Assessment of HFI line pipe for Strain-Based Design via Full-Scale Testing

The present paper addresses issues of pipeline design associated with unintended actions due to external loads or ground movements. These may introduce longitudinal strains in the pipeline owing to combinations of curvatures and axial forces. Such scenarios must be tackled with Strain-Based Design approaches. The following sections elaborate on the strain capacity of HFI-welded pipes checked via material testing and a full-scale test performed on a pressurized HFI-pipe under bending load. Analytic modeling procedures for predicting the structural behavior using certain assumptions are described.

The conventional approach for pipeline design, a stress-based approach, may be insufficient for displacement-controlled or partly displacement-controlled load scenarios, such as pipeline deformations due to ground movement. 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, alternative strain-based design methods are introduced for cases where ground movements may play a role.

Strain-based scenarios have in common that axial strains from curvatures or external forces are considered in addition to circumferential stresses due to internal pressure in the pipeline. Safety assessments of such pipelines under combined loading require the knowledge of the plastic response of line pipe. The plastic deformation capacity depends on the pipe dimensions, loading and the strain hardening behaviour. The complexity of Strain-Based Design increases with the variety of newly developed pipe steels and pipe manufacturing processes, where experience from the past is not available. Reliable predictive models are needed, validated by experimental data. In testing, it is important that a realistic scenario is simulated using a full-scale pipe specimen in order to comprehend the structural performance. If the constitutive properties are assessed on material level, without full-scale data, essential information of the multiaxial pipe behaviour will be missing, for example strain redistribution, residual stresses or imperfections. The link between the full-scale test results and the input material parameters, supported by predictive validated modeling, will help to proceed a further step towards the comprehension of Strain-Based Design.

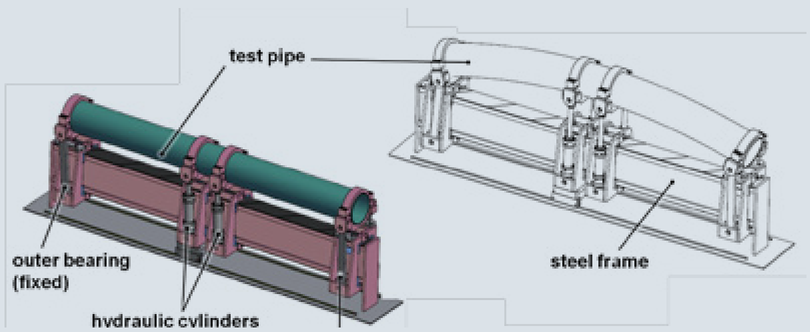

***Figure 1**: Full-scale bending test rig at SZMF*

INFLUENCES ON STRAINING CAPACITY OF HFI-PIPES

The deformation capacity of pipelines subject to strain-based scenarios (e.g. ground movements) is steered by some factors: Loading (internal pressure level), pipe dimensions (determining the D/t ratio), pipe geometry (possible ovality or imperfections) and pipe string material. Obviously, loading and pipe dimensions are design issues. Imperfections may be essential in connection with the girth welds in terms of flaws or geometric offset. Also the position of the longitudinal weld seam may influence the pipeline's straining capacity if positioned unfavourably in relation to the direction of unwanted bending load or curvature. These issues more or less are considered to be matters of pipeline manufacturers.

A pipe manufacturer can contribute to Strain-Based Design, by delivering pipe properties best fit to these scenarios. Pipe manufacturers in the last years have concentrated on optimizing their pipe material. Increasingly, pipe mills have been confronted with severe demands on strain values, e.g. uniform elongation, and yield-to-tensile-ratios Y/T, and have made efforts to respond to these requirements via enhanced material and rolling concepts.

The material properties in longitudinal and transverse direction as well as tensile and compression characteristics influence the pipe behaviour when subject to external loads. For both directions and tensile and compressive straining, the strain hardening behaviour, given either by the stress-strain characteristics or alternatively by strain hardening exponents, are needed, see [1]. Generally, the determination of material anisotropy becomes essential for calculation of critical strain-based design parameters [2] [3].

Strain aging of the steel also has to be considered. It can occur during the standard polymer- or FBE- (fusion bonded epoxy) coating treatment of the pipe where the temperature of the linepipe can reach 250 °C for several minutes. This causes thermal aging because of the cold pre-deformation during pipe forming process [4]. Strain aging is a thermally activated process

where carbon and/or nitrogen atoms diffuse to dislocation cores, thereby pinning them and preventing dislocation movement [5]. The mechanical properties such as R_t, R_m, Y/T-ratio, uniform elongation A_g and stress-strain curve shape can change due to thermal aging. Additionally an embrittlement of the pipe material can occur, due to sub microscopic precipitation on the cleavage plane of the crystals grains. The quantification of strain ageing effects is essential, because the pipeline in the field shows material properties after coating treatment, whereas requirements in standards refer to "as rolled" material properties (without coating treatment).
In order to determine the anisotropy as well as the strain-aging resistance of High-Frequency-Induction (HFI)-welded pipes in grades X52 to X65 from MLP, extensive mechanical characterisation tests of the base material were carried out. Specimens taken longitudinally and transversely to the pipe axis out of non-coated and PE-coated pipes were investigated in tensile and compressions tests, [7]. Anisotropy is generated mainly for the yield strength by the pipe forming process. The $R_{t0.5}$ values are higher in longitudinal pipe direction than for the transverse direction. As expected, a reverse behaviour was found for the compressive yield strength $\sigma_{d0.5}$. The coating process tends to lower $\sigma_{d0.5}$ more severely than it raises the tensile yield strength. Therefore the compression yield-to-tensile ratio is decreased more than the tensile Y/T is elevated when the pipe material is exposed to typical coating temperatures. It occurs that the elongation at break is slightly reduced by the coating process.

FULL-SCALE TESTING OF X70 HFI-PIPE

Four-point-bending testing device

The test rig located at Salzgitter Mannesmann Forschung GmbH (SZMF) in Duisburg, Germany, is a vertical four-point-bending device. It is equipped with four hydraulic jacks with each 2.500 kN (two cylinders act on one load application point, respectively). Thus, a total load capacity of 10.000 kN (1.000 tons) can be supplied. The bearings are supported by a welded steel frame. An overview of the test rig is sketched in ***Figure 1***.
Maximum width between supports is about 15.5 m; diameters may reach up to 56". The hydraulic jacks allow for a maximum stroke of 1.100 mm. One of the outer bearings is undisplaceably fixed to the steel frame while the other bearing and the two loading planes can be moved flexibly

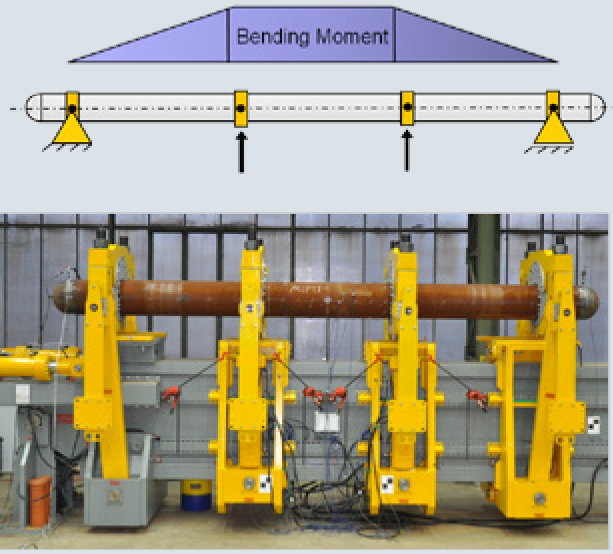

Figure 2: *Schematic and photo of four-point bending test at SZMF*

along the pipe axis, see ***Figure 2***. Thus, the pipe length and the distance between the supports can be chosen according to the pipe dimensions and test requirements. If a pressurized pipe is bent the internal pressure is achieved by water filling. For this purpose the pipe ends are sealed via end caps welded onto them.

Test pipe X70, 24"

The test has been performed on an HFI pipe produced by Salzgitter Mannesmann Line Pipe GmbH in API X70 steel grade and 24" diameter (OD x t: 609.6 x 10 mm). In order to include any thermal aging effects from the polymer-coating process, the test pipe had undergone a heat treatment as if being provided with poly-ethylene (PE)-coating. In fact the test pipe was heated for 5 minutes with the temperature of 210 °C. Thus, a realistic application of a three-layer poly-ethylene (PE)-coated pipe was simulated.
To achieve an overview of the mechanical properties, tensile and compressive material tests were carried out taking into account different hoop positions of the pipe cross section. Both longitudinal and hoop direction were tested in order to identify possible anisotropic material behaviour. ***Table 1*** presents the tensile material data; ***Table 2*** contains the compressive test results.

Clock position, orientation		$R_{p0.2}$ MPa	R_m MPa	Y/T -	A_g %	A_5 %
3°°	Long.	509	609	0.84	13.3	27.5
6°°	Long.	510	609	0.84	13.1	27.3
6°°	Transv.	497	625	0.80	13.3	28.3
9°°	Long.	508	608	0.84	12.9	27.0

Table 1: *Tensile test results (mean values from two single tests; samples: longitudinal: flat specimens with width 25mm, transverse: round bar B5x25, not flattened, DIN 50125 [8])*

Clock position, orientation		$\sigma_{d0.2}$ MPa	$\sigma_{d3.0}$ MPa	$\sigma_{d0.2}/\sigma_{d3.0}$ -
3°°	Long.	518	599	0.86
6°°	Long.	512	615	0.83
6°°	Transv.	534	634	0.84
9°°	Long.	518	603	0.86

Table 2: *Compressive test results (mean values from two single tests; cylindrical samples Ø 8 mm, height 16 mm, extracted from exterior of pipe wall)*

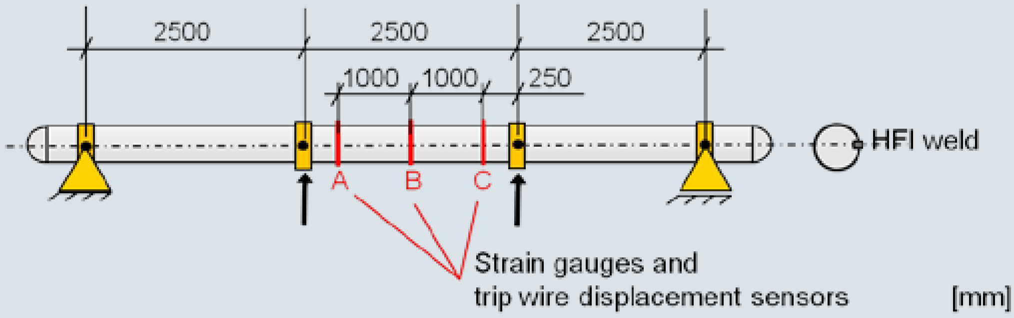

Figure 3*: Schematic of test pipe installation and instrumentation*

The test pipe was installed in the test rig such that the 3°° o`clock fibre was positioned in the extrados and so the 9°° o`clock position in the intrados. The HFI weld was located in the neutral bending axis. The pipe was instrumented with strain gauges and trip wire displacement sensors in three measuring planes (planes A, B, C) within the test section, see ***Figure 3***.

The test has been carried out in displacement controlled condition. The internal pressure level of 66% SMYS was selected (corresponding to a hoop stress equal to 66% of SMYS) which lead to a pressure of 100 bar. The pressurization has been completed before bending and pressure was kept constant throughout the bending test.

Test results

After reaching the load maximum buckling appeared. The test was continued into the post-buckling regime where load decrease was observed, but after a certain cylinder stroke (500 mm) the test was discontinued and the pipe unloaded. As usual for pressurized pipes, buckling occurred in form of characteristic outward bulges. In this case, two bulges developed symmetrically to the pipe mid-length section (***Figure 4***, ***Figure 5***). No leakage or rupture occurred.

Figure 6 presents the load-deflection curve which is an average curve of the left and right jacks' forces and strokes recorded during the test. Strain measurements from strain gauges are reported in ***Figure 7*** and ***Figure 8***. The strains in plane A and plane C (Figure 7) indicate a symmetric behaviour of the pipe related to mid-length section, as plane A and plane C show almost identical curves, both on the tensile and the compressive fibre. Strain records in plane B (Figure 8) are supplemented by transverse direction.

Figure 8 reveals different load-strain curves for the extrados and intrados. On the one hand the pipe behaviour differs for compressive and tensile loading, which already

Figure 4*: Pipe deformation after test; close-up view of test section*

Figure 5*: Close-up view of bulges*

became clear when looking at the material tests where compressive and tensile data differ slightly. Secondly, due to the influence of the internal pressure which imposed a multiaxial stress state onto the pipe, it did not deform symmetrically towards the neutral bending axis. The strains measured in the neutral bending axis, in 90° angle with respect to intrados and extrados, are not depicted in this paper. They were close to zero with marginal deviations, as expected for this load case.

Figure 7 and Figure 8 point out very similar longitudinal strains recorded on the extrados, in all three planes A, B and C. In contrast, on the intrados, higher strains are observed in planes A and C in comparison to plane B (mid section). Measurement planes A and C are near the loading planes, and next to planes A and C the bulges developed as a consequence of the higher strains. The load devices may have contributed to this behaviour by inducing local deformation into the pipe wall. In addition, the relatively high pipe pressure may have had an influence. Other test series have shown that highly pressurized pipes tend to shift the bulges towards the loading planes, while pipes with lower or zero pressure buckled in mid section. The quantification of these effects is studied in current and further research work.

ANALYTIC PREDICTION OF PIPE BEHAVIOUR

Analytic formulation of three-dimensional plastic straining

An analytic model to predict multi-axial stress and strain states in pipelines subject to external axial forces and bending loads has been developed. The general format of the assessment procedure was already published in [9] and its extension in [1]. Basically, the von Mises yield criterion is applied in an isotropic manner. The strain hardening behaviour is introduced as a function of the plastic strains using Hollomon power law with strain hardening exponents. The Hollomon parameters are gained from the stress-strain

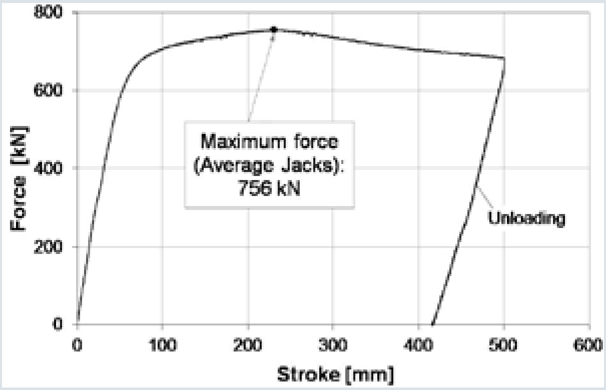

***Figure 6**: Load-deflection diagram (average of left and right jacks)*

results derived from uniaxial tensile or compression tests.

Model application on bending test on pressurized HFI pipe

For an analytic assessment of a bending test combined with pressure both tensile straining and buckling must be addressed. Literature and codes provide a variety of formulae to determine buckling loads or critical compressive strains. Comparing different theoretical modelling approaches it was shown, that the DNV-OS-F101 [10] provides a suitable assessment of critical buckling strains for line pipe when exposed to axial forces, bending moment and internal pressure [12]. The analytic calculation was carried out stepwise, namely:

» The critical buckling strain for the compressive zone of the bent pipe section was calculated via the procedure given in DNV-OS-F101 [10]. The material data used are compressive data gained from the 9°° o`clock position in longitudinal direction (Table 2), as the 9°° o`clock position of the pope corresponded the intrados in the full-scale test.

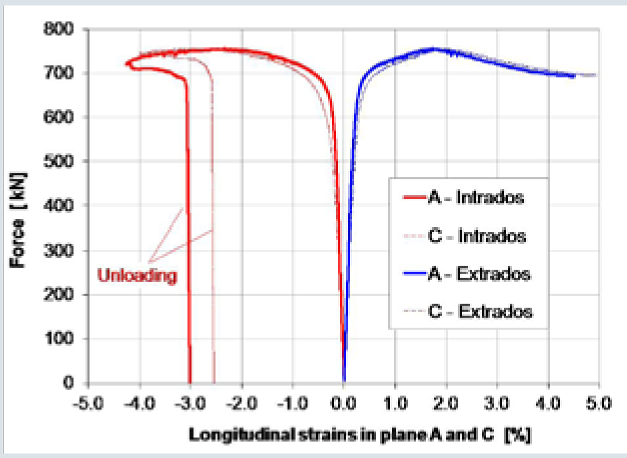

***Figure 7**: Load-strain curves in measurement planes A, C acc. Figure 3*

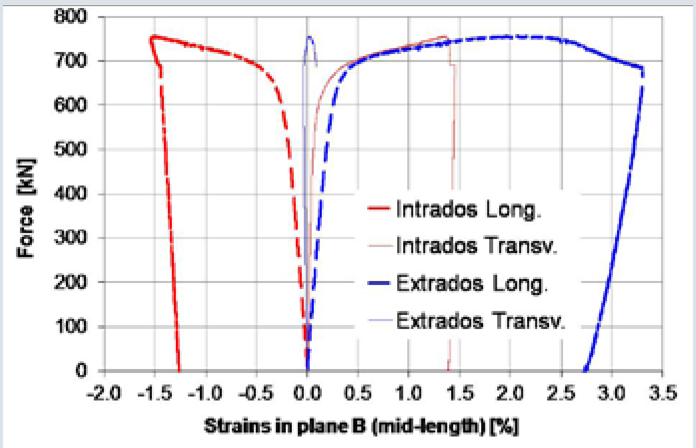

***Figure 8**: Strains in plane B (mid-pipe length section acc. to Figure 3)*

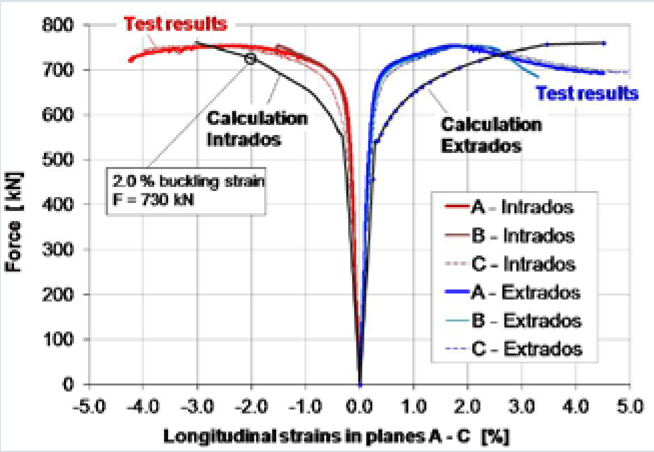

***Figure 9**: Load-strain evolution from test records compared to model calculations*

- The stress-strain evolution until the buckling strain is reached and the corresponding bending moment (and bending force) came from the analytic calculation described in the equations above. The same compressive material data was inserted as in step 1.
- The stress-strain evolution for the tensile zone of pipe section was calculated via the analytic equations using tensile test material data. The material data from 3°° o`clock position in longitudinal direction (Table 1) was applied as the 3°° o`clock pipe position was placed in the extrados position in the bending test.

Figure 9 shows the load-strain evolution determined for the compressive zone (intrados: red graphs) and tensile zone (extrados: blue graphs) in comparison to the test graphs recorded during the test in planes A, B and C according to Figure 3. In the diagram total strains are plotted (including elastic and plastic deformation) in axial pipe direction. A circle in the calculated curve marks the critical buckling state: The buckling strain of 2.0% has been estimated via DNV-OS-F101 [10]. The corresponding force was F = 730 kN.

The load–strain evolutions for both the compressive and the tensile zone of the pipe show higher strains and thus lower forces in the calculation compared to the test measurements. The calculated force-strain curves leave the elastic path once the elastic bending moment has been exceeded, steered by the yield strength ($R_{p0.2}$ and $\sigma_{d0.2}$, respectively) gained in the material tests. The actual structure showed a much stiffer and less "round-house shape" behaviour. The elastic path is continued to higher bending forces before the pipe showed significant plastic deformations. As a consequence the predicted buckling force (730 kN) is 3.5% lower than the measured load maximum (756 kN).

The deviation of test and analyses proves once more that the complex structural performance of a pipe under such a multiaxial load case cannot be described by simple uniaxial material tests or material parameters anymore. Brauer et. al made similar observations on ring expansion tests [11]. Even the here applied three-dimensional analytical model represents the structural pipe behaviour only with a certain inaccuracy. An important reason for the deviation is the material anisotropy which has not been considered in the analytical model. The model is, in the present case, based on longitudinal material data (tensile and compressive), where anisotropy of longitudinal versus hoop direction is not included. Yet, it is known that PE coated HFI pipes show a greater anisotropy than "as rolled" pipes [7]. In such a multiaxial load case with high pressure loading, the transverse behaviour influences the pipe performance considerably.

CONCLUSION

High-Frequency-Induction (HFI) welded line pipe subject to bending loads was investigated via a full-scale bending test and predictive modeling. The investigations provide a further step to support the development of suitable strain-based design concepts. In the experiment the pressurized pipe showed typical buckling behaviour by developing outward bulges. The load-deflection curves and strain measurements reflected the typical buckling phenomenon.

Modeling was based on isotropic strain hardening material. The results reveal the complexity of pipe behaviour in terms of anisotropy. Anisotropic material properties need to be considered in further modelling, especially if PE-coating is applied on the pipes. Approaches for the implementation of anisotropy into analytical and FE calculations have been treated by Hilgert et al. in [2] where extended von Mises plasticity is applied using Hill parameters.

Future tests should include the comprehension of weld behaviour under bending loads. Girth welded pipe sections on the one hand will show a different plastic straining behaviour compared to a plain pipe. On the other hand the orientation of the longitudinal weld (HFI weld) may play a role, if placed on the extrados or intrados in the bending test.

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