TRENDS TO DETERMINE FRACTURE INTIATION AND PROPAGATION OF A PIPE UNDER SERVICE PRESSURE

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Abstract

A fracture toughness transferability curve has been established for the X52 pipe steels described by a linear relationship between the notch critical stress intensity factor and the average value of T stress over the opening stress distribution. This curve is used to determine the fracture toughness associated with the structure.

the characteristic length of the fracture process. Crack extension modelled by Finite Element method using CTOA criterion coupled with the the node release technique is used to predict the crack velocity, the arrest pressure and crack length. This method is compared with the different Two Curves Methods Batelle, HLP and HLP-Sumitomo

1. INTRODUCTION

Gas pipeline fracture initiation is usually followed by extended running crack propagation. Such disasters lead to significant financial loss, and should be avoided as much as possible or

confined to a short portion of the pipe. Therefore, Two important questions are whether and when the fracture will initiated and self-arrest.

Fracture initiation occurs when the crack driving force overcomes the fracture resistance of the material. This fracture resistance is expressed in terms of stress intensity factor, J energy parameter or critical opening displacement.

Fracture are not intrinsic to material but depend on geometrical factors such as the specimen geometry, thickness, surface roughness and length, defect geometry such as the relative length, radius, or opening angle, loading mode, and environment. The fracture resistance to be used in a structure R_{struct} are deduced from the reference properties R_{ref} and the transferability function f (p), where p is the transferability parameter.

$$R_{struct} = R_{ref}. f(p) \quad (1)$$

For fractures emanating from a defect where fracture mechanics can be applied, the transferability is treated with the concept of stress constraint. These transferability parameters emanate from the defect tip distribution (notch or crack). If we compare the stress distribution obtained in a reference situation (generally small scale yielding) with another general one, the stress distribution is modified in two ways: there is a shift of the stress distribution and a small rotation. These modifications of the stress distribution are considered as transferability problems. The shift of the stress distribution is introduced into the plastic constraint, which is used as the transferability parameter. In the literature, we can note the following constraint parameters: the plastic constraint factor L [1], the stress triaxiality β [2], the Q parameter [3], T stress [4], and A_2 [5].

Even if brittle crack propagation can be successfully avoided by using high toughness steel, the running ductile fracture remains the most important failure mode in modern gas pipelines [6]. It occurs when driving force energy, caused by internal pipe pressure, overcomes the crack propagation toughness.

In fracture mechanics, the crack resistance growth can be expressed by the experimental crack growth resistance curve (R-Curve), crack tip opening displacement (CTOD) or crack tip

opening angle (CTOA) interconnected parameters based on the crack extension Δa. In terms of a limit state design, the arrest pressure can be predicted by solving the equality between the fracture toughness and component stress which depend on the pipeline dimensions, internal pressure and material strength. This material resistance is balanced with a component stressing which is determined involving specific pipe dimensions, pressure p and material strength. In terms of a limit state design, the arrest pressure can be predicted by solving the equality between the stress state at crack tip:

$$\langle \sigma_{ij}(p) \rangle = \langle \sigma_{ij,c}(p_{ar}) \rangle \qquad (2)$$

where p_{ar} is the pressure at arrest. Condition of arrest can be transformed by the new following condition :

$$\text{CTOA (p)} = \text{CTOA}_c\ (p_{ar}) \qquad (3)$$

where CTOA is the crack tip opening angle induced by the current pressure and CTOA_c the fracture toughness.

In the standard codes for gas transmission pipelines, the toughness requirement for crack arrest is based on models which express the fracture resistance and driving force in terms of the fracture and gas decompression wave velocities. This approach involves the superposition of two curves: the gas decompression wave speed and the ductile fracture propagation speed characteristic, each as a function of the local gas pressure. For this reason, they are called Two Curves Method (TCM).

In this paper, new approaches of predicting fracture initiation of a pipe under service pressure are presented :

the material failure master curve fracture toughness versus constraint is used to predict stress conditions of fracture initiation,

the crack arrest criterion, given by equation (2), is extended to the two-curve method through an FE simulation model in conjunction with the node release technique.

2. CONSTRAINT

Constraint is considered as a modification of the defect tip distribution under the effects of specimen or defect geometries or loading mode. Different constraint parameters are defined and associated with the defect type or stress-strain behaviour.

For a notch with infinite acuity, Williams [7] has given a solution for elastic stress distribution as the following series:

$$\sigma_{ij} = \sum_{n=1}^{\infty} Re\left[A_n r^{\lambda_n - 1} f_{ij}(\lambda_n, \theta)\right] i, j = r, \theta \qquad (4)$$

For a crack, Larson et al. [8] have suggested describing the elastic stress field at the crack tip by three terms and introduce for the first time the T term as the second one of the series:

$$\sigma_{ij} = \frac{K_{ij}}{\sqrt{2\pi r}} f_{ij}(\theta) + T\delta_{1i}\delta_{1j} + O(\sqrt{r}) \qquad (5)$$

Therefore, ideally T stress is a constant stress which acts along the crack direction and shifts the opening stress distribution according to the sign of this stress. For stress distribution emanating from a blunted crack or notch, T stress is not constant along the ligament. This leads to consider a conventional value defined as the effective T stress.

An example of the computed T stress distribution along the ligament for a Roman tile specimen with a notch is given in Fig. 1. It can be seen that T is not really constant as it is in theory. For short cracks, distribution of the T stress is stabilized after some distance. For long cracks, T increases linearly with the ligament except in a region close to the crack tip. To avoid this dependence of the T stress on distance, it is attractive to use a conventional definition of the effective T stress.

3. DETERMINATION OF EFFECTIVE T STRESS

The stress distribution ahead of a crack tip depends on the polar angle θ, as we can see in Eq. (4). However for some particular θ angles, the T stress is given by particular values of the difference between the opening stress σ_{yy} and the stress parallel to the crack σ_{xx} (see Table 1). Particularly for θ = 0, the T stress is given by :

$$T = \left(\sigma_{xx} - \sigma_{yy}\right)_{\theta=0} \tag{6}$$

Table 1: T stress values according to polar direction θ.

θ = 0	θ = ± π	θ = ± π/3	θ = ± π/2	θ = ± 2π/3
$T = \left(\sigma_{xx} - \sigma_{yy}\right)$	$T = \sigma_{xx}$	$T = \sigma_{xx} - \sigma_{yy}/3$	$T = \sigma_{xx} - \sigma_{yy}/3$	$T = \left(\sigma_{xx} - \sigma_{yy}\right)$

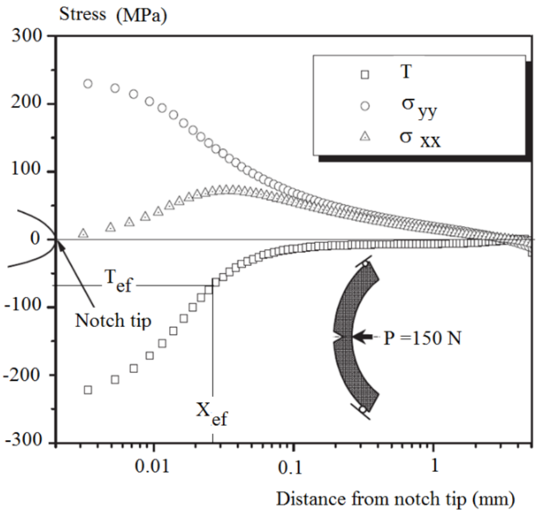

Fig. 1 : T stress evolution with distance for a Roman tile specimen. Values of T_{ef} parameter obtained by extrapolation or volumetric methods.

Maleski et al. [9] suggested representing the *T* stress evolution by a linear relationship with distance x:

$$T(x) = T_{ef} + \gamma^{*}(x/a)) \tag{7}$$

where γ^{*} is a constant and a is the crack depth. T_{ef} is obtained by extrapolation $x \rightarrow 0$. Using the volumetric method, Hadj Meliani et al. [10] suggested defining the effective *T* stress as the corresponding value in the T stress distribution for a distance equal to the effective distance X_{ef}. Figure 1 gives the T stress evolution with distance for a Roman tile specimen and the definition of T_{ef}. One notes that in this case the values of T_{ef} obtained by extrapolation or the volumetric method are relatively close. In the following, the T_{ef} parameter obtained from the critical stress distribution is called $T_{ef,c}$.

4. **MATERIAL FAILURE MASTER CURVE**

In [10], the Material Failure Master Curve (MFMC) of X65 pipe steel has been determined. It represents the evolution of fracture toughness with constraint. Several specimens of four types, namely CT, DCB, SENT, and RT, were extracted from a steel pipe of diameter 610 mm. The geometries of these specimens were as follows: SENT specimen: thickness = 5.8 mm, width = 58.40 mm; CT specimen: thickness = 5.8 mm, width = 63.80 mm, height = 61 mm; DCB specimen: thickness = 5.8 mm, height = 45.70 mm; RT specimen: thickness = 5.8 mm, width = 40 mm, length = 280 mm. The specimens have a notch with a notch angle $\psi = 0$ and a notch radius $\rho = 0.25$ mm and an a/W ratio in the range 0.3–0.6. The stress distribution used was computed by the finite element method at a load level corresponding to the fracture force. T_{ef},c was determined by the volumetric method. It can be noted in Fig. 2 that the fracture toughness decreases linearly with the constraint according to

$$K_{\rho,c} = a\,T_{ef,c} + K^0_{\rho,c} \tag{8}$$

where $K^0_{\rho,c}$ is the fracture toughness corresponding to $T_{ef,c} = 0$, which is considered as a reference. $a = -0.069$ and $K^0_{\rho,c} = 77.2\ MPa\sqrt{m}$ for the API X52 pipe steel.

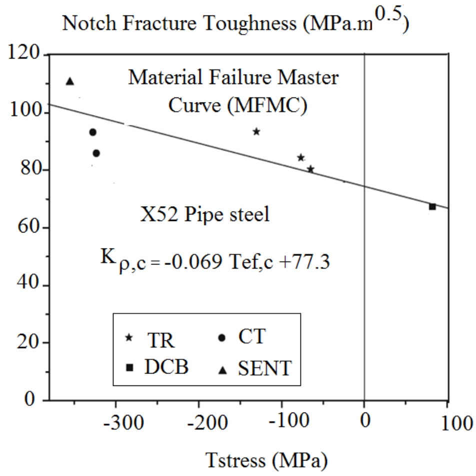

Fig. 2: Material Failure Master Curve $K_{\rho,c}$–$T_{ef,c}$ of X65 pipe steel [10].

5. FRACTURE TOUGHNESS RELATED TO A STRUCTURE

The fracture toughness $K_{c,\ sruct}$ related to a pipe made of API 5L X65 with 355-mm diameter and 19-mm thickness has been determined using the MFMC. This pipe exhibits a surface notch with a notch angle φ = 0°, a notch radius ρ = 0.25 mm and a notch depth (a) to thickness (B) ratio equal to a/B = 0.5. The loading curve K_{ap} = f (T) has been computed by the finite element method assuming material elastic behaviour. This loading curve K_{ap} = f (T) intercepts the material master curve at point (T^*_{ef}, $K_{c,\ sruct}$) (Figure 3). The obtained value of T^*_{ef} is -495 MPa. This methods allows to choose a test specimen with a constraint close to the structure in order to minimize the conservatism.

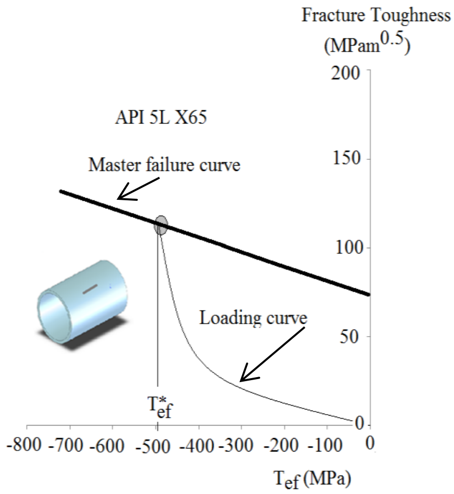

Figure 3. Material failure curve for API 5L X65 steel and loading curve K_{ap} = f (T) for a pipe exhibiting a surface notch.

6. CRACK-TIP OPENING ANGLE (CTOA) OF API 5L X65

CTOA is conventionally defined as the angle comprise between two lines emanating from crack tip and intercepting the crack profile at a conventionally distance Δa* with 0.5< Δa* < 1.5

mm. The crack length Δa* depends on the condition of the crack surface. Several experimental methods have been proposed for measuring CTOA, for example, optical microscopy [11], image correlation [12], microtopography [13], the δ_5 technique [12] and interpolation from the force-displacement curve [14].

Experimental determination of CTOA on API 5L X65 has been performed on A modified Compact tension (CT) specimen. A commercial Digital Image correlation (DIC) camera and an software analysis package with integrated length and angle measurement tools is used to measure CTOA and crack extension Δa. The recording time is automatically available from the videotapes where a digital stopwatch was used to synchronize the still images. All of this allowed the correlation between test parameters such as load, displacement, crack length Δa and CTOA. The recorded video was transformed into an image sequence file then 25 of this images are selected to measure the evolution of CTOA as a function of crack extension Δa. According to ASTM (E 2472) [15] requirements the CTOA measurements were made at a distance behind the crack tip ranging between 0.5 and 1.5 mm.

A second method involve to reproduce experimental test by combining experimental load-deflection data and finite element analysis then measure the evolution of a CTOA numerically (Combining Numerical Method CN).

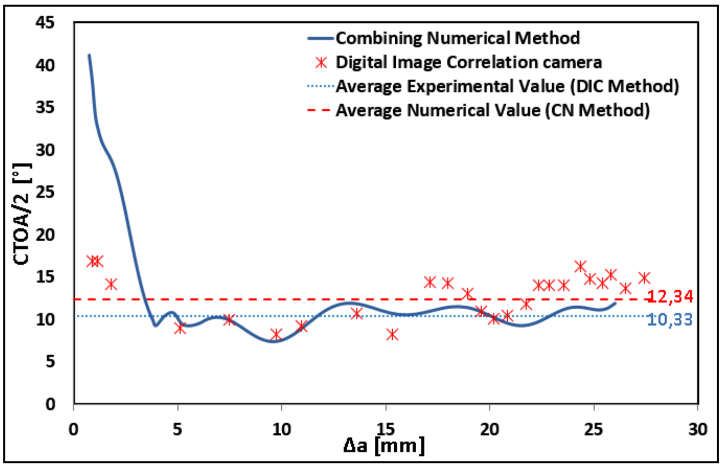

Fig.4 the CTOA vs. crack extension for API5L X 65 pipe steel measured on a modified CT specimen with 6mm thickness.

In Fig.4, the CTOA vs. crack extension data obtained from modified CT specimens using the DIC method and CN method. As we observe, the DIC measured data do not exhibit the initial rapid decrease in CTOA which correspond to instable crack growth, however they are quite comparable to the CTOA measurements obtained using the CN method in the constant CTOA range where stable crack growth occurs.

7. MODELLING CRACK EXTENSION IN A PIPE UNDER INTERNAL PRESSURE

Crack extension is modelled by the finite element method using the CTOA criterion coupled with the node release technique. The node release technique algorithm has been presented in an earlier study [16]. It is based on the assumption that cracks grow step by step, and each step has the length of one mesh element. Boundary conditions were imposed on the pipe in order to make the simulation as real as possible. They consisted of imposing symmetry along the crack plane and constraining the closed part of the crack with fixed nodes in the circumferential direction. These fixed nodes were then removed by the nodal release user subroutine to provoke crack extension. Acting tractions on uncoupling nodes at the crack faces are reduced as the crack opens. This event occurs when CTOA reaches its critical value, and then the representative node of the crack tip is released and the new position of the crack is deduced. This algorithm requires several time increments and a fine mesh (element size under 1.5 mm) around the crack tip for accurate evaluation of the CTOA. In this approach, the evolution of the crack strictly depends on the mesh element size around the crack tip, since it governs the amount of the crack advance. Moreover, the advancing process is not really continuous since a proper iteration scheme is necessary to evaluate the dynamic crack growth accurately during the integration time.

Crack arrest in gas pipelines was performed with the release user subroutine, in conjunction with the FEM Abaqus code. The computing phase begins by generating a 3D finite element implicit dynamic analysis. Because of the symmetry of the crack planes, only a quarter of the pipeline was analysed. A combined 3D-shell mesh was used to reduce the computing time. A total of 50976 eight node, hexahedral elements were generated along the crack path and combined with 6000 shell elements, as shown in Fig.5.

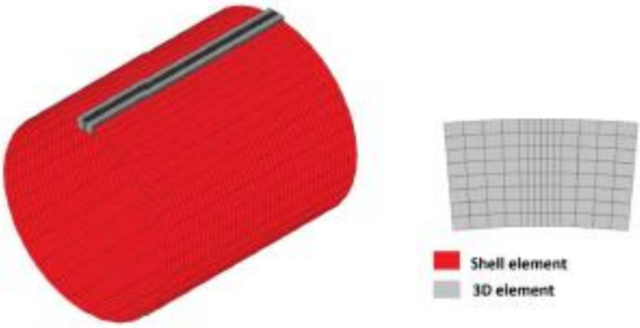

Fig.5 :Combined Shell-3D mesh for numerical simulation of running crack extension

Instantaneous internal pipe pressure was imposed along a certain distance behind the crack-tip node. This distance was given by the cohesive zone model of Dugdale-Barenblatt [17]. The distance is $2b = 3\sqrt{R.t}$ where R and t are outer radius and wall thickness, respectively (Fig.6).

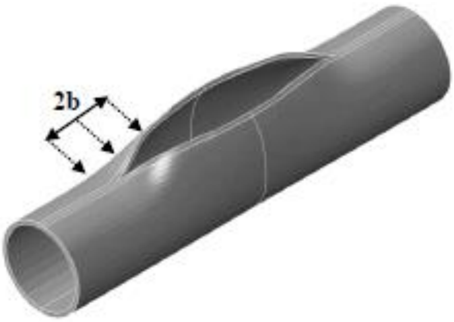

Fig.6 .Zone length where gas pressure is imposed on coupled nodes.

Intensity of this pressure is given by the decompression wave. A simplified gas depressurization model is adopted in this work and assumes that the gas decompression depends only on time and distance from the crack tip. These assumptions are justified by the fact that crack propagation cannot outrun the decompression wave. This means that the crack tip is always present in pipe section affected by the decompression process. Secondly, the expansion of ideal gas is isentropic, the pipe is considered as a large pressure vessel with constant volume. The drop pressure ahead the running crack tip is given by equation as:

$$p(t) = p_0.\exp(kt) \tag{9}$$

where k is a constant k=-7.5 [18] that can be related to the gas parameters and initial conditions of pressure and temperature.The simulation is performed on a pipe of 393 mm outer diameter, 19 mm wall thickness an6 m length. The pipe was made of API 5L X65 steel with a critical CTOA of 20° or API 5L X100 steel with a critical CTOA of 14°.

8. PREDICTION OF PRESSURE AND CRACK EXTENSION AT ARREST.

Crack extension modelled by Finite Element method using CTOA criterion coupled with the the node release technique allows to predict the crack velocity, the arrest pressure and crack length. It has been applied for a pipe with wall thickness equal to t = 19 mm and external diameter OD = 355 mm made in API L X65. The arrest pressure is obtained by using the CTOA Abaqus user subroutine within a static analysis.

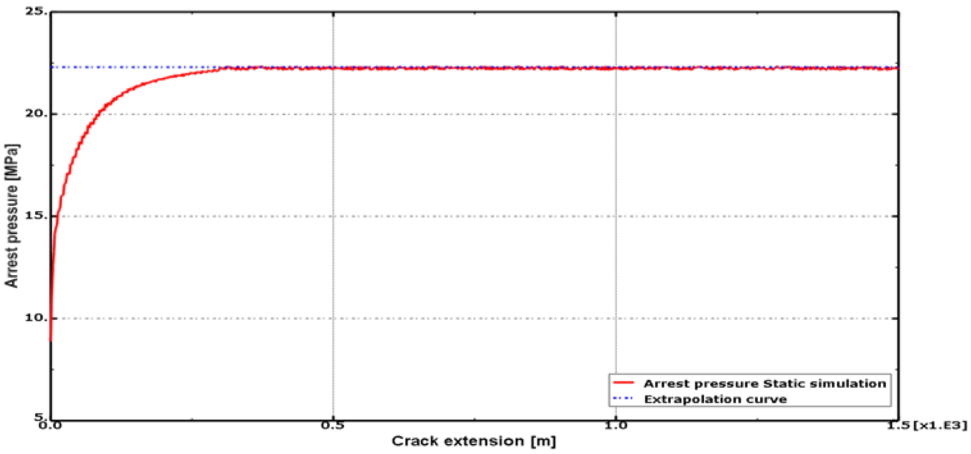

Fig.7 : determination of arrest pressure by static analysis using CTOA Abaqus User Subroutine.

Here the arrest pressure is defined relatively to crack propagation and not arrest. Therefore it is considered as the minimum pressure level to ensure the steady crack propagation. Above this pressure par, the crack propagates in instable manner and along a long distance. Under this value, the crack propagation will auto-arrest or propagates along a short distance. A numerical simulation at initial pressure equal to p_0= 22 MPa, lower than the arrest pressure has been performed and presented in fig 7. In this figure, one notes the absence of steady crack propagation and a quick crack arrest after 9ms. The crack extension is less than 0.5 m.

Crack extension at arrest is obtained from the graph crack velocity half of the crack extension to take into account the symmetry of the problem. For the above mentioned conditions of geometry, material and initial pressure, the numerical simulation gives a crack extension of 42 meters which is of the same order of magnitude than those obtained experimentally

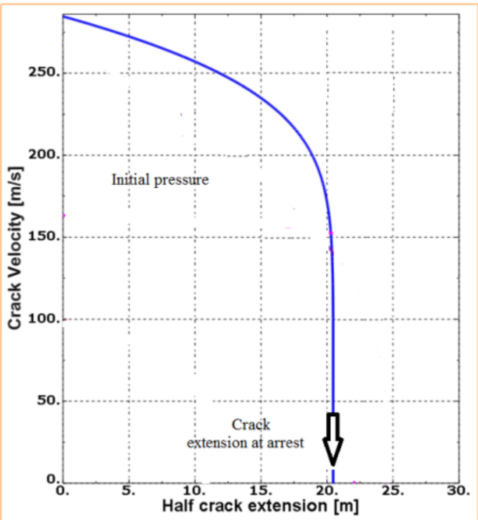

Fig. 8: graph crack velocity half of the crack extension, determination of crack extension at arrest X65 pipe steel, initial pressure p_0=45 MPa .

9. DISCUSSION

In the following section, the Batelle TCM [19] HLP [20], HLP-Sumitomo [21] and CTOA Two Curves methods are compared using the following data D_{DWTT} = 280 J for HLP and HLP-Sumitomo and CTOA = 20°. The resulting crack velocity curves are reported in Table é and Fig.8. Therefore predictions of arrest pressure and crack extension are obtain and reported in Table 10

Table 2 : Analytic and numerical equations of crack velocity curves from BTCM, HLP , HLP-Sumitomo and CTOA models.

Model	Analytic equation	Numerical Equation for X65
BTCM [19]	$V_c = 0.379 . \frac{\sigma_0}{\sqrt{R_f}} . \left(\frac{p_d}{p_a} - 1\right)^{1/6}$	$V_c = 90.2 * (\frac{p_0}{16.6 * 10^6} - 1)^{1/6}$
HLP [20]	$V_c = 0.670 . \frac{\sigma_0}{\sqrt{R_f}} . \left(\frac{p_d}{p_a} - 1\right)^{0.393}$	$V_c = 211 * (\frac{p_0}{15.84 * 10^6} - 1)^{0.39}$
HLP-Sumitomo [21]	$V_c = \alpha . \frac{\sigma_0}{\sqrt{R_f}} . \left(\frac{p_d}{p_a} - 1\right)^{\beta}$	$V_c = 161 * (\frac{p_0}{15.86 * 10^6} - 1)^{0.023}$
CTOA		$V_c = 290 * (\frac{p_0}{24 * 10^6} - 1)^{0.14}$

Table 3 : predictions of arrest pressure and crack extension from BTCM, HLP , HLP-Sumitomo and CTOA models for API5L X65 pipe steel.

Model	Arrest Pressure (MP0)	Crack extension at arrest (m)
BTCM [19]	16.6	23.8
HLP [20]	15.84	40.7
HLP-Sumitomo [21]	15.86	39
CTOA	23	32.1

These results prove that:

- Results obtained in this study are in agreement with the results of HLP-Sumitomo model.
- The BTCM model underestimates arrest pressure and crack extension at arrest. This inconvenient is not taken into consideration in the present CTOA approach which represents probably a future way to predict crack-arrest in pipe lines.

- HLP's equation overestimated the crack propagation velocity and its extension, this could be explained by the fact that HLP Model has not been validated for smaller pipe diameter . HLP parametric correction is therefore insufficient.
- One has to notes that HLP-Sumitomo model use not a material intrinsic curve of crack velocity but a curve which depends strongly of pipe geometry (outer diameter and thickness). HLP was extended with more parameters in the Sumitomo version. This correction is doubtful since it is only based on pipe geometrical reference point (outer diameter and thickness) instead of the material mechanical intrinsic properties, which implies a deviation in smaller pipelines
- The presented CTOA approach results show a significant gap, over 35%, in the prediction of the arrest pressure compared with those obtained by HLP methods This drawback is not taken into consideration in the present CTOA approach which probably represents the best way to predict crack-arrest in pipelines.

10. CONCLUSION

The new trends in pipe design against brittle fracture is to consider both initiation and propagation. For initiation, real fracture toughness has to be checked by the way of two parameters fracture mechanics. True fracture toughness during crack propagation is given by COA value during stable crack extension corrected to take into account constraint effect associated with thickness.

REFERENCES

[1] Mouwakeh M, Pluvinage G. and Masri S. “Failure of water pipes containing surface cracks using limit analysis notions”. *Res. J. of Aleppo Univ. Engineering Science Series,* Vol 63, (2011).
[2] Henry B. S, and Luxmore A. R. “The stress triaxiality constraint and the Q-value as a ductile fracture parameter” *Engineering Fracture Mechanics,* Vol **57** : 375–390, (1997).
[3] Ruggieri C,Gao X and Dodds R. H “Transferability of elastic–plastic fracture toughness using the Weibull stress approach: Significance of parameter calibration”, *Engineering Fracture Mechanics* Vol **67** : 101–117, (2000).
[4] Hadj Meliani M , Matvienko, Y. G , Pluvinage G. “Two-parameter fracture criterion (K□□□□-$T_{ef,c}$) based on notch fracture mechanics”, *Inter. Journal of Fracture* Vol 167: 173–182, (2011).
[5] Nikishkov G.P.”An algorithm and computer program for the three-term asymptotic expansion of elastic–plastic crack tip stress and displacement field ”*Engng Frac Mech*; Vol 50 : 65–83, (1995).
[6] Maxey, W. A., 5th Symp. on Line Pipe Research, PRCI Catalog No. L30174, Paper J, (1974).
[7] Williams M.L ” On the stress distribution at the base of stationary Crack”, *ASME J Appl Mech*, Vol 24:109–114, (1957).
[8] Larsson S.G and Carlsson, A. J “Influence of non-singular stress terms and specimen geometry on small-scale yielding at crack tips in elastic–plastic materials”, *J Mech Phys Solids* **1** Vol (21), : 263–77, (1973).
[9] Maleski M.J, Kirugulige M.S and Tippur H.V. “A Method for Measuring Mode I Crack Tip Constraint Under Static and Dynamic Loading Conditions*”. Society for Experimental Mechanics.* Vol. 44, No. 5, October, (2004).
[10] Hadj Meliani M , Matvienko, Y. G , Pluvinage G. “Two-parameter fracture criterion (K□□□□-$T_{ef,c}$) based on notch fracture mechanics”, *Inter. Journal of Fracture* Vol 167: 173–182, (2011).
[11] D. Dawicke et M. Sutton, « CTOA and crack-tunneling measurements in thin sheet 2024-T3 aluminum alloy », Experimental Mechanics, vol. 34, no. 4, p. 357-368, déc. 1994.
[12] J. Heerens et M. Schödel, « On the determination of crack tip opening angle, CTOA, using light microscopy and δ5 measurement technique », Engineering fracture mechanics, vol. 70, no. 3-4, p. 417-426, 2003.
[13] W. Lloyd et F.McClintock, « Microtopography for ductile fracture process characterization Part 2: application for CTOA analysis », Engineering Fracture Mechanics, vol. 70, no. 3-4, p. 403-415, févr. 2003.
[14] S. Xu, R. Bouchard, et W. R. Tyson, « Simplified single-specimen method for evaluating CTOA », Engineering fracture mechanics, vol. 74, no. 15, p. 2459-2464, 2007.
[15] ASTM E2471-12e1, Standard Test Method for Determination of Resistance to Stable Crack Extension under Low-Constraint Conditions.
[16] M.Ben amara , J.Capelle ,Z.Azari and G.Pluvinage” The application of CTOA criterion to simulate crack propagation and arrest in a modified CT test specimen”, Congress NT2F14” Belgrade Serbia, (2014).
[17] Espen Jakobsen, “Deformation of pressurized pipelines”, Master Thesis, Norwegian University of Science and Technology, (2013).
[18] H.O. Nordhagen, S. Kragset, T. Berstad, A.Morin, C. Dørumb, S.T. Munkejord, “A new coupled fluid-structure modeling methodology for running ductile fracture”, Computers and Structures ,94-95 : 13-21, (2012).
[19] Maxey, W. A., 5th Symp. on Line Pipe Research, PRCI Catalog No. L30174, Paper J, (1974).
[20] E. Sugie, M. Matsuoka, H. Akiyama, T. Mimura, Y. Kawaguchi, “A study of shear crack-propagation in gas-pressurized pipelines”,J. Press. Vess. – T. ASME 104 (4): 338–343, (1982).
[21] R. Higuchi, H. Makino, I. Takeuchi, “New concept and test method on running ductile fracture arrest for high pressure gas pipeline”, in: 24th World Gas Conference, WGC 2009, Vol. 4, International Gas Union, Buenos Aires, Argentina,: 2730–2737,(2009).