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Environmental Security

Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines

Edited by
Guy Pluvinage
Mohamed Hamdy Elwany

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Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines

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Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines

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PREFACE

Pipes are of major importance for transport of liquids and gas mainly for water, natural gas and oil. In Western Europe, the distribution of drinking water has been achieved 20 years ago and the problem of renewal of the networks is now considered as an accurate question in terms of money and time. From the quantitative point of view, it has been shown that the quality of the networks is highly perfectible: the primary rate is about 70% that means about 30% of water is lost by leak or break. In Mediterranean countries the rate is lower and sometimes more than 80% is lost by leaks, breaks and illegal withdrawing. From the qualitative point of view, a degradation of the distributed water has been pointed out, which is due to pollution of resource and damage of the network.

Length of the water networks is greatly different from one country to another. Total gas pipes length in the world is estimated to 1 million km for gas transport (pipes of diameter 80–1,000 mm), in the USA 450,000 km, in Russia 235,000 km, in Canada 71,300 km, in France 30,815 km. In China, the construction of the natural gas pipelines has gained its initial scale. By the end of 2003, the total length of the national natural gas pipe was about 21,000 km, represented by such long-distance gas pipelines as WEP, Shaan-Jing (Jingbian-Beijing), Se-Ning-Lan (Sebei-Xining-Lanzhou) and Ya13-1- Hong Kong pipelines.

The pipelines are of capital importance for the landlocked countries. Currently, only crude exports of Russia towards Europe completely depend on the pipelines. The pipeline of Drushba, for instance, is built on a distance of 3,640 km, from the area of Samara in Russia to the refinery of Leuna in Germany, with 34 stations of pumping.

The pipelines of long distance have a great geopolitical importance. It is the case, for instance, for the area of the Caspian Sea, where all the plans of export of oil starting from this area primarily depend on the construction of pipelines. The pipeline remains the mean of transcontinental transport least expensive compared to the rail-bound or ground transport. It constitutes under this aspect an important mean of transport between the USA and Canada, but also between the various European countries where the pipelines are relatively of short distance. One of the biggest is Trans-Alaska oil pipe (TAPS) of length 1,270 km. This pipeline connects the Arctic coast to the Western coast of Alaska. It transports 2 million oil barrels per day.

It became increasingly paramount to ensure the safe utilisation of such plants in order to prevent economical, social and ecological losses. From a technical point of view, pipelines are complicated 3D structures that include straight pipes, nozzles, pipe-bends, dissimilar welded joints, etc. In addition, their operating conditions can be quite severe, that is, internal pressure and cyclic loading (vibration) combined with the influence of internal and external corrosive environments. The potential synergy of such parameters can lead to an increase in the risk of damage and unexpected fracture of these structures during their long-term exploitation.

Leak and fracture of pipes is assumed to be achieved by initiation and propagation of a defect and final failure when defect reaches a critical length. To have a precise idea of life duration of the water pipes the three following components need to be precisely described:

1. Defect initiation
2. Crack propagation
3. Final failure

Defect Initiation

Initial defect is assumed in one case as being corrosion pitting and, in the second case, scratches, gouges, etc., made during implementation or service life.

When local corrosion is the principal mode of damage, due to the statistical character of corrosion pits, it needs to be characterised by a probabilistic distribution such as Weibull's or Gumbel's laws in order to determine the probability of the most severe damage or the deepest corrosion crater. Scratches, gouges or dents are now considered as more frequent damage than corrosion. They do not appear at the beginning, but at an uncertain part of the life. They are due to impact with foreign objects such agriculture or civil engineering equipments. Statistical distribution on geometry and orientation are needed to determine also the probability of the most severe defect. In both cases, this gives the initial defect size a_i for a reference time and its probability of occurrence. This initial defect can be related with the defect detected during inspection, if it occurs.

Crack Propagation

In service, cyclic variation of internal pressure is present, but also bending coming from soil movement or repeated vehicles passage, which generate fatigue loading. An initial defect is growing under mechanical and environmental conditions. The current status, in terms of prediction of failure, is based on corrosion studies of unstressed components and fracture and fatigue of pipes within non-aggressive environments. This approach has a number of fundamental limitations: corrosion effects are influenced by applied stress state and damage is not constant over the duration of stress–corrosion interaction; the description of the stress field around corrosion defects is not adequately described and therefore the fracture criterion may be non-conservative. Furthermore, corrosion science studies have shown that differences in electrochemistry exist between a pit cavity and an open smooth surface.

Final Failure

An initial defect is growing under mechanical and environmental conditions. Fracture occurs when defect has reached its critical size corresponding to service conditions $a_{cr,1}$. Under over-pressurised conditions the critical defect is $a_{cr,2}$, which has a size smaller than $a_{cr,1}$. For a well-controlled and programmed replacement of the water grids, it is necessary to know kinetics of crack growth of the defect size between $a_{cr,2}$ and $a_{cr,1}$. From this, it is possible to know the residual life duration of the examined water pipes.

A more conservative approach consists in taking into account the possibility of crack extension of surface defects. A surface crack can be extended under fatigue, corrosion or combined corrosion and fatigue and reach a critical size with wall perforation behind crack front. Crack growth until this size is possible as far as length and crack opening displacement are insufficient to ensure a detectable leak, or until the critical crack size to lead to brittle fracture is not reached. In any case, used method to apply the “Leak Before Break” concept needs to ensure a given conservatism given by experimental data.

This book presents papers, which were delivered at the NATO Workshop “Safety, reliability and risks associated with water, oil and gas pipelines” held in Helnan Palestine Hotel, Alexandria (Egypt), 4th–8th February 2007, under the auspices of the NATO Science for Peace and Security Program. The organisers acknowledge the Program Committee for attribution of a support grant. Three major defect assessment tools for pipes are presented:

(a) Failure assessment diagram and particularly the SINTAP
(b) Limit analysis
(c) Strain design approach

Repairing methods are based on results of investigation. Methods such as welded sleeve, clamped composite sleeve, grinding and pipe replacement are described.

Professor Guy Pluvinage
Professor Mohamed Hamdy Elwany

GENERAL APPROACHES OF PIPELINE DEFECT ASSESSMENT

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Abstract: In this paper the three major defect assessment tools for pipes are presented: (i) the failure assessment diagram and particularly the SINTAP procedure, (ii) a notch adapted failure assessment diagram by modification of the SINTAP using the volumetric method, (iii) different pipe limit analysis and their comparison for the same kind of defects.

Keywords: failure assessment diagram, SINTAP, notch, limit analysis

1. Introduction

Pipelines have been employed as one of the most practical and low price method for large oil and gas transport since 1950. The pipe line installations for oil and gas transmission are drastically increased in last three decades. Consequently, the pipeline failure problems have been increasingly occurred. The economical and environmental and eventually in human life considerations involve the current issue as structural integrity and safety affair. The explosive characteristics of gas provide high wakefulness about the structural integrity. Therefore, the reliable structural integrity and safety of oil and gas pipelines under various service conditions including presence of defects should be warily evaluated. The external defects, e.g., corrosion defects, gouge, foreign object scratches and pipeline erection activities are major failure reasons of gas pipelines. A typical example of a corrosion defect is given in Figure 1. According to numerous design codes, this kind of defects is considered as a semi-elliptical crack-like surface defect of aspect ratio a/c. The aspect ratio varies in range [0.1–1] depending on corrosion rate anisotropy. Another example of dents produce by impact of foreign object (IFO) is presented in Figure 2.

G. Pluvinage and M.H. Elwany (eds.), Safety, Reliability and Risks Associated with Water, Oil and Gas Pipelines, 1–22.

Several types of pipes failures can be distinguished as longitudinal, circumferential or helicoidally failures. These types depend mainly on pipe diameter. For small diameter pipes, where bending stresses are predominant, circumferential failure occurs. For large diameters, hoop stresses are more important than bending stresses and longitudinal failure appears. When bending and hoop stresses are of the same importance, fracture path becomes spiraled.

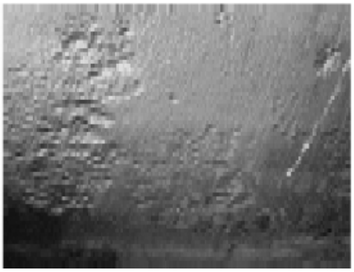

Figure 1. Example of corrosion defect on pipe.

Figure 2. Example of dent on pipe.

Pipe steels have yield stress up to 700 MPa for the most recent quality in order to ensure enough ductility and weldability. Failures emanating from the above mentioned defect are elasto-plastic fracture or plastic collapse. For these two situations, defect assessment is made generally by two tools: failure assessment diagram (FAD) and limit analysis.

According to numerous design codes, all defects are considered as a semi-elliptical crack-like surface defect of aspect ratio a/c. This is a very conservative approach. Trends are now to take into account the real geometry of the defect and particularly its finite tip radius. For this reason, tools like the FAD need to bee modified.

In this paper the two major defect assessment tools for pipes are presented:

1. The FAD and particularly the Structural Integrity Assessment Procedure (SINTAP) [1]
2. A notch-adapted failure assessment diagram (NFAD) by modification of the SINTAP using the volumetric method
3. A comparison of different limit analysis for the same kind of defect is given in the third part.

2. Sintap Procedure for Crack-Like Defect

In a FAD, the basic fracture mechanics relationship with three parameters: applied stress (σ_{app}), defect size (a) and fracture toughness (K_{IC} or J_{IC}) is replaced by a two parameters relationships f(k_r, S_r). Stress and defect size are combined into the applied stress intensity factor K_{app} or applied J parameter J_{app} and the parameter k_r and S_r are non-dimensional according to the following initial definitions:

$$k_r = \frac{K_{app}}{K_{Ic}} \text{ and } S_r = \frac{\sigma_{app}}{Rm} \tag{1}$$

where Rm is the ultimate strength. In the plane {S_r; k_r}, a given relationship $k_r = f(S_r)$ delimits the safe zone and the failure zone (Figure 3).

Initially, the relationship between non-dimensional stress intensity factor and non-dimensional stress was issued from a plasticity correction able to describe any kind of failure continuously from brittle fracture to plastic collapse.

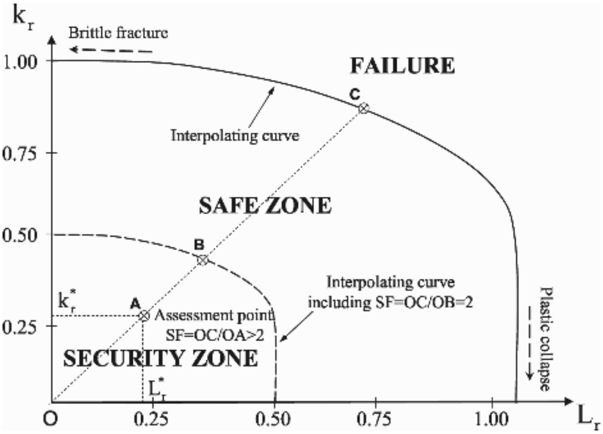

Figure 3. Typical presentation of failure assessment diagram (FAD). Definition of safety factor.

A typical representation of a FAD is given in Figure 3. On the same figure, the load safety factor F_s is defined according to:

$$F_s = \frac{OB}{OC} \tag{2}$$

The advantages to the use of FAD are:

- The use of an unique tool for any critical situations (in other way, several failure criteria need to be used from LFM, EPFM and LA)
- To get, for any non-critical situation the safety factor F_s.

The SINTAP procedure is derived from the initial FAD. However, definitions of non-dimensional parameters are little different: k_r parameter is derived from the applied J_{ap} parameter and fracture toughness J_{Ic}

$$k_r = \sqrt{\frac{J_{ap}}{J_{Ic}}} \tag{3}$$

and the S_r parameter is replace by the L_r parameter

$$L_r = \frac{P}{P_L} = \frac{\sigma_{ref}}{\sigma_0} \tag{4}$$

where P is the applied load, P_L the limit load. The material behaviour is assumed to follow the Ramberg–Osgood relationship:

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_0} + \alpha\left(\frac{\sigma}{\sigma_0}\right)^n \tag{5}$$

where ε_0 and σ_0 are respectively the reference strain and stress and n the strain hardening exponent. The reference stress is given by:

$$\sigma_{ref} = \frac{P}{P_0}\sigma_0 \tag{6}$$

where P_0 is the reference load.

The applied J parameter is obtained by assuming proportionality between J_{app} and the elastic value of J parameter J_{el}. The coefficient of proportionality is derived from the constitutive non-dimensional stress–strain relationship of the material.

The relationship between k_r and L_r is considered as a limit curve obtained from numerous experimental data. This limit curve is more physically an interpolation curve between brittle fracture representative assessment point and plastic collapse. In these methods, failures near plastic collapse are represented by data in the “tail” of the diagram.

There are several similar FAD procedures, i.e., EPRI in the USA, R6 in the UK, RCCMR in France with small and more and less conservative difference in the safe zone area. The SINTAP is the result of a European project of a multidisciplinary approach in order to get a unify multilevel method useful for SME to large companies. The level hierarchy depends on knowledge of description of stress–strain curve and fracture toughness. Lower levels are used with simple description of stress–strain curve but with higher conservatism.

The mathematical expressions of SINTAP for the lowest and more conservative (default level) is given as below:

$$f(L_r) = \left[1 + \frac{L_r^2}{2}\right]^{\frac{-1}{2}} \left[0.3 + 0.7 \times e^{\left(-0.6 \times L_r^6\right)}\right], \quad \text{for } 0 \le L_r \le 1 \text{ where } L_r^{\max} = 1 + \left(\frac{150}{\sigma_Y}\right)^{2.5} \tag{7}$$

where $f(L_r)$, L_r, $L_r^{\max}$, σ_Y, are interpolating function, non-dimensional loading parameter, maximum value of non-dimensional loading or parameter, yield stress, respectively.

In this paper, SINTAP Level 1 has been used to determine the safety factor and the reliability factor for a boiler tube (Figure 4) exhibiting a longitudinal defect inside the tube weld, applying deterministic and probabilistic methods [2]. The influence of temperature is discussed.

The material is a steel used for boiler pipes. Its mechanical properties for five different temperatures are reported in Table 1.

TABLE 1. Mechanical properties of a boiler steel for five different temperatures.

T [c°]	20	400	520	540	560
K_{Ic}[MPa√m]	167.1	160.7	117.9	106.5	94.1
$R_{p0,2}$ [MPa]	380	275	275	255	240
R_m [MPa]	500	470	420	400	380

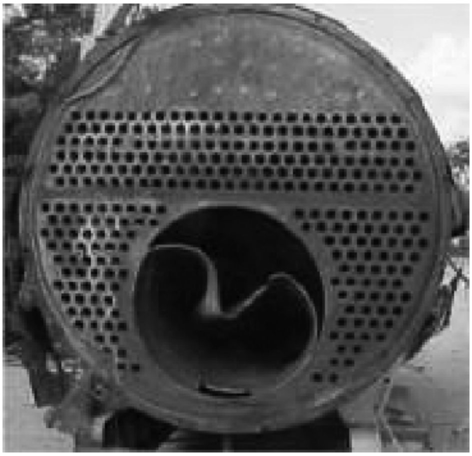

Figure 4. Example of a boiler with the different tubes.

The boiler pipe has an external diameter of 273 mm and a wall thickness of 24 mm. The pipe is welded and the butt weld is assumed to exhibit a longitudinal semi-elliptic surface defect of depth a = 2.25 mm, its great axis is 2c = 15 mm and its aspect ratio a/2c = 0.15.

Under the effect of internal pressure the hoop stress of 77 MPa is produced in the tube. The stress intensity factor for a semi-elliptic surface defect is given in code SINTAP in the following form:

$$K_I = \frac{PR_m}{t}\sqrt{\pi a}\; F(\frac{R_i}{t}, \frac{2c}{a}, \frac{a}{t}) \tag{8}$$

R_i is the internal half diameter, t is the wall thickness of the pipe and R_m its mean half diameter.

The value of the geometrical correction for this defect is equal to $F(\frac{R_i}{t}, \frac{2c}{a}, \frac{a}{t}) = 1.445$. Variations of F with small variation are small and F is considered as constant in the present study.

3. Probabilistic Approach of Safety Factor by Coupling Sintap and FORM/SOTM Method

First-Order Reliability Methods (FORM) and Second-Order Reliability Methods (SORM) are general methods of structural reliability theory [2]. These methods are based on linear (first-order) and quadratic (second-order) approximations of the limit state surface $g(X) = 0$ tangent to the closest point of the surface to the origin of the space. The determination of this point involves non-linear programming.

The FORM/SORM algorithms involve several steps:

- In the first step, the space of uncertain parameters x is transformed into a new N-dimensional space u consisting of independent standard Gaussian variables. The original limit state $g(x) = 0$ then becomes mapped onto the new limit state $g_u(u) = 0$ in the u space.
- In the second step, the point on the limit state $g_u(u) = 0$ having the shortest distance to the origin of u space is determined using an appropriate non-linear optimization algorithm. This point is referred to as the design or β-point, and has a distance β_{HL} to the origin of the u space.
- In the third step, the limit state $g_u(u) = 0$ is approximated by a surface tangent to it at the design point. Lets such limit states be $g_L(u) = 0$ and $g_Q(u) = 0$, which correspond to approximating surfaces of hyperplane (linear or first-order) and hyperparabolic (quadratic or second-order), respectively.

The probability of failure P_F is thus approximated by

$$P_{F,1} = \phi(-\beta_{HL})$$

$$P_{F,2} \approx \phi(-\beta_{HL}) \prod_{i=1}^{N-1} (1-\kappa_i \beta_{HL})^{-1/2} \tag{9}$$

$$\phi(u) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u} exp(-\frac{1}{2}\xi^2) d\xi \tag{10}$$

$\phi(u)$ is the cumulative distribution function of a standard Gaussian random variable, and k_i' are the principal curvatures of the limit state surface at the design point. FORM/SORM are analytical probability computation methods. Each input random variable and the performance function *g(x)* must be continuous.

Until the 19th century, all constructions were conceived and carried out mainly in an empirical way. The introduction of the steel construction required development of strength of materials. The principle of safety initially adopted consisted in making sure that the maximum stress in the most critical section of construction remained lower than a working load *L* obtained by dividing the resistance of material *R* by conventionally accepted safety factor F_s The engineers realized gradually the disadvantage of this design approach, and this contributed to develop the reliability concept based on a probabilistic approach. According to new approach, a structure is considered safe if probability of its failure is lower than a conventional accepted value, value that depends on many factors like the expected life of the structure, consequences generated by its failure, risks of obsolescence, relevant economic criteria like the costs of replacement, maintenance costs.

Instead of imposing a safety factor based on the material resistance or on load or on defect size or all the three, the probabilistic approach introduces the reliability factor as quantitative criterion of a low failure probability.

Within the chosen procedure, the following parameters are treated as random parameters:

- Fracture toughness
- Yield strength
- Ultimate tensile strength
- Defect distribution
- Pressure distribution

These random parameters are treated as not being correlated with one another. The parameters can follow a normal, log-normal, Weibull or some special distributions (for the defects).

The coefficient of variation CV_x is an excellent indicator of the homogeneity of the analyzed unit. This one will be declared homogeneous if CV < 1/3, concerning the properties of materials, if the mechanical tests were carried out carefully, the coefficient of variation is an excellent indicator of the manufactures quality, thus, the manufacture of low carbon steel leads to a coefficient of variation CV = 0, 1, for ultimate strength, yield stress and fracture toughness. The pressure distribution obeys to the same coefficient of variation. We notice that for exponential distribution the coefficient of variation is necessary taken as unit. The presentation of the method will be arrived out with the value of coefficient of variation.

The fracture toughness is assumed to be a Weibull's distribution. The Weibull's probability density function has the following form:

$$f(K_{IC}) = C \times m \times K_{\rho,c}^{m-1} \exp\left(-C \times K_{\rho,c}^{m}\right) \quad (11)$$

where C (scale) and m (shape) are the Weibull's distribution parameters. μ (mean) and σ (standard deviation) are the input data into the program and are related to the Weibull's distribution parameters as follows:

$$\mu = \frac{C^{-1}}{m * \Gamma\left(1+\frac{1}{m}\right)} \qquad \sigma = C^{\frac{-2}{m}}\left[\Gamma\left(1+\frac{2}{m}\right) - \Gamma^2\left(1+\frac{1}{m}\right)\right] \quad (12)$$

where Γ(Z) is the gamma function, defined by the following integral:

$$\Gamma(Z) = \int_0^\infty t^{Z-1} e^{-t} dt \quad (13)$$

Yield strength ultimate, tensile strength and internal pressure can be mainly assumed as a normal distribution. The normal probability density function has the following form:

$$F(X) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)\right] \quad (14)$$

For defect, depth a is assumed to follow an exponential distribution. The probability density function has the following form:

$$F(X) = \lambda \exp\left(-\lambda a\right) \quad (15)$$

where λ is the exponential distribution parameter. μ (mean), the standard deviation, σ is related to λ as below:

$$\mu = \sigma = \frac{1}{\lambda} \tag{16}$$

We can calculate the probability of rupture by using methods FORM/ SORM. The results show that the probability of rupture decreases when the temperature grows at constant stress. The following Table 2 gives the fracture stress for a probability of 10^{-6} for different temperatures.

TABLE 2. Evolution of the fracture stress corresponding to a probability of failure Pf $=10^{-6}$ with temperature.

Stress (MPa)	150	110	100	95	90
Temperature (C°)	20	400	520	540	560

From obtained results it is possible to find the reliability factor F_s which decreases with increasing temperature T according to the following equation:

$$F_s = 2.7879\ T^{-0.1167} \tag{17}$$

4. Modified Sintap for Fracture Emanating from Notches

In the present section, the structural integrity of corroded pipes is addressed [3]. The semi-spherical defects, semi-elliptical defects and long blunt notch are taken into account and are not considered as crack-like defects. Pipes are made in API X52 which is considered as following as exhibiting strain hardening behaviour. The obtained stress distributions at defect tip yield the notch stress intensity factor and stress parameters which are needed to assess structural integrity by the notch-adapted SINTAP.

4.1. MECHANICAL PROPERTIES OF API X52

API X52 was the most common gas pipeline material for transmission of oil and gas during 1950–1960. The chemical composition of API X52 is shown in Table 3.

TABLE 3. Chemical composition of API X52 (Weight %).

C	Mn	Si	Cr	Ni	Mo	S	Cu	Ti	Nb	Al
0.22	1.22	0.24	0.16	0.14	0.06	0.036	0.19	0.04	<0.05	0.032