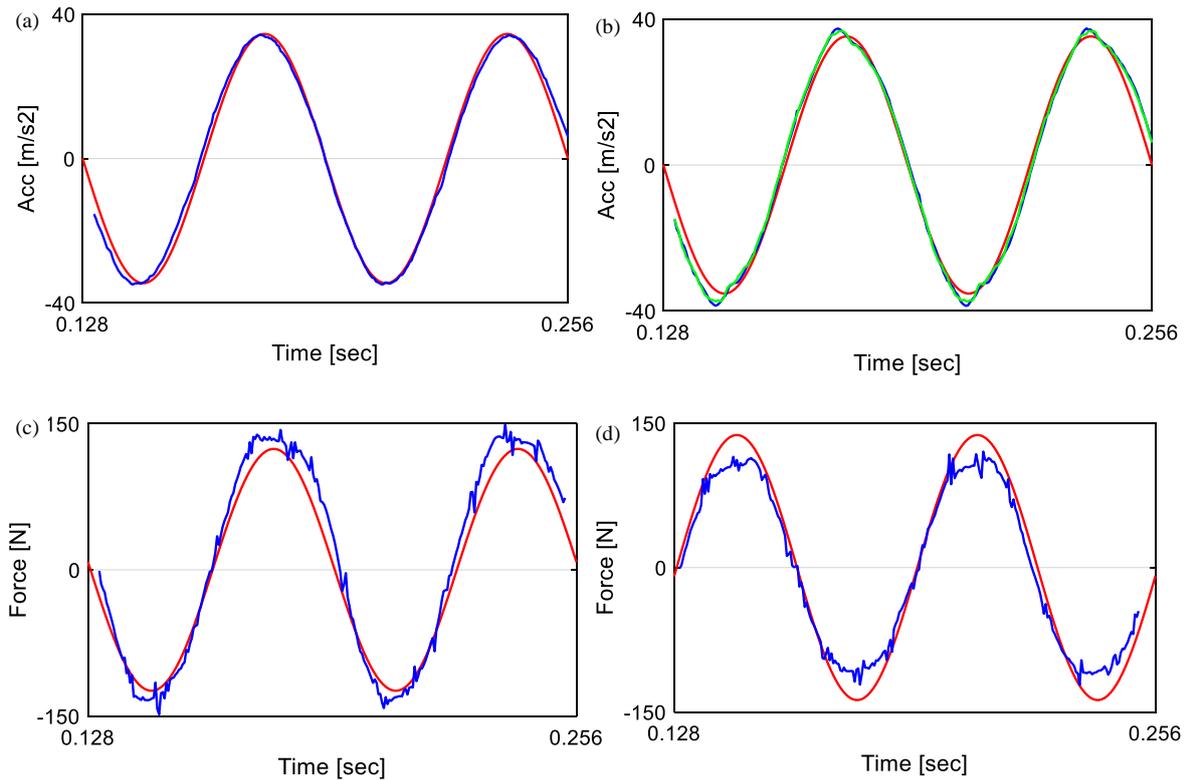


Figure 5: (a) Base acceleration from numerical predictions shown in red with experimental data shown in blue; (b) Mass A and B accelerations from numerical predictions shown in red with experimental data for Mass A acceleration shown in blue and Mass B acceleration from the experiment shown in green; (c) Force A from numerical predictions shown in red with experimental data shown in blue; (d) Force B from numerical predictions shown in red with experimental data shown in blue

4. CONCLUSIONS

The modified fatigue rig can be used to perform experiments on a variety of pipe sections to investigate the fatigue life of specimens and crack propagations. Designing and implementing two loadcells close to the specimen resulted in the direct measurement of the loads to derive the stress and stress range in the specimen and perform real condition fatigue testing. Finite element analysis was used to calculate the stress concentration factor and used to amplify the stress in the calculations.

The new fatigue rig enabled investigating the fatigue behaviour of the tubular specimens and the performance of the cracked specimens. Harmonic and stochastic loading can also be applied in the tests. In addition, different stress raisers such as grooves and holes on the tube specimens can be tested.

The ACPD readings enabled direct monitoring of the crack propagation in experiments. Comparison of elastic displacement and the records from ACPD allows locating the transition from linear elastic to nonlinear phase, indicating the time at which a crack is formed. The onset of crack propagation is observed from experimental time histories.

The mathematical model of the fatigue rig was enhanced to account for the subcomponent stiffnesses. The mathematical model prediction of the accelerations and forces tallied well with the readings from the experiment. The mathematical model can be further developed and enhanced for the nonlinear phase by implementing the nonlinear stiffness of cracked specimens as a function of crack growth. This can be achieved by performing series of finite element analyses to derive the nonlinear stiffness curve of each specimen type. The fatigue rig can be used for random and impact loading in future. For this purpose, a signal generation activity is needed to define the required signals to excite the shaker.

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