Full-scale Fatigue and Burst Tests on Notched Pipeline Girth Welds, under Complex Loading Conditions

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Abstract: Hydrocarbon transporting pipelines contain a large number of girth welds, which are made under field conditions. The construction and the long-term operation often result in additional stresses to the internal pressure in these girth welds. The experience of the damage that has occurred and the requirement for safe operation necessitate full-scale tests to model and analyze these effects. The article presents a test system developed to investigate full-scale pipeline sections subjected to cyclic internal pressure and static external bending. The results obtained from tests of girth welds, with artificial circumferential and axial notches, are described herein. The results are used to draw conclusions on the load bearing capacity and integrity of the girth welds.

Keywords: transporting pipeline; full-scale test; complex loading; cyclic pressure; static bending; safety factor

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1 Introduction

Hydrocarbon transport pipelines have a strategic importance within a country, but also between countries and nowadays even between larger geographical entities. The failures of these pipelines, for whatever reason, usually causes longer or shorter disruptions to the energy balance of a geographical unit. The direct consequence of this is that different levels of laws and standards of varying scope apply to all stages of the life-cycle of the pipelines [1-5].

Transporting pipelines are typically made up of 12-18 m long pipe strands and are joined by welding, in case of both seamless and longitudinally welded. A pipeline several hundred kilometers long will therefore have thousands of such girth welds, typically made by welding on site. The logical consequence of this is that different standards apply to the welding tasks and the assessment of the completed circumferential welds, too [6] [7].

A statistical-like study [8] summarizes the reportable incidents of a 6.5-year research process. Figure 1 shows the cause distribution of all incidents (621 items), of not weld defects (571 items) and of weld defects (50 items). Because we do not have reason to assume that welds have a more favorable position from the point of view of corrosion and external force than the other pipeline parts, it can be stated that welds are the more damageable parts. However, the construction defects and material discontinuities occur in a much higher ratio in welds than in the other parts of the pipelines.

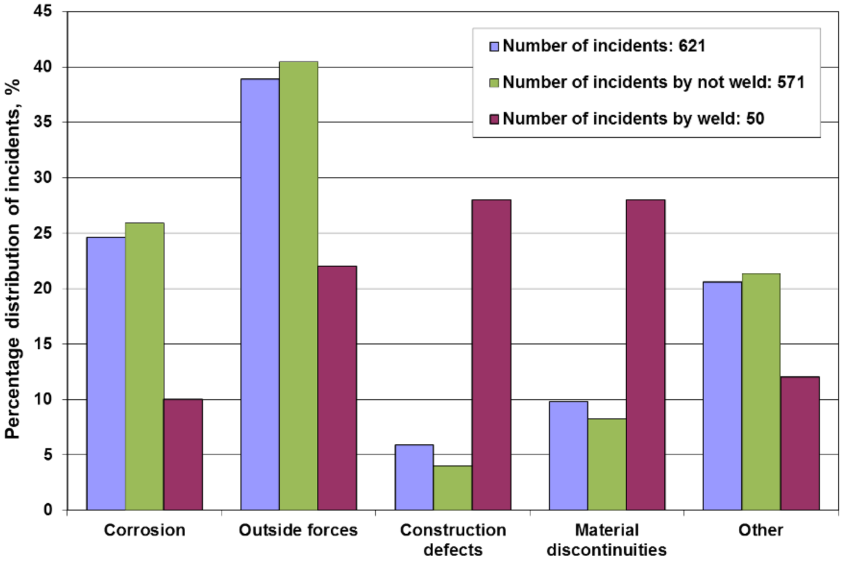


Figure 1
Pipeline incident distributions by cause [8]

Unfortunately, the Hungarian failure statistics [9] demonstrate a more negative picture than the international data. The comparison of the international and the Hungarian data show, on the one hand, that the ratio of the weld defects in Hungarian hydrocarbon transporting pipelines is higher than the international practice; on the other hand, weld defects typically occur in girth welds. This statement can be applied to both the past and the present.

The following figures show three examples of damages on girth welds in Hungary. Figure 2 illustrates a DN400, Figure 3 a DN600, and Figure 4 a DN800 gas transmission pipeline girth weld damage.

Figure 2
The damaged area of a girth weld on a Hungarian DN400 pipeline: crack in a repaired girth weld. Pipeline materials designation by API 5L: Grade B and X52

Figure 3
The damaged area of a girth weld on a Hungarian DN600 pipeline: crack caused by repair and unforeseen (not planned) cyclic loads. Pipeline materials designation by API 5L: X52 and X60

Figure 4
The damaged area of a girth weld on a Hungarian DN800 pipeline: crack caused by geometrical irregularities and unforeseen (not planned) cyclic loads, and initiated in the intersection point of a girth weld and spiral weld. Pipeline material designation by API 5L: X65

The different defects of girth welds can be classified into three groups of acceptability [10-12]: (i) defect acceptable by the assessment rules (workmanship criteria) of welded joints; (ii) defect unacceptable by the assessment rules of welded joints, but having no influence on the Fitness for Purpose (FfP) or Fitness for Service (FfS) of the welded joint; (iii) defect influencing the FfP or FfS of the welded joint. Based on the pipeline girth welds characteristics, these groups require different approaches [13] [14]. The girth weld integrity puzzle (see Figure 5 [15]) summarizes these characteristics, and demonstrates that the girth weld integrity depends on several interacting factors.

Forasmuch as there are several influencing factors on the failures, consequently on the integrity of pipeline girth welds, there are different opportunities for prevention of the damages, too. These opportunities can be divided into three groups [16]: (i) observance of the technological discipline and prescriptions; (ii) applying Engineering Critical Assessment (ECA) methods; reinforcing the girth welds, primarily using additional non-thermal, non-welded methods (e.g., composite wrap systems, non-welded sleeves as temporary or permanent repairs). The ECA methods reflect the operational experiences, demonstrate and endorse the compromise of rational risk and striving for safety, apply the results of the non-destructive testing (NDT), and should be validated by the results of full-scale tests on relevant pipeline sections. As the girth welds of pipelines are subjected to external loads in addition to internal pressures due to construction and operational reasons (e.g., ground movement), full-scale tests should be carried out taking this into account.

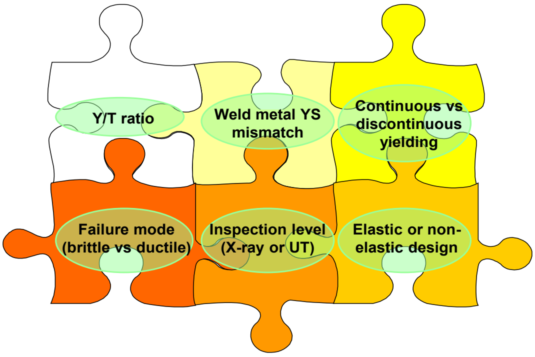


Figure 5
Puzzle of girth weld integrity [15]

The purpose of this article is twofold. On the one hand, we present a test system developed to investigate full-scale pipeline sections subjected to cyclic internal pressure and static external bending. On the other hand, we describe the results obtained from tests of girth welds with artificial notches. The results are used to draw conclusions on the load bearing capacity and integrity of the girth welds.

2 Experimental Setup and Testing Circumstances

Full-scale tests have important role during the assessing of the integrity of girth welds. These investigations should reflect the real operating conditions. This means that, in addition to internal pressure and its variation, external loads need to be modelled.

2.1 Experimental Setup

There are two testing systems for pressure vessels and piping at the Institute of Materials Science and Technology, University of Miskolc. Both systems are computer controlled electro-hydraulic setups; the newest system can be used up to 100 bar, and the oldest up to 700 bar internal pressure. The investigated pressure vessels or pipeline sections are located in a pit outside the laboratory building; all other components of the systems are located inside. The block diagrams of the lower-pressure and the higher-pressure systems are shown in Figures 6 and 7, respectively. The logical structure of the two systems is identical; the regulation and the control of the pressure were implemented during the whole tests in a closed loop.

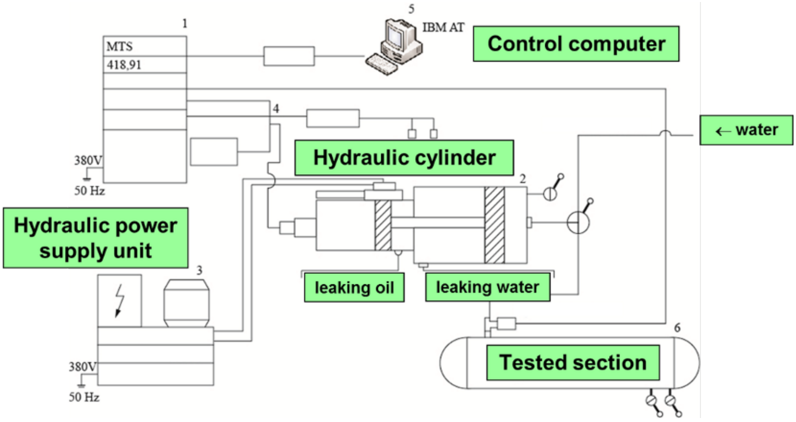


Figure 6
The block diagram of the lower-pressure testing system with a maximal applicable pressure of 100 bar

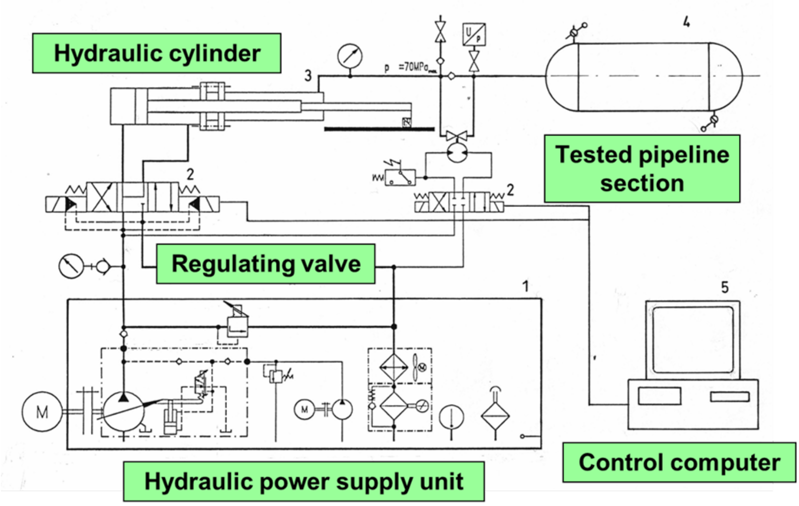


Figure 7
The block diagram of the higher-pressure testing system with a maximal applicable pressure of 700 bar

Based on these capabilities, a unique testing system has been developed for the complex loading of pipeline sections, applying cyclic internal pressure and superimposed external bending. In the three-point bending (3PB) layout, the tested girth weld was positioned in the middle of a nominal 4 meters long pipeline section. The experimental setup can be seen in Figure 8.

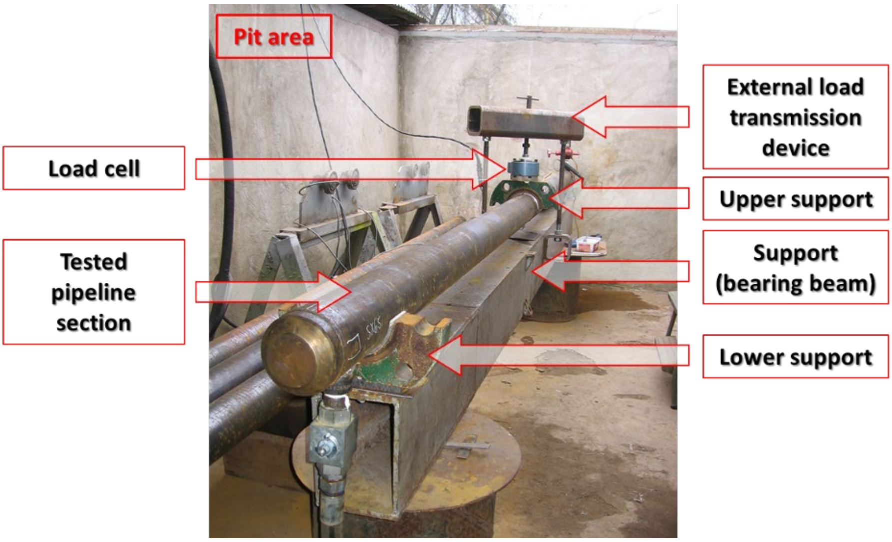


Figure 8

The pit area of our developed system for testing of pipeline sections under complex loading

The superimposed bending load was set via a load cell and checked by using a deflection meter (see Figures 9 and 10).

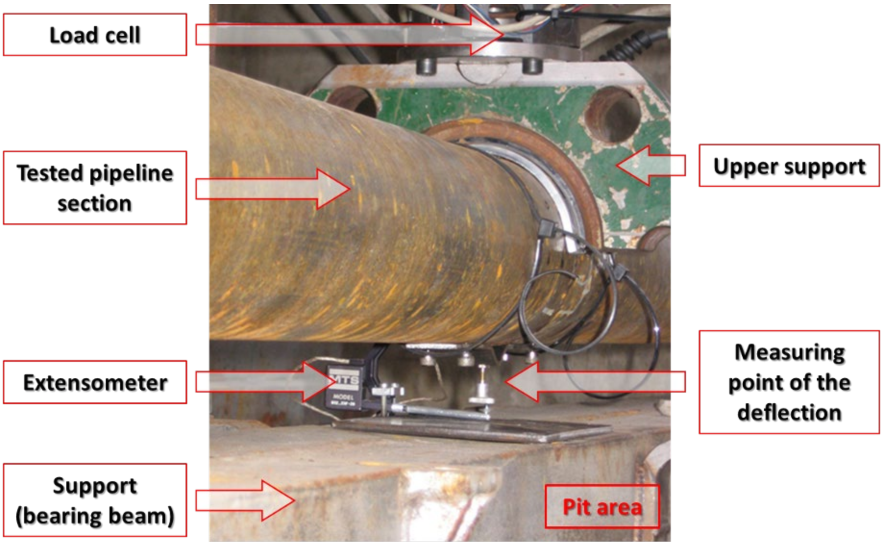


Figure 9

Setting the deflection by load cell and its measuring by extensometer

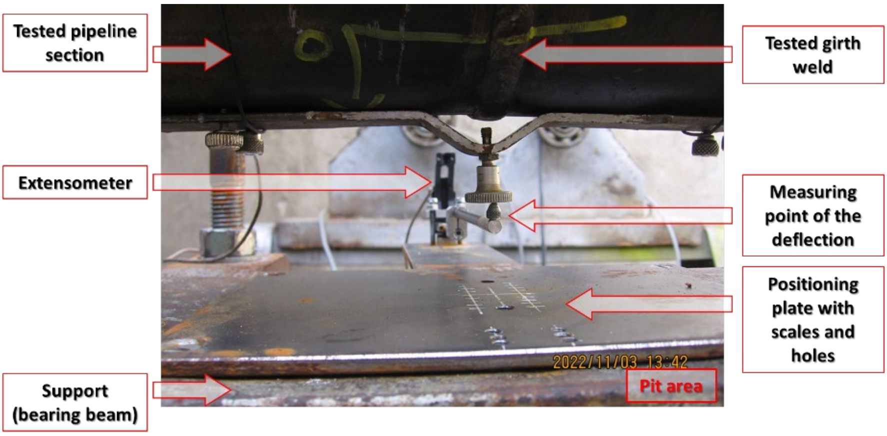


Figure 10

Measuring the deflection by extensometer

Two video cameras were used for the recording of the burst process; the one recorded the process parallel and the other one perpendicular to the longitudinal axe of the investigated pipeline.

2.2 Testing Circumstances

The investigated pipeline sections were made of P355NH steel [17] with a nominal diameter of DN100 (114.3 mm) and with a nominal wall thickness (t) of 5.6 mm. The chemical composition of the pipe material can be found in Table 1.

Table 1

Chemical composition of the pipe material based on inspection certificate, weight%

C	**Mn**	**Si**	**P**	**S**	**Cu**	**Cr**
0.18	1.24	0.22	0.016	0.009	0.19	0.08
Ni	**Al**	**Mo**	**Ti**	**V**	**Nb**	**N**
0.06	0.027	0.02	0.001	0.004	0.000	0.090

The tested girth welds were made by manual metal arc welding (MMAW). The chemical composition of the used welding electrodes were summarized in Table 2, and the main characteristics of the welding process can be found in Table 3.

Table 2

Chemical composition of the applied filler metals based on company specifications, weight%

Filler metal	**C**	**Si**	**Mn**	**Mo**
Böhler FOX CEL – E 38 3 C 2 1	0.12	0.14	0.5	N/A
Böhler FOX CEL Mo – E 42 3 Mo C 2 5	0.1	0.14	0.4	0.5

Table 3

Main characteristics of the manual metal arc welding process

Layer	**1st (root)**	**2nd**	**3rd**
Position	PH	PJ	PJ
Filler metal	Böhler FOX CEL	Böhler FOX CEL Mo	
Diameter, mm	3.2	3.2	3.2
Current, A	DC/EN 45-55	DC/EP 55-70	DC/EP 50-65
Voltage, V	21.8-22.2	22.2-22.8	22.0-22.6
Welding speed, cm/min	7-12	15-20	10-15

The girth welds were inspected before the investigations by visual testing (VT), liquid penetrant testing (PT), and radiographic testing (RT). Only girth welds that have been produced to an acceptable quality level based on the specification of the Hungarian pipeline system operator (FGSZ Ltd.) have been tested. Consequently, the evenly high quality of the girth welds made it possible to investigate the impact of not resulting from welding influencing factors on the failure characteristics.

Five pipeline sections were tested, one of them without and four with artificial notches. The notches were cut using a hand grinding machine and located either in the heat-affected zone (HAZ) of the girth weld (circumferential direction) or through the girth weld (axial direction). Transporting pipeline operator experiences have shown that external undercuts and lack of fusions (between the base materials and weld metals) are common in poor quality girth welds. These defects were modelled using circumferential notches. Furthermore, transporting pipeline operator experiences have demonstrated the high incidence of longitudinal defects and their increased risk in welds (girth and spiral welds). The interaction of these defects with girth welds were modelled by longitudinal notches. Since the notches were made with the same hand grinder, their maximum nominal width was 2 mm. The shape of the notches followed the shape of the grinding wheel, with the width dimension narrowing slightly in the direction of depth (see left part of Figure 11).

For all pipeline sections, external bending loads were applied during the cyclic loading (100,000 cycles) and the burst test. The cyclic internal pressure was varied between 60% and 100% of the maximum allowable operating pressure (MAOP, 64 bar) with the lower-pressure system (see Figure 6). The applied axial stress from bending was four times and six times the axial stress from the maximum internal pressure (σ_a = 29 MPa), and were designated as 4 sigma and 6 sigma in relevant figures of the manuscript. The applied frequency during the fatigue test was 0.2 Hz. Furthermore, the testing media during both the fatigue and the burst tests was water, and the testing temperature was 15-25 °C. Due to changes in the ambient temperature, the test temperature was varied within a narrow range throughout the whole test program, this change in itself had no significant effect on the behavior of the tested pipeline sections, their fracture mode was not changed. Table 4 summarizes the main characteristics of the full-scale tests.

Table 4
Main characteristics of the full-scale pipeline tests

Pipeline section ID	**Applied bending stress**	**Notch location**	**Notch direction**	**Notch depth**	**Notch length, mm**
Y6	$4 * \sigma_a$	N/A	N/A	N/A	N/A
Y7	$4 * \sigma_a$	girth weld HAZ	circumferential	0.37 * t	29
Y8	$4 * \sigma_a$	through girth weld	axial	0.5 * t	41
Y9	$4 * \sigma_a$	girth weld HAZ	circumferential	0.67 * t	40
Y10	$6 * \sigma_a$	girth weld HAZ	circumferential	0.5 * t	30

Figure 11 shows a notch in a girth weld HAZ (Y9 pipeline section) and through a girth weld (Y8 pipeline section) as examples.

Figure 11
Notch in the girth weld HAZ of the Y9 pipeline section (left) and through the girth weld of the Y8 pipeline section (right)

For the fatigue tests, the system with a maximum applicable pressure capacity of 100 bar was used (see Figure 6). Before starting the fatigue tests, the axial stress value from bending was set for each pipeline section separately. During this time, the load-deflection data pairs were continuously recorded to check the consistency of the theoretical and practical values. These curves are shown in Figure 12. On the one hand, the curves show the differences in deflection due to the difference in external load, and on the other hand, they demonstrate the almost identical behavior of the pipe sections under external load.

During the fatigue tests, the changes in the internal pressure and the deflection values and their variation were continuously monitored. These values were recorded using a data acquisition system every 5,000-10,000 cycles, applying a time interval of 50-70 fatigue cycles (equal to 250-350 s). In Figures 13 and 14 can be seen examples from the Y10 pipeline section. Figure 13 illustrates the consistency of internal pressure and deflection variation, and both figures confirm the stability of the deflection variation. (It should be remembered that the fatigue tests were carried out over a period of more than four days per pipe section.)

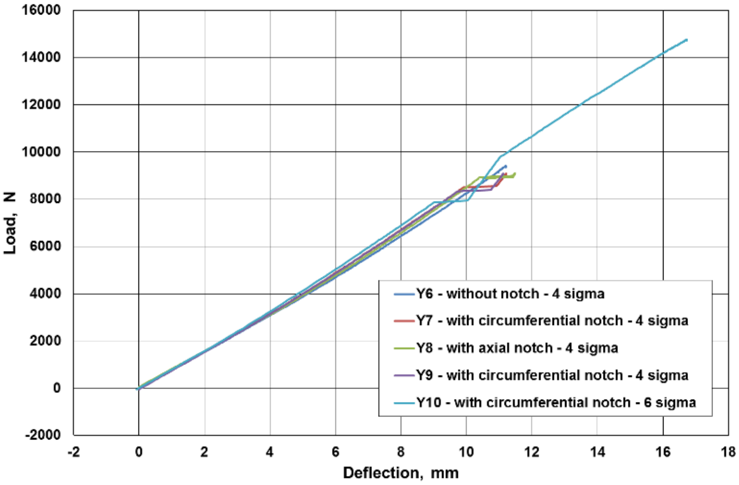
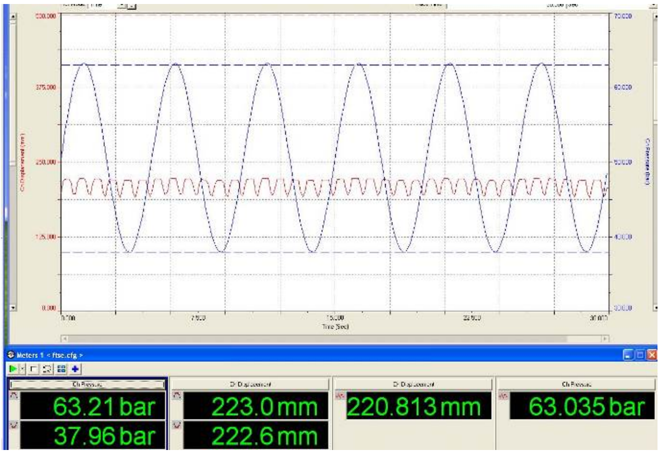


Figure 12

Load-deflection curves before the fatigue tests for setting the axial stress values from bending: the applied axial stress from bending was four times (4 sigma) and six times (6 sigma) the axial stress from the maximum internal pressure



Ch Pressure
63.21 bar
37.96 bar

Ch Displacement
223.0 mm
222.6 mm

Ch Displacement
220.813 mm

Ch Pressure
63.035 bar

Figure 13

Part of the screen of the MTS control system: main testing parameters, sinusoidal type programmed internal pressure (blue curve), recorded displacement from the extensometer (red curve)

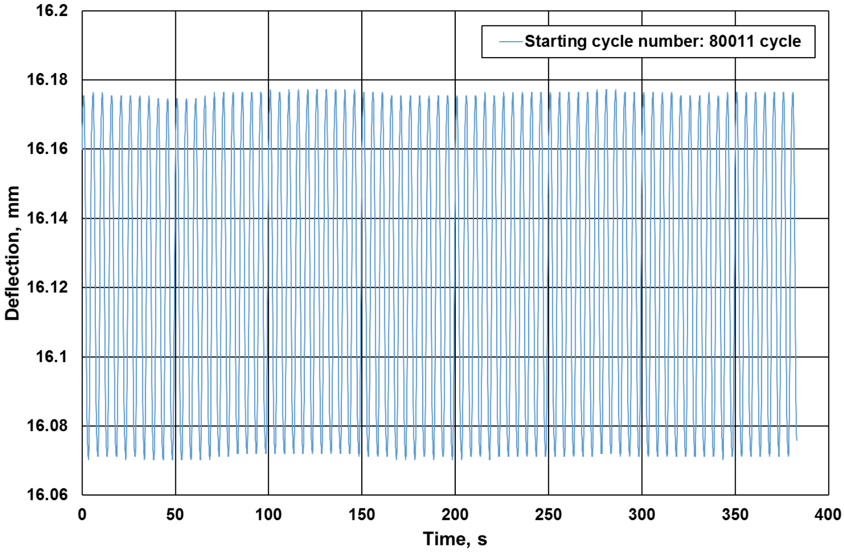


Figure 14

Change of deflection value during fatigue test (Y10 pipeline section) from number of cycles 80011, on the fourth day of the continuous fatigue test

After the fatigue tests, visual testing (VT) and liquid penetrant testing (PT) were performed, and the radiographic testing (RT) was repeated; the results showed no changes in any of the cases. This means that the fatigue stage did not cause a significant change in the quality of the girth welds tested.

For the burst tests, the system with a maximum applicable pressure capacity of 700 bar was used (see Figure 7). The internal pressure values were registered during the burst tests per second.

3 Results

The following diagrams and figures (Figures 15-17) introduce the results of the full-scale burst tests; furthermore, a table (Table 5) summarizes the results.

Figure 15 illustrates the average deflection vs. fatigue cycle number curves for each pipeline section, which are derived from the systematic processing of diagrams similar to the type of diagrams shown in Figure 14. The curves for both the 4 * σ_a and 6 * σ_a stresses and the circumferential and axial notches are clearly distinguished in the figure. It is remarkable that the curves have the same trend and are consistent with the approach.

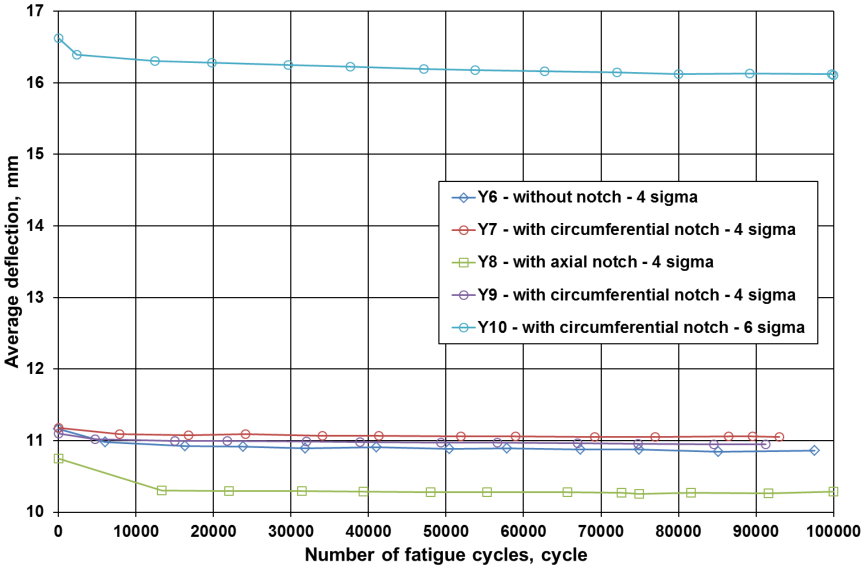


Figure 15

Change of the average deflection values during the fatigue tests

Figure 16 introduces the internal pressure vs. burst test time diagrams for the investigated pipeline sections. The average pressure growth rate values in the first stage can be evaluated as quasi-static values; therefore, the change in pressure cannot be considered as a dynamic effect. The other characteristics of the diagrams are the same, except for the diagram of the Y8 pipeline section. The tines-like changes of the diagrams demonstrate the volume increase of the pipeline sections in a consequence of the elastic-plastic deformation; during these periods, the system draws water from the water supply network. The damage to the tested pipeline sections, with the exception of the Y8 pipeline section, occurred on the pipe surface away from the investigated girth weld. The exception, pipeline section Y8, was damaged by splitting at the axial notch without significant volume increase. This is the reason for the lack of tines-like sections in the Y8 curve in Figure 16, and furthermore, for the shorter burst test or failure time.

The different failure behavior of the Y8 pipeline section compared to the other sections also highlighted the differences in the behavior of the different directions of the defects (in our case, notches) and their hazardousness. Of course, there is a close correlation between the location and size of the notches and the burst pressure, assuming other conditions are constant. The investigations confirmed that axial defects carry a higher risk than circumferential defects.

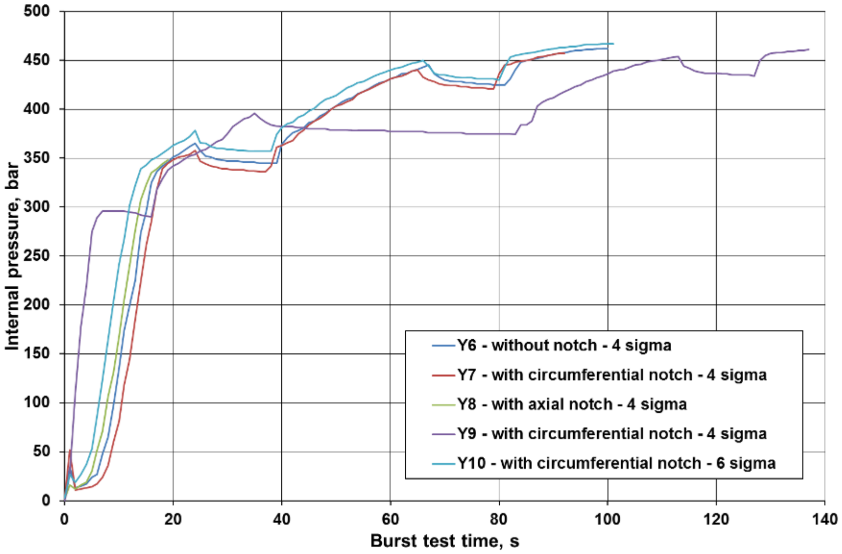


Figure 16

Internal pressure vs. burst test time diagrams of the investigated pipeline sections

A safety factor was defined to characterize the failure of the pipeline sections, with the following equation:

$$\text{Safety Factor} = \text{Burst Pressure} / \text{Maximum Allowable Operating Pressure} \quad (1)$$

Table 5 summarizes the notch characteristics; the burst pressure and the safety factor values of the investigations. The safety factor of the pipeline sections containing notch but not burst at the girth weld was almost the same.

Table 5

Notch characteristics, burst pressure and safety factor values of the full-scale pipeline tests.

Pipeline section ID	**Notch characteristics**	**Burst pressure, bar**	**Failure location**	**Safety factor, –**
Y6	N/A	462	pipe surface	7.22
Y7	circumferential in girth weld HAZ	457	pipe surface	7.14
Y8	axial through girth weld	348	axial notch through girth weld	5.44
Y9	circumferential in girth weld HAZ	461	pipe surface	7.20
Y10	circumferential in girth weld HAZ	467	pipe surface	7.30

The investigated pipeline sections at the end of their burst tests, at the moment of their failures, can be seen in Figure 17. The details of the figure show same characteristics, only the pipeline section containing the longitudinal notch remained in place until the end of the burst test.

Y6 pipeline section Y7 pipeline section

Y8 pipeline section Y9 pipeline section

Y10 pipeline section

Figure 17
The pipeline sections at the moment of their failures

Figure 18 shows a closer look of the damaged area of the Y8 pipeline section.

Figure 18
The damaged area of the Y8 pipeline section after the fatigue and burst tests

Conclusions

The developed test system (Section 2.1) is suitable for testing full-scale pipeline sections with girth welds, subjected to cyclic internal pressure and superimposed external bending.

The failure of the tested unnotched and circumferentially notched pipeline sections occurred similarly, in all cases, away from the investigated girth weld and in the pipe surface, regardless of the notch depth and the magnitude of additional stress from bending. Failure of the pipeline section containing the axial notch in the investigated girth weld occurred in the notch at significantly lower pressures in the other pipeline sections.

The executed full-scale tests and the determined safety factor have confirmed the high load-bearing capacity of the girth welds produced to the required quality. This also implies that previous industrial damages have occurred in girth welds of unacceptable quality and/or subjected to significantly higher overloads.

The investigations and their results have confirmed that further full-scale tests should be executed in the near future, as follows. Pipeline sections with girth weld should be investigated applying higher axial stresses from the superimposed external bending as well as using deeper and/or longer artificial notches on the tensile bending stress side of the girth weld. The effect of temperature should also be investigated, given that the temperature at the laying depth is 8 °C and that the pipelines have above-ground sections. As the explicit intention is to blend hydrogen into the natural gas transporting system [18], it is necessary to extend the full-scale tests, to the transported medium. Although it seems realistic to consider these impacts separately, in the near future, in the medium term, we should be prepared to consider them together.

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