Longitudinal welded pipes with enhanced fatigue strength (Hifa ® pipe)

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The transportation and storage of fluids in pipes can lead to cyclic loading due to fluctuating internal pressure which exceeds the normal pipeline operation range. In this special case, the design of the pipe is based on the fatigue strength rather than on the static strength.

Normally a welded structure has a reduced fatigue resistance compared to a none-welded component. Europipe and SZMF have developed the Hifa® pipe with enhanced fatigue strength to allow for a design with a higher stress range or a larger number of cycles.

The fatigue strength of pipes is generally governed by the strength, geometry and the surface condition. Whereas the surface quality and the geometry of the pipe body of longitudinally welded pipes are favourable for the fatigue loading, the fatigue strength of longitudinal welded pipes is normally limited by the stress concentration that is induced by the geometry of the weld.

It is well established that a suitable treatment of welds may enhance the fatigue strength of welded structures, however the effect on longitudinal welded pipes has not been investigated until now. Therefore, a limited-lot production of Hifa® pipes, patent published, has been manufactured to carry out a detailed investigation of the fatigue resistance including full scale fatigue tests.

KEY WORDS: longitudinal welded pipes, enhanced fatigue strength, fatigue tests, fluctuating internal pressure

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Introduction

In cases where fluids are stored in pipes the design has to be based on the fatigue rather than the static properties because the internal pressure changes in the course of the time. If the stress ranges are relatively high, welded pipes cannot withstand the loads due to the stress concentration adjacent to the weld. Up to now, other solutions have to be sought to solve the problem.

In recent times there had been increasing demand for economical or technical reasons to use longitudinal welded pipes as storage units. Examples are the storage of gas within pipeline systems or the transport of compressed natural gas on ships. In both cases, there is a fluctuating internal pressure caused by charging and discharging. The loads which occur can be so high that a conventional welded pipe cannot comply with the requirements.

The fatigue strength of a pipe is dependant on the surface quality, the geometry in terms of ovality or out-of-roundness and the stress concentration induced by welds. It is clear that the fatigue resistance of a welded pipe is lower than of a seamless pipe due to the stress concentration in the transition region, whereas in other senses the welded pipe is more favourable. The advantages can be utilised if the stress concentration is sufficiently reduced.

Following the market demands, Europipe in collaboration with SZMF developed a pipe that can meet enhanced fatigue requirements. An important issue was then to verify the fatigue resistance and to review the currently available standards regarding their applicability to the product. Both the standard review and the test program are based upon one case study of high fatigue loads imposed on pipes storing compressed gas.

In the first part of this paper, the standards for pipelines and pressure vessels will be reviewed with a focus on the allowable number of cycles for the case study. The second part of the paper is addicted to the test program that was executed. Due to the fact that full scale tests can be expensive and time consuming, suitable small scale testing methods have been sought for. The test program consists of full scale and small scale tests.

Relevant standards for the design against fatigue

Basically there are two different approaches for fatigue analyses, the nominal stress approach and the fracture mechanics approach. The standards available for the design against fatigue can be classed into these categories.
• Codes and standards based on welded joint classes (nominal or structural stress approach)

In general, this type of standards is based on fatigue tests of different welded joint details. In the DNV standard RP – C203 [1], a standard for offshore steel structures, plated structures, tubular joints and fillet welds are directly addressed. The structures are divided into detail categories according to their constructional detail; an example is provided in Figure 1. Hollow sections, in this case both non-welded and automatically seam welded sections, are only addressed in terms of longitudinal loads, a typical load for an offshore structure but not so for a pipe subjected to fluctuating internal pressure. The transverse butt weld, welded from both sides, is classed in category D, the corresponding S-N curve in air is presented in Figure 2.

Other examples for this type of standards are EN 13480 [2] for the design of industrial piping and AD Merkblatt S2 [3] for the design of pressure vessels.

• Standard based on fatigue tests of pipes (nominal stress approach)

The only commonly used standard in this group is DIN 2413 [4], a German standard based on S-N curves of pipe fatigue tests. As such, it represents a special case within the former concept because it is focussed only on pipes subjected to fluctuating internal pressure. The S-N curves represent the lower bound curve of tests on pipes produced until 1972. The influence of the weld, surface conditions and shape deviations within the limits of production tolerance are included in the tests results.

The pipes are classed in two different categories according to their manufacturing process:

♦ SAW pipes
♦ Seamless pipes and ERW pipes

It is worthwhile to note in this context that ERW pipes, although they are welded pipes, are combined with the seamless pipes.

The S-N curves are shown in Figure 3 and Figure 4, respectively. The fatigue strength of a seamless pipe is in the range of 10 times higher than the strength of a SAW pipe.

• Codes and standards based on fracture mechanics

There are several standards (e.g. DNV RP-C203) that allow for a fatigue analysis according to fracture mechanics approaches, but it is most commonly seen as a supplement to the use of S-N curves. The purpose in this case is to document that a fatigue crack, which might occur during service life, will not exceed the crack size corresponding to unstable fracture. This adds a margin of safety to the fatigue analysis.

On the contrary, IGE/TD/1 [5], a code for high pressure gas transmission pipelines, contains an S-N curve noticeably lower than the ones discussed before (Figure 5).
This is justified by the fact that every structure is thought to contain defects, and it has to be ensured that any defect that survived the hydrostatic test does not grow to a critical crack size under the influence of internal pressure cycling. Therefore, the prerequisite to utilise the S-N curve provided within the paper is the execution of a hydrostatic test as it is specified within the chapter for testing requirements. The highest stress range according to [5] for a pipe subjected to internal pressure fatigue is 165 MPa, for any higher stress range a detailed fracture mechanics analysis is mandatory.

- **Design example and corresponding fatigue analysis**

The fatigue analysis is based on the design pressure of a cargo tank containing compressed natural gas, the details are listed in Table 1. The hoop stress is calculated utilising the Barlow formula:

\[
\sigma_h = \frac{P_d m}{2t} \quad (1)
\]

Within the codes and standards, the main procedure after the stress evaluation is an estimation of the allowable number of cycles that are provided within the SN curves. A fatigue analysis according to DIN 2413 leads to a lifetime of 9000 cycles for an SAW pipe, whereas a seamless pipe can be exposed to 100000 cycles (Table 2). No reference is made to a fabricated SAW pipe. According to EN 13480, for a longitudinal double sided weld 11000 cycles are applicable, 70000 for a seamless structure with an as rolled surface. These figures demonstrate that, regardless of the applied standard, there is a great advantage for the non welded components which is in the order of the factor 7-10. The figures also show that there is a rather large difference between the individual S-N curves. According to IGE/TD/1, the pipes could not be exposed to this pressure range without a detailed fracture mechanics analysis which would lead to a significantly lower number of cycles.

**Pipe production**

To meet the challenge of high fatigue loads with longitudinally welded pipes, Europipe in collaboration with SZMF developed a pipe which can meet these enhanced requirements. Measures were taken to reduce the stress concentration factor of the longitudinal weld, in combination with an aggravated surface inspection, a pronounced effect on the fatigue resistance can be expected. This type of pipes will be produced under the trade mark Hifa® pipe.

The first limited-lot production was manufactured in 2002. The pipes were of API 5L Grade X80, the dimensions were 42" OD x 33,5 mm WT. In addition to the standard test program, i.e. tensile and Charpy V notch tests to characterise the base material, an extensive fatigue test series was executed including small scale and full scale tests. Details are presented in the following chapter.
Testing methods and correlation

One of the major issues of the fatigue testing program was to produce results on a sound statistical basis. This can be achieved in a cost-effective and time-saving manner by conducting a series of small scale tests which should then be verified by a reduced number of full scale test.

This procedure is used by [6] - [8] in the fatigue analysis of girth welds on seamless pipes for offshore applications. In the case of girth welds, the specimen extraction is rather simple in the sense that it is similar to a tensile strip test in longitudinal orientation with the girth weld crossing the middle of the specimen (Figure 6a).

Difficulties are to be expected when applying the above-named procedure to longitudinal seam welds. The specimens cannot be exposed to axial loading after sampling because of the pipe curvature, instead they have to be flattened prior to testing. This process introduces plastic deformation to the weld area. As there is no experience with this procedure it is difficult to estimate the impact of the resulting effects.

It was shown in [6] - [8] that small scale specimens tend to give a non-conservative lifetime estimation in comparison to full scale test results. This is thought to be a statistical size effect in the sense that a greater length of weld in the full scale specimen will have a greater probability of encountering regions of high stress concentration. Therefore, a correlation of small scale and full scale test results has to be defined for the assessment. [6] and [7] also attribute the longer life of the strip specimens to a relaxation of residual stresses but they suggested further investigations to clarify this point.

A more direct approach towards the fatigue analysis of longitudinal seam welds is fatigue testing of pipe sections, the ring fatigue test. Ring fatigue testing is a mid-scale test that permits the analysis of the complete pipe circumference, therefore the correlation between ring and full scale tests should be good. As regards the residual stress relaxation and the statistical size effects, the ring expansion test seems to be advantageous because the test specimen is bigger in size than the strip specimens.

Testing program

The specimens’ extraction, set-up and execution of each test will be described within the following chapters.

Small scale tests on strip specimens extracted from the longitudinal weld

The strip specimens were extracted from the longitudinal weld of the pipe, the dimensions are given in Figure 6b. The strips were then flattened to allow for axial testing and machined to the actual dimensions subsequently to minimise the misalignment (Figure 7a). 6 specimens were fabricated from a conventional longitudinal weld and a total number of 16 specimens were extracted from the two Hifa® pipes selected for the full scale tests.
The strip specimens were fatigue tested axially under load control. They were cycled at the stress level specified in Table 1, the resulting stress ratio R was 0.08. The tests were performed in a servo-hydraulic testing machine at a frequency of 5 Hz (Figure 7b). The specimens were tested to complete failure.

The results of the strip tests are presented in Figure 8. In all cases, the fracture initiated in the weld area at one corner of the specimen. The comparison of the mean value of tests on regular and optimised welds indicate an increase in lifetime in the order of factor 2.

Ring fatigue tests

The specimens were fabricated by cutting rings from a pipe, the height of the rings was 150 mm. The test was designed such that the ring experiences radial expansion only, and no axial loading. This is achieved by applying axial forces only to the seals and not directly to the ring specimen. The set-up for the ring fatigue test is shown in Figure 9.

The rings were pressurised with inhibited water to the pressure levels specified in Table 1. Fatigue failure is expected to correspond to the achievement of through thickness cracking. Ring fatigue tests have been started recently, the first test is at present a run-out at 100000 cycles.

Full scale tests

Full scale tests were conducted with 2 Hifa® pipes and 1 conventional pipe for the sake of comparison. Each test body consisted of two pipe lengths of 3m each welded together by GMAW girth welds and two cylindrical end caps. Thereby, the test cylinder had a total length of 7m.

The test set up is shown in Figure 10. Each test cylinder was pressurised with inhibited water to the pressure levels specified before. 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 the leakage that occurred after a through wall crack had developed.

The conventional pipe failed after 12000 cycles by a fatigue crack in the longitudinal weld. Both Hifa® pipes had a failure in the girth weld that had to be repaired. Following these failures, 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 due to corrosion in the centre of the longitudinal weld after 41000 cycles (Figure 11). 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. 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.
Discussion of the test results

Comparison of regular and Hifa pipe fatigue resistance

In both small scale and full scale tests, there was a clear indication of the increase in the fatigue resistance of the Hifa® pipes. The comparison of the test results will be introduced separately for each testing method, the correlation of the small scale and full scale test results is discussed in the next section.

The strip tests showed that the mean value of Hifa® pipes fatigue limit is about 2-3 times higher than that of the conventional pipes. In both cases, the scatter is comparable, therefore the mean-minus-2 standard deviation values are also parted by the factor of 2. This number may be regarded as the minimum raise in lifetime that can be expected from the Hifa® pipe considering the uncertainties that are entailed by the testing procedure as the result of the more realistic ring fatigue test (>100000 cycles) confirms.

As the full scale tests did not exhibit signs of crack initiation after 40000 cycles and the crack propagation life can be estimated to around 10000 cycles, the total life results in at least 50000 cycles. At the same load level, the regular pipe failed after 12000 cycles.

Comparison of small scale and full scale test results

As mentioned above, the correlation of strip or plate samples and pipe specimens has been investigated for girth welds. In these cases it was always demonstrated that results for the strip specimens tend to be higher than the corresponding results for pipe specimens. The authors attributed this to the statistical size effect and the residual stresses within the welds.

In this investigation, the opposite results were obtained, i.e. the mid- and full scale tests resulted in a higher 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 may effect 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 test results lead to the conclusion that strip specimens sampled from the longitudinal weld may not be in all details representative of full scale specimens but they lead to conservative life predictions and may be used to estimate the lower bound of the actual life time.

Ring fatigue test can be considered a better choice to substitute full scale tests because they expose the complete and undeformed pipe circumference to fatigue loads.
Comparison of small scale and full scale test results to S-N curves in relevant standards

The strip test results are compared to S-N curves for butt welds as well as S-N curves for flush ground welds. Figure 12 presents a diagram comprising applicable S-N curves and the actual test results in terms of single and mean values as well as the mean-minus-two standard deviation value. Most of the fatigue resistance curves in standards represent the values of test results, typically the mean-minus-2 standard deviation value. Nevertheless these curves exhibit a considerable scatterband. The test results of the regular pipes are above the resistance curves for double sided butt welds with the exception of the DNV curve, which predicts a larger number of cycles at the same stress range than the other standards. The mean value of the Hifa test results is above the curves for flush ground welds but due to the large scatter attributed to the sampling procedure, the mean-minus-2 standard deviation value falls below most of the curves.

The ring and full scale test results are depicted in Figure 13 alongside the S-N curves. It should be noted that DIN 2413 is included in this graph as it was derived from pipe fatigue tests whereas the other codes are based upon strip tests. All test results available are run-outs that are still in the crack initiation phase. In comparison to DIN 2413, the number of cycles of the full scale tests is just in between the resistance curve of an SAW and a seamless or HFI pipe, whereas the ongoing ring test is in the range of the latter curve.

Summary

Following an increasing demand for longitudinal welded pipes with enhanced fatigue resistance properties, Europipe and SZMF developed such a pipe that will be produced under the trademark Hifa® pipe in future.

A test program was conducted to verify the properties of the product and to assess the results on basis of existing fatigue resistance curves within codes and standards. A major objective of the test program was to carry out accompanying small scale tests to establish an adequate statistical basis.

Fatigue tests were conducted on regular pipes for a reference and on Hifa® pipes. In detail, the program comprised strip tests, ring fatigue tests and full scale internal pressure fatigue tests.

The full scale tests did not lead to a fatigue failure in the modified longitudinal weld but were stopped at 31000 and 41000 cycles, respectively. At that stage, there were no signs of crack initiation along the weld. On the other hand, the regular pipe failed after 12000 cycles at the same load level.

Strip tests were executed on a total number of 6 conventional and 16 Hifa® specimens. The results indicate a raise in lifetime in the order of 3. This number may be regarded as the minimum raise in lifetime that can be expected from the Hifa® pipe considering the uncertainties that are entailed by the sampling procedure.
Ring fatigue tests permit the exposure of the complete and undeformed pipe circumference to the internal pressure loads and have therefore been conducted in addition to the strip tests. The tests are still ongoing, the first ring is a run-out at 100000 cycles.

In comparison to standards for the design of pipes exposed to internal pressure fatigue, the results of the Hifa® pipes are as good as or better than the S-N curves for flush ground welds which are the only curves for welds that were fabricated in any way to enhance the fatigue resistance. In DIN 2413, a code for pipes subjected to internal pressure fatigue, there is an S-N curve for seamless and HFI pipes, i.e. pipes without a stress concentration induced by the longitudinal weld, which is touched by the first ring fatigue test result. The verification by a larger number of tests must be awaited before a final conclusion can be drawn.

REFERENCES

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<th>Internal pressure [bar]</th>
<th>Hoop stress [MPa]</th>
<th>Usage factor %SMYS</th>
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<tr>
<td>Upper pressure level</td>
<td>250</td>
<td>385</td>
<td>70</td>
</tr>
<tr>
<td>Lower pressure level</td>
<td>20</td>
<td>31</td>
<td>5.6</td>
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**Table 1:** Test details

<table>
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<tr>
<th></th>
<th>Number of cycles SAW pipe</th>
<th>Number of cycles seamless</th>
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</thead>
<tbody>
<tr>
<td>DIN 2413</td>
<td>9000</td>
<td>100000</td>
</tr>
<tr>
<td>Double sided butt welds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN 13480</td>
<td>11000</td>
<td>70000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of cycles Fabricated welds Double sided butt welds Double sided butt welds</td>
<td>35000</td>
<td>70000</td>
</tr>
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</table>

**Table 2:** Example of a fatigue analysis
### Table 2.12-1 Classification of welds in pipelines

<table>
<thead>
<tr>
<th>Description</th>
<th>Tolerance requirement</th>
<th>S-N curve</th>
<th>Thickness exponent k</th>
<th>SCF</th>
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</thead>
<tbody>
<tr>
<td>Single side</td>
<td>$\delta \leq \min (0.1t, 3 \text{ mm})$</td>
<td>F1</td>
<td>0.00</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>$\delta \leq \min (0.1t, 3 \text{ mm})$</td>
<td>F3</td>
<td>0.00</td>
<td>1.0</td>
</tr>
<tr>
<td>Single side on backing</td>
<td>$\delta \leq \min (0.1t, 2 \text{ mm})$</td>
<td>F</td>
<td>0.00</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>$\delta \leq \min (0.1t, 2 \text{ mm})$</td>
<td>F1</td>
<td>0.00</td>
<td>1.0</td>
</tr>
<tr>
<td>Single side</td>
<td>$\delta \leq \min (0.15t, 4 \text{ mm})$</td>
<td>D</td>
<td>0.15</td>
<td>Eq. (2.12.1)</td>
</tr>
<tr>
<td>Double side</td>
<td>$\delta \leq \min (0.15t, 4 \text{ mm})$</td>
<td>D</td>
<td>0.15</td>
<td>Eq (2.12.1)</td>
</tr>
</tbody>
</table>

**Figure 1:** Constructional details of welded members according to DNV RP-C 203 [1]
Figure 2:  S-N curves according to DNV RP-C203, "SN curves in air" [1]

Figure 3:  S-N curves for seamless and ERW pipes (OD > 114.3 mm) according to DIN 2413 [4]
Figure 4: S-N curve for SAW pipes according to DIN 2413 [4]

Figure 5: Relationship between stress range and number of cycles according to IGE/ TD/1 [5]
Figure 6: Sampling of girth weld (a) and longitudinal weld (b) strip specimens

Figure 7: Fabrication and testing of strip specimens
**Figure 8:** Fatigue test results obtained from strip specimen

![Fatigue test results](image)

**Figure 9:** Schematic representation of a ring fatigue testing device

![Schematic representation](image)
Figure 10: Schematic representation of the fatigue test set-up

Figure 11: Failure of the longitudinal weld in test no.2
Figure 12: Comparison of strip test results and S-N curves in standards

Figure 13: Comparison of ring and full scale test results and S-N curves in standards