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Design of the Fracture Arrestors for Natural Gas Transmission Pipelines

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Abstract

In this paper there is defined the functional role of fracture arrestors designed in order to be installed over natural gas transmission pipelines and there is made an original classification of these, while presenting the constructive features and the way of achieving a wide range of arrestor types. There is presented an analytical method for assessing the reinforcement effects of the application of fracture arrestors with continuous disposal over pipelines, method that can be successfully used while designing (determining the thickness of) fracture arrestors of this type.

Key words: *gas transmission pipeline, fracture arrestors classification and design.*

Definition and Classification of Fracture Arrestors

The necessity of increasing the in-service safety of natural gas transmission pipelines led to the idea of installing some fracture arrestors, which can be defined as additional elements that mechanically co-act with the steel pipe and have the ability to absorb a lot of energy by elastic-plastic deformation before fracture. If the failure of a pipe occurs during the operation of such a pipeline, the unstable propagation of the fracture is possible only up to the first arrestor installed over the pipeline, whose deformation until the fracture implies an important energetic consumption, that wastes the energy available for the crack propagation and stops the fracture process; obviously, the inhibition of the fracture propagation process limits or diminishes the consequences of the pipeline failure.

In the technical literature there is no classification of pipeline fracture arrestors; the authors of this paper have tried to define a series of classification criteria and to perform the classification of fracture arrestors according to each of these criteria. Thus:

A. ***Depending on their extension and the way of application over the pipeline,*** fracture arrestors may be:

A1. Fracture arrestors of limited extension, applied from place to place over the pipeline;

A2. Fracture arrestors with continuous disposal, over the whole length of the pipeline or over long enough pipe sections;

B. Depending on the condition of the pipeline in the area of application, fracture arrestors may be:

B1. Fracture arrestors applied over a non-defective pipeline;

B2. Fracture arrestors applied over the pipeline's defects (acting also as reinforcement elements for the steel pipe and restoring the loading capacity of it in the defective areas);

C. Depending on the material they are made of, fracture arrestors may be:
C1. Fracture arrestors made of metallic material (steel) similar to the one the pipes are made of ;
C2. Fracture arrestors made of metallic materials, other than those the pipes are made of: austenitic stainless steel, aluminium alloys, copper alloys etc.;
C3. Fracture arrestors made of polymeric or composite materials;
D. Depending on the constructive design and on the technology used for the application over the pipeline, fracture arrestors may be:
D1. Fracture arrestors such as type A or B repair sleeves (used for repairing defective pipelines);
D2. Fracture arrestors such as polymeric resin or composite material filled sleeves/shells (used for repairing defective pipelines);
D3. Fracture arrestors such as circular or helical wraps of wire (with circular or square section) ***or tape*** (made of metallic materials of high plasticity and toughness);
D4. Fracture arrestors such as circular or helical weld depositions (using metallic additional elements, of high plasticity and toughness);
D5. Fracture arrestors such as circular or helical wraps of polymeric or composite materials.

The coding of fracture arrestors can be made in alphanumeric system, using the OR symbol followed by the symbols previously named for the categories they belong to according to the four classification criteria. For instance, the fracture arrestor codified ***OR – A1.B2.C1.D1*** is an arrestor with limited extension (A1), applied in an area of the pipeline where defects have been found (B2), made of a steel similar to the one the pipes are made of (C1) and having the configuration corresponding to a type A or B repair sleeve (D1), while the fracture arrestor codified ***OR – A2.B1.C3.D5*** is an arrestor with continuous extension (A2), applied over a non-defective pipeline section (B1), made of polymeric or composite materials (C3) and having the configuration corresponding to a continuous wrap, such as those used for the cathodic protection (D5).

Regarding the constructive design of fracture arrestors, there is a great variety of solutions, beginning with the simple variants presented in figure 1 and figure 2 and similar ones covered by the invention patents [3,4], synthetically reproduced in figures 3 and 4 and ending with complex variants, such as those outlined in figure 5, that make the object of the invention patents [5-7].

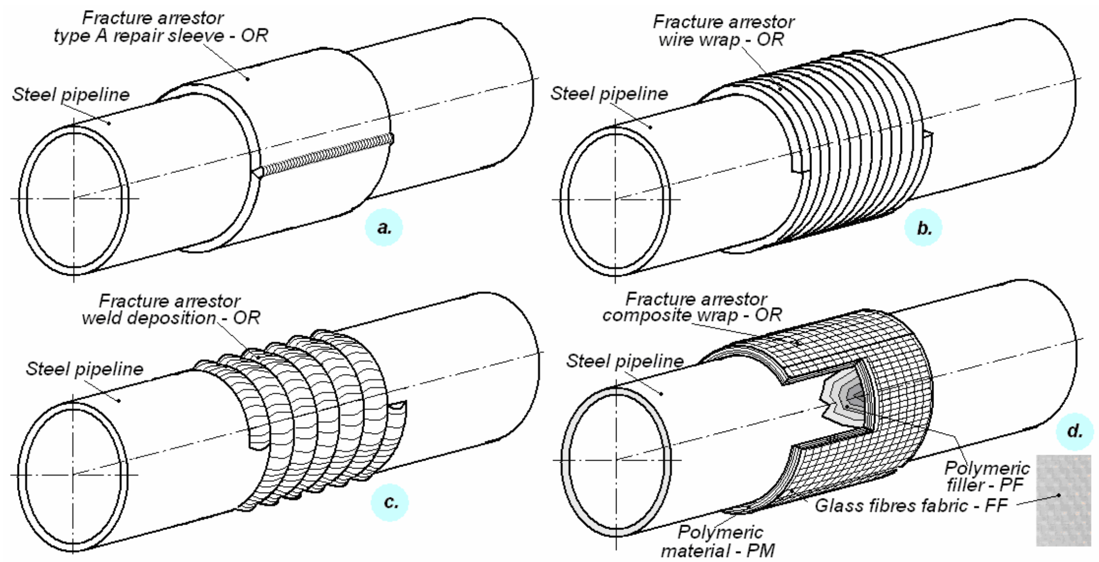

Fig. 1. Types of fracture arrestors and their coding:
a. fracture arrestor A repair sleeve, code OR – A1.B1.C1.D1 or OR – A1.B2.C1.D1;
b. fracture arrestor wrap of stainless steel wire, code OR – A1.B1.C2.D3;
c. fracture arrestor helical weld deposition, code OR – A1.B1.C2.D4;
d. fracture arrestor composite material wrap, code OR – A1.B1.C3.D5 or OR – A1.B2.C3.D5

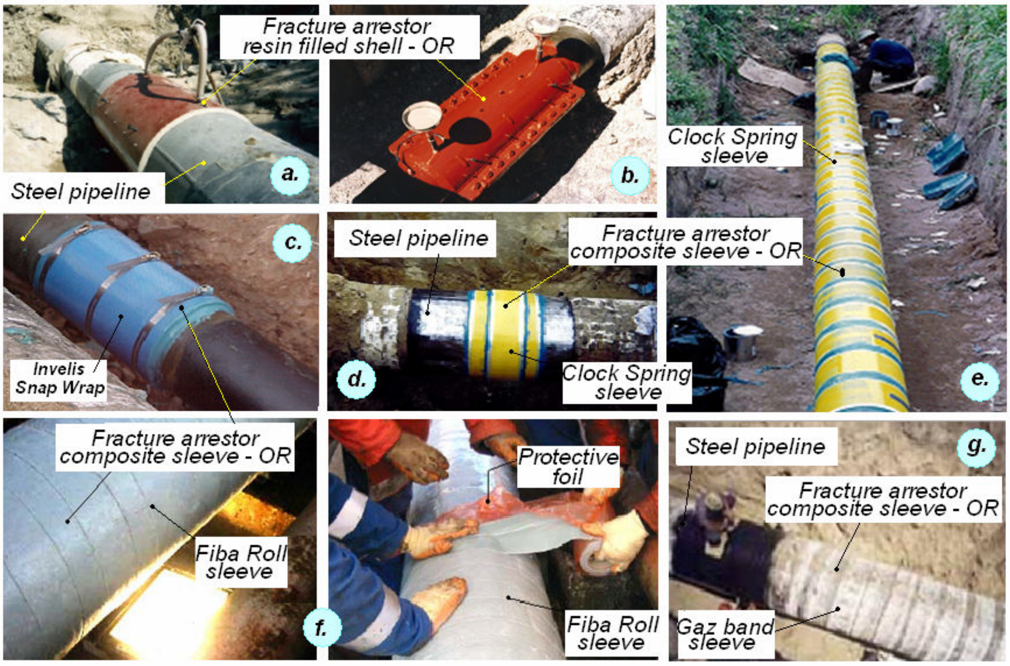

Fig. 2. Types of fracture arrestors and their coding
a, b fracture arrestors resin wrap, code OR – A1.B1.C1.D1 or OR – A1.B2.C1.D1;
c, d. fracture arrestor composite wrap, code OR – A1.B1.C3.D5 or OR – A1.B2.C3.D5 ;
e, f, g. fracture arrestor composite wrap, code OR – A2.B1.C3.D5 or OR – A2.B2.C3.D5

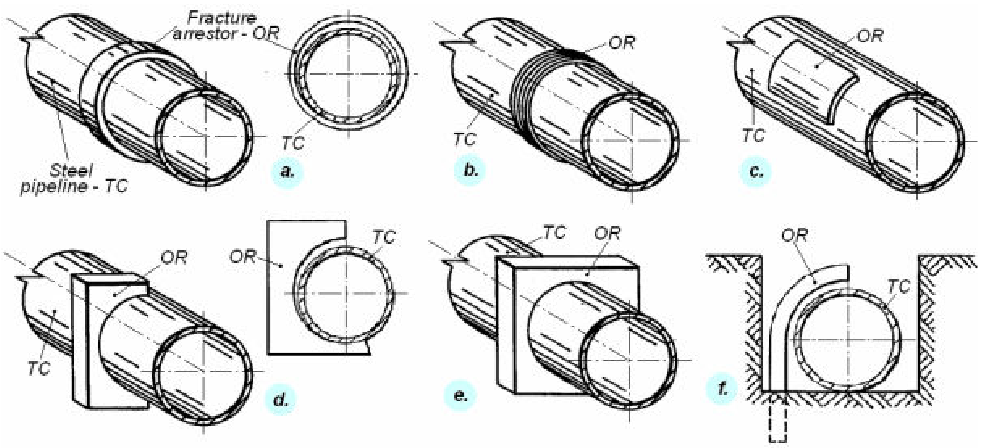

Fig. 3. Constructive types of fracture arrestors, such as elements applied while repairing defective pipelines, covered by the U.S. patent – 4.195.669
a, c. OR – A1.B2.C1.D1; b. A1.B2.C2.D3; d,e. OR – A1.B1.C3.D5; f. OR – A1.B2.C2.D1

Designing Fracture Arrestors and Assessing Their Reinforcement Effects

For designing fracture arrestors of various types there have been developped a series of standardized procedures, some of them reduplicated by softwares to facilitate their application. For instance, for designing, fabricating, testing, inspecting and qualifying fracture arrestors of OR – A2.B1.C3.D5 type there are applied the procedures included within the standard [8], while for the fracture arrestors codified OR – A2.B1.C3.D5 (made of composite materials with continuous disposal over non-defective pipelines) there can be used the procedure suggested by the authors of this paper, presented herein.

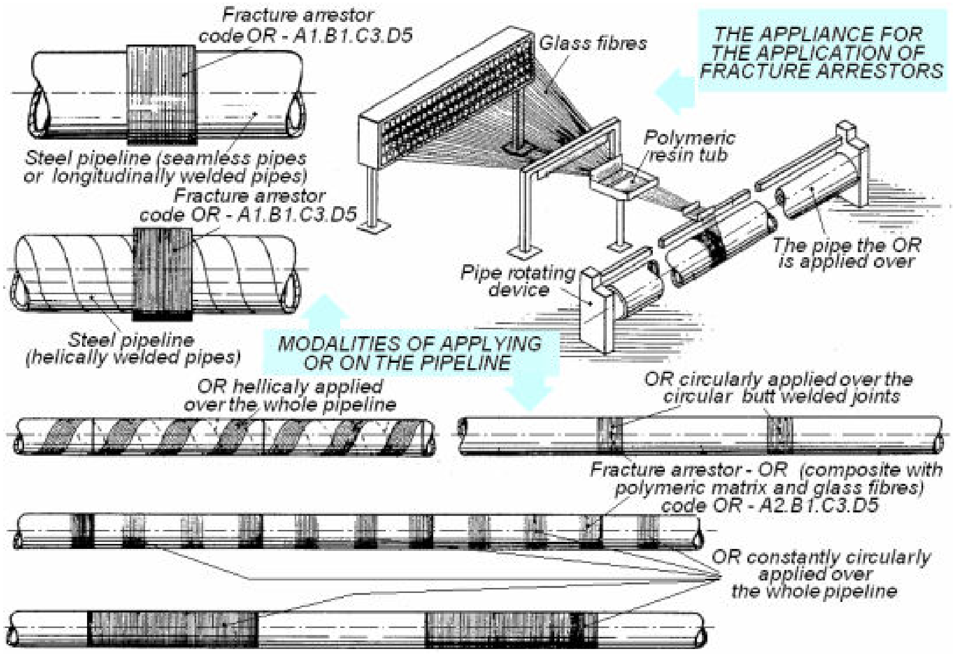

Fig. 4. Constructive variants of fracture arrestors, such as composite wraps, covered by the U.S. patent– 4.559.974

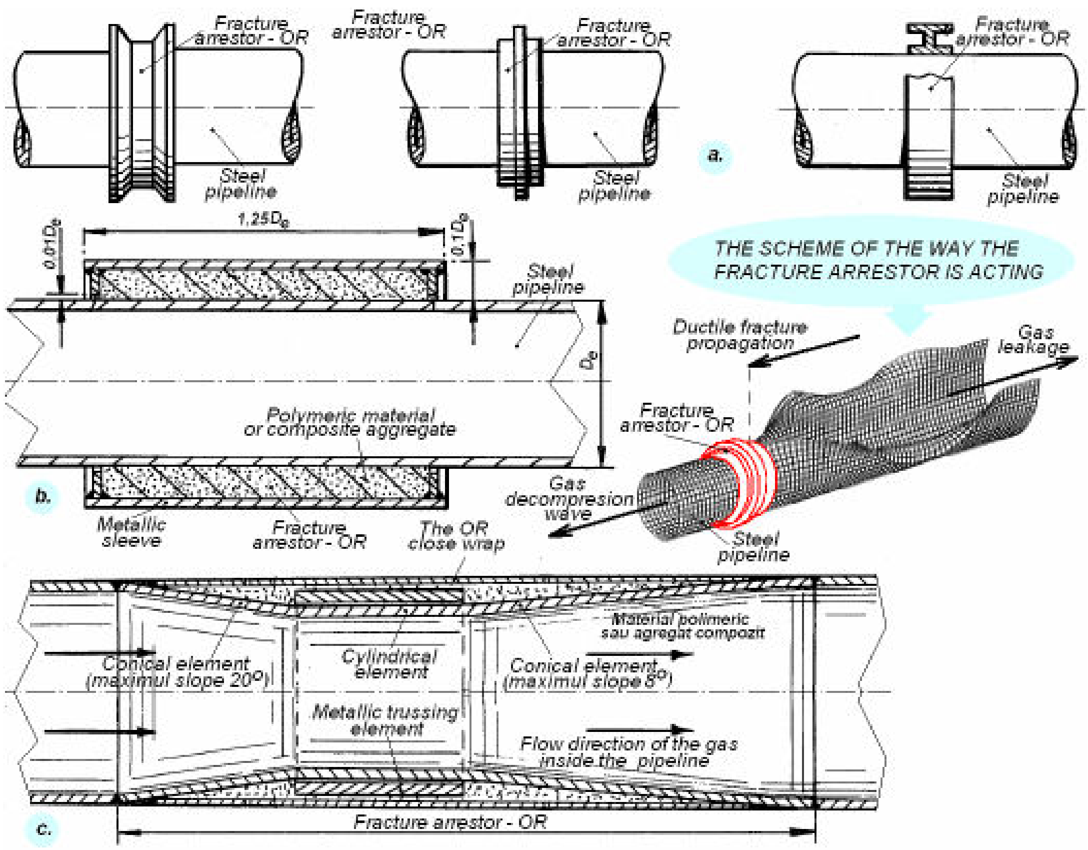

Fig. 5. Constructive types of fracture arrestors
a. OR according to the U.S. patent– 4.180.104 (OR are applied over the pipeline with a clearance equal to the one corresponding to the deformation of it when reaching the yield strength of the steel it is made of); b. OR according to the U.S. patent – 4.176.691; c. OR according to the U.S. patent – 4.284.107

The procedure suggested for designing fracture arrestors OR – A2.B1.C3.D5 includes the following steps:

➢ Input data are determined: a) data regarding the steel pipeline the fracture arrestors are installed over: the outside diameter D_e, the wall thickness s, the properties of the steel the pipes are made of: yield strength $R_{t0,5}$, modulus of elasticity E_S and Poisson's ratio μ_S, factors used during the design $c_{lt} = F\varphi$ [1], maximum operating pressure p; b) data regarding the composite wrap applied as fracture arrestor: the wrap thickness s_C, the mechanical features: ultimate tensile strength R_{mC}, modulus of elasticity E_C, Poisson's ratio μ_C and the elongation at failure A_C.

➢ There are calculated the radii determined in the diagram in figure 6 and their ratios, by using the following formulae:

$$a = \frac{D_e}{2} - s\,;\; b = \frac{D_e}{2}\,;\; c = b + s_C\,;\; k_t = \frac{b}{a}\,;\; k_C = \frac{c}{b}\,. \tag{1}$$

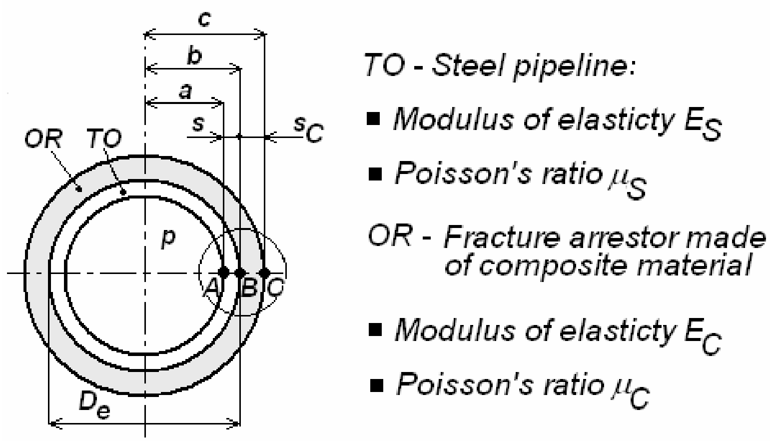

Fig. 6. Diagram for the estimate of the reinforcement effects of fracture arrestors OR – A2.B1.C3.D5

➢ There is calculated the allowable stress for the pipes of the pipework σ_a, the strain corresponding to this stress ε_{aS} and the maximum stress that can develop in the composite wrap σ_{aC}, by applying the formulae:

$$\sigma_a = R_{t0,5} F\varphi = R_{t0,5} c_{lt}\,;\; \varepsilon_{aS} = \frac{\sigma_a}{E_S} < \frac{A_C}{100}\,;\; \sigma_{aC} = \varepsilon_{aS} E_C < R_{mC}\,. \tag{2}$$

➢ There is determined the intensity of the maximum hoop stress $\sigma_{\theta\max}$, generated within the pipework (without outer wrap as fracture arrestor) due to the action of the operating pressure p:

$$\sigma_{\theta\max} = p\frac{k_t^2 + 1}{k_t^2 - 1} \tag{3}$$

and there is checked if the following criterion is fulfilled: $\sigma_{\theta\max} \le \sigma_a$.

➢ There is calculated the value of the pressure q that develops on the interface pipework – fracture arrestor due to the mechanical co-acting of the two components [9]:

$$q = \frac{2p}{P_t + r_{tC} P_C}, \tag{4}$$

where

$$P_t = (k_t^2 + 1) - \mu_t (k_t^2 - 1)\,;\; P_C = (k_C^2 + 1) + \mu_C (k_C^2 - 1)\,;\; r_{tC} = \frac{E_S}{E_C}\frac{k_t^2 - 1}{k_C^2 - 1}. \tag{5}$$

➢ There are calculated the radial stresses $\sigma_{rt}(r)$ and hoop stresses $\sigma_{\theta t}(r)$ and the radial displacements $u(r)$ of the pipework for different current radii $r \in$ [a; b], by using the formulae [9]:

$$\sigma_{rt}(r) = \frac{p - k_t^2 q}{k_t^2 - 1} - \frac{p - q}{k_t^2 - 1}\frac{b^2}{r^2}, \tag{6}$$

$$\sigma_{\theta t}(r) = \frac{p - k_t^2 q}{k_t^2 - 1} + \frac{p - q}{k_t^2 - 1}\frac{b^2}{r^2}, \tag{7}$$

$$u(r) = \frac{1 - \mu_t}{k_t^2 - 1}\frac{p - k_t^2 q}{E_S} r + \frac{1 + \mu_t}{k_t^2 - 1}\frac{p - q}{E_S}\frac{b^2}{r}. \tag{8}$$

➢ There are calculated the radial stresses $\sigma_{rC}(r)$ and the hoop stresses $\sigma_{\theta C}(r)$ and the radial displacements $u_C(r)$ of the wrap acting as fracture arrestor for different current radii $r_C \in$ [b; c], by using the formulae [9]:

$$\sigma_{rc}(r_C) = \frac{q}{k_C^2 - 1}\left(1 - \frac{c^2}{r_C^2}\right), \tag{9}$$

$$\sigma_{\theta c}(r_C) = \frac{q}{k_C^2 - 1}\left(1 + \frac{c^2}{r_C^2}\right), \tag{10}$$

$$u_C(r_C) = \frac{1 - \mu_C}{k_C^2 - 1}\frac{q}{E_C} r_C + \frac{1 + \mu_C}{k_C^2 - 1}\frac{q}{E_C}\frac{c^2}{r_C^2}. \tag{11}$$

➢ There is verified whether the continuity condition of the deformations on the interface pipework – fracture arrestor is fulfilled $u(b) = u_C(b)$ and there is estimated the level of the reinforcement effect or the growth rate of the loading capacity determined by the application of the fracture arrestor G_{CP}, by using the formula:

$$G_{CP} = \frac{\sigma_{\theta\max} - \sigma_{\theta t}(a)}{\sigma_{\theta\max}}100. \tag{12}$$

In order to facilitate the practical use, it was applied the procedure elaborated in a software, called *CONSOPCON1*, made in MathCad. The elaborated procedure can be used for at least two purposes: a) in order to determine the reinforcement effect of a fracture arrestor made of a specific composite material (with certain physical-mechanical properties) depending on the thickness s_C; b) in order to determine the reinforcement effect of the fracture arrestors having a specific thickness s_C depending on the properties of the composite material used (E_C and μ_C).

For exemplification, in figure 7 there are presented the results of the application for the analysis of the reinforcement effects of the fracture arrestors codified OR – A2.B1.C3.D5, made of composites such as Fiba Roll, MCM (reinforced with glass fibres fabric) or TDW RES-Q Wrap (reinforced with glass fibres and carbon fibres fabric), having the following properties E_C = 8...70 GPa, μ_C = 0,1...0,25, R_{mC} = 80...800 MPa and A_C = 1...3 %, applied over a natural gas transmission pipeline, made of X60 steel grade pipes ($R_{t0,5}$ = 414 MPa; E_S = 205 GPa; μ_S = 0,3), designed for $c_{lt} = F\varphi$ = 0,4 and the pressure p = 4 MPa, having D_e = 508 mm and s = 10,3 mm.

The results synthesized in the diagrams in figure 7 highlight the important influences of the elastic properties (the module of elasticity) of composite materials on their applicability to be used for the reinforcement sleeves or wraps of pipelines. As it can be seen by analyzing the diagrams in figure 7, the most important reinforcement effects can be achieved if the fracture arrestor is made of a composite material having the modulus of elasticity close to the one of the steel (205 GPa); such an idea has already been tested with good results, the fracture arrestors were made of a composite with 4 alternating layers of martensitic steel tape having the thickness 0,5 mm and a polymeric adhesive, the main particularities of this technical solution are presented in figure 8 [10].

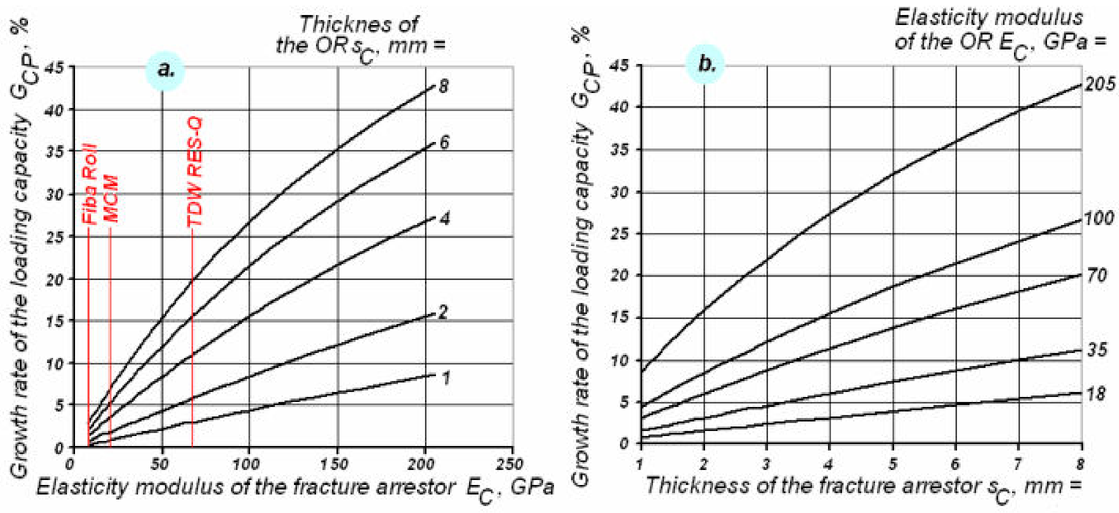

Fig. 7. The influences of s_C and E_C on the reinforcement effects of fracture arrestors code OR – A2.B1.C3.D5

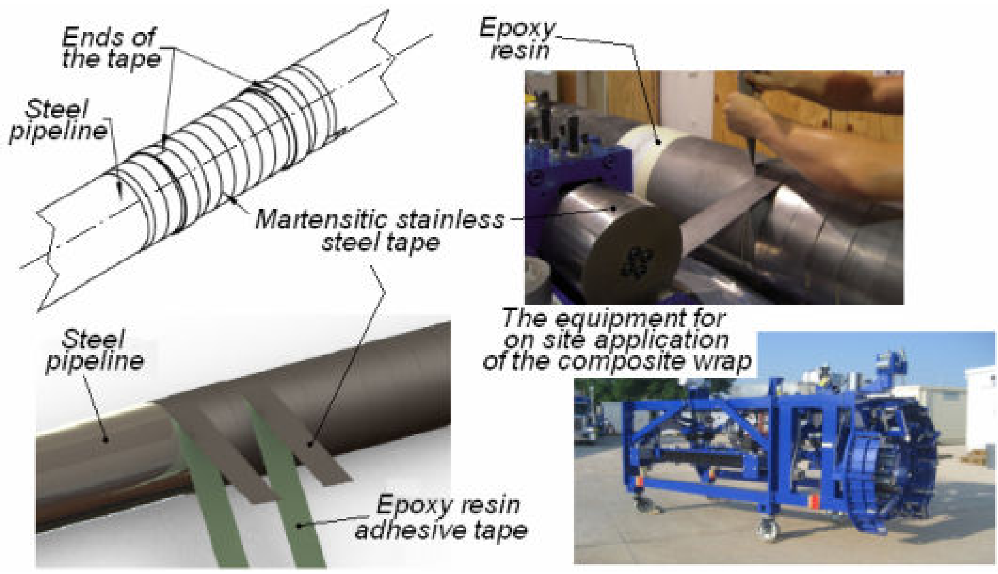

Fig. 8. Fracture arrestors made of layered composite with tapes of martensitic steel and epoxy resin

Conclusions

The aspects regarding the determination of the functions, the coding and the principles of designing fracture arrestors for natural gas transmission pipelines, analyzed within this paper, led to the following conclusions:

- The application of fracture arrestors may represent an important way to increase the in-service safety of natural gas transmission pipelines, and the use of the suggested principles for the classification and the coding of fracture arrestors allows their complete characterization and the synthetic description in the technical documents of the pipelines they are applied over.
- In order to facilitate their application over in-service (pressurized) pipelines and in order to avoid welding procedures onto these, there is applied now worldwide the solution of using fracture arrestors made of composite materials.

- The procedure for designing and assessing reinforcement effects of fracture arrestors with continuous disposal over the pipework, such as anticorosive wraps, showed that the level of the reinforcement effect or the growth rate of the loading capacity determined by the application of these fracture arrestors is influenced both by their thickness and by the elastic properties (mainly by the value of the modulus of elasticity E_C) of the composite material they are made of.
- The application of the suggested procedure in a case study showed that in the future there must be developed composite materials (for the fabrication of fracture arrestors) having the moduli of elasticity close to the ones of the metallic material the pipes of the pipeline are made of, this pre-requisite imposing the wider use of polymeric composites reinforced with carbon fibers or metallic fibers, tapes or fabrics.

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Proiectarea opritorilor de rupere pentru conductele de transport al gazelor naturale

Rezumat

În lucrare se defineşte rolul funcțional al opritorilor de rupere destinați aplicării pe conductele de transport al gazelor naturale şi se face o clasificare originală a acestora, cu prezentarea particularităților constructive şi modului de realizare a unei game largi de tipuri de opritori. Se prezintă o metodă analitică de evaluare a efectelor de consolidare a tubulaturii conductelor prin aplicarea opritorilor de rupere cu dispunere continuă, care poate fi folosită cu succes la proiectarea (stabilirea grosimii) opritorilor de rupere.