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Fatigue Testing of Large-Scale Steel Structures in Resonance with Directional Loading Control

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Abstract

Offshore structures such as jacket and monopile foundations for wind towers and platforms for oil and gas are large steel structures that are subjected to severe fatigue loading conditions. When developing constructions using novel welding techniques, high-strength steel grades or specific bolted assemblies there is a need for validation testing of large-scale components. Conventionally, such fatigue tests are carried out on servo-hydraulic test which are time-consuming.

Alternatively, fatigue tests can be performed in resonant bending by a cyclic excitation force with frequency close to the first eigenfrequency of the test specimen. In this paper a new test setup is presented suitable for testing large-scale steel components in resonance with control of the loading direction by two counter-rotating excentric masses.

A wide range of loading conditions can be applied with a frequency from 20 to 40 Hz. The test specimen, that can weigh up to 25 ton, is supported in the nodes of its natural wave-form, so that no dynamic forces are transmitted to the setup.

The working principles of the test setup are illustrated based on test results of a 711 mm diameter x 25.4 mm wall thickness steel pipe, a welded X-node representative for a welding detail of an offshore jacket foundation structure and a large-scale HE-beam. Crack initiation is detected using acoustic emission while crack growth is monitored by local strain gauge measurements as well as the global stiffness reduction of the test specimen. Finally, the beach marking method is used to visualize crack fronts for post-mortem analysis.

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Keywords: fatigue testing; resonance; resonant bending; steel; jacket; beam; pipeline; large-scale testing.

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1. Introduction

Nomenclature

F_1, F_2	excenterforces
F_r	resulting excenterforce
L	length
OD	outer diameter
WT	wall thickness
φ	phase difference between the two excenterforces F_1 and F_2
ω	angular rotation speed

Large structures for demanding environments are often constructed from steel components. Offshore structures such as jacket and monopile foundations for wind towers and oil and gas platforms are examples of such structures that are subjected to severe fatigue loading conditions. When developing constructions using novel welding techniques, high-strength steel grades or specific bolted assemblies there is a need for validation testing of large-scale components. In addition, for purposes of life extension of offshore structures, there is a need to test components from decommissioned structures to determine their remaining life (Ersdal et al, 2019). Traditionally, such fatigue tests are carried out on servo-hydraulic test which are time-consuming because high forces are required in combination with large displacements. Consequently, the testing speed is typically in the order of 1 Hz (Wylde, 1982 and Larsen, 2019). Targeting a similar fatigue life as in a wind turbine of 20 million cycles can require more than 6 months of testing time.

For other applications, resonant fatigue testing is used as an alternative to servo-hydraulic test rigs. In this type of setups, the test specimen is loaded by exciting one of the eigenmodes instead of cyclically loading the specimen by external application of high forces. This offers the advantage of testing at higher frequencies and at low energy consumption. For typical material test specimens such as round bar and strip specimens, resonant fatigue test systems exist that utilize a mass-spring system to control the resonance frequency. This method has been upscaled for the fatigue testing of beams (Schneider et al, 2018). In oil and gas resonant bending fatigue tests are common practice for full-scale testing tubulars such as pipeline girth welds (Zhang, 2011), casing, tubing and drill pipes (Bertini et al, 2008). Also, wind turbine blades are commonly tested in resonance (Malhotra et al, 2012).

In this paper, a new setup is presented able to perform accelerated fatigue testing of large-scale structures in resonant bending. In the following sections, the test setup is described, and the working principles are illustrated by presenting three different cases.

2. Resonant bending fatigue test setup

2.1. Setup overview

The newly developed resonant bending fatigue test setup CRONOS (Continuous Resonant Oscillating Node test Setup) has been developed in-house at OCAS and includes several unique patented features which are described below. The setup can be used for testing axisymmetric test samples such as pipelines (Figure 1) as well as for non-axisymmetric samples such as large-scale welded structures and beams (Figure 2). To obtain this, an innovative excitation system is used allowing directional loading control as detailed in section 2.2. For testing structures in resonance, a detailed analysis of its eigenmodes and eigenfrequencies is necessary. This can be obtained through analytical calculations for simple axisymmetric test samples (e.g. a pipe) or by finite element analysis for more complex structures. In the design and selection phase of the test material, the optimal geometry should be determined to make sure the resonance frequencies are in the working range of the test setup. The eigenfrequencies of a structure are a function of its mass per unit of length and stiffness distribution. When the bending frequency of a test specimen is too high it can be decreased by increasing its length to reduce the bending stiffness or by adding mass to the ends of the test specimen.

The working principle of the setup can be explained using Figure 1. An excitation force is generated by the shaker assembly (1) attached to the end of the sample (2), in this case a pipe with diameter of 711 mm (28”), 25.4 mm wall thickness and 9.25 m total length. The total weight of the pipe is 3.9 ton. The shaker assembly is powered via a cardan shaft by an electrical motor (3). The shaker assembly is connected to the test sample by either a sleeve or weld-on flange (4). The same connection is used to attach a compensating endmass (5) to the opposite end of the test sample. Two supports (6) are positioned in the nodes of the excited eigenmode of the test specimen, in this way the dynamic forces that are transmitted to the supports are minimized. The weight of the pipe is carried by air cushions. The setup is suitable for testing structures up to 4 m high and pipe diameters between 400 and 1200 mm in diameter (16” to 47” outer diameter) with a length over 12m. The tests are controlled, and data is logged through the integrated control and monitoring unit (7). Test samples can be instrumented with displacement sensors, accelerometers and strain gauges. Hollow test samples can be filled with water and pressurized to detect through-thickness cracks.

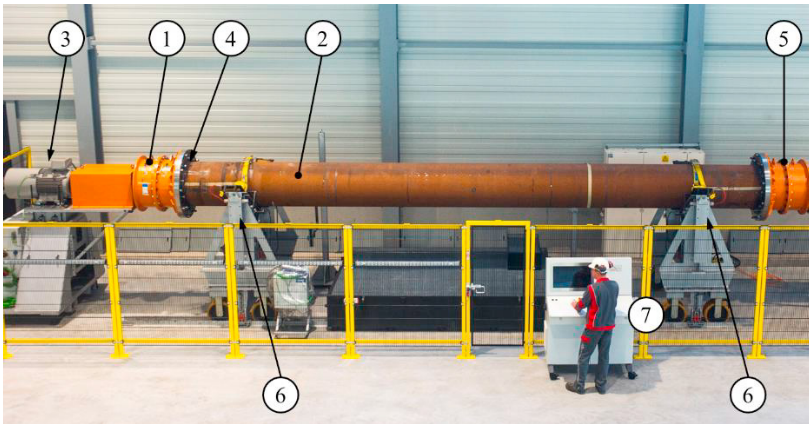


Figure 1: Overview of the CRONOS test setup with a 28” outer diameter pipe section.

Figure 2: welded X-joint node (left) and beam (right) in the CRONOS test setup.

2.2. Directional loading control

To allow the testing of complex large-scale structures the test setup is equipped with a double excenter assembly that allows for a wide range of loading conditions. In Figure 3 two typical load cases are shown. Figure 3.a illustrates two excenters with the same mass are rotating at equal angular speed ω, but in opposite direction. This results in a linear reciprocating force F_r. In the figure below, the resulting force is vertical since the horizontal components of F_1 and F_2 cancel each other out. Figure 3.b illustrates contra-rotating excentric masses with unequal mass ($F_1 > F_2$). This results in an excitation force with an elliptical shape over a revolution. By changing the phase difference φ between force vectors F_1 and F_2, the orientation of both the linear or elliptical loading can be controlled. More details and other loading conditions have been published by Van Wittenberghe and Thibaux (2018).

Figure 3: Combined force vectors for the double excenter assembly: a) $F_1 = F_2$; b) $F_1 > F_2$.

3. Fatigue testing of large-scale steel structures: 3 cases

3.1. Large-diameter pipe

In this paragraph the directional loading control system is illustrated by test results obtained on the 711mm OD x 25.4mm WT x 9.25m L pipe (see Figure 1), the analytically calculated eigenfrequency for the first bending mode is 29.1 Hz.

In Figure 4.a the horizontal and vertical displacements are plotted for contra-rotating excentermasses of equal weight. This results in a linear pipe deflection. The response at 27.50 Hz is plotted for 4 different phase differences (φ = 0°, 22.5°, 45° and 90°).

When an elliptical force vector is applied like schematically shown in Figure 3.b, an elliptical response of the pipe deflection can be observed as shown in Figure 4.b. This plot shows 3 pipe deflections for an excenter combination with 50% compensation ($F_1 = 2 \cdot F_2$). The 3 ellipses correspond to values of the phase difference φ = 0°, 45° and 90°. The elliptical deflection shape is again following the orientation which is controlled by the phase difference φ = 0°, 45° and 90°. When only one excentermass is used, the excitation force is circular, and a circular pipe response can be measured at the center of the pipe (see Figure 3.c).

These response graphs illustrate that the general shape of the pipe deflection correspond to the applied excitation force. The loading direction is controlled by the phase difference that can be controlled during a running fatigue test. This allows to either compensate for pipe imperfections such as excentricity and ovality, or to apply non-axisymmetric loads for example to concentrate the loading on a certain location around the circumference or to simulate more realistic loading conditions.

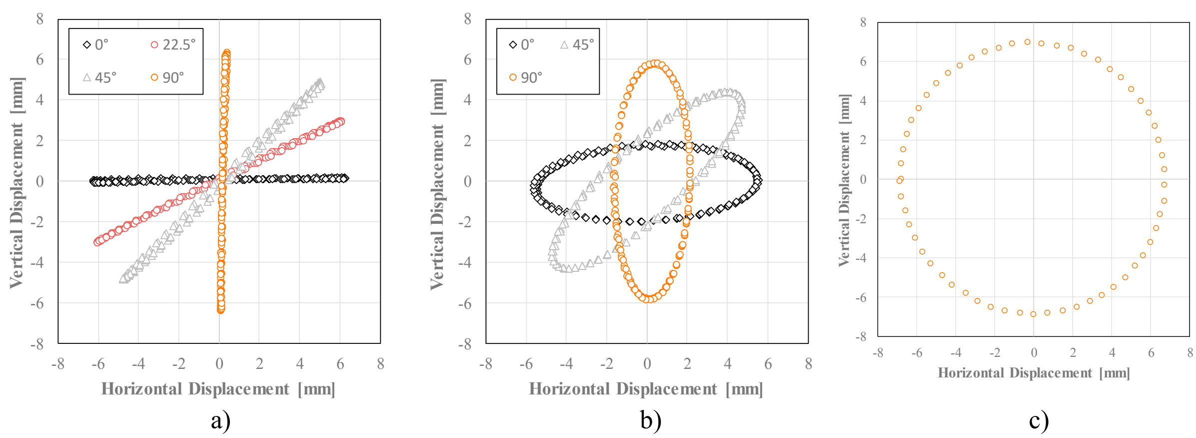


Figure 4: XY-plot at 27.50 Hz for different phase differences for a) $F_1 = F_2$, b) $F_1 = 2 \cdot F_2$. The circular response is obtained with a single excentermass and plotted for a frequency of 28.00 Hz.

3.2. Welded X-joint

In the framework of the EU funded RFCS project JABACO on offshore wind jacket foundations, welded X-joints have been tested. In Figure 5 the test specimen geometry is shown. It consists of a central vertically oriented chord member (1) and two horizontal braces (2) which are connected to the chord by the welds (3). The sample weighs 3.9 ton and is 7.5 m long with a height of 1.56 m.

The chord has a nominal diameter of 816 mm with 38 mm wall thickness; the legs have a nominal diameter of 711 mm with 19 mm wall thickness, the material is S355-J2 steel according to EN10025-2. Before the start of the fatigue test, dye penetrant investigation is used to confirm the welds are free from surface defects.

The sample geometry is designed so that the in-plane and out-of-plane bending modes have the same frequency of 24.0 Hz, this allows to excite them simultaneously. This is verified using finite element analysis (FEA). The simulated mode shapes for the test sample with nominal dimensions are shown in Figure 6. Before starting a test, the eigenfrequencies are experimentally measured, in all cases deviations up to 5% have been observed between the FEA results and actual measured frequencies. This can be attributed to the differences between nominal and actual dimensions. Common deviations in wall thickness, ovality and length as well as the actual shape of the weld can often cause differences between measured and modelled results. When actual sample dimensions and the actual weld shape are used in the FEA the correspondence is improved (cfr. Thibaux et al 2019).

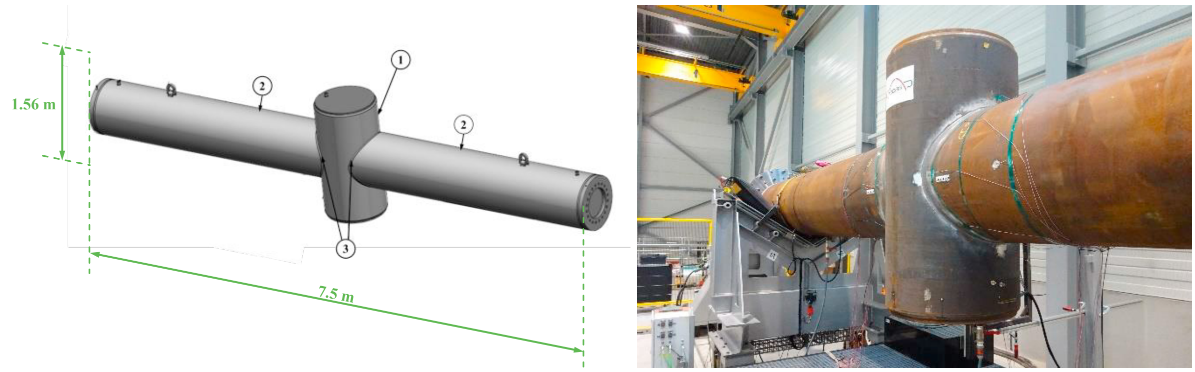
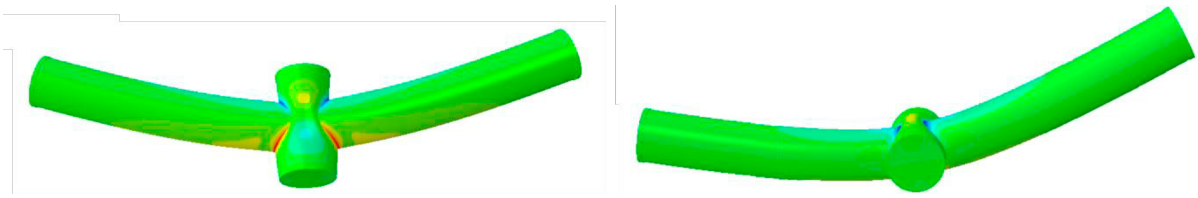


Figure 5: left: X-joint overview; right: X-joint in CRONOS.

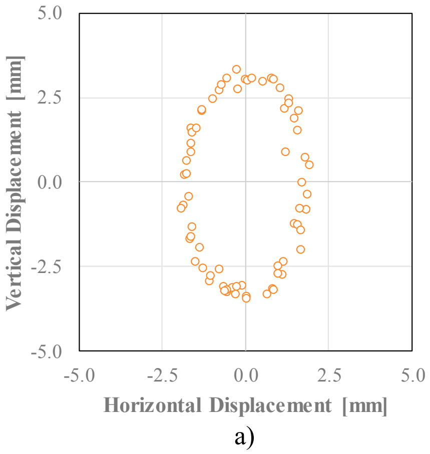


a) b)

Figure 6: Eigenmode shapes of the X-joint: a) in-plane bending; b) out-of-plane bending.

The fatigue tests on the X-joints have been carried out in two phases. During the first phase, both the in-plane and out-of-plane modes are excited simultaneously. The amplitude in both planes is fine-tuned to obtain a stress distribution that is as uniform as possible over the circumference of the weld. This to initiate fatigue cracks over the complete weld. Crack initiation is detected using local strain gauge measurements and confirmed using non-destructive testing. For all samples, the largest cracks initiated in the in-plane position. During the second phase, the sample is excited in-plane for the remainder of the test until a through-thickness crack appears.

The displacement response for both the crack initiation and propagation phases is plotted in Figure 7. This shows that modes with similar eigenfrequencies can be excited not only simultaneously, but also separately.



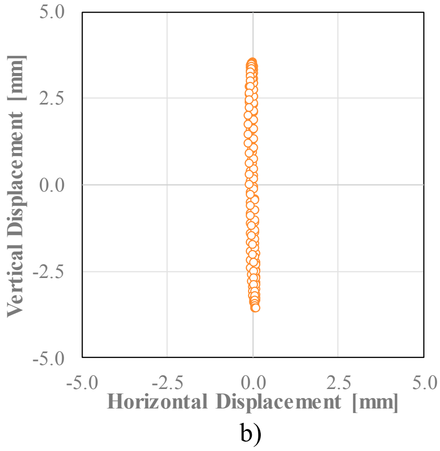


Figure 7: XY plots of the X-node a) *crack initiation phase at 23.5 Hz with combined excitation of the in- and out-of-plane bending mode*, b) *crack propagation phase: in-plane excitation.*

By reducing the bending amplitude during a running fatigue test for a limited number of cycles, beach mark lines can be introduced in the fracture surfaces. These lines give valuable insights in the crack propagation behaviour. In Figure 8 an example is given of a fracture surface of one of the X-joints. The dashed lines highlight the position of the beach mark lines that mark the shape of the fracture surface after a certain amount of cycles. For this specimen, crack initiation from the weld area was confirmed after 60 000 cycles, after that the crack propagated through the wall of the material of the chord member.

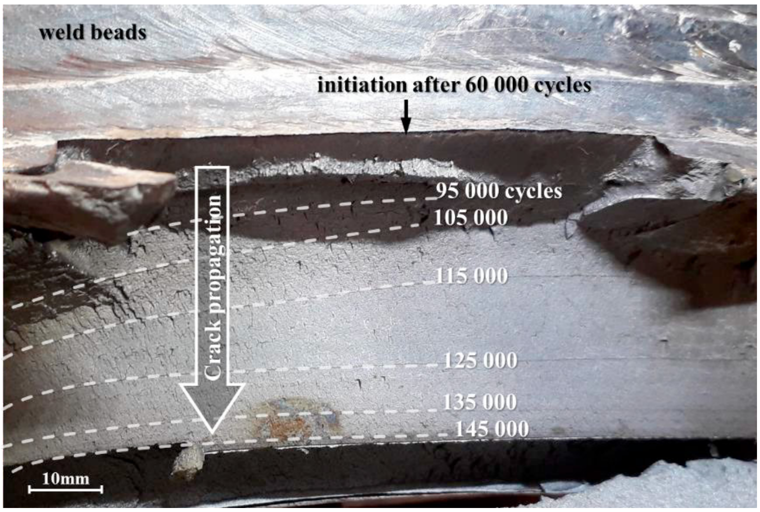


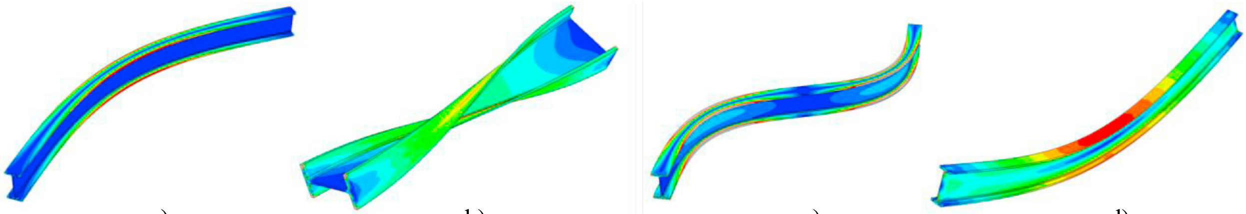
Figure 8: Example of beach mark lines in the fracture surface of an X-joint.

3.3. HE Beam

CRONOS can also be used to test long products such as beams, rails and girders. This is illustrated by a test on an ArcelorMittal HE-650-M HISTAR beam. This beam is shown on the right picture of Figure 2. It has a nominal height of 668 mm and width of 305 mm. The total length of the beam is 9 m and it weighs 2.6 ton.

The particular case with beams is that they have a strong and weak plane, the latter one is the plane with the lowest bending stiffness. In practice a beam is typically loaded in its strong plane, hence fatigue testing in the strong plane would be required. Due to the lower stiffness of the weak axis, the eigenfrequency of the bending mode in the weak plane is significantly lower than the bending eigenfrequency in the strong plane. For the tested beam, the strong plane bending mode is the 4th order mode. As illustrated in Figure 9 and Table 1, there are two bending modes in the weak plane as well as a torsional mode with a lower frequency. This means that test are carried out at a frequency laying above three lower eigenfrequencies. When the beam is brought into resonance, care must be taken to avoid excitation of the lower mode shapes. Also, fatigue crack propagation causes a stiffness reduction which affects the different eigenmodes differently. In such a case, simulations are required to study the effect of fatigue crack propagation to avoid that undesired mode shapes are excited.

Prior to starting the fatigue test, the different eigenfrequencies are experimentally measured. As can be seen from Table 1, a good correspondence was found between the eigenfrequency values coming from FEA.



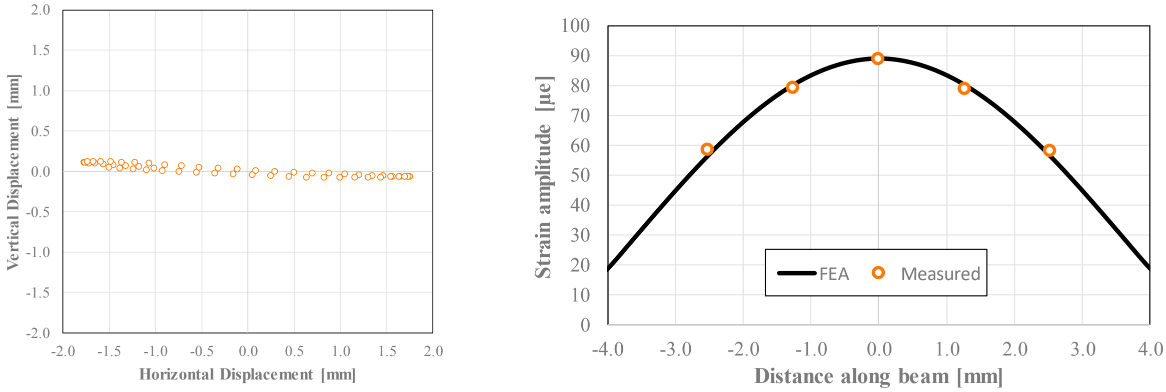
a) b) c) d)

Figure 9: First 4 eigenmodes of the tested beam: a) weak plane bending; b) torsion; c) second order weak plane bending; d) strong plane bending.

Table 1: Eigenfrequencies of the different mode shapes

Eigenmode shape	FEA Frequency [Hz]	Measured Frequency [Hz]
Weak plane bending	8.1	8.1
Torsion	14.6	15.2
2nd weak plane bending	26.4	25.2
Strong plane bending	30.7	30.1

In Figure 10.a the displacement response is plotted at 29.85 Hz. In this case the strong bending plane corresponds to the horizontal direction because the way the sample was installed in the test setup. Figure 10.b provides a comparison between the modelled and measured axial strain values along the length of the beam. Strains are measured by strain gauges installed at the center of the flange of the beam. A good correspondence can be observed between the simulated and measured strain amplitudes.



a) b)

Figure 10: a) XY-plot at 29.85 Hz bending in the strong plane of the beam; b) simulated and measured strain distribution during excitation of the strong bending mode shape..

4. Conclusions

In this paper a new resonant bending fatigue test setup is introduced for testing large-scale steel components. The system includes an advanced shaker assembly that can combine the excenter force of two rotating excentric masses that enable directional loading control.

Apart from testing axisymmetric structures like pipes, this setup can be used for fatigue testing of more complex non-axisymmetric test samples. This is illustrated by different cases.

The results from the X-joint indicate that different eigenmodes can be excited combined or separately when the resonance frequencies of these different mode are laying close together.

Test results from a beam show that tests can be carried out at higher modes without interference with modes with lower eigenfrequencies.

In all cases, analytical models or FEA are required to calculate the dynamic behaviour of the test sample prior to installing it in the test setup.

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