MODICATION OF FAILURE RISK BY THE USE OF HIGH STRENGTH STEELS IN PIPELINES

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Abstract: The use of new generation of pipe steels with high yield stress increases potentially the risk of brittle fracture. In order to evaluate this risk, safety factors associated with a surface crack and an operating pressure have been evaluated for three pipe steels: X52, X70 and X100. This evaluation has been made using a Failure Assessment Diagram and SINTAP procedure. This analysis has been extended to X120 pipe steel. The use of a Domain Failure Assessment diagram indicates that for this steel a risk of elastic plastic fracture exists. However, for pipe steels X52, X70 and X 100, failure occurs potentially by plastic collapse.

Key words: High strength steels, pipe line, failure risk, failure assessment diagram

1. INTRODUCTION

At present, requirement for natural gas is rapidly increasing internationally. Pipelines are used for natural gas transmission over long distance. Amelioration of gas transportation capacity is possible by increasing pipe diameters, operating pressure, gas cooling, decrease of the internal surface roughness and increase of service reliability. Several studies have shown that the most efficient factors on gas transportation capacity are in a decreasing order, pipe diameter, operating pressure distance between compression stations, compression rate and service temperature. By increasing the operating pressure and pipe diameter, the gas transportation capacity is increased and this results in obvious economic advantages. Table1 summarizes the evolution of pipelines operating pressure and diameter over the last century.

Today several pipelines are built with 1420 mm pipe diameter. The use of this large diameter pipes needs to use high strength steels in order to avoid thickness difficult to weld and minimize steel weight. There are significant advantages of using higher grade line pipes, such as X100 even X120 grade pipeline, in constructing long distance pipeline, because it can improve transportation efficiency of the natural gas pipelines by increasing internal transportation pressure, and material cost can be saved correspondingly by reducing wall thickness of pipe body and consumable for girth welding However, there are still many transportation safety problems laying high strength pipelines. First of all, due to line pipes laid through complicated regions, such as earthquake region with high-risk, gas pipelines in service may endure large displacement and stress, the maximum flexure deformation at part of the pipeline reaches to 4%~5% when it lays through multiple-region of earthquake and geology casualty.

Table 1: Evolution of transportations Conditions in Gas Pipelines

Year	**Operating Pressure**	**Diameter**	**Annual capacity**	**Power Gas Consumption over 6000Km**
1910	2 bar	400 mm	80 $10^3 m^3$	49 %
1930	20 bar	500 mm	650 $10^3 m^3$	31%
1965	66 bar	900 mm	830 $10^3 m^3$	14 %
1985	80 bar	1420 mm	26000 $10^3 m^3$	11 %

Secondly, the increased pressure in modern pipelines also causes the danger of running ductile cracks as the results of the stored high energy content of the compressed gas.

Due to combined use of high strength steel, high operating pressure and large diameter pipe, risk of brittle failure has increased.

By comparing remaining safety factor due to presence of crack like defects, it is the possible to describe evolution of this risk versus time through evolution of pipe design. This is made in the following by using Failure Assessment diagram (FAD) and particularly SINTAP procedure.

2. MATERIAL

Three pipe steels have been studied X52, X70 and X100.Chemical compositions of these steels are given in Table 2

Table 2: Chemical composition of the studied steels.

	C	**Mn**	**Si**	**Cr**	**Ni**	**Mo**	**S**	**Cu**
X52	0.206	1.257	0.293	0.014	0.017	0.006	0.009	0.011

X70	0.125	1.68	0.27	0.051	0.04	0.021	0.005	0.045
X100	0.059	1.97	0.315	0.024	0.23	0.315	0.002	0.022

Tensile properties (average values) are given in Table 3 and typical stress–strain curves in figure 1. One notes that yield stress of the studied steel is higher than the standard requirements and elongation at fracture is strongly reduced when yield stress increase.

Table 3 : Tensile properties of studied steels X52, X70 and X100.

	Young's modulus (MPa)	**Yield stress (MPa)**	**Ultimate strength (MPa)**	**Elongation at fracture %**
API 5L X52	194 000	437	616	23 .14
API 5L X70	215 000	590	712	18.3
API 5L X100	210 000	866	880	6.75

Fracture toughness K_{IC} and δ_c have been determined using compact tension specimen according to French standards NF A 03-180 [2] (K_{Ic}) and NF A 03-182 [3] (δ_c). Specimen dimensions are extracted from 3 different pipe as given in Table 4

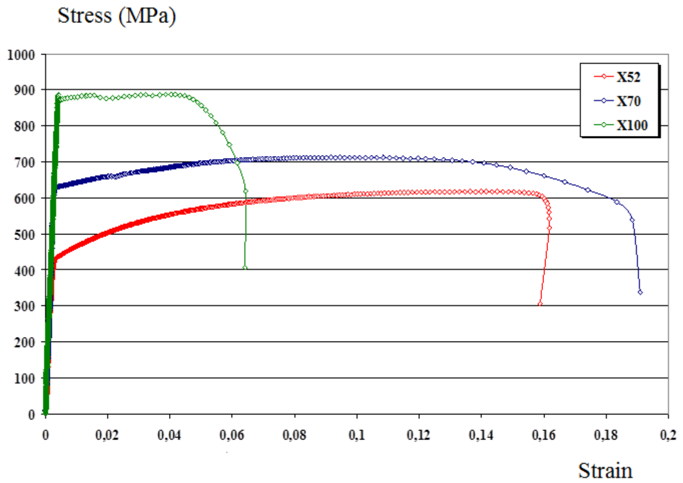

Figure 1 : Stress strain curves of API 5L X52, X70 and X100 pipe steels

Specimen dimensions are extracted from 3 different pipes as given in Table 4

Table 4 Diameter and thickness and material of the 3 studied pipes.

Steel	**Diameter**	**Thickness**
API 5L X52	610 mm	11 mm
API 5L X70	710 mm	12.7 mm
API 5L X100	950 mm	16 mm

One note that pre crack is along the longitudinal direction of the pipe. Critical load has been determined using acoustic emission which determine crack initiation (subscript i). The obtained critical load is well correlate with the traditional offset procedure failure load. Individual and mean values are listed in Table 5.

Table 5 : Fracture Toughness of studied steels X52, X70 and X100.

		$K_{I,i}$ (MPa√m)	$K_{I,imean}$ (MPa√m)	δ_i (mm)	$\delta_{i,mean}$ (mm)
API 5L X52	CT1	97,59	95,54	0,21	0,18
	CT2	93,49		0,14	
API 5L X70	CT1	117,99	118,59	0,102	0,112
	CT2	119,19		0,123	
API 5L X100	CT1	159,98	151,82	0,125	0,108
	CT2	143,66		0,091	

3. FAILURE ASSESSMENT DIAGRAMME AND SINTAP PROCEDURE

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 relationship 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:

$$k_r = \frac{K_{app}}{K_{Ic}} \quad and \quad S_r = \frac{\sigma_{app}}{\sigma_u} \tag{1}$$

where σ_u 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 2). Initially, the relationship between non dimensional stress intensity factor kr and non-dimensional stress S was issued from a plasticity correction able to describe any kind of failure continuously from brittle fracture to plastic collapse.

A typical representation of a failure assessment diagram is given in figure 1.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 Failure Assessment diagram are:

-the use of a 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.

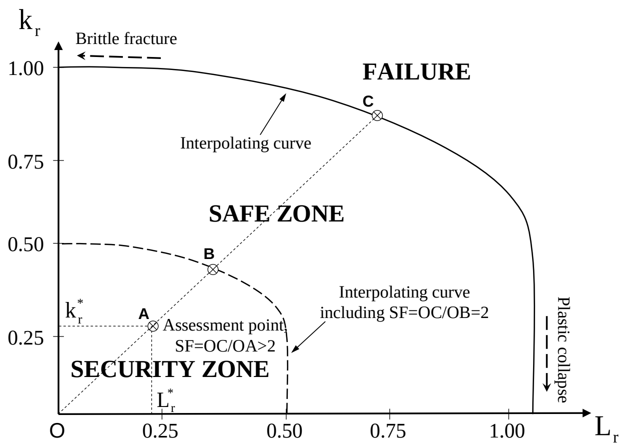

Figure 2. Typical presentation of Failure Assessment Diagram (FAD). Definition of safety factor.

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

$$k_r = \sqrt{\frac{J_{ap}}{J_{Ic}}} \qquad (3)$$

and the S_r parameter is replace by the L_r parameter

$$L_r = \frac{P}{P_L} = \frac{\sigma_{ref}}{\sigma_0} \qquad (4)$$

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

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

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:

$$\sigma_{ref} = \frac{P}{P_0}\sigma_0 \qquad (6)$$

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 this method, failure near plastic collapse is represented by data in the "tail "of the diagram.

There are several similar Failure Assessment Diagram procedures i.e. EPRI in USA; R6 in UK, RCCMR in France with small and more and less conservative difference in the safe zone area. The SINTAP [4] procedure is the result of a European project of a multi-disciplinary approach in order to get an unify multi-level 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 procedure for the lowest and more conservative (basic level) is given as below:

$$f(L_r) = \begin{cases} \left[1+\frac{L_r^2}{2}\right]^{-\frac{1}{2}}\left[0.3+0.7\times e^{\left(-\mu\times L_r^6\right)}\right], & 0 \le L_r \le 1 \\ \left[1+\frac{1}{2}\right]^{-\frac{1}{2}}\left[0.3+0.7\times e^{(-\mu)}\right]\times L_r^{\frac{N-1}{2N}}, & 1 < L_r \le L_r^{max} \end{cases} \quad (7)$$

$$\text{where } \mu = \min\left[0.001\times\frac{E}{\sigma_Y}, 0.6\right],\ L_r^{max} = \frac{1}{2}\left(\frac{\sigma_Y+\sigma_U}{\sigma_U}\right),\ N = 0.3\left(1-\frac{\sigma_Y}{\sigma_U}\right)$$

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.

4. PIPE DEFECT AND ASSOCIATED STRESS INTENSITY FACTOR

We have chosen to study a surface longitudinal semi-elliptical crack in the wall of a pipe. This can of defect represent in a conservative way, the crack-like defect approach, the most current type of defect detected in pipe such as corrosion defects, gouges, scratches etc.
The stress intensity factor for such a crack is given by the general formula:

$$K_I = \frac{pR_{int}}{t}.\sqrt{\pi a}.\frac{M}{\Phi} \quad (8)$$

Where p is the internal pressure, R_{int} is the internal radius of the pipe, t the wall thickness, *a* the crack depth, M the geometrical factor correction and Φ the elliptic integral of second species.

$$\Phi = \int_0^{\pi/2} 1 - \frac{c^2 - a^2}{c^2} \sin^2\theta d\theta \qquad (9)$$

An approximate value of this elliptic integral is given by:

$$\Phi^2 = 1 + 1.464 \left(a/c\right)^{1.65} \qquad (10)$$

5. RESULTS

Three cases have been studied and corresponding to different steels. Operating pressure is considered higher for X100 steel because it is used for new generation of pipe lines working at higher operating pressure and higher diameter.

Table 6 : List of the studied cases

Steel	$2R_{int}$ (mm)	t (mm)	Operating pressure (bars)	Crack depth (mm)	Crack ratio (a/c)
API 5L X52	610	11	70	2.2	0.4
API 5L X70	710	12.7	70	2.54	0.4
API 5L X100	950	16	100	3.2	0.4

k_r parameter as been determined using equation (1) and (8) and L_r using equation (1).For each case, an assessment point with coordinates (L_r*, k_r*) and reported in a Failure assessment diagram (Figure 6). Each steel has its own failure assessment diagram because the μ parameter is different for each steel. However the difference is relatively small particularly for $L_r < 0.8$. We note that the three assessment points are in the safe zone i.e below the failure curve given by equation (1). Then, using the procedure described in figure 4, the safety factor is then determined and reported in table 7

Table 7 Safety factor according to pipe steel.

Steel	API 5L X52	API 5L X70	API 5L X100
Safety factor	3.38	3.87	3.23

One notes that safety factors are more than 2 for all steels. According to this conventional value, pipe is safe and defect doesn't need to be repaired.

6) DISCUSSION

The previous results indicates that the safety factor decreases when we change the pipe design using high strength steel like X100. In this case, we increases pipe diameter and thickness and operating pressure simultaneously with pipe yield stress. In order to have an idea of the consequence of new pipe design with API 5L X120 steel, safety factor was determined using the following data.

Table 8 : API 5L X120 steel pipe design conditions.

Diameter (mm)	**Thickness (mm)**	**Operating pressure (bars)**	**Crack depth (mm)**	**Crack ratio (a/c)**
1420	23	120	4.6	0.4

The diameter has been chosen as the biggest actual pipe diameter and the thickness is compatible for the seam welding of the X120 pipe with the submerged arc welding (SAW) method with one pass each for the inside and outside welds, which had been employed for conventional grades. Operating pressure has the expected value for future.
Due to unavailability of X120 pipe steel, mechanical properties (yield stress and ultimate strength) are obtained from [6] and are reported in Table 9. Fracture toughness is deduced from two required values of critical CTOD δ_c in base metal and in welds at temperature -20°c given in table 1. CTOD is converted into Fracture toughness using the following LFM relationship:

$$K_c = \sqrt{\sigma_y . \delta_c . E} \tag{11}$$

Table 9 : mechanical properties of API 5L X120 steel

Yield stress (MPa)	**Ultimate strength (MPa)**	**CTOD Base metal (mm)**	**CTOD Welds (mm)**
908	981	0.14	0.08

Required Crack Tip Opening Displacement (CTOD) was calculated on an assumption of the existence of a surface-breaking crack 2 mm in depth at a seam weld toe and possible shape irregularity and stress distribution. As a result, it was concluded that a CTOD of 0.08 mm or more was good enough. Since a defect equal to or larger than 2 mm is detected at a non-destructive inspection and an internal defect up to 4 mm in width will be permissible under the same value of critical CTOD.
Ones notes that safety factor decreases when the yield stress of the pipe steel increases together with diameter, thickness and operating pressure. Evolution of failure type when increasing yield stress of pipe steels can be predicted by using a Domain Failure Assessment Diagram (DFAD).

A domain failure assessment diagram is a failure assessment diagram divided in three zones of potential failure type: brittle fracture, elastic plastic failure and plastic collapse. A D 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 elasto-plastic fracture

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

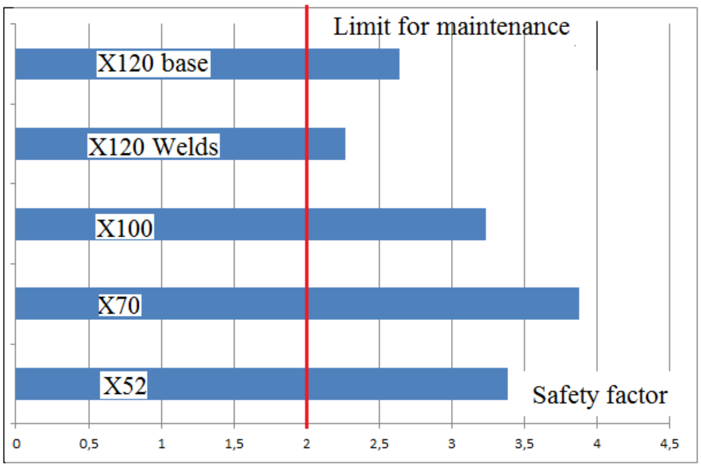

Figure 3: Values of safety factors associated with different pipe steels.

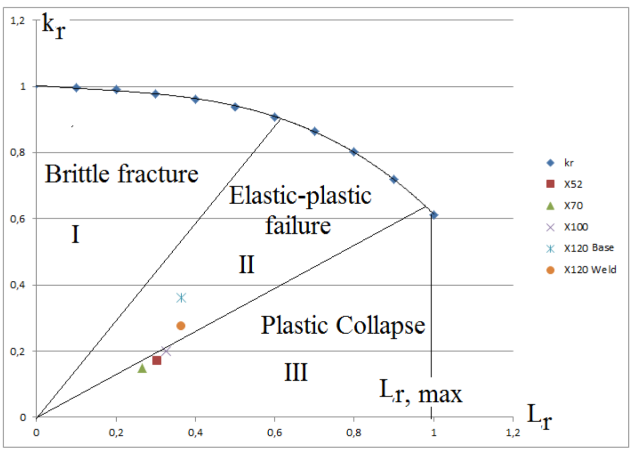

Figure 4 : Domain Failure assessment diagram and assessment points for the 4 studied pipe steels.

Based on Feddersen diagram [8] 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. In figure 4, in a domain failure assessment diagram are reported the assessment point of the 4 studied pipe steels. One notes that X52, X70 and X100 have a fully ductile failure potential. However, the X120 steels as a more pronounced risk of elastic plastic failure.

7 CONCLUSION

The risk of failure for a steel pipe has been evaluated through a conventional defect type. Under operating pressure safety factor is always over the conventional value of 2. It can be concluded that is not necessary from a fracture mechanics point of view to repair this defect.
The use of Domain failure assessment diagram gives in addition the potential of brittle or elastic fracture risk. It has been seen that X120 has an elastic plastic failure potential risk. In this case, it seems necessary to evaluate in addition risk of brittle running crack. This risk is associated with high stored energy due to large pipe diameter and high operating pressure.

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