

INTERNAL PRESSURE FATIGUE OF PIPES, PIPELINES AND CYLINDERS

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Abstract

In pipelines and cylinders, pipes are exposed to both static and fatigue loads. In this context, especially internal pressure fatigue is of importance.

Because of the incompressibility of liquid media, significant internal pressure fluctuations have to be taken into account when designing oil and water pipeline systems. While during regular service of high pressure gas transmission lines major fluctuations are not expected, internal pressure fatigue may occur in storage systems like natural gas storage arrays constructed large diameter pipes. Such storage systems are used by local gas distributors in order to compensate for consumption peaks. For the future it is anticipated that also larger sections of gas transmission lines will be used for storage reasons and thereby will be exposed to internal pressure fatigue. Fatigue loads have to be evaluated on the basis of lifetime assessments.

Another future application of gas storage systems is the transportation of natural gas by ship using the compressed / pressurized natural gas technology (CNG / PNG®). In this technology, large diameter UOE pipes are used to construct pressure vessels on ships. The cylinders are exposed to pressure cycles between 25 and 250 bars and, thus, require specific fatigue design.

In the present paper, design conditions for pipes, pipelines and cylinders subjected to internal pressure fatigue will be discussed. National and international standards will be compared to results of internal pressure fatigue tests. Applications and their safety concepts will be introduced.

Introduction

In pipelines pressure, vessels and many engineering structures, pipes are subjected to both static and time-variant loads. Fatigue may occur due to external loads deriving from longitudinal, bending or torsion stresses but may also result from internal pressure fluctuations.

Transport of liquid media, for example oil or water, by means of pipelines may be associated with significant internal pressure cycles due to the quasi-incompressibility of these media. In contrast to this, high pressure gas transmission lines are not subjected to such operating pressure

fluctuations under normal service conditions. Exceptions may be storage systems such as natural gas storage arrays constructed using large diameter pipes. Such systems are used by local gas distributors in order to compensate for consumption peaks. For the future, it is anticipated that larger sections of gas transmission lines will be used for storage reasons as well, thereby being exposed to significant internal pressure fatigue.

An upcoming application of gas storage systems is natural gas transportation by ship using the “Compressed Natural Gas” (CNG) or the “Pressurized Natural Gas” technology (PNG®). Here, large diameter pipes are used to construct pressure vessels, which are accommodated on ships. The total length of pipe per vessel can be equivalent to a pipeline of up to 100 km [1]. The cylinders are subjected to pressure cycles between 25 and 250 bar and therefore require dedicated fatigue design. In order to utilize cost efficient DSAW pipe for such applications, a special pipe was developed with outstanding fatigue properties (Hifa®).

This paper will focus on the comparison and application of design criteria of weld seams in pipes and pipelines. Results from internal pressure fatigue tests will be compared to requirements stated in national and international codes and standards. An extensive test program with regard to fatigue endurance qualification of the Europipe Cargo Tank Cylinders for pressurized natural gas transportation in vessels will be introduced.

Codes of Practice for Fatigue Life Assessment of Pipes

Fatigue strength of pipeline systems may be verified with a number of national and international standards [2-13]. In Germany, commonly the code DIN 2413 [4] had been employed until it was replaced by the European standard EN 13480-3 [9].

Only DIN 2413 and the English standard IGE/TD/1 [5] are specifically dedicated to pipeline systems. For instance, DIN 2413 relies on a large collective of internal pressure fatigue data developed on seamless, ERW and SAW pipes. It is for this reason that the S-N curves depicted in these codes capture pipeline specific geometry and loading conditions.

IGE/TD/1 is valid for high pressure gas transmission lines only. It is based upon a fracture mechanics approach, which, by definition, presupposes the presence of defects, notably within the weld. A maximum defect size is assumed which will not result in a failure during hydraulic pressure testing. This sort of defect is neither allowed to cause leaks nor fracture before a certain number of load cycles has been attained.

The other standards referred to above treat internal pressure fatigue on the basis of weld seam and notch classifications. In these cases, S-N curves are given as a function of weld seam characteristics and load introduction. As an example, the S-N curves according to DNV RP C 203 are given in Figure 1. Longitudinal seams in pipes are assumed to be adequately represented by full seam butt welds of plates. For seamless pipes only longitudinal loads are considered in this standard. Special assumptions have to be made to accommodate internal pressure. Pipe-inherent features such as ovality, variation of wall thickness and weld seam finish are not considered in most cases.

Comparison of Test Results with Specifications

In Figure 2a the results from internal pressure fatigue tests (minimum stress close to zero) for seamless, ERW and SAW pipes are shown, which formed the basis of the S-N curves given in

DIN 2413. Two groups are distinguished - seamless/ERW and SAW pipes - resulting in different S-N curves, which are dependent on tensile strength. The DIN 2413 S-N curves relate to a probability of survival of 90 percent. Figure 2b presents the S-N curves for SAW pipes.

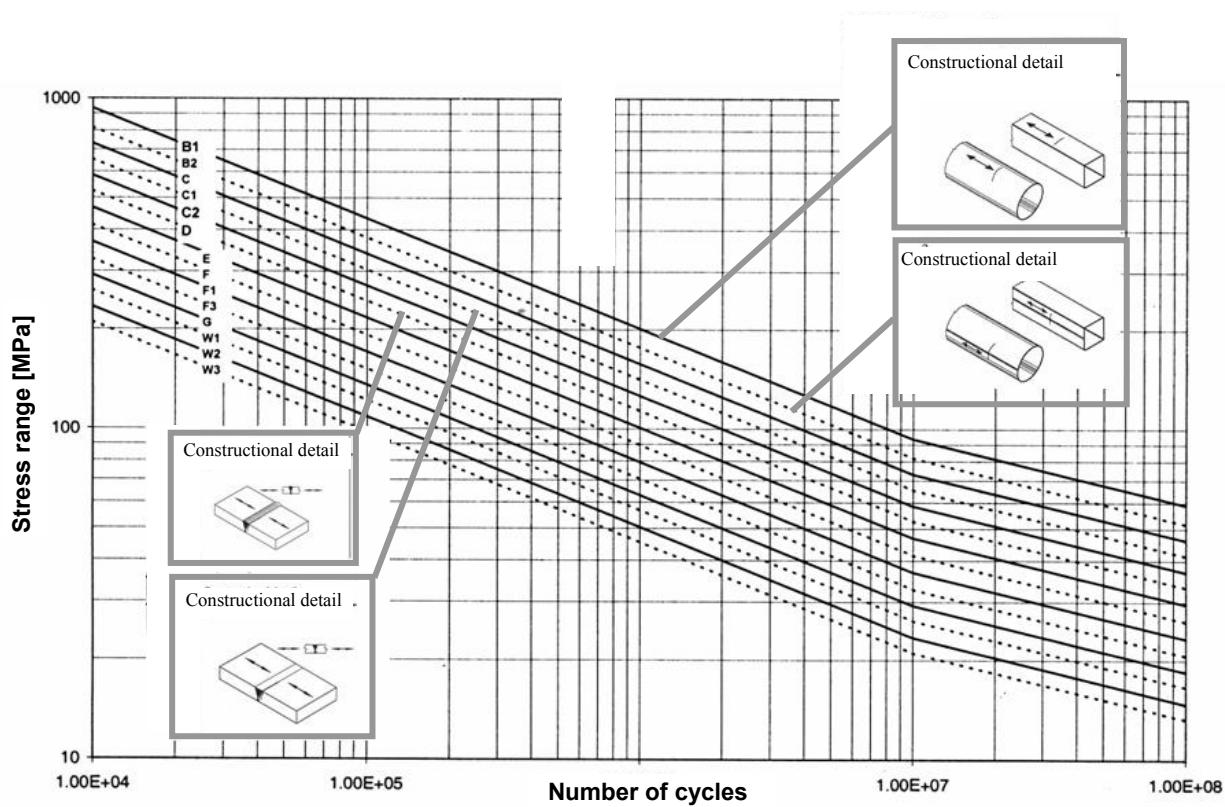


Figure 1. S-N curves and notch classes according to DNV – RP-C203

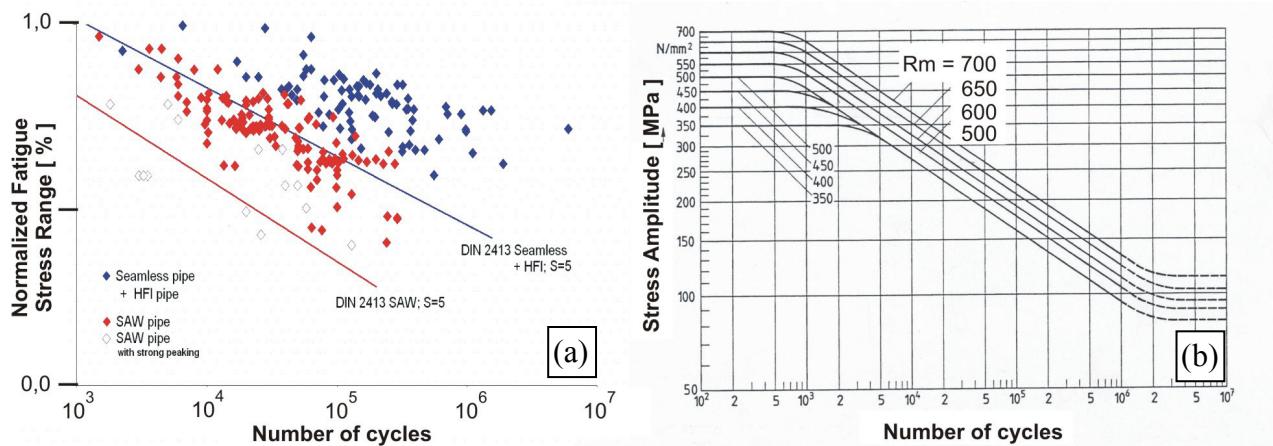


Figure 2. S-N curves according to DIN 2413

In Figure 3, S-N curves for welded pipes are compared. Five standards have been considered, namely DIN 2413, IGE/TD/1/4, EN 13480, IIW, Eurocode 3 and DNV RP-C203. In the case of DIN 2413, an ultimate tensile strength $UTS = 575$ MPa has been assumed. It is seen that the predictions of the standard IGE/TD/1, edition 4.0 are most conservative by far. As opposed to the majority of codes, no additional safety factors have to be considered.

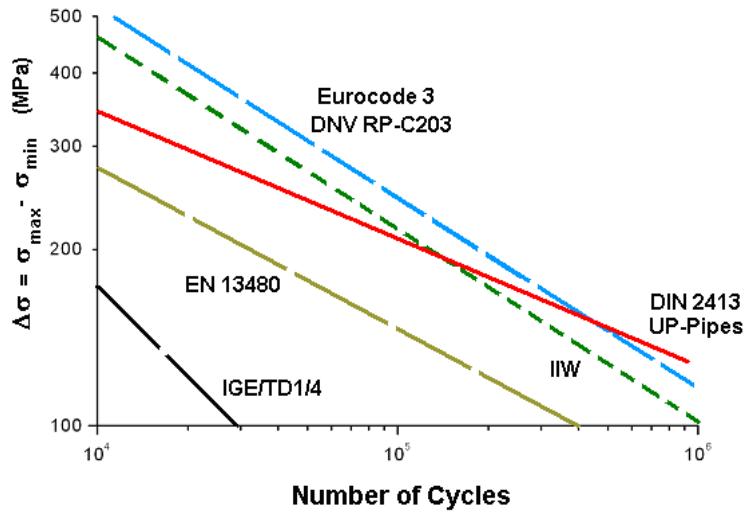


Figure 3. Comparison of S-N curves in different codes (SAW-pipes)

EN 13480-3 associates double-sided welds with notch class K1, leading to an admissible permanent stress amplitude of 63 MPa. It is important to notice that EN 13480-3 deals with admissible stresses. That is to say there is no need to introduce additional safety factors.

IIW groups X-shaped and V-shaped welds either into FAT 100 or FAT 80 (admissible stress range after $2 \cdot 10^6$ load cycles), dependent upon the angle of weld reinforcement. In Figure 3, the S-N curve for X-shaped welds of notch class FAT 80 is represented.

In Eurocode 3, longitudinally welded pipes correlate with notch class FAT 90 and in the case of DNV with class D. For high-cycle fatigue ($N > 1 \cdot 10^6$) the S-N curves of both Eurocode 3 and DNV are in accordance with the one of DIN 2413. In the medium cycle regime, DIN 2413 returns stress amplitudes which are considerably smaller.

For seamless and ERW pipes, the comparison of the referenced design codes leads to similar trends as in the case of SAW pipes (see Figure 4). For high-cycle fatigue, the S-N curve according to EN 13480-3 shows a significantly smaller stress range than that according to DIN 2413. At lower cycles to failure, EN and DIN S-N curves are in accordance.

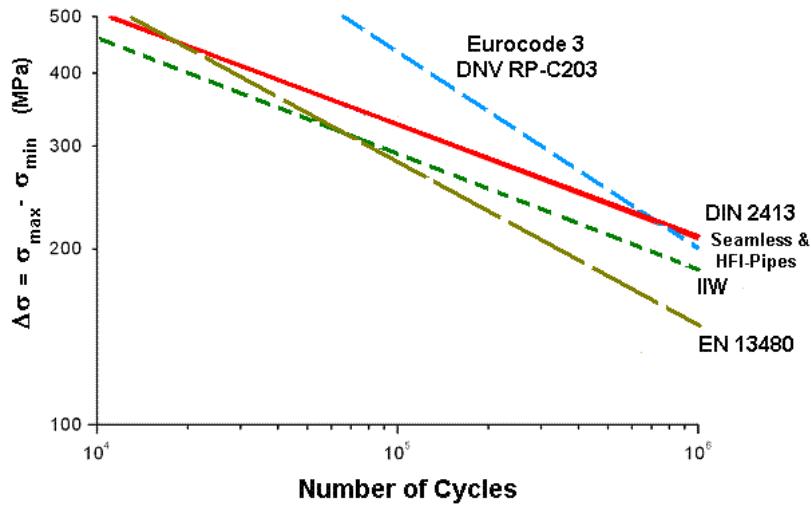


Figure 4. S-N curves according to different codes (seamless pipes)

According to the standard IIW, seamless pipes would have to be grouped into notch class “FAT 160” (endurance fatigue limit = 160 MPa). This approximately corresponds to the recommendation stated in DIN 2413 for a material with UTS = 500 MPa. The slope of the IIW curve in the time-variant branch is very similar to the one of DIN 2413. The EN and IIW S-N curves for ERW pipes allow lower stress ranges than for seamless pipes.

In the case of DNV RP-C203 and Eurocode 3 the S-N curve has a slope, which is significantly steeper than that of the DIN-curve. For assessment of high-cycle fatigue, DNV and Eurocode 3 correspond to the requirements laid down in IIW or DIN 2413. In the medium-cycle regime, application of both Eurocode 3 and DNV RP-C203 leads to significantly higher acceptable stress amplitudes.

Appraisal of Fatigue Concepts

Each individual code handles safety factors differently. For example, the factors may apply for the stress range in one code, while another code changes the number of load cycles. In fact, this is due to different assumptions with respect to the expected type of failure. Therefore, a general comparison and qualitative judgement is not possible. Nevertheless, some general tendencies can be observed.

Only DIN 2413 and IGE/TD1 were specifically developed for design of pipelines and gas transmission lines. The latter one relies on fracture mechanics. It therefore implies a very conservative design philosophy. DIN 2413 takes an exceptional position because it does not deal with notch classes. In addition, DIN 2413 accounts for the ultimate tensile strength of the pipe material.

EN 13480-3 that has replaced DIN 2413 contains extensive information on the design of industrial metallic piping / pipeline systems. However, classification of welded pipes into notch classes is not trivial, and sometimes even not possible. In the case of high-cycle fatigue, allowable stress ranges are predicted too much on the conservative side. Therefore, mechanical capacity of steel pipes is often utilized only in part.

In the regime of high-cycle fatigue, Eurocode 3, IIW and DNV RP-C203 state design requirements, which are generally in compliance with DIN 2413. In the regime of medium-cycle

fatigue Eurocode 3, IIW and DNV RP-C203 represent actual internal pressure fatigue test results non-conservatively.

A large number of tests form the background of the S-N curves given in DIN 2413. In drafting this code, pipes representing a considerable bandwidth of dimensions, steel grades and production processes were considered and internal pressure fatigue tested. Thus, the design requirements are supported by extensive experimental and statistical evidence, notably with respect to pipe-specific material properties and pipeline-typical loading. It would be considered as beneficial and desirable if the succeeding code EN 13480, in a future revision, captured the specific geometrical boundary and loading conditions of pipes as well. Finally, the effect of mean stress on fatigue life is disregarded. Its implementation into the new code is of importance particularly with respect to gas transmission lines with designated storage function.

Properties and application of Hifa® pipes

The internal pressure fatigue properties of DSAW pipe are governed by stress concentration in the area of the longitudinal seam weld. Gas storage systems with significant pressure fluctuations point out the limitations of fatigue properties of pipes with DSAW welds. These limitations can be managed by appropriate selection of the applied load (reduced pressure range or increased wall thickness), or by significant improvement of the internal pressure fatigue behaviour (development of UOE Hifa® pipe).

Challenges

Pipeline Sections and Large Diameter Pipe Arrays for Gas Storage Purposes

Gas consumption is subject to fluctuations. It varies throughout a day, from day to day and in the course of the seasons.

For pipeline operators and gas distributors it is vital to firmly control these daily and seasonal fluctuations, in terms of needed quantities and economics. Especially for pipelines built from high and ultra high strength grades the use of pipeline sections for storage is considered. The resulting operational conditions to be expected are pressure fluctuations with high mean stresses. The pipes that are used have to meet the related fatigue requirements.

Local gas distributors make use of natural gas storage arrays built from large diameter pipes (see Figure 5) to mainly compensate for consumption peaks. In Germany, today these storage arrays are designed according to quasi-static operational conditions by choosing appropriate wall thicknesses and diameters. Therefore, they can be treated as part of the gas pipeline system with the related frequency of inspection. As soon as design leads to a significant fatigue load, the design code that is to be applied will change and the storage arrays have to be treated as special pressure containments with more complex and costlier inspections. Nevertheless, it is considered to extend the volume capacity by utilising larger pressure differences.



Figure 5. DSAW pipes as onshore pipe array

PNG® Cargo Tank Cylinders

The discussion about compressed natural gas (CNG) transportation on vessels becomes more and more intense and a first project may be realized soon. The transportation of gas by the CNG concept closes the gap between offshore gas pipelines and LNG transportation. CNG transportation does not require gas liquefaction plants and low temperature storage tanks. For short and medium distances, the PNG® system offers a most economical and reliable solution [14] for gas transmission between the offshore gas field and the onshore pipeline grid.

Cargo tank cylinders for the different CNG principles are mostly based on the utilization of larger diameter pipes, see Figure 6. In the case of PNG® the containment tanks are installed vertically on the ship. These containments are typically built from two UOE pipes, which are closed by appropriate end caps.

DSAW pipes are the favourite choice because of cost effectiveness, the capability to manufacture heavy wall pipes with larger diameters and the possibility to provide enough production capacities for the number of pipes needed.

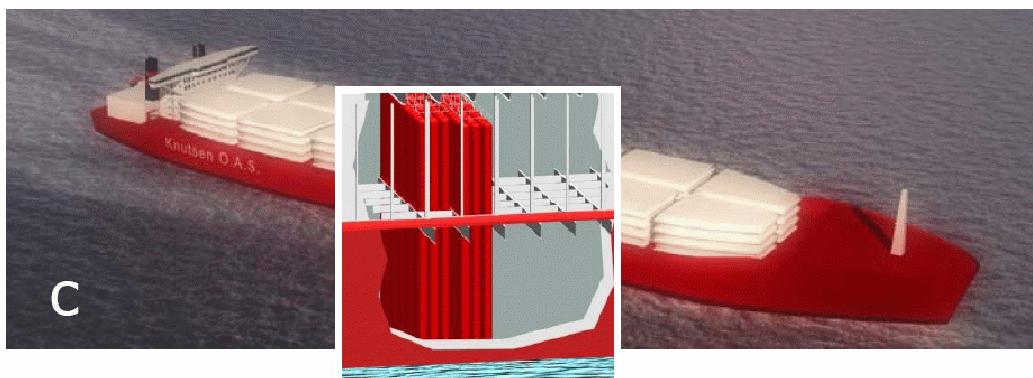


Figure 6. PNG® Cargo Tank Cylinders

Charging/discharging of natural gas from the cargo tank cylinders creates fatigue due to internal pressure variation (25 to 250 bar). Because of internal pressure the main stresses are in the circumferential direction perpendicular to the longitudinal seam weld. Consequently, the longitudinal seam is the most exposed design element of the tank cylinder. The surface quality of

the pipe body is also critical. Gouges, pitting, scale marks etc. work as fatigue crack starters. For girth welds it is most important to create flush transitions from one pipe to another. Stress concentrations due to deviations from the nominal diameter and from ideal roundness have to be minimized. These aspects help to create a stable welding process with flaw free welds. The recently developed DSAW Hifa® pipes are ready to serve these market needs.

Design of Cargo Tank Cylinders according to DNV Rules for Classification of ships

The cargo tank cylinders were designed according to DNV rules for classification of ships . Two different approaches had to be applied, the nominal stress approach and the fracture mechanics approach.

The fracture mechanics approach investigates the reaction of the material to given defects. In the context of fatigue loads two main aspects are commonly investigated. The first one is avoidance of crack initiation. The second aspect is the investigation of how the material reacts to a crack, which has been initiated and starts to propagate.

Depending on the toughness of the material and underlying conditions such as ambient temperature and stress, the assessment provides a critical defect size. This is the maximum size of a defect, which the material is able to withstand without the risk of a spontaneous failure of the component. The intention is to determine the number of cycles from the point at which a defect is just too small to be detected during non-destructive inspection or pressure testing and the point where this defect reaches its critical size. Design life time or inspection intervals have to be shorter than this time and the critical defect size has to be significantly larger than the detectable defect size. Because inspections are cost intensive and might lead to a longer out-of-service time, components are desired which provide long inspection cycles.

The DNV rules for compressed natural gas transportation [15] require full fatigue analysis for cargo tank cylinders, including a fracture mechanics assessment, which serves as proof that after a fatigue crack starts crack propagation will be stable from the point of initiation to three times the design life. This requirement implies a safety margin in addition to the regular fatigue design approach which involves constructing an individual S-N curve for the specific product.

Salzgitter Mannesmann Forschung GmbH (SZMF) and EUROPIPE GmbH developed measures to improve fatigue strength of DSAW pipes significantly, while maintaining the economical competitiveness of the UOE pipe. The tank cylinders went through a comprehensive approval program including fatigue and fracture analysis.

For the approval program three full scale cargo tank cylinders were produced, see Figure 7. The cargo tank cylinders were assembled out of two pipe sections of 3 m each and two hemispherical end caps of the same material and wall thickness as the pipes, produced by Dillinger Hüttenwerke. The pipes were 42" DSAW UOE pipes of Grade 555 according to DNV OS F101 with a wall thickness of 33.5 mm, produced by Europipe GmbH. The pipe sections were manufactured as Hifa® pipe with a special weld seam treatment. For the sake of comparison one test body was produced keeping the long seam intact.



Figure 7. Fatigue full scale Cargo Test Cylinder

Test and Validation Program

The test program comprised small scale, mid-scale and full size component testing. For the fatigue and fracture tests, the design life of the vessel was assumed to be 40 years with one loading cycle per week. This corresponds to about 2000 cycles in a lifetime and together with the requested safety factor of 15, to 30000 cycles, which had to be verified by the tests. The load condition for the full scale tests was pressure cycling from 20 to 250 bar. The pressure of 250 bar stressed the cylinder wall up to 70 percent (385 MPa) of SMYS. As a starting point for the full scale tests, a first pressure loading was carried out up to 325 bar, simulating the initial hydro test for the finally installed containment system.

In detail, one combined full scale fatigue - burst test and two full scale fatigue tests on containments built from Hifa® pipes had to be carried out reaching 30000 cycles . One fatigue test was carried out on a test body made from conventional UOE pipes. The cylinders were pressurized with inhibited water to the pressure levels specified above. The test frequency was at 90s per cycle, the test was executed in a burst pit at ambient temperature. Failure was monitored by a drop in the fluid level due to leakage that occurred after a through-wall crack had developed. In the combined test, the test body burst after having been exposed to 4000 cycles – which is two times the design life – and the vessel was expected to show the full burst capacity of an undamaged containment

Small sample fatigue testing was carried out on flattened strip specimens containing the weld seam (Figure 8). The requirement for the statistical testing included a safety factor of ten leading to 20000 cycles as a minimum number of mean- minus- three standard deviation. In carrying out and interpreting the results of these tests, it has to be considered that the flattening of the specimens resulted in plastic deformation of the weld area.



Figure 8. Strip sample testing

Therefore, as a third type of fatigue testing (mid-scale), pipe rings - 150 mm in length - were exposed to internal pressure fluctuations. The testing scheme is demonstrated in Figure 9.

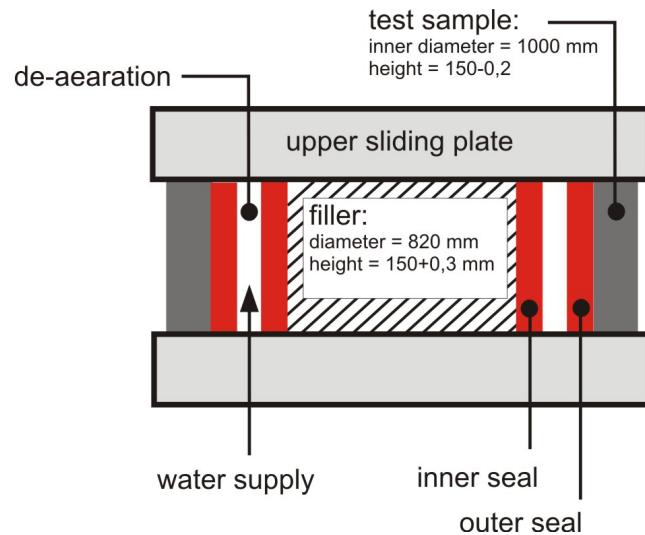


Figure 9. Fatigue tester for ring samples

This test was assumed to be more advantageous compared to small-scale testing because no plastic deformation was induced in the weld area. Because of higher test frequencies and lower costs, this test device is seen as being competitive to full-scale testing as a result of the firm representation of full-scale loading.

Together with the full-scale fatigue tests, the small-scale sample and the ring tests were used in order to create statistical back up of the individual S-N curve for the special product and associated production method. Evidence was to be given on the improvement of lifetime for the specially treated long seam weld with respect to the DNV Rules for CNG carriers.

Finally, a fracture mechanics assessment had to be carried out in order to show that crack propagation does not lead to failure until three times the lifetime (6000 cycles) has been reached.

Full Scale Test Results

The cylinder constructed from conventional pipe failed after 12000 cycles by fatigue cracking in the longitudinal weld. After the body was opened dye-penetration inspection exposed indications over the entire length of the seam. Fatigue cracks propagated 50-80 percent through the wall thickness and at the point of leakage completely through the wall. This test result is very much in line with lifetime predictions according to [4] and [9].

Both Hifa® pipes had a failure in the girth weld before reaching 30000 cycles and had to be repaired (Figure 8). Initial defects in the girth welds had been detected by non-destructive examination before testing but, intentionally, were not repaired - although beyond the allowable defect sizes - in order to support an engineering critical assessment (ECA) of the critical defect size for the PNG® application.

After repair of the girth weld defect, test body No. 1 was a run-out at about 31000 cycles. After the test was completed, the longitudinal weld was inspected with dye-penetration testing and there were no signs of crack initiation along the weld. The second cylinder failed after 41000 cycles (Figure 10) due to corrosion in the centre of the longitudinal weld. The corrosion resulted from the repair welding procedure after the girth weld failure, which left a considerable amount of corrosion on the surfaces. The failure is therefore considered not to be characteristic for a non-corrosive test.



Figure 10. Fatigue failure at corrosion pitting in long seam

The parts of the weld not being involved in the above mentioned failure were exposed to dye-penetration inspection and exhibited no signs of crack initiation. Thereby, this test result can again be seen as a lower bound or run-out.

All failures occurred due to defects, which were expected not to be present during the use as PNG® tank cylinders for dry gas transportation. However, the tests demonstrated a lifetime capacity of at least 15 to 20 times the design life of 40 years for the PNG® vessels.

Comparison of Test Results with S-N curves from relevant standards

In Figure 11 the S-N curves taken from different codes are outlined and plotted together with the results of the strip sample testing referred to above. Based on the strip samples, which provide lower bound values, the lifetime of a Hifa® pipe is higher by a factor of 2 to 3 as compared to a conventional pipe. The mean value of Hifa® strip samples is in the same range as the DNV C203 C1-ground flush-curve and the line for seamless pipes according to EN 13480. The large scatter band of the strip sample results might be an indication of the influence of the flattening process and results in a considerable standard deviation. Although taking this into account, the final result from strip sample testing meets the “average-minus-three standard deviations” criterion put forward in the DNV specifications for CNG carriers.

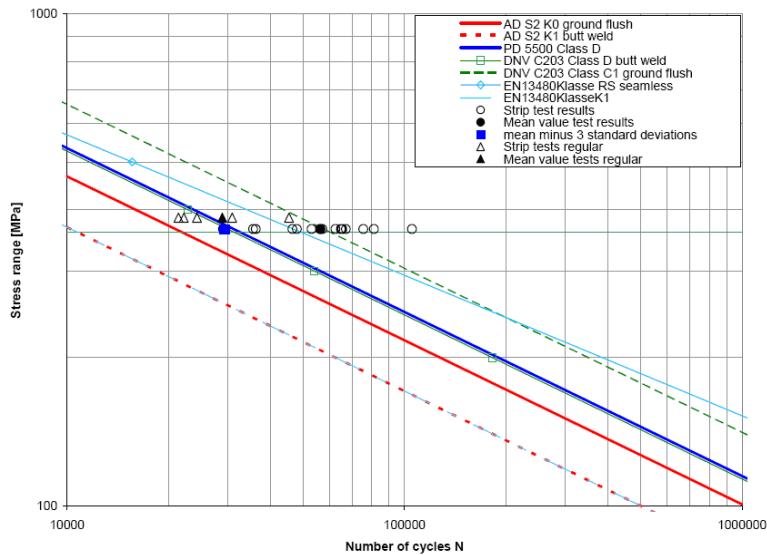


Figure 11. S-N Curve strip sample fatigue tests

The results from the ring tests are expected to be more representative of the full-scale test as compared with strip sample tests. Figure 12 shows the results from the three full-scale tests and the results from the ring tests.

The full-scale test result with the conventional DSAW pipe is very much in line with the curve provided by DIN 2413 for SAW pipes with conventional welds, whereas the ring tests are in the range of the curve for ERW / seamless pipes. Some test results are run-outs that are still in the crack initiation phase.

For fatigue testing on girth welds it was shown in [16-18] that small-scale strip specimens tend to give a non-conservative lifetime estimation in comparison to full-scale test results. This is attributed to statistical size effects in the sense that a greater length of weld in the full-scale specimen will have a greater probability of regions of high stress concentration. In this investiga-

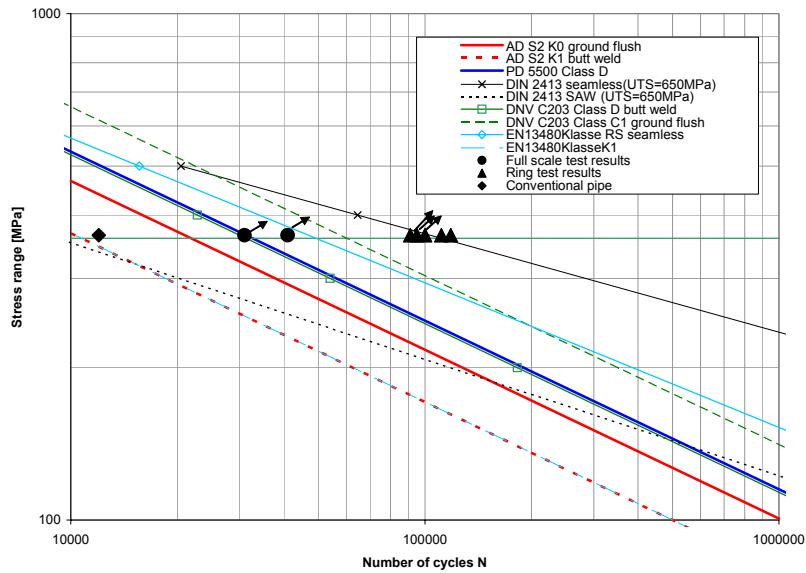


Figure 12. S-N Curve short ring and full scale

tion, the opposite was seen, that is the mid- and full-scale tests resulted in a higher fatigue life than the strip tests. The statistical size effect cannot contribute towards an answer as it is similar for both types of tests. One difference lies in the specimen preparation where plastic deformation is introduced in the case of the longitudinal weld. This is assumed to affect the fatigue resistance of the specimens. Moreover, the transition radius is slightly changed by the flattening process resulting in a possibly higher stress concentration.

The two Hifa® pipe samples passed the approval limits for PNG®. The lifetime of these pipes was not finally determined but can be expected to be in the range of the lifetime of seamless pipes. The cylinder will most likely fail due to an imperfection in a localised area either in the girth weld or somewhere in the pipe body. The long seam is not the critical element anymore. In each case failure will occur in cycle times much longer than required by applicable codes.

Conclusions

The lifetime of components exposed to fatigue loading can be determined on the basis of a variety of international and national codes. The majority of codes provide fatigue classifications on the basis of stress concentration factors and, generally, do not cover all loading aspects of pipes, pipelines and cylinders subjected to internal pressure fluctuations. The transfer of S-N curves generated for welds using flattened strips, and the need of assumptions for loading situations which are not covered in the code lead - especially in the case of the medium cycle regime - to non-realistic fatigue life assumptions. It would be considered beneficial and desirable if codes like EN 13480 or DNV RP-C203, in a future revision, captured more appropriately the specific geometrical boundary and loading conditions of pipes under internal pressure fatigue as well.

The DSAW manufacturing process, and the UOE method in particular, offers a competitive, high volume capacity production option for pipes with larger diameters and wall thickness. In principle, due to the tight geometric tolerances and the excellent surface quality, DSAW pipes should provide advanced fatigue behaviour. Nevertheless, the stress concentration in the area of the long seam provides significant limitations in their fatigue strength. For the Knutsen PNG®

carriers a special treatment for the long seam of the DSAW pipe was developed and tested. This treatment raises the fatigue life of DSAW pipes into the range of seamless pipes while maintaining the high productivity of the DSAW fabrication process. Different tests with a higher number of samples were performed to simulate the long seam under internal pressure.

The difference in the load profile between small-sample testing and full-scale testing has to be considered. A correct interpretation of the small-sample test results provides statistical evidence to the expensive full-scale tests and supports the final conclusion about the real lifetime of a tank cylinder. The short ring test creates results, which correlate much better with full-scale tests of pipes under internal pressure compared with strip samples.

A DSAW pipe with the specially treated long seam reached a lifetime in the range for seamless pipe. For internal pressure fatigue the long seam of the DSAW pipes is not a critical design element anymore. It is for this reason that DSAW pipes are ready for advanced gas storage arrays and pipeline sections used for intermediate gas storage.

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