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Influence of hydrogen exposure on the behaviour of transporting pipeline sections

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Abstract. Before blending hydrogen to a natural gas transmission system, it is necessary to analyse how the system will respond to the changed medium. There are several possible ways of analysis, of which the three most common are as follows: processing of literature data; carrying out specimen tests on the pipe material properties of the own system; and investigations on artificial pipeline sections (full-scale tests). In the latter two cases, tests should be carried out on samples without hydrogen exposure as well as on samples exposed to hydrogen. Our full-scale tests and analyses were carried out on X52 grade (API 5L) pipeline section, without and with artificial notches. The tests on full-scale pipeline sections were compared with each other (unexposed and exposed cases, unnotched and notched cases). For the tests safety factors were interpreted and compared.

1 Introduction

There are three possible ways to transport hydrogen through pipelines, one is to use the existing natural gas transmission system essentially unmodified up to a few percentage hydrogen content (blending), another is to make the existing natural gas transmission system fit for the task up to 100% hydrogen content (repurposing or retrofitting), and the third is to build new pipelines to transport (pure) hydrogen (constructing) [1-3]. The safe application of all three solutions can be based on investigations, where full-scale tests are of particular importance. The pipe sections of any pipeline system are joined by girth welds, and girth welds are considered potentially more dangerous places than the base pipe, so investigations should cover girth welds too.

Full-scale tests are expensive possibilities of assessing the integrity of different structural elements or structures [4], which also applies to structures subjected to internal pressure (e.g. pipelines, pressure vessels [5]).

Different solutions are used to test full-scale pipeline sections. Naturally, the different full-scale testing options are influenced by the dimensions of the pipe, especially its outer diameter, because this also affects the length of the tested pipe section. Tests can be performed with external load and/or internal pressure, or with quasi-static and/or cyclic loading conditions. Three-point and four-point bending tests (3PB and 4PB) are commonly used configurations, both for smaller diameters [6] and larger diameters [7], and for fatigue tests [8] too.

Considering that the girth welds of pipelines often contain imperfections due to the applied welding technology and may be subject to external impacts (damages) during their installation and operation, the use of artificial defects (foremost notches) is also appropriate when designing and implementing full-scale tests [9]. The combined application of FEM modelling and full-scale testing to girth welds with complex loads containing defects is presented in [10].

For our investigations, pipeline sections of P355NH steel with girth welds were prepared and exposed to pure hydrogen at twice the maximum allowable operating pressure (MAOP) for 41 and 92 days. Subsequently, full-scale burst tests were carried out. The results obtained were evaluated and compared with data from previous full-scale tests on pipeline sections without hydrogen exposure. In the present article, the test system designed for complex testing of pipeline sections, the performed fatigue and burst tests and their results are presented.

2 Testing system and tested items

2.1 Testing system

The elements of our full-scale test system can be divided into two parts. The first part consists of the control unit, the hydraulic power supply, and the working cylinders, and is in the enclosed place of the laboratory. The second part consists of the test item (internally pressurized structural element), the gripping and supporting elements and the various fittings and is located outside the laboratory, in the open air, in the test pit. Two systems can be used for the testing of structural elements subjected to internal pressure, and a separate system has been developed for the transfer of external bending loads.

The two different pressure intensifier can be applied in two pressure ranges, one up to 100 bar, mainly for fatigue tests, the other up to 700 bar, mainly for burst tests. Based on these two systems, a unique test part has been developed for complex loading of internally pressurized sections. External bending load has been superposed on the cyclic internal pressure, using three-

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point bending arrangement. The tested girth weld can be found in the centre of the pipeline section (the location of the maximum bending stress) and a notch, if applicable, is always located on the tensioned side. The complex system, the laboratory and the pit parts can be seen in Figs. 1 and 2, respectively.

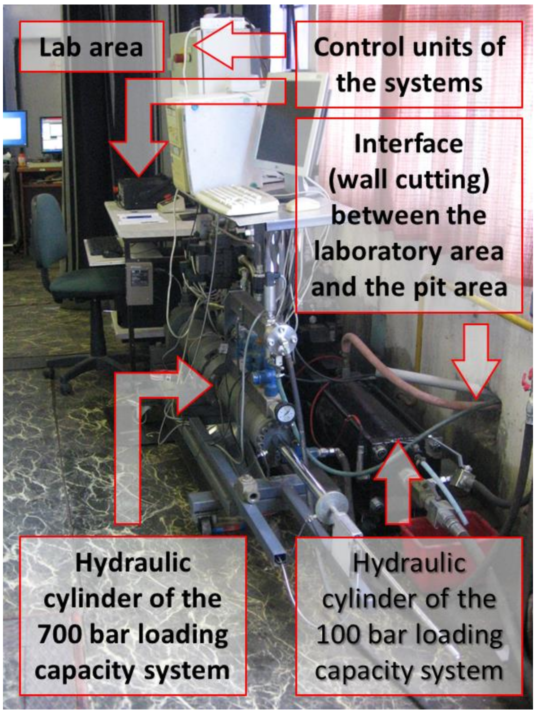

Fig. 1. The laboratory part of the testing system.

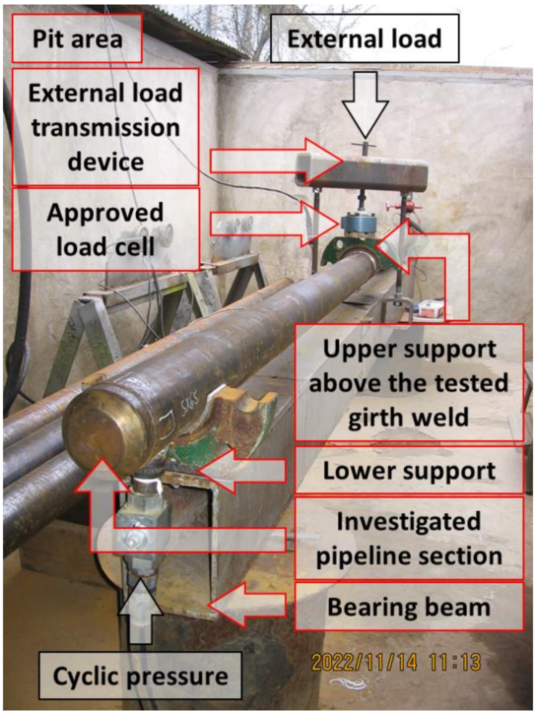

Fig. 2. The pit part of the testing system.

The bending load can be set with an approved load cell and verified by measuring the deflection with an approved (MTS type) extensometer having extended arm. Both the pipeline section and the tested girth welds can be positioned using a master-plate containing scales and drilled holes, implementing symmetrical three-point bending (see Fig. 3).

The whole bursting process can be recorded from above with two video cameras, positioned at the edge of the pit area. One camera follows the process in the longitudinal, the other one in the perpendicular direction belonging to the axis of the tested pipeline section.

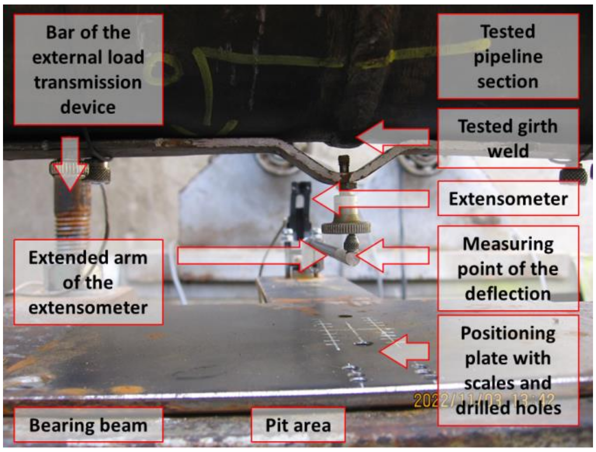

Fig. 3. The master-plate for the positioning of the pipeline section and the girth weld.

2.2 Tested items

Hydrogen-exposed pipeline sections were “redesigned” and rebuilt from previously fatigued and burst pipeline sections. The original pipeline sections were made of P355NH seamless steel pipes for pressure purposes [11] (equivalent with X52 [12]). The nominal outside diameter was 114.3 mm (DN 100) and the nominal wall thickness was 5.6 mm (t), furthermore the nominal lengths of the tested items were 4,000 mm. Fig.4 shows both the original pipe sections (drawing with black) and their rebuilding (marked with red). Based on the rebuilding, the nominal lengths of the “redesigned” items were approximately the same and 1,100 mm.

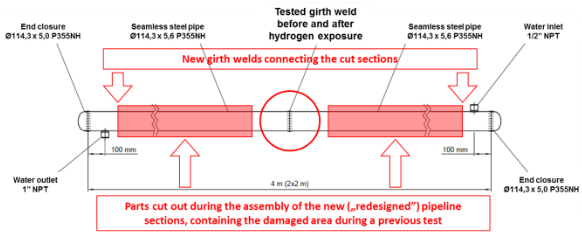

Fig. 4. The original and the “redesigned” pipeline section for full-scale tests.

The tested girth welds were manufactured under industrial conditions using manual metal arc welding (PH and PJ positions), while the new girth welds (hybrid welds) were manufactured under workshop conditions (PA position) using TIG welding with solid filler rode material (root) and manual metal arc welding (further layers).

A total of five pipeline sections were “redesigned” and rebuilt, of which the tests for the pipeline sections with 41 days (Y2, Y4) and 92 days (Y9, Y10) of hydrogen exposure are presented in this article. Two or two pipeline sections were exposure for these times and the planned exposure time of the last section is of 180 days (ongoing test). The hydrogen exposure was implemented at the Linde Gas Hungary Ltd. site in Budapest, at twice the operating pressure (128 bar) in pure hydrogen. The “redesigned” and rebuilt pipeline sections with the girth welds, during the exposure period, can be seen in in Fig. 5.

Fig. 5. The realisation of the hydrogen exposure.

3 Full-scale fatigue and burst tests

3.1 Full-scale tests before hydrogen exposure

The main characteristics of the tested pipeline sections before hydrogen exposure are summarized in Table 1.

Table 1. Full-scale test characteristics of the pipeline sections before hydrogen exposure.

ID	Bending	Notch		
		direction	depth	length
Y3	N/A	N/A	N/A	N/A
Y2	N/A	N/A	N/A	N/A
Y4	2 * σ_a	N/A	N/A	N/A
Y8	4 * σ_a	a / tgw	0.50 * t	41
Y11	6 * σ_a	a / tgw	0.67 * t	40
Y9	4 * σ_a	c / gwHAZ	0.67 * t	40
Y10	6 * σ_a	c / gwHAZ	0.50 * t	30

The axial notches were perpendicular and symmetrical to the girth weld, and the circumferential notches were located in the heat affected zone (HAZ) of the girth weld. (In the tables “a / tgw” means axial / through girth weld and “c / gwHAZ” means circumferential / girth weld HAZ.) The applied axial stress from bending was two, four and six times (in Figs. 6 and 8 2 sigma, 4 sigma and 6 sigma, respectively) of the axial stress (σa) from the maximum internal pressure. The fatigue tests were executed applying 0.2 Hz testing frequency, and water was used as testing media during both the fatigue and the burst tests. The test temperature was the same as the ambient temperature.

3.2 Full-scale test after hydrogen exposure

After 41 and 92 days, the two or two hydrogen-exposed pipeline sections were returned to the University of Miskolc and the burst tests were performed on the next day. (The letter “H” has been added to the original ID of the pipeline sections.) Superposed bending loads were not applied.

Since the pipeline sections were not damaged until the nominal internal pressure of 300 bar was reached, the original notches were gradually deepened, and the burst test was repeated several times. (The serial number of the repeated burst test has been added to the ID of the pipeline section.)

In the case of the HY2 pipeline section, the failure occurred after the third loading (HY2-3). In the cases of the HY4, HY9 and HY10 pipeline sections, after the fourth, the first and the sixth loading, respectively, the wall thickness was cut through during the notch deeping, consequently no further bursting could be performed. The main characteristics of the tested pipeline sections after hydrogen exposure are summarized in Table 2.

Table 2. Full-scale test characteristics of the pipeline sections after hydrogen exposure.

ID	Notch		
	direction	depth	length
HY2-1	N/A	N/A	N/A
HY2-2	a / tgw	0.50 * t	80
HY2-3	a / tgw	0.67 * t	80
HY4-1	N/A	N/A	N/A
HY4-2	c / gwHAZ	0.50 * t	40
HY4-3	c / gwHAZ	0.67 * t	40
HY4-4	c / gwHAZ	0.80 * t	40

ID	Notch		
	direction	depth	length
HY9-1	c / gwHAZ	0.67 * t	40
HY10-1	c / gwHAZ	0.50 * t	30
HY10-2	c / gwHAZ	0.63 * t	60
HY10-3	c / gwHAZ	0.71 * t	60
HY10-4	c / gwHAZ	0.71 * t	70
HY10-5	c / gwHAZ	0.77 * t	70
HY10-6	c / gwHAZ	0.84 * t	70

4 Results of full-scale fatigue and burst tests

4.1 Results of full-scale tests before hydrogen exposure

The test results for the pipeline sections before hydrogen exposure are summarized in Table 3.

Table 3. Full-scale test results of the pipeline sections without hydrogen exposure.

ID	Burst pressure	Failure location	Safety factor
Y3	446	pipe body	6.97
Y2	447	pipe body	6.98
Y4	473	pipe body	7.39
Y8	348	a / tgw	5.44
Y11	152	a / tgw	2.38
Y9	461	pipe body	7.20
Y10	467	pipe body	7.30

Safety factor (SF) was defined and calculated as the ratio of the burst pressure to the maximum allowable operating pressure (MAOP = 64 bar). The internal pressure-burst test time connections were recorded during the burst tests and can be seen in Figs. 6 and 7.

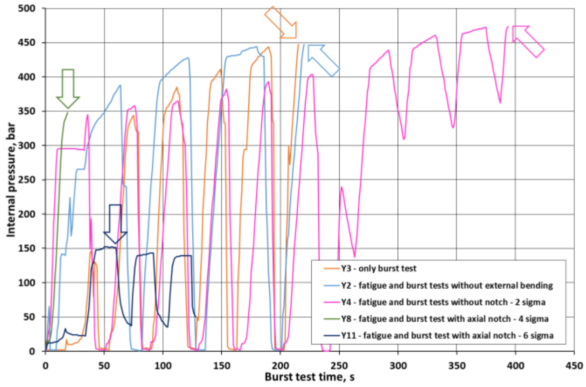

Fig. 6. Internal pressure-burst test time functions of full-scale burst tests on Y3, Y2, Y4, Y8 and Y11 pipeline sections without hydrogen exposure.

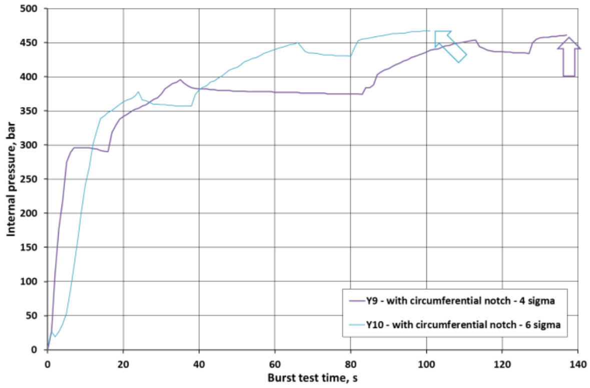

Fig. 7. Internal pressure-burst test time functions of full-scale burst tests on Y9 and Y10 pipeline sections without hydrogen exposure.

The Y2, Y9 and Y10 pipeline sections at the end of their burst tests can be seen in Figs. 8-10, respectively.

Fig. 8. The Y2 pipeline section at the end of the burst test.

Fig. 9. The Y9 pipeline section at the end of the burst test.

Fig. 10. The Y10 pipeline section at the end of the burst test.

4.2 Results of full-scale tests after hydrogen exposure

The test results for the pipeline sections after hydrogen exposure are summarized in Table 4.

Table 4. Full-scale test results of the pipeline sections after hydrogen exposure.

ID	Burst pressure	Failure location	Safety factor
HY2-1	> 299	not failured	> 4.67
HY2-2	> 297	not failured	> 4.64
HY2-3	199	a / tgw	3.11
HY4-1	> 290	not failured	> 4.53
HY4-2	> 294	not failured	> 4.59
HY4-3	> 297	not failured	> 4.64
HY4-4	> 298	not failured	> 4.66
HY9-1	> 299	not failured	> 4.67
HY10-1	> 295	not failured	> 4.61
HY10-2	> 293	not failured	> 4.58
HY10-3	> 296	not failured	> 4.63
HY10-4	> 293	not failured	> 4.58
HY10-5	> 293	not failured	> 4.58
HY10-6	> 293	not failured	> 4.58

The internal pressure-burst test time connections recorded during the burst tests can be seen in in Figs. 11 and 12. The connections show the same characteristics for the pipeline sections (HY2, HY4, HY9 and HY10) and for the individual loads. The figures do not demonstrate the time intervals (a few minutes in each case) during which the notches were cut and/or deepened in a depressurized state.

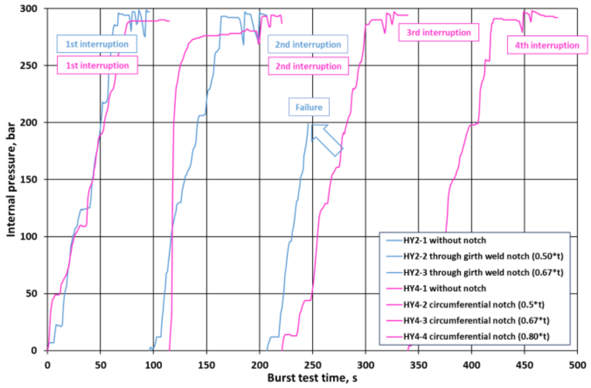

Fig. 11. Internal pressure-burst test time functions of burst tests on pipeline sections with 41 days hydrogen exposure (HY2 and HY4).

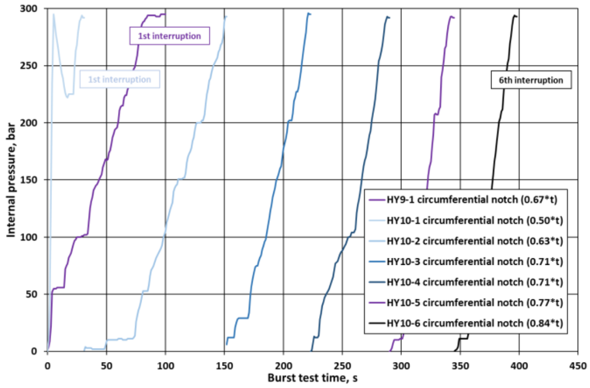

Fig. 12. Internal pressure-burst test time functions of burst tests on pipeline sections with 92 days hydrogen exposure (HY9 and HY10).

The HY2-3 pipeline section at the end of the burst test can be seen in Fig. 12.

Fig. 12. The HY2 pipeline section at the end of the burst test (HY2-3).

5 Summary and conclusions

Based on our full-scale tests and their results, the following conclusions can be drawn.

(1) Using the developed test layout complex loading of pipeline sections with static / cyclic internal pressure

and static bending moment can be performed. The test arrangement and the applied methodology can be considered as general, but the geometric dimensions of the investigated pipeline or pressure vessel sections have an influence testing possibilities.

(2) In post fatigue burst tests of unnotched or circumferentially notched pipeline sections without hydrogen exposure, failure occurred at pressures significantly above the operating pressure. The fatigue loading (100,000 cycles), the superimposed bending loading, furthermore the circumferential notches have not significant effect on the failure pressure, the burst occurred in all cases on the pipe body surface, and the tested girth welds were not damaged. In the cases where the girth welds contained axial notches, failure occurred in both cases in the notch at pressures higher than the operating pressure. The safety factors reflect the effect of the magnitude of the superposed bending load and the size of the notch.

(3) No failure of the pipeline sections without notching exposed 41 days to hydrogen occurred up to nearly five times the operating pressure, and the tested girth welds were not damaged. The tested girth welds with circumferentially oriented 40 mm long artificial notches in their heat affected zone (HAZ) to a depth of 80% of the nominal wall thickness also withstood nearly five times the operating pressure. For the artificial notches perpendicular to the tested girth welds, axial and 80 mm long, failure occurred at a depth of 67% of the nominal wall thickness in the artificial notch at three times the operating pressure.

(4) The pipeline sections with circumferential notches in girth welds HAZ, tested after 92 days of hydrogen exposure did not suffer any damage to the original notches, despite the higher superposed bending loads applied earlier. Increasing the sizes of the notches, the tested girth welds with circumferentially oriented 40 mm and 70 mm long artificial notches to a depth of 67% and 70% of the nominal wall thickness also withstood nearly five times the operating pressure.

(5) The safety factors obtained for the pipeline sections without and with hydrogen exposure are consistent, reflecting the combined effects of complex loading, notch geometry and hydrogen exposure.

(6) Further experimental work is needed, including the comparison of mechanical properties (e.g. yield strength, percentage elongation, percentage reduction of area) and the addition of macro- and microstructural analyses. On the other hand, the systematic studies should be repeated for longer exposure times to map the expected tendencies as fully as possible.

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