Reinforcement Effects Obtained by Applying Composite Material Sleeves to Repair Transmission Pipelines

GHEORGHE ZECHERU[1], ANDREI DUMITRESCU[1]*, GHEORGHE DRAGHICI[1], PETRO YUKHYMETS[2]

[1]Petroleum – Gas University of Ploiesti, 39 Bucure°ti Bvd., 100680, Ploiesti, Romania

[2]E.O.PATON Electric Welding Institute of the National Academy of Science of Ukraine, 15 Bogenko Str, 03150, Kiev, Ukraine

This paper presents the results of the research work performed by the authors aiming at highlighting and quantifying the reinforcement effects (restoring of the mechanical strength) on transmission pipelines, generated by applying composite material sleeves in the areas in which the steel pipes of these lines have local surface defects (metal loss – like flaws). The models proposed to that purpose have been confirmed by performing some experimental programs, the first one consisting of the examination of the behaviour of some full-scale steel pipe specimens, with metal loss – like flaws (made by machining), on which reinforcing wraps made of composite material have been applied (with polymeric matrix and fiberglass fabric), subjected to internal pressure loading, up to bursting, and the second one aiming at the determination of the state of stress and strain in the pipelines on which reinforcing wraps made of composite material have been applied and which are subjected to internal pressure loading, in the elastic range. The items discussed and the results presented in the paper are mainly useful for the development and qualification of the composite materials repair systems for the transmission pipelines, according to the requirements of the standards ASME-PCC2 and ISO 24817.

Keywords: Transmission pipeline, Local metal loss – like defects, Repair by applying composite material sleeves, Reinforcement effects of composite sleeves / wraps

The transmission pipelines intended for hydrocarbons (named in the followings HTP), whose steel pipes have local surface defects of the type metal loss, produced by means of internal and/or external corrosion processes (Locally Thin Areas – LTA, Pittings – PIT, Grooves – GLF or Gauges – GAU), can be repaired, with or without removing the pipelines from service, using a wide variety of technological procedures [1, 2].

Because HTPs must usually ensure the continuous supply (without interruptions or, eventually, with scheduled short-time interruptions) for the clients of the transported fluids (petroleum, petroleum products, natural gas etc.), the repair technologies developed for in-service (under pressure) pipelines are preferred. The in-service repair technologies which require welding operations are not preferred, because they use concentrated heat sources, and the possible burn through of the HTP wall while executing the repair works can have serious consequences, the transported fluids (petroleum, liquid petroleum products, natural gas etc.) having an increased flammability and exploding potential. Therefore, the in-service repair technologies consisting of the application of composite materials wraps / sleeves are perceived as being advantageous alternative solutions for substituting the classical technologies, based on the repair by welding of the areas with defects or on the application by welding of steel patches, wraps or sleeves in the damaged HTP areas [1-3].

Previous research works [1, 2] have shown that the quality level of the repairs performed by applying, in the damaged HTP areas, reinforcing wraps / sleeves of different types (metallic sleeves of type A or type B, metallic wraps filled with polymeric materials or composite materials wraps) is in direct correlation with the measure in which they guarantee: a) the restoration of the HTP mechanical strength; b) the taking over of the HTP mechanical loadings (reduction of the stresses generated in the damaged pipe wall / with defects); c) the inhibition of the growth processes of the defects dimensions and diminution of their stress concentrator effects.

The analysis of the behaviour of a HTP upon which a composite wrap – CW has been applied, having a polymeric matrix (polyester, vinyl ester, epoxy or polyurethane) reinforced with fibres (glass, carbon, aramid, polyester or similar material), have led to the drawing of the schemes from figure 1, build considering that the steel from which HTP pipes are manufactured has a true/effective stress – strain characteristic curve, $\sigma = f(\varepsilon)$, of the type "with linear strain hardening". The investigation of these schemes highlights the following issues regarding the technical performances of the repairs with CW: a) for the HTP normal operating conditions (at a pressure $p_o \le$ MAWP, MAWP – Maximum Allowable Working Pressure of HTP), which assumes its loading in the elastic region, the degree of taking over the mechanical loads by the CW and of unloading of the HTP damaged areas is in direct dependance with the ratio $\rho_E = E_{CW}/ E_{SP}$, E_{CW} being the elasticity modulus of the composite material from which the CW is made ($E_{CW} = tg\alpha_{CW}$), and E_{SP} – elasticity modulus of the steel from which HTP pipes are manufactured ($E_{CW} = tg\alpha_{SP}$); using the information summarised in table 1 regarding the mechanical properties of the composite materials which are presently used with priority to make CWs [4, 5], it results that ρ_E = 0.05…0.20 (0.350) and, as a consequence, the CW takes over on a small scale the HTP mechanical loads; b) in the conditions of HTP overloading, which presupposes the occurrence of plastic deformations in its damaged areas, CW is gradually loaded, and the degree of taking over the mechanical loads by the CW could become equal or even greater than the one corresponding to the HTP; if the overloading is large enough,

* email. andrei.upg@gmail.com; Tel. 0723 298506

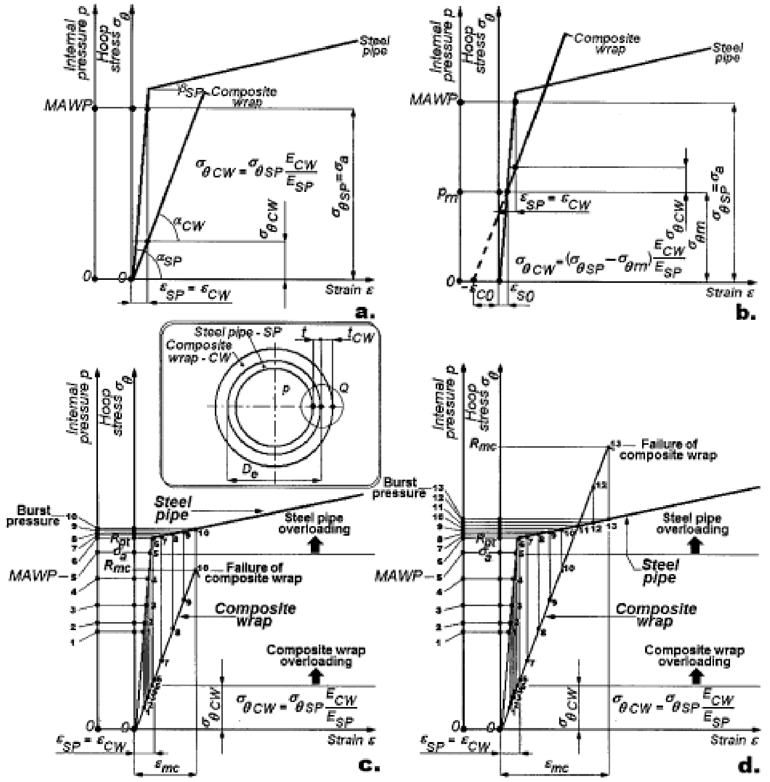

Fig. 1. Schemes for the analysis of the technical performances of the repairs with CW

Table 1
THE MAIN MECHANICAL PROPERTIES OF THE COMPOSITE MATERIALS FOR CW

Property e)	Composite material of CW a)						
	Perma Wrap b)	Fiba Roll b)	Clock Spring b)	RKIT 4D	RES-Q Wrap b)	IWR	KPB
Tensile modulus E_{CW}, GPa	34.0… 38.0	7.9… 8.7	33.8… 34.5	48.0… 49.3	67.5… 69.8	17.5… 22.7	2.8… 3.1
Poisson's ratio μ_{CW}, -	0.30… 0.32 c)	0.15… 0.23	0.22… 0.25	0.18… 0.19	0.30… 0.33	0.40… 0.47	0.27… 0.30
Shear modulus G_{CW}, Gpa	3.1… 6.5 c)	-	3.1… 5.9	4.2… 5.5	6.5… 6.8 c)	1.8… 2.3 c)	-
Tensile strength R_{mCW}, Mpa	580… 620	72… 190	630… 650	188… 205	822… 1020	265… 315	30… 31
Elongation at break ε_{mCW}, %	1.0… 1.1	2.8… 3.7	1.0… 1.2	1.3… 1.4	0.25 d)	1.8… 2.2	1.1… 1.3
Adhesion to steel A_{dzCW}, Mpa	-	min. 11	-	-	-	12.5… 14.9	-

a) Perma Wrap, Fiba Roll, Clck Spring, IWR and KPB are armed with fibreglass, RKIT 4D – with aramid fibres, and RES-Q Wrap – with carbon fibres; b) these types of materials are delivered in different alternatives / grades (for instance, Fiba Roll delivers the CW grades: VECR, VECR HS1, VEFR, ISO etc.), the table presenting the ranges which frame the properties values existing in the catalogues and presentation documents for all grades belonging to the same type of composite material; c) these values have been determined based on the similarity with the values of the same properties for similar composite materials; the values are informative, as the degree of anisotropy of the materials is not precisely known; d) the value represents the allowable circumferential strain for CW; e) the values of the mechanical properties are for the CW circumferential direction.

failure will occur in the CW and then in the HTP damaged areas, because the CW elongation at break ε_{mc} is inferior to the one corresponding to the steel from which HTP pipes are manufactured ε_{ms} ($\varepsilon_{mc} << \varepsilon_{ms}$); c) if CW is applied upon a HTP subjected to a pressure p_m (fig. 1.b), and then the operating pressure is increased at a value p_o ($p_m < p_o \leq MAWP$), the HTP behaviour and the CW reinforcement effects will be as mentioned before; however, if the HTP will be operated at $p_o < p_m$, the mechanical co-operation between CW and HTP will depend upon the preservation of the CW adherence on the external surface of the HTP pipes.

Experimental part

In order to underline the measure in which the issues previously presented (obtained on the ground of examining the schemes from fig. 1), regarding the technical performances of the repairs using CW, are confirmed experimentally, several specimens of the type full-scale segment of steel pipe – TP have been constructed, upon which CWs have been applied in the areas where local surface defects of the type metal loss have been executed by machining. The general layout of TP, which has been provided with $n_d = 1…3$ areas with defects reinforced by applying some CWs, is presented in figure 2. Table 2 and Figure 3 present the configuration and dimensions of the defects made by machining and the dimensions of CW applied on each specimen. The method of applying CWs on the specimen is shown in Figure 4, with the following specifications: a) CWs applied on TP1…TP3 have been of the IWR type, and CWs applied on the specimens TP4 and TP5 have been of KPB type (with the mechanical properties included in table 2); to cover the defects, before applying the CW, it has been used a polymeric filler – PF (reactive polymeric system modified with flexibility additive and mineral filler): ICECHIM type, for making

Table 2
DIMENSIONS OF THE DEFECTS AND OF THE REINFORCING WRAPS FROM THE TPs

Sample	Main dimensions (fig. 2)			Steel grade Standard	Mechanical properties a)			
					specified values		effective values b)	
	D_e, mm	t, mm	L_p, mm		$R_{t0.5}$, MPa	R_m, MPa	$R_{t0.5}$, MPa	R_m, MPa
TP1	114.3	4.5	480	L290/X42 EN ISO 3183	290…495	415…760	302	419
TP2	168.3	7.1	940	L245/Gr B EN ISO 3183	245…450	415…760	285	433
TP3	168.3	7.5	905	L245/Gr B EN ISO 3183	245…450	415…760	278	459
TP4	530	7.4	4000	17G1S-U/K52 GOST 20295	360…460	510…630	392	598
TP5	720	9.9	4000	13G1S-U/K55 GOST 20295	380…480	540…660	388	565
Sample	n_d	Defect	d_p, mm	s_p, mm	c_p, mm	Defect shape	t_{mm}, mm	Obs.
TP1	1	D11	2.7	80	10	Fig. 3.b	1.8	-
TP2	3	D21	5.6	86	4	Fig. 3.d	1.5	-
		D22	6.0	99	10	Fig. 3.a	1.1	-
		D23	5.5	84	9	Fig. 3.b	1.6	-
TP3	2	D31	5.2	97	21	Fig. 3.c	2.1	-
		D32	5.0	100	10	Fig. 3.a	1.6	-
TP4	1	D41	3.5	146	91	Fig. 3.e	3.9	s_{pb}= 40 mm
TP5	1	D51	4.8	145	119	Fig. 3.e	5.1	s_{pb}= 40 mm
Sample	Defect	Repair wrap	t_{CW}, mm	l_{CW}, mm	A_{CW}, mm	Polymeric Filler – PF	Composite material of repair wrap – CW	
TP1	D11	CW1	5.3	200	85	ICECHIM [4]	IWR – Table 1	
TP2	D21	CW1	5.7	175	180			
	D22	CW2	5.7	200	430			
	D23	CW3	5.7	200	710			
TP3	D31	CW1	5.0	200	125			
	D32	CW2	5.0	210	405			
TP4	D41	CW1	4.5	460	1170	REM-stali [6]	KPB – Table 1	
TP5	D51	CW1	4.5	490	1155			

a) $R_{t0.5}$ – yield strength (0.5 % total extension); R_m – tensile strength; b) determined experimentally by tensile testing some samples of the type pipe strip cut longitudinally from the SP used to make the TP

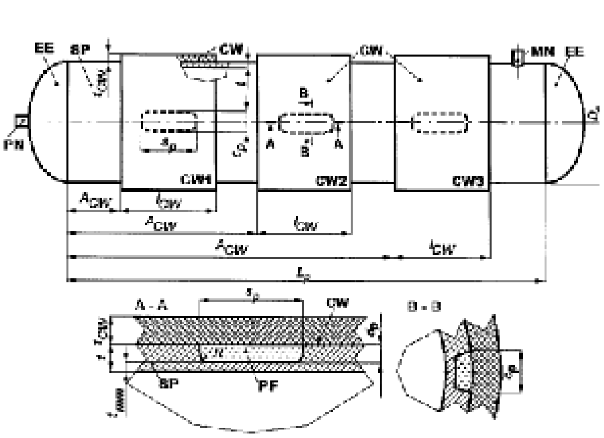

Fig. 2. General layout of the TP with CWs applied over the defects made by machining: SP-steel pipe; EE - ellipsoidal end; CW - composite wrap; MN - nozzle for pressure gauge (manometer); PN -- nozzle for TP pressurization; PF - polymeric filler

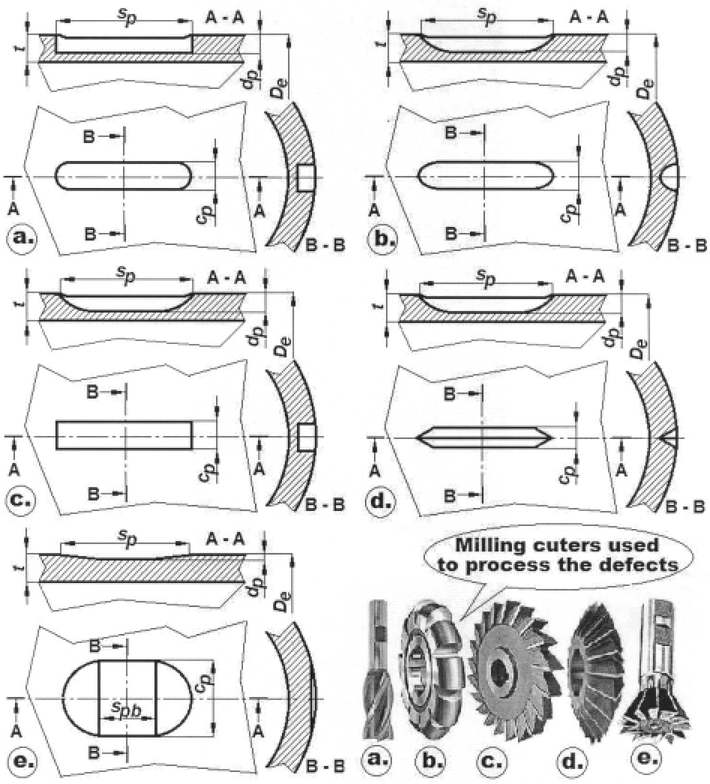

Fig. 3.Configuration and dimensions of the deffects made by machining / milling on the TP

TP1…TP3 and REM-stali type, for TP4 and TP5 [4, 6]; b) CWs from TP1…TP3 have been applied upon the unpressurized specimens, while CWs from TP4 and TP5 have been applied after the internal pressurization of the specimens (filled with water) at $p_p \cong 5$ MPa; b) CWs from TP1, TP3, TP4 and TP5 have been applied after preparing by sandblasting the SP external surface, while CWs from TP2 have been applied without a previous preparation of the SP external surface; c) before applying CWs upon TP4 and TP5, on the external surfaces, prepared by sandblasting, of SPs a polymeric film of primer has been applied. TPs obtained in such way are shown in figure 5.

TPs (filled with water) have been subjected to the internal pressure testing up to bursting (using the pressurization systems, with high pressure, up to 150 MPa, pumps existing in the laboratories of the Petroleum – Gas University of Ploiesti, where TP1…TP3 have been made and tested, and of the E.O. PATON Electric Welding Institute,

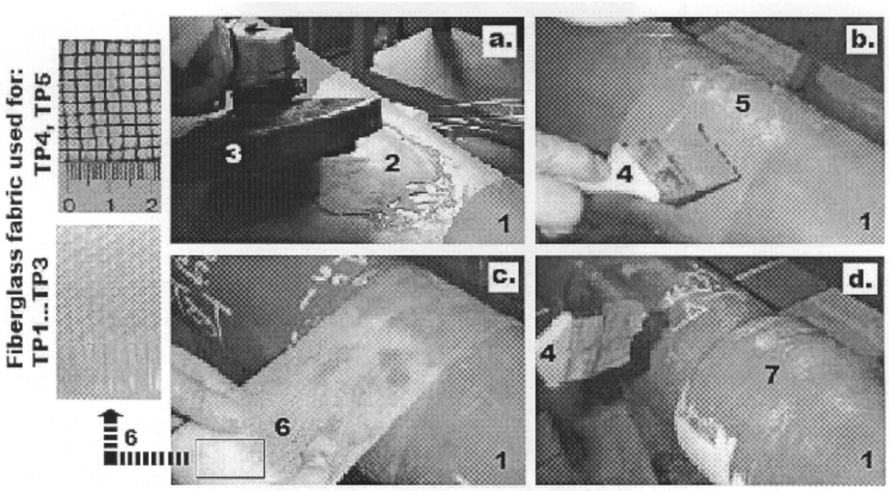

Fig. 4. The method of applying a CW in the TP areas with deffects: a. PF application on the defect and smoothing of the SP surface; b. application of the first layer of the polymeric matrix PM of the CW; c. d. obtaining the CW by applying succesive layers made of polymeric matrix PM reinforced with fibreglass fabric FW 1. steel pipe of TP; 2. polymeric filler applied on the defect; 3. manual grinderl 4. brush; 5. polymeric matrix; 6. fibreglass fabric; 7. repair wrap made of composite material CW

where TP4 and TP5 have been built and tested), obtaining on such basis the information regarding: a) the value of the burst pressure p_b; b) the position and mode of failure occurrence for each specimen; c) the peculiarities of the behaviour of the CW applied upon each specimen and the characterization of their reinforcement effect in the SP areas with defects.

In order to study experimentally the reiforcement effects of a CW applied upon a steel pipe subjected to internal pressure loading (in the elastic range), a specimen of the type full-scale segment / section of steel pipe (without local surface defects of the type metal loss) – TPT has been made using a segment of a L290 / X42 steel pipe (having the mechanical properties, determined experimentally by performing tensile tests on samples of the type pipe strip cut longitudinally from the SP used to built the TPT, $R_{t0.5}$ = 327 MPa and R_m = 445 MPa) – SP with two ellipsoidal ends – EE welded at its extremities, onto which a composite wrap – CW of IWR type has been applied (with the procedure used to build TP1…TP5 – fig. 4). On the external surface of the steel pipe – SP, with the external diameter D_e = 168.3 mm, the length L_p = 620 mm and the wall thickness t = 7.1 mm, used to make the TPT, the strain gauges – TERs LG_{SP} (in the longitudinal direction) and CG_{SP} (in the circumferential direction) have been applied, and upon the composite wrap – CW, with the length l_{CW} = 200 mm and the thickness t_{CW} = 5.8 mm, positioned on the TPT at the quota A_{CW} = 225 mm, the TERs LG_{CW} (in the longitudinal direction) and CG_{CW} (in the circumferential direction) have been applied, as it can be seen in figure 6. All used TERs have been of the type 1-LY11-10/120, manufactured by Hottinger Baldwin Messtechnik – HBM.

TPT (filled with water) has been subjected to the internal pressure testing, aiming at, by recording the signals received from the TERs LG_{SP}, CG_{SP}, LG_{CW} and CG_{CW}, obtaining information regarding the amplitude of the mechanical stresses and strains generated in the components SP and CW. The internal pressure, recorded with the help of the pressure gauge / digital manometer – DM (type P3MBP – 1000, manufactured by HBM), has been progressively increased up to the level p_{tmax} = 24 MPa, defined in such way that the components SP and CW of TPTs will be loaded only in the elastic range. During testing, the signals received from the DM and TERs have been acquired (with the speed of 5 values per second) and processed with the help of a system made of a Quantum X – SM device (manufactured by HBM), provided with an amplification module MX840 (universal amplifier achieving the power supply of the gauges, their signal conditioning, data acquisition and transmission towards the PC, ensuring the linearity for the range 0…12500 mm/m of TER deformations) and a computer

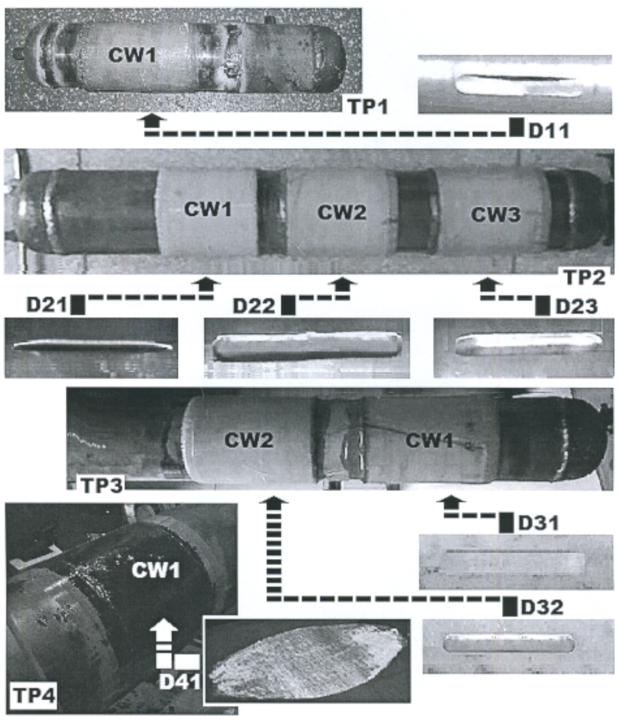

Fig. 5. Layout of TP prepared for the internal pressure testing up to bursting

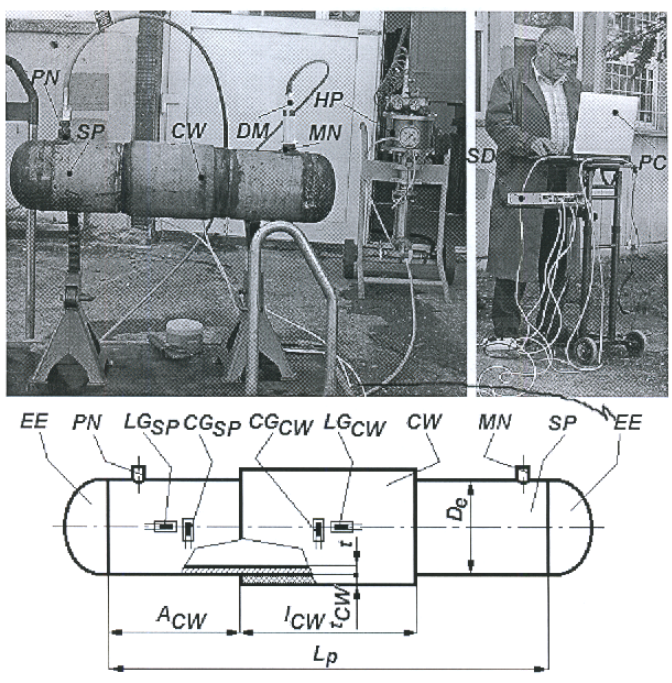

Fig. 6. Layout of TPT, prepared for the internal pressure testing

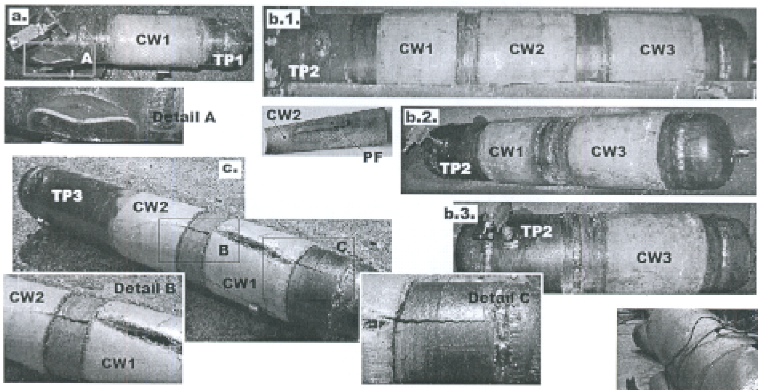

Fig. 7. TP1...TP3 layouts afer the internal pressure testing up to bursting

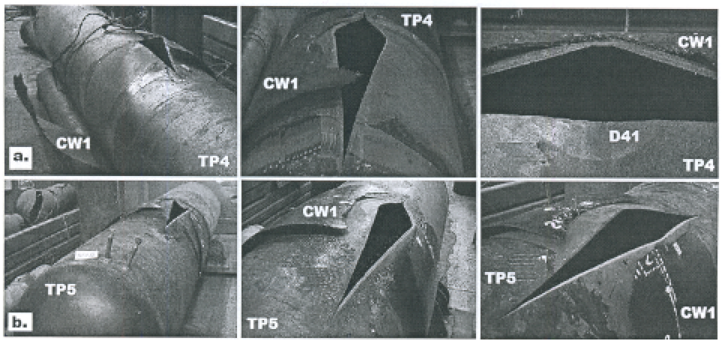

Fig.8. TP4 and TP5 layouts after the internal pressure testing up to bursting

– PC, provided with the software Catman® Expres V3.0 (fig. 6).

Results and discussions

The results of the experimental program regarding the TP internal pressure testing up to bursting are summarised in table 3, and the TP layout after failure is shown in figures 7 and 8. Table 3 also contains the assessments made, after performing the tests, in order to obtain the landmarks needed for the interpretation of the experimental results, regarding the values ranges of the TP burst pressure: a) p_{bw}, corresponding to the TPs with SP without defects; b) p_{bd}, corresponding to the TPs with defects executed by machining on the SP; c) p_{br}, corresponding to the TPs reinforced by applying CWs in the areas with defects. In order to obtain the ranges for p_{bw}, the burst pressures of the SPs (from which each TP has been made) have been calculated with the 12 formulae presented in [7], the obtained values have been ordered in an increasing series and the extreme values (minimum and maximum) have been eliminated; to obtain the ranges for p_{bd} it has been proceeded similarly, only that the processed values have been the burst pressures of the SPs containing the defects made by machining, calculated applying the 11 formulae from [7], and to obtain the ranges for p_{br}, the following formula [2, 8] has been used:

$$p_{br} = \frac{2}{D_e}\left[R_{mp} t_{mm} + R_{mCW} t_{CW}\right] \quad (1)$$

considering the values from tables 1 and 2 for D_e, t_{mm}, t_{CW}, R_m and R_{mCW}.

With the estimated values of the pressures p_{bw}, p_{bd} and p_{br} and with the values determined experimentally for the TP

Table 3
RESULTS OF INTERNAL PRESSURE TESTING OF THE TPs UP TO BURSTING

TP	Test sequence	Estimated values of burst pressure (MPa) for TP: without defect p_{bw}	with defect p_{bd}	repaired with CW p_{br}	I_{so}; I_{rt} a)
TP1	Fig.7.a	39.3 … 41.0	17.9 … 21.8	37.8 … 42.4	I_{so} = 0.445 … 0.563; I_{rt} = 0.390 … 0.623
TP2	Fig. 7.b.1	42.3 …43.3	11.9 … 18.4	23.6 … 27.0	I_{so} = 0.565 … 0.725; I_{rt} = 0.120 … 0.357
	Fig. 7.b.2		8.7 … 16.1	25.7… 29.1	I_{so} = 0.619 … 0.799; I_{rt} = 0.222 … 0.482
	Fig. 7.b.3		12.7 … 19.0	26.2 … 29.6	I_{so} = 0.551 … 0.707; I_{rt} = 0.166 … 0.400
TP3	Fig. 7.c	45.7 … 48.5	16.1 … 23.4	28.3 … 31.3	I_{so} = 0.488 … 0.668; I_{rt} = 0.101 … 0.359
TP4	Fig. 8.a	18.6… 19.3	10.1… 13.4	9.3… 9.4	I_{so} = 0.279 … 0.477; I_{rt} < 0
TP5	Fig. 8.b	17.5… 18.1	10.3… 12.8	8.3 … 8.4	I_{so} = 0.293 … 0.431; I_{rt} < 0
TP	Test sequence	Burst pressure p_b, MPa	Burst location	CW behaviour	I_r; RE b)
TP1	Fig.7.a	39.5	SP, near CW1	CW unbroken	I_r = 0.432 … 0.550 RE – Major
TP2	Fig. 7.b.1	29.5	SP – D22, under CW2	CW unbroken Water leaking under CW2	I_r = 0.256 … 0.416 RE – Moderate
	Fig. 7.b.2	30.0	SP – D21, under CW1	CW unbroken Water leaking under CW1	I_r = 0.321 … 0.504 RE – Moderate
	Fig. 7.b.3	31.5	SP – D23, under CW3	CW unbroken Water leaking under CW3	I_r = 0.289 … 0,444 RE – Moderate
TP3	Fig. 7.c	31.5	SP – D31 + CW1 & propagation of burst at CW2	CW1 broken & cracks on CW2	I_r = 0.167 … 0.337 RE – Minor
TP4	Fig. 8.a	14.2	SP – D41 + CW1	SP – D41 + CW1 broken	I_r = 0.041 ... 0.234 RE – Insignificant
TP5	Fig. 8.b	14.9	SP – D5 +CW1	SP – D51 + CW1 broken	I_r = 0.116 ... 0.262 RE – Insignificant

a) $I_{so} = 1 - p_{bd}/p_{bw}$; $I_{rt} = (p_{br}/p_{bd} - 1)(p_{bd}/p_{bw}) = (p_{br} - p_{bd})/p_{bw}$; b) $I_r = (p_b - p_{bd})/p_{bw}$; RE – CW reinforcement effect burst pressures p_b, the typical ranges have been calculated (table 3) for the values of the following indices for the syntetical characterization of a TP: a) I_{so} – the softening index of the TP mechanical strength due to the presence of the defects existing on the SP; b) I_{rt} and I_r – the index, assessed / theoretical and effective, characterizing the TP reinforcement effect, produced by applying CWs in the SP areas with defects. The reinforcement effect RE obtained by applying CWs on the TP areas with defects has been qualitatively evaluated (major, moderate, minor, insignificant) taking into account the measure in which the criteria have been fulfilled: a) p_b ³ p_{br} ³ p_{bw} > p_{bd}; b) $I_{so} \leq I_{rt} \leq I_r$; in order to perform these assessments, a diagram summarising the results of the experimental program, shown in figure 9, has been built.

Regarding the particularities of completing the experimental program regarding the TP internal pressure testing up to bursting and the interpretation of the results of

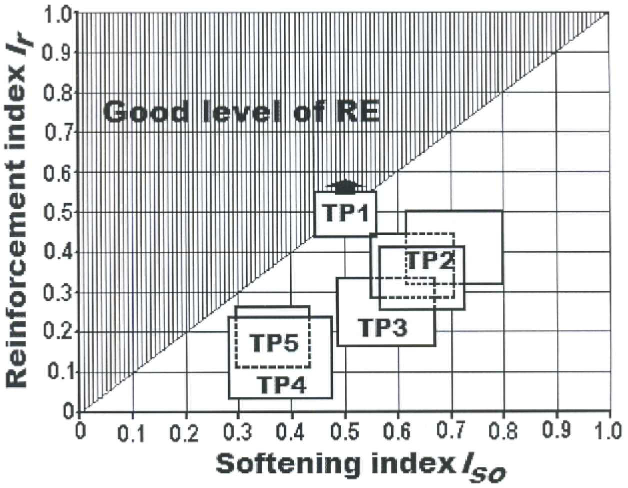

Fig.9. Results summary for the TPs internal pressure testing up to bursting and assessment of the RE of the CWs

this program, the following comments must be made: a) testing of TP1 have led to its bursting outside the area where CW has been applied (fig. 7.a) and has disclosed that $p_b > p_{bw} >> p_{bd}$ and $I_{so} \cong I_{rt} \cong I_r$, justifying the assessment of a major RE; b) the first testing sequence of TP2 have led to its failure and tightness loss in the area of defect D22 (under CW2, fig. 7.b.1); the area in which failure occurred has been removed by cutting, TP2 has been reconstituted, joining by welding the undamaged parts (fig. 7.b.2), and its second testing sequence has been executed, leading to its failure and tightness loss in the area of defect D21 (under CW1); the area in which the second failure took place has been removed by cutting, TP2 has been reconstituted again from the undamaged parts (fig. 7.b.3) and the third testing sequence has been performed, which has led to TP2 failure and tightness loss in the area of defect D23 (under CW3); as for PT2 it has been noted that $p_b \geq p_{br} > p_{bd}$, but $p_b < p_{bw}$, $I_{rt} \leq I_r$ but $I_{so} > I_r$ and, in addition, all CWs have not been adherent to the SP (due to the fact that the SP was unprepared by sandblasting before applying the CW), it has been estimated that the CW used to repair the TP2 defects had a moderate RE; c) testing of TP3 have led to its bursting in the area of defect D31, full breakage of CW1 applied over the defect D31, fracture propagation towards the area with defect D32 and cracking of CW2 applied over it (fig. 7.c); because TP3 testing showed that $p_b \cong p_{br} > p_{bd}$, but $p_b < p_{bw}$ and $I_{so} >> I_{rt} \cong I_r$, it has been assessed that the RE of the CW applied on TP3 has been minor; d) testing of TP4 have led to its bursting in the area of defect D41, full rupture and detachment of the CW from the SP; as it has been noted that $p_b < p_{bw}$, $p_{br} < p_{bd} \cong p_b$ and $I_{so} >> I_r$, it has been estimated that the RE of applying the CW from the composite material KPB (with a low mechanical strength, due to the weak properties of the polymeric matrix and the inadequate structure of the fibreglass fabric, which did not assure an adequate density of the fibres in the CW) has been insignificant; e) testing of TP5 have led to conclusions similar to the ones resulting in the case of TP4.

The experimental program whose results have been described has emphasized the possibility for CWs applied in the HTP areas with defect to increase their mechanical resistance, expressed using the level of the internal pressure at which the ultimate limit state corresponding to bursting / failure of HTP pipes is reached, the conditions that must be fulfilled to that purpose being: a) the adequate selection of the composite material from which CWs are made; b) the application of CWs with the thickness t_{CW} appropriately choosen. Hence, if the CWs (made of composite material of IWR type) applied upon TP2 would have had $t_{CW} \geq 12$ mm, and the ones applied upon TP3 would have had $t_{CW} \geq 8$ mm, the internal pressure testing would have disclosed a similar behaviour to the one observed for TP1 (bursting / failure outside the areas reinforced with CW); however, in the case of CWs applied on TP4 and TP5, the CW thicknesses which would have led to the fulfilment of the conditions p_b ³ $p_{bw} > p_{bd}$ and $I_{so} \leq I_r$ would have been, due to the low mechanical strength of the KPB composite, $t_{CW} > 50...60$ mm, an inapplicable solution due to the high costs and to the difficulties of obtaining a good quality (without defects, of the type gas inclusions in the polymeric matrix, which drastically diminishes the mechanical properties of the composite [2, 9]) of CWs with such great thickness.

The results of the experimental program aiming to emphasize the states of strains and mechanical stresses generated by the internal pressure loading (in the elastic region) of the TPT are summarised in figure 10. The strains ε_{qSP} and ε_{lSP} have been obtained by recording the signals received (during the TPT loading at different levels of the internal pressure p_i) from the gauges CG_{SP} and LG_{SP}, and the strains $\varepsilon_{\theta CW}$ and ε_{lCW} have been obtained by recording the signals received from CG_{CW} and LG_{CW}; the mechanical stresses $\sigma_{\theta SP}$, σ_{lSP}, $\sigma_{q\theta CW}$ and σ_{lCW} have been calculated with the formulae:

$$\sigma_{\theta SP} = \frac{1}{1-\mu_{SP}^2}(\varepsilon_{\theta SP} + \mu_{SP}\varepsilon_{lSP})E_{SP};$$
$$\sigma_{lSP} = \frac{1}{1-\mu_{SP}^2}(\varepsilon_{lSP} + \mu_{SP}\varepsilon_{\theta SP})E_{SP}; \quad (2)$$

$$\sigma_{\theta CW} = \frac{1}{1-\mu_{CW}^2}(\varepsilon_{\theta CW} + \mu_{CW}\varepsilon_{lCW})E_{CW};$$
$$\sigma_{lCW} = \frac{1}{1-\mu_{CW}^2}(\varepsilon_{lCW} + \mu_{CW}\varepsilon_{\theta CW})E_{CW}, \quad (3)$$

considering $\mu_{sp} = 0.3$, $E_{sp} = 205$ GPa (for SP) and the values given in table 4 for the IWR μ_{CW} and E_{CW}. In order to validate the experimental results, the diagrams from fgure 10 also show the variations, as a function of p_i, of the stresses and strains calculated with the formulae developed in the thick-wall theory of tubes [10]: a) with continuous lines, $\varepsilon_{\theta SP}$ and ε_{lSP}, $\sigma_{\theta SP}$ and σ_{lSP} on the external surface of TPT without CW; b) with dotted lines, $\varepsilon_{\theta SP}$ and ε_{lSP}, $\sigma_{\theta SP}$ and σ_{lSP} on SP, at the SP – CW interface, respectively $\varepsilon_{\theta CW}$ and ε_{lCW}, $\sigma_{\theta CW}$ and σ_{lCW} on the CW external surface.

The results shown in figure 10 clearly highlights that the RE of CWs applied in the HTP areas with defects, expressed by the CW capacity to unload the HTP damaged areas, is low, being equal with the ratio $\rho_{\sigma\theta}$ of the intensity of the circumferential stresses generated in the CW and in the SP upon which CWs have been applied in the conditions of HTP

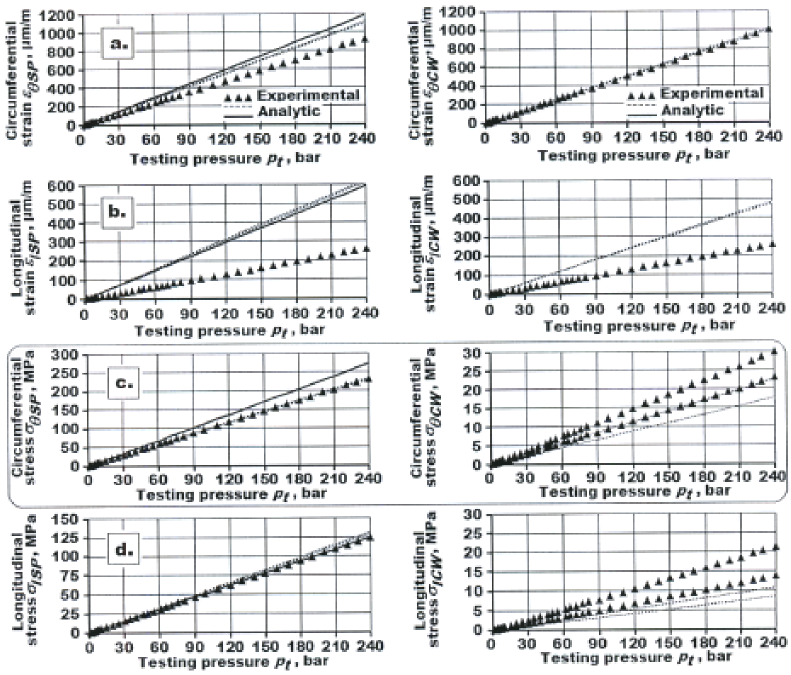

Fig. 10. The diagrams of the state of mechanical streses and strains determined experimentally and analitically on the SP and CW of the TPT subjected to internal pressure p_t loading: a. circumferential strain $\varepsilon_{\theta SP}$, $\varepsilon_{\theta CW}$ = $f_1(p_t)$; b. longitudinal strain ε_{lSP} ε_{lCW}= $f_2(p_t)$; c. circumferential stress $\sigma_{\theta SP}$ $\sigma_{\theta CW}$= $g_1(p_t)$; d. longitudinal stress σ_{lSP} σ_{lCW}= $g_2(p_t)$;

operating at internal pressure, $\rho_{\sigma\theta} = \sigma_{\theta CW}/\sigma_{\theta SP} = \rho_E = E_{CW}/E_{SP}$; for the TPT (with CW made of IWR composite (table 1) tested within the experimental program, $\rho_{\sigma\theta}$ = 0.096...0.125 (fig. 10), and ρ_E = 0.085...0.110 (and if using CWs made of last generation composites, of RES-Q Wrap type, with carbon fibres, 7…8 times more expensive than the ones with fibreglass, it is possible to ensure at the most $\rho_{\sigma\theta} \cong \rho_E$ = 0.329…0.340). Remarks of the same kind, regarding the modest level of $\rho_{\sigma\theta} = \sigma_{\theta CW}/\sigma_{\theta SP} = \rho_E$ assured by CWs made of composite materials, are also suggested in other papers [11], the increase of the CW capacity to unload the HTP damaged areas having to be one of the forefront requirements in the development of composite materials for such technical applications.

Conclusions

The results of the experimental research programs described in this paper have led to the following conclusions:

The reinforcement effect of the composite materials wraps – CW (applied in the areas with defects of the hydrocarbon transmission pipelines – HTP), expressed using the loading conditions at which the ultimate limit state corresponding to HTP bursting / failure is reached, is dependent on the mechanical strength properties of the composite material from which CWs are manufactured and on the CWs thickness; the use of CWs made of composite material of the IWR type (or other similar materials (table 1), with thicknesses t_{CW} = 5...25 mm, is suitable, as it can guarantee levels of the internal burst pressure of the HTP area repaired by applying CW superior to the burst pressure of HTP without defects, while the use of CWs made of KPB type materials is not convenient, because getting a reinforcement effect similar to the one ensured by CWs made of IWR type composites implies the usage of very thick CWs ($t_{CW} \geq$ 50...60 mm), inappropriate due to high costs and technological problems of implementation.

The reinforcement effect of the composite materials wraps – CW, expressed by the CW capability to unload (to reduce the stress intensities generated in) the HTP damaged areas, is low, being equal to the ratio r_E of the elasticity (Young's) module of the CW and of the steel from which HTP pipes are manufactured, $\rho_E = E_{CW}/E_{SP}$; making the CW from composite material of the IWR type (or other similar materials (table 1) guarantees levels of ρ_E = 0.085...0.110; the use of CWs made of materials of the KPB type is not considered appropriate, because it does not ensure values of r_E greater than 0.015, and, if one appeals to the CW made of last generation composite materials, with E_{CW} = 50...70 GPa (table 1), it is possible to reach ρ_E = 0.240...0.340.

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