BURST PRESSURE PREDICTION OF MULTIPLE CRACKS IN PIPELINES

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ABSTRACT

Available industrial code such as ASME B1G, modified ASME B1G and DNV RP-F101 to assess pipeline defects appear more conservative for multiple crack like- defects than single crack-like defects. Thus, this paper presents burst pressure prediction of pipe with multiple cracks like defects. A finite element model was developed and the burst pressure prediction was compared with the available code. The model was used to investigate the effect of the distance between the cracks and the crack length. The coalescence diagram was also developed to evaluate the burst pressure of the multiple crack.It was found as the distance between crack increases ,the interaction effect comes to fade away and multiple cracks behave like two independent single cracks.

Keywords: collinear cracks, crack interaction, Burst pressure

INTRODUCTION

Engineering structures such as aircraft, pressure vessels and piping may contained cracks like defects. These defects may be inherent in the material or may exist at the beginning of service, being caused by manufacturing and installation process. Alternatively, the defects may develop during service as a result of microstructural damage and reduces its burst strength with increased potential for catastrophic failure. Pipelines are normally subjected to a uniform internal pressure. As part of assessing the integrity, of such structure under design and in service loading, it is necessary to determine their plastic collapses pressure or burst pressure. The burst pressure is the maximum internal pressure that a pipeline can sustain (Zarrabi,1994).

There are many design codes and standards to determine the burst pressure of pipelines such as ASME B31G (ASME B31G, 2009), Modified ASME B31G (ASME B31G, 2009), DNV RP-F101 (DNV RP-F101, 2010) and etc. All these codes clearly simplified integrity assessment of in service piping components. According to ASME B31G and DNV-RP-F101 codes, the failure of corroded pipeline is controlled by the defect size as well as the flow stress, S_f of the material. The input parameters are the outer diameter of the pipe, D, wall thickness, t, yield strength of the material, σ_y , ultimate tensile strength, σ_u, the length of the defect, L and defect depth, d. The equations used to calculate the burst pressure, P_b based on these codes are as follow. For ASME B31G, the flow stress, S_f and bulging factor M is given by;

$$S_f = 1.1 \times SMYS \quad , \quad z = \frac{L^2}{Dt} ,$$

For z ≤ 20,

$$M = \sqrt{1 + 0.8z}$$

$$P_b = S_{flow} \frac{2t}{D} \left[\frac{1 - \frac{2}{3}\left(\frac{d}{t}\right)}{1 - \frac{2}{3}\left(\frac{d}{t}\right)\frac{1}{M}} \right] \tag{1}$$

For z > 20

$$P_b = S_F \frac{2t}{D}\left(1 - \frac{d}{t}\right) \tag{2}$$

For DNV-RP S_f and bulging factor M is given by;

$$S_f = SMTS$$

$$M = \sqrt{1 + 0.31\left(\frac{1}{\sqrt{Dt}}\right)^2}$$

$$P_b = \frac{2(S_f)t}{D-t}\left[\frac{1 - \left(\frac{d}{t}\right)}{1 - \left[\left(\frac{d}{t}\right)/M\right]}\right] \tag{3}$$

However, these codes concern about single defect, whereas the multiple crack like defect has a great potential to cause the structure to early fail. The failure of the multiple cracks like defect is usually preceded by the interaction and coalescence of these cracks. In this process, the interacting crack growth rates and direction are significantly affected by their size, shape and proximity (Moussa et.al., 1999). API 579 states that, two cracks can be characterized as a single equivalent cracks following certain rules accounting the flaw shape orientation and interaction. Figure 1 illustrates the characterization rule as in API 579 (API 579, 2000). Table 1 shows the criteria for characterize the multiple cracks into equivalent single cracks.

The knowledge of the multiple cracks is great importance in assessing the structural integrity since the interacting cracks are much more sensitive to fracture. There are several methods for assessing the structural integrity of pipeline steel multiple cracks. These include the body force method, the boundary element method and the finite element method (Moussa et.al., 1999). All these methods employed the stress intensity factor to evaluate the cracks which however were complicated solution.

Table 1. Equivalent single cracks characterization rule

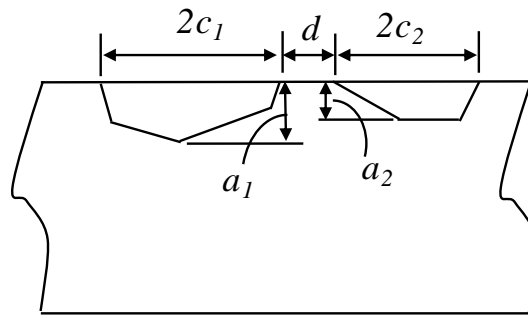| Criterion For Interaction	Effective Dimensions After Interaction
$c_1 + c_2 \geq d$	$2c = 2c_1 + 2c_2 + d$ $a = \max[a_1.a_2]$

Figure 1. Multiple Crack Like defect configuration

A coalescence diagram evaluation had been proposed for steam generator tube (Lee et.al, 2001). The diagram can be used to determine the burst pressure at the moment the cracks coalescence. It is assumed that the region or ligament between the crack tips cannot sustain the applied load anymore when it is subjected to the fully yielding condition. Later, a total of ten failure pressure prediction model such as flow stress model, necking base model, stress based model, reaction force model, plastic zone contact model had been developed (Moon et. al., 2005). By comparing the experimental results and with the prediction results, the reaction force model and the plastic zone contact model were selected as the optimum ones to predict the coalescence pressure. The interaction effect of two cracks in pipelines had been investigated in the presence of pressure on the defect (Gonzales et.al, 2008). Gonzales employed the condition where the critical lamination pressure defines as the pressure in the lamination that makes the von Mises stress in the interlaminar region to reach or surpass the ultimate strength of the material. This condition is assumed to be the initiation point for the formation of the interconnecting cracks. Thus, while previous research provided promising method, the present paper predicts the burst pressure of collinear cracks and develops the coalescence diagram for pipeline steel. The burst pressure was predicted when the region between cracks fully yielding. The effect of distance between crack and the crack length also the main interest in this research paper.

METHODOLOGY

Material

The material used was made of pipeline steel Grade B. Table 2 shows the chemical composition of the material. The mechanical properties were obtained by performing the tensile test according ASTM E8 (2001) as tabulated in Table 3. Figure 2 shows the true stress strain curve for Grade B steel pipe.

Table 2. Chemical Composition of Grade B Steel Pipe

Fe	C	Si	Mn	P	S	Cr	Mo
98.5	0.28	0.38	0.62	0.01	0.01	0.03	0.01

Table 3. Mechanical Properties of Grade B Steel Pipe

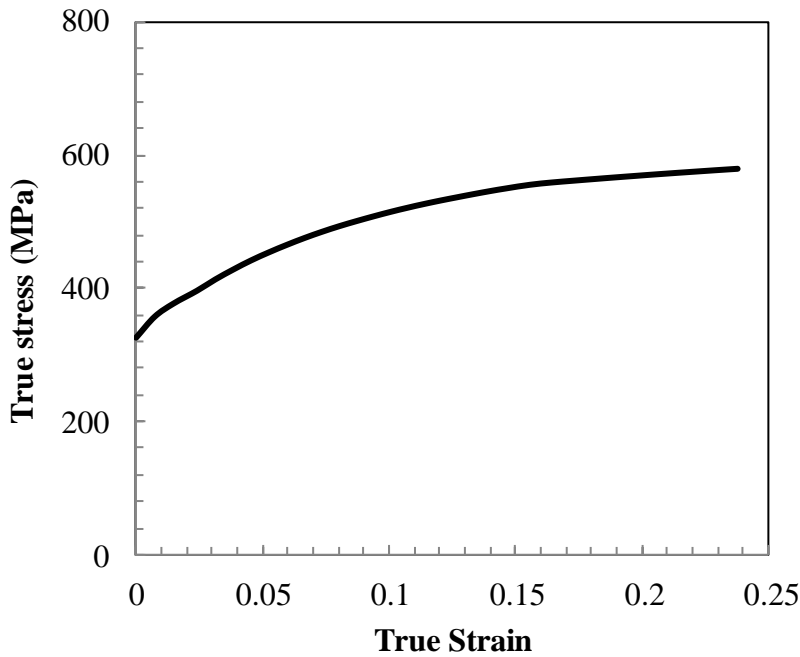|	Young Modulus,E (MPa)	Possion Ratio, ν	Yeild Strength,σ_y (MPa)	Tensile Strength,σ_t (MPa)
Experimental	207	0.3	362	464

Figure 2. Stress strain curve for Grade B Steel Pipe

Finite Element Modelling

Figure 3 illustrates the schematic pipe containing two collinear cracks. The outer diameter, *D* and thickness, *t* of the pipe are 605 mm and 4 mm respectively. The overall length, *L* of the pipe was 600 mm. The crack length and the distance between cracks designated by *2c* and *d* respectively. 3D nonlinear finite element analysis was performed using MSC Marc 2008r1. Figure 4 shows typical finite element model of pipe containing two collinear cracks. A half of the pipe was modelled by considering symmetrical condition. The finite element mesh was constructed by using 20 node quadratic brick elements with reduced integration point. The boundary condition was applied at the end of the pipe to simulate the closed cap condition and the internal pressure was applied to the inner surface of the pipe. The material is model as an isotropic elasto-plastic material and the true stress strain data were employed. A series of finite element analyses were carried out for the tube containing crack length. to investigate the effect of crack length and the distance between cracks. The crack length of 25mm, 50mm, 75mm and 100 mm and distance between cracks of 0.5mm, 2 mm, 4 mm and 8 mm was used.
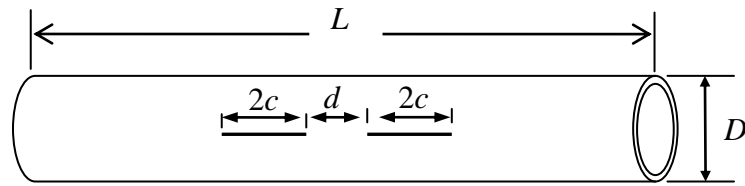
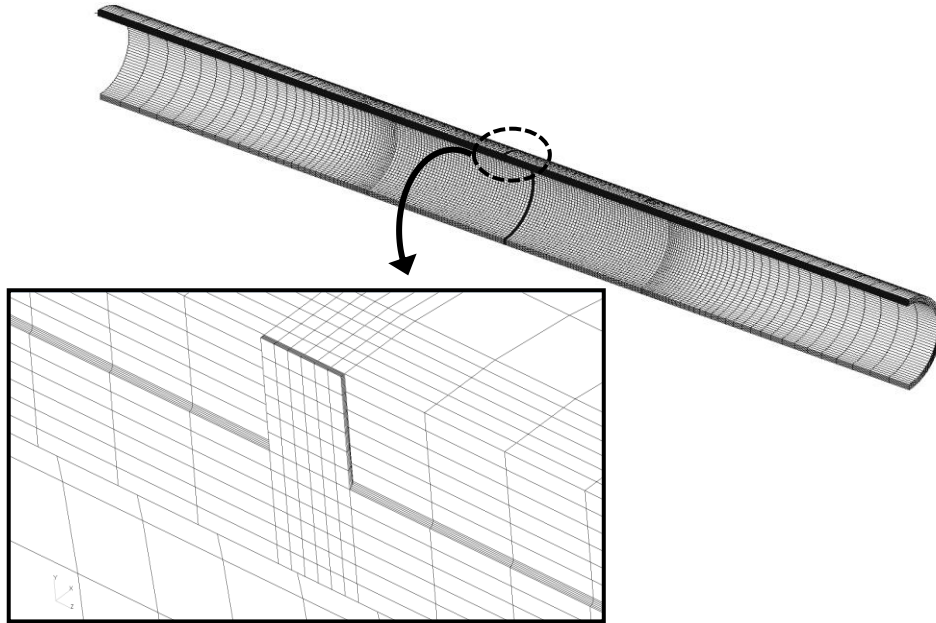Figure 3. Schematic of pipe containing two collinear cracks.

Figure 4. Crack modelling

RESULTS AND DISCUSSION

Stress Contour

In the present paper, the burst pressure was taken when the von Mises stress in at the crack tip reach the ultimate strength of the material. So, it is assumes that the coalesnce occur when the ligament between the cracks is fuly yielding. Figure 5 shows distribution of von Mises stress at the region between the collinear cracks for the case of $2c = 100$ mm and distance, $d = 2$ mm with the increase of applied pressure. The maximum stress occurred at the internal tips of the crack indicate there is an interaction of the stress field since the first pressure step.Figure 5(b) shows that at a pressure of 14.4 MPa, there is noticeable yeiding at the internal crack tips, but not across the entire region between the crack. Figure 5(c) shows at a pressure of 32.4 MPa, the von Mises stress distribution are above the yield strength of the material, so it is fully plasticied. Finally, at a pressure in the region of 44.1 MPa, the spread of von Mises stress reached the ultimate strength of the material and therefore the burst pressure was predicted.
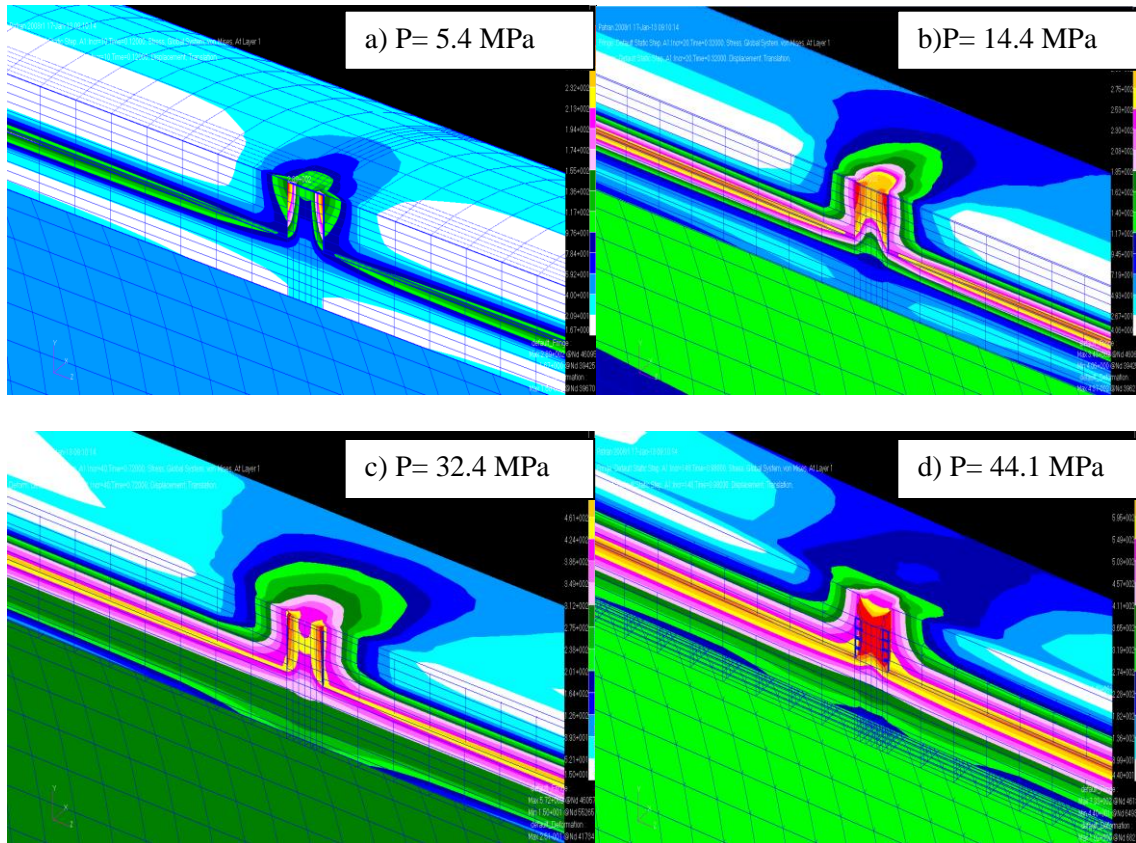
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Figure 5. Stress distribution at region between crack tips

Table 4 represent the predicted result obtained by using FEA models and calculated burst pressure according to ASME B31G (ASME B31G, 2009) and DNV (DNV RP-F101, 2010). The burst pressures for single crack were calculated using Eq. (1) and Eq. (3) to acquire a baseline data. For the purposed of calculated single crack, *2c* = 25, 50, 75 and 100 mm was used.

Figure 6 shows the coalescence load crack length curve obtained from finite element analysis results. This curve can be used to determine the pressure at the moment of crack coalescence or the burst pressure. In this figure, the solid line indicates the burst pressure of the pipe containing single crack calculated using Eq. (3).It is noted that the burst pressure of adjacent collinear cracks with a value *d* greater than 2mm with crack length greater than 75 mm closely approached to the burst pressure of pipe containing a single cracks. This means that if the distance between a pair of cracks is longer than 2 mm with crack length longer than 75 mm, the interaction effect comes to fade away and collinear cracks behave like two independent single cracks.

Table 4. Burst pressures value

Pipe dimensions		Burst Pressure (MPa)		
$2c$(mm)	d(mm)	FEA	ASME	DNV
25	0.5	31.0		
	2	43.4	23.8	51.47

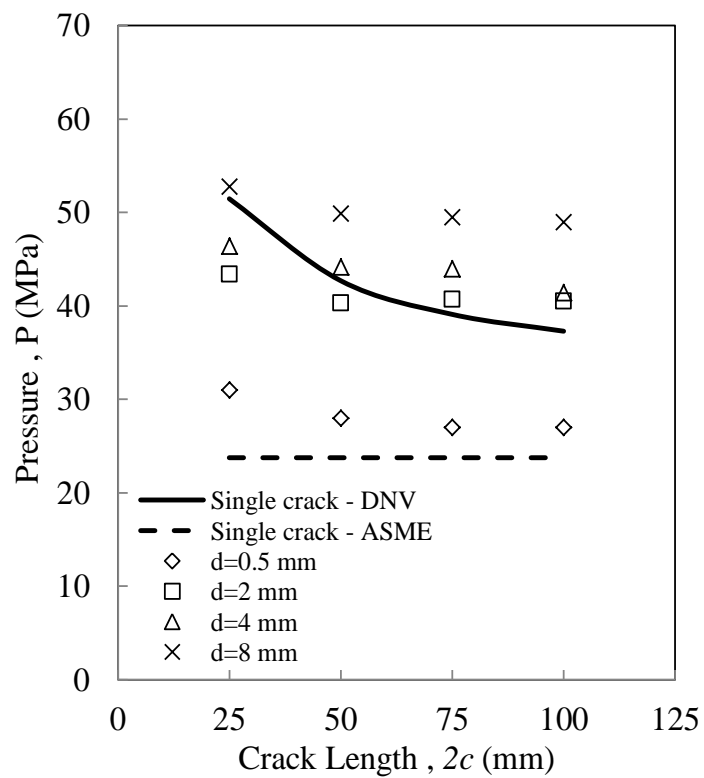|				
	4	46.4		
	8	52.8		
50	0.5	28.0		
	2	40.3	23.8	42.70
	4	44.2		
	8	49.9		
75	0.5	27.0		
	2	41.0	23.8	39.1
	4	44.0		
	8	49.5		
100	0.5	27.3		
	2	40.5		
	4	41.4	23.8	37.3
	8	49.0		

Figure 6. Coalescence diagram

CONCLUSION

In this paper, the burst pressure of pipe containing collinear axial through wall cracks was evaluated based on detail three dimensional elastic plastic finite element analyses and following key finding has been derived:

i)   As the crack length increases the burst pressure decreases.
ii) As the distance between cracks increases, the burst pressure also increases..
iii) It is noted that the burst pressure of adjacent collinear cracks with a value d greater than 2mm with crack length greater than 75 mm closely approached to the burst pressure of pipe containing a single cracks.
iv) This means that if the distance between a pair of cracks is longer than 2 mm with crack length longer than 75 mm, the interaction effect comes to fade away and collinear cracks behave like two independent single cracks.

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