Integrity increasing of damaged steel pipelines using external and internal reinforcing

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Abstract The integrity management and the lifetime assessment of different engineering structures and structural elements is one of the important technical-economic problems nowadays. The aim of the paper is to present the role of the external and internal reinforcing on the structural integrity of transporting steel pipelines, based on own experimental investigations. On the one hand, external and internal reinforcement technologies were developed using carbon fibre reinforced polymer matrix composite (CFR PMC) and glass fibre reinforced polymer matrix composite (GFR PMC), respectively. On the other hand, known external technology was used for the reinforcing of girth welds. Fatigue and burst tests were performed on large pipeline sections containing natural and artificial metal loss defects, and girth welds including weld defects (passed and not passed quality). Burst tests were executed after fatigue tests, using 20.000 or 100.000 cycles. Different corrosion defects were tested as natural defects, and longitudinal and circumferential gouges as well as holes and through holes were investigated as artificial defects. Both unreinforced and reinforced pipeline sections were examined. The applicability of the hybrid structures (steel + polymer matrix composites) were demonstrated by means of the experimental results and defined safety factor.

Keywords pipeline, reinforcing, structural integrity, PMC, burst test

1. Introduction

The treatment of the degradation and failure of different engineering structures, structural elements and equipment, the management of their lifetime is one of the important technical and economic problems of nowadays [1]. The cause of it is unambiguous: on the one hand, significant part of the structures have already reached or exceeded their originally planned lifetime [2], accordingly their following operation is a general interest; on the other hand, the safe and economic operation of the new structures is a key-question. The experiences of the operation [3], the frequency data of fractures, and the different failure statistics [4-6] of the engineering structures having great importance show, that the significance of cyclic loadings, fatigue and fatigue crack propagation is emphasized in general.

Among the engineering structures, hydro-carbon transporting pipelines fill an important part. Approximately, the half of the total length of the Hungarian gas transporting system is over 30 years. In the technical requirements for the pipelines, the estimated lifetime was 30 years in the 1970's [7]. However, as the pipeline age is over 30 years, a sharp increase can be experienced in the probability of failures, according to the "bath tub" failure curve [8]. Therefore, the first global aim of our research work is to improving the integrity of the Hungarian natural gas transmission system.

Material databases play important role both on the integrity management and on the Engineering Critical Assessment (*ECA*) of the pipeline systems. Therefore, the second global aim of our research work is to establish a Pipeline Integrity Management System (*PIMS*) with different data, frequently with experimental data. Material databases collected for general or special purposes and the synergy among the databases can be used to increase the efficiency of the user decisions and the reliability of the lifetime estimation. Different databases were developed for managing different pipeline systems. Data found in standards, in rules, in prescriptions and measured values were integrated in the databases. Additional databases were developed for design calculations and numerical analysis, including physical and plasticity constants of steels, polymers and Polymer Matrix Composites

(*PMCs*), such as potential reinforcing materials. Accordingly, material databases contain data of steel pipe materials, mechanical properties, geometrical dimensions; polymer matrix composite materials, mechanical properties; physical properties of steels and *PMCs* [6].

The most frequently joining technology in the field of steel pipes is the welding, numerous girth welds can be found on the pipelines. The girth welds, as separated parts of the pipeline, have own integrity [9] and the girth weld integrity has influence on the pipeline integrity. The girth weld integrity depends on many factors – *Y/T* ratio, weld metal yield strength (*YS*) mismatch, continuous or discontinuous yielding, elastic or non-elastic design, inspection level (x-ray or ultrasonic), failure mode (brittle vs. ductile) – interacting with each other [6, 9, 10].

Based on the above mentioned facts, the direct purpose of the paper is to present the role of the external and internal reinforcing on the fatigue and burst behaviour of transporting steel pipelines, reviewing our full-scale examinations. External and internal reinforcement was developed using carbon fibre (*CF*) and glass fibre (*GF*) polymer matrix composites (*PMC*), respectively [6, 11]. Known external reinforcing technology (*Clock Spring*) was used, too [12]. Fatigue and burst tests were performed on full scale pipeline sections containing natural and artificial metal loss defects, and girth welds including weld defects. Both unreinforced and reinforced pipeline sections were examined. Safety factor, burst pressure divided by Maximum Allowable Operating Pressure (*MAOP*), was defined and their calculated values demonstrate both the reserves of steel pipes and the usefulness of the reinforcing materials and technologies.

2. Testing circumstances

Full-scale, seamless (*SMLS*), seam welded (*SW* and *SW/HFW*) and spiral welded (*SPW*) steel pipeline sections were examined. Pipeline sections with and without girth welds were investigated, too, in order to study the influence of the girth weld quality and integrity on the pipeline integrity. Manual metal arc welding (*111*) and tungsten inert gas welding combined with manual metal arc welding (*141/111*) technologies were used for the making of the girth welds. The main characteristics of the investigated pipeline sections are summarized in Table 1, where *DN* is the diameter nominal of the steel pipe, d_k is the external/outside diameter of the steel pipe (*OD*) and t_a is the wall thickness of the steel pipe.

Table 1. The main characteristics of the investigated pipeline sections

Mark	DN	d_k, mm	t_a, mm	Pipe Material	Pipe Type	Girth Weld
A_e	100	108,0	4,5	L360NB	SMLS	111
B_a	200	219,1	5,0	L360MB	SW/HFW	no or 111 or 141/111
B_b	200	219,1	5,0	L360MB	SW/HFW	no or 111 or 141/111
C_d	300	323,9	7,1	L360MB	SW/HFW	no
CS_a	400	410,4	7,2-8,0	A35K	SMLS	111
CS_b	400	405-412	7,7-8,3	DX42	SPW	111
D_c	600	609,0	7,92	DX52	SW	no
E_o	200	219,1	5,0	L360MB	SW/HFW	no

The investigated pipeline sections are divided into testing sections, as follows:

- burst test of base (unwelded) pipeline;
- fatigue test (10^5 *cycles*) + burst test of base (unwelded) pipeline;
- burst test of operated (fatigued and replaced) pipeline containing girth weld with „NOT PASSED” quality;
- fatigue test ($2*10^4$ *cycles*) + burst test of pipeline containing girth weld with „PASSED” quality;

- fatigue test (*2*10⁴* or *10⁵ cycles*) + burst test of pipeline containing girth weld or seam weld or artificial discontinuity with „NOT PASSED” quality;
- burst test of operated (fatigued and replaced), externally reinforced pipeline containing girth weld with „NOT PASSED” quality;
- fatigue test (*10⁵ cycles*) + burst test of externally or internally reinforced pipeline containing girth weld or artificial discontinuity with „NOT PASSED” quality.

Clock Spring glass fibre reinforced *PMC* (*CS*), and own developed carbon fibre reinforced *PMC* (*CFRPMC*) were used for external reinforcing. The application of the *Clock Spring* composite sleeve reinforcing system can be found in the literature [13]. The installation of the own developed external reinforcing consists of five steps: cleaning and drying of the pipe; preparation of the reinforced area with resin; reinforcing with carbon fibre (tape); covering with polymer film; hardening using heat treatment. Own developed glass fibre reinforced *PMC* (*GFRPMC*) was used for internal reinforcing. The applied reinforcing technology was as follows: cleaning and drying of the pipe; proofing of the shell material; reeling up of the proofed shell onto packet; setting of the packet into the pipe; reinforcing using internal pressure; hardening.

One pipeline section was prepared for strain-gage measurements in order to investigate the behaviour of artificial failures under internal pressure and to establish basic data for finite element (*FEM*) calculations. Fig. 1 shows the detail of this pipeline section (*B_b8*) with artificial longitudinal gouge, strain-gages and an extensometer (see Table 2 and Table 3, too).

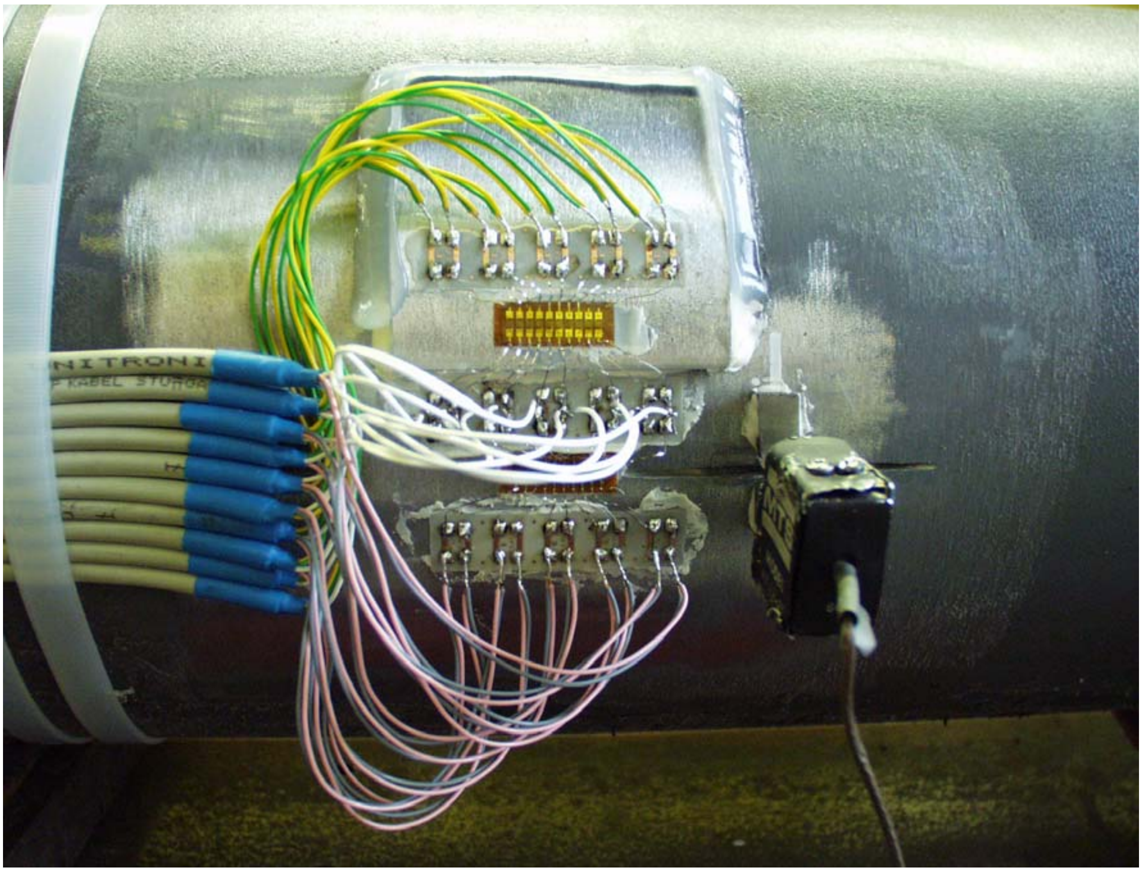

Figure 1. Pipeline section (*B_b8*) with artificial longitudinal gouge, strain-gages and an extensometer

The important characteristics (girth or seam welds and the quality of the welding, types and measurements of the failures, reinforcing) of the investigated pipeline sections are summarized in

Table 2; where h_k and h_b are the longitudinal dimension, m_k and m_b are the depth of the external and internal failures (gouges and holes), respectively, furthermore *d* is the diameter of the artificial holes (holes and through holes).

Table 2. The important characteristics of the investigated pipeline sections

Mark	Details of Pipeline Section	Reinforcing
	Groups of externally reinforced pipeline sections	
A_e1	111 girth weld, „NOT PASSED” quality	–
A_e2	111 girth weld, „NOT PASSED” quality	CFRPMC
B_a1	base (unwelded) pipe	–
B_a3	141/111 and 111 girth welds, „PASSED” quality	–
B_a4	111 girth weld, „NOT PASSED” quality	–
B_b1	base (unwelded) pipe	–
B_b2	141/111 girth weld, “NOT PASSED” quality	–
B_b3	114/111 girth weld, “NOT PASSED” quality	CFRPMC
B_b4	114/111 girth weld, “NOT PASSED” quality	CFRPMC
B_b5	114/111 girth weld, “NOT PASSED” quality	CFRPMC
B_b6	artificial longitudinal gouge (h_k = 75 mm, m_k = 2 mm), circumferential gouge (h_k = 85 mm, m_k = 4,1 mm and interacting circumferential gouges (h_k = 2*75 mm, m_k = 3,2 mm)	–
B_b7	artificial longitudinal gouge (h_k = 75 mm, m_k = 2 mm), circumferential gouge (h_k = 100 mm, m_k = 2,9 mm and interacting circumferential gouges (h_k = 2*75 mm, m_k = 3,2 mm)	CFRPMC
B_b8	artificial failure: longitudinal gouge (h_k = 70 mm, m_k = 2 mm)	–
C_d1	artificial longitudinal gouge (h_k = 100 mm, m_k = 3 mm), circumferential gouge (h_k = 150 mm, m_k = 4,7 mm and interacting circumferential gouges (h_k = 2*130 mm, m_k = 4 mm)	–
	artificial longitudinal gouge (h_k = 100 mm, m_k = 3 mm)	–
	new artificial longitudinal gouge (h_k = 100 mm, m_k = 3,1 mm)	–
C_d2	artificial longitudinal gouge (h_k = 100 mm, m_k = 3 mm), circumferential gouge (h_k = 150 mm, m_k = 4,7 mm and interacting circumferential gouges (h_k = 2*130 mm, m_k = 4 mm)	CFRPMC
	artificial longitudinal gouge (h_k = 100 mm, m_k = 3 mm)	CFRPMC
CS_a1	111 girth weld, „NOT PASSED” quality	CS
CS_b1	111 girth weld, „NOT PASSED” quality	–
CS_b2	111 girth weld, „NOT PASSED” quality	CS
CS_b3	111 girth weld, „NOT PASSED” quality	CS
CS_b4	111 girth weld, „NOT PASSED” quality	CS
D_c1	seam weld, “NOT PASSED” quality	–
	Group of internally reinforced pipeline sections	
E_o4	artificial holes (d = 4, 8, 10, 12, 16 and 20 mm, m_b = 4 mm)	–
E_o1	artificial longitudinal gouge (h_b = 70 mm, m_b = 3,2 mm)	GFRPMC
E_o2	artificial through holes (d = 4, 8, 10, 12, 16 and 20 mm)	GFRPMC
E_o3	artificial holes (d = 4, 8, 10, 12, 16 and 20 mm, m_b = 4 mm)	GFRPMC

3. Results of the full-scale investigations

Fig. 1 demonstrates the internal pressure vs. time diagrams of the investigated *DN 200* pipeline sections in the *B_a* and *B_bi* testing groups (see Table 1 and Table 2) during their burst tests. Fig.1

displays the average pressure growth rate range (*0,15 – 0,52 MPa/s*) at the initial stage of the burst tests, which can be evaluated as quasi-static value range.

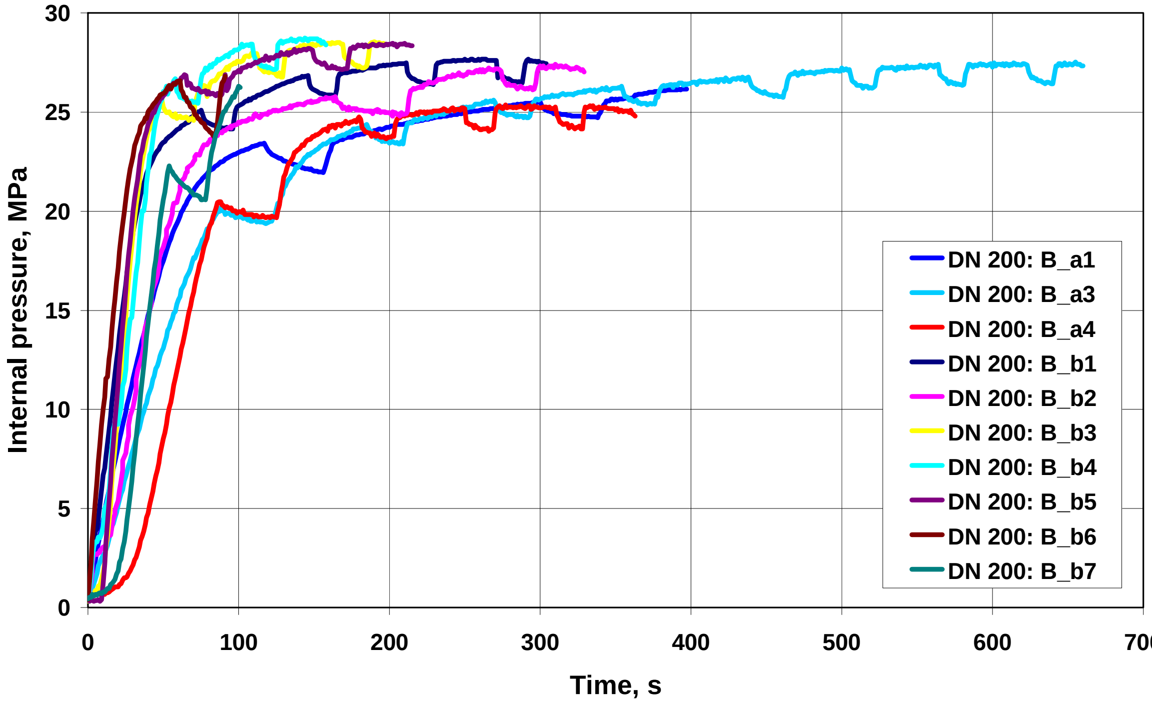

Figure 2. Internal pressure vs. time diagrams during the burst tests of the pipeline sections in the *B_a* and the *B_b* testing groups

Fig. 2 demonstrates the internal pressure vs. time diagrams of the investigated *DN 400* pipeline sections in the *CS_b* testing group (see also Table 1 and Table 2) during their burst tests.

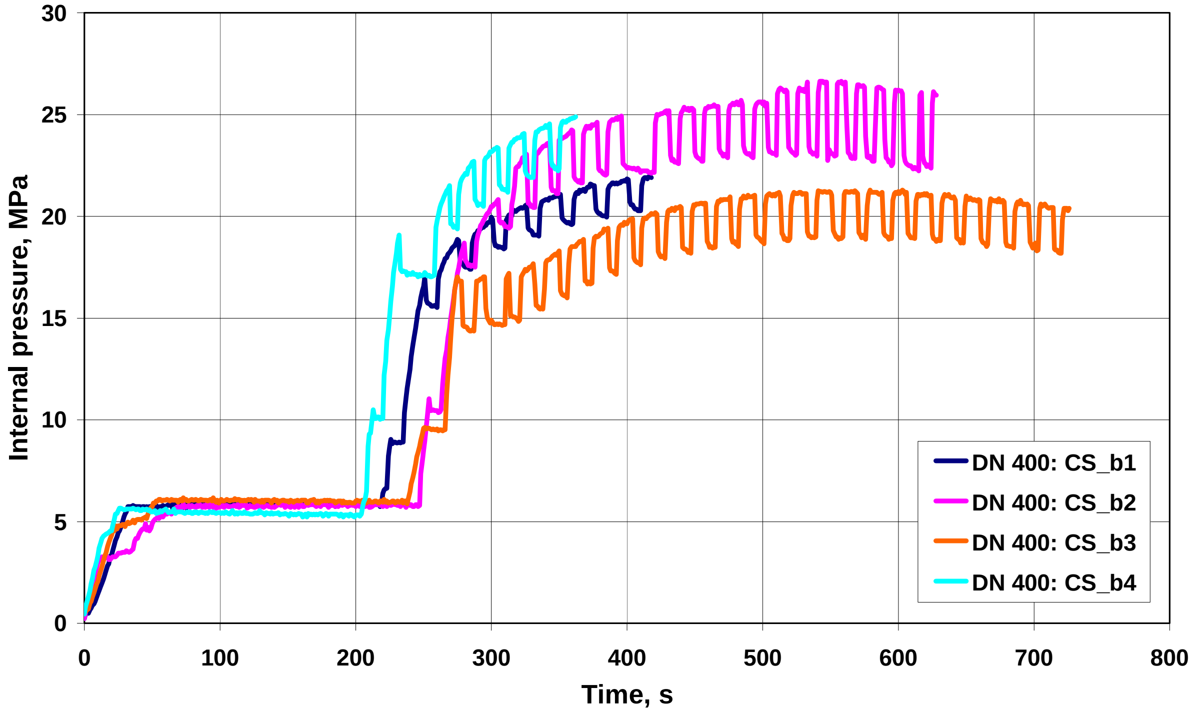

Figure 2. Internal pressure vs. time diagrams during the burst tests of the pipeline sections in the *CS_b* testing group

Fig. 2 shows the loading history of the pipeline sections, which consists of three parts: rising the pressure up to the operating pressure (*6,4 MPa*), holding the pressure (*3 min = 180 sec*), and rising the pressure up to the final damage. Fig. 1 and Fig 2 show the volume growth of the pipeline sections through the pressure growth, too.

Fig. 3 and Fig 4 show the externally reinforced pipeline section *CS_a1* (reinforced girth weld) using *Clock Spring* repair system before and after the burst test, respectively.

Figure 3. Externally reinforced pipeline section (girth weld) *CS_a1* before the burst test

Figure 4. Externally reinforced pipeline section (girth weld) *CS_a1* after the burst test

Fig. 5 and Fig. 6 show the externally reinforced pipeline section *CS_b3* (reinforced girth weld) using *Clock Spring* repair system and the failured area after the burst test, respectively.

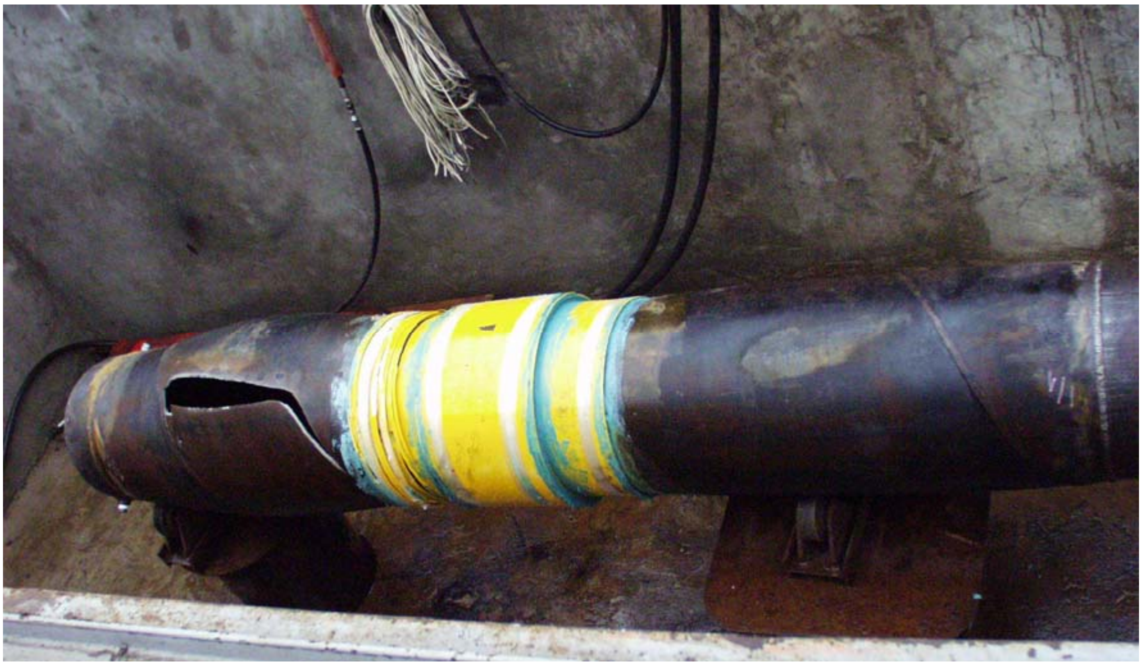

Figure 5. Externally reinforced pipeline section (girth weld) *CS_b3* after the burst test

Figure 6. The failured area of the externally reinforced pipeline section (girth weld) *CS_b3* after the burst test

Fig. 4 and Fig. 6 demonstrate that in these cases, the failed area located far from the girth weld area, and the reinforcing material has riven through the deformation of the unreinforced pipe body.

The results of the investigations executed on the unreinforced and externally or internally reinforced pipeline sections, furthermore the calculated safety factors are summarized in Table 3.

Table 3. Results of the executed full-scale investigations

Mark	Examination	Cycles	Failure location	Burst pressure, bar	Safety factor, –
Groups of externally reinforced pipeline sections					
A_e1	fatigue + burst	10^5	pipe body	464,6	7,26
A_e2	fatigue + burst	10^5	pipe body	472,3	7,38
B_a1	burst	–	pipe-end seam	> 261,7	> 4,09
B_a3	fatigue + burst	$2*10^4$	pipe body	275,3	4,30
B_a4	fatigue + burst	$2*10^4$	pipe body	253,5	3,96
B_b1	fatigue + burst	10^5	pipe body	276,6	4,32
B_b2	fatigue + burst	10^5	pipe body	274,0	4,28
B_b3	fatigue + burst	10^5	pipe body	285,6	4,46
B_b4	fatigue + burst	10^5	pipe body	287,2	4,49
B_b5	fatigue + burst	10^5	pipe body	284,7	4,45
B_b6	fatigue + burst	10^5	pipe body	268,1	4,19
B_b7	fatigue + burst	10^5	pipe body	262,9	4,11
B_b8	strain-gage measurements	–	pipe body	not relevant	not relevant
C_d1	fatigue	$0,795*10^5$	circumferential gouge	not relevant	not relevant
	fatigue	$0,936*10^5$	longitudinal gouge	not relevant	not relevant
	burst	–	new longitudinal gouge	233,5	3,65
C_d2	fatigue + burst	10^5	circumferential gouge	264,6	4,13
	fatigue + burst	10^5	longitudinal gouge	273,2	4,27
CS_a1	burst	operated	pipe body	245,0	3,83
CS_b1	burst	operated	girth weld	220,0	3,44
CS_b2	burst	operated	pipe body	270,0	4,22
CS_b3	burst	operated	pipe body	220,0	3,44
CS_b4	burst	operated	pipe body	250,0	3,91
D_c1	fatigue	10^5	–	–	–
Group of internally reinforced pipeline sections					
E_o4	fatigue + burst	10^5	hole (d = 12 mm)	255,7	4,00
E_o1	fatigue + burst	10^5	longitudinal gouge	241,6	3,78
E_o2	fatigue + burst	$0,447*10^5$	through hole (d = 20 mm)	242,9	3,80
E_o3	fatigue + burst	10^5	hole (d = 20 mm)	268,5	4,20

4. Conclusions

Based on the results of our full-scale examinations and the calculated safety factors, the following conclusions can be drawn.

The reinforcing materials (carbon fibre reinforced *PMC* and glass fibre reinforced *PMC*) and the own developed external and internal reinforcing technology can be used

– for transporting and industrial steel pipelines;

- for wide variety of pipe diameters and length (e.g. for casings);
- for both quasi-static and cyclic loaded pipeline sections or pipelines;
- for both workshop-work and field-work.

Beside the *Clock Spring* (*CS*) repair system, the developed external technology is suitable for the reinforcing of girth welds, frequently “NOT PASSED” quality girth welds, too.

The usability of the own developed external reinforcing technology and the effectiveness of the external reinforcing for “NOT PASSED” quality seam welds (*D_c* pipe section) require further investigations.

The defined safety factor and their calculated values demonstrate both the reserves of the steel pipes and the usefulness of the reinforcing materials and technologies.

Results of full-scale tests correspond with results of numerical investigations [14-17] in case of externally and internally reinforced damaged pipelines.

Databases and especially experimental data have a determinant role in the integrity assurance of different structures, like pipeline systems [18]. With the help of these databases and frequently with the using of the experimental data, integrity management tasks can be solved [1].

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