ISSN 1392 - 1207. MECHANIKA. 2008. Nr.1(69)

Influence of properties of large pipes on the reliability of pipelines

N. Abdelbaki*, E. Bouali, M. Gaceb***, R. Bouzid******
**University of Boumerdes, FHC, LFEPM. Algeria, E-mail: doyenfhc@umbb.dz*
***University of Boumerdes, FHC, LFEPM. Algeria, E-mail: e_bouali@umbb.dz*
****University of Boumerdes, FHC, LFEPM. Algeria, E-mail: gaceb_m@yahoo.fr*
*****University of Boumerdes, FHC, LFEPM. Algeria, E-mail: r_bouz@yahoo.fr*

1. Introduction

Big diameter steel pipelines working at high service pressures are used in many fields of industry and more particularly in oil industry. Their ecological reliability and safety depend on continuous improvements of the technological process of big diameter pipe manufacture, on execution quality of construction works and on the nondestructive testing [1].

The welded joints of pipelines have always some differences in shape, dimensions and relative disposition of the ends to be welded with respect to those projected. Add to this are the metal heterogeneous properties which have a significant influence on working capacity of the pipes in pipeline exploitation conditions. The study of the influence of big diameter pipe properties on the working safety of pipelines by a physico-statistical approach makes it possible to take into account the physical, statistical and probabilistic dimensions of the primary data.

In such context, this paper has as an objective to study the influence of manufacturing dispersions of large pipes made of grade X52 steel on the reliability of pipelines. These dispersions are related with the material properties as well as with aspects of pipe configuration. The evaluation of the influence of these parameters is partly made on the basis of experimentation.

Amongst functional models of the reliability theory, the model used in this study is the one we called "Elements parametrical reliability" [2]. Functional models used for reliability characteristics determination of mechanical elements from the view point of failure physics are little developed actually. The major difficulties of using functional models for the determination of reliability characteristics of the elements are: firstly the complexity of the influence of a great number of internal and external factors on the processes to be taken into account, secondly the great diversity of internal processes makes it difficult to elaborate generalized mathematical models taking into account the complex influence of exploitation factors on the initiation and development of defects. But despite the above mentioned difficulties this route is one perspective [3].

Such approaches during pipeline design, allow to avoid their over sizing.

2. Functional model: “load – bearing capacity”

By bearing capacity it is meant the property of a structure to support loads. Rupture probability P_r of the structure according to “load – bearing capacity” [3] is given by the expression

$$P_r = \left\{ \left[R(t), S(t) \right] \in D \right\} = \iint_D f_{RS}(r, s)\, dr(t)\, ds(t) \quad (1)$$

where the condition of bidimensional density $f_{RS}(r, s)$ falling in the domain D, is given by the inequality

$$\left. \begin{array}{l} 0 \le r(t) < \infty \\ 0 \le r(t) \le s(t) < \infty \end{array} \right\} \quad (2)$$

where $R(t)$ and $S(t)$ are transient functions of the bearing capacity and the load respectively. It is possible to obtain analytical relation ships for the property P_r as a function of three variables. The load variance coefficient $v_S(t)$, the bearing capacity variance $v_R(t)$ and the reserve coefficients $\eta_R(t)$, $\eta_e(t)$, with respect to elastic strength limits.

During the computation of constitutive elements of a pipeline, we start from the fact that during service the state of strength limit does not occur

$$S(X) \le R(X) \quad (3)$$

as R and S are transient quantities, the pipeline good working condition can be achieved with a certain probability. The reserve coefficient is also a transient quantity

$$\eta_R(X) = \frac{R(X)}{S(X)} \quad (4)$$

Introducing the function $H = R - S$, it can be shown that for a normal distribution of the R and S, the rupture probability is given by [3]

$$P_r = \frac{1}{2} - \Phi(\gamma) \quad (5)$$

where $\Phi(\gamma)$ is Laplace function, γ is the safety characteristic

$$\gamma = \frac{\overline{\eta}_R - 1}{\sqrt{v_R^2 \ \eta_R^2 + v_S^2}} \quad (6)$$

where $\overline{\eta}_R = \frac{\overline{R}}{\overline{S}}$

3. Relationship between pipe properties and reliability

Rupture probability of the tube can be expressed by specimen’s rupture probability P_r^t [4]

$$P_r^t = 1 - \left[1 - \bar{P}\right]^{V_t / V_e} \tag{7}$$

where V_t is the volume of tube material, V_e is the volume of test specimen.

Mathematical expectation of the tube strength limit, the rupture limit is determined by [5]

$$\bar{R}^t = \bar{R}\ k_e\ k_h \tag{8}$$

where $k_e = 1 - t_\xi\, v_R$ is the scale coefficient, t_ξ is determined from the equation $t_\xi = 0.5 + \Phi\left(t_{p^*}\right) = \left(0.5\right)^{V_e / V_t}$,

$$k_h = 1 - k_T^\infty\, v_R^e \tag{9}$$

where k_T^∞ is the unilateral tolerated limit for a general set ($n = \infty$), determining how many average quadratic deviations it is necessary to subtract from the mathematical expectation of the tube strength limit $\bar{R}^t$, for the rupture probability to be $P_r(T)$. The tolerated limit k_T^∞ is given by the expression

$$\Phi_0\left(k_T^\infty\right) = P\left(T\right) - 0.5 \tag{10}$$

If the tube strength distribution parameters are determined from a specimen n, then k_T^∞ must be corrected according to the formulae [6]

$$k_T^n = k_T^\infty \left(1 + \frac{t_q}{\sqrt{n}} - \frac{5t_q^2 + 10}{12n}\right) \tag{11}$$

t_q is a parameter indicating that k_T^n is determined by expression (11) with a certain confidence probability q.

Taking the stress concentration in the tube walls into account, the bearing capacity reserve coefficient of a tube $\bar{\eta}_R^t$ is given by the expression:

$$\bar{\eta}_R^t = \frac{1}{k_c} \cdot \frac{\bar{R}^t}{\bar{C}_{eq}} = \frac{\bar{\eta}_R}{k_c} \tag{12}$$

where k_c is stress concentration coefficient, $\bar{C}_{eq}$ is mathematical expectation of equivalent stresses in the tube walls.

Equation (12) can be written in the form

$$\bar{\eta}_R^t = \frac{m}{k_c}\, \bar{\eta}_e^t \tag{13}$$

where $m = \bar{R}^t / \bar{R}_e^t$, and $\bar{\eta}_e^t = \bar{R}_e^t / \bar{C}_{eq}$ is strength reserve coefficient according to the tube material lower yield limit.

To clarify the influence of the tube properties on exploitation safety, stress state under the action of internal pressure is considered, and using the load configuration energy hypothesis [7], equivalent stress is given by the expression

$$C_{eq} = \sqrt{C_c^2 + C_l^2 - 2C_l\, C_c} \tag{14}$$

where C_{eq} is equivalent value of the stress, $C_c = \frac{P_S\, D}{2\delta}$ is circumferential stress in the pipe body, $C_l = \nu \frac{P_S\, D}{2\delta} + \frac{E\, D}{2\rho} + \alpha\, l\, \Delta T$ is longitudinal stress in the pipe body, P_S is internal pressure in the tube, D is tube diameter, δ is tube wall thickness, ν is tube steel Poisson's ratio, α is thermal expansion coefficient, ρ is tube flexion radius, E is coefficient of longitudinal elasticity, l is tube length considered.

From graphical presentation of the ratio σ_{eq}/σ_c in terms of σ_l/σ_c, it can be deduced, as shown in Fig. 1, that an increase or decrease of material effort in the pipe walls takes place depending on the value and sign of the longitudinal stress.

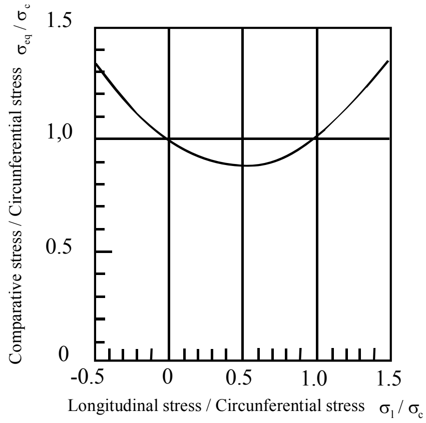

Fig. 1 Comparative stress/ circumferential stress ratio as a function of the longitudinal stress / circumferential stress ratio

In the case of a pipeline in service, we are confronted in principle, with load states such that the extension of pipe section is resisted by a compressed soil or by anchorage in the longitudinal direction. But the resulting longitudinal stress in the pipe walls is practically brought back to smaller values, because of the supplementary compressive forces, following an increase in temperature or flexion stress. In the bent sections of the pipe the longitudinal stress vary in the limits (0.3 to 0.5) σ_c [8]. It results from the above that the tolerable internal pressure increases in terms of the longitudinal stress and the studies established on the basis of the circumferential stress only are made for the must unfavourable working conditions of the pipes.

For the analysis it is important to show the dependence of the tube working safety characteristic γ_t, in terms of reserve coefficient $\bar{\eta}_e^t$, in case of no correlation between strength limit, tube dimensions and nonsignificant deviations of the strength R, inside diameter D_{in} and the internal pressure with respect to their mathematical expectation. The function H can be replaced by the linear relationship following decomposition into a Taylor series at the neighbourhood of the mathematical expectations of the transient quantities. In this case expression (6) takes the form

$$\gamma_t = \frac{\overline{\eta}_e^t \cdot k_c - 1}{\sqrt{\left(\overline{\eta}_e^t\right)^2 k_c \left(v_R^2 + v_\delta^2 + V_{D_{in}}^2\right) + v_p^2}} \qquad (15)$$

It is considered that the tube begins to rupture, if normal tension in the weld joint is

$$k_c\, C_c = R^t \qquad (16)$$

Supposing that the same equivalent stress is produced all along the length of the pipeline section considered and bearing in mind that the defects will be different along the section, then the value of safety characteristic will be different at the areas where the defects are located. If it is sought to insure the same level of safety over the section, then it is necessary to satisfy the condition:

$$\gamma_t\left(\overline{\eta}_e^t\right) \geq \gamma_{ad}\left[P\left(T\right)\right] \qquad (17)$$

where $\gamma_t\left(\overline{\eta}_e^t\right)$ characterizes the safety corresponding to a given value of the safety factor $\overline{\eta}_e^t$, $P(T)$ is the reliability level of the section, $\gamma_{ad}\left[P\left(T\right)\right]$ is the safety characteristic corresponding to a required minimal value of $P(T)$.

For a given stress concentration coefficient in the weld joints, the value of the bearing capacity reserve coefficient of the tube must satisfy the condition

$$\overline{\eta}_e^t \geq \overline{\eta}_{ad} \qquad (18)$$

where $\overline{\eta}_{ad}$ is the bearing capacity reserve corresponding to a given value of the safety characteristic $\gamma_{ad}\left[P\left(T\right)\right]$.

4. Results and discussion

To verify the hypothesis used during the deduction of expression (15), stipulating that there is no correlation between the quantities R, D_{in}, δ and P, the results of tests on specimens taken from grade X52 steel tubes of 1220 mm diameter and of different wall thicknesses have been analysed. Starting from the distributions of the specimen thickness and strength, the average of their values were determined and the regression lines are constructed (Fig. 2). The regression lines obtained being perpendicular, it is concluded that $\overline{R}_t$ and δ are independent. On the other hand, the distribution of the diameter of the tubes depends mainly on their manufacturing process and is related neither to the thickness distribution, nor to the material properties. Lastly, the calculation parameters contributing to expression (14) are transient quantities mutually independent. On the other hand, the deviations of quantities R, D_{in}, δ and P are effectively small with respect to their mathematical expectations (Table 1). In this way the linearization of the H used in the deduction of expression (15) is justified.

To verify the hypothesis on the influence of the rupture strength scale factor (8), the tests results on specimens taken from tubes of different thicknesses made of grade X52 steel and of dimensions 300x30xδ (in mm) have been processed. The treatment of the test results is presented in Fig. 3 and despite the small specimen volume; the departure of the curves for the greater wall thicknesses towards the left is perfectly visible. This shows the existence of an influence of the scale factor on the strength limit.

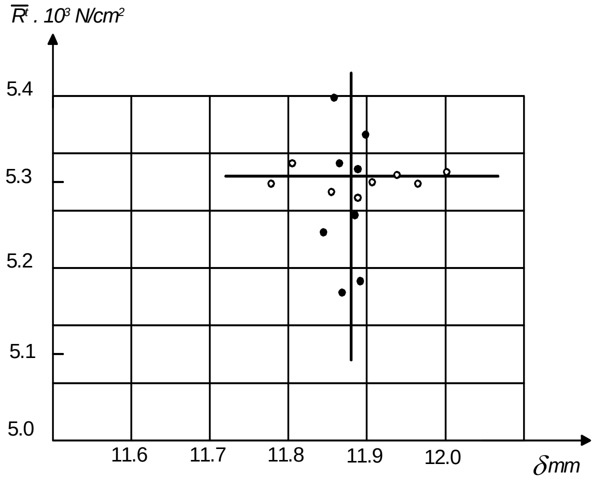

Fig. 2 Regression line of the deviation tube thickness and strength limit

Table 1

Statistical treatment of mechanical test data results

Average values (mathematical expectations of the computation quantities)	Quadratic deviations of the computation quantities	Variation coefficient of the computed quantities
$\overline{R}^t = 5.259.10^2\ \mathrm{N/mm^2}$	$\sigma_R = 0.0258 \cdot 10^4$	$v_R = 0.0495$
$\overline{\delta} = 11.89\,\mathrm{mm}$	$\sigma_\delta = 0.2135$	$v_\delta = 0.01795$
$D_{in} = 1196\ \mathrm{mm}$	$\sigma_{D_{in}} = 2.343$	$v_{D_{in}} = 0.00196$

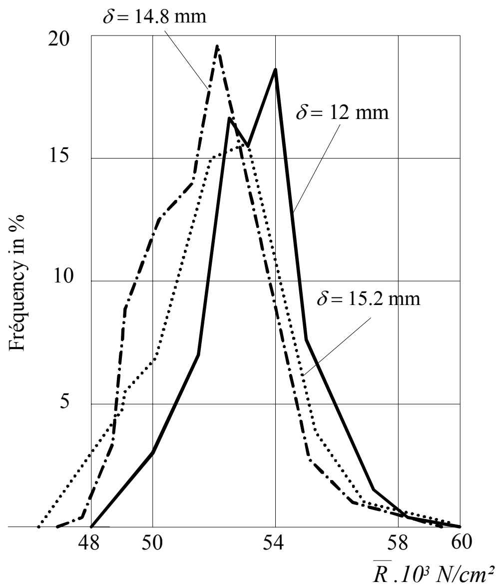

Fig. 3 Strength limit distribution curve for specimens of different thickness

For the analysis of the influence of pipe properties on the pipeline reliability, a study was conducted on tubes of 1200 mm diameter, of 12 m average length and whose tube metal strength characteristics, determined by tests on specimens taken directly from sections of grade X52 steel pipes. The results of statistical treatment of the data obtained for mechanical tests on grade X52 steel specimens are recorded in Table 1. The metal under consideration has the following chemical composition: 0.127 C, 0.18 Si, 0.96 Mn, 0.02 P, 0.012 S.

The dependence of safety characteristic γ and tube rupture probability P_r has been studied in terms of reserve coefficient $\overline{\eta}_e^t$ for a tube without weld (Fig. 4). If the reliability of a tube supposed without weld joints and with dimensions 1220 x 12 mm made of grade X52 steel is calculated for $C_{eq} = 0.65\overline{R}^t$, then the reserve coefficient is found to be equal to 1.53, the safety characteristic γ = 9.77 and the rupture probability P_r = 1.93.10^{-8}. This corresponds to a pipeline reliability of the conduit $P(T)$ = 0.99999999.

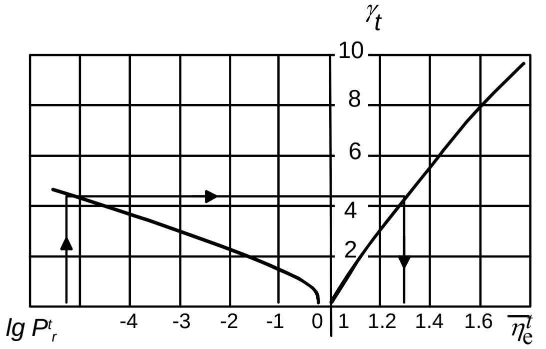

Fig. 4 Dependence of safety characteristics γ and rupture probability P_r^t in terms of the reserve coefficient $\overline{\eta}_e^t$ for a tube assumed without weld joints

The results of the influence study of the weld joints on the reliability are shown in Fig. 5. It is noted from the graph that $P(T)$ = 0.99 corresponds to $\gamma_{ad} = 4.5$ and $\overline{\eta}_e^t\left(\gamma_{ad}\right) \geq 1.28$; while it is sufficient for $P(T)$ = 0.90 to satisfy the condition $\overline{\eta}_e^t\left(\gamma_{ad}\right) \geq 1$.

Expressions (17) and (18) show that by a convenient choice of the value of coefficient $\overline{\eta}_e^t$ we can distribute the bearing capacity reserve according to the working conditions of each pipeline section and determine admissible value of the coefficient of the corresponding stresses, a value which imposes conditions to the reception test methods and to the choice of the pipeline service pressure. The choice of the value of coefficient $\overline{\eta}_e^t$ must be made according to the condition under which stress concentration level does not go beyond the value $[k_c]$. C_N in order to ensure the given reliability level.

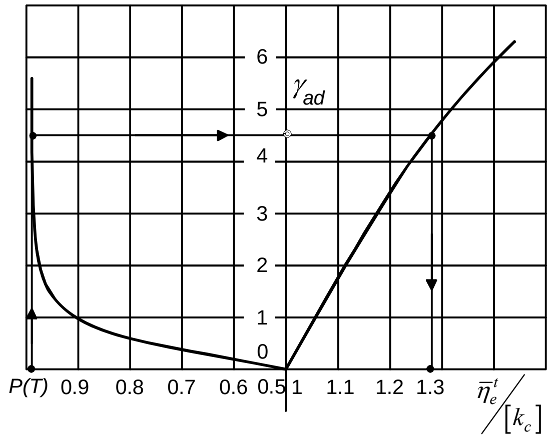

Fig. 5 Dependence of reliability function $P(T)$ and safety characteristic γ on reserve coefficient $\overline{\eta}_e^t$ for tube with longitudinal weld

The test pressure should correspond to the detection of all the defects whose stress concentration coefficient is greater than the admissible values corresponding to the chosen values of $\overline{\eta}_e^t$, in other words the pipelines pressure of the reception test should be equal to the product of $\overline{\eta}_e^t$ and service pressure. It is convenient to use the effective stress concentration coefficient k_c because it depends not only on the shape and dimensions of the defect but also on the load, and in particularly on internal pressure. Just before the start of plastic flow in concentration zones, the coefficient k_c is equal to the strain concentration coefficient k_d [3].

The estimated values of stress and strain concentration coefficients are given in Table 2. The results show that the average value of $\overline{\eta}_e^t$ for the three sections considered is 1.3 for k_d = 4 to 5.

Table 2

Estimated values of admissible stress concentration coefficient (D = 1220 mm)

Reliability of the section $P(T)$	Section length, km	Admissible stress concentration coefficient	Admissible stress concentration coefficient for different values of $\overline{\eta}_e^t$					
			1	1.1	1.2	1.3	1.4	1.5
0.99	100	$[k_p]$	1.12	1.23	1.34	1.45	1.56	1.68
		$[k_d]$	2.05	3.06	4.07	5.08	6.09	7.09
	130	$[k_p]$	1.11	1.22	1.33	1.45	1.56	1.67
		$[k_d]$	1.93	2.87	3.8	4.74	5.67	6.61
0.999	100	$[k_p]$	1.09	1.20	1.30	1.41	1.52	1.63
		$[k_d]$	1.60	2.34	3.09	3.83	4.60	5.32
	130	$[k_p]$	1.08	1.19	1.31	1.41	1.52	1.63
		$[k_d]$	1.53	2.22	2.92	3.61	4.30	5.01

5. Conclusion

In order to assess the analysis of the influence of pipes properties on pipelines reliability a mathematical model has been elaborated which clearly gives pipe reliability dependence in terms of strength limit variance coefficient, wall thickness, pipe diameter, exerted load and strength reserve coefficient.

The hypotheses put forward have been confirmed by the results obtained from statistical analysis of measurement and mechanical tests data on specimen taken from X52 steel pipes. The results of the analysis of the influence of X52 steel pipes properties (dimensions 1220 x 12 mm) on pipeline reliability has confirmed that the most influential factor is tress concentration in welds and defines the necessary strength reserve coefficient value corresponding to a given pipeline reliability level.

References

1. **Genod V.** Transport des hydrocarbures liquids et gazeux par canalisation.-Ed. Technip, 1980.-260p.
2. **Melchers, R.E.** Structural reliability analysis and prediction. -Ed. by Wiley and Sons, 2nd ed, 1999, p.239-250.
3. **Procaccia, H., Morilhat, P.** Fiabilité des structures des installations industrielles.-Ed. Eyrolles, 1996, p.50-73.
4. **Abdelbaki, N., Bouzid, R., Bouali, E., Gaceb, M.** Statistical approach to the analysis of the strength of pipes used in gazoducs.-16th Int. Congress of Chemical and Process Engineering. -CHISA, Prague, 2004, p.160-173
5. **Kapur, K.** Reability in engineering design.-John Wiley and Sons, 1980**,** p.94-155.
6. **Dacumha D., Duflo M.** Probabilités et statistiques. -Ed. Masso, 1994.-166p.
7. **Lemaitre J., Chaboche J.L.** Mécanique des matériaux,.-Ed. Dunod, 2ème ed., 1980, p.60-75.
8. **Yen, B.C., Tofani, G.D.** Geometrical asserment of soil stress on pipeline croating. -Pipiline Ind. 1985, No5, p.50-55.

N. Abdelbaki, E. Bouali, M. Gaceb, R. Bouzid

ILGŲ VAMZDŽIŲ SAVYBIŲ ĮTAKA VAMZDYNŲ PATIKIMUMUI

R e z i u m ė

Vamzdynų, sumontuotų suvirinant galais didelio skersmens vamzdžius, elgseną veikia keli faktoriai. Heterogeninės vamzdžių metalo savybės, suvirinimo defektai turi įtakos vamzdyno darbingumui, jį tenka papildomai remontuoti. Projektuojant vamzdynus taikomas patikimumo metodas, tuo pat metu įvertinantis suirimo tikimybę, ir saugumo faktorių. Tai padeda nustatyti vamzdyno būsimą rizikos faktorių ir kartu jos neperdėti. Taigi, taikant šiame darbe naudojamas formuluotes, galima kiekybiškai ir kokybiškai įvertinti įvairius galais sujungtų pavienių vamzdžių savybių įtaką viso vamzdyno patikimumui. Metodas taikytas didelio skersmens vamzdžiams pagamintiems iš X52 markės plieno.

N. Abdelbaki, E. Bouali, M. Gaceb, R. Bouzid

INFLUENCE OF PROPERTIES OF LARGE PIPES ON THE RELIABILITY OF PIPELINES

S u m m a r y

Several factors affect the behaviour of pipelines constructed by butt welding of big diameter tubes. The heterogeneous properties of the tubes' metal and weld defect affect the working capacity of pipelines once put into service. The recourse to a reliability approach, during the projection of pipelines makes it possible, on the one hand to measure the risk incurred, by the association of a pipeline fracture probability to a safety factor and on the other hand this allows to avoid its over sizing or to estimate the under sizing risk. Thus, in this context, the formulation put forward in the present work allows to reason qualitatively as well as quantitatively on the effects of various properties of pipes assembled end to end on the reliability of pipelines. An application example is given for big diameter pipes made from grade X52 steel.

Н. Абделбаки, Е. Боуали, М. Гацеб, Р. Боузид

ВЛИЯНИЕ СВОЙСТВ БОЛЬШИХ ТРУБ НА НАДЕЖНОСТЬ ТРУБОПРОВОДОВ

Р е з ю м е

На поведение трубопроводов построенных из сваренных встык труб большого диаметра, оказывает влияние несколько факторов. Гетерогенные свойства металла труб и дефекты сварки, влияют на работоспособность трубопровода, его обслуживание. Во время проектирования трубопроводов использован метод надежности при одновременной оценке вероятности разрушения и запаса прочности помогает определить фактор риска, таким образом, избегая превышения риска или его переоценки. Используя примененные в настоящей работе формулировки, можно качественно и количественно оценить надежность трубопровода, изготовленного из встык соединенных труб. Пример расчета дается для труб большого диаметра, изготовленных из стали X52.

Received August 03, 2007