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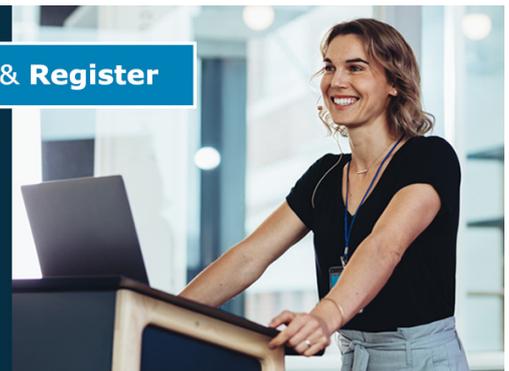
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# Fracture toughness assessment of axial partially through cracks in X65 and X70 steel pipes

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**Abstract** This paper presents analysis of fracture assessment methods of axial partially-through crack in X65 and X70 steel pipes with internal pressure. Two analytical methods Folin–Ciocalteu method (FC method) and Gauss–Seidel method (GS method) are used to make assessment for two steel pipes (steel X65 and X70). Finite Element model of X65 and X70 steel full-scale pipes with axial part-through crack was established. In this work, a comparison is made between results obtained from FC and GS methods and finite element model with previous experimental results. The GS is more conservative assessment method as it provides smaller crack depth ( $a$ ) corresponding to ( $J_{cr}$ ). Finite Element model in case of steel X70 is more conservative than the analytical methods and its results close to the experimental values.

## 1. Introduction

The defects in the wall thickness of thin-wall pipelines are very serious. During service, these defects are sources for crack initiation and propagation until the pipe failure [1-4]. In some cases, catastrophic failure with human casualties occurs especially if these fluids/gases are flammable.

Investigation of the crack propagation in pipes is very important to avoid catastrophic failure of pipes. The pipes material undergo in elastic-plastic fracture mechanics methods [5]. J-integral [6] and crack tip opening displacement (CTOD) [7] are two fracture assessment methods used to describe the behavior of elastic-plastic fracture material [8].

Fracture assessment methods of defected pipes are exposed to internal pressure got a great consideration in lots of previous works [9-16]. In most cases, the pipe got axial crack (parallel to pipe axis), circumferential crack (on the pipe circumference) or inclined to the pipe axis.

Two analytical methods (i.e. FC method [17] and GS method [18]), for crack propagation, were used to get critical crack depth ( $a_{cr}$ ) from each method, beyond this value unstable crack growth occurs. The objective of this work is to establish a finite element model for full scale pipe with axial partially-through crack and compare the results of finite element model and analytical methods with experimental results. This study is considered very useful for maintenance planes of gas pipelines.



## 2. Material

This work focused on two types of steel pipes steel X65 and X70. Mechanical properties in a circumference direction were determined previously by L.Gajdoš [9]. The fracture toughness of the material ( $J_{cr}$ ) was determined using J-R curve from compact tension specimen (CT) [9]. Table 1 summarizes the mechanical properties and fracture toughness of these pipes.

**Table 1.** Mechanical properties and fracture toughness of steel X65 and X70 [9].

Steel grade	Yield strength in (MPa)	Ultimate strength in (MPa)	Ramberg–Osgood parameters		$J_{cr}$ N/mm
			$\alpha$	m	
Steel X65	496	582	5.34	8.45	432
Steel X70	536	643	5.92	9.62	439

Analytical fracture assessment methods (FC and GS methods) and Finite Element method were applied to these two materials. Table 2 summarizes both the fracture pressure and crack depth at fracture obtained from previous work [9, 15].

**Table 2.** Fracture pressure and critical crack depth for tested pipes [9].

Steel grade	Outer diameter (D) mm	Thickness (t) mm	Half crack length (c) mm	critical crack depth (a) mm	Fracture pressure (MPa)	Plastic constraint factor C
Steel X65	820	10.6	100	7.0	9.86	2.30
Steel X70	1018	11.7	127	6.7	9.86	2.07

## 3. Analytical Methods

### 3.1. The Folin–Ciocalteu method (FC method)

It is an analytical method for estimating J-Integral for non-linear material Equation (1). This method depends on Ramberg-Osgood parameters for the material. This method was described in addendum A16 of the French nuclear code RCC-MR.[17]

$$J = \frac{K^2}{E'} \left[ \left( 1 + \alpha \left( \frac{\sigma}{\sigma_0} \right)^m \right) + \frac{0.5 \left( \frac{\sigma}{\sigma_0} \right)^m}{\left( 1 + \alpha \left( \frac{\sigma}{\sigma_0} \right)^m \right)} \right] \quad (1) [17]$$

where

K: stress intensity factor in case of pipe with axial semi-elliptical partially through crack

$\sigma$ : nominal stress  $\sigma = \frac{\sigma_h}{1 - \frac{\pi a c}{2t(t+2c)}}$  [9]

$\sigma_h$ : hoop stress  $\sigma_h = \frac{PD}{2t}$

c: half crack length

a: crack depth, as shown in Figure 1

$$E^* = E \quad \text{for the plane stress}$$

$$= \frac{E}{1-\nu^2} \quad \text{for the plane strain, where } \nu: \text{poisson' ratio}$$

$$\sigma_0 \text{ is the yield strength and } \varepsilon_0 = \frac{\sigma_0}{E}$$

$\alpha, m$  : material constants (Ramberg-Osgood parameters) [8]

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

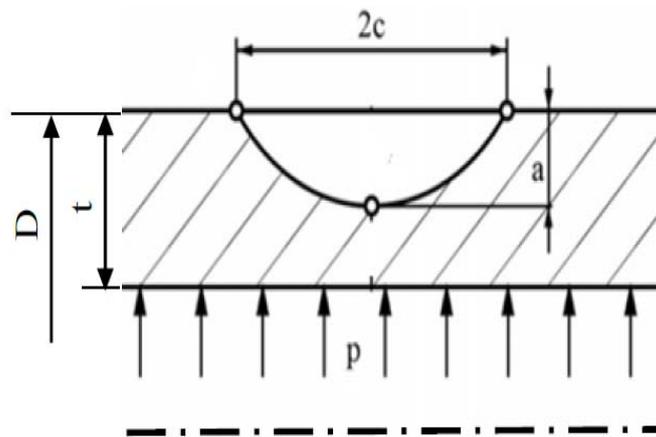


Figure 1. Semi-elliptical partially through crack in pipe.[9]

### 3.2. The Gauss–Seidel method (GS Method)

It is another analytical method for determining J-Integral particularly for semi-circular crack, Equation(2).[18]

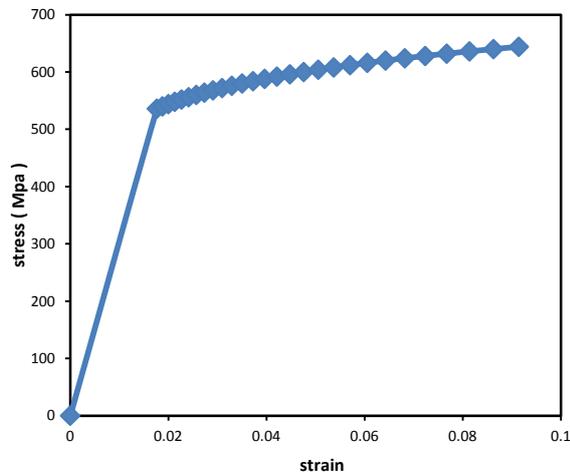
$$J = \frac{K^2}{E^*} \left[ 1 + \frac{2\alpha m \left( \frac{\sigma}{\sigma_0} \right)^{m-1}}{m+1} \right] \quad (2) [18]$$

## 4. Finite Element Method

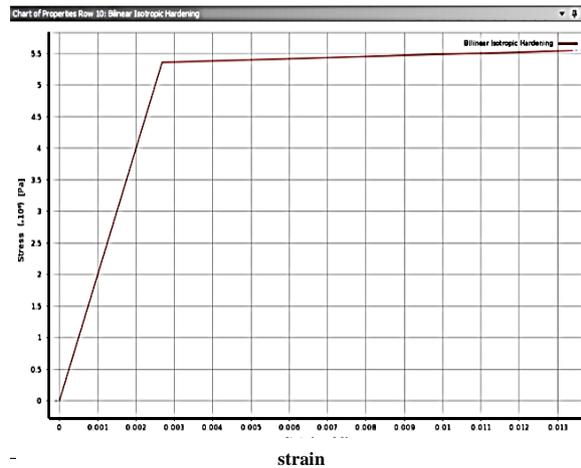
ANSYS program is used to simulate semi-elliptical axial partially-through crack in a full-scale pipe similar to the pipes tested previously [9, 15]. Comparison is made between the values of fracture pressure and crack depth obtained from finite element and experimental values obtained by Gajdoš et. al. [9, 15].

The steel X65 and X70 properties were identified to Ansys program via the material yield strength and the tangent modulus. From figure 2, the tangent modulus of steel X70 was calculated to identify the material to ANSYS program, figure 3.[21]

The proper mesh for the crack configuration was determined to facilitate the steps of establishing the Finite Element model. Many trials were conducted to get the appropriate meshing. In this work, tetrahedral mesh was selected because it is more proper and suitable for this kind of crack.



**Figure 2.** The behavior of steel X70 according to Ramberg-Osgood parameters.



**Figure 3.** The behavior of bilinear material steel X70 from ANSYS program.

### 5. Results and Discussion

The J-integral was determined using ANSYS under same fracture pressure obtained experimentally for each pipe at different crack depth to establish relationship between J and  $a_{cr}$  using finite element to get the critical crack depth ( $a_{cr}$ ) corresponding to  $J_{cr}$ . Figure 4 shows the two analytical methods (FC and GS methods) compared to the Finite Element method.

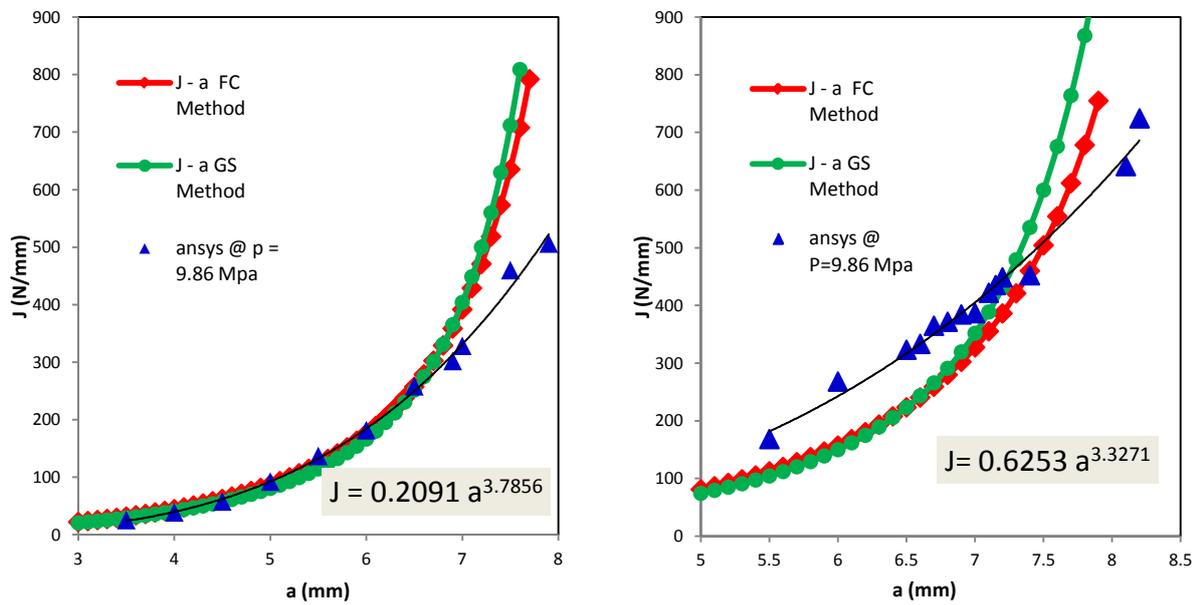
Generally, the Finite Element method is in good agreement with the analytical methods (FC and GS methods). This is obvious hence,  $a_{cr}$  for steel X70 according to Finite Element method = 7.169 mm while according GS method  $a_{cr} = 7.218$  mm, Table 3. The Finite Element method is more conservative than FC and GS methods.

**Table 3.** The critical crack depth ( $a_{cr}$ ) for steel X65 and X70 using FC, GS and Finite Element methods.

Steel grade	critical crack depth ( $a_{cr}$ ) mm		
	The FC method	The GS method	The Finite Element method
Steel X65	7.109	7.065	7.511
Steel X70	7.348	7.218	7.169

The critical crack depths ( $a_{cr}$ ) corresponding to ( $J_{cr}$ ) obtained at the fracture pressure by two analytical methods and Finite Element are summarized in Table 3.

Figure 5 shows the value of J-integral at the critical crack depth ( $a_{cr}$ ) which obtained from finite element method for steel X65 and X70 at the same fracture pressure obtained experimentally [9].

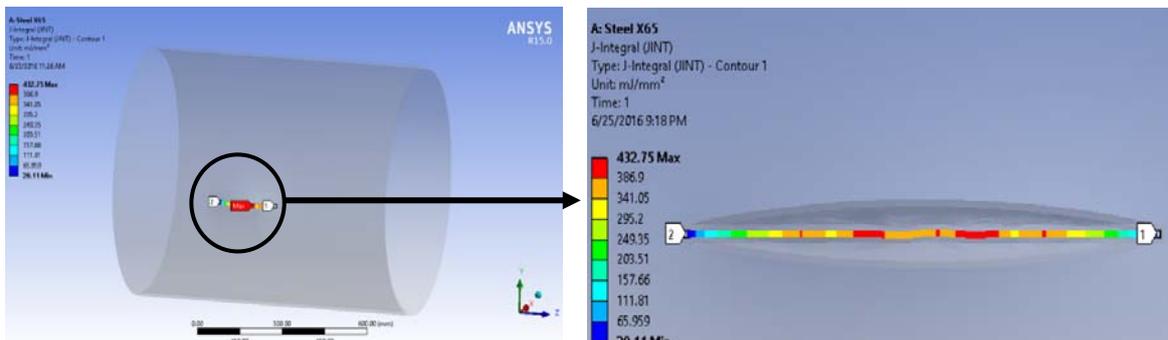


(a) Steel X65

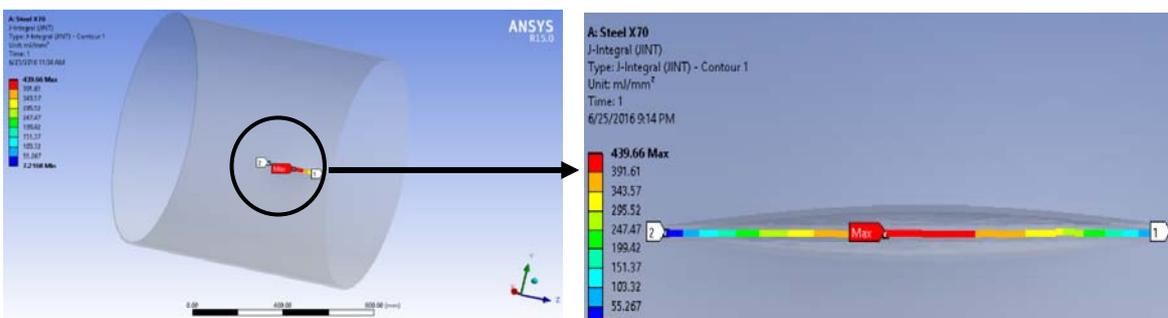
(b) Steel X70

**Figure 4.** Comparison between the FC, GS and Finite Element methods for: (a) steel X65 and (b) steelX70.

Table 4 refer to the deviation between critical crack depth ( $a_{cr}$ ) determined by different methods and the one obtained experimentally [9, 17].



(a) Steel X65



(b) Steel X70

**Figure 5.** The J-integral at fracture pressure for (a) Steel X65 and (b) Steel X70.

**Table 4.** The deviation in crack depth of each method relative to the experimental value.

Steel grade	Deviation from experimental value		
	The FC method	The GS method	The Finite Element method
Steel X65	1.56%	0.93%	7.30%
Steel X70	9.67%	7.73%	7.00%

## 6. Conclusions

The FC and GS analytical methods for fracture assessments worked well in determining fracture parameters. GS method is more conservative to be used in maintenance plans. This means it gives the minimum crack depth at fracture under same internal pressures.

The Finite Element method is successfully simulated fracture assessment of natural gas pipelines. In addition, Finite Element method is very simple tool to get the critical crack depth (or fracture parameters) in case of semi elliptical partially-through crack. Finite Element method is more conservative compared to analytical methods.

## References

- [1] Shalaby H, Riad W and Behbehani M 2006 Failure analysis of fuel supply pipeline *Engineering Failure Analysis* **13** pp789–96
- [2] Azevedo C R 2007 *Engineering Failure Analysis* **14** pp978–94
- [3] Hasan F, Iqbal J and Ahmed F 2007 Stress corrosion failure of high-pressure gas pipeline *Engineering Failure Analysis* **14** pp 801–9
- [4] Majid Z, Mohsin R, Yaacob Z and Hassan Z 2010 *Engineering Failure Analysis* Failure analysis of natural gas pipes **17** 818–37
- [5] API Specifications 5L 2012 *Specifications for Line Pipe* 43<sup>rd</sup> Edition (Washington D.C: American Petroleum Institute)
- [6] Rice J R A 1968 Path independent integral and the approximate analysis of strain concentration by notches and cracks *J. of Applied Mechanics* **35** pp 379–86
- [7] Wells A 1961 Unstable crack propagation in metals: cleavage and fast fracture *Proc. of the crack propagation Symp.* vol 1 (Cranfield, UK)
- [8] Anderson T 2005 *Fracture mechanics: fundamentals and applications* (Boca Raton: CRC)
- [9] Gajdoš E and Šperl M 2011 Application of a Fracture-Mechanics Approach to Gas Pipelines *Proc. of World Academy of Science* **73** 480–7
- [10] El-Sayed M, El Domiaty A and Mourad A 2015 Assessment of Axial Crack in Steel Pipe under Internal Pressure *Procedia Engineering Fracture* **130** pp 1273–87
- [11] Sharma R, Shrivastava S and Basu S 2006 *International Journal of fracture* **140** 269–75
- [12] Hopkins P 2002 *Comprehensive Structural Integrity* (Berlin: Elsevier)
- [13] Hernandez-Rodriguez M and Rodriguez J 2007 Corrosive wear failure analysis in a natural gas pipeline *Wear* **263** 5 pp 67–71
- [14] Cravero S and Ruggieri C 2006 Structural integrity analysis of axially cracked pipelines using conventional and constraint-modified failure assessment diagrams *Int. J. of Pressure Vessels and Piping* **83** pp 607–17
- [15] Gajdoš E and Šperl M 2012 Evaluating the Integrity of Pressure Pipelines by Fracture Mechanics *Applied Fracture Mechanics* ed Alexander Belov (IntechOpen) chapter 10 pp 283–310
- [16] Adib-Ramezani H, Jeong J and Pluvinaige G 2006 Structural integrity evaluation of X52 gas pipes subjected to external corrosion defects using the SINTAP procedure *Int. J. of Pressure Vessels and Piping* **83** pp 420–32

- [17] D. RCC-MR 1985 *Construction Rules for Mechanical Components of FBR Nuclear Islands* vol. 1 Section I Subsection B
- [18] Gajdoš Ľ and Srnec M 1994 An approximate method for J integral determination *Acta Technica CSAV***39** pp 151–64
- [19] Newman J 1976 *NASA-TN* Fracture Analysis of Surface and Through Cracks in Cylindrical Pressure Vessels D-8325
- [20] Folias E 1970 On the theory of fracture of curved sheets **2** *Engineering Fracture Mechanics* pp 151–64
- [21] Tian C and Gao Y 2005 Role of elasticity in elastic–plastic fracture *Int. J. of Solids and Structures* **42** pp 951–70
- [22] Shih C, Moran B and Nakamura T 1986 Energy release rate along a three-dimensional crack front in a thermally stressed body *Int. J. of Fracture* **30** pp 79–102