Development of an Experimental Programme for Industrial Approbation

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Abstract This chapter describes the planning and development of an experimental programme performed by the authors, with the aim of studying the reinforcement (consolidation) effects of a given repair system using composite material wraps for damaged transmission pipelines (intended for petroleum, liquid petroleum products or natural gas), with defects of the type metal loss (also named volumetric surface defects, VSDs). Such programme could be applied to any type of advanced pipeline repair system with composite wraps in view of its qualification and industrial approbation. The results (briefly described in Sect. 2) of experimental tests executed within previous research activities together with the necessity to validate numerical methods developed for the simulation of composite repair systems have emphasized the need to define and perform a new set of tests for such repair systems. The selection of the materials (pipe steel, composite) to be tested, the testing conditions and their parameters are detailed in this chapter and the plan and objectives of such experimental programme are also explained. The results of our experimental programme will be described in Chapter "Inner Pressure Testing of Full-Scale Pipe Specimens", while Chapter "Effectiveness Assessment of Composite Repair Systems" will present the efficiency assessment of the investigated composite repair system, performed on the base of our experimental data.

Keywords Transmission pipelines · Composite repair system · Volumetric surface defect (VSD) · Composite material wrap · Qualification

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1 Introduction

The transmission pipelines (normally made of steel) used to transport natural gas, petroleum or liquid petroleum products are providing services of great importance and therefore their maintenance and repair activities need special attention. Among the most common defects that might be detected on these pipelines are the ones of the metal loss type (also called volumetric surface defect, VSD), due to corrosion and/or erosion processes.

In the last years, the repair of the transmission pipeline areas with such defects was frequently performed by means of applying composite materials sleeves/wraps, because this repair technology did not require welding operations and could be applied without removing the pipelines from service. However, even if such repair procedure (described in Chapter "Comparative Analysis of Existing Technologies for Composite Repair Systems") has been used from some time, the problems regarding its application did not found yet technical solutions fully underlain and unanimously accepted.

For this reason, we have carried out an extended research programme (which we plan to continue in the near future) that studies both theoretically and experimentally the transmission pipeline repair systems using composite materials. One of the main goals of our research programme is to investigate experimentally the efficiency of the repair systems using composite materials applied on transmission pipelines with VSDs, under various loading conditions (internal pressure, low cycle loaing). The main objectives of our past and future experimental work are the following:

(i) to evaluate the consolidation effect, considered as a measure of their effectiveness, for some composite repair systems used for damaged pipelines, by investigating the stress–strain state in the damaged area under the operational (internal) pressure, and also by determining the burst pressure value (such evaluation is described in Chapter "Effectiveness Assessment of Composite Repair Systems");

(ii) to validate numerical and analytical models developed by the authors of this book for the assessment of the remaining strength of a pipeline with VSDs reinforced using composite repair systems (these models have been described in Part 5) and also the design procedures defined in Chapter "Design of Composite Repair Systems" for the composite wraps applied for pipelines repair;

(iii) to compare, in the future, the obtained experimental data and results with similar investigations performed by other research teams.

The development of our research programme has also considered the requirements of international standards dealing with the pipeline repair methods using composite materials, including their qualification procedures. Currently, two standards involving such issues are in use, ASME PCC-2 [1] and ISO/TS 24817 [2]. Article 4.1 from [1] provides the requirements for pipeline repair using a qualified

Table 1 Repair system required material and performance properties, according to [1]

Material property	International test method	ASTM test method
Tensile strength, Young's modulus and Poisson's ratio	ISO 527	ASTM D 3039
In-plane shear modulus	NA	ASTM D 5379
Thermal expansion coefficient	ISO 11359-2	ASTM E 831
Glass transition temperature of polymer	ISO 11357-2	ASTM E 1640, ASTM D 6604 or ASTM E 831
Heat distortion temperature (HDT)	ISO 75	ASTM D 648
Barcol hardness	BS EN 5	ASTM D 2583
Shore hardness	ISO 868	ASTM D 2240
Lap shear adhesion strength (of composite bond to substrate)	EN 1465	ASTM D 3165, ASTM D 5868
Long-term strength (creep-rupture) (optional)	ASME PCC-2 mandatory appendix V	ASTM D2990, ASTM D2992
Toughness parameter, energy release rate (optional)	ASME PCC-2 mandatory appendix IV	NA
Structural strengthening (optional)	ASME PCC-2 mandatory appendix III	NA

non-metallic repair system, while the standard [2] covers the requirements and recommendations for the design, installation, testing, and inspection for the external application of composite repairs to pipes affected by corrosion or other sources of damage. Both standards require the determination of the characteristics summarised in Table 1 for the qualification of a composite repair system intended for pipelines.

The use of the standards [1] or [2] is limited to those composite repair systems for which the qualification testing has been completed. Any change to any element of the repair system constitutes a different and therefore new repair system that shall require qualification in view of its industrial approbation.

In the followings, after a brief description of the experimental results previously obtained by the authors (in Sect. 2), the definition of the parameters for the future tests (pipe material and geometry, VSD geometry, loading conditions etc.) is detailed and the plan for the experiments carried out jointly is described.

2 Previous Experimental Tests on Pipelines Repaired with Composite Wraps

The authors have been involved in several testing programmes regarding pipeline repair systems with composite materials. These tests constituted the starting point for the development of the experimental programme described in the followings and whose results are included in Chapter “Inner Pressure Testing of Full-Scale Pipe Specimens”. A brief description of the results of some tests previously executed is included below.

Among the analyses regarding the repair methods intended for transmission pipelines, a repair system using composite materials conceived by ICECHIM Bucharest, named IWR (ICHECHIM Wrap Repair) has been the object of investigations under an extensive research programme carried out within the University of Ploiesti. The IWR material is made of a multilayer composite material, in which the reinforcement component consists of layers of fibreglass fabric, while the matrix is the polymeric material used to impregnate the fabric. This polymeric resin has been conceived as a modified polymeric system having flexibilization components with small molecular weight and with mineral fillings.

The IWR mechanical properties (E_C is the elastic modulus, R_{mC} is the tensile strength, A_C is the elongation at fracture) are compared in Table 2 with the ones of other composite repair systems developed for transmission pipelines (for other details, see Chapter “Review on Materials for Composite Repair Systems”).

The IWR repair has the structure shown in Fig. 1, and its achievement requires the following three steps: (i) pipeline preparation for repair (cleaning its surface using an appropriate procedure; polishing, grinding or sand blasting in order to round the edges and smooth the VSD profile, eliminating the possible micro-cracks initiated by the defect and transforming the VSD in long-radius curvature groove, with reduced mechanical stress concentration effects); (ii) rehabilitation of the pipe external configuration, by filling the VSD using a polymeric filler; (iii) rehabilitation of the pipe mechanical strength, applying the reinforcing composite wrap in the defects area.

The IWR research programme was included, but not limited to the experimental testing of the IWR system, applied to three full-scale pipe specimens, all made of steel grade L245/B (with the yield strength $R_{t0.5}$ = 245 MPa, and the tensile strength R_m = 415 MPa) and with one or several VSDs, obtained by machining,

Table 2 Comparison between the mechanical characteristics of IWR, KPB and other composite materials intended for transmission pipelines repair

Composite material	Reinforcement material	Mechanical characteristics of the composite material[a]		
		E_C (GPa)	R_{mC} (MPa)	A_C (%)
IWR	Fibreglass	17.5–22.7	265–315	1.32–1.60
KPB	Fibreglass	2.8–3.1	30–31	0.90–1.10
EC 10 1680	Fibreglass	25.5–34.6	403.2–503.6	1.36–1.58
Perma Wrap	Fibreglass	34.0–38.0	580–620	1.00–1.10
Fiba Roll	Fibreglass	7.9–8.7	72–86	2.60–3.10
Clock Spring	Fibreglass	33.8–34.5	630–650	1.06–1.36
TDW RES-Q	Carbon fibre	68.8	1028	–

[a] Measured in the direction corresponding to the composite wrap circumference, when applied on the pipeline

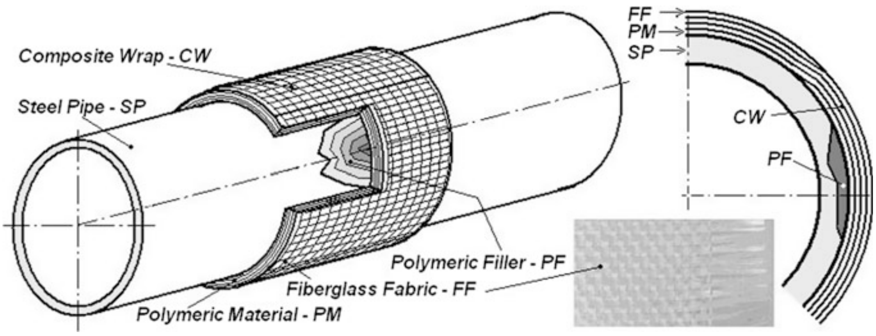

Fig. 1 Structure of IWR composite repair system for pipelines

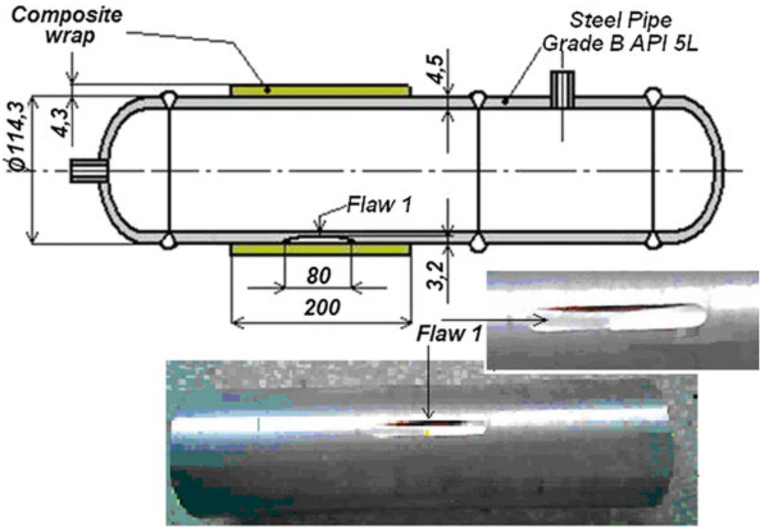

Fig. 2 Geometry of specimen P1 (with only one flaw/VSD)

subjected to internal pressure loading (maximum allowable operating pressure *MAOP* = 5.5 MPa). Figures 2–7 illustrate the test method applied and the behaviour of specimens, reinforced with composite wraps, after being subjected to bursting tests.

An important research programme regarding the KPB composite repair system has been carried out within E.O. Paton Institute in Kiev, including the experimental testing of two full-scale pipe specimens after repair. The KPB material, provided by Kailas Ltd., was made of a multilayer composite material, in which the reinforcement component consists of layers of fibreglass fabric, and the matrix is the polymeric resin used to impregnate the fabric.

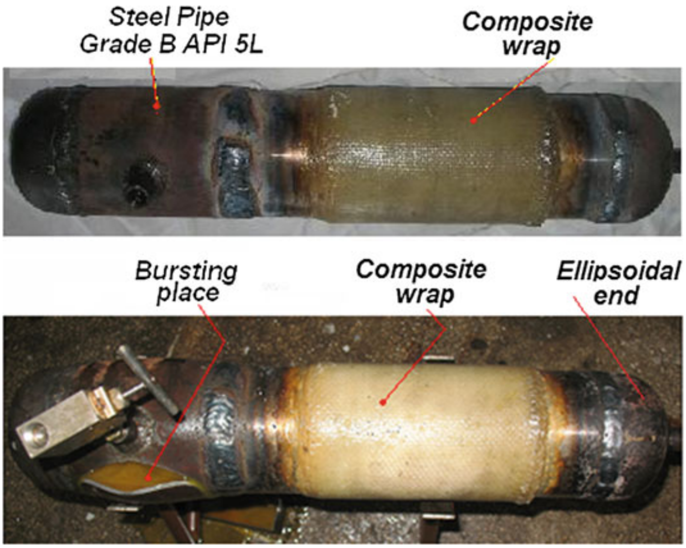

Fig. 3 Specimen P1 before and after testing

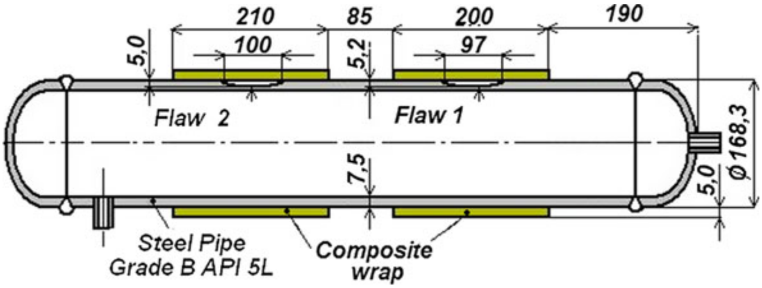

Fig. 4 Geometry of specimen P2 (with two flaws/VSDs)

KPB wrap repair has the structure shown in Fig. 8, and its achievement requires four steps: (i) pipeline preparation (cleaning, etc.); (ii) rehabilitation of the pipe external configuration, by filling the VSD using REM-stal filler; (iii) covering the pipeline surface using a polymeric primer (MB); (iv) rehabilitation of the pipe mechanical strength, applying the composite wrap (KPB) for reinforcement in the defects area.

The testing method and parameters are illustrated in Figs. 9–12 for both specimens (made of the same steel grade, similar to L360/X52), while the mechanical behaviour of the pipes, reinforced with KPB composite wraps, during the bursting test, is summarised in Fig. 13.

Table 3 includes a brief summary of all tests described above. In the table, the estimated value of the burst pressure for the steel pipe (without defects), p_b, has

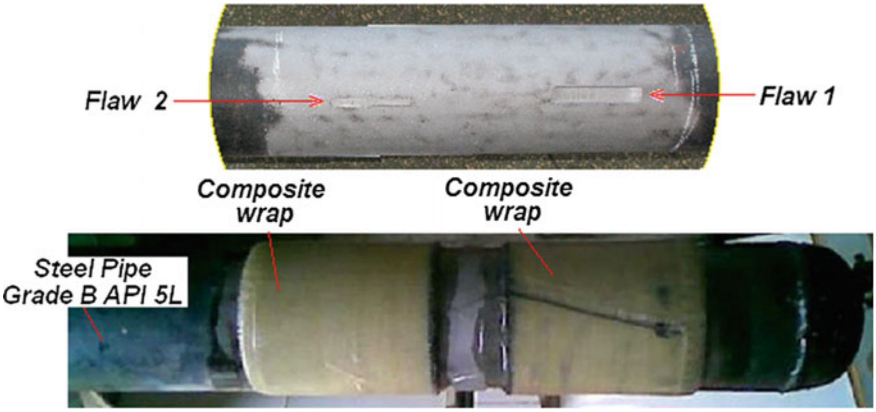

Fig. 5 Specimen P2 before and after repairing

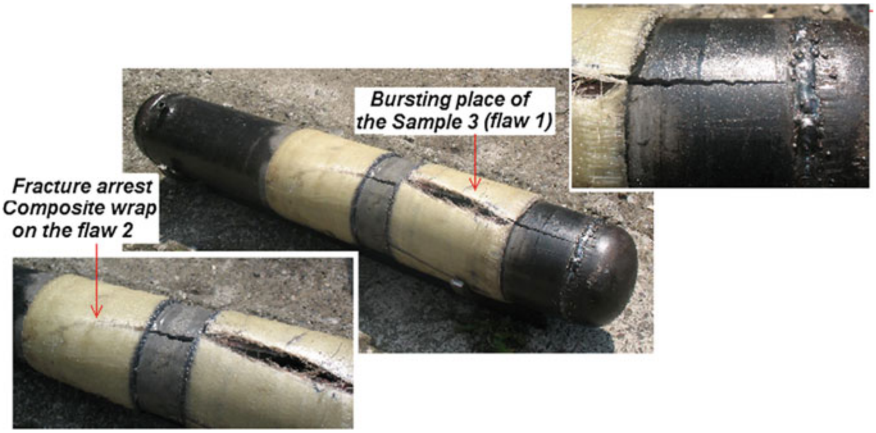

Fig. 6 Specimen P2 after testing

been calculated using the equation from DNV RP-F 101 [3], Sect. 2.1, while the same estimated value for the repaired pipe (with the composite wrap applied), p_{br}, has been calculated with as follows [4]:

$$p_{br} = \frac{2}{D_e}\left(R_{m,p}t_{mm} + R_{m,c}t_c\right) \tag{1}$$

where D_e is the pipe outside diameter, $R_{m,p}$ is the tensile strength of steel pipe, $R_{m,c}$ is the tensile strength of composite wrap, t_c is the composite wrap thickness, t_{mm} is the minimum remaining thickness of the pipe in the defect area.

The main conclusion on the previous tests (summarised in Table 3) is that the use of wraps made of composite material of the IWR type (or other similar materials

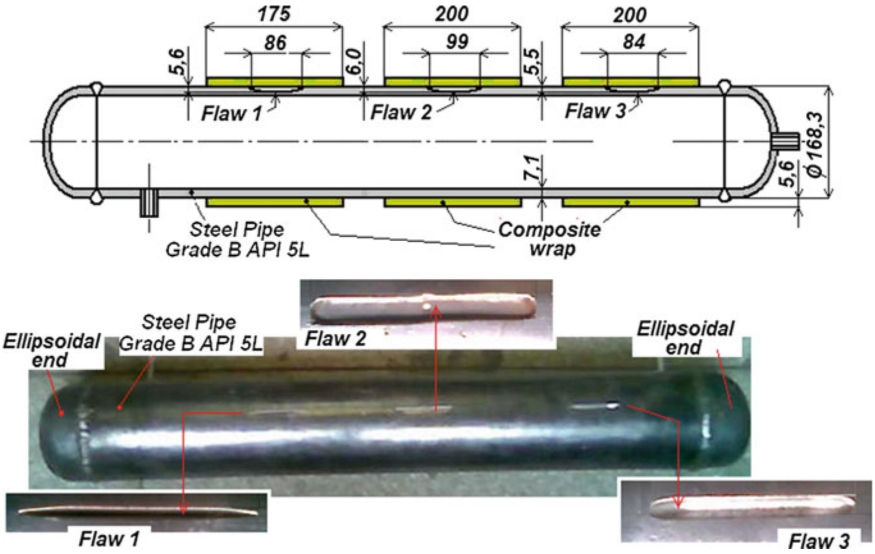

Fig. 7 Geometry of specimen P3, with three flaws/VSDs

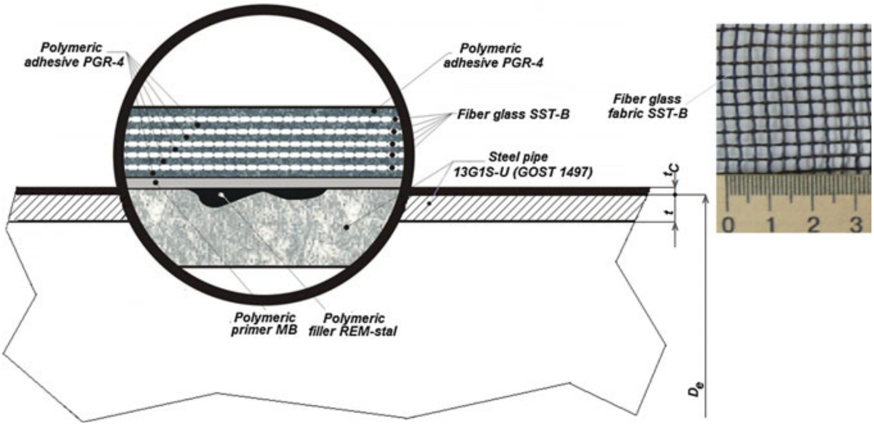

Fig. 8 Structure of KPB composite repair system for pipelines

—see Table 2), is suitable, because it can guarantee levels of the burst pressure in the repaired area superior to the burst pressure of the pipe without defects. At the same time, the use of composite wraps made of KPB type materials is not convenient, because a reinforcement effect similar to the one of IWR type wraps requires a very thick wrap (more than 50 mm), inappropriate due to high costs and technological implementation problems.

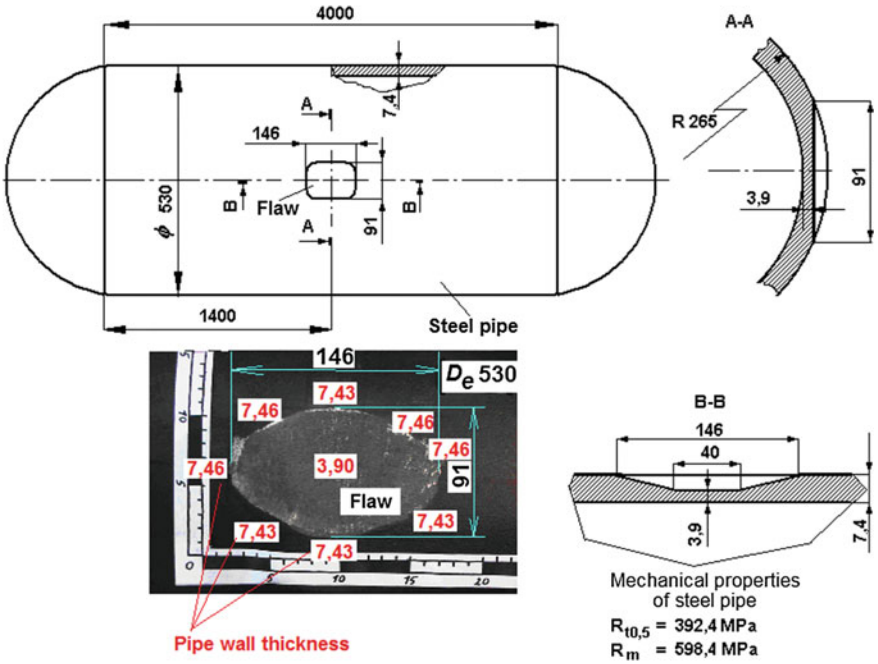

Fig. 9 Geometry of specimen K1 before repair, with VSD details

3 Definition of the Experimental Parameters and Planned Experimental Programme

First, the most adequate pipe materials to be tested were considered the steel grades L290/X42 and L360/X52 (or equivalent) [5], because they ranged among the most frequently used steel grades in European natural gas transmission pipelines systems, especially in the older ones that usually present VSDs and therefore require repair systems. For the same reason, the most suited values for the outside diameter of the pipes tested were considered D_e = 219.1; 323.9; 508.0; 711.0 mm.

The pipe specimens finally selected for testing, based also on available pipe materials and dimensions, are manufactured of Steel 20 (according to GOST 550-75 [6]). They are very similar to L290 and have the outside diameter D_e = 219.0 mm. Table 4 compares the mechanical properties of steels L290, L360, Steel 20 given in their standards [5, 6] with the ones determined by performing tensile testing on samples cut in the axial and circumferential direction for the specimens material.

In order to compare the results of our research work with those of other similar researches, we select a pipe wall thickness and define a defect geometry equivalent to the values, used within an extensive experimental programme currently underway. It investigates the long-term performance of composite repair systems, and it is organized by Pipeline Research Council International—PRCI [7] and sponsored

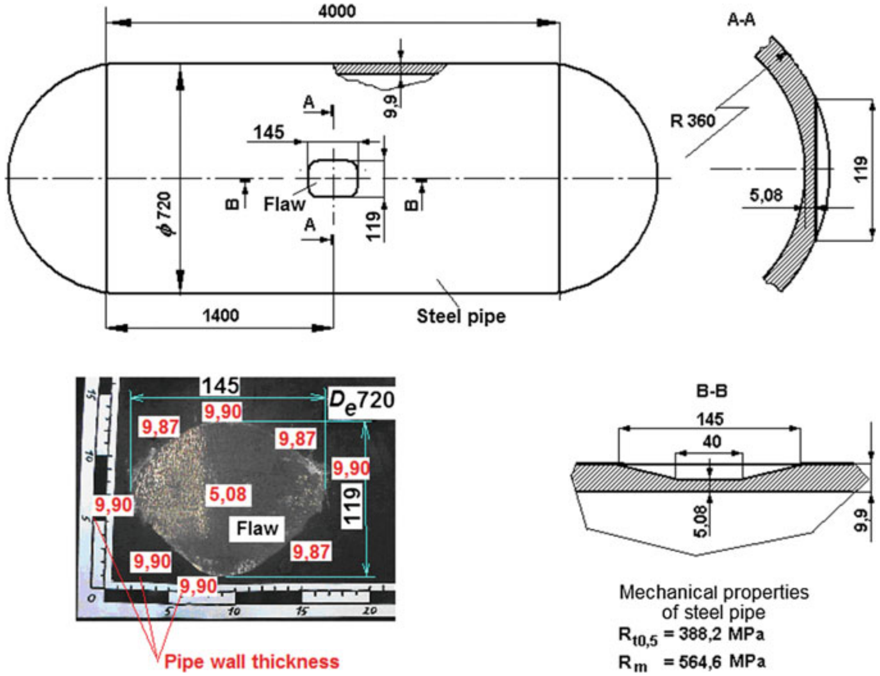

Fig. 10 Geometry of specimen K2 before repair, with VSD details

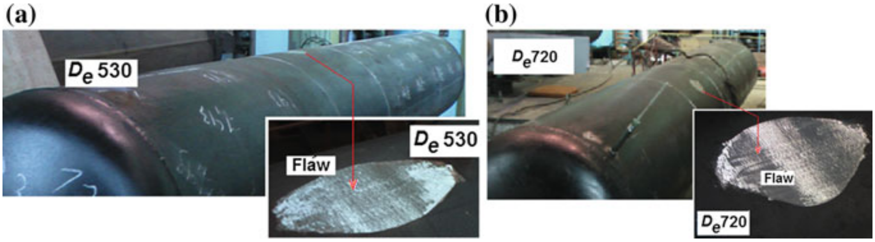

Fig. 11 Photos of the specimens before repairing: **a** specimen K1; **b** specimen K2

by 13 composite manufacturers from around the world, among which we mention: Armor Plate, T.D. Williamson, Clock Spring Company, Pipe Wrap. The programme consists of the preparation of grade L290/X42 test specimens with welded end caps and machined VSDs having the geometry as shown in Fig. 14, repaired by the participating manufacturers.

Burst tests were planned for all the repaired specimens at 0, 1, 2, 3, 5, 7.5, and 10 years. While 36 samples were burst immediately after repair, 144 samples were buried in the ground and continuously pressurized at 36% SMYS, then cycled 75

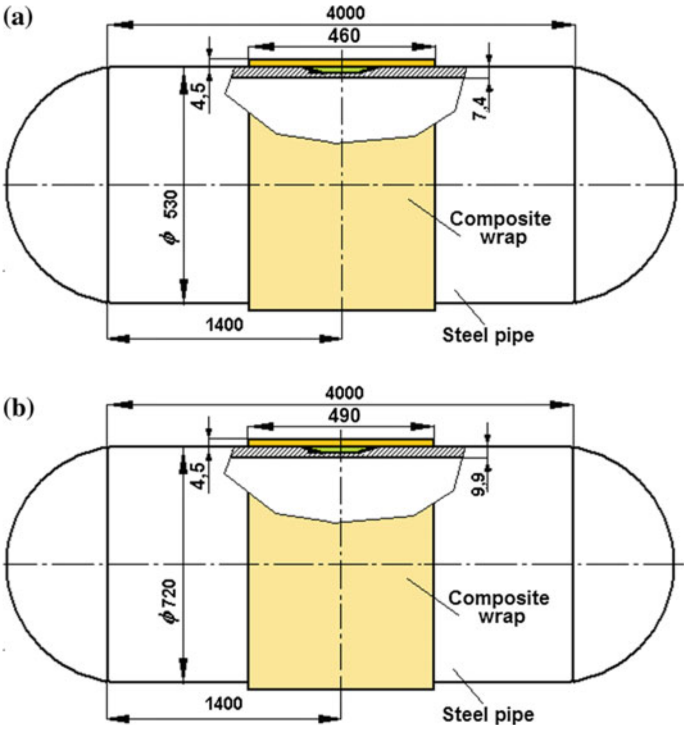

Fig. 12 Geometry of specimens after repairing (with KPB wrap): **a** specimen K1, **b** specimen K2

times once per month at 36% SMYS and once per quarter at 72% SMYS. Burst test samples are being removed from the buried trenches at the designated test periods. During the testing period, strain gauges are used to monitor strain in the corroded steel beneath the composite repair systems.

The nominal wall thickness of the pipe specimens, t_n, has been selected such that to obtain approximately the same *SDR* (Standard Dimensional Ratio−$SDR = D_e/t_n$) as the PRCI pipes. As these pipes have $SDR = 34.09$, the resulting value for the nominal wall thickness has been $t_n = 6.0$ mm. The defect dimensions have been determined to obtain the same values as per the PRCI experimental programme (including three different values for the defect depth corresponding to 40, 60, and 75%, respectively, of the nominal thickness t_n) for the non-dimensional parameters of the defect defined in the API 579 standard [8], characterizing its depth, length and width, respectively

$$h_d = \frac{d_m}{t_n}, \ \lambda = \frac{1.285 \cdot s_p}{\sqrt{D_e \cdot t_n}}, \ \lambda_c = \frac{1.285 \cdot c_p}{\sqrt{D_e \cdot t_n}}, \tag{2}$$

where d_m is the maximum defect depth, s_p is the axial extent (length) of the defect, c_p is the circumferential extent (width) of the defect.

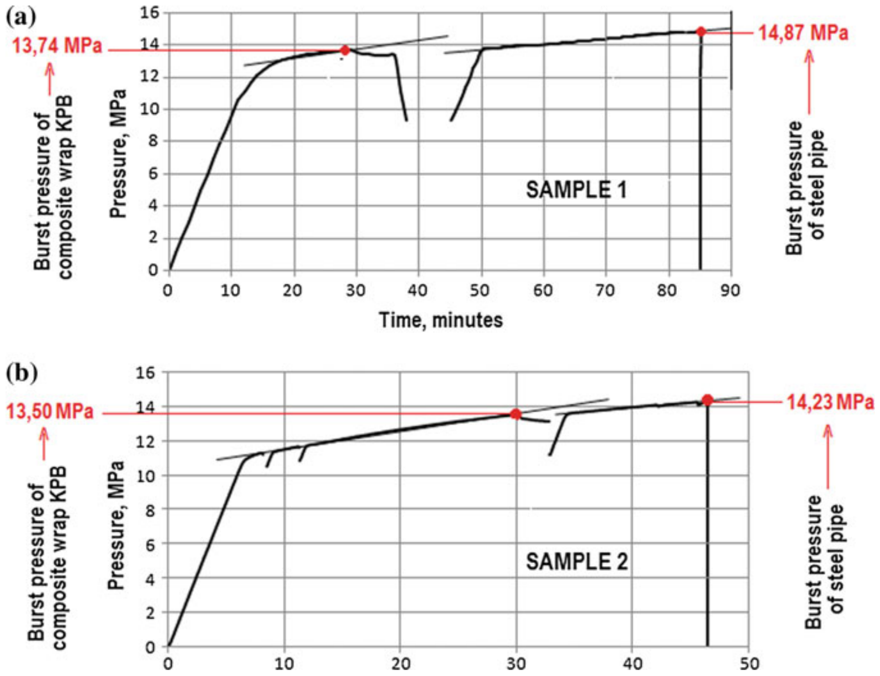

Fig. 13 Test results for both specimens: **a** specimen K1, **b** specimen K2

Table 3 Summary of the results of previously performed composite repair system tests

Specimen/pipe material	Pipe outside diameter, D_e (mm)	Pipe wall thickness, t_n (mm)	Burst pressure, p_b (MPa)	Burst location/composite wrap behaviour	Estimated burst pressures (MPa)	
					p_b (steel pipe)	p_{br} (with wrap)
P1/L245	114.3	4.5	39.5	Steel pipe/wrap unbroken	35.7	37.6
P2/L245	168.3	7.5	31.5	Flaw 1/wrap broken with crack propagation	40.6	26.1
P3/L245	168.3	7.1	29.5	Flaw 2/wrap unbroken, but tightness loss under it	38.4	23.4
K1/L360	530	7.4	14.9	Flaw area/full wrap rupture	15.2	8.0
K2/L360	720	9.9	14.2	Flaw area/full wrap rupture	15.8	8.0

Table 4 Mechanical properties comparison

Pipe grade/sample direction		SMYS[a], $R_{t0.5}$ (MPa)	Tensile strength, R_m (MPa)
L290/X42		290	415
L360/X52		360	460
Steel 20	GOST	240[b]	431
	Axial sample	314	461
	Circumferential, straightened	323[b]	474
	Circumferential, not straightened	305[b]	475

[a] Specified minimum yield strength
[b] $R_{c0.2}$ (corresponds to residual elongation 0.2%)

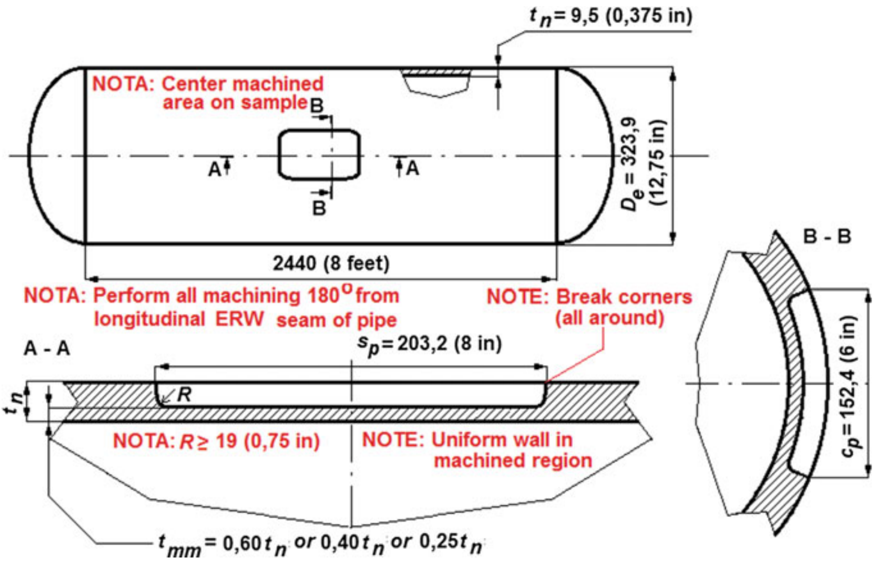

Fig. 14 PRCI full-scale test specimen [7]

Applying Eq. (2) for the PRCI pipes (with the defect dimensions shown in Fig. 14) and then for our pipes, we have obtained the following defect dimensions values: s_p = 133 mm; c_p = 103 mm; d = 2.4, 3.6, 4.5 mm. The pipes used as specimens are shown in Fig. 15a before machining the VSDs and in Fig. 15b after machining the defects. The specimen geometry is the same as the one used by PRCI (see Fig. 14).

Two composite repair systems were initially intended for investigation in our experiments, the ICECHIM wrap repair (was described in Sect. 2, while its main properties are indicated in Table 2) and a system using fibreglass EC 10 1680 N-U10(168), combined with the polymeric resin KDA-HI (its properties are also

Fig. 15 **a** Blank pipes used for specimens; **b** VSDs machined on two specimens

shown in Table 2). It was decided to use this system instead of KBP as its properties are more suitable for pipeline repair. Up to now, only the second system mentioned above has been investigated, while the IWR system will be tested in a future research programme. The composite wrap thickness has been defined according to the recommendations of ISO/TS 24817 [2] and the design procedure used was the one presented in Chapter "Design of Composite Repair Systems".

The test planned have comprised hydraulic bursting tests performed on four specimens, as follows: (i) a bare pipe specimen without defect; (ii) a specimen without defect, but with a composite wrap applied on it; (iii) a specimen with a machined VSD, but without composite repair applied; (iv) a specimen having a VSD and repaired with composite wrap. The composite repair system applied has been the one using EC 10 1680 fibreglass.

During the first stage of pressure loading (from zero up to the strain limit of gauge), the measurement of pipe strains has been done using strain gauges preliminary installed on each specimen surface. Two gauges (one in the axial direction and one in circumferential direction) were placed outside the repaired area of the specimen and another two in the VSD area, before applying the filler and composite wrap. Strain measurement of repaired specimens were done before (in the elastic region) and after applying the wrap. The detailed description of the tests performed and their main results are included in Chapter "Inner Pressure Testing of Full-Scale Pipe Specimens".

Within upcoming research programmes, we are considering the possibility to apply a composite wrap on a specimen with a VSD while subjected to internal pressure (thus simulating an in-service pipeline repair) and to analyse the effect of a pressure decrease on the system pipe wrap. In the future, we plan to execute also experimental tests under cyclic pressure loading due to the reasons briefly explained below.

In the most cases, the main load of a transmission pipeline is the internal pressure, that is not constant in service and changes very significantly during pumping starts/stops and periodical hydraulic tests. This creates the prerequisites for low cycle failure in the zones of stress concentration, among which VSDs areas. Furthermore, any cyclic loading could adversely influence the reinforcement effect of composite wraps applied in the damaged zone. Therefore, we regard the cyclic testing of full-scale specimens with composite wrap repair system as another important direction of our future experimental activity, which could develop the experience in this field accumulated by E.O. Paton Institute [9].

In the end, we mention that recent testing has shown fatigue lives for pipelines repaired with composite wraps ranging from 20,000 to 500,000 cycles, at a pressure level equivalent to 36% SMYS and VSDs with a depth equal to 75% of the wall thickness [7].

4 Conclusions

This chapter described the plan developed to perform an experimental programme with the aim of studying the reinforcement effects of composite materials repair systems designed for transmission pipelines. This joint research programme has completed previous results obtained separately by the authors and presented in Sect. 2. The results of our programme are described in Chapter "Inner Pressure Testing of Full-Scale Pipe Specimens", while their application in order to assess the efficiency of the investigated repair system is shown in Chapter "Effectiveness Assessment of Composite Repair Systems". Our programme could constitute an example of how to test a newly developed composite repair system in view of its industrial approbation.

The reasons for which we decided to execute new tests has been to validate the numerical methods developed for the simulation of composite repair systems (described in Part 5) and the composite wrap design method proposed in Chapter "Design of Composite Repair Systems" (as the wrap thickness used in our tests was calculated accordingly), and also to enrich our database of experimental results. In the near future, additional tests are planned to investigate other important issues regarding composite wrap repair systems, such as the behaviour under low cycle internal pressure loading and testing of specimens repaired while the pipe is subjected to internal pressure (simulating the repair of an in-service transmission pipeline).

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