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Quasi-static and dynamic indentation of offshore pipelines with and without multi-layer polymeric coating

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A B S T R A C T

Offshore pipelines are occasionally subjected to accidental impact loads from trawl gear or anchors, which may damage the pipe. In this study, a series of indentation experiments carried out on offshore steel pipes covered by a multi-layer polymeric coating solution is presented. Polymeric coating solutions are often applied to pipelines to act as corrosion protection and thermal insulation. Despite not being designed for it, the polymeric coatings are experienced to have an energy absorbing capacity, which is the main topic of the investigation herein. In design codes and guidelines, coatings are traditionally not accounted for when determining the energy absorbed by a pipeline during impact. This makes estimates overly conservative. The main goal of this experimental work is thus to investigate the contribution a typical polymeric coating makes to the energy absorption in a pipeline during impact. To this end, a series of indentation experiments carried out on offshore steel pipes covered by a multi-layer polymeric coating solution is performed. The test program includes quasi-static and dynamic denting experiments on both coated and uncoated full-scale pipe cross-sections. All pipes tested have a length of approximately 1 m. The sharpest indenter from the relevant guidelines is used, as a sharp indenter is more likely to penetrate the coating compared with a blunter one. Based on the outcome of the tests, the polymeric coating is found to absorb a considerable amount of the kinetic energy delivered by an impacting object.

1. Introduction

In the offshore petroleum industry, far-stretching pipeline networks are used to transport crude oil and natural gas along the ocean floor. When specialized protective measures (e.g; trenching, burial, protective covers or armored coatings) either are considered not plausible or too costly [1,2], pipelines are often left exposed and vulnerable on the seabed. Such pipeline systems are often covered with other coating solutions whose primary purpose is not to physically protect, but rather provide corrosion protection, negative buoyancy or thermal insulation. However, while not primarily being designed for it, various coating solutions are known to have beneficial mechanical effects [3–5], such as protection from impacts by foreign objects [6]. As subsea installations tend to attract fish [2], they are sometimes intersected by sharp-edged and massive structures used in fish trawling [2,7] or struck by falling anchors [3,8]. Several studies on interaction between bare pipes and foreign objects have been made [9–15]. A general trend in the literature is that while the presence of different coating solutions is observed to influence the pipeline integrity [3,4,6], a quantitative evaluation of the isolated contributions are omitted – with a few exceptions [5,16–18]. As there is a large variation in coating solutions (e.g., material used and design), it is difficult to establish common design rules for all different products. The behavior of only the bare steel has therefore traditionally been used in assessing structural aspects of pipelines. However, in recent

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issues of the governing pipeline design codes [2,19], the potential beneficial mechanical effects of coatings are accepted as long as their effectiveness are documented – thus allowing such products to also be included in other aspects of pipeline design, such as impact mitigation. As precipitates form in hydrocarbon fluids when the temperature decreases, pipelines are often insulated with coating products made out of foamed materials. Apart from their excellent thermal properties [20], cellular materials are also known to be great impact mitigators [21]. Due to the progressive damage mechanisms experienced in cellular cores during crushing, combined with the superior rigidity of an internal steel pipe and good ductility of polymers, multi-layer polymeric insulation coatings may be thought to have an especially good mitigating effect during impact events.

As the risk of impact burdens the choice of pipeline design and route, the inclusion of thermal insulation coatings in structural assessments presents a great economical potential. However, there exists little documentation demonstrating the impact mitigating and load distribution effects of polymeric insulating coatings in the published literature. To this end, this work aims to provide experimental results which (i) documents the possible energy absorbing capabilities of a typical polymeric insulating coating system during impact and (ii) investigate the mechanical characteristics of the insulating layer. As a means in achieving these goals, a comprehensive experimental program has been conducted. The response to lateral impact of two different X65 steel pipeline designs, both with and without insulating coating systems, have been studied using quasi-static and dynamic test setups. Coating specimens from one of these coating designs have also been studied in detail both with respect to compressive behavior and structural composition. In addition, quasi-static tensile tests of X65 steel specimens were conducted to ascertain the grade of the internal pipe material. It is believed that the results from this work will provide a proof of concept for polymeric coatings as energy absorbents in design against pipeline impacts, and contribute to the understanding of how such insulation products may be analyzed using simulation tools like the finite element method. However, any simulation attempts are left for further work.

2. Impact events

If a pipeline is left exposed on the seabed, it is vulnerable to impact from foreign objects. de Groot [3] stated that falling and dragging anchors pose a serious threat to subsea equipment. This was exemplified when a 10 ton ship anchor hooked onto and pulled the Kvitebjørn gas pipeline 53 m out of its installed position [8], which resulted in an extended shut-down period [22]. Another possible interaction is with trawl gear. Bai and Bai [23] distinguished between three occurrences to be considered during trawl gear interference; impact, pull-over and hooking. These events are sometimes mutually exclusive, and differs with respect to loading conditions. During an impact interaction, the loading has a duration less than some hundredths of a second and the response is confined locally to the region of intersection. If the trawl equipment is continuously pulled over the pipeline, large global deformations with significant bending moments and axial forces may be induced. This pull-over action is typically over within a few seconds. The third possible outcome is known as hooking. During this occurrence, the fishing gear does not pass over, but hooks and laterally tows the pipeline out of its initial position. This latter case may cause extreme loads on the subsea installation, but this is a rare event. It is the former of these three interactions, namely impact, which is of immediate interest in the work related to this article. While impact against concrete-coated pipelines have recieved some attention [6,16,18], little available research is found in the literature on the impact response of thermally insulated pipes. Because offshore installations in the Norwegian maritime economic zone are required not to an unnecessarily or to an unreasonable degree interfere or hinder fishing activities [2], future occurrences of such events are to be expected. Thus, the pipelines must be designed to sustain impact scenarios.

3. Pipeline design

3.1. General

Offshore pipelines are exposed to a range of harsh environmental conditions. Operating on great water depths, large hydrostatic pressures are exerted on the outer surface of the pipeline whilst a multi-phase fluid flow is confined by the inner diameter of the pipe. The fluids hold high temperatures and pressures, which drive the flow through the pipeline. Bare and untreated steel pipes subjected to these environments would suffer greatly under such extreme conditions and heat loss in the oil and gas flow enables the formation of precipitates which could clog the pipe. Therefore, the steel pipes are coated with external layers serving various purposes. Two different polymer-coated pipeline designs illustrated in Fig. 1 are studied in this paper. Both designs consist of an inner steel pipe coated with a multi-layer porous polymeric coating system known under the general product name of Thermotite Polypropylene produced by Bredero Shaw (now Shawcor Norway AS) at their facilities in Orkanger, Norway. The complete general coating solution is herein referred to as multi-layer polypropylene (MLPP) and can be produced in a wide range of thicknesses and layer configurations. The innermost portion of the MLPP consists of a three-layer polypropylene coating solution (product name 3LPP) composed of one layer of fusion-bonded epoxy providing corrosion protection, one layer of extruded adhesive and a layer of solid polypropylene. The 3LPP is essentially the same for both designs, though layer thicknesses may differ. The 3LPP is followed by additional insulation layering as a part of the total MLPP solution. The two pipeline designs studied herein are denoted Pipe S and Pipe L and their respective layer configurations are illustrated (in scale) in Fig. 1.

Both the geometrical characteristics and the insulation layer compositions vary in the two designs, i.e., the layer thicknesses, diametrical values and total number of layers are different in Pipe S and Pipe L. Fig. 2 gives an overview and the values for the different layers in both designs. The values stated in this figure are approximate as they may vary along the pipeline.