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The Use of Toughness Criteria for Designing Natural Gas Transmission Pipelines

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Abstract

In this work there are analyzed the main toughness criteria that have to be fulfilled by steel pipes designed for natural gas transmission pipelines and there are also suggested some modalities for combining mechanical strength and toughness criteria while designing these types of pipelines. The application of the solutions suggested within this paper ensures the avoidance of brittle failure of in-service pipelines, conferring them the ability to arrest the propagation of ductile fracture and causes the significant diminution of the risk associated to the use of natural gas transmission pipeline systems.

Key words: *natural gas transmission pipelines, strength and toughness criteria, risk assessment*

Particularities of the Actual Pipeline Design Procedures

The pipelines the natural gas transmission system consists of, that convey and deliver to the customers natural gases with the necessary flow rates and pressures, are mainly buried on land pipelines and only sections of these are aerial lines. While designing these pipelines, the following steps have to be followed [1-5]:

A. Pipeline route selection, ranking the pipeline sections in location classes and choosing the pipeline location parameters on this route (the depth of installation for the buried sections or the height of installation for the aerial sections).

B. Determining the main technical parameters of the pipeline (based on the calculation of the gas flow in the pipeline and providing the gas delivery with the necessary flow rates and pressures): the pressure regime parameters (internal design pressure p_c; maximum operating pressure $MOP \le p_c$ etc.), the range in fluid temperatures during normal operations [t_{min}; t_{max}] and the outside diameter of the pipework D_e. (from the normalized series of steel pipe diameters).

C. Determining the mechanical loads that act upon the pipelines in every class location assessment area, taking into account all categories of mechanical loads: C.1. loads with permanent action: pressure of the conveyed gases; mass loads (weight of pipes and components, weight of conveyed gases and of the corrosion protection layers applied onto the pipework, weight of insulations); loads due to the interaction with the environment (soil) the pipeline is located in; C.2. loads with temporary action: loads generated by the variation in temperature;

the pressure of the fluid used for pressure tests; loads due to the circulation of the vehicles in the road or railway crossing areas; wind loads and snow or ice loads in aerial locations etc.; C.3. loads with accidental action: loads generated by the dynamic effects of the conveyed gases; seismic loads or possible ground movements loads; loads due to flow induced vibration etc.

D. Choosing the constructive type of the pipes the pipeline is made of (seamless pipes or longitudinal or helical seam welded pipes), choosing the group and grade of steel for pipes and determining the wall thickness of the pipeline in all characteristic areas (location class units with the same mechanical load conditions) by means of an iterative process, including more cycles with the following work / calculation sequences:

➢ The allowable design strength / stress σ_a is determined as a fraction from the minimum specified value of yield strength $R_{t0,5}$ of the steel chosen for the pipes, by using one of the relations:

$$\sigma_a = R_{t0,5}\frac{\varphi}{S} \text{ sau } \sigma_a = R_{t0,5}F\varphi, \tag{1}$$

where S is the safety factor, F – the design factor, and φ – the longitudinal / helical joint factor, the usual values of these are shown in table 1.

Table 1. Values of the factors used for calculating the allowable strength of steel pipes for natural gas transmission pipelines

Class location	1	2	3	4
Safety factor S [1]	1.39	1.67	2.00	2.50
Design factor F [1,3]	0.72	0.60	0.50	0.40
Design factor F [4]	0.80	0.72	0.56	0.44
Design factor F [4]	0.77	0.67	0.55	0.45

Type / Class of pipe [3-5]	Joint factor φ [1,3-5]
S; HWF; SAWL; SAWH; COWL; COWH	1.00
EW; BW; SAW	0.80

➢ Considering only the pipework loads due to the action of the pressure p_c, there is calculated a value s_i of the pipe wall thickness, using formula [2,4]:

$$s_i = \frac{1}{2}\frac{p_c}{\sigma_a}D_e = \frac{1}{2F\varphi}\frac{p_c}{R_{t0,5}}D_e. \tag{2}$$

The thickness s_i is corrected by the addition factor $a = a_1 + a_2$, where the component a_1 is the addition factor that takes into account the uniform pipe wall loss due to corrosion and erosion allowance, and a_2 – the absolute value of the negative tolerance taken from the material standards or as provided by the pipe manufacturer – see. fig. 1); this way there is obtained the thickness $s_{ic} = s_i + a$. From the normalized / standardized range of pipe thicknesses (having the diameter D_e) there is chosen a value $s > s_{ic}$ (meaningly $s = s_{ic} + \delta_s$, where $\delta_s > 0$ is the rounding addition factor for choosing a pipe with the thickness within the normalized / standardized range).

➢ Considering the pipeline with the diameter D_e and the wall thickness s, its strength is checked under the action of the conveyed gas pressure and of the other mechanical loads. Diverse scenarioes of the simultaneous load actions are formulated, and each scenario is accompanied by the shares the mechanical stresses generated by the considered loads appear with in the condition for the verification of the mechanical strength of the pipeline:

$$\sum_{i=1}^{n}\sigma_i q_{si} \le \sigma_{aq}, \tag{3}$$

where σ_i are the stresses generated in the pipe wall every time from the n pipe loads, q_{si} are the summation shares of the stresses generated by different loads (having the values specified in the calculus standards or norms), and σ_{aq} is the allowable strength of the material exposed to composed loads (which, usually, are determined by the formula $\sigma_{aq} = \min[k_{s1}\sigma_{aq}; k_{s2}R_{t0,5}]$, with

k_{s1} = 1,8 and k_{s2} = 1,5, if in the verification criterion there are included only the loads with permanent and temporary action and with k_{s1} = 2,25 and k_{s2} = 1,8, if the load scenario contains additionally the load with accidental action [3,4,8]). Obviously, if the criterion (3) is not fulfilled, a new calculation cycle is followed, by increasing the thickness s of the pipe wall and by making new verifications regarding the fulfillment of this criterion. Finally, after the thickness s considered fulfills the criterion (3), it is verified whether this thickness fulfills the condition:

$$s \geq s_{D,\min}, \qquad (4),$$

where $s_{D,\min}$ is the minimum wall thickness allowed for the construction of pipelines having the diameter D_e (so that no failure occurs due to processes not taken into account during the design steps), having the values specified in [5-8]. Obviously, if the thickness s considered does not fulfill the condition (4), it is chosen $s = s_{D,\min}$

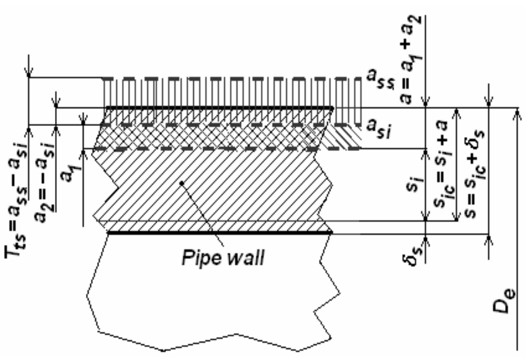

Fig. 1. Scheme of the additional factors applied while designing the wall thickness of pipelines

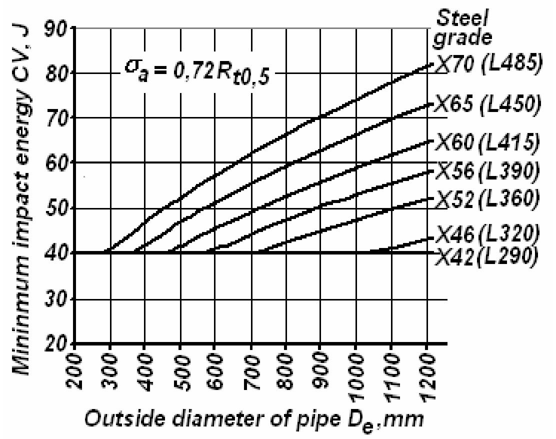

Fig. 2. Diagram for determining the minimum toughness requirements for pipes

Combining the Mechanical Strength and Toughness Criteria While Designing Pipelines

The actual procedure for designing natural gas transmission pipelines, previously synthetically described, doesn't stipulate the use of criteria for verifying the rupture (brittle or ductile) behaviour, but requires the use of PSL2 (class B) steel pipes, for which there are safe values of toughness characteristics (at the minimum operating temperature of the pipeline) that assure their ductile rupture behaviour. For instance, [6,7] recommends the use of steel pipes for which the rupture toughness is verified by the notched bar impact test (Charpy V-notch impact test – CVN impact test), performed at the temperature of 0 °C. The pipes are considered of satisfactory quality, if the average value KV_m, of the CVN absorbed energy established while testing three standard full size specimens, fulfills the criterion:

$$KV_m \geq CV, \qquad (5)$$

with CV, in J, given by the relation:

$$CV = 3{,}61 \cdot 10^{-4} \sigma_a^{1,5} \sqrt{D_e}\,, \qquad (6)$$

where σ_a is introduced in MPa, and D_e – in mm; furthermore, the individual values of the rupture energy KV determined during the three specimen test (by means of which one can calculate the average KV_m) must fulfill the condition $KV \geq 0{,}75CV$, and the average of the areas with shear appearance, of ductile fracture, on the fracture surfaces of the three specimen must fulfill the condition $S_{Fm} \geq 0{,}6S_{ep}$, where S_{ep} is the area of the cross-section of the specimen.

The datum level CV used while applying the toughness criterion (5) can be defined by using different relations (determined by processing the experimentally obtained results), as it can be seen by analyzing the information synthesized in table 2 [3,4]; with any of these relations there can be configured a diagram like the one shown as an example in figure 2, obtained using the CV given by (6), which the minimum toughness requirements can identify with, requirements that have to be imposed to pipes the natural gas transmission pipelines will be made of.

Table 2. Definition alternatives of the CV for the application of the toughness criterion (5) while designing natural gas transmission pipelines

Alternative	Steel pipe	Minimum absobed energy CV *, J
[3] – Battelle Columbus Laboratories	L290...L450	$CV = 8{,}5765 \cdot 10^{-6} \sigma_a^2 \sqrt[3]{D_e s}$
[3] – American Iron and Steel Institute		$CV = 3{,}61 \cdot 10^{-4} \sigma_a^{1{,}5} \sqrt{D_e}$
[3] – British Gas Council		$CV = 6{,}146 \cdot 10^{-3} \sigma_a \dfrac{D_e}{\sqrt{s}}$
[3] – British Steel Corporation		$CV = 6{,}682 \cdot 10^{-7} \sigma_a^2 D_e$
[4]	L245...L450	$CV = 2{,}67 \cdot 10^{-4} \sigma_a^{1{,}5} \sqrt{D_e}$
	L485	$CV = 3.21 \cdot 10^{-4} \sigma_a^{1{,}5} \sqrt{D_e}$
	L555	$CV = 2{,}83 \cdot 10^{-5} \sigma_a^2 \sqrt[3]{D_e s}$

* CV results in J, if σ_a is introduced in MPa, and D_e and s are introduced in mm

If the criteria regarding the assurance of the mechanical strength and toughness are applied successively while designing pipelines, as it resulted from the previous description, it is possible that the requirements that result regarding the toughness of the pipes to be very high (CV = 60...100 J), and their fabrication to imply very high costs. As a consequence, in order to use pipes having toughness characteristics of usual levels (CV = 27 J, in case of pipes having the D_e < 457 mm or the CV = 40 J, in case of pipes having $D_e \geq 457$ mm), the authors of this paper, developping the idea suggested in [5], suggest the combining of the mechanical strength and toughness criteria while designing pipelines. For this purpose, using the relations for defining the datum levels σ_a and CV (for the mechanical strength and toughness of pipes), there are two ways of proceeding, easy to describe and easy to use if a diagram like the one shown in figure 3 is configured:

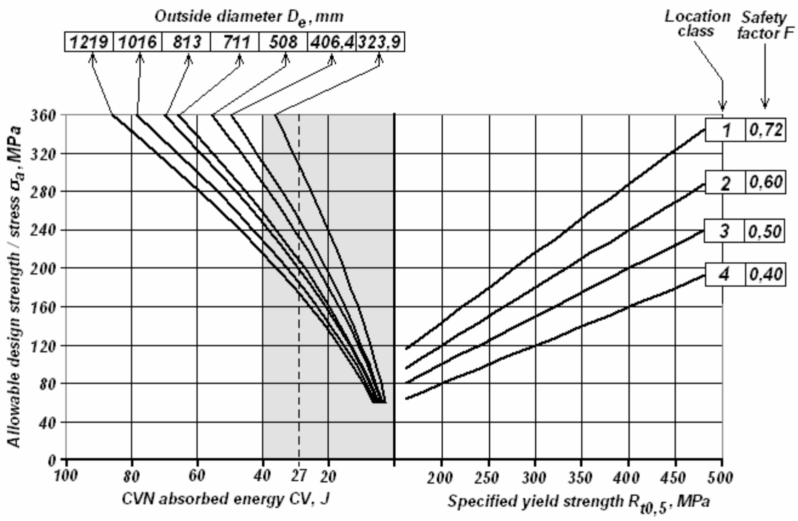

Fig. 3. Nomogram for choosing the steel grades for natural gas transmission pipelines

- If there are known the outside diameter of the pipeline D_e, the location class (the value of the safety factor F) and the type of pipes (the value of the longitudinal / helical joint factor of the pipes φ) and the steel grade of pipes is chosen (the minimum specified value of yield strength of the steel $R_{t0,5}$), there can be determined the allowable design strength σ_a (used in order to determine the wall thickness s) and the datum level of toughness (the minimum value of the rupture energy following the notched bar impact test) CV . Obviously, this way of work, which corresponds to the actual design procedure, may require the use of pipes having a high level of safe toughness and the fabrication costs are very high.
- If there are known the outside diameter of the pipeline D_e, the location class (the value of the safety factor F) and the type of pipes (the value of the longitudinal / helical joint factor of the pipes φ) and there is chosen a usual level for the CV energy (the minimum safe level of the pipe toughness), there can be used relations of type (6) in order to determine the maximum allowable level of the steel grade the pipes are made of, and the value of the specified yield strength $R_{t0,5}$ of this steel is used for the calculation of the allowable strength σ_a and then, applying the formula (2), in order to determine the pipe wall thickness s. Using this way of work there will be used pipes having level of toughness easy to provide, but it is possible that the wall thickness is

Applying for designing a pipeline of the two ways of works suggested can lead to different technical solutions for its construction, the recommended solution for the construction of the pipeline must be the one that provides minimum purchase costs of the pipework material and of welded joints while constructing the pipeline. The veracity of these statements resulted after analyzing the results obtained during the case study for designing a natural gas transmission pipeline having the outside diameter D_e = 1016 mm (40 in) and the pressure p_c = 4 MPa, with the route ranked in the location class 1 (F = 0,72) and that will be constructed using welded pipes with $\varphi = 1$:

- when using the first way of work, there was chosen the pipe steel X70, having $R_{t0,5} \geq 483$ MPa, it resulted σ_a = 348 MPa and s_i = 5,84 mm and, after applying the addition factor a = 2,5 mm, it was decided that there must be used pipes having the thickness s = 8,5 mm; under these circumstances, in order to fulfill the requirements regarding the toughness, the pipes must fulfill the condition $KV_m \geq CV$ = 75 J (where the pipe mass is m_t = 211 kg/m);
- because the toughness condition previously resulted is relatively severe, it was used again the first way of work, but it was chosen the pipe steel grade X60, with $R_{t0,5} \geq 415$ MPa, it resulted σ_a = 299 MPa and s_i = 6,80 and, after applying the addition factor a = 2,5 mm, it was decided that there must be used pipes having the thickness s = 10,0 mm; under these circumstances, in order to fulfill the requests regarding the toughness, the pipes must fulfill the condition $KV_m \geq CV$ = 60 J (where the pipe mass is m_t = 248 kg/m);
- because the second design solution implied also high design requests regarding the pipe toughness, it was chosen the second way of work, considering that the pipe should fulfill the usual toughness requirement $KV_m \geq CV$ = 40 J, which imposes that $\sigma_a \leq 230$ MPa, implying the use of pipes with $R_{t0,5} \leq 319$ MPa; choosing the use of X42 steel pipes, with $R_{t0,5} \geq 290$ MPa, there were obtained the following results: σ_a = 209 MPa, s_i = 9,73 mm and s = 12,5 mm (where the pipe mass is m_t = 309 kg/m);
- using the second way of work, but with the condition $KV_m \geq CV$ = 27 J (whose fulfillment imposes that $\sigma_a \leq 177$ MPa, which implies the use of some pipes with $R_{t0,5} \leq 245$ MPa) and choosing the use of Grade B steel pipes, with $R_{t0,5} \geq 241$ MPa, there were obtained the following results σ_a = 174 MPa, s_i = 11,71 mm and s = 14,2 mm (where the pipe mass is m_t = 351 kg/m).

The correctness of the indications regarding the toughness of pipes obtained by applying the previously described procedures can be verified using, for instance, the Battelle Two Curve Method [9].

Conclusions

The work highlights the following aspects as conclusions regarding the design of natural gas transmission pipelines:

- The design procedure must also include the checking of some criteria regarding the safe toughness of steel pipes that will be used when constructing pipelines;
- The toughness criteria used must assure that the pipes are not exposed to brittle failure in in-service pipelines and they have the ability to arrest the propagation of ductile fracture initiated by possible cracks generated on them;
- The use of a combination of mechanical strength and toughness criteria allows the obtaining of some rational technical solutions, which provide the pipelines wtih a high level of technical security (a minimum level of technical in-service failure risk) and a low level of construction costs (a maximum level of economic efficiency of the investments for constructing the pipelines)

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Utilizarea criteriilor de tenacitate la proiectarea conductelor destinate transportului gazelor naturale

Rezumat

În lucrare sunt analizate principalele criterii de tenaciate care trebuie respectate de către țevile din oțel destinate realizării conductelor pentru transportul gazelor naturale şi sunt propuse câteva modalități de combinare a criteriilor de rezistență mecanică şi tenacitate la proiectarea acestor tipuri de conducte. Aplicarea soluțiilor propuse în lucrare asigură evitarea cedării fragile a conductelor în cursul exploatării, conferă conductelor capacitatea de oprire a propagării ruperii ductile şi determină diminuarea substanțială a riscului ataşat utilizării sistemelor de conducte pentru transportul gazelor naturale.