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Combined three-point bending and axial tension of pressurised and unpressurised X65 offshore steel pipes – Experiments and simulations

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ABSTRACT

Subsea pipelines are occasionally struck and hooked by objects such as anchors or trawl gear. The initial denting, followed by potential hooking and displacement of the pipeline, give rise to a complex load and deformation history. Transverse displacements cause a simultaneous increase in tensile axial forces, further complicating the load sequence. This study examines the effect of applying one of three different axial loads (zero, constant, and linearly increasing) to a pipe while simultaneously deforming it transversely. The three tests were repeated with an internal pressure of 10 MPa (100 bar), and all tests were recreated numerically in finite element simulations using both iterative (implicit) and non-iterative (explicit) approaches. As expected, adding an axial load increased the pipe's resistance to bending in terms of force-displacement, and the same can be said of including internal pressure. However, a more localised dent was observed in the pressurised pipes, which in turn could affect the onset of failure. The experimental results were well captured by the finite element simulations.

1. Introduction

Pipelines are a crucial part of the offshore industry, and will remain so for the foreseeable future. Along the seabed, pipelines may be exposed to various hazards [1], among them being impact, hooking and release of the pipeline by e.g. anchors or trawl gear [2,3], which is treated in the DNV GL guidelines [4]. This load cycle causes a complex stress and strain history which in turn may lead to fracture [5]. The load sequence of denting followed by stretching was applied quasi-statically to strips of an X65 pipeline material by Manes et al. [6], without producing any significant cracks. Further, Kristoffersen et al. [7] carried out dynamic impact tests on simply supported pipes followed by quasi-static stretching of the dented pipes to emulate the rebound of a pipeline after release from a hooking event. The subsequent stretching always resulted in fracture in the material, ranging from surface cracks to through-thickness cracks. When a pipeline is displaced transversely, an axial force builds up simultaneously [8], and this was not accounted for in the experimental procedure by Kristoffersen et al. [7]. The current study includes experiments that encompass the tensile force caused by the transverse displacement.

The open literature provides many studies on transverse loading of tubular structures of various character, ranging from rectangular cross-sections [9] to more complicated T-joints [10]. Circular cross-sections are the most common, and have been studied experimentally [11,12], theoretically [13] and numerically [14]. Pipe impact problems have been studied with various boundary

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conditions, from simply supported pipes [15] to fully clamped pipes [16–18] and pipes resting on a foundation [19]. Pipeline coating intended for ballast or thermal insulation, usually made from concrete [20] or polymers [21], also offer some protection from impact loads. Combinations of axial loading and bending moment have been examined in several studies [22–25], where load history, anisotropy, diameter to thickness ratio, and other parameters are discussed. While some works consider the effect of external pressure on tubular structures [26–29], this work will consider internal pressure caused by e.g. an internal fluid or gas. Internal pressure can reduce the ovalisation of the cross-section [30], and simultaneously increase the resistance load during denting and transverse deformation [31,32]. Large transverse displacements combined with a tensile axial load and internal pressure have not, to the best knowledge of the authors, been studied in detail previously. In addition to providing experimental data on this problem, an elaborate numerical study is also carried out herein.

This work investigates the local indentation and subsequent bending of an uncoated X65 steel pipe due to a transverse load [33], while simultaneously applying one of three axial tensile loads: 1) no axial load, 2) a constant axial load, or 3) a linearly increasing axial load. These three cases are then repeated with an internal pressure of about 10 MPa, amounting to six different stretch-bending tests in total. The order in which the loads are applied can affect the results [23,34,35], but in this case the pipe is assumed to be in operation when being deformed, meaning that the pressure is applied before the transverse and axial loading. These experiments were recreated numerically using the finite element software ABAQUS [36] with a calibrated and tested material model [37]. A comprehensive numerical study is conducted using different numerical approaches (iterative versus non-iterative), and some suggestions for modelling this type of problem are made. In general, the experimental results were well captured by the numerical simulations.

2. Material characterisation

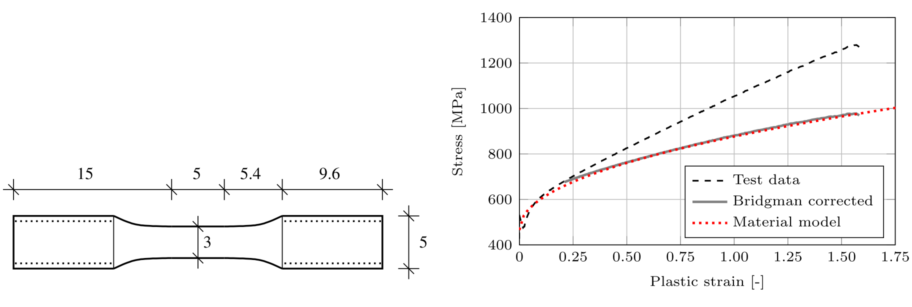
2.1. Description

The pipeline material used in this study is an X65 grade offshore steel, a material widely used in pipelines conveying oil and/or gas [38]. According to the material inspection certificate, the nominal yield strength is $\sigma_0 = 450$ MPa and the ultimate tensile strength is $\sigma_{UTS} = 535$ MPa. Young's modulus is $E_s = 208\,000$ MPa. The pipes used herein are made seamless by utilising the Mannesmann effect [39], and are supplied by Tenaris, Argentina.

2.2. Material tests

Quasi-static material tests investigating the cross-sectional homogeneity and possible anisotropy of this material have been carried out [7], and are succinctly summarised here. Specimens of geometry as shown in Fig. 1 (a) were loaded to failure in tension at quasi-static strain rate (approximately $10^{-3}\,s^{-1}$). By using a laser-based measuring device [40], the minimum diameters in perpendicular directions were recorded continuously during testing. This provides the true stress-true plastic strain curve beyond necking, and data from a typical test is shown in Fig. 1(b). A detailed characterisation of the material is important in order to obtain accurate analyses [41].

For engineering and design purposes, the material is found to be both homogeneous and isotropic. Based on values from 12 tests, the material yields at 478 ± 15 MPa and has an engineering peak stress of 572 ± 14 MPa. The material strain hardens to a true peak stress of $1\,314 \pm 12$ MPa and fails at a true strain of w_i in a ductile cup-and-cone fracture mode. This study does not include investigation of fracture, which has been studied elsewhere [7,42]. All tests (both material and component) are carried out at room temperature, so no investigation into temperature effects is made although such effects may be present in both arctic environments and dynamic events [43].



(a) Specimen geometry in mm (b) Stress-plastic strain curves

Fig. 1. Tensile test data, where (a) shows the specimen geometry while (b) shows a representative stress-plastic strain curve from the tests along with Bridgman corrected data and a power law fit.