Innovative solution for water injection pipes in secondary oil recovery

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Cement mortar lined steel pipe made up with slip welding joints was subjected to FEM simulation and laboratory tests to determine its mechanical loadability in the transportation of oil/water mixes encountered in secondary oil recovery. The criteria examined also include combined loads of bending stress and internal pressure as involved in pipe-laying and under service conditions.

Effective corrosion protection for oil pipelines is the subject of intensive research around the globe, given the high aggressiveness of the media transported. The need for a dependable solution is becoming even more urgent as recovery methods switch from primary to secondary. In primary production, the oil is brought up by the natural pressure in the reservoir. However, this pressure – and hence the production rate – decreases with time. In secondary oil recovery, water is injected into the reservoir to keep up the pressure and increase the recovery rate. Thus, besides oil gathering lines operated at a relatively low pressure of up to about 40 bar, secondary oil recovery requires injection pipes, which have to resist service pressures of up to 200 bar in order to build up the necessary pressure in the reservoir.

Compared to primary recovery, the media transported in secondary recovery vary significantly in terms of their chemical composition and properties. The chemical analysis of oil/water mixes encountered in secondary recovery shows high mineral levels as well as the presence of solids and dissolved gases, such as H_2S or CO_2 (***Table 1***). Media with this kind of composition call for a chemically resistant pipe lining that prevents the penetration of corrosive constituents to the steel surface. In addition, with a view to the solids contents, the lining must be resistant to abrasion. These requirements also apply to the joint areas in a pipe string.

Cement mortar lined steel pipes have been used for a long time in pipelines transporting untreated waters and drinking water, industrial waters, saltwater and brines, as well as wastewaters. The high strength and elasticity of steel pipes coupled with their high temperature resistance and problem-free weldability make them suitable for a wide range of applications. Here is a brief summary of their most important advantages:

» The high degree of utilization and the wide range of applications of various steel grades allow an optimized design in terms of wall thickness and savings in weight and thus costs despite maximum pressure loads.

» The problem-free weldability of steel results in force-locking pipe joints for maximum pressure stages. In addition, fittings can be produced onsite quickly and inexpensively by segment cuts.

» Thanks to the elastic behavior of steel, the laying of pipe strings lined with cement mortar poses no problem.

» The broad range of joining techniques for steel pipes ensures optimum product designs for all applications.

» The longitudinal conductivity of welded pipe joints allows the implementation of cathodic corrosion protection and thus condition-based pipeline monitoring.

Based on the above, it was an obvious conclusion to test whether the described pipe design is also suitable for use in secondary oil recovery. Another decisive advantage is that these pipes are standardized in DIN 2460 (Steel water pipes and fittings) [1], which describes the essential design features and joining techniques as well as the various options of effective corrosion protection. The standard also gives the applicable technical delivery

***Table 1**: Chemical composition of oil/water mixes in secondary recovery (example)*

Anions mg/l			Cations mg/l				pH value	Solids content mg/l
Cl^-	SO_4^{2-}	HCO_3^-	Ca^{2+}	Ba^{2+}	Mg^{2+}	$\sum(Na^+ + K^+)$		
37590	37	231.8	3406.8	310.00	413.4	19783.9	6.48	76
41090	3	158.6	3607.2	245.00	790.4	21084.1	6.67	107
36750	30	170.8	3086.2	345.00	632.3	19169.9	6.65	116
34650	0	183.0	3006.0	570.00	620.2	17927.0	6.47	174

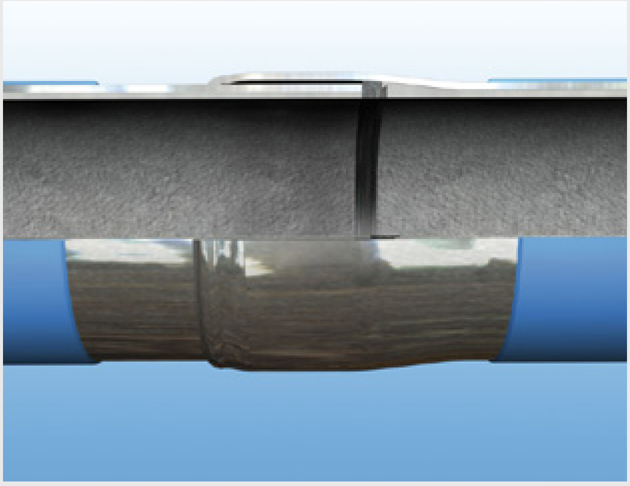

***Figure 1**: Slip welding joint*

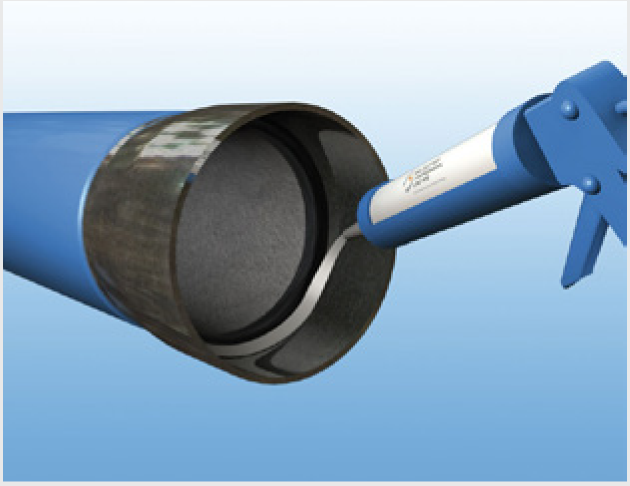

***Figure 2**: Sealant application to the socket base before welding*

conditions for the components included in the product (steel pipe, lining, coating, joining technique, etc.). In addition, DIN 2460 specifies the minimum requirements on the steel pipe design, taking into account various static constraints such as the pipe-laying depth, traffic loads and pressure fluctuations.

While polyethylene or polypropylene coatings – where appropriate also in conjunction with a cement mortar top coat – provide efficient external corrosion protection in soils of all classes, including severely aggressive environments, corrosion protection against the transported medium on the pipe inside is often a limiting factor for a given application. The decisive criteria that must be given special attention where secondary recovery applications are concerned are the corrosion resistance of the cement mortar lining and the pipe joint used. As early as back in 1996, an article [2] was published on the successful use of cement mortar lined pipelines at Petrobras. In addition, standards such as DIN 2880 or DIN EN 10298 provide valuable assistance when it comes to specifying limit values for the chemical composition of the transported media [3].

DIN 2880, for example, provides no indication of a temperature limit for the transportation of aqueous media in cement mortar lined steel pipes. The essential requirement is to avoid the formation of gas bubbles and thus conditions for cavitation. This is ensured at appropriately high service pressures. Tests at 250 °C (test pressure 43 bar) did not produce any damage in the lining even after 60 days. Service loads on the pipe wall during the operation of pressure pipes should remain below 50 % of the yield strength, to avoid spalling of the cement mortar lining in the case of sudden load removal [3]. In addition, modification of the blast furnace cement mortar used here will ensure compliance with the type test requirements specified by DIN EN 598 for high-alumina cement linings [4].

Suitable pipe designs complete with welding joints and cement mortar linings for the service conditions in oil gathering and water injection lines can be found in DIN 2460. As regards the corrosion protection to be considered when running the pipe string, the slip welding joint (***Figure 1***) recommends itself, which is predominantly used in aggressive waters, saltwater, brines and wastewater. The joint area is protected with a special sealant, an elastic thermosetting material that is applied to the socket base before inserting the spigot end (***Figure 2***). After tack-welding the spigot end, any excess sealant can be smoothed out with the aid of a foam pig before welding the pipe joint. The basics for the steel pipe design calculations are described in the appendices of the standard. The use of this piping system as an oil gathering line operated at up to 40 bar poses no special challenge. Its reliability under these moderate conditions was proved in a five-year trial operation. Conversely, the service conditions of injection systems are far more demanding than the load cases considered in DIN 2460. Anyhow, DIN EN 10224 and DIN EN 10311 give examples of joint types including the slip welding joints without any limitation for wall thickness. Hence, the suitability of this pipe design should be verified, especially with a view to the necessary pipe wall thicknesses and the pipe-laying conditions involved.

Problem description

Welded steel pipes are preferably laid in strings (***Figure 3***). In pipe handling, including lowering of the string into the trench, care must be taken to avoid bending beyond the minimum permissible bend radius. The permissible bend radius for steel grade L235, the standard material for water pipes, the minimum permissible bending radius is r_{perm} = 500 OD. This bend radius has established itself in pipeline construction, including directional changes, as a standard parameter for water pipe. Whether this mini-

Figure 3: *Bend radii in a welded pipe string being lowered into the trench*

Figure 4: *Test portal for bending tests (manufacturer: FORM+TEST, Riedlingen, Germany)*

mum bend radius can also be maintained in pipe strings with slip welding joints and wall thicknesses greater than 10 mm, as required for injection pipes, was to be verified in appropriate tests, which were also to consider the internal pressure under service conditions.
Since it was impossible to include all the potential service conditions in the tests, a FEM simulation model was created as a basis for predictions regarding similar load cases and other pipe designs.

Methods

FEM simulation

Local stresses and deformation can be derived by means of FEM simulation using the Abaqus program. In the formation of a model, the flow stress curves of the various materials have to be considered. The yield stress of the steel is 510 MPa, while that of the welding material is set at 380 MPa, based on the minimum yield strength given in the Datasheet. In accordance with the laboratory tests, the model takes account of the bearings at the pipe ends and includes them as constraints. In the simulations, the von Mises reference stress [5] and the equivalent plastic reference strain are calculated and output.

Laboratory tests – test setup

To cross-check the results of the FEM calculations, we carried out the bending tests in a test portal (***Figure 4***), which accommodates unsupported spans of up to 8 m and the time-dependent application of a bending force of up to 400 kN.
The pipes rest on three bearings. The two outer ones are

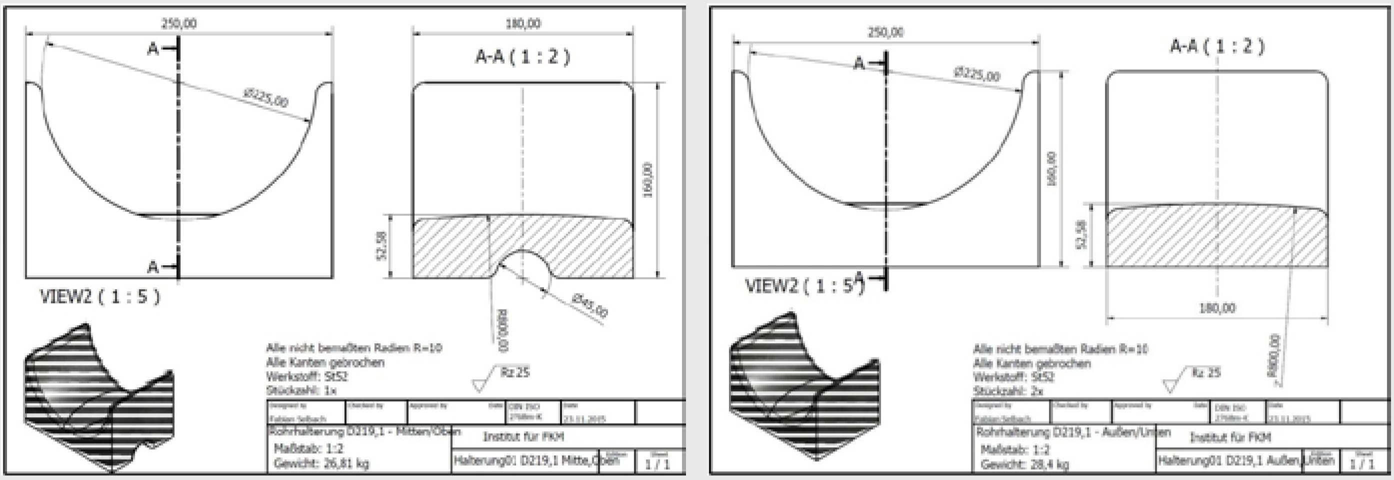

Figure 5: *Bearing halves for bending tests on pipe size 219 x 12 mm*

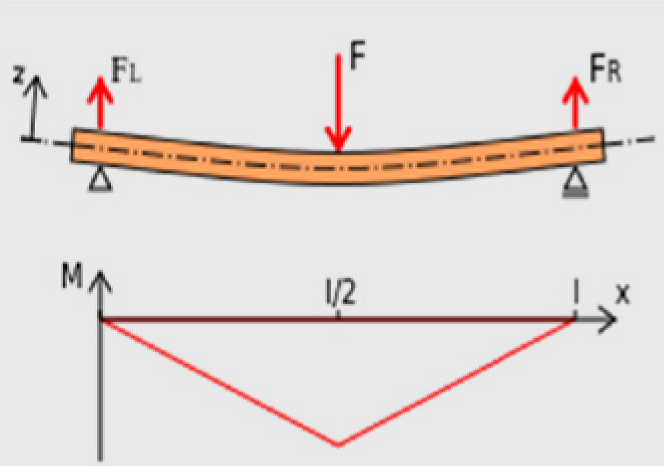

Figure 6: *Bending moment curve for the three-point bending test*

Figure 7: *The pressure booster (make: Haskel) used for the tests*

floating bearings, and the inner one is designed as a fixed bearing, which means it is secured against lateral shift and only permits a reciprocating movement (***Figure 5***).

With this test setup it must be considered that a major share of the force applied during the three-point bending test concentrates on the joint area. The load case examined here is much more critical than the actual loads encountered in pipe-laying, so the test results are on the safe side (***Figure 6***).

In some of the tests, the pipes were additionally subjected to internal pressure at different levels. For this purpose, the pipes were filled with water, and the required internal pressure was generated by means of a pressure booster (make: Haskel) capable of generating pressures of up to 500 bar (***Figure 7***).

FEM results

Pipes in the dimensions 168 x 10 mm were subjected to the following load cases: internal pressure only (e.g. p = 200 bar), bending load only (e.g. bend radius r = 500 OD) and a load combination (first internal pressure, then bending load).

Pure internal pressure load produces a rotationally symmetrical tensile allocation, with the highest levels of about 210 MPa occurring in the weld, and stress levels outside the weld reaching 150 MPa at the most. There were no indications of plastic deformation anywhere along the pipe (***Figure 8***).

In the case of pure bending load, the highest stresses occur in the weld area on the lower outside surface of the pipe, whereas the stresses on the upper pipe surface and outside the weld area are significantly lower (***Figure 9***), with a maxi-

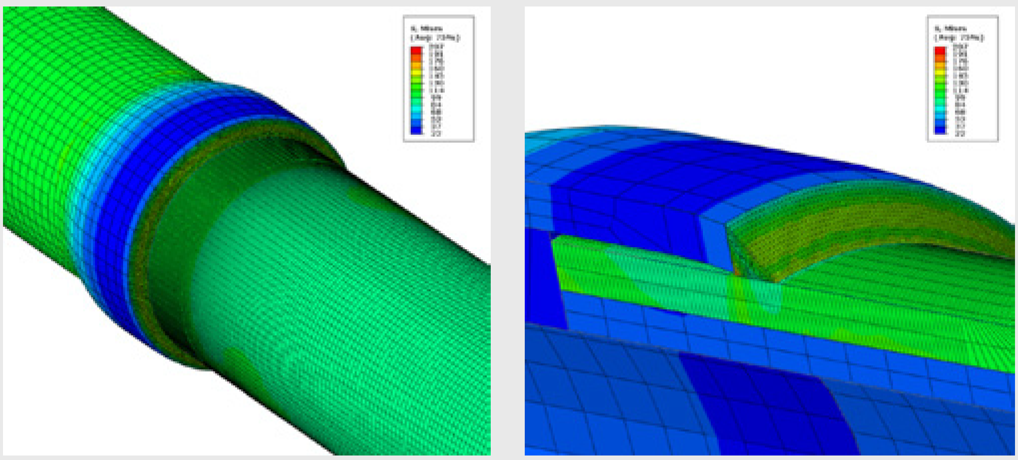

Figure 8: *Tensile allocation [MPa] on the outside of the pipe joint (left) and along the axial cross section (right) under an internal pressure of 200 bar*

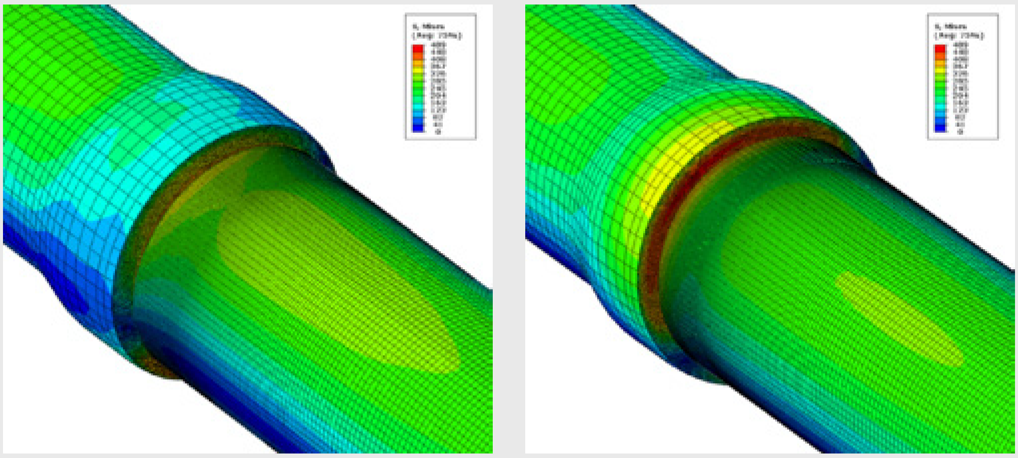

Figure 9*: Tensile allocation [MPa] in the upper (left) and the lower (right) outside surface of a deflected pipe*

mum of about 490 MPa measured in the weld area on the lower pipe surface. The plastic deformation observed there is due to stresses in the weld area that locally exceed the yield strength. The extent of plastic deformation on the upper surface is negligible (***Figure 10***). Maximum strain on the lower weld surface amounts to about 3 %.

The simulation of the combined load produced a tensile allocation that was very similar to the one of the pure bending load, with slightly higher stress levels in the area of the joint (***Figure 11***). Regarding plastic deformation in the weld area, there is also no significant difference to the pure bending load simulation (cf. Figure 10 and ***Figure 12***).

The results show that in the case of combined loads acting on the pipe joint, the highest stresses are to be expected in the weld area. As regards tensile allocation and plastic strain, the contribution of the bending load is substantially greater than of internal pressure.

Laboratory test results

Taking into account the results of FEM simulation, the tests on the bending machine were carried out on pipes of the same dimensions. The pipe length was 5.6 m. The welded joints to be tested were centrally positioned. The bending force was transferred via a half shell adapted to the pipe size and positioned next to the joint weld (cf. Figure 5).

While the FEM simulation was restricted to the service conditions to be expected, the conditions for the laboratory tests were sometimes more severe with a view to determining the limits of the pipe design. Based on the FEM simulation, the behavior of the slip-welding joint and, above all, of the weld itself, is of particular interest. Since the strength of the welding material was given as 380 MPa, this value was also used for the calculations of the load cases under examination, although the strength of the pipe material was substantially higher. According to DIN 2880, a bend radius of 51 m (300 OD), cor-

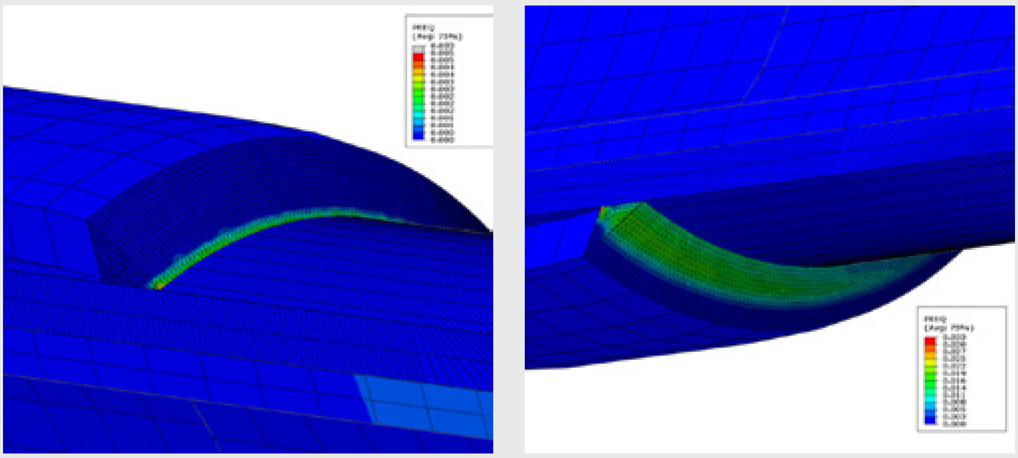

Figure 10*: Plastic strain in the axial pipe cross section on the upper (left) and the lower (right) outside surface during pipe bending (bend radius r = 500 OD)*

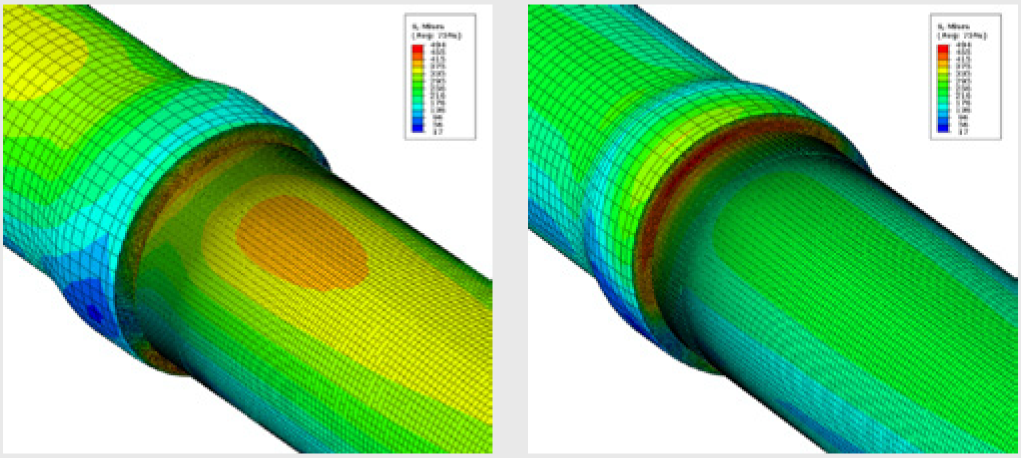

Figure 11*: Tensile allocation [MPa] on the upper (left) and the lower (right) outside surface of a pipe joint under combined load (internal pressure: 200 bar, deflection 500 OD)*

responding to a deflection of 77 mm (pipe length: 5.6 m), is permissible for a material with a strength of 380 MPa. During the first step, this bend radius was combined with an internal pressure of 275 bar. No leakage was detected during the test. The test cycle for this load combination is shown in ***Figure 13***. The results of the FEM simulation revealed that the contribution of the bending force to the forces acting on the slip-welding joint is much greater than that of the internal pressure. In order to determine the actual changes in the joint area, the obvious approach was to subject the pipe and the joint to a significantly higher bending force, until a deflection of 225 mm was achieved. This corresponded to a bend radius of almost 17 m (100 OD).

Figure 14 shows the force-path-time curve up until a bending of R = 100 OD. The transition from elastic to plastic behavior can be clearly seen at a deflection of about 110 mm. This is an interesting result, because the resultant bend radius of 35 m is significantly smaller than 51 m, i.e. the permissible bend radius for a material of the strength assumed for the weld metal. The safety coefficient S = 1.1 provides no explanation, because even without it, a load limit corresponding to a bend radius of 46 m would be obtained. Examination of the joint area after the test revealed that the deformation was highest in the joint itself and not in the weld (***Figure 15***). The cement mortar lining in the joint area was found to be severely damaged.

A subsequent test of the pipe body and the joint showed that the heating of the pipe end during the manufacture of the slip-welding joint had a significant effect on the material's physical properties (***Table 2***). The tensile strength is reduced from 520 MPa, which was measured in the pipe body, to about 460 MPa in the socket area. Since the strength of the weld metal is significantly higher, no failure occurred in the weld area under laboratory conditions.

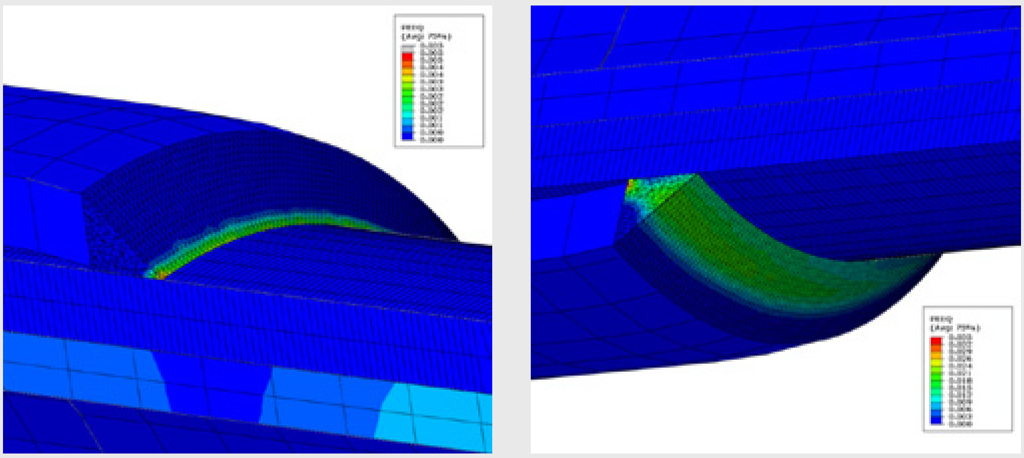

Figure 12*: Plastic strain in the axial cross section of the upper (left) and the lower (right) outside surface of the pipe joint under combined load (internal pressure 200 bar, deflection 500 OD)*

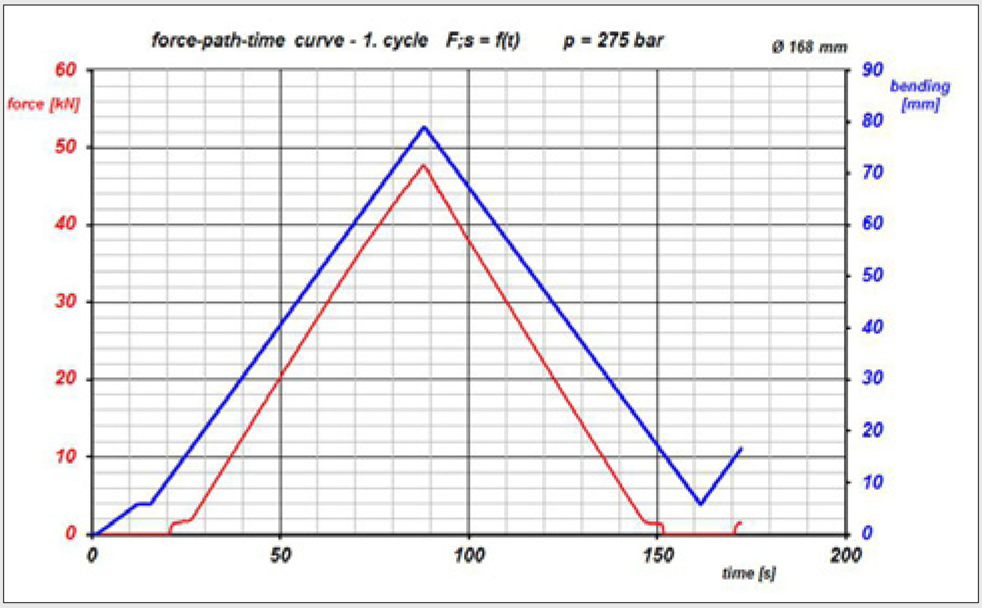

Figure 13: *Force-path-time curve up to a pipe bending of R = 300 OD and internal pressure of 275 bar*

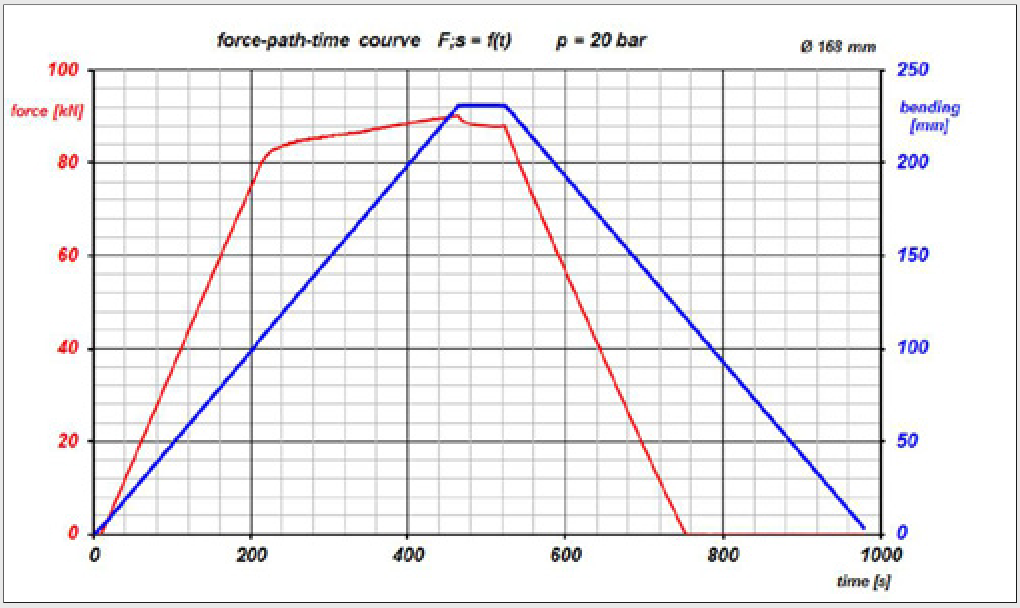

Figure 14: *Force-path-time curve up to a pipe bending of R = 100 OD*

Table 2: *Tensile test results as per DIN EN ISO 6892-1 (socket, pipe)*

Specimen	Size (mm)	L_0(mm)	R_e(MPa)	R_m(MPa)	A (%)	Z (%)	Specimen type	T (°C)	Remark
Pipe	Ø 6.01	30	518/514	591	30	71.7	PML	RT	Y/T = 0.88
Pipe	Ø 6.01	30	520/515	587	28.5	68.0	PML	RT	Y/T = 0.89
Pipe	Ø 6.02	30	540/539	612	26.5	75.2	PML	RT	Y/T = 0.88
socket	Ø 6.01	30	460/456	574	26.5	68.0	PML	RT	Y/T = 0.80
socket	Ø 6.02	30	469/457	574	28.5	70.0	PML	RT	Y/T = 0.82
socket	Ø 6.02	30	465/465	576	28.5	70.0	PML	RT	Y/T = 0.81

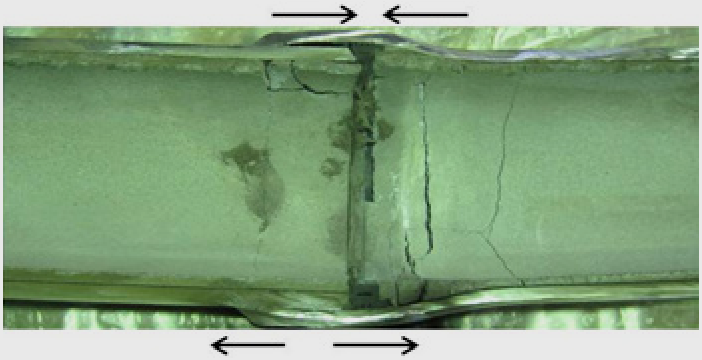

***Figure 15**: Deformation of the slip welding joint after a bending of R = 100 OD*

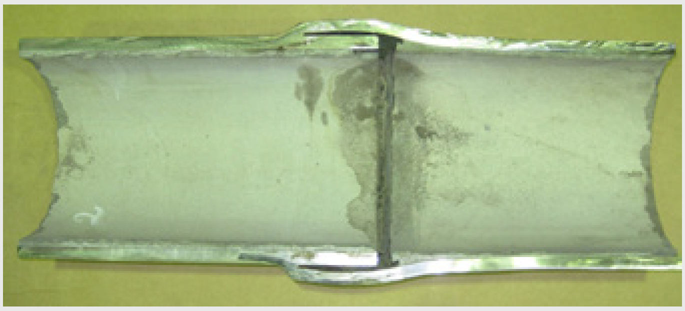

***Figure 16**: Cement mortar lining in the joint area after ten bendings (500 OD)*

A further laboratory test showed that the permissible bend radius of 500 OD has no effect on the cement mortar lining. Based on this rule of thumb, the permissible bend radius is about 84 m, with a deflection of 47 mm. To simulate the dynamic load involved in pipe-laying, the bending process was repeated ten times (***Figure 16***) without any signs of deformation being observed in the area of the joint.

Conclusion

Both the FEM simulation and laboratory results confirmed that the high wall pipes examined are suitable for the intended application under normal pipe-laying conditions for water pipe. No problems have to be expected regarding the weld, because a strength of the welding material is at least equal to that of the pipe material.

The deformation in the joint area observed during the laboratory test could not be anticipated in the FEM simulation, because the tensile strengths of the pipe and the weld material were assumed to be the same, and the effective strength of the weld metal was not known. After adjusting the flow curves in the simulation model, the changes observed can be explained. In this way, predictive statements can be derived for other materials and wall thicknesses subjected to similar load cases.

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