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Failure assessment of cracked pipe due transient

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Abstract

The water distribution networks during their operation undergo to different type of damage that leads to degradation of the material, and possibly to the initiation of cracks which can propagate under some conditions such as transient phenomenon which causes the appearance of very high pressure leads to disastrous consequences for the integrity of the installation, and also considerable impact on ecological. In order To reduce the risk of rupture and established a reliable method decision that we can use to predict the acceptable defect when the transient flow occur, a failure assessment diagram (FAD) have been used to calculate the safety factor with finite element method applied to the fracture mechanics to calculate the stress intensity factor. The transient flow model has been established based on the mass, momentum conservation laws, the system of hyperbolic partial differential equations has been solved by the method of characteristics.

Key words: Cracks, Failure assessment diagram, water hammer, Method of Characteristics

1. Introduction

The increasing demand of water to meet the needs of different water uses requires an increase in the water distribution networks which requires implantation of adequate maintenance strategy to avoid the additional costs of maintenance, and increase the pressure of the service which begs the question about the safe operating of the system. And despite the security measures and standardized design method, there are other inevitable factors that can affect the structure integrity and leads to the failure of water pipelines. This failure may manifest by two cases, either by rupture or leak, and in both cases the consequences are very disastrous. Specially, on health population due to water contamination.

The water pipeline failure [1] reason can be assumed to be corrosion pitting ,scratches, gouges, and also service loading conditions depend on soil movement e.g. ground slip, earthquakes or repeated loading due to road traffic.

The presence of cracks in water pipelines is related to many causes e.g. micro-void, inclusion, manufacturing defects. Theses defects grows under mechanical an environment condition and failure occurs when defect has reached the critical size under service condition or under unusual loading condition such as water hammer.

Water hammer is produced by a rapid change of flow velocity in the pipe line that may caused by sudden valve opening or closure, failure of a pump, mechanical failure of device, rapid change in demand condition, etc. It could result in violent change of the pressure head, which is then propagated in the water pipeline in the form of a fast pressure wave leading to severe damage [2].

In this present work is described to the water hammer assessment in order to provide a reliable structure integrity and safety method. The case of cast iron pipe for water distribution is considered.

2. Theory/calculation methodology

The defect can be detected by non destructive test [3] and the question is the defect is acceptable or not. In order to answer to this question there are various methods of assessment of defect nocivity. e.g. (R6 Method, BSI PD6493, SINTAP) in this study a failure assessment diagram is used according to the SINTAP procedure with level 1 to be able to make decision about the failure risk of the water pipeline, when the water hammer occur.

The high instantaneous pressure due to water hammer is calculated from the mathematical model of fluid transient, and then the value of maximum pressure is incorporated into finite element code to calculate the stress intensity factor at the vicinity of crack tip. Once the value of stress intensity factor is calculated it used to plot the defect assessment point coordinates.

The value of maximum stress can be calculated via thin-walled hollow cylinder assumption σ=PD/2t where *P* = pressure, *D* = diameter, *t* =thickness.

3. Failure assessment diagram

3.1 SINTAP procedure

This procedure [4, 5] is a unitary European community approved programme to assess structure integrity have defect, against the level of failure risk. This procedure is based on the failure mechanics principles. The relationship between applied stress sig defect size a and toughness is replaced by tow parameters corresponding to brittle fracture K (K_r=1, L_r=0) and plastic collapse L (K_r=0, L_r=L_{max})

These parameters can be defined as follows

$$K_r = \frac{K_I}{K_{IC}} \quad (1)$$

$$L_r = \frac{\sigma_n}{R_C} \quad (2)$$

Where

$$R_C = \frac{1}{2}\left(\sigma_y - \sigma_u\right)$$

These two variables represent the ratio between the applied value of either stress or stress intensity factor and the resistance parameter of the corresponding magnitude (yield stress or fracture toughness).

3.2 Level 1 of investigation

The failure assessment diagram is limited by the failure assessment curve defined by a relation K_r=f(L_r), the level of analysis allow us to choose the parameters necessary to establish the risk analysis. The level 1 of analysis is the minimum recommended level. This level requires the yield strength, the ultimate stress, and the value of fracture toughness of the material.

The FAD curve is defined as follows:

For $0 \leq Lr \leq 1$

$$f\,(L_r) = \left[1 + \frac{L_r^2}{2}\right]^{-\frac{1}{2}} . \left[0.3 + 0.7e^{-\mu L_r^6}\right] \qquad \textbf{(3)}$$

Where

$$L_r^{max} = 1 + \left(\frac{150}{\sigma_y}\right)^{2.5}$$

2.3 Assessment diagram drawing

The assessment diagram is plotted in coordinates K_r and L_r [6]. Two particular points of this diagram represent successively brittle fracture conditions (K_r=1, L_r=0) and plastic collapse (K_r= 0, L_r=1). The curve which defined the assessment diagram encloses between the coordinates a safe domain.

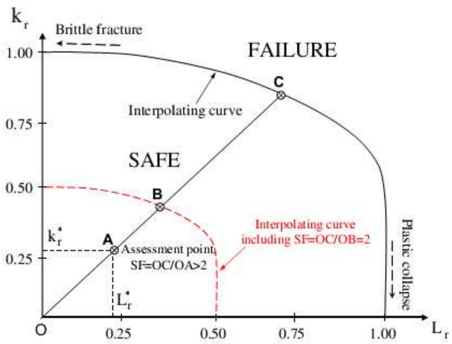


Figure 1. Typical Failure Assessment Diagram (FAD)

The loading conditions of a structure are represented by a point A of coordinates (K_r^*, L_r^*). If this point is inside of his domain, this ensures the structure's integrity. If this point C is on the curve the failure occurs Fig 1.

3. Water hammer equation

The mathematical formulation of the transient is developed based on the equation of conservation of mass, the conservation equation of momentum, the equation of thermodynamic behavior [7], for calculation of the liquid unsteady pipe flow. The classical theory of water hammer takes into account the effect of skin (fluid-wall) friction, approximated by Trikha model. The pipe is straight, thin-walled, linearly elastic and of circular cross-section. The two equations, governing velocity V and pressure P are

$$\frac{\partial V}{\partial x} + \frac{1}{\rho a^2}\frac{\partial P}{\partial t} = 0 \qquad \textbf{(4)}$$

$$\frac{\partial V}{\partial t} + \frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{4T_f}{\rho D} + g.\sin\theta = 0 \qquad \textbf{(5)}$$

where *x*=axial distance, *ρ*=mass density of liquid, *a*=liquid (elastic) wave speed, *t*= time, T_f = friction term, *D*=internal pipe diameter, *g*=gravitational acceleration and *θ*= pipe slope.

Equation 4 and 5 makes a system of partial differential equations of hyperbolic type which connects the pressure *P*, the fluid velocity *V*.

3.1 Determination of the shear stress

To model the friction term, we used the model Trikha [8], Relate wall shear stress in transient laminar pipe flow to instantaneous mean velocity and weighted past velocity changes.

$$T_f\,(x,t) = \frac{8\rho \upsilon_c}{D}\left\{V\,(x,t) + \frac{1}{2}\int_0^t \frac{\partial V}{\partial t} W\,(t-s)ds\right\} \qquad \textbf{(6)}$$

In which υ_c fluid kinematic viscosity, W=*a* weighting function and *s*= variable of integration.

3.2 Method of resolution

The method used to solve mathematical systems that govern the phenomenon is the method of characteristic. It is used to transform the equations of partial derivative equations to total derivatives which

are integrated along the characteristic direction of lines. The MOC transformation of Eqs (4) and (5) yields the water hammer compatibility equations which are valid along the characteristic lines. Physic meaning of the characteristics lines is propagation path of pressure wave. The compatibility equations, written in a finite-difference form within the staggered grid Fig 2 .

Along the C$^+$ characteristic line ($\Delta x/\Delta t = +a$):

$$H_i^{j+1} - H_{i-1}^j + B\left(Q_i^{j+1} - Q_{i-1}^j\right) + RQ_{i-1}^j\left|Q_{i-1}^j\right|\Delta x = 0 \quad (7)$$

Along the C$^-$characteristic line ($\Delta x/\Delta t = -a$):

$$H_i^{j+1} - H_{i-1}^j + B\left(Q_{i+1}^j - Q_i^{j+1}\right) - RQ_{i+1}^j\left|Q_{i+1}^j\right|\Delta x = 0 \quad (7)$$

with $B = \dfrac{a}{(gA)}$ **And** $R = \dfrac{f}{\left(2gDA^2\right)}$

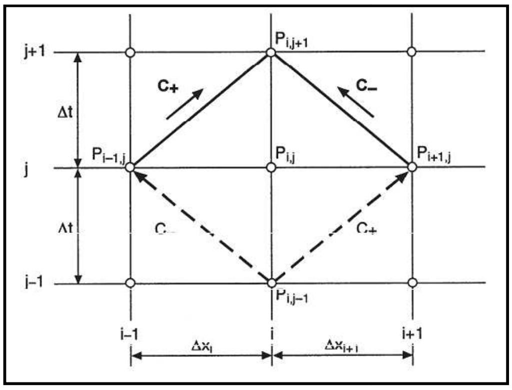


Figure 2. staggered grid for internal points

4. Case study

In this study a tank pipe valve system is considered Fig 3. The pipe have an axial edge defect of length a subjected to an internal source pressure P=1.688 MPa. The cast iron pipe is used with diameter D=450 mm and thickness t=8.6 *mm* with Poisson's ratio *ν*=0.28. The mechanical properties are defined in table 1.

Table 1. Mechanical properties of cast iron material

σ_y (MPa)	σ_u (MPa)	ρ (Kg/m^3)	K_{Ic} (Mpa.m$^{1/2}$)
300	420	7050	14.90

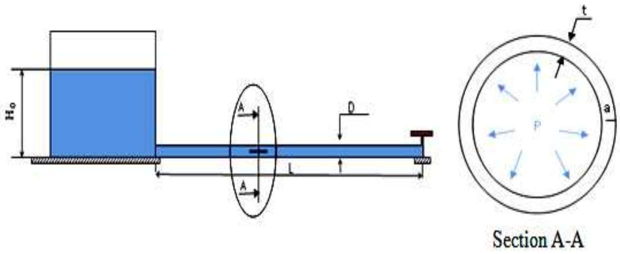


Figure 3. pipe with external surface crack.

5. Finite element modelling

A finite element code called Ansys APDL has been used to modeling the pipe geometry Fig 4, the problem is considered as plan strain state. And according to the symmetry we have been done only on half of the pipe. An 8 node quadrilateral elements has been adapted to meshing the pipe, and we have been refine the mesh near the crack tip which represents the critical zone of the pipe.

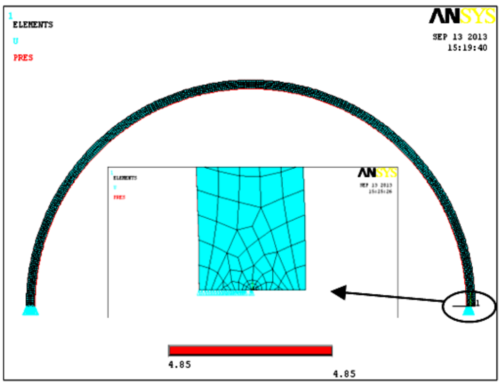


Figure 4. Pipe modeling and Meshing around the crack tip

6. Results and discussion

A different *a/t* ratios has been computed to find stress intensity factor. The K_I has been calculated for service pressure *p*=1.688 Mpa and for maximum pressure resulting from water hammer, and for a thickness of *t*=8.6 *mm*

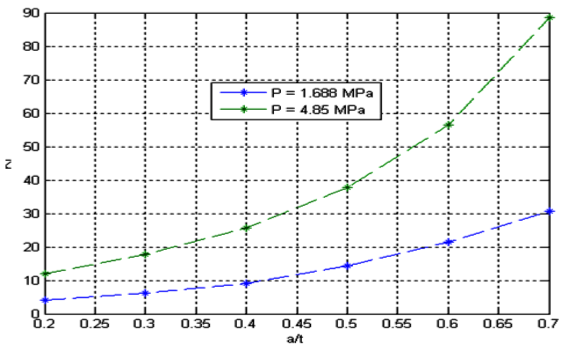


Figure 5. Variation of stress intensity factor with a/t for P=1.688 MPa and P=4.85 MPa

According to Fig 5 we note that the stress intensity factor increases with increase in service pressure. And more the ratio a/t of the defect size increase more the pressure signification is important. The arise of stress intensity factor value is due to pipe well section reduction by the crack, which lead to stress concentration effect at the vicinity of the crack tip.

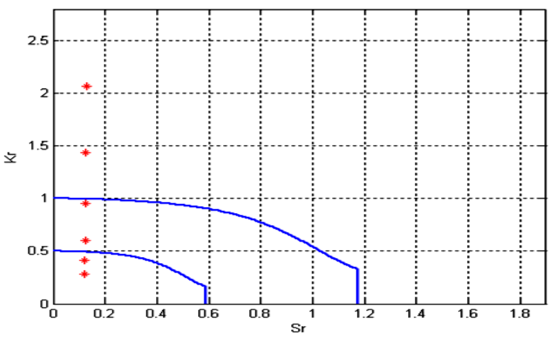


Figure 6. FAD Diagram for pressure =1.688 Mpa

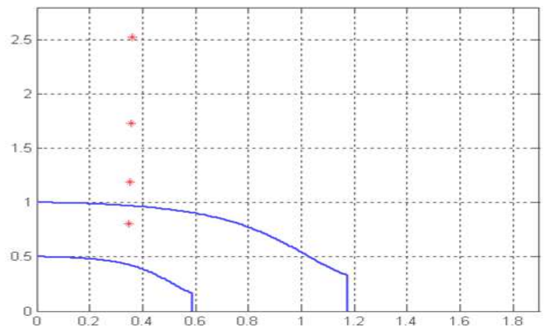


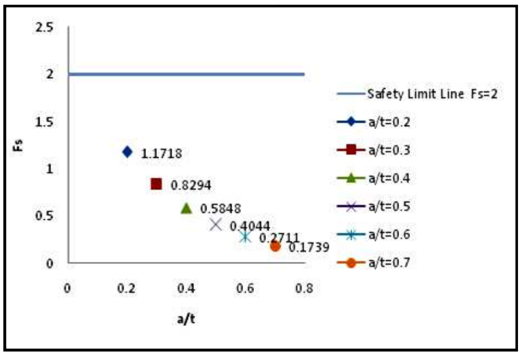
Figure 7. FAD Diagram for pressure =4.85 Mpa

The Fig 6 and Fig 7 show the calculus of the pair (K_r, L_r) for ratios a/t (0.2,0.3,0.4, 0.5,0.6,0.7) using SINTAP code for cracked pipe. The assessment points are given on the diagram for different ratios crack size. The interpolating curve defined for safety factor Fs=2, established the limit zone between safety zone and the security zone.

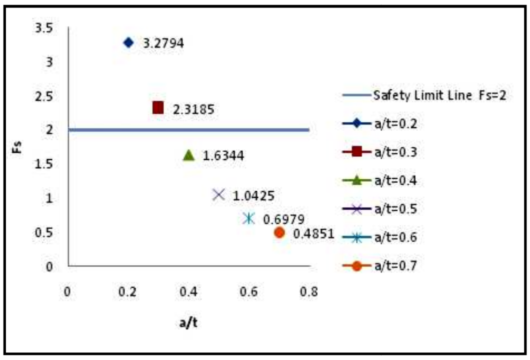
Table 2. Safety factor for two different pressures

a/t	*P = 1.688 Mpa*	*P = 4.85 Mpa*
0.2	3.2794	1.1718
0.3	2.3185	0.8294
0.4	1.6344	0.5848
0.5	1.0425	0.4044
0.6	0.6979	0.2711
0.7	0.4851	0.1739

The failure prediction of the pipe due to water hammer may be considered from the safety factor calculation. Conventionally, it is considered the failure is possible to occur if the safety factor is less 2.



(a)



(b)

Figure 8. safety factor evolution for (a) P= 1.688 Mpa and (b) p=4.85 Mpa

Whenever the ratio *a/t* increase, the safety factor increase also, this means that the risk of failure of water pipeline increase. According to Fig 8 (a) the structure is reliable if the value of safety factor is greater than 2. Also has been found more the pressure increases more safety factor decreases significantly.

According to Fig 8 and Fig 8 (b) it has been shown that the pressure is most influential factor on the safety factor than the ratio a/t of crack size.

It has been found that the safety factor is reduced from the value of safety factor Fs= 3.2794 of pressure *p* = 1.688 MPa to *Fs* = 1.1718 of pressure *P* = 4.85MPa issue of water hammer for the ratio *a/t* = 0.2, which proves that the phenomenon of water hammer is dangerous for the integrity of the structure, which can lead to failure.

7. Conclusion

A numerical model based on mass, momentum conservation laws is developed to simulate the transient flow and predict the maximum pressure value in the pipe. By using the failure diagram assessment according to SINTAP code we can able to decide rapidly about the acceptability of the crack defect size. We can use this diagram as tools combined with safety factor parameter to minimize the water network exploitation costs.

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