Deformation behaviour of HFI-welded pipes
– some examples of present applications –

Holger Brauer[1*], Susanne Höhler[2], Marion Erdelen-Peppler[2], Gerard Jonkergouw[3]

* corresponding author

[1]Salzgitter Mannesmann Line Pipe GmbH
Kissinger Weg
59067 Hamm
Germany
Phone +49 2381 420-447
Fax +49 2381 420-454
holger.brauer@smlp.eu

[2]Salzgitter Mannesmann Forschung GmbH
Ehinger Straße 200
47259 Duisburg
Germany
Phone +49 203 999-3192
Fax +49 203 999-4352
s.hoehler@du.szmf.de
m.erdelen-peppler@du.szmf.de

[3]Visser & Smit Hanab bv
Papendrecht
Niederlande
Phone: +31 78 6417222
g.jonkergouw@vshanab.nl

Introduction

HFI welded steel pipe has been used successfully for decades in technically demanding applications and severe service conditions. Line pipe designed for high operating pressures ensures reliable transportation and distribution of gas, oil, water and other media. And without welded steel pipe, the exploration and extraction of essential resources would be impossible. Even in machinery and plant construction, welded steel pipe has established itself as an indispensable structural element. In the last years requirements for laying and operation of pipelines have become more and more challenging. On the one hand this is related to national regulations and complex laying situations, such as pipeline installation in high density residential areas. On the other hand the pipe material and coating itself are exposed to multiple loads during laying activities and the use of pipelines, for example because of the geological conditions.
The paper shows the behaviour and applicability of high-frequency induction (HFI) welded pipes of Salzgitter Mannesmann Line Pipe GmbH on three different stress and strain demanding applications.

Strain-Based Design

In order to meet the increasing safety demands by assuring integrity of new pipelines of modern steels even in a terrain with challenging soil conditions, the conventional stress-based design approach may be insufficient. Therefore strain-based design methods have been developed as an alternative for cases where ground movements may play a role. During these, large plastic strains can develop in the pipe wall from curvatures or bending forces, as well as additional circumferential elongation from internal pressure. The assessment of the structural safety of such pipelines under combined loading requires the knowledge of the plastic deformation capacity, which depends on the pipe dimensions and geometry, the type of loading and notably the strain hardening behaviour. Not much experience exists to predict the pipe deformation response under the more and more increasing complexity of strain-based design. For that reason reliable predictive models are needed, validated by experimental data gathered by full-scale tests, simulating realistic scenarios. That is the only way to determine and understand the structural performance of the pipes, and to identify the relevant material properties for consideration of the multiaxial pipe behaviour.

A full-scale four-point bending test has been performed on a High-Frequency-Induction (HFI) welded pipe produced by Salzgitter Mannesmann Line Pipe GmbH, after heat-treatment like during the typical three-layer PE-coating process, in order to include thermal aging effects. The test-rig LiSA (Limit State Analyser) of the Salzgitter Mannesmann Forschung GmbH (SZMF) in Duisburg (Germany) has been used (Figure 1 [1]), which introduces bending load on the pipe specimen in a vertical four-point bending procedure. An internal pressure of 100 bar has been adjusted before bending, corresponding to a hoop stress equal to 66 % of SMYS. During the test the strains in the test section have been measured.

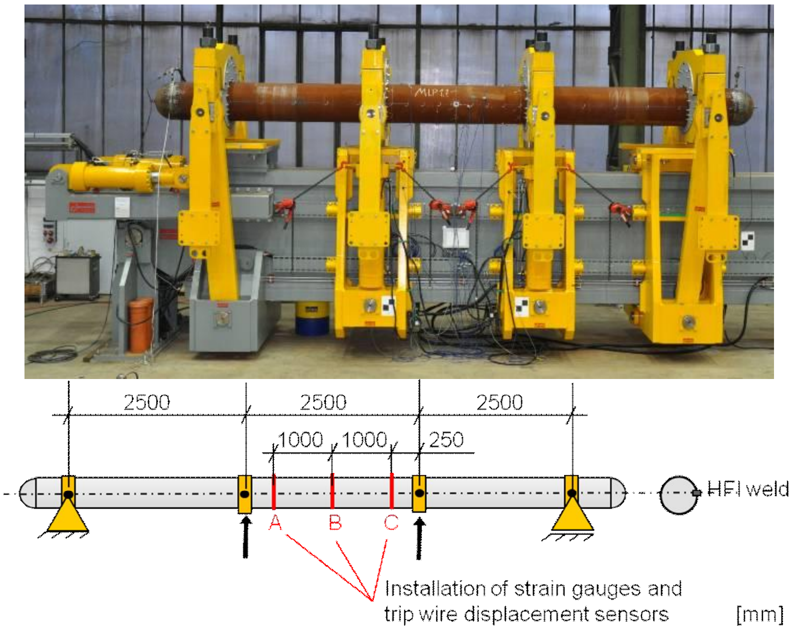

Figure 1: Four-point bending test at SZMF and schematic test pipe installation and instrumentation (pipe: HFI-welded, grade API X70, OD x t: 609.6 x 10 mm)

The load-deflection curve (average curve of the left and right jacks' strokes) is shown in Figure 2. After reaching the load maximum two characteristic outward bulges occurred, in this case symmetrically to the pipe mid-length section (Figure 3). Buckling in form of outward bulges is usual for pressurized pipes. Strain measurements reveal different load-strain curves for the extrados and intrados (Figure 4). This was expected when looking at the standard material tests before the full-scale test, where compressive and tensile data differ slightly. Additionally the pipe did not deform symmetrically towards the neutral bending axis, due to the influence of the internal pressure.

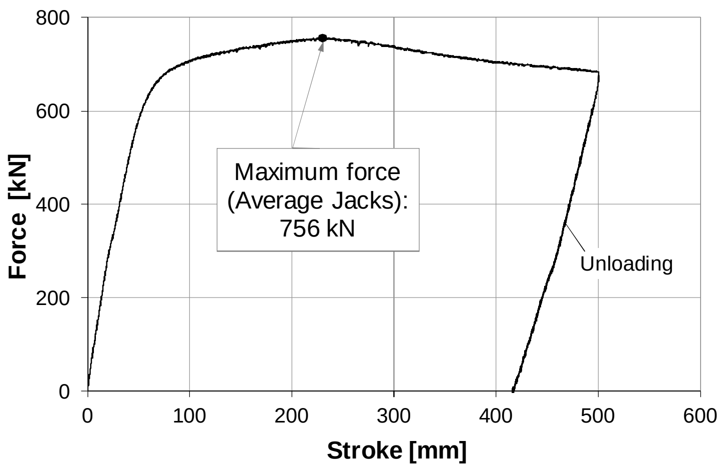

Figure 2: Load-deflection diagram

Figure 3: Pipe deformation after test, with buckles next to the clamping supports

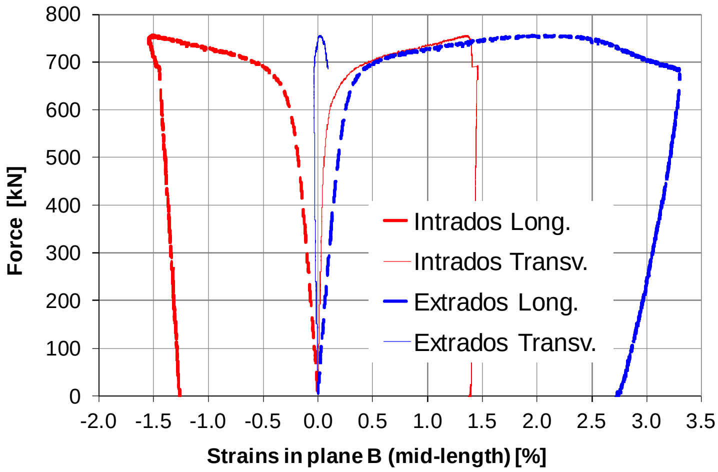

Figure 4: Load-strain curves in plane B (intrados: compressive area, extrados: tensile area)

The strains in the buckling areas measured at buckling amounted to 2.77 % and 2.32 %. In the DNV OS F101 or customer requirements critical buckling strains of up to 2 % are required.
For the calculation of such pipe bending scenarios, it is common to use either Finite Element Simulations or analytical models. In both ways, a yield criterion must be applied. An analytical assessment format based on von Mises plasticity was developed earlier to predict the multi-axial pipe behaviour under combined loading. Both the three-dimensional stress states as well as the pipe material's strain hardening are introduced. The analytic procedure is presented e.g. in [1].
It must be noted that the von Mises plasticity approach considers isotropic pipe material properties. However, to predict pipe bending behaviour under combined loading more realistically it is essential to include the material anisotropy in the calculations, both in FEM simulations and in analytic procedures. It is known that a certain material anisotropy exists in HFI line pipe due to forming processes, and it may be increased even by ageing effects. Approaches for the implementation of anisotropy into analytical and FEM calculations have been treated by [2] where extended von Mises plasticity is applied using Hill parameters. This modelling method the material properties, as is the tensile and compressive stress-strain behaviour, in all three coordinate pipe directions are required, meaning in longitudinal, transverse and radial direction. Since the radial direction is very difficult to investigate in material tests for thin-walled pipe material, other approaches have been researched, some of them presented in [2]. These topics are currently treated in research projects. First encouraging efforts to develop and combine analytic procedures and FEM simulations have been presented e.g. in [3].

Reeling

A plastic deformation by bending is also introduced into the pipe during the offshore reel-laying process. This process is the most cost efficient offshore laying method, as the welding that is the most time consuming process on lay barges is conducted onshore and the reel barges merely install the welded line. However it is suitable only for smaller diameter pipes up to 18“. The cyclic deformations the pipes are exposed to during reel-laying can be simulated either by a pre-straining in full-scale bending tests of whole pipes sections (full-scale reeling FSR), or as tension/compression straining of material cut from the pipe wall (small-scale reeling SSR). After straining the pipe material has to be artificially aged at 250 °C for one hour before the mechanical testing can be performed, as it is specified e.g. in DNV OS F101 [4].
Typically, two to three strain loops consisting of single cycles of plastic strains in the range of 1.5 % and 3 % are required. The cycles are chosen such that they are suited to simulate the actual reeling installation process that typically consists of reeling on, reeling off, aligning and straightening. The straining in the plastic regime during the laying process does change the material properties, a generally irreversible process that potentially affects both strength and toughness of the material. Mainly the three physical phenomena Bauschinger effect, strain hardening and strain aging are of relevance to the pipe and its behaviour [5]. During reel-laying the “fibers” of the pipe in 12 (extrados with respect to the drum) and 6 (intrados) o'clock position are exposed to cycles ending in both compression and tension, respectively. As these differences in strain history may have a major influence on material properties, it is recommended to simulate both in SSR. Also for the FSR simulation the mechanical-technological characteristics of the pipe material on the extrados and intrados have to be investigated after the reeling simulation. Therefore the reeling simulation consisted of experimentally investigating both loading paths ending in compression load (normal, extrados) and in tension load (reversed, intrados).
Reeling simulation on a laboratory scale (SSR) is performed in accordance with DNV-OS-F101, requirement P, unless otherwise specified by the customers. For the SSR-simulation tests standard reeling coupons of full wall thickness are used, and test-specimens for the tensile and Charpy-impact testing machined afterwards (Figure 5).

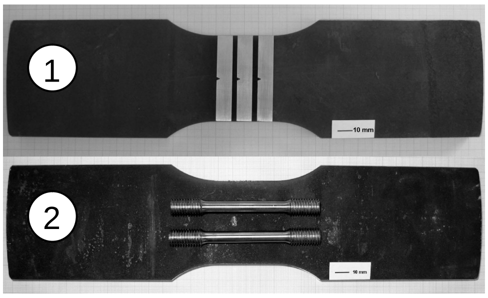

Figure 5: Example for SSR coupons and following test specimens

Figure 6 shows the stress-strain path of the coupons extracted from the pipes in both loading conditions. The Bauschinger effect can be observed after applying the first plastic load (tension or compression). In both cases of normal and reverse load path there is a significant drop in Yield strength (YS) in the opposite load direction. The YS upon reloading in initial directions is slightly decreased with respect to the initial YS, too. Towards higher amounts of plastic strain, the two curves tend to follow the same path again. This reflects the fact that the Bauschinger effect affects YS rather than the ultimate tensile strength (UTS).

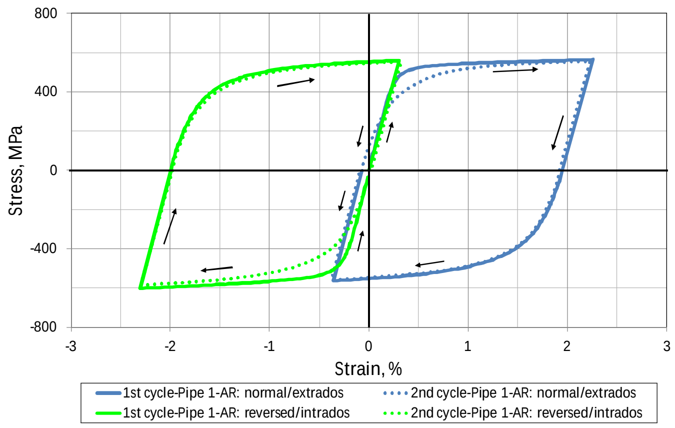

Figure 6: Normal and reversed hysteresis

For the FSR-tests the same HFI welded pipe was used as for the preparation and testing of the SSR-coupons, produced by Salzgitter Mannesmann Line Pipe GmbH in API X65M steel grade and 323.9 mm x 15.9 mm. The pipe testing took place at the SZMF on the LiSA-test rig, as described above. In the FSR-tests the same maximum strain of around 2 % at each cycle was chosen as in the SSR-test. During the displacement controlled tests the strain values were continuously recorded by strain gauges (Figure 7). Furthermore, force and displacement of the hydraulic jacks were measured throughout the tests. An example for the strain measurements is given in Figure 8 for the 12 o'clock position (strain cycle tension – compression – tension – compression).

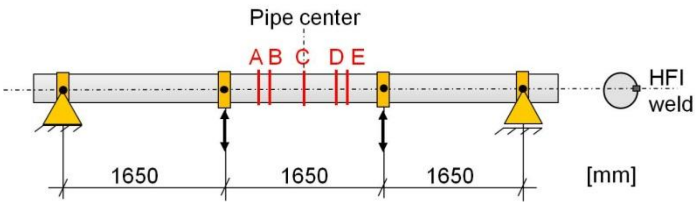

Figure 7: Test pipe installation and instrumentation with measurement planes A to E

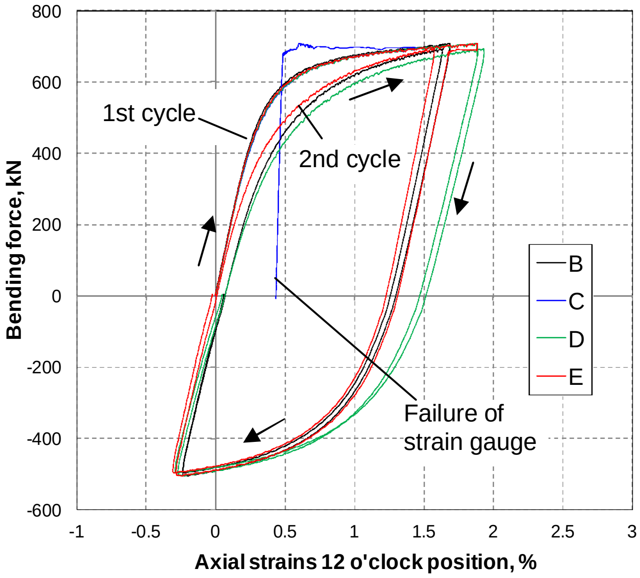

Figure 8: Strain measurements in 12 o'clock

A comparison between SSR and FSR-tests is given in Figure 9 and Figure 10. Detailed results have been published in [5,6]. Overall it can be noticed, that no major influences between FSR and SSR on mechanical properties exist. The properties of the HFI pipes are basically suited for reeling installation according DNV-OS-F101, as tensile and toughness requirements after reeling simulation were widely fulfilled. The results of the strain measurements carried out by FSR show an acceptable reproducibility and traceability of the deformations. Therefore the strain values are controllable and interpretable as in the case of SSR simulation tests. Like in the SSR-tests the tensile properties in FSR-tests depend mainly on the last load cycle. In contrast to this, the toughness properties are not significantly affected by the last load cycle.

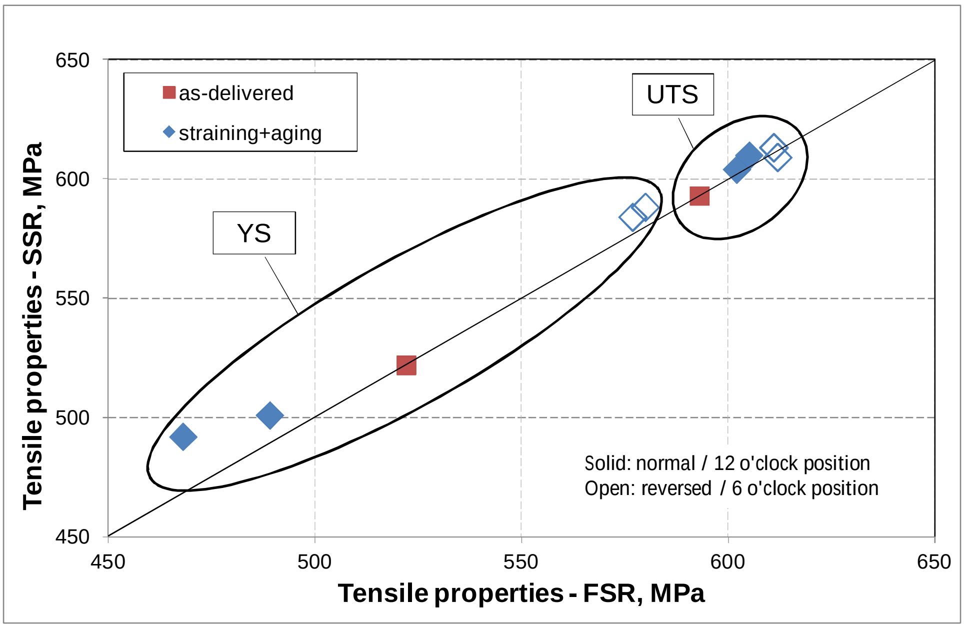

Figure 9: Tensile properties

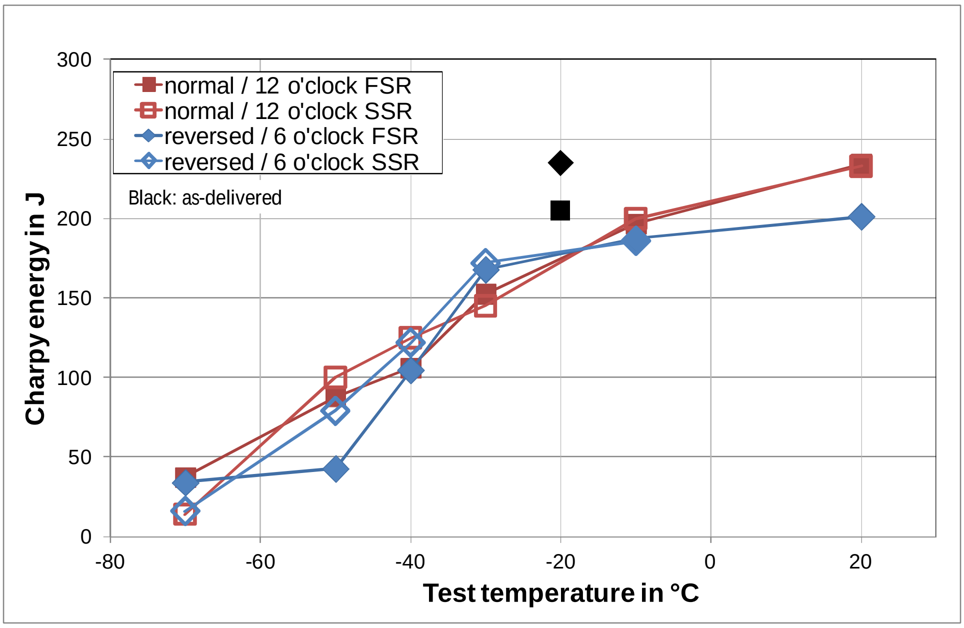

Figure 10: Toughness transition curves

Pipeline laying by Horizontal Directional Drilling and thrust bores

In 2012 MLP delivered pipes to the FW Celle GmbH (Gemany) for the construction of district heating pipes. This had been realised as two “telescope” pipes. The pipes with diameter 16” (406.4 mm) and wall thickness of 6.3 mm had been used as the inner pipe, the pipes with 24” (610 mm) as the outer casing pipe (wall thickness 12.5 mm). For the protection of the outer pipe during inserting the pipe into the borehole and because of the long and complex drilling and laying operation, a special three-layer polypropylene coating with a thickness of 6 mm had been chosen. To minimise the temperature loss a special isolation material is placed, as well as a vacuum generated in between the two pipes. The temperature fluctuations during the operation of the pipeline are critical in this case because of the special pipe laying operation and the course of the pipeline. In order to absorb and compensate the resulting expansion forces during operation, the steel pipe in steel pipe system had been chosen. This offered the possibility to realise a pre-stressing of the medium carrying inner pipe.

Visser & Smit Hanab (VSH) from the Netherlands then used these pipes to complete a section of the 27 km dual pipeline for the DNWW (De Nieuwe Warmte Weg), a pipeline for “Warmtebedrijf Rotterdam”, a heat supply company in Rotterdam. These new steel pipelines will supply 50,000 homes and a hospital with a new source of heating from the stream discharged from an industrial area in Rozenburg situated on the outskirts of Rotterdam. Visser & Smit Hanab has completed several Horizontal Directional Drills (HDD) and thrust bores along the route of the project. Although, the two 1500 m long HDD's below Katendrecht was something rather unique. The drilling and laying had to be carried out next and below to the historic Hotel New York (build in 1901) situated at the end of the Wilhelminapier (Figure 11). VSH had to devise a method of how to create minimal down hole pressure which could potentially unsettle the wooden piles that the hotel was constructed on. Having reviewed all of the requirements relating to the HDD profile and route VSH designed the routes to be drilled at a depth of -50 m and -60 m which enabled one pipeline to be installed above the other due to the extremely narrow drilling corridor between the entry to the exit locations. In addition to the deep drilling depths VSH also had to incorporate a 60° right hand turn to ensure the drilling exited at the required tie in point. On the 28th of February 2013 VSH opted to utilize both their 450 t and 100 t rigs to simultaneously drill from both entry and exit positions of the first HDD. Both rigs commenced drilling with the 450 t machine drilling to 1000 m and the 100 t rig drilling 500 m from the exit location. The GST Gyro positioning system has been developed and used to make high accuracy pilot bores possible. Advantage of this technology is that it has no restriction on drilling depth and knows continually where the drill-head is located. Prior to installation of the pipeline a 28" barrel was used to complete a wiper run to check the integrity of the drilled hole before the pullback operation was started on Saturday 9th of March. All the drilling operation has been completed in just five weeks.

Whilst the HDD reaming operation was still in progress VSH's marine division floated two strings each of 750 m (which had been constructed earlier by VSH at a location 21 km away) into vicinity of the drilling location where the two sections were subsequently welded and tested. VSH's final challenge was to coordinate with all the local authorities the closure of a major bridge in the city and closure of the tram system. This meant that the pipeline could only be pushed the 500 m towards the drilling location once the final tram service had passed at 02:00 a.m. on Saturday morning. Finally once the pipe had reached the entry pit a total of 14 AT mobile cranes were mobilized to place the pipeline in an over bend which extended to some 22 m high due to the combined steep exit angle of the HDD and minimum bending radius which had to be adhered to. The pullback operation of the 1500 m string started at 09:30 a.m. (Figure 12), and was carried out with a speed of 100 m per hour. At 6:00 p.m. the whole laying operation was successfully completed without any problems within the predetermined time frame of two days. The inspection of the pipeline afterwards showed the faultless and not influenced condition of the pipes and the coating itself, regardless of the stresses and strains during laying operation.

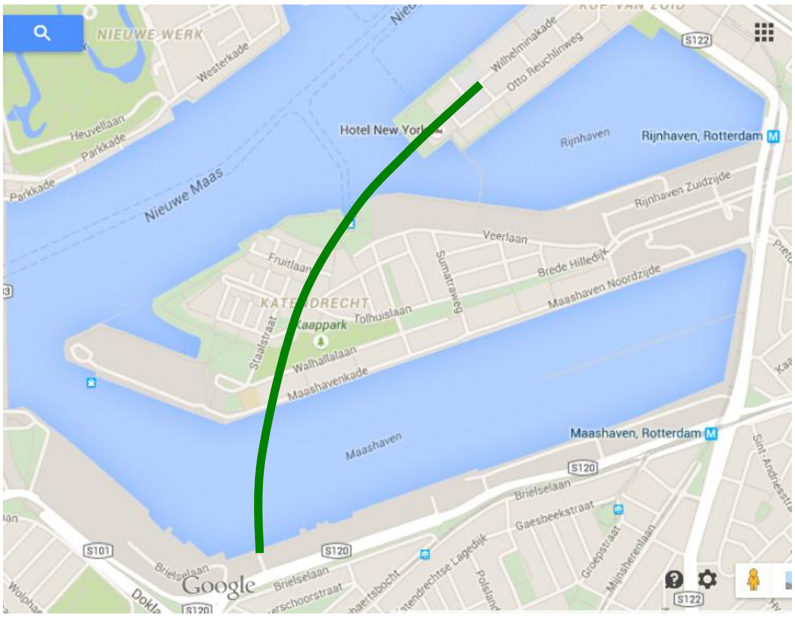

Figure 11: Pipeline route for HDD drilling at Katendrecht Rotterdam (length 1500 m)

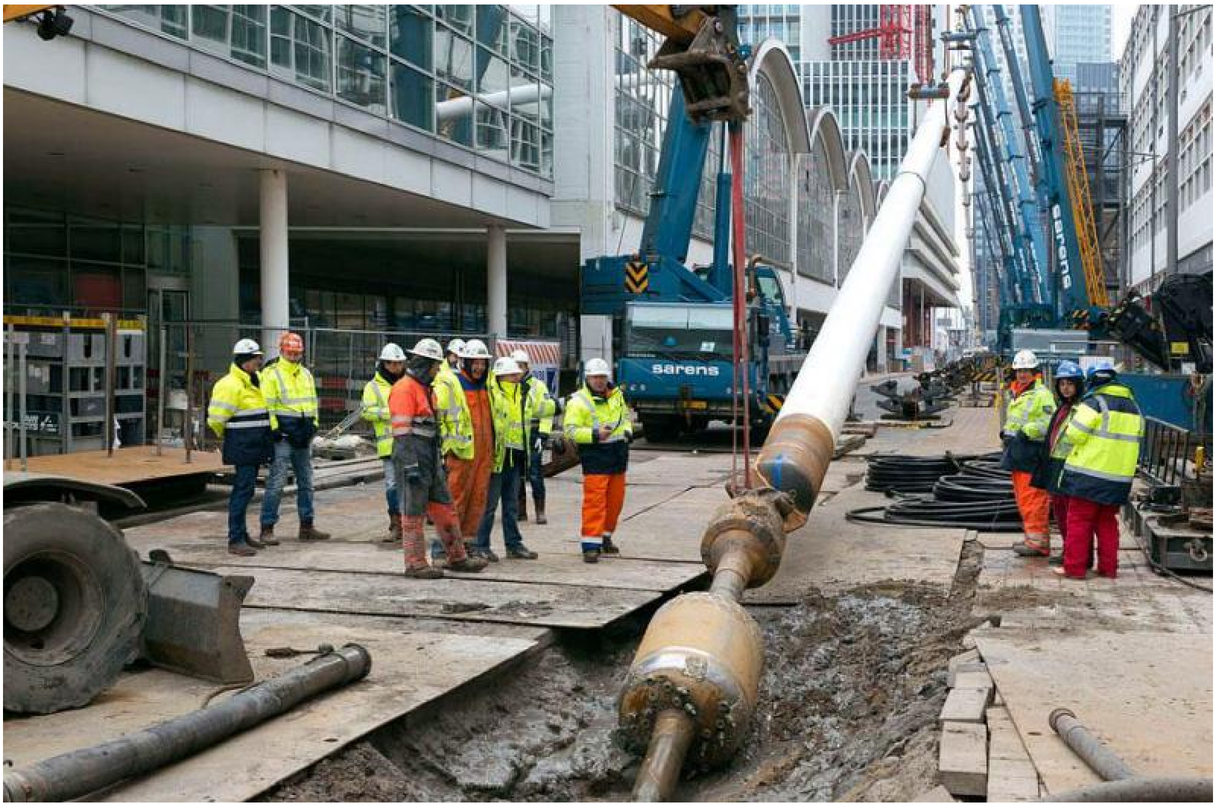

Figure 12: Entry of the district heating pipeline

Summary

Over the years the applications of steel pipes for transportation of media have become more and more demanding. Also the amount of special solutions and pipe products increase. This led to highly sophisticated requirements based on regulations and customers specifications. Additionally a narrowing of tolerances and combinations of requirements make it even more difficult for pipe manufactures to meet these challenges.
The examples presented in this paper demonstrate, that HFI-welded pipes of Salzgitter Mannesmann Line Pipe GmbH are very well suitable for different kinds of applications with high stresses and strains. Not only the simple material characteristics have been investigated, but also the pipe response under real loads in full-scale tests and after operational use have been incorporated.
The *strain based design* test on the example of the combined loads of internal pressure and bending resulted in a buckling before leakage occurred, with strains measured, that were beyond specifications of customers and typical standards.
Reeling simulations on HFI-pipes revealed no major difference between typical small-scale reeling tests and specially designed full-scale tests. The tensile properties depend on the last load cycle, but toughness properties are not significantly affected by the last load cycle.
No damages of pipes and coating occurred during a *Horizontal Direct Drilling* laying procedure, with high stresses and strains from laying process and multiple curvature of laying route.

Literature

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