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# Design of Composite Material Reinforcing Sleeves Used to Repair Transmission Pipelines

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## Abstract

*This paper presents and analyses the existent procedures and proposes a new procedure for the design of the reinforcing sleeves made of composite materials which are applied in the areas with local surface defects (of the type metal loss) of the transmission pipelines intended for petroleum, liquid petroleum products and natural gas. In addition, the technical requirements regarding the definition and qualification of the pipelines repair systems using composite materials, and the information which must be made available as input data for the design of reinforcing sleeves intended for various applications (repair of pipeline with different locations, shapes and dimensions of the metal loss – like defects) are also presented. The items discussed and the solutions formulated in the paper can be useful both to the manufacturers of the components of the composite materials repair systems and to the ones dealing with the design and performance of the maintenance works for the pipelines belonging to the transmission systems of petroleum, liquid petroleum products and natural gas.*

**Key words**: *transmission pipeline, pipeline repair, composite repair system, composite reinforcing sleeve design*

## Introduction

The repair of the areas with local surface defects (of the type metal loss) of the **t**ransmission **p**ipelines – TPs (the great majority of which are made from steel pipes and components) by means of applying composite materials sleeves / wraps has been used from some time, but the problems afferent to the application of this repair procedure did not found yet technical solutions fully underlain and unanimously accepted [1-10]. As it is specified in [4-7], any **r**epair **s**ystem (with composite materials, for pipelines and pipeline systems) – RS is defined as a combination of the following elements (for which the qualification tests have been performed): a. the **s**u**b**strate – SB (the pipe or pipeline component which is to be repaired); b. **s**urface **p**reparation – SP (the preparation of the SB surface in the area which is repaired); c. the **p**olymeric **f**iller – PF (used to fill the defects and to reconstruct the external configuration of the SB, before applying the composite material sleeve); d. the repairing **w**rap from **c**omposite material – CW and its components: the **p**olymeric **r**esin matrix – PR and the **r**einforcing material with **f**ibres – RF or the **l**ayer from **c**omposite material – CL and the polymeric adhesive – PA); the **r**epair **p**rocedure – RP (the PF and CW application procedures, and the verification procedures for the repair quality).

The RS types presently in use are: a. RS with CW obtained by wrapping a CL, known under the name Layered Systems (e.g. Clock Spring, Perma Wrap, WeldWrap), that are the first types of CW used, but which have a limited usage field to the repair of pipes (straight areas of TPs); b. RS with CW of monolithic type, obtained by applying successive layers of PR and RF, known under the name Wet lay-up system (e.g. Armor Plate Pipe Wrap, Black Diamond, Aquawrap, ICECHIM Wrap), which can be used for the repair of both the rectilinear areas of TPs and the non-rectilinear components (elbows, bends, tees, valves etc.); c. hybrid RS, using complex CWs, obtained by combining the repair components of the Layered Systems and of the Wet lay-up systems (see, as an example, the RSs proposed in [9, 10]). [4, 5] recommend the RSs which use composite materials with polymeric matrix (e.g., polyester, polyurethane, phenolic, vinyl ester, or epoxy resin), reinforced by including fibres or fabrics made of continuous fibres (e.g., aramid, carbon, glass or polyester fibres or fabrics).

The activities that must be achieved for the repair of a TP using such a RS (with all the elements qualified accordingly) are shown in the scheme from Figure 1, drawn by processing the information from [11]. The present paper describes and analyses the existing procedures, and it proposes a new procedure for the design of the CWs which are applied in the areas with local surface defects of the TPs for petroleum, liquid petroleum products and natural gas [1,2]; all the procedures for CW design contain the sequence of steps outlined in Figure 2.

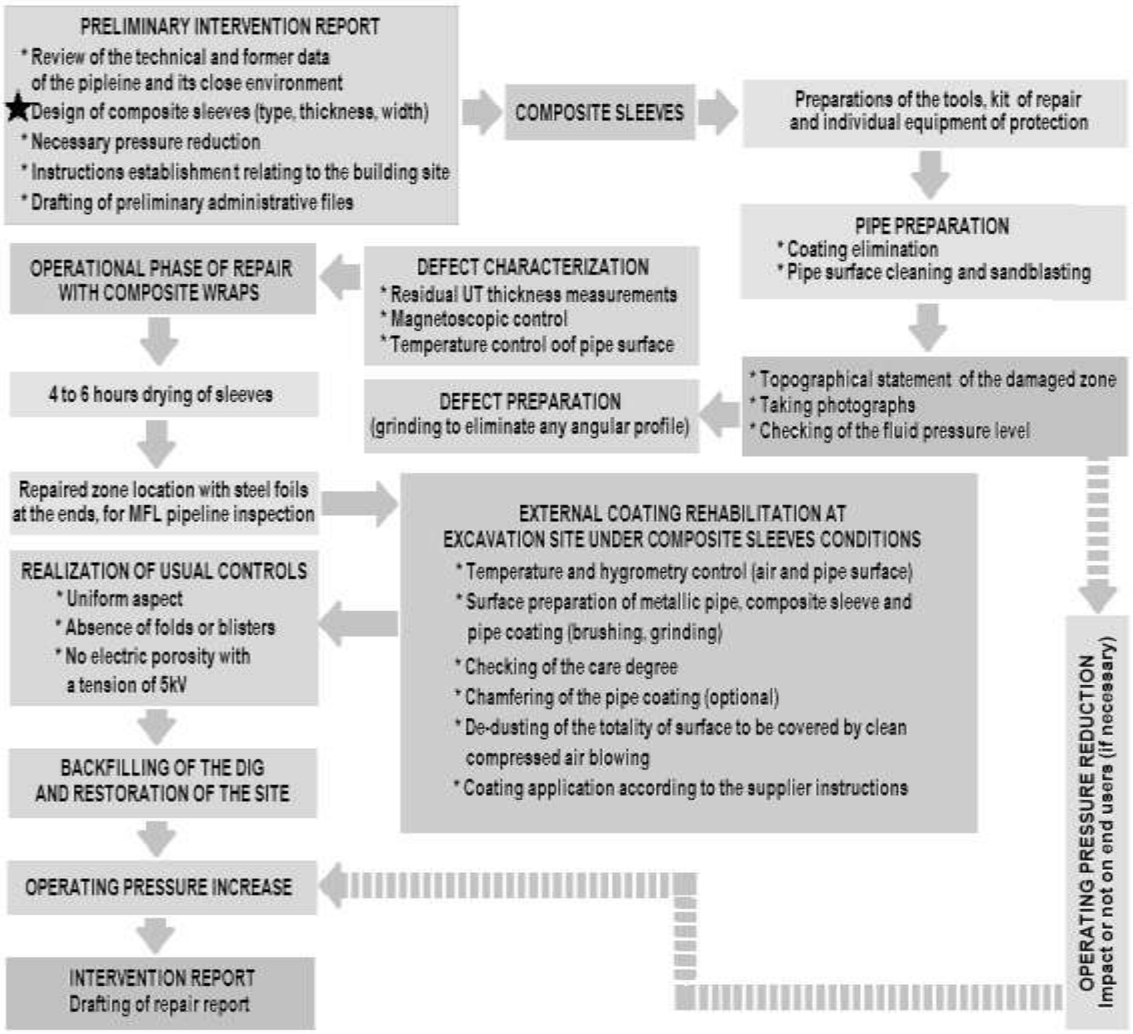

**Fig. 1.** Activities of pipeline repair using composite sleeves or wraps

## Determination of the Necessity and Opportunity of Repairing the TP Areas with Defects

The first step of the design procedure for a CW used to repair a TP that presents a local surface defect consists in the determination and the analysis of the design and operational parameters for the TP (without defects): a. the technical design – operating conditions of the TP: design pressure, $p_c$; maximum allowable operating pressure, $p_o = MOP \leq p_c$; additional / supplementary loads (axial load, $F_a$, bending moment, $M_b$, torsional moment, $M_t$, shear load, $F_s$); operating temperature (minimum, $t_{\min}$, and maximum, $t_{\max}$); b. outside diameter, $D_{ep}$, and nominal wall thickness, $t_p$ (of the steel pipes used to build the TP); c. effective/true mechanical properties of the steel pipes: Young modulus, $E_p$; yield strength, $R_{yp}$ (upper yield strength, $R_{eHp}$, proof strength, plastic extension, $R_{p0,2p}$, or proof strength, total extension, $R_{t0,5p}$); tensile strength, $R_{mp}$; allowable stress, $\sigma_{ap} = f_d R_{yp} = p_{ao}(D_{ep} - t_p)/(2t_p)$ (in which $f_d$ is the design factor for TP, and $p_{ao}$ – the maximum allowable operating pressure of TP, $p_{ao} = MAOP \geq p_c$); percentage elongation after fracture, $A_{fp}$; Poisson's ratio, $\mu_p$; full-size Charpy V-notch absorbed energy $KV_p$ (or other toughness properties, at $t_{min}$). Obviously, to these properties one should add the data regarding the characteristic dimensions of the defect detected on the TP: maximum depth, $d_{ml}$; minimum remaining thickness, $t_{mm} = t_p - d_{ml}$; circumferential extent or width, $c_{ml}$, longitudinal / axial extent or length, $s_{ml}$.

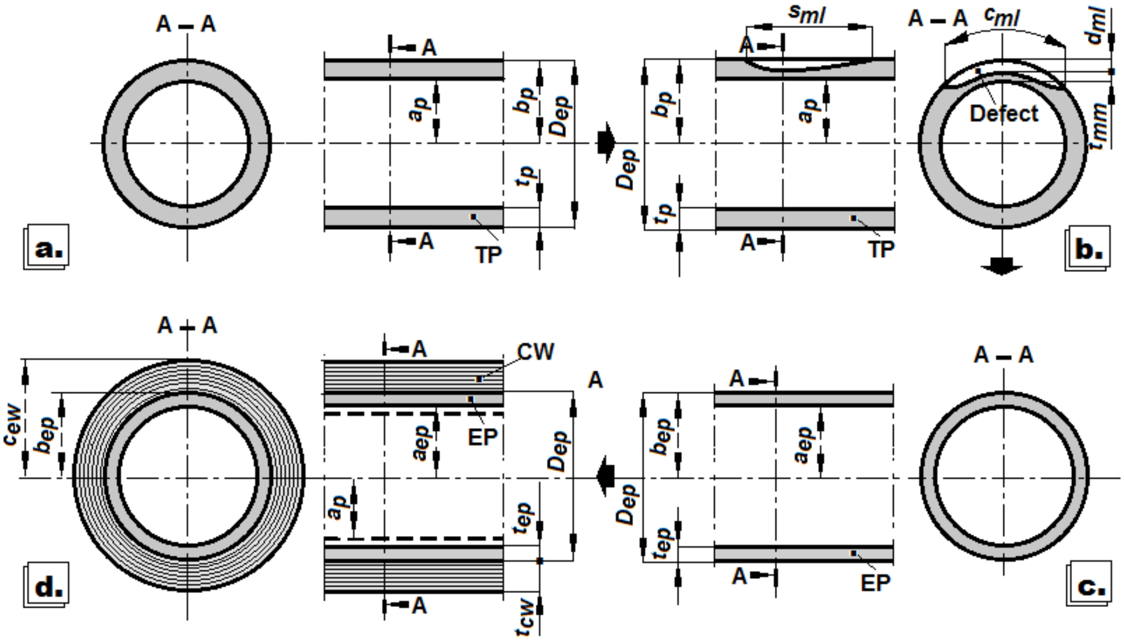

**Fig. 2.** Structure of the CW design procedure:
a. evaluation of the mechanical strength of the TP without defects; b. evaluation of the mechanical strength of the TP with local surface defects and determination of the opportunity of the repair by applying CW; c. definition of the characteristic dimensionilor of the TP without defects equivalent (as mechanical strength) to the TP with defects; d. CW design: selection and definition of the composite material properties for CW and calculation of CW dimensions.

The second step of the CW design procedure consists of the evaluation of the severity of the defect detected on the TP and the evaluation of its residual mechanical strength. The characteristic with which the residual mechanical strength of the TP with defect is usually appreciated is its maximum (safe) operating pressure $p_d = RSF\ p_{ao}$, with $RSF$, named Remaining Strength Factor, determined using one of the following formulae:

- formula recommended in [12]:

$$RSF = \frac{1-k_d d_{rd}}{1-\frac{k_d d_{rd}}{M_d}}, \tag{1}$$

$k_d$ being a coefficient that takes into account the configuration of the longitudinal profile of the defect ($k_d$ = 0.67...1.00), $d_{rd}$ – relative depth of the defect, $d_{rd} = d_{ml}/t_p$, and $M_d = f(s_{rd})$ – a factor depending on the relative length of the defect, $s_{rd} = s_{ml}/(D_{ep}t_p)^{0,5}$, which is usually calculated with the formula recommended (together with $k_d$ = 0.67) in [13]:

$$M_d = \sqrt{a_0 + a_1 z_d + a_2 z_d^2}, \text{ if } z_d \le 50 \text{ or } M_d = b_0 + b_1 z_d, \text{ if } z_d > 50, \tag{2}$$

with $z_d = 0.893s_{rd}$ and $a_0 = 1$; $a_1 = 0.6275$; $a_2 = -0.003375$; $b_0 = 3.3$; $b_1 = 0.032$;

- the formula recommended in [3]:

$$RSF = 1.1\frac{1-0.85d_{rd}}{1-0.85d_{rd}\left(1+0.8s_{rd}^2\right)^{-0.5}}, \text{ if } s_{rd} \le 4.5 \text{ or } RSF = 1.1(1-d_{rd}), \text{ if } s_{rd} > 4.5; \tag{3}$$

- the formula recommended in [15]:

$$RSF = 1 - 0.945t_{rp}^{0.2}d_{rd}^{1.6}s_{rd}^{0.4}, \tag{4}$$

$t_{rp}$ being the pipe relative thickness, $t_{rp} = t_p/D_{ep}$;

- the formula recommended in [13]:

$$RSF = 1 - d_{rd}\left[1 - exp\left(-0.222\frac{s_{rd}}{\sqrt{1-d_{rd}}}\right)\right]. \tag{5}$$

Taking into account the operational requirements of the TP, allowability criteria can be formulated for the defect (for operating the TP without the reinforcement, by applying a CW, of the area which contains the defect), of the form $p_d \ge p_{da}$ or $RSF \ge RSF_a$, $p_{da}$ (which is usually considered $p_{da} = p_o$) and $RSF_a$ being the minimum allowable levels for the operating pressure, $p_d$, and the remaining strength factor, $RSF$, respectively. Obviously, if the allowability criteria are not fulfilled, the decision to repair the TP by applying a CW in the defect area is taken, and, until the execution of the maintenance works is scheduled, it will be necessary to operate the TP at a pressure not more than equal to $p_d$.

If the decision to repair the TP by applying a CW has been taken, the third step of the CW design procedure is performed, and it consists in the calculation of the characteristic dimensions of an equivalent pipeline – EP, defined as being a TP without defect, made of pipes from the same steel as the TP with defect, and which has the same mechanical strength as the TP area containing the defect. Because, as it can be seen in Figure 2, EP is considered to have the same outside diameter, $D_e$, as the TP with defect, and its maximum (safe) operating pressure is $p_d = RSFp_c$, its characteristic dimensions (wall thickness, $t_{ep}$, internal radius, $a_{ep}$, and external radius, $b_{ep}$) can be determined by applying the formulae:

$$t_{ep} = \frac{p_d}{2\sigma_a + p_d}D_{ep};\ a_{ep} = \frac{D_{ep}}{2} - t_{ep};\ b_{ep} = \frac{D_{ep}}{2}. \tag{6}$$

## Selection and Characterisation of CWs for TP Repair

The accomplishment of a good quality repair (with CW) presupposes the definition of all RS elements which are applied: SB, SP, PF, CW and RP; an example of a complete RS characterisation is given in [14]. For the design of the CW dimensions (thickness $t_{cw}$ and length / axial extent $l_{cw}$), one must know (besides the information obtained in the steps previously performed) the physical and mechanical properties of the composite material (of the type PR + RF or CL + PA): a. the elastic constants; the fact that the overlapped layers from which the CW is made of have the behaviour of an orthotropic plate makes them four: tensile modulus in circumferential direction, $E_{cc}$, and in axial direction, $E_{ac}$; Poisson's ratio in circumferential direction (load in circumferential direction, contraction in axial direction), $\mu_c$, and shear modulus, $G_c$; b. tensile strength: short-term, in circumferential direction, $R_{mcc}$, and in axial direction, $R_{mac}$, and long-term (defined as being greater or equal to 1000 hours), in circumferential direction, $R_{mclc}$, and in axial direction, $R_{malc}$; c. elongation at break in circumferential direction, $A_{cc}$, and in axial direction, $A_{ac}$; d. other characteristics: bending / flexural modulus, $E_{bc}$; flexural strength, $R_{mbc}$; impact resistance (Izod), $KV_{ic}$; hardness (Barcol, Shore etc.); adhesion to steel, $A_{dsc}$; thermal expansion coefficient in circumferential direction, $\alpha_{cc}$, and in axial direction, $\alpha_{ac}$.

Table 1 presents the mechanical properties of the composite materials for the most used CW, as well as those of some composite materials (IWR and KPB) tested by the authors in view of their qualification and future usage [14, 17-19].

**Table 1.** Main mechanical properties of the composite materials of CWs

| Property | Composite material of CW a) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Perma Wrap b) | Fiba Roll b) | Clock Spring b) | RKIT 4D | RES-Q Wrap b) | IWR | KPB |
| Tensile modulus $E_{cc}$, 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 |
| Tensile modulus $E_{ac}$, GPa | 7.8... 8.7 c) | - | 6.1... 11.1 c) | 18.8... 19.6 | 26.5... 27.4 | 4.1... 7.4 c) | - |
| Poisson's ratio $\mu_c$, - | 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 $G_c$, 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 $R_{mcc}$, MPa | 580... 620 | 72... 190 | 630... 650 | 188... 205 | 822... 1020 | 265... 315 | 30... 31 |
| Tensile strength $R_{mac}$, MPa | 42... 75 c) | 5.4... 13.3 c) | 44... 55 c) | 50... 54 | 270... 305 c) | 210... 245 | 28... 29 |
| Elongation at break $A_{cc}$, % | 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 |
| Elongation at break $A_{ac}$, % | - | - | - | - | 0.10 d) | 1.2... 1.3 | - |
| Flexural modulus $E_{bc}$, GPa | - | 6.1... 9.0 | - | - | - | - | - |
| Flexural strength $R_{mbc}$, MPa | - | 162... 287 | - | - | - | - | - |
| Impact resist. $KV_{ic}$, kJ/m$^2$ | 45... 60 c) | 55... 60 | 55... 60 c) | 11.... 13 | - | - | - |
| Adhesion to steel $A_{dsc}$, MPa | - | min. 11 | - | - | - | 12.5... 14.9 | - |

a) Perma Wrap, Fiba Roll, Clock Spring, IWR and KPB are armed with glass fibres, RKIT 4D – with aramid fibres, and RES-Q Wrap – with carbon fibres; b) these types of materials are delivered in different variants / labels (for instance, Fiba Roll deliveres the CW labels: VECR, VECR HS1, VEFR, ISO etc.), the table indicating the range enclosing the properties values existing in the leaflets and presentation documents for all labels belonging to the same type of composite material; c) these values have been defined by analogy with the values of the same properties at similar composite materials; the values are only indicative, because the degree of anisotropy of the materialels is not accurately known; d) these values represent the allowable circumferential and axial strain for the CW.

Regarding the mechanical properties of the composite materials intended for the repair the TP areas with local surface defects, the following remarks and recommandations can be made: a. the manufacturers provide no information or insufficient information regarding the physical and mechanical properties guaranteed for (ensured by) these materials; because, as it can be noticed examining the information from Table 1, the manufacturers do not specify the manner in which the properties of the delivered composite materials modify themselves in time (the long-term values of the mechanical properties are absent in almost all brochures and presentation documents of the composite materials), it is recommended – when applying the CW design procedure – to use a factor accounting for the decrease in time of the mechanical strength (service factor), $f = 0.50...0.67$ [4]; b. the information provided is not always correlated with the types of delivered materials; for instance, the manufacturer states that the CL it delivers can be made with different contents of chopped glass rovings (non-woven glass tissue) from glass fibres E (225, 300, 450 or 600 g/m$^2$), but he specifies a single set of properties for CL, albeit, as it is known, the properties of the composite materials armed with fibres modify themselves as a function of the volumetric fraction of fibres they contain [18]; c. when the repair kits are ordered from various manufacturing companies, one should require, as accompanying documents, the CW design procedure and the testing reports regarding the determination of and the warranty for the mechanical properties values considered in the calculations for the definition of the CW dimensions (thickness $t_{cw}$ and length $l_{cw}$);

Due to the manner in which it has been conceived (see fig. 2), the CW design procedure does not require the knowledge of the mechanical properties of the PF which is used to fill the defects (and to restore the external shape of the SB, before applying the CW). However, if, for a given case, one wants to check the results obtained by applying the CW design procedure, using, for instance, a numerical simulation with the Finite Element Method – FEM of the operational behaviour of repaired TPs, the knowledge of these properties will impose itself. It has to be mentioned that also for PFs (which can be simple polymeric materials or aggregate composite reinforced by incorporating metallic or non-metallic particles) the manufacturing companies provide a small amount of information regarding their mechanical properties. The range encompassing the values of the main properties of PFs frequently used for TP repair are indicated in Table 2 [19].

**Table 2.** Mechanical properties of the fillers used for pipelines repair

| Property | Value |
|---|---|
| Tensile modulus $E_{pf,}$ at 25 °C, GPa | 10 ... 15 |
| Poisson's ratio $\mu_c$, at 25 °C, – | 0.30 ... 0.38 |
| Tensile strength $R_{mpf}$, at 25 °C, MPa | 45 ... 50 |
| Elongation at break $A_{pf}$, % | 0.7 ... 1.0 |
| Compression strength, at 25 °C, MPa | 95 ... 110 |
| Compression strength, at 60 °C, MPa | 68 ... 80 |
| Hardness, at 25 °C, Shore D | min. 80 |

For the CW design, the temperature influences upon the properties of the used composite materials must also be considered; to that purpose [4,5] the following statements should be made: a. the CW application temperature and the repaired TP operating temperature must fulfil the condition: $t_{max} \leq t_{mc} = \min[t_g - 20^oC; t_{hd} - 15^oC]$, $t_g$ being the glass transition temperature, $t_{hd}$ – the heat distorsion temperature for the polymeric components of the CW, and $t_{mc}$ – the upper temperature of RS; because the operating temperatures range for the majority of TPs is [$t_{min} = -10$ °C; $t_{max} = +40$ °C], while PAs and PRs used to obtain CW have $t_g$ and $t_{hd}$ over 80 °C, the above condition is fulfilled; b. the service factor $f$, used for CW design, must be multiplied with a temperature derating factor, $f_t$, which is calculated with the formula [4]:

$$f_t = 0.7014 + 10^{-3}(t_{mc} - t_{rs}) + 6 \cdot 10^{-5}(t_{mc} - t_{rs})^2, \tag{7}$$

in which $t_{rs}$ is the RS design temperature; because the RSs for TP are commonly characterised by values $t_{mc} - t_{rs} = 40...60$ °C ($t_{rs} = 20...40$ °C), $f_t = 0.7...1.0$; c. the allowable (long-term) strains of the CW in the circumferential direction, $\varepsilon_{acc}$, and in the axial direction, $\varepsilon_{aac}$, are determined with the formulae [4]:

$$\varepsilon_{acc} = f_t\, \varepsilon_{c0} - \Delta t(\alpha_p - \alpha_{cc})\ ;\ \varepsilon_{aac} = f_t\, \varepsilon_{a0} - \Delta t(\alpha_p - \alpha_{ac}), \qquad (8)$$

where $\alpha_{cc}$ and $\alpha_{ac}$ are the thermal expansion coefficient in circumferential direction and in axial direction of the CW, $\alpha_p$ is the thermal expansion coefficient of TP, $\Delta t$ is the absolute value of the difference between the (average) TP operating temperature and the temperature at the moment of applying the CW, while $\varepsilon_{c0}$ and $\varepsilon_{a0}$ are the reference values for the allowable (long-term) strains of the CW in circumferential direction and in axial direction. [4] recommends to consider the following values for $\varepsilon_{c0}$ and $\varepsilon_{a0}$: $\varepsilon_{c0} = 0.0040$ and $\varepsilon_{a0} = 0.0040$, if $E_{cc}/E_{ac} \leq 2$, and $\varepsilon_{a0} = 0.0025$, if $E_{cc}/E_{ac} > 2$, for TPs which are not frequently overloaded during operation, respectively $\varepsilon_{c0} = 0.0025$ and $\varepsilon_{a0} = 0.0025$, if $E_{cc}/E_{ac} \leq 2$, and $\varepsilon_{a0} = 0.0010$, if $E_{cc}/E_{ac} > 2$, for TPs with frequent overloads during operation, while [5] recommends (for TPs conveying petroleum, liquid petroleum products and natural gas) to consider the following values for $\varepsilon_{c0}$ and $\varepsilon_{a0}$, as a function of the TP remaining life (after repair) $\tau_{Lp}$ (in years): $\varepsilon_{c0} = 0.003228 - 0.000164\sqrt{\tau_{Lp}}$ and $\varepsilon_{a0} = 0.003228 - 0.000164\sqrt{\tau_{Lp}}$, if $E_{cc}/E_{ac} \leq 2$, and $\varepsilon_{a0} = 0.0010$, if $E_{cc}/E_{ac} > 2$; d. allowable (long-term) stresses of the CW in circumferential direction $\sigma_{acc}$ and in axial direction $\sigma_{aac}$ are determined (as a function of $\varepsilon_{acc}$ and $\varepsilon_{aac}$): $\sigma_{acc} = \min[E_{cc}\varepsilon_{acc}\ ;\ fR_{mcc})$ and $\sigma_{aac} = \min[E_{ac}\varepsilon_{aac}\ ;\ fR_{mac}]$.

## Determination of the Characteristic Dimensions of the CW

If the composite material used to make the CW for the repair of a TP on which one has detected a local surface defect (not through-wall) has been selected, and its physical and mechanical properties are known, one goes to the definition of the CW characteristic dimensions, which, as previously stated, are the thickness $t_{cw}$ and the width $w_{cw}$.

For the calculation of the CW thickness, $t_{cw}$, several methods have been proposed, the most used ones being presented and commented in the followings.

A. By interpreting and processing the methodology proposed in [4, 5] (named in [4], *Design Methodology for Underlying Substrate Does Not Yield* and in [5], *Design Based on Substrate – Allowable Stress*), it resulted the following formula for the determination of the CW thickness which is applied for the repair of a defect detected on a TP, in the case in which it is assumed that, during TP operation, plastic deformations will not occur in the steel pipe containing the defect (with a reduced thickness due to the presence of the defect):

$$t_{cw} \geq \max\left[\frac{D_{ep}}{2}\frac{E_p}{E_{cc}}\frac{p_{ao}}{R_{yp}} f_p(f_{CL} - RSF);\ \frac{D_{ep}}{4}\frac{E_p}{E_{ac}}\frac{p_{ao}}{R_{yp}} f_p(f_{AL} - RSF)\right], \qquad (9)$$

in which the (dimensionless) factors $f_p$, $f_{CL}$ and $f_{AL}$ (for TP loading) are determined with the formulae:

$$f_p = \frac{p_o}{p_{ao}};\ f_{CL} = 1 + \frac{16}{\pi}\left[\frac{F_s}{D_{ep}^2 p_c} + \frac{2M_t}{D_{ep}^3 p_c}\right]^2\ ;\ f_{AL} = 1 + \frac{4}{\pi}\left[\frac{\sqrt{F_a^2 + 4F_s^2}}{D_{ep}^2 p_c} + \frac{4\sqrt{M_b^2 + M_t^2}}{D_{ep}^3 p_c}\right]; \qquad (10)$$

obviously, if the TP is not subjected to additional / supplementary loads (axial load, $F_a = 0$, shear load, $F_s = 0$, bending moment, $M_b = 0$, torsional moment, $M_t = 0$) and, in addition, $p_o = p_{ao}$, the formula (9) is easier to apply, because $f_{CL} = f_{AL} = 1$ and $f_p = 1$.

B. By interpreting and processing the methodology proposed in [4,5] (named in [4], *Design Methodology for Underlying Substrate Yields* and in [5], *Design Based on Repair Laminate Allowable Strains*), it resulted the following equation for the determination of the CW thickness which is applied for the repair of a defect detected on a TP, in the case in which it is assumed that, during TP operation, plastic deformations are generated in the steel pipe containing the defect (with a reduced thickness due to the presence of the defect):

$$t_{cw}^2 + [\alpha + \beta + \gamma]t_{cw} + \alpha\beta = 0, \tag{11}$$

$$\alpha = t_{mm}\frac{E_p}{E_{cc}};\ \beta = t_{mm}\frac{R_{yp}}{E_{cc}\varepsilon_{acc}} - \frac{D_{ep}}{2}\frac{p_o}{E_{cc}\varepsilon_{acc}}\ ;\ \gamma = \frac{D_{ep}}{2}\frac{p_r}{E_{cc}\varepsilon_{acc}}, \tag{12}$$

in which $p_r$ is the TP operating pressure during CW application, $p_r \in [0\ ;\ p_d]$; evidently, if the TP is removed from service during CW application, $p_r = 0$ and equation (11) has the root (positive):

$$t_{cw} = -\beta = \frac{R_{yp}}{E_{cc}\varepsilon_{acc}}\left[f_d t_p - t_{mm}\right] = t_p\frac{R_{yp}}{E_{cc}\varepsilon_{acc}}\left[f_d + d_{rd} - 1\right]. \tag{13}$$

Certain manufacturers of composite materials for CWs recommend a conservative determination of the thickness $t_{cw}$, with the formula (obtained by considering, in (13), $t_{mm} = 0$ or $d_{rd} = 1$) [18]:

$$t_{cw} = \frac{D_{ep}-t_p}{2}\frac{p_{ao}}{E_{cc}\varepsilon_{acc}} = t_p\frac{R_{yp}f_d}{E_{cc}\varepsilon_{acc}} = t_p\frac{\sigma_{ap}}{\sigma_{acc}}. \tag{14}$$

When applying this method, the allowable (long-term) strain value of the CW in circumferential direction, $\varepsilon_{acc}$, must be determined using the first one from the formulae (8), which implies the knowledge of the properties $\alpha_p$ and $\alpha_{cc}$, and the adoption of a value for $\Delta t$; it is recommended: a. if possible, the CW application conditions are selected so that $\Delta t = 0$, which simplifies the formula (8) and increases the level of confidence in the results obtained by using it; b. if the previous recommendation is not pertinent, it will be taken into account the fact that $\Delta t \leq 40$ °C, $\alpha_p \cong 1.1\cdot10^{-5}$ °C$^{-1}$, and the usual CWs (see Table 1) have $\alpha_{cc} = 1.2\cdot10^{-5}...2.9\cdot10^{-5}$ °C$^{-1}$ [17-20].

C. By interpreting and processing the methodology from [20], the following formula resulted for the determination of the (minimum value of the) CW thickness applied for repair of a TP:

$$t_{cw} \geq \frac{D_{ep}-t_p}{2}\frac{p_{ao}}{R_{mcc}}\frac{1-RSF}{f f_t} = t_p\frac{R_{yp}}{R_{mcc}}\frac{f_d(1-RSF)}{f f_t}. \tag{15}$$

D. Starting from the formula proposed in [21]:

$$p_{bdp} = \frac{2}{D_{ep}}\left[R_{mp}t_{mm} + R_{mclc}t_{cw}\right], \tag{16}$$

which allows for the evaluation of the bursting pressure, $p_{bdp}$, of a TP which has been repaired by applying a CW with the thickness $t_{cw}$, and imposing the condition that $p_{bdp}$ is equal with the bursting pressure of the TP without defect $p_{bp}$, which can be determined with the formulae [22]:

$$p_{bp} = R_{mp}\frac{4}{\left(\sqrt{3}\right)^{n_{sp}+1}}\frac{t_{rp}}{1-2t_{rp}};\ n_{sp} = 0.224\left(\frac{R_{mp}}{R_{yp}}\right)^{0.604}, \tag{17}$$

the authors have obtained the following formula for the CW thickness:

$$t_{cw} = t_p\frac{R_{mp}}{R_{mcc}}\frac{1}{f f_t}\left[\frac{2}{\left(\sqrt{3}\right)^{n_{sp}+1}}\frac{1}{1-2t_{rp}} + d_{rd} - 1\right]. \tag{18}$$

E. Considering that, in the repaired area, the TP is a multi-layered tube, the inner layer being a steel pipe with the dimensions corresponding to EP, calculated with the formulae from the group (6), and the outer layer being a CW from the composite material applied to repair the TP area with defect, the authors have developed the following calculation formula for the CW thickness in order for the TP to withstand the pressure $p_c$:

$$t_{cw} = \frac{D_{ep}}{2}\left[\sqrt{\frac{K_{EP}-\mu_c+1}{K_{EP}-\mu_c-1}} - 1\right], \tag{19}$$

$$K_{EP} = \frac{E_{cc}}{E_p}\frac{1}{k_{ep}^2-1}\left[\frac{8t_{rp}k_{ep}^2}{t_{rp}(3k_{ep}^2+1)-k_{ep}^2+1} - K_{EP0}\right];\ K_{EP0} = \left(k_{ep}^2-1\right)\left(1-\mu_p\right)+2\ , \tag{20}$$

in which $k_{ep} = b_{ep}/a_{ep} > 1$, $a_{ep}$ and $b_{ep}$ being the EP radii, calculated with (6). It is possible that, for defects with reduced axial extent (small values of $s_{ml}$ and $s_{rd}$), the formula (19) woud be too conservative (providing $t_{cw}$ values greater than the needed ones), because, for its deduction, a great longitudinal extent of the TP area weakened due to the defect presence has been considered, and the reinforcing effects on the TP area containing the defect given by its adjacent areas, without defects, has not been taken into account.

To obtain the CW length $l_{cw}$, the following formula is used [4, 5]:

$$l_{cw} = s_{ml} + 2(s_{tl} + s_{ol}), \tag{21}$$

in which the overlap length, $s_{ol}$, corresponds to the distance with which the CW over-distances (in the TP axial direction, on both its sides) the defect with the length $s_{ml}$, and the taper length, $s_{tl}$, corresponds to the projection on the TP axial direction of the bevel from each CW extremity; $s_{tl}$ and $s_{ol}$ are adopted so that the following conditions are fulfilled [4, 5, 18-20]:

- if the TP is not subjected to additional / supplementary axial loads:

$$s_{ol} = \max\left[1.77\sqrt{D_{ep}t_p}; 38 \text{ mm (1.5 in)}\right];\ s_{tl} \geq 1.1t_{cw}; \tag{22}$$

- if the TP is subjected to additional / supplementary axial loads:

$$s_{ol} = \max\left[1.77\sqrt{D_{ep}t_p};\ \frac{E_{ac}\varepsilon_{aac}t_{cw}}{A_{dsc}}; 38 \text{ mm (1.5 in)}\right];\ s_{tl} \geq 5t_{cw}. \tag{23}$$

The methods and formulae for the CW design have been compared by applying them for several case studies; in the followings, one of these is presented as an example. The target of the case study has been the CW design for the repair of a TP for natural gas; the initial data and RS properties considered in the case study are:

- the characteristic dimensions of the TP pipes: $D_{ep}$ = 508 mm; $t_p$ = 8 mm; to these correspond: $t_{rp}$ = 0.01575; $a_{ep}$ = 246 mm; $b_{ep}$ = 254 mm (see fig. 2);
- the mechanical properties (effective) of the TP pipes made of L290N / X42N steel: $E_p$ = 200 GPa; $R_{yp}$ = 320 MPa > 290 MPa, $R_{mp}$ = 450 MPa > 415 MPa, $A_{fp}$ = 18 %, $\mu_p$ = 0.3;
- the design conditions and the present operating conditions of the TP: $p_c$ = 6.5 MPa, $p_o$ = *MOP* = 6.0 MPa ≤ $p_c$, $F_a = F_s = 0$, $M_b = M_t = 0$, $f_d$ = 0.72; to these conditions correspond: $\sigma_{ap} = f_dR_{yp}$ = 230.4 MPa and $p_{ao}$ = *MAOP* = 7.37 MPa;
- the characteristic dimensions of the local surface defects (separated, without interaction) detected on the TP: $d_{ml} = k_{de}t_p$, with $k_{de}$ = 0.2...0.8, $c_{ml}$ = 150 mm, $s_{ml}$ = 200 mm; to these characteristics correspond: $d_{rd} = k_{de}$, $c_{rd}$ = 2.353 and $s_{rd}$ = 3.137;
- the CW properties (of the type PR + RF): $E_{cc}$ = 35 GPa, $E_{ac}$ = 28 GPa, $\mu_c$ = 0.35, $R_{mcc}$ = 350 MPa, $R_{mclc}$ = 175 MPa ($f$ = 0.5), $A_{cc}$ = 1.5 %, $\alpha_{cc}$ and $\alpha_{ac}$ unknown ($E_{cc}/E_{ac} = 1.25 < 2$, $\varepsilon_{c0} = \varepsilon_{a0} = 0.0040$);
- the CW application conditions for TP repair: $t_{mc} - t_{rs}$ = 60 °C, $\Delta t$ = 0 °C, $p_r$ = 0 ($f_t$ = 0.977, $\varepsilon_{acc} = \varepsilon_{aac}$ = 0.0039; $\sigma_{acc}$ = min[136.5MPa; 175.0 MPa] = 136.5 MPa).

Going through the steps from the CW design procedure for TP repair from the case study, the results summarised in Table 3 have been obtained. The reinforcing effects of the CW, with the characteristic dimensions (thickness $t_{cw}$ and width $w_{cw}$) determined using the methods and formulae from the present paper, have been checked using the calculation diagram proposed in [22], whose steps have the following content:

- definition of the TP characteristic dimensions in the area in which the CW has been applied: $a_{ep}$, $b_{ep} = D_{ep}/2$; $c_{ew} = b_{ep} + t_{cw}$ and the initial internal radius $a_p = b_{ep} - t_p$ (see fig. 2), and determination of the values for the ratios $k_{ep} = b_{ep}/a_{ep}$; $k_c = c_{ew}/b_{ep}$;
- calculation of the pressure $q_{pc}$ at the contact between TP and CW, using the formula:

$$q_{pc} = \frac{2p_o}{K_{EP0}+R_{PC}K_{EC0}}, \tag{24}$$

$$K_{EP0} = \left(k_{ep}^2 - 1\right)\left(1 - \mu_p\right) + 2; K_{EC0} = \left(k_c^2 - 1\right)\left(1 + \mu_c\right) + 2; R_{PC} = \frac{E_p}{E_{cc}}\frac{k_{ep}^2-1}{k_c^2-1}; \tag{25}$$

- determination of the stress and strain state in the TP area in which the CW has been applied, using the formulae:

$$\sigma_{rp}(r_p) = \frac{p_o - k_{ep}^2 q_{pc}}{k_{ep}^2 - 1} - \frac{p_o - q_{pc}}{k_{ep}^2 - 1}\frac{b_{ep}^2}{r_p^2};\ \sigma_{\theta p}(r_p) = \frac{p_o - k_{ep}^2 q_{pc}}{k_{ep}^2 - 1} + \frac{p_o - q_{pc}}{k_{ep}^2 - 1}\frac{b_{ep}^2}{r_p^2}; \tag{26}$$

$$u_p(r_p) = \frac{1-\mu_p}{k_{ep}^2 - 1}\frac{p_o - k_{ep}^2 q_{pc}}{E_p} r_p + \frac{1+\mu_p}{k_{ep}^2 - 1}\frac{p_o - q_{pc}}{E_p}\frac{b_{ep}^2}{r_p}; \varepsilon_{\theta p}(r_p) = \frac{u_p(r_p)}{r_p}, \tag{27}$$

where $\sigma_{rp}(r_p)$ and $\sigma_{\theta p}(r_p)$ are the stresses on the radial and circumferential directions, $u_p(r_p)$ – the radial displacements, while $\varepsilon_{\theta p}(r_p)$ – the circumferential strains in the TP points placed at the radius $r_p = (a_p)...a_{ep}...b_{ep}$;

**Table 3.** Results obtained for the design of the CW used to repair the TP from the case study

| $d_{rd} = d_{ml}/t_p = k_{de}$ | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 |
|---|---|---|---|---|---|---|---|
| *RSF* formula (1) | **0.8868** | **0.8281** | 0.7680 | 0.7064 | 0.6432 | 0.5785 | 0.5120 |
| *RSF* formula (3) | 0.9683 | 0.8962 | 0.8195 | 0.7378 | 0.6503 | 0.5567 | 0.4561 |
| *RSF* formula (4) | 0.9504 | 0.9052 | 0.8498 | 0.7853 | 0.7126 | 0.6322 | 0.5445 |
| *RSF* formula (5) | 0.8918 | 0.8305 | **0.7628** | **0.6867** | **0.5995** | **0.4963** | **0.3686** |
| $p_d = \min[RSF]p_{ao}$, MPa | 6.54 | 6.10 | 5.62 | 5.06 | 4.42 | 3.66 | 2.72 |
| DECIZI ANALIZEI [a)] | **NR** | **NR** | **R** | **R** | **R** | **R** | **R** |
| $t_{ep}$, mm – formula (6) | – | – | 6.10 | 5.50 | 4.80 | 4.00 | 3.00 |
| $a_{ep}$, mm – formula (6) | – | – | 247.9 | 248.5 | 249.2 | 250.0 | 251.0 |
| $k_{ep} = b_{ep}/a_{ep}$ [b)] | – | – | 1.0247 | 1.0222 | 1.0194 | 1.0160 | 1.0119 |
| $t_{cw}$, mm (adopted) | – | – | 3.0 | 6.5 | 11.0 | 16.5 | 23.0 |
| $l_{cw}$, mm (min) | – | – | 433 | 441 | 452 | 465 | 481 |
| $q_{pc}$, MPa – formula (24) | – | – | 0.45 | 1.00 | 1.63 | 2.39 | 3.29 |
| $\varepsilon_{\theta p}(b_{ep})\cdot 10^6$ [c)] | – | – | 1107 | 1115 | 1113 | 1110 | 1122 |
| $\sigma_{\theta p}(a_p)$, MPa [d)] | – | – | 228.7 | 230.1 | 229.5 | 228.8 | 230.9 |
| $\sigma_{\theta c}(b_{ep})$, MPa [d)] | – | – | 38.6 | 38.7 | 38.4 | 38.0 | 38.1 |

a) NR – TP shoud not be repaired ($p_d \geq p_o$); R – the TP repair is required ($p_d < p_o$); b) $b_{ep} = D_{ep}/2 = 254$ mm; c) $\varepsilon_{\theta p}(b_{ep}) = \varepsilon_{\theta c}(b_{ep}) < \varepsilon_{acc} = 0.0039$; d) $\sigma_{\theta p}(a_p) \cong \sigma_{ap} = 230.4$ MPa ; $\sigma_{\theta c}(b_{ep}) < \sigma_{acc} = 136.5$ MPa.

- determination of the stress and strain state in the CW applied for TP repair, with the help of the formulae:

$$\sigma_{rc}(r_c) = \frac{q_{pc}}{k_c^2 - 1}\left[1 - \frac{c_{ew}^2}{r_c^2}\right];\ \sigma_{\theta c}(r_c) = \frac{q_{pc}}{k_c^2 - 1}\left[1 + \frac{c_{ew}^2}{r_c^2}\right]; \tag{28}$$

$$u_c(r_c) = \frac{1}{k_c^2 - 1}\frac{q_{pc}}{E_{cc}}\left[(1-\mu_c)r_c + (1+\mu_c)\frac{c_{ew}^2}{r_c}\right]; \varepsilon_{\theta c}(r_c) = \frac{u_c(r_c)}{r_c}, \tag{29}$$

where $\sigma_{rc}(r_c)$ and $\sigma_{\theta c}(r_c)$ are the stresses on the radial and circumferential directions, $u_c(r_c)$ – the radial displacements, while $\varepsilon_{\theta c}(r_c)$ – the circumferential strains in the CW points placed at the radius $r_c = b_{ep}...c_{ew}$;

- validation of the design solutions ($t_{cw}$ and $l_{cw}$) for which there are simultaneously fulfilled: a. the deformations continuity condition: $\varepsilon_{\theta p}(b_{ep}) = \varepsilon_{\theta c}(b_{ep})$; b. the strength condition for the TP: $\sigma_{\theta p}(a_p) \leq \sigma_{ap}$; c. the strength condition for the CW: $\sigma_{\theta c}(b_{ep}) \leq \sigma_{ac}$; d. the allowability condition for CW deformations: $\varepsilon_{\theta c}(b_{ep}) \leq \varepsilon_{acc}$;
- the acceptance for application of the validated solution, characterised by the $\sigma_{\theta p}(a_p)$ value nearer to $\sigma_{ap}$. The verification results and the adopted solutions are presented in Table 3 and in Figure 3.

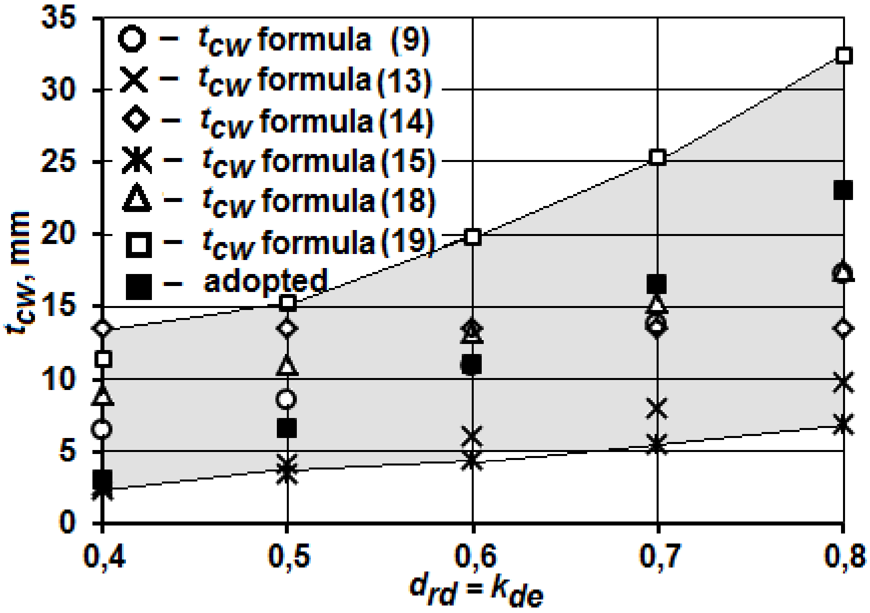

**Fig. 3.** The results of CW design for the case study

## Conclusions

The issues analysed and treated in this paper have led to the following conclusions regarding the design of the CWs (composite materials wraps) for TP repair:

- the schedule for the maintenance works for TPs having local surface defects of the type metal loss will be completed only after the assessment of the defects severity and the definition of *RSF* for the TP area in which defects have been detected; only the areas with defects for which the maximum safe operating pressure $p_d$ is inferior to the maximum operating pressure $p_o$ of the TP ($p_d < p_o$) must be repaired;
- the TP repair method by applying CWs for the reinforcement of the areas with defects is advantageous, because it allows to perform maintenance works without removing the TP from service, but it raises a series of problems regarding CW design (determination of the thickness $t_{cw}$ and length $l_{cw}$ of the composite wraps), as there is insufficient information regarding the mechanical properties of the composite materials from which CW is made, and a procedure theoretically underlain and unanimously accepted for the definition of the characteristic dimensions ($t_{cw}$ and $l_{cw}$) of the CW does not exist;
- the comparative analysis of the design methods for CWs has highlighted the fact that the method proposed by the authors is very advantageous, because it takes into account the real mode in which TP and CW work together (during normal TP operation and not in the situation of reaching an ultimate limit state, of TP failure); the method has the disadvantage to be very conservative (leading to CW thickness values greater than the ones required to ensure the safe service of the TP at the operating pressure $p_o$), because – when defining the CW thickness – it does not take into account the limited axial extent of the defect over which the composite wrap is applied (it cannot take into account the reinforcing effects of the TP areas, undamaged, adjacent to the defect).
- the authors intend to improve the proposed method for CW design (and the software products developed for its operative application), by defining (based on the results of numerical simulation analyses using FEM and of experimental research activities to be performed in the future) adequate correction factors for the calculation formulae from the present paper.

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# Proiectarea învelişurilor de consolidare din materiale compozite pentru repararea conductelor de transport

## Rezumat

*În lucrare sunt prezentate şi analizate procedurile existente şi este propusă o nouă procedură pentru proiectarea învelişurilor de consolidare din materiale compozite care se aplică în zonele cu defecte superficiale locale de tip lipsă de material ale conductelor destinate transportului petrolului, produselor petroliere lichide şi gazelor naturale. De asemenea, se prezintă cerinţele tehnice privind definirea şi calificarea sistemelor de reparare a conductelor cu materiale compozite şi informaţiile care trebuie să fie disponibile ca date de intrare la proiectarea învelişurilor de consolidare destinate diverselor aplicaţii practice (repararea conductelor cu diferite localizări, forme şi dimensiuni ale defectelor superficiale locale de tip lipsă de material). Aspectele discutate şi soluţiile formulate în lucrare pot fi utile atât producătorilor componentelor sistemelor de reparare cu materiale compozite, cât şi celor care se ocupă cu proiectarea şi realizarea lucrărilor de mentenanţă la conductele aparţinând sistemelor de transport ale petrolului, produselor petroliere lichide şi gazelor naturale.*