UNIVERSITY OF MISKOLC
FACULTY OF MECHANICAL ENGINEERING AND INFORMATICS

# INTEGRITY OF TRANSPORTING PIPELINE GIRTH WELDS BASED ON FULL-SCALE TESTS UNDER COMPLEX LOADING CONDITIONS

Booklet of PhD Theses

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**2025**

# 1. INTRODUCTION, THE AIM OF THE RESEARCH WORK

## 1.1 INTRODUCTION

Pipelines for the transportation of hydrocarbons are strategically important not only within a single country but also between countries and, more recently, even between bigger geographical groupings. Regardless of the origin, these pipeline failures typically result in longer or shorter disruptions to a geographic unit's energy balance. This has the direct effect of applying various tiers of regulations and standards with differing purview to every phase of the pipelines' life cycle [1], [2].

Usually consisting of 12–18 m long pipe strands, transporting pipes are joined by welding, either longitudinally or seamlessly. There will consequently be thousands of these girth welds, usually created by welding on location, along a pipeline that is several hundred kilometers long. This logically means that various standards also apply to the welding jobs and the evaluation of the finished circumferential welds [3].

Assessing the integrity of an operating structure or structural element is a complex task [4]. The content of the term already indicates this complexity: the suitability for operation at any moment of its lifetime. Understanding the practical problems and tasks requires or presupposes theoretical knowledge, structure-specific knowledge and relevant experimental work [5], [6]. Structure-specific knowledge includes design, technological and operational elements.

Pipelines used to transport crude oil or natural gas over long distances and at high pressures need a mix of high strength and toughness, as well as good weldability, to save transportation costs. The use of higher-grade steel pipes with improved weldability is being advocated to improve pipeline transport efficiency [6], [7], [8]. As a result, a major aspect in the pipeline sector is the exploration and development of enhanced and creative welding procedures to meet new technical problems. The ability of steel to be welded, and hence its good weldability, allows for the adoption of welding technology in general and the manufacturing of welded pipes [10], [11], [12], [13]. Weldability, as a technological quality, thus dictates the application of welding production technology, which has been increasingly popular in recent years across all industries. Steel is one of the most common materials used in the manufacture of welded structures in general, and welded pipes, due to its welding ability and good weldability. It's worth noting that weldability is a complicated concept that is influenced by a variety of factors, ranging from the chemical composition of steel to its processing history, welding technology applied to the interaction with the environment, temperature, air humidity, wind intensity in an open ground, and so on.

Girth welds play an important role during both the construction and the operation of the transporting pipelines [14]. Only high-quality girth welds reassure the operators of reliable function of the pipeline systems during their lifetime. Numerous girth welds can be found in different transporting systems, Table 1, Figure 1 summarizes the main characteristics (type, length and number of girth welds) of the Hungarian hydro-carbon transporting systems [15].

The loads on the girth welds are not only due to internal pressure, but also the location and the path as well as the construction of the pipeline, and the modifications during the operation can cause additional loads superposed on the internal pressure. Both base and superposed loads can be quasi-static and cyclical in nature.

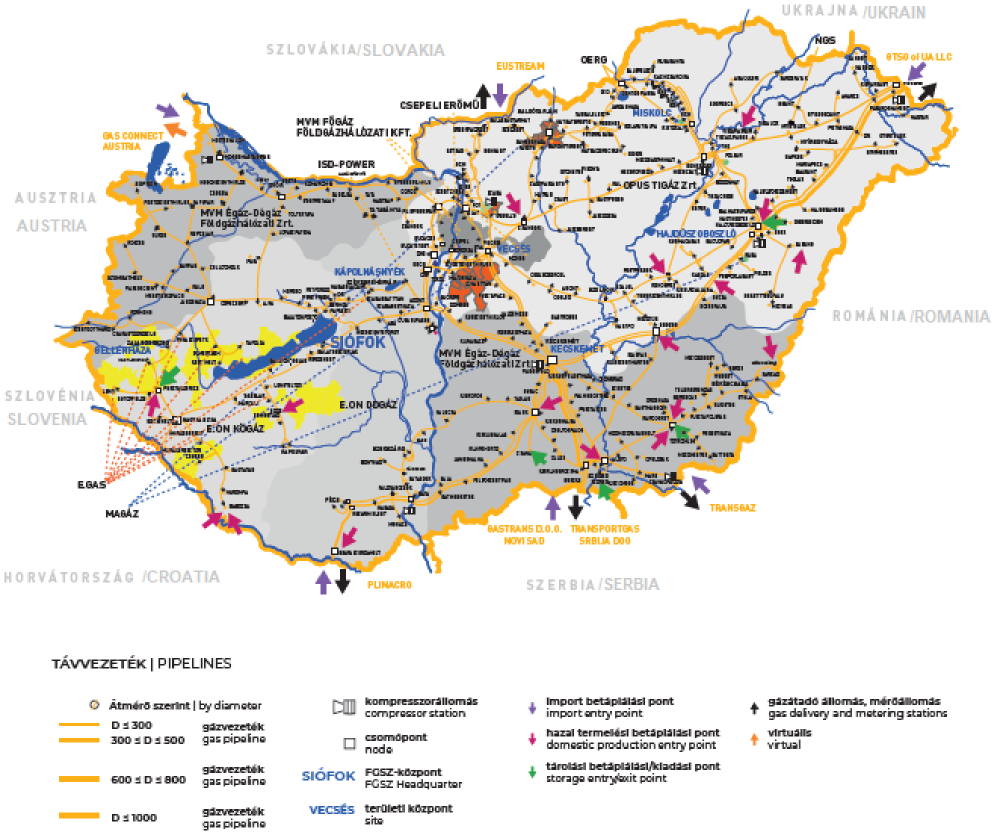


**Figure 1. high-pressure natural gas transmission pipelines of FGSZ Ltd. [15]**

**Table 1 Main characteristics of the Hungarian hydro-carbon transporting pipelines systems [15], [16]**

| **Characteristic** | **Value** | **Unit** |
|---|---|---|
| **Natural gas system** | ~ 6000 | km |
| **Crude oil system** | ~ 850 | km |
| **Other systems transporting liquid media** | ~ 1200 | km |
| **Total length** | ~ 8050 | km |
| **Average length of individual pipe sections** | ~ 11 | m |
| **Girth welds** | ~ 732.000 | item |

Because of the huge number of the girth welds the global aims of the research are as follows:

- Investigation and analysis of the development of a measurement possibility for girth welds subjected to complex loads.
- Assessment of the integrity of girth welds subjected to complex loads.
- Exploration of operational reserves in girth welds through assessment of the hazardousness of different types of failures.

## 1.2 THE AIM OF THE RESEARCH WORK

The steels used for hydrocarbon transporting pipelines are based on or correlate to [17], worldwide. The increase in strength for this type of steel is also continuous, but the increased strength must also be matched with adequate ductility. As the joining of the pipe segments is done by welding (girth welds), the welding technology must also follow the evolution of the base materials.

Damage statistics for pipelines show well-defined groups of causes. The ratios between each group are different based on international and Hungarian data, with Hungarian data showing less favourable data for damage to girth welds compared to international data.
There can be, and are, many causes of damage to girth welds, and the same is true of the possibilities for preventing damages. In the case of transporting pipelines, especially those in service for a long time, it is no longer possible to speak of clearly quasi-static operation and simple loads, but of cyclic and/or complex loads.
Despite the fact that several modelling options and computational algorithms are known, their limitations are also known, thus the role and importance of full-scale tests has been enhanced.
Based on the previously mentioned facts, the objectives of the research work are as follows:

- to develop a measurement system for full-scale tests of pipeline sections containing girth welds under cyclic internal pressure and superposed external loads;
- to design experimental pipeline sections with the same characteristics for full-scale tests;
- to design and perform full-scale tests on girth welds under complex loading conditions, for girth welds with different discontinuities (defects) and artificial defects;
- to identify the operational reserves in girth welds based on a safety factor;
- to rank the hazard of different discontinuities and defects;
- to propose options and requirements for safer operation of girth welds.

# 2. METHODOLOGY

## 2.1 MANUFACTURING OF THE PIPELINE SECTIONS

The investigated pipeline sections were made of P355NH seamless steel tubes for pressure purposes [18]. The welding process was made entirely by the industrial partner, The nominal geometrical sizes were as follows: OD = 114.3 mm (DN 100) outside diameter, t = 5.6 mm wall thickness, L = 4,000 mm (4 m) pipeline section length (Figure 3). The tested girth welds located in the middle of the pipeline section were made under industrial conditions using manual metal arc welding (MMAW). The chemical composition of the base material and applied filler metals are summarized in Table 2, furthermore, the basic mechanical properties of the base material can be found in Table 3.

**Table 2 Chemical composition of the pipe material based on inspection certificate and the applied filler metals based on company specifications, weight%**

| Material | Element | | | | | | |
|---|---|---|---|---|---|---|---|
| | **C** | **Mn** | **Si** | **P** | **S** | **Cr** | **Mo** |
| **P355NH** | 0.18 | 1.24 | 0.22 | 0.016 | 0.009 | 0.08 | 0.02 |
| **Böhler FOX CEL–E383C21** | 0.12 | 0.14 | 0.5 | N/A | N/A | N/A | N/A |
| **Böhler FOX CEL Mo–E423MoC25** | 0.1 | 0.14 | 0.4 | N/A | N/A | N/A | 0.5 |
| | **Ni** | **Al** | **Cu** | **Ti** | **V** | **Nb** | **N** |
| **P355NH** | 0.06 | 0.027 | 0.19 | 0.001 | 0.004 | 0.000 | 0.090 |

**Table 3 The basic mechanical properties of the pipe material based on the inspection certificate**

| Yield strength, $R_{eH}$ (MPa) | Tensile strength, $R_m$ (MPa) | Elongation, $A_{65}$ (%) | Charpy-V impact energy at -20 °C, KV (J) | |
|---|---|---|---|---|
| | | | **Individual values** | **average value** |
| 406 | 536 | 28.4 | 150, 154, 160 | 155 |

We can see in Table 4, Charpy-V impact energy (KV) data for two filler materials at different temperatures, along with the mechanical properties like yield strength ($R_y$), tensile strength ($R_m$), and elongation (A). Comparing the strength properties of the base material and the filler materials, the welded joints produced can be classified as matching (the strength of the base material and the filler metal are approximately the same).

**Table 4 Key mechanical properties of welding filler metals**

| $R_y$ (MPa) | $R_m$ (MPa) | A (%) | Charpy-V impact energy at the following temperatures, KV (J) | | | | |
|---|---|---|---|---|---|---|---|
| | | | 20 °C | 0 °C | -20 °C | -30 °C | -40 °C |
| **Böhler FOX CEL (E383C21)** | | | | | | | |
| 450(≥380) | 550 (470-600) | 26(≥22) | 100 | 90 | 70 | 55 (≥ 47) | N/A |
| **Böhler FOX CEL Mo (E423MoC25)** | | | | | | | |
| 480(≥420) | 550 (500-640) | 23(≥20) | 100 | 95 | 85 | 50 (≥ 47) | 42 |

In Figure 2, a metal welding process involving two different materials, A1 and A2 can be seen and that is the general situation. However in our study A1 and A2 from the same material, the preparation phase (a) and the layers of the welding process (b) can also be seen.

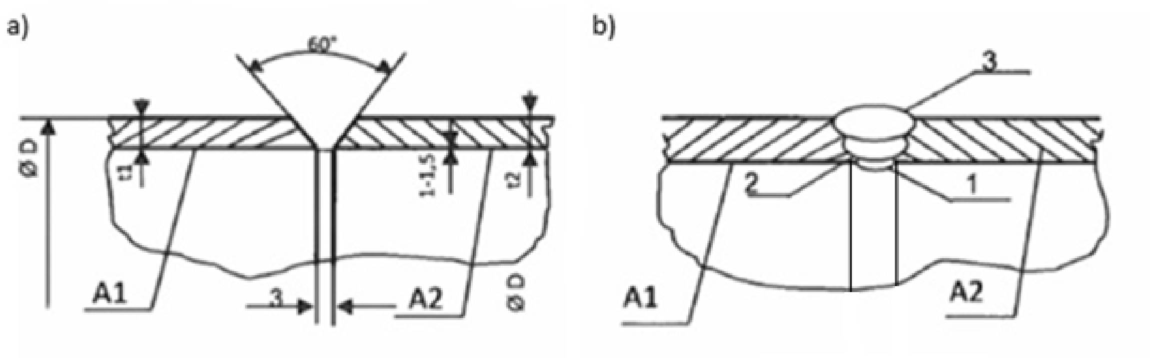


**Figure 2 Preparation phase (a) and layer structure (b) [19]**

Table 5 shows the main characteristics of the applied welding processes for the tested girth welds.

**Table 5 Main characteristics of the welding process for the tested girth welds**

| Layer | 1st (root) | 2nd | 3rd |
|---|---|---|---|
| **Position** | PH | PJ | PJ |
| **Filler metal** | Böhler FOX CEL | Böhler FOX CEL Mo | Böhler FOX CEL Mo |
| **Electrode 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 |

Figure 3 shows the main characteristics of the pipeline sections investigated. And Figure 4 shows the investigated Pipelines.

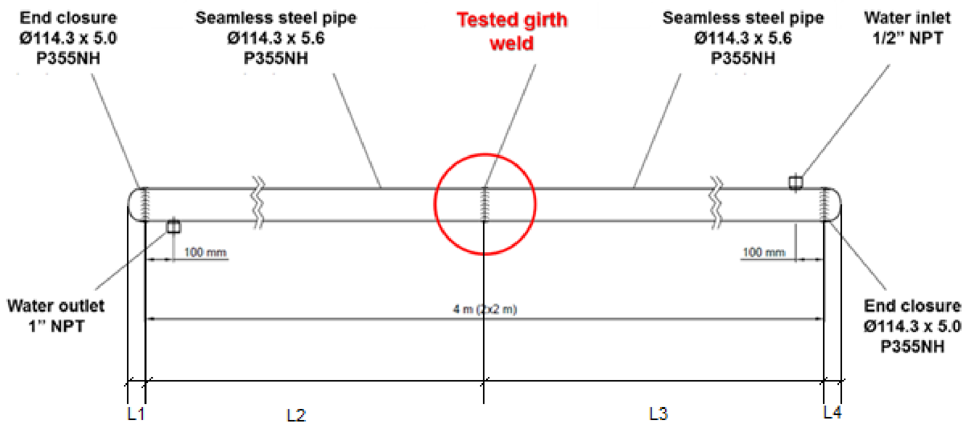


**Figure 3 The investigated pipeline sections**

The samples were already measured, dividing into four parts, L1, L2, L3, and L4. Also, the wall thickness was measured at four points, the first one at the fitting, the second and the third are before and after our studied girth weld, and the fourth one at the second fitting (Table 6).

**Table 6 The length measurements and wall thicknesses**

| Sample number | Length (mm) | | | | Wall thickness(mm) | | | |
|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L4 | 1st | 2nd | 3rd | 4th |
| Y1 | 50 | 2010 | 2010 | 50 | 5.9 | 6.3 | 5.9 | 5.7 |
| Y2 | 50 | 2010 | 2015 | 50 | 5.7 | 5.5 | 6 | 6 |
| Y3 | 48 | 2008 | 2008 | 48 | 5.8 | 5.8 | 5.6 | 5.7 |
| Y4 | 48 | 2012 | 2010 | 50 | 6 | 5.7 | 5.8 | 5.8 |
| Y5 | 50 | 2010 | 2008 | 50 | 5.7 | 6.1 | 5.6 | 5.8 |
| Y6 | 50 | 2010 | 2010 | 50 | 5.7 | 5.8 | 5.6 | 5.7 |
| Y7 | 50 | 2012 | 2012 | 50 | 5.9 | 5.6 | 5.9 | 5.8 |
| Y8 | 50 | 2005 | 2010 | 50 | 5.3 | 5.3 | 5.4 | 5.7 |
| Y9 | 50 | 2010 | 2010 | 50 | 6.2 | 5.9 | 5.4 | 6.2 |
| Y10 | 50 | 2015 | 2010 | 50 | 5.9 | 5.9 | 5.8 | 6.1 |
| Y11 | 50 | 2010 | 2010 | 50 | 5.8 | 5.7 | 6 | 6.1 |
| Y12 | 50 | 2010 | 2010 | 50 | 5.7 | 5.5 | 5.7 | 5.8 |

**Figure 4 The investigated samples**

## 2.2 DESIGN THE FIXING DEVICE

Before the next part of the investigations was started, the fixing device had to be designed to hold the samples during the cycle fatigue test and the burst test. The fundamental requirements were as follows:

- ensuring the reproducibility of the tests;
- the use of robust support beams made of steel;
- enabling the interchangeability of smaller components, both in case of potential damage and when changing the diameter of the tested pipe;
- ensuring the safe execution of the tests;
- cost-effectiveness.

The fixing device should be designed to perform three points bending (Figure 5-a) or four points bending (Figure 5-b); the three points bending was chosen for maximum bending moment..

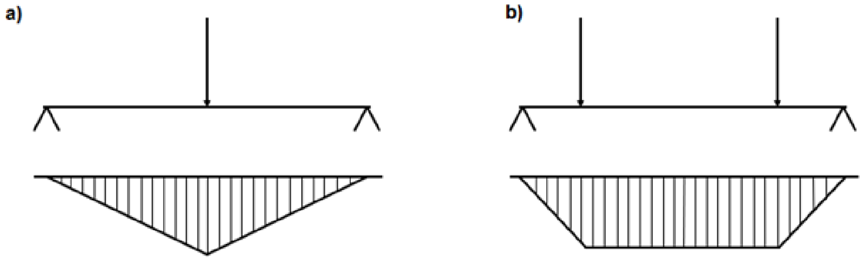


**Figure 5 3BP or 4BP**

Should the structure of the load transfer be designed as a close frame (Figure 6-a) or a simple load transfer (Figure 6-b)? The simple load transfer was chosen for easier construction.

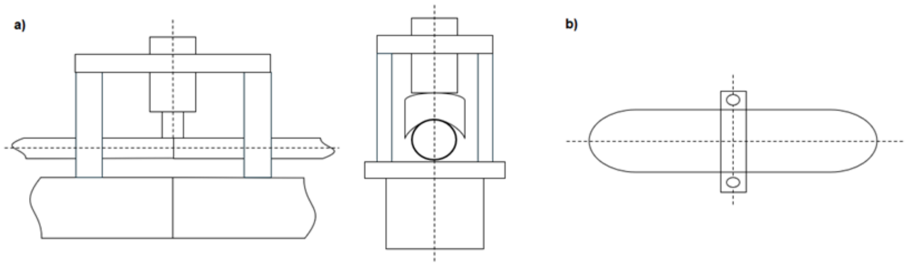


**Figure 6 The structure of the load transfer**

Regarding the support method, should a Closed (rigid) grip be used at the ends (Figure 7-a) or free support (Figure 7-b), free support was chosen for a better approximation of real conditions.

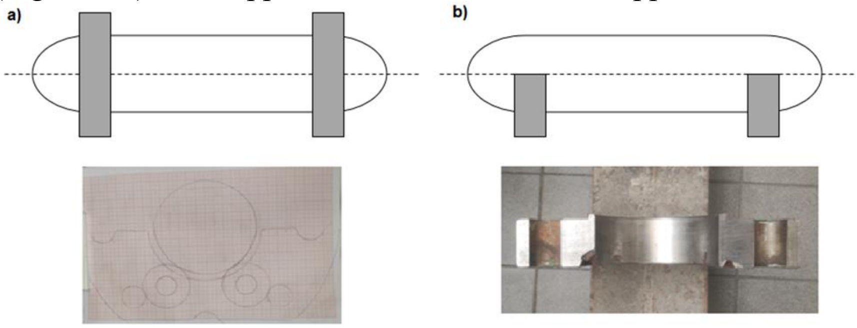


**Figure 7 The support method**

Regarding the position of the external load transition device, should it be positioned perpendicular to the longitudinal axis of the pipe (Figure 8-a) or at an angle to the longitudinal axis of the pipe (Figure 8-b), The angled position relative to the longitudinal axis of the pipe was chosen because the deflection can be reliably measured and easier access to the tested section is provided.

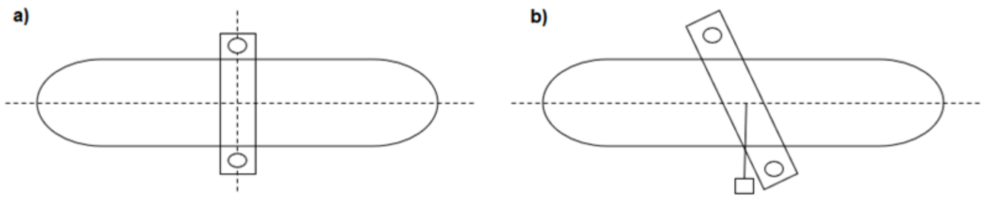


**Figure 8 The Position of the external load transition device**

## 2.3 CALCULATIONS FOR TESTING EXPERIMENTAL PIPE SECTIONS WITH COMPLEX LOADS

The initial data and their sources for the calculations performed using the relationships from the reference [20] were as follows:

Calibration of the force from bending on pipe section Y4 can be seen in Figure 9.

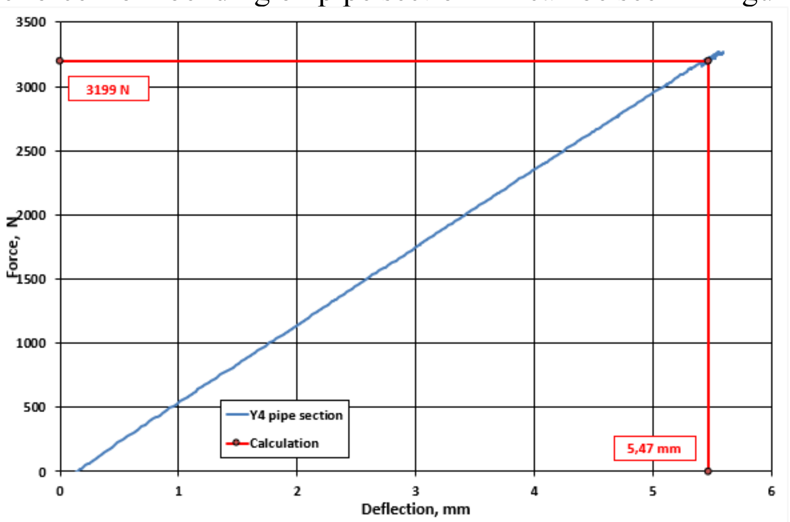


**Figure 9 Calculation of the bending force on the experimental pipe section Y4**

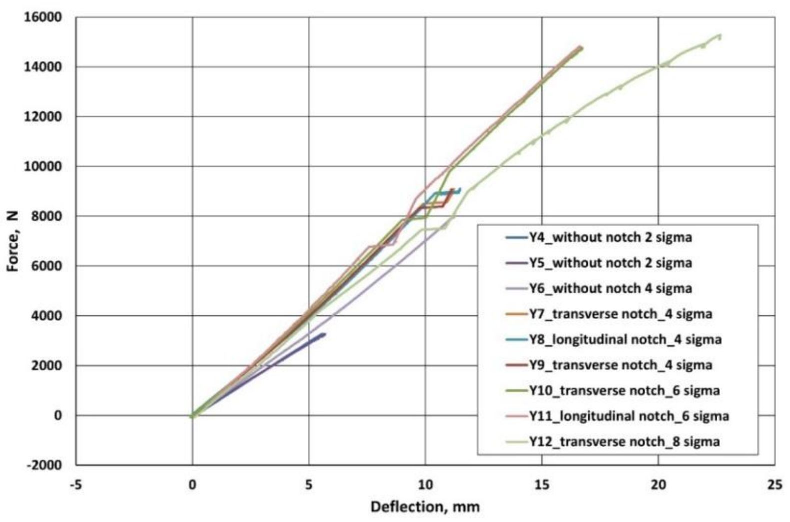


**Figure 10 Force-deflection functions of pipe sections with external load**

In the context of Figure 10, we make the following observations:

- the minimum negative values (not all force-deflection curves start from positive ranges) are due to the measurement conditions and can be neglected;
- the force-deflection values are consistent with the multiplication of the excess loads;
- the different behaviour of pipe sections without notches (Y4, ..., Y6) and pipe sections with notches (Y7, ..., Y12) is due to the notches themselves.
- the deformations are elastic, except for the Y12 section, with a nominal value of $8*\sigma_a$ of 232 $N/mm^2$, which could already cause a small plastic deformation near the notch, and which is reflected in the corresponding force-deflection function.

## 2.4 TESTING EQUIPMENT AND THEIR CHARACTERISTICS

The elements and equipment that make up the test system are located in two areas, one in a laboratory building and the other in a test pit built in front of the building. The tests are controlled from the building, and the experimental pipeline sections are located in the test pit. Two systems are available for testing structures subjected to internal pressure, and a separate system has been developed for external bending loading.

The two pressure increasing systems are essentially identical in design, one for pressures up to 100 bar (called NEW) and the other up to 700 bar (called OLD). The lower capacity system is used for fatigue testing and the higher capacity system for burst testing. The hydraulic cylinders and control units in the laboratory area are shown in figure 11; the hydraulic power supplies are located in a separate room directly next to the laboratory to reduce operating noise.

Based on these abilities and capacities a unique testing system has been developed for the complex loading of pipeline sections. Cyclic internal pressure and superimposed external bending loads can be applied for the investigations in the three-point bending (TPB or 3PB) configuration. In this series of experiments the tested girth weld was positioned in the middle of the tested pipeline section. The experimental layout together with the introduction of the key elements in the test pit can be seen in figure 12.

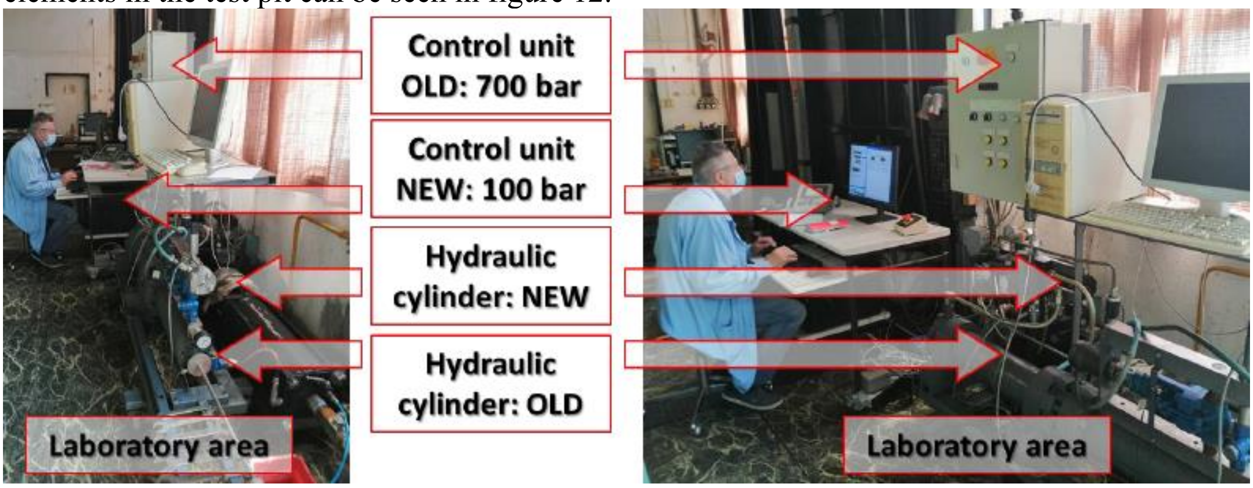


**Figure 11 The laboratory area with hydraulic cylinders and control units of the testing systems.**

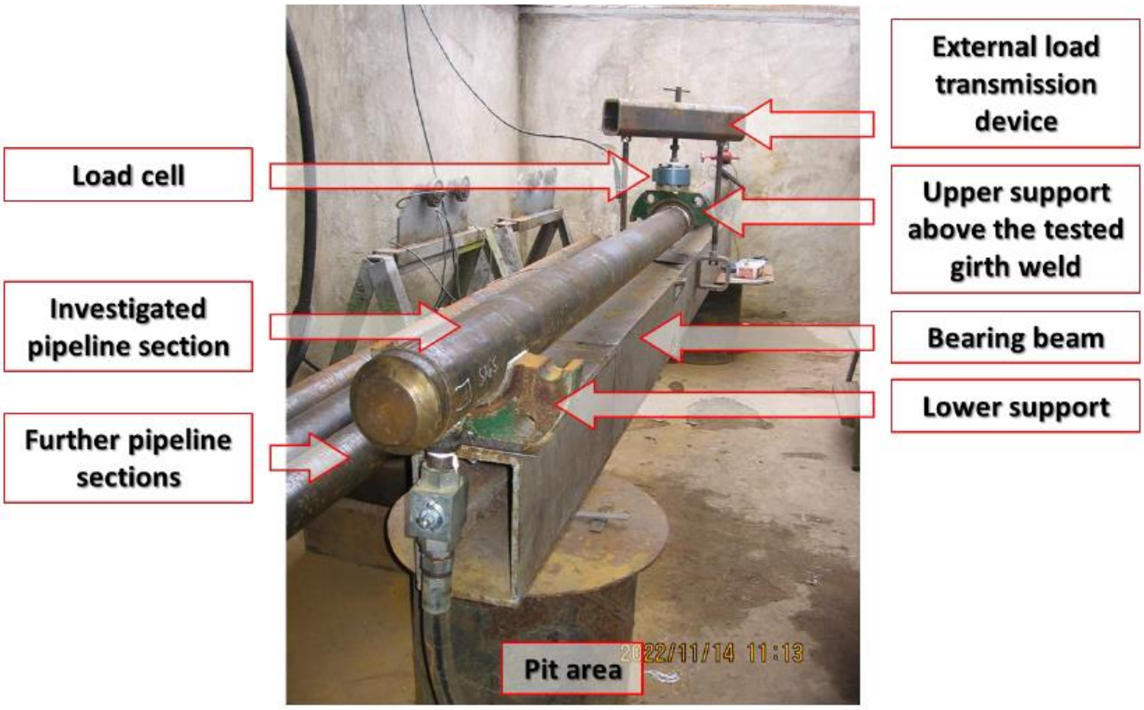


**Figure 12 The pit area of our developed system with a pipeline section.**

The superimposed bending moment was set using a certified load cell and verified using a certified extensometer with an extended arm. The positioning of the tested girth welds was performed using a scaled plate with drilled holes (see Figure 13 and Figure 14).
The burst process was recorded with two video cameras, both positioned at the edge of the pit area, following the burst process from above. One camera was positioned in the direction of the longitudinal axis of the tested pipeline section and the other perpendicular to it.

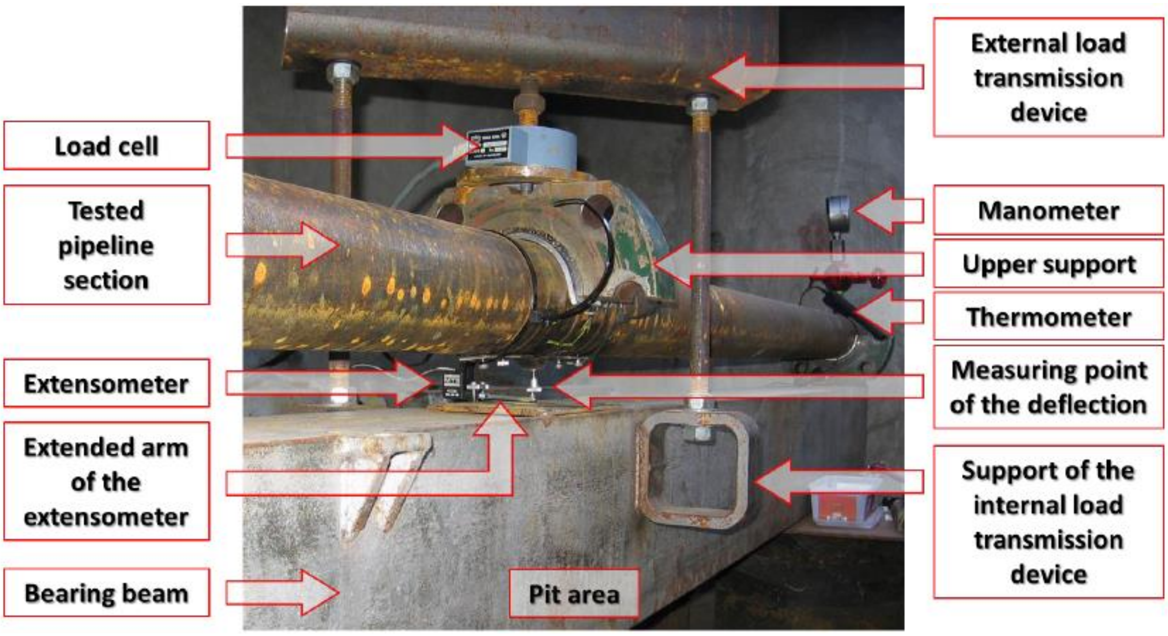


**Figure 13 Setting the deflection by load cell and its verification by extensometer with an extended arm.**

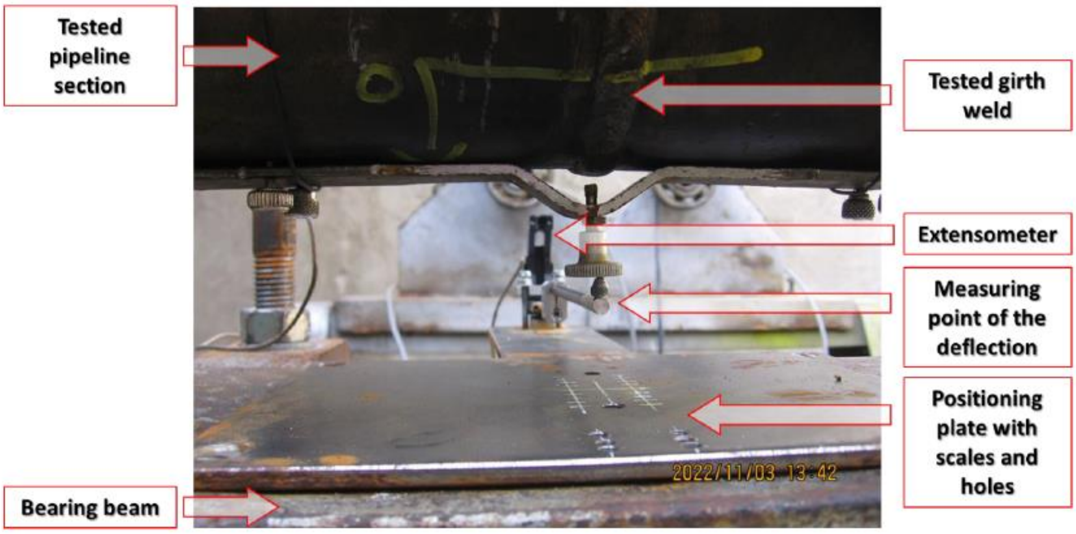


**Figure 14 The positioning plate with scales and holes, and the measurement of the deflection by extensometer with extended arm.**

Twelve pipeline sections were tested with different characteristics. The experiences of the Hungarian transporting pipeline operator (FGSZ Ltd.) have pointed to that external undercuts and lack of fusions (between the base materials and weld metals) can be found in inadequate girth welds. Other experiences of the Hungarian transporting pipeline operator have shown that third-party (near) longitudinal damages are also common and significantly increase the operational risk, especially when interacting with both girth and spiral welds. These were the reasons why we also tested girth welds 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). The external undercuts and lack of fusions were modelled using circumferential notches, the third-party (near) longitudinal damages interacting with girth welds were modelled by longitudinal notches. Since the artificial notches were made by the same person using the same hand grinder, their maximum nominal width was 2 mm. The shape of the artificial notches followed the shape of both the pipe and the grinding wheel (Figure 17), with their width decreasing slightly in the direction of the pipe wall thickness. Figure 18 demonstrates the two types of notch configurations.


**Figure 15 The artificial notch configurations**

**Figure 16 Artificial notch in the girth weld HAZ of the Y10 pipeline section (left), artificial notch through the girth weld of the Y8 pipeline section (right)**

All pipeline sections, except Y3, were subjected to 100,000 cycles of fatigue loading. The cyclic internal pressure was adjusted to the real operating pressure and was changed between 60% and 100% of the maximum allowable operating pressure (MAOP, 64 bar). The applied axial stress from bending was two, four, six and eight times (in relevant figures 2 sigma, 4 sigma, 6 sigma and 8 sigma, respectively) of the axial stress ($\sigma_a$) from the maximum internal pressure. During the fatigue tests 0.2 Hz testing frequency was applied, moreover during the fatigue and the burst tests water was used as testing media. During the long test period, the ambient temperature varied between 15 °C and 30 °C, but this variation had no significant effect on the implementation of the tests or the mode of the fracture behaviour of the pipeline sections. The main characteristics of the full-scale tests can be found in Table 8.

After the girth welds were made, they were radiographed by Gamma-Control Ltd. The results of the investigations are summarised in Table 7, which shows that the girth welds contained only tolerable or suitable (S) discontinuities. Therefore, the condition that the quality of the girth welds should not influence the results of the mechanical tests was fulfilled.

**Table 7 Main characteristics of the RT carried out on the full size test pipe sections after preparing the weld**

| Pipeline section ID | Weld No. | | Gamma-Controll Kft. | |
|---|---|---|---|---|
| | Girth welds | GWS | T/E | D&C [21] |
| Y3 | F3, F15, F27 | F15 | 2022.04.12 | Nothing |
| Y1 | F1, F13*, F25 | F13 | 2022.04.12 | 2011 – S; 3012 – S; 514 – S |
| Y2 | F2, F14, F26 | F14 | 2022.04.12 | 504 – S; 507 - S |
| Y4 | F4, F16, F28 | F16 | 2022.04.12 | 504 – S; 514 – S |
| Y5 | F5, F17, F29 | F17 | 2022.04.12 | 2011 – S; 514 – S |
| Y6 | F6, F18, F30 | F18 | 2022.04.12 | 504 – S; 5013 – S |
| Y7 | F7, F19, F31 | F19 | 2022.04.12 | 5013 – S; 515 – S |
| Y8 | F8, F20, F32 | F20 | 2022.04.12 | 2011 – S; 504 – S |
| Y9 | F9, F21, F33 | F21 | 2022.04.12 | 2011 – S; 504 – S |
| Y10 | F10, F22*, F34 | F22 | 2022.04.12 | 3012 – S |
| Y11 | F11, F23, F35 | F23 | 2022.04.12 | 504 – S; 507 – S; 514 – S |
| Y12 | F12, F24, F36 | F24 | 2022.04.12 | 3012 – S; 504 - S |

**Table 8 The main characteristics of the full-scale tests**

| Pipeline section ID | Fatigue* | External bending | Notch location | Notch direction | Nominal notch depth | Nominal notch length (mm) |
|---|---|---|---|---|---|---|
| **Y3** | N/A | N/A | N/A | N/A | N/A | N/A |
| **Y1** | performed | N/A | N/A | N/A | N/A | N/A |
| **Y2** | performed | N/A | N/A | N/A | N/A | N/A |
| **Y4** | performed | $2\sigma_a$ | N/A | N/A | N/A | N/A |
| **Y5** | performed | $2\sigma_a$ | N/A | N/A | N/A | N/A |
| **Y6** | performed | $4\sigma_a$ | N/A | N/A | N/A | N/A |
| **Y7** | performed | $4\sigma_a$ | girth weld HAZ | circumferential | 0.37 t | 29 |
| **Y8** | performed | $4\sigma_a$ | through girth weld | axial | 0.50 t | 41 |
| **Y9** | performed | $4\sigma_a$ | girth weld HAZ | circumferential | 0.67 t | 40 |
| **Y10** | performed | $6\sigma_a$ | girth weld HAZ | circumferential | 0.50 t | 30 |
| **Y11** | performed | $6\sigma_a$ | through girth weld | axial | 0.67 t | 40 |
| **Y12** | performed | $8\sigma_a$ | girth weld HAZ | circumferential | 0.50 t | 40 |

* If fatigue was applied, the number of cycles was 100,000 cycles

## 3. FULL-SCALE INVESTIGATIONS PROCESS

Our samples (pipeline sections) had the following tests in order:

- visual, liquid penetrant, and radiographic investigations (VT, PT, and RT, respectively);
- radiographic investigation (RT);
- fatigue test (100,000 cycles);
- radiographic investigation (RT)
- pressure test (6 hours);
- burst test.

### 3.1 VISUAL, LIQUID PENETRANT, AND RADIOGRAPHIC INVESTIGATIONS

The tested girth welds were made by manual metal arc welding and were inspected by visual, liquid penetrant, and radiographic tests (VT, PT, and RT, respectively). Only girth welds that have been produced to an acceptable quality level have been tested. This also means that the consistently high quality of the girth welds made it possible to investigate the impact of other influencing factors on the damage characteristics.

### 3.2 RADIOGRAPHIC INVESTIGATIONS BEFORE AND AFTER THE FATIGUE TEST

After each investigation, a radiographic test was performed to check the girth weld and see if there was any significant change that could affect our investigation (Figure 17).

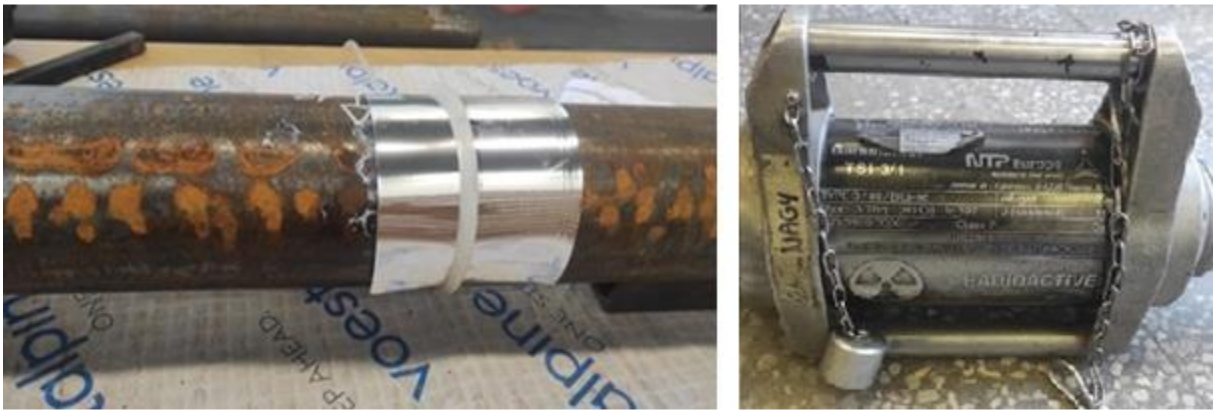


**Figure 17 The preparation for the RT test (left), The device we used to do the RT (right)**

## 3.3 Fatigue test

The cycle fatigue test was for 100,000 cycles of internal pressure loading, with or without external bending loading. The cyclic internal pressure varied between 60% and 100% of the operational pressure (64 bar). The external bending loads were applied during the cyclic loading (100,000 cycles) and the burst test. The applied axial stress from superimposed bending was two, four, six and eight times (in relevant figures 2S, 4S, 6S and 8S, respectively) of the axial stress ($\sigma_a$) from the maximum internal pressure. In the three-point bending arrangement, the tested girth weld was positioned in the middle of a nominal 4 meters long pipeline section; the bending load was set via a load cell and checked by means of a deflection meter [22], [23] (Figure 18). During the fatigue tests 0.2 Hz testing frequency was applied; in addition, during the fatigue and the burst tests water was used as testing media. During the long test period, as the test pit is located outdoors, the ambient temperature changed between 15 °C and 30 °C. This variation of the outside temperature had no significant effect on the execution of the tests or the mode of the fracture behavior of the pipeline sections

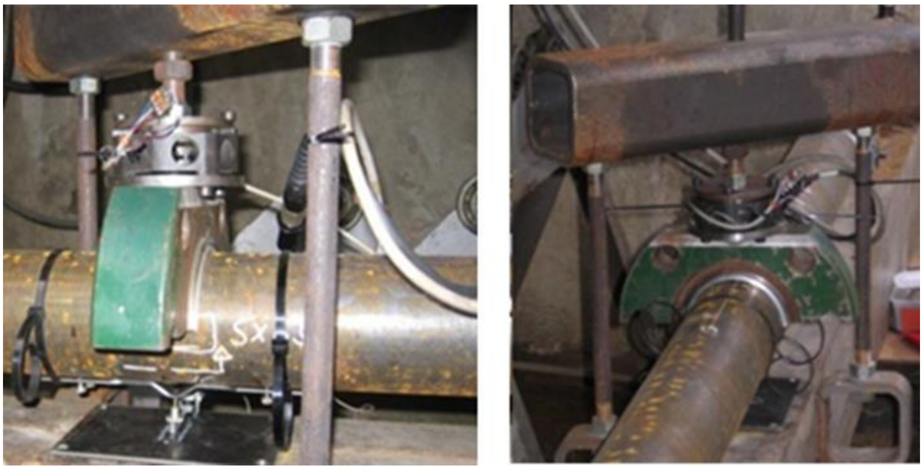

**Figure 18 Load cell and deflection meter for the external bending(left), Transfer of external load for the external bending (right)**

The time required to complete 100,000 fatigue cycles was nearly 6 full days (nearly 139 hours) of uninterrupted testing. By looking at Figure 19, it can be stated that the variation of the internal pressure was stable throughout the whole process, except for the initial and final transients.

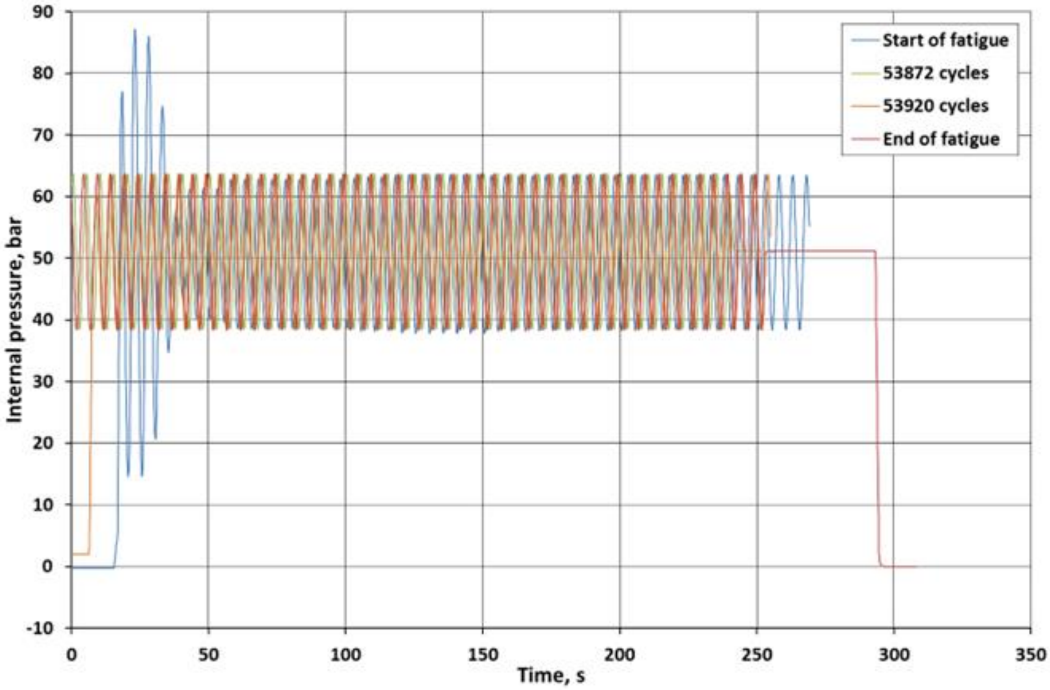


**Figure 19 Internal pressure vs. time functions recorded during the fatigue test of pipeline section with minimum superposed external bending load (Y4)**

The deflection value and its variation were continuously monitored. These values were recorded every 5,000-8,000 cycles, with a time interval of 50-60 cycles (250-300 s).

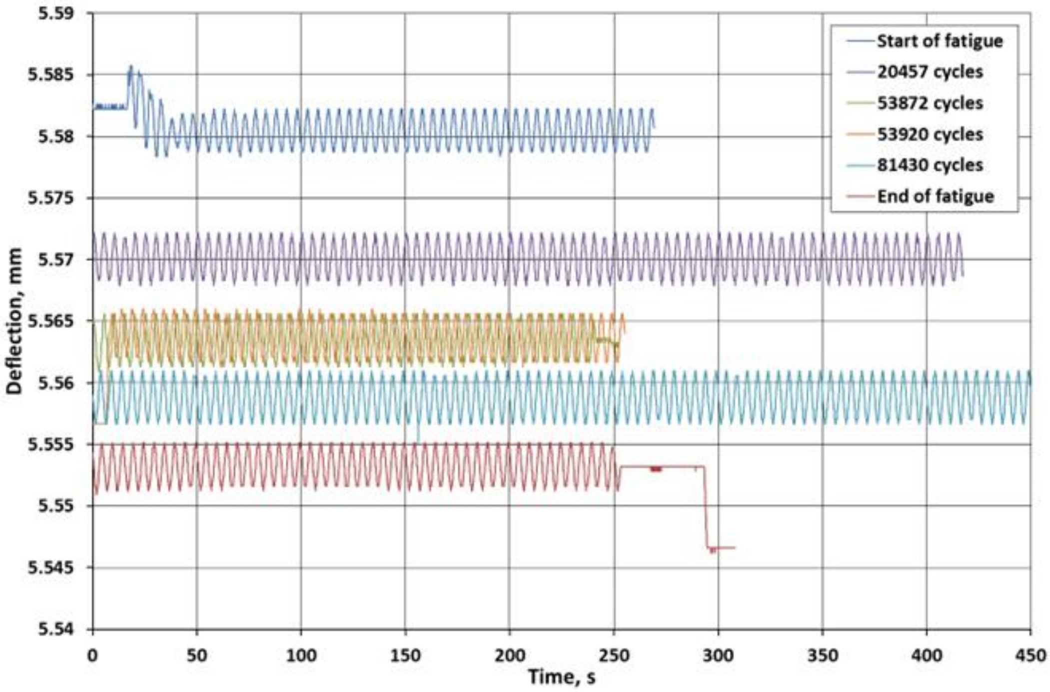


**Figure 20 Deflection vs. time functions recorded during the fatigue test of pipeline section with minimum (2 $\sigma_a$) superposed external bending load (Y4)**

The deflection-time plots in Figure 20 reflect the change in internal pressure and its stability and illustrate the magnitude of the deflection and the extent of its change. The two figures also highlight the difference in deflection due to minimum and maximum superposed bending loads.

## 3.4 PRESSURE TEST

Every sample from our twelve pipeline sections was subjected to a pressure test for 1.5 times the operation pressure (95 bar) in a closed system for six hours. During this period, the pressure and temperature were recorded almost every hour (Figure 21).

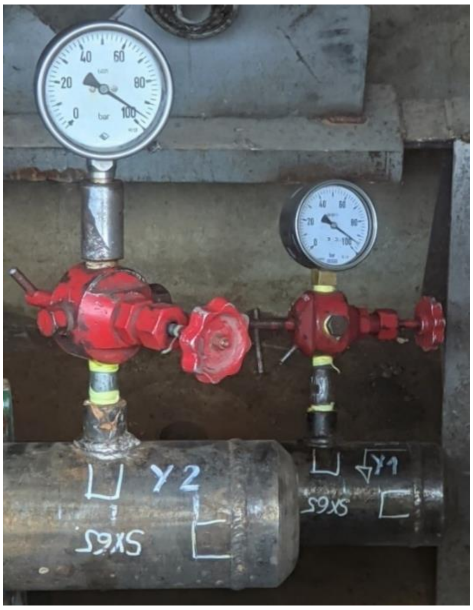


**Figure 21 The samples Y1 and Y2 during the pressure test**

During the pressure test, no pipe sections were damaged and temperature and pressure values remained within acceptable ranges. All tested pipeline sections withstood the 6-hour-long hydrostatic pressure test without any significant loss of internal pressure. The result indicates that the quality of the pipe sections and the test girth welds was not significantly altered by the strength pressure test phase.

## 3.5 BURST TEST

After the burst tests were completed (Figure 22), the video camera recordings were reviewed, the picture-frames corresponding to the moment of failure were cut, and the internal pressure vs. burst test time diagrams were plotted from the recorded internal pressure values (Figure 23).

**Figure 22 Y1 pipeline section at the moment of its failures**


**Figure 23 The pressure value during the burst test (example)**

## 4. TESTING RESULTS

Results of the visual testing (VT) and the radiographic testing (RT) repeated after the fatigue tests showed no detectable decisive changes in any of the cases. Table 9 summarizes the results of the radiographic examinations performed by Albera'97 Ltd. before and after the fatigue tests. This means that the fatigue stage did not cause significant changes in the quality of the investigated girth welds.

Figure 24 illustrates the average deflection vs. fatigue cycle number curves for each pipeline section subjected with minimum, intermediate, maximum and all superimposed bending. The data are derived from the systematic processing of functions similar to the functions of the diagram. The curves for 2 σa, 4 σa, 6 σa, and 8 σa stresses, furthermore for circumferential and axial notches are clearly distinguished in the figure. As the figure illustrates, the magnitude of the stress plays a determining role. It is noteworthy that the curves for each pipeline section show the same trends and their location is fully consistent with our approach.

**Table 9 Results of radiographic testing (RT) performed on the test girth welds by Albera'97 Kft., before and after the fatigue test**

| **Pipeline section ID** | **Before the fatigue test** | | | **After the fatigue test** | | |
|---|---|---|---|---|---|---|
| | **GWS*** | **T/E** | **D&C** [21] | **GWS*** | **T/E** | **D&C** [21] |
| **Y3** | **Y3** | 2022.06.30. | 602 – S | **N/A** | N/A | N/A |
| **Y1** | **Y1/V13** | 2022.06.15. | 2015 – S; 602 – S and "Film error" | **13** | 2022.07.27. | Nothing |
| **Y2** | **Y2** | 2022.06.30. | 5013 – S | **14** | 2022.07.27. | Nothing |
| **Y4** | **Y4** | 2022.06.30. | 602 – S | **Y4** | 2022.10.06. | Nothing and "Contamination in the pipe" |
| **Y5** | **17** | 2022.07.27. | 2011 – S; 602 – S | **Y5** | 2022.10.06. | 2011 – S |

| Pipeline section ID | Before the fatigue test | | | After the fatigue test | | |
|---|---|---|---|---|---|---|
| | **GWS*** | **T/E** | **D&C** [21] | **GWS*** | **T/E** | **D&C** [21] |
| **Y6** | **18** | 2022.07.27. | Nothing | **Y6** | 2022.11.10. | Nothing |
| **Y7*** ** | **Y7** | 2022.10.06. | 515 – S | **Y7** | 2022.11.10. | 604 – NS |
| **Y8*** ** | **Y8** | 2022.10.06. | 2016 – NS | **Y8** | 2022.11.10. | 604 – NS |
| | | | | **Y8** | 2022.11.29. | 2015 – NS; 604 – NS and „Grinding traces across the weld” |
| **Y9*** ** | **9** | 2022.11.10. | 5012 – S | **Y9** | 2022.11.29. | 604 – NS and „Grinding traces near the weld” |
| **Y10*** ** | **10** | 2022.11.10. | 2015 – S | **Y10** | 2022.11.29. | 604 – NS and „Grinding traces near the weld” |
| **Y11*** ** | **11** | 2022.11.10. | Nothing | **R23** | 2023.11.07. | 602 – S; 604 – S |
| **Y12*** ** | **12** | 2022.11.10. | Nothing | **R24** | 2023.11.07. | 602 – S; 604 – S |

* Notation applied by the investigators, which are intentionally disclosed for the identification with official "Radiographic Test Report"-s.
** The radiographic investigations and their assessments are not necessarily carried out by the same persons before and after the fatigue tests.
*** It was not known to the radiographers that artificial notches were present around the girth welds - in all cases 604 reference numbers (grinding mark, local damage due to grinding) of imperfections were noted, and in some cases the presence of a grinding mark was specifically noted.

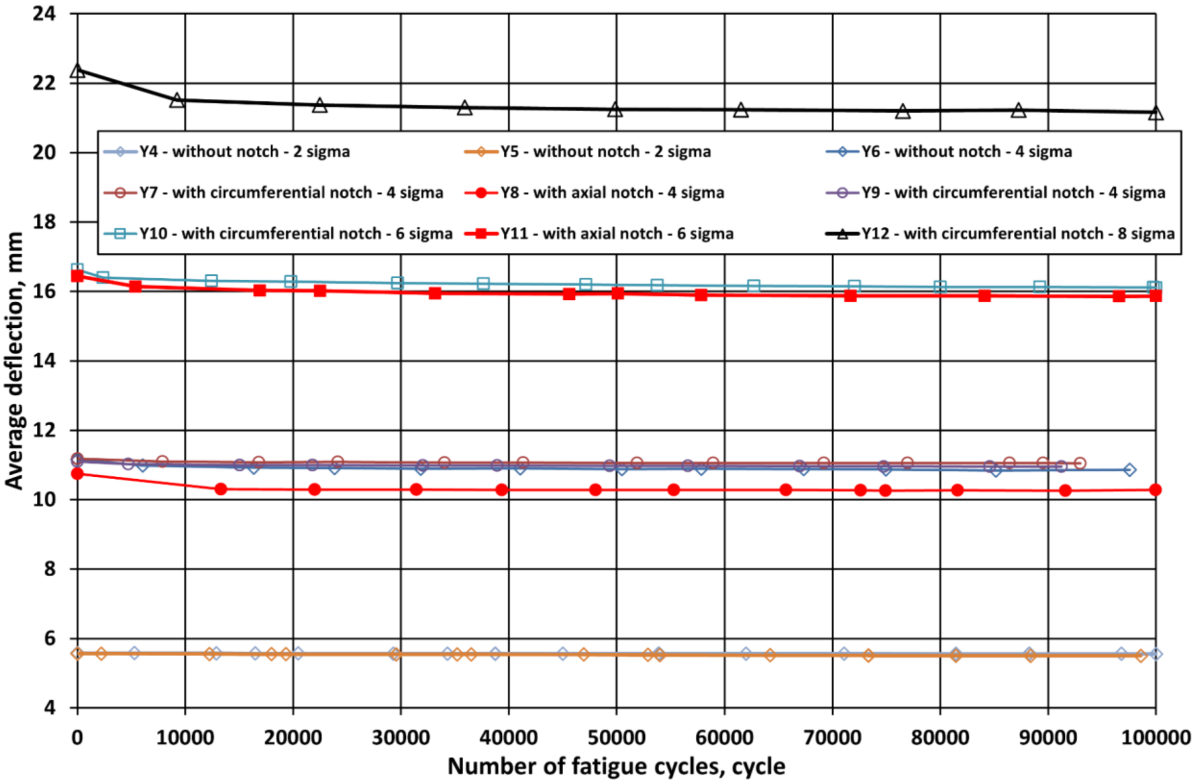


**Figure 24 Average deflection values and their changes during the fatigue tests: all pipeline sections**

Figure 25 and Figure 26 show the internal pressure vs. burst test time diagrams for the investigated pipeline sections, where the arrows indicate the burst points.

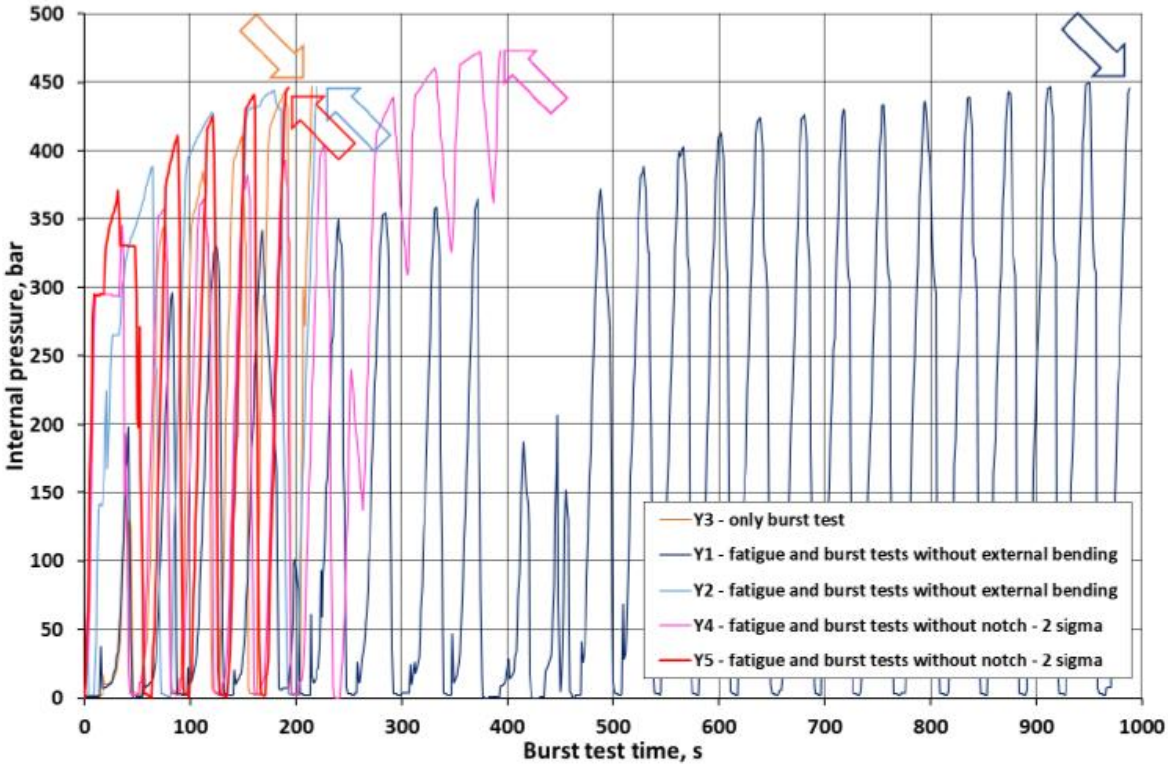


**Figure 25 Internal pressure vs. burst test time diagrams of the investigated Y1-Y5 pipeline sections**

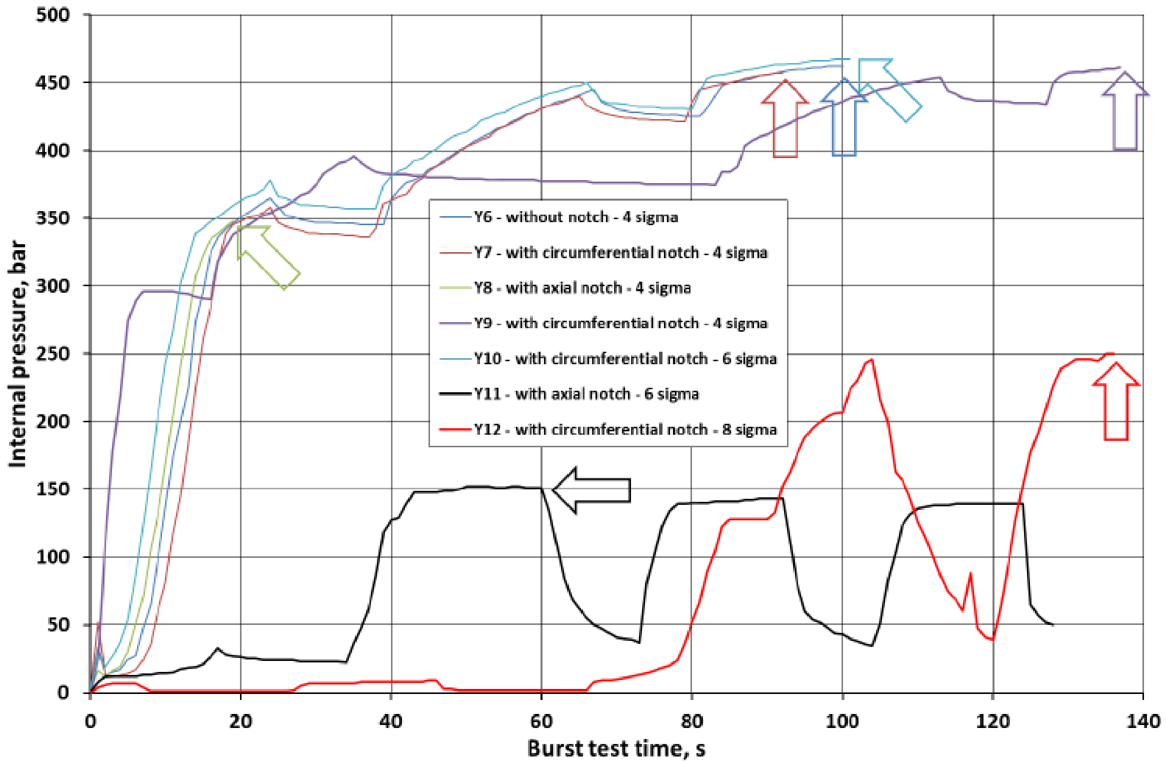


**Figure 26 Internal pressure vs. burst test time diagrams of the investigated Y6-Y12 pipeline sections**

The main characteristics of the Y1-Y5 and Y6-Y10 diagrams are the same; however different burst test times can be noticed. Partially different behavior was observed for Y11 and Y12

pipeline sections, due to the larger size of the notches and the higher stress ($\sigma_a$) resulting from the higher bending load.
The average internal pressure growth rate values both in the first stage and in the latter stages can be assessed as quasi-static values, no significant dynamic effects were observed. In all cases, we have experienced different numbers of tines-like changes on the curves which demonstrate the volume increase of the pipeline sections. The increase in volume is the natural result of elastic-plastic deformation; during these periods, the system draws water from the water supply network.
A dimensionless safety factor was interpreted to quantify the behavior of the pipeline sections, with the following equation:

$$Safety\ factor = \frac{Burst\ Pressure}{Maximum\ Allowable\ Operating\ Pressure} = \frac{BP}{MAOP}$$

where BP is the measured burst pressure [bar] and MAOP is the Maximum Allowable Operating Pressure [bar].
Table 10 summarizes both the main characteristics and the burst pressure (BP), furthermore the safety factor (SF) values of the investigations, assuming that the value of the MAOP is 64 bar. the locations of damage followed by the damage section and the outer diameter of the pipelines after the burst test (Figure 34, Table 11).
Images cut from the video recording show clearly and distinctly in which cases the failure occurred on the pipe body and in which cases it occurred in the tested girth weld.

**Table 10 The main characteristics and the burst pressure (BP) and the safety factor (SF) values of the investigations**

| Pipeline section ID | Notch location | Notch direction | Burst pressure(bar) | Failure location | SF ( – ) |
|---|---|---|---|---|---|
| **Y3** | N/A | N/A | 446 | pipe surface | 6.97 |
| **Y1** | N/A | N/A | 447 | pipe surface | 6.98 |
| **Y2** | N/A | N/A | 447 | pipe surface | 6.98 |
| **Y4** | N/A | N/A | 473 | pipe surface | 7.39 |
| **Y5** | N/A | N/A | 446 | pipe surface | 6.97 |
| **Y6** | N/A | N/A | 462 | pipe surface | 7.22 |
| **Y7** | girth weld HAZ | circumferential | 457 | pipe surface | 7.14 |
| **Y8** | through girth weld | axial | 348 | axial notch through girth weld | 5.44 |
| **Y9** | girth weld HAZ | circumferential | 461 | pipe surface | 7.20 |
| **Y10** | girth weld HAZ | circumferential | 467 | pipe surface | 7.30 |
| **Y11** | through girth weld | axial | 152 | axial notch through girth weld | 2.38 |
| **Y12** | girth weld HAZ | circumferential | 250 | circumferential notch | 3.91 |

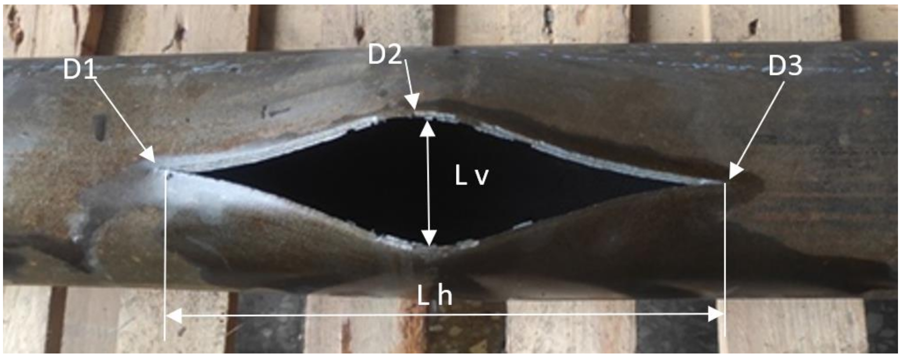


**Figure 27 The damage section**

**Table 11 The damage section measurements**

| Pipeline ID | Lv (mm) | Lh (mm) | D1 (mm) | D2 (mm) | D3 (mm) |
|---|---|---|---|---|---|
| **Y1** | 56 | 261 | 126 | 129 | 127 |
| **Y2** | 41 | 234 | 125 | 127 | 124 |
| **Y3** | 64.5 | 243 | 124 | 131 | 124 |
| **Y4** | 50 | 240 | 124 | 129.5 | 122 |
| **Y5** | 60 | 245 | 123 | 133 | 125 |
| **Y6** | 70 | 255 | 123 | 145 | 122 |
| **Y7** | 61 | 234 | 118 | 151 | 121 |
| **Y8** | 39 | 174 | 115 | 137 | 116 |
| **Y9** | 55 | 254 | 118 | 144 | 117 |
| **Y10** | 61 | 269 | 121 | 151 | 121 |

Based on the results of the burst test, we found that:

- The failure of the investigated pipeline sections without artificial notches (Y1-Y6 pipeline sections) occurred similarly, but in none of the cases in a girth weld, and the burst pressures were significantly higher than the operating pressure.
- The failure of the investigated (in the girth weld HAZ) circumferentially notched pipeline sections Y7, Y9, Y10, and Y12 pipeline sections with one exception (Y12) occurred similarly too, in all cases in the pipe body, regardless of the notch depth and the magnitude of additional stress from bending load. The failure of the exceptional pipeline section (Y12) occurred in the notch at a significantly lower pressure than in other circumferentially notched cases. Furthermore, the burst pressures were significantly higher than the operating pressure.
- Failure of the pipeline sections containing axial notch Y8 and Y11 pipeline sections occurred in the notch and at significantly lower pressure than the other notch-free and notched pipeline sections.
- The failure sections of all the pipelines except Y11, Y12 are measured, in addition to the outer diameter of the pipeline in the middle and at the sides of the failure section, after the failure measurements described in Figure 34 and Table 11. Based on those results, we can notice that the failure for all the samples started at one point, which we measured D2, then extended in both directions, and at the end of the failure section, we measured D1 and D3.

## 5. NEW SCIENTIFIC RESULTS – THESES

T1. The damage cause distributions of domestic (Hungarian) hydrocarbon transmission pipelines differ from those of foreign pipelines; the differences can be originated in a higher ratio of damage on the girth welds of the domestic system. The statement has been proved by an analysis and a comparison of domestic and international damage statistics. (1) (2) (8) (11)

T2. The own designed and implemented device for transmitting bending load, in cooperation with and forming an integrated system with the pressure intensification unit, is suitable for reliable testing of full-scale pipeline sections without and with girth welds subjected to cyclic internal pressure and superposed external bending. The statement has been confirmed by the investigations carried out and their results. However, the outside diameter of the investigated pipeline sections depends on the structural element (device) designed to transmission the bending load, therefore limited. (1) (3) (5) (15)

T3. The material discontinuities of the girth welds loaded with a number of internal pressure cycles (60% MAOP - 100% MAOP) in the range of high cycle fatigue did not increase under cyclic loading, and new material discontinuities did not develop; furthermore, this was not affected by the superposition of external loads on the cyclic loading. This statement has been confirmed by the results of radiographic examinations carried out before and after the fatigue tests. (1) (2) (3) (4)

T4. In the case of external loads being superposed on cyclic loads, as complex loads, the damage to the girth welds is primarily influenced and determined by the external load and its magnitude. This statement has been verified by the fact that no failure occurred in the girth welds either under fatigue loading or during the pressure test following fatigue loading. (2) (3)

T5. The load bearing capacity and safety of complex loaded girth welds with artificial defects (notches) is determined by the interaction of location, length and depth of the artificial notches. This statement has been confirmed by the results of tests carried out on pipeline sections containing artificial notches. (3) (6) (7)

T6. Girth welds have a (residual) load-bearing capacity, in other words an operating reserve, even in cases where they contain defects not permitted by the specifications. This statement has been confirmed by the results of tests, where, despite the presence of artificial defects not allowed, the failure did not occur in the girth welds but in the pipe body. The statement is valid up to the limit of the investigated defects. (6) (7) (12)

## 6. SUMMARY AND FURTHER PLANS

This study focused on developing the structural integrity of pipelines through a series of full-scale tests, based on the results of the previous research that helped us understand pipeline behavior under operational and extreme conditions. Collaborating with an industrial partner, an on service pipeline samples were acquired to perform the research. A special fixing device was designed and built to hold the samples during testing, to make sure of consistent and reliable results. Starting with radiographic testing (RT) to start with a baseline assessment of the samples' structural integrity, ensuring no pre-existing defects. The samples were subjected to a six-hour hydrostatic pressure test, simulating the operational pressures. After the test, the radiographic test confirmed no structural changes, indicating robust performance under sustained pressure. Following that, a cyclic fatigue test (100,000 cycles) was performed between the 60% and the 100% of the actual working pressure values to simulate long-term operational stress. The radiographic tests again showed no signs of deformation or micro-cracking. The final test part involved burst tests to evaluate failure under varied conditions: Simple burst test: Assessing baseline failure pressure. Burst tests with superimposed loads: Applying external forces to simulate geological or mechanical stresses. Notches during the burst test were performed to conducted on samples with axial and circumferential notches to study crack propagation under stress concentrations. These burst tests, designed to induce failure, provided critical data on pipeline performance under extreme and defect-prone conditions. While the pressure and fatigue tests demonstrated the samples' resilience, the burst tests revealed failure modes dependent on load type and notch orientation, offering insights for pipeline design and safety protocols.

The own-developed test system is suitable for testing full-scale pipeline sections without and with girth welds subjected to cyclic internal pressure and superimposed external bending. The outside diameter of the pipes to be investigated is limited by the structural element (device) designed to transmission the bending load.

The failure of the tested pipeline sections without artificial notches occurred similarly, but in none of the cases in a girth weld, and the failure pressures (burst pressures) were significantly higher than the operating pressure. The failure of the tested circumferentially notched pipeline sections with one exception (Y12 pipeline section) occurred similarly too, in all cases in the pipe surface, regardless of the notch depth and the magnitude of additional stress from bending. The failure of the exceptional pipeline section (Y12) occurred in the notch at a significantly lower pressure than in other similar cases. Furthermore, the failure pressures (burst pressures) were significantly higher than the operating pressure. Failure of the pipeline sections containing axial notch (Y8 and Y11 pipeline sections) occurred in the notch and at significantly lower pressure than the other unnotched and notched pipeline sections.

Both the performed full-scale tests and the determined safety factor values have confirmed the high load-bearing capacity of the girth welds produced to the required quality. The high load-bearing capacity covers both cyclic and complex loads. This also implies that previous damages in the Hungarian gas transporting system have occurred in girth welds of unacceptable quality and/or subjected to significantly higher overloads.

The investigations and their results have demonstrated the importance of the full-scale tests. Moreover, these investigations have confirmed that further full-scale tests should be executed in the near future.

- Pipeline sections containing girth weld should be investigated applying higher axial stresses from the superimposed external bending (e.g. eight times of the axial stress from the maximum internal pressure).

- Similarly necessary to test pipeline sections that contain deeper and/or longer artificial notches on the tensile bending stress side of the girth welds.
- The effect of the temperature, basically the lower temperatures, should also be investigated. The operating pipelines have below-ground sections, where the temperature at the laying depth is 8 °C under the climatic conditions in Hungary.
- In many countries, including Hungary, there are plans to blend hydrogen into the natural gas transmission system [24]. Therefore, the tests should be extended to cover the testing of girth welds exposed to hydrogen.
- The future planned studies and investigations should be carried out by varying the parameters separately in the short term, and jointly in the medium and long term.

# 7. APPLICATION POSSIBILITIES OF THE RESULTS

Based on the experiences acquired from the use of the developed testing system, as well as the tests performed and their results, the potential applications of the research work are as follows.

- The developed testing system is suitable for full-scale testing of cylindrical structural elements (industrial and transporting pipelines, pressure vessels) subjected to complex loading (static or cyclic internal pressure and external bending). During the investigations, geometric constraints of the system must be taken into account.
- The developed testing system enables and offers possibilities for further development and may serve as a basis for the construction of similar systems. Several directions for further development can be projected: the application of non-ambient temperatures, the use of external media different from the environment and internal media different from water, and the application of tensile and/or torsional static preloading.
- The existing results and the results of further similar tests allow operators to establish rankings. On the one hand, allowable discontinuities can be ranked, and on the other hand, potential loads can also be ranked in terms of both hazard and acceptability. These rankings may influence the design and implementation of welding technologies, as well as the planning and execution of non-destructive testing of welded joints. There is no realistic prospect that the extent of testing for girth welds could be reduced below 100%, but a differentiated and optimized application of testing techniques seems achievable.
- The results can provide a basis for a deeper and/or more complex assessment of the integrity of girth welds by evaluating the influencing effects of welding discontinuities and artificial flaws. This may lead to the revision of currently valid prescriptions and the modification of the limit values of the criteria contained therein. The modification of limit values is conceivable in both directions: both tightening and relaxation are possible.
- The experiences acquired from the examination of girth welds may contribute to the modification of intervention strategies, and thereby help in the prevention and reduction of failures.
- The experiences acquired from the examination of girth welds may also support the assessment of the integrity of seam and spiral welds.

# 8. LIST OF PUBLICATIONS RELATED TO THE TOPIC OF THE RESEARCH FIELD

**In English:**

(1) J. Lukács and A. Y. Dakhel, “Full-scale Fatigue and Burst Tests on Notched Pipeline Girth Welds, under Complex Loading Conditions,” Acta Polytechnica Hungarica, vol. 21, no. 5. Obuda University, pp. 53–70, 2024. doi: 10.12700/aph.21.5.2024.5.5.

(2) Dakhel Ahmad Yasser, Gáti József, Koncsik Zsuzsanna, Lukács János, “Fatigue and burst tests of pipeline girth welds under simple and complex loading conditions”, 77th IIW Annual Assembly and International Conference on Welding and Joining IIW (2024) pp. 1-21. Paper: XI-1140-2024 , 21 p.

(3) A. Y. Dakhel, M. Gáspár, Zs. Koncsik, and J. Lukács, “Fatigue and burst tests of full-scale girth welded pipeline sections for safe operations,” Welding in the World, vol. 67, no. 5. Springer Science and Business Media LLC, pp. 1193–1208, Feb. 25, 2023. doi: 10.1007/s40194-023-01501-x.

(4) A. Y. Dakhel and J. Lukács, “Full-Scale Tests of Pipeline Girth Welds Under Complex Cyclic Internal Pressure and Static Bending Loading Conditions,” International Journal of Engineering and Management Sciences, vol. 8, no. 1. University of Debrecen/ Debreceni Egyetem, pp. 76–82, Apr. 30, 2023. doi: 10.21791/ijems.2023.1.10.

(5) A. Y. Dakhel and J. Lukács, “Full-scale tests of transporting pipeline sections : A review and consequences to our investigations,” Design of Machines and Structures, vol. 13, no. 1. Design of Machines and Structures, pp. 24–44, Jun. 15, 2023. doi:10.32972/dms.2023.003.

(6) Ahmad Yasser Dakhel, János Lukács, “Full Scale Tests on Pipeline Sections with Girth Welds under Complex Loading Conditions”, Koncsik, Zsuzsanna; Lukács, János (eds.) Kutatási eredmények a Miskolci Egyetem Gépészmérnöki és Informatikai Karának Anyagszerkezettani és Anyagtechnológiai Intézetében Miskolc, Hungary : Miskolci Egyetem, Gépészmérnöki és Informatikai Kar, Anyagszerkezettani és Anyagtechnológiai Intézet (2023) 214 p. pp. 169-184. , 16 p.

(7) A. Y. Dakhel, M. Gáspár, Zs. Koncsik, J. Lukács Fatigue, Burst Tests Among Best Ways Assess Pipeline Welds PIPELINE & GAS JOURNAL 250 : 8 pp. 1-17. , 17 p. (2023)

(8) Dakhel Ahmad Yasser, Lukács János, “Failure statistics of transporting pipelines and their consequences”, Vadászné Bognár, Gabriella; Piller, Imre (eds.) Doktoranduszok fóruma: Miskolc, 2020. november 19-20. : Gépészmérnöki- és Informatikai Kar szekciókiadványa Miskolc, Hungary : University of Miskolc (2022) 108 p. pp. 23-28. , 6 p.

(9) DAKHEL Ahmad Yasser, LUKÁCS János, “Full-Scale Tests of Pipeline Girth Welds Under Complex Cyclic Internal Pressure and Static Bending Loading Conditions”, Homolya, Márton; Mankovits, Tamás (eds.) 8th International Scientific Conference on Advances in Mechanical Engineering (ISCAME 2022) : Conference proceedings (Book of Extended Abstracts) Debrecen, Hungary : DE Műszaki Kar, Gépészmérnöki Tanszék (2022) 114 p. pp. 29-30. , 2 p. Scientific

(10) Dakhel Ahmad Yasser, Gáspár Marcell, Koncsik Zsuzsanna, Lukács János,” Safety of pipeline girth welds based on fatigue and burst tests of full-scale pipeline sections” 75th International Institute of Welding (IIW) Online & Offline Annual Assembly (2022) Paper: IIW DOC XI-1116-2022 , 17 p.

(11) Dakhel Ahmad Yasser, Lukács János, “Szállító csővezetékek tönkremeneteli módjai és annak következményei - Failure Statistics of Transporting Pipelines and their Consequences” GÉP 72 : 1-2 pp. 15-18. , 4 p. (2021)

(12) A. Y. Dakhel and J. Lukács, "How to prevent damages of transporting pipeline girth welds?," Multidiszciplináris tudományok, vol. 11, no. 4. Multidiszciplinaris tudomanyok, pp. 208–217, 2021. doi: 10.35925/j.multi.2021.4.25.

**In Hungarian:**

(13) Lukács János, Ahmad Yasser Dakhel, "Kísérleti csőszakaszok körvarratainak vizsgálata ciklikus belső nyomás és statikus külső hajlítás együttese esetén", Koncsik, Zsuzsanna; Lukács, János (eds.) Kutatási eredmények a Miskolci Egyetem Gépészmérnöki és Informatikai Karának Anyagszerkezettani és Anyagtechnológiai Intézetében, 2022 Miskolc, Hungary : Miskolci Egyetem, Gépészmérnöki és Informatikai Kar, Anyagszerkezettani és Anyagtechnológiai Intézet (2022) 250 p. pp. 157-166. , 10 p.

(14) J. Kovács, A. Y. Dakhel, and J. Lukács, "A diffúziós hidrogéntartalom hegesztett kötésekre gyakorolt hatása," Multidiszciplináris tudományok, vol. 11, no. 4. Multidiszciplinaris tudomanyok, pp. 227–240, 2021. doi: 10.35925/j.multi.2021.4.27.

(15) Lukács János, Ahmad Yasser Dakhel, "Hogyan előzhetők meg a csőtávvezetékek körvarratainak káresetei?", XII. Roncsolásmentes Anyagvizsgáló Konferencia és Kiállítás (RAKK) és 10. Anyagvizsgálat a Gyakorlatban (AGY) Konferencia (2021) Paper: D-4

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