DOMAIN FAILURE ASSESSMENT DIAGRAMS

FOR DEFECT ASSESSMENT OF GAS PIPES

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Key words : Failure assessment diagram, Defects, pipe, limit analysis

Abstract

The Concept of Failure Assessment Diagram (FAD) as a tool for pipe defect assessment is extended. A new approach is presented : the Domain Failure Assessment Diagram (DFAD). Some examples used for notch like defects as corrosion craters, gouges and combined gouge-dente defects are described : brittle fracture of grey cast iron pipes for water transport, elastoplastic failure and plastic collapse of X52 steel pipe for gas transport.

Introduction

Over the last 50 years, gas transmission pipelines have become significant networks to transmit high energy quantities on long distances from gas deposits to consumption areas. Considering European transmission pipelines only, the onshore network mileage has been multiplied by more than for times between 1970 and 2010. Despite the growth of the gas transmission pipeline mileage, the failure frequencies by leak or rupture have been reduced by five in Europe at the same time. According to the European Gas pipeline Incident data Group report (EPRG) [1] which has collected incident data along 129, 719 Km since 1970, the primary failure frequency over the entire period (1970-2007) was equal to 0.37 per 1,000Km.year and over the last five years in 2011 was equal to 0.11 per 1,000 Km./year. The economic, 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.

In this paper , we describe the concept of domain failure assessment diagram which is a classical FAD but divided in three domains: brittle fracture, elasto plastic fracture and plastic collapse. Examples of pipe failures occurring in each three domains are proposed.

Domain Failure Assessment Diagram (DFAD)

In a failure assessment diagram, 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 $f(k_r, L_r)$. k_r represents the non-dimensional Fracture Driving Force (FDF) and L_r the non-dimensional applied load.

$$k_r = FDF/FDF_c \qquad (1)$$

where FDF_c is the material fracture resistance. The Fracture Driving Force can be defined as *J* integral or applied Stress Intensity factor. The non- dimensional applied force for a pipe can be defined as the ratio of service pressure p_s over limit pressure p_L:

$$L_r = p_s/p_L \qquad (2)$$

An example of such DFAD is given in figure 1 where A represents the defect assessment point of coordinates [l^*_r,k^*_r]. This FAD is limited by the failure assessment curve that gives the limit of a safe and an unsafe pipe. The safe area is divided conventionally into three zones:

Zone I: if the assessment point lies in this zone, increasing the applied pressure leads to brittle fracture

Zone II: where increasing the applied pressure leads to elastoplastic fracture

Zone III: where plastic collapse occurs by increasing service pressure.

Based on Feddersen diagram [2] the limit of these three zones is defined conventionally as follows:

Zone I : $0 < L_r < 0{,}62\ L_{r,y}$

Zone II : $0.62\ L_{r,y} < L_r < 0.95\ L_{r,L}$

Zone III : $0.95\ L_{r,\ max} < L_r < L_{r,max}$

where $L_{r,y}$ is associated with the yield pressure and $L_{r,max}$ is the maximum value of L_r.

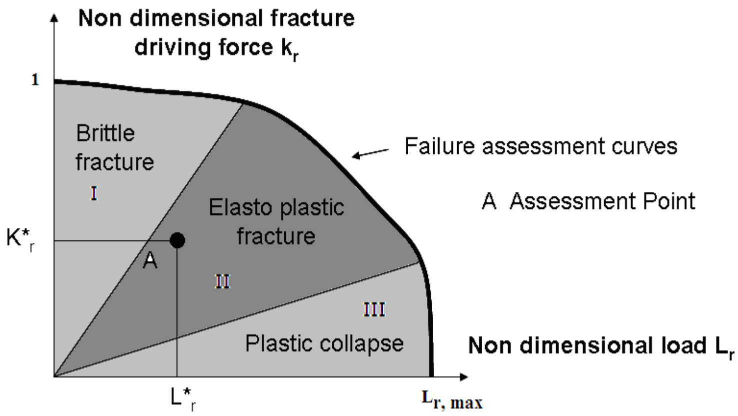

Figure 1 : Notch failure assessment diagram indicating the domain of limit analysis and notch fracture mechanics for gouges and dents as pipe defects.

The relationship between k_r and L_r considered as a failure curve is obtained from numerous experimental data. This failure curve is more physically an interpolation curve between pure brittle fracture representative assessment point (k_r=1, L_r =0) and plastic collapse assessment point (k_r=0, $L_r = L_{r,max}$). An example of failure assessment curve is given in Structural Integrity Assessment Procedure (SINTAP) procedure [3] for the lowest and more conservative level (default level). The relationship k_r= f(L_r) describing the failure assessment curve is given as below and used in the present work:

$$f(L_r) = \left[1 + \frac{L_r^2}{2}\right]^{-\frac{1}{2}} \left[0.3 + 0.7 \times e^{\left(-0.6 \times L_r^6\right)}\right],$$
$$\text{for } 0 \le L_r \le 1 \text{ where } L_r^{max} = 1 + \left(\frac{150}{\sigma_Y}\right)^{2.5} \tag{3}$$

2. BRITTLE FRACTURE OF CAST IRON PIPES

Cast iron is a material which was used before the sixties for gas transport. Cast iron is a brittle material and known by gas companies as “a material with problems. In France, it seems that about 1000Km of cast iron pipes still exists over 200 000Km of length. They are replaced progressively but not so fast it was expected.

In following an example of water pipe brittle failure [4] due to a pressure peak induced by water hammer is reported. Mechanical properties of this cast iron are given in table 1.

Table 1 : mechanical properties of cast iron.

Young’s modulus E (GPa)	Yield stress σ_y (MPa)	Ultimate strength σ_{ul} (MPa)	Fracture toughness K_{Ic} (MPa√m)
172	300	320	14.9

These pipes exhibit often corrosion defects. These defects are modelled as semi-elliptical or semi- spherical notch and surface defects. DFAD method is applied to determine the failure potential of the pipe when subjected to water hammer and assuming one-half pipe thickness as defect depth and aspect ratio a/c = 200 as long defect. The method uses SINTAP code and concept of notch stress intensity methods [5]. Table 2 gives values of coordinates k_r and l_r of the assessment point and the corresponding safety factors. Defects are located in 4 types of cast iron pipes which are constitutive of the water network

Table 2 : k_r, L_r and safety factor for semi-elliptical and semi-spherical defects via SINTAP in a cast iron pipe submitted to water hammer.

Pipe type	Over pressure	k_r		L_r		Safety Factor	
		S-E	S-S	S-E	S-S	S-E	S-S
D=450mm, t=8.6 mm	16.88 bar	0.3259	0.1979	0.1065	0.1065	2.99	4.72
D=500mm, t=9.1 mm	17.21 bar	0.3245	0.2279	0.1153	0.1153	2.99	4.14
D=600mm, t=9.9 mm	16.74 bar	0.3786	0.2707	0.1224	0.1224	2.58	3.56
D=800mm, t=11.7 mm	6.99 bar	0.2116	0.1430	0.0577	0.0577	4.64	6.73
S-E: Semi-Elliptical defect, **S-S:** Semi-Spherical defect							

Figure 2 presents the DFAD using the SINTAP failure assessment curve showing the 4 assessment points concept and indicates the brittle assumption for cast iron material. A comparison of the results reveals that the semi-elliptical defects behave in a more brittle manner than semi-spherical defects and consequently, the safety factor for semi-elliptical defects substantially diminishes. As a matter of fact, the semi-elliptical defects are more critical than semi-spherical defects for a given defect depth, pipe geometry and loading conditions

However, safety factor was in any studied case, over the conventional value of 2 and this situation doesn't need defect reparation. This can be also verified by examining the ratio overpressure over yield stress with a maximum value of 0.56 for the first pipe (D=450mm).

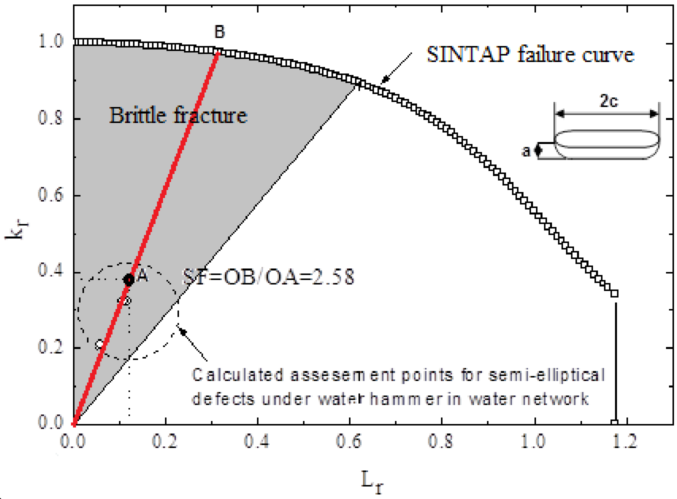

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Figure 2: DFAD diagram and position of assessment points for a brittle material in a cast iron pipe submitted to water hammer.

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Elastoplastique failure potential of a gas pipe made in API X 52 steel

X52 steel is an ancient gas pipe steel mainly and was the most common gas pipeline material for transmission of oil and gas during 1950-1960. API X52 (API American Petroleum Institute) is a low strength steel with high ductility. 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

In Table 4, the mechanical properties of API X52 are presented.

Table 4. Mechanical properties of API X52.

E (GPa)	ν	σ_Y (MPa)	σ_U (MPa)	A%	n	K (MPa)	K^*_C (MPa√.m)
203	0.30	410	528	32	0.164	876	116.6

where E, ν, σ_Y, σ_U, A%, n, K and K^*_C are Young's modulus, Poisson's ratio, yield stress, ultimate stress, relative elongation, hardening exponent, hardening coefficient and fracture toughness respectively. The failure potential of a pipe made in API X52 steel was studied under the service pressure of 70 bars [6]. The pipe diameter was 219.1 mm and the wall thickness t = 6.1 mm. Three kind of defects were studied semi-spherical (SS), semi-elliptical (SE) and long notch (N) defect. Each defect depth a is half of the thickness and is considered with its length 2c along longitudinal direction (L) or along circumferential direction (R) (t = 6.1 mm, a = t/2, a/c =

0.2). Assessment points for the 6 defects treated as notch have been determined using Volumetric Method [5] and reported in a Domain Failure Assessment Diagram. Values of safety factor has been obtained and reported in table 5.

Table 5 Safety factor or the 6 defect types and obtained from the DFAD.

Defect Type	longitudinal	circumferential
Semi-spherical	3.91	3.84
Semi-elliptical	3.97	3.47
Blunt notch	3.61	2.6

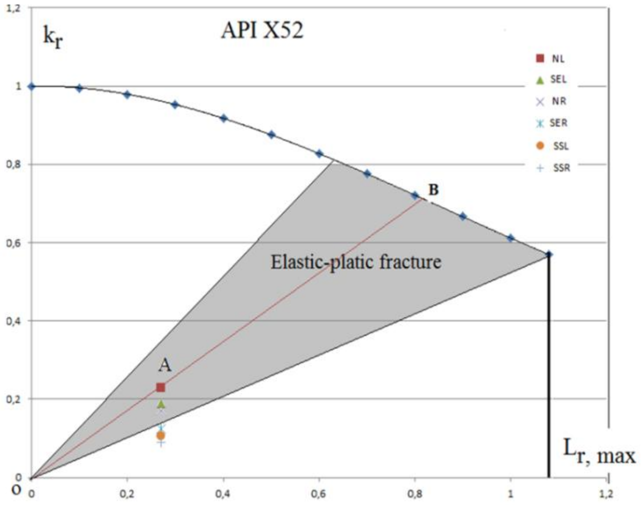

Figure 3 : DFAD for semi long notch (N), semi elliptical (SE), semi spherical (SS) defect in a pipe made in API X52 steel. Service pressure 70 bars. Defect along longitudinal (L) and circumferential direction (R).

Plastic collapse potential for a steel pipe

Any assessment point in a Failure Assessment Diagram is localised by polar coordinates r an θ. Theta angle θ* is a parameter which represents the belonging of the assessment point to a failure domain. For this reason it is called the angle domain. According to the following table, the angle domain indicates the failure type.

Table 6 : Failure domain represented by domain angle.

Pure brittle fracture	Brittle fracture	Elastic-plastic fracture	Plastic collapse	Instability
$\theta^*=90°$	$0 > \theta^* \geq \theta_1$	$\theta_1 > \theta^* \geq \theta_2$	$\theta_2 > \theta^* > 90°$	$\theta^*=0°$

Domain angles θ_1 and θ_2 are presented in figure (7). In the case of a failure curve given by the SINTAP procedure, values of θ_1 and θ_2 are respectively θ_1 =55° and θ_2 = 22°. It has been shown that general trend is that the margin of safety on the FAD is minimum in the middle (elastic-plastic) region, slightly higher in the 'plastic collapse" region and maximum in the 'brittle fracture' region. However, this overall trend is complicated by varying degree of scatter in the different regions. For this reason, we have examined the evolution of the safety factor with the θ angle on a statistical point of view.

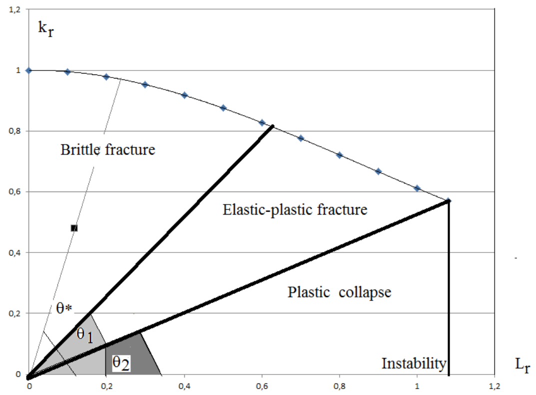

Figure 4 : Definition of domain angle in Failure Assessment Diagram .

In the next, we have used a probabilistic approach of the safety factor [7-8]. We consider a pipe made in API X52 steel and submitted to a random internal pressure governs by a Gauss distribution. The characteristics of this distribution are given in Table 7.

Table7 : Statistical characteristic of the pipe internal pressure distribution.

	Pipe Steel
Mean (MPa)	41.8
Standard deviation (MPa)	18.44
Coefficient of variation CV	0.44

This pipe exhibits a longitudinal semi elliptical defect with a notch angle Ψ = 0° and notch radius of ρ = 0.25 mm. the defect depth is a=2mm for steel and cast iron with an aspect ratio c/a of 4. Pipe defect and material are also assumed to be randomly distributed. Material distribution characteristics are given table 8. Note that the coefficient of variation CV (standard deviation σ over mean value μ) is taken as CV= 0.1 which is an upper bound value of a material of good quality and then this approach is conservative.

Table 8: Mechanical properties of used steel and used distribution.

Mechanical properties	Yield Strength Re	Ultimate strength	circumferential stress	Fracture Toughness	Defect
mean μ	410 MPa	528 MPa	41.8 MPa	116 MPa√m	2 mm
CV	0.1	0.1	0.4	0.1	
σ	41 MPa	52.8 MPa	18.44 MPa	11,6 MPa√m	
Distribution	Normal	Normal	Normal	Weibull	Exponential

Using Monte Carlo method , k^*_r and l^*_r coordinates of the assessment points have been computed and reported in Domain Failure Assessment diagram and the associated safety factor is computed. It has been shown that the θ angle is in range [0-7°] and typically in the plastic collapse region.,

Values of the distribution characteristic are reported in table 9. Note that the value of the safety factor is relatively high because the internal pressure is relatively low (4 bars).

Table 9: Mean values and standard deviation for the safety factor .

Mean μ	Standard deviation σ	Coefficient of variation CV
12.32	1.58	0.12

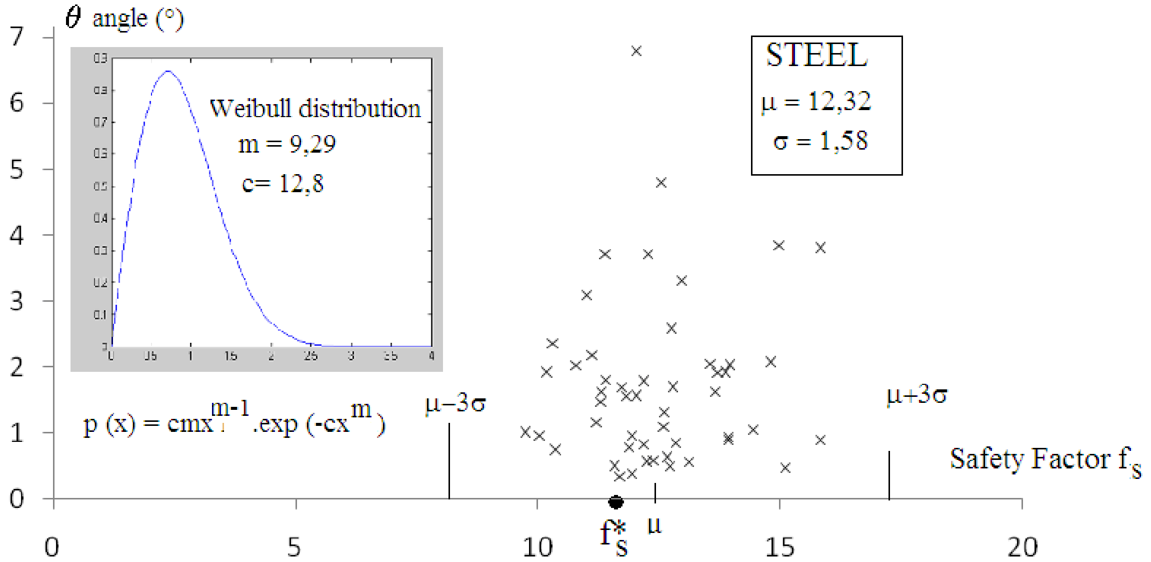

Figure 5: Distribution of the safety factor with θ angle for pipe steel [7].

All data are in a narrow scatter band of range [μ−3σ ; μ+3σ] and in the region of plastic collapse. The safety factor f*s computed from the ultimate pressure done by code ASME B31G is also reported. The safety factor distribution is represented with a Weibull distribution. Kolmogorov-Smirnov test results indicates that the Weibull distribution is significant at 57 % .
In the Domain Failure Assessment diagrams, particular assessment point is calculated from mean values of all the variable parameters.

Conclusion

Failure Assessment Diagram (FAD) is a tool for pipe defect assessment as Crack Driving Force versus defect length curve CDF = f(a). Like these Fracture mechanic methods, it gives information on defect failure potential but in addition, FAD gives the value of the safety factor and then it is a tool for a maintenance policy.
The Domain Failure Assessment Diagram (DFAD) make a bridge with the design based on material transition temperature and gives the failure type potential. It is used for notch like defects like corrosion craters, gouges and combined gouge-dente defects by coupling with a Notch Failure Assessment Diagram. For small defects in a ductile pipe material, the limit analysis is the appropriate tool. This tool needs to know the value of constraint factor and the influence of pipe and defect geometries on this parameter.

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