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Determination of Geometry Factor of Crack in Dented API 5L X65 Pipeline Using Finite Element Method

Arianta, Ricky L.T, Ahmad T., Rildova

Abstract— Oil and gas transmission pipelines during its construction, laying and operation period may undergo local plastic deformation due to mechanical impact, which some of them can be in the form of dent with crack. With the presence of crack, the acceptance criterion is no longer used alone where design or operational pressure are compared to SMYS. Therefore additional different acceptance criterion must be used based on fracture mechanics, where the stress intensity factor is compared to fracture toughness of material. Stress intensity factor depends on the geometry of pipe, size of crack, and the magnitude and direction of the loading system acting on the pipeline. The study was conducted based on the experimental test and numerical models using steel plate as one approach to large pipe diameter. The steel plate is made of a piece of material API-5L-X65 gas pipeline. Result of the research was the geometry factor of dented plate with crack. The geometry factor equation of dented plate with crack was then used to modify the geometry factor equation of crack pipe based on standard API RP 579. The value of geometry factor of crack in dented pipe was limited to ratio a/t = 0.5, a/c = 0.4 and 0 < Hr/t ≤ 2.

Index Terms— Pipeline, fracture mechanics, finite element, geometry factor, stress intensity factor, dent, crack, plate

1 Introduction

Pipeline has a good safety factor and economics to delivery oil or gas from wells to production. However, during its construction, laying and operation, pipelines sometimes subject to leaks or ruptures. Generally, the failure caused by external interference or mechanical damage. The type of mechanical damage which is common in pipeline is dents and cracks. The combination of dent and crack make pipeline is more vulnerable to failure. Therefore, it is important to evaluate the integrity of pipeline that contain a defect that contain both dent and crack.

Fitness for service (FFS) assessments are quantitative engineering that are performed to evaluate the structural integrity of pipeline that may contain a flaw or damage and to make decision run-repair-replace or down rate. API 579/ASME FFS-1 [4] is a standard method for assessment to evaluate the integrity of pipeline that has a size and a geometry of certain defects. The acceptance criterions of API 579 for dented pipe are i) the maximum allowable the dent depth, ii) Remaining Strength Factor (RSF) and iii) the maximum allowable stress of dented pipe. The recommendation from standard API 579 for dented pipeline case is reflected in the maximum allowable operating pressure (MAOP).

With the presence of crack in dented pipe, the design criterion is no longer used alone where the operational stress compare to SMYS (Specified Minimum Yield Strength) is set as an acceptance criterion. Therefore additional different acceptance criterion must be used based on fracture mechanics, where the stress intensity factor is compared to fracture toughness of material. Stress intensity factor is the stress field around crack tip that depend on geometry of pipeline, size of crack and direction of the loading system acting on the structure. Geometry factor is a function of crack depth, crack length, thickness of structure and the parametric angle of ellipse crack.

Yong Bai [6] has studied the case to determine the geometry factor of dented pipe with crack. He used theoretical approach from the stress intensity factor of crack plate by Newman and Raju [17], and the uniaxial tensile stress and bending moment of dented pipe by Shannon [6].

Experimental test and numerical analysis were carried out to determine the geometry factor (F) of dented pipe with crack. Experimental tests was validated the numerical model simulations. Steel plates was used as an approach to pipe geometry and it is made of a piece of material API-5L-X65 gas pipeline. XFEM (eXtended Finite Element Method) modeling as numerical simulation was used to determine the stress intensity factor of dented plate with crack.

2 Stress Intensity Factor of Dented Pipes With Cracks

Yong Bai has determined the geometry factor equation of dented pipe with crack [6] theoretically. He is used the stress intensity factor by Newman-Raju [17]; the bending moment and uniaxial tensile stress in a dented pipe by Shannon [6] as an approach. The stress intensity factor (K) for wide plate under combined tension and bending is given below

- *Arianta is currently pursuing doctoral degree program in civil engineering in Institute Technology of Bandung, Indonesia, PH-08122125915. E-mail: arianta.l@gmail.com*
- *Ricky. L. T is professor in ocean engineering in Institute Technology of Bandung, Indonesia,. E-mail: ricky@ocean.itb.ac.id*
- *Ahmad. T is lecturer in ocean engineering in Institute Technology of Bandung, Indonesia,. E-mail: a.taufik@ocean.itb.ac.id*
- *Rildova is lecturer in ocean engineering in Institute Technology of Bandung, Indonesia,. E-mail: a.taufik@ocean.itb.ac.id*

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$$K = \frac{F}{\sqrt{Q}}\sigma\sqrt{\pi a} + H\frac{F}{\sqrt{Q}}\frac{6M}{t^2}\sqrt{\pi a} \qquad (1)$$

Where factor F, Q and bending correction H are given by Newman and Raju. σ is the nominal stress, t is the thickness of material and a is the crack length.

Shannon is given an approach solution for bending moment M and uniaxial tensile stress σ in a dented pipe.

$$\sigma = \sigma_H\left(1-1.8\frac{H_r}{D}\right) \qquad (2)$$

$$M = 0.85\,\sigma_H\, t\, H_r \qquad (3)$$

Where D is the diameter of pipe, σ_H is the nominal hoop stress and H_r is the dent depth

Substituting equation 2 and 3 into equation 1,

$$K = \frac{F}{\sqrt{Q}}\left(1-1.8\left(\frac{H_r}{D}\right)+5.1H\left(\frac{H_r}{t}\right)\right)\sigma_H\sqrt{\pi a} \qquad (4)$$

Therefore, the geometry factor of dented pipe with crack can be expressed as

$$F_{YongBai} = \frac{F}{\sqrt{Q}}\left(1-1.8\left(\frac{H_r}{D}\right)+5.1H\left(\frac{H_r}{t}\right)\right) \qquad (5)$$

3 The Extended Finite Element Method

The extended finite element method (XFEM) is an extension of the conventional finite element method based on the concept of partition unit. This method was introduced by Ted Belytschko and his colleagues in 1999 [24]. XFEM models a crack as an enriched feature by adding degrees of freedom in elements with special displacement functions. XFEM does not require the mesh to match the geometry of the discontinuities. It can be used to simulate initiation and propagation of a discrete crack along an arbitrary, solution-dependent path without the requirement of remeshing. XFEM can also be used to perform contour integral evaluation without the need to refine the mesh around the crack tip. The approximation for a displacement vector function u with the partition of unity enrichment is [1]

$$u = \sum_{i=1}^{N} N_i(x)\left[u_i + H(x)a_i + \sum_{\alpha=1}^{4} F_\alpha(x) b_i^\alpha\right] \qquad (6)$$

where N_i (x) is the shape functions on node I, u_i is the nodal displacement vector associated with the continuous part of the finite element solution, a_i is the nodal enriched degree of freedom vector, and the associated discontinuous jump function (H(x)) across the crack surfaces; b_i^α is the product of the nodal enriched degree of freedom vector, and the associated elastic asymptotic crack-tip functions (Fα (x)). The jump function and the enrichment function at the crack tips are given by

$$H(x,y) = \begin{cases} 1 & if\ (x-x^*).n \ge 0 \\ -1 & otherwise \end{cases} \qquad (7)$$

$$F_\alpha(x) = \left[\begin{array}{l}\sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\theta\sin\frac{\theta}{2}, \\ \sqrt{r}\sin\theta\cos\frac{\theta}{2}\end{array}\right] \qquad (8)$$

4 Dent Model

Experimental tests are carried out to know the material behavior API-5L-X65 at the process of the formation of a dent. The experimental tests used plates as an approach to model pipeline geometry with large diamater. The plate had the following dimension length 70 mm, width 40 mm and thickness 4 mm. Dent forming on steel the plate was made by applying pressure on the indenter until it reached the depth of dent. The geometry of indenter was based on DNV RP F107, it had conical shape. Figure 1 shows the shape and dimensions of indenter.

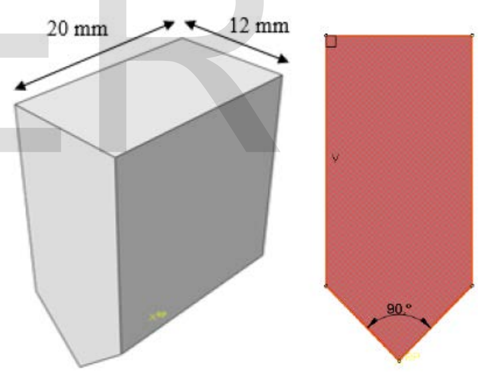

Figure 1. Indenter

The dent process produces both elastic and plastic responses in the material. When the indenter was removed, the elastic component of the deformation was recovered and the dent will move outward, therefore the depth of dent will decrease. This recovery is termed spring back. LVDT (Linear Vertical Displacement Transducer) tool was installed below the plate to measure the change of the dent depth.

The change of the dent depth can be determined by the value of elastic recovery. Elastic recovery (ER) is the percentage change in the dent depth, during and after (spring back) the process of dent.

$$ER = \frac{H_0 - H_r}{H_0} \times 100\% \qquad (9)$$

ISSN 2229-5518

Where H_0 is the maximum of dent depth and H_r is the dent depth after spring back. Experiments have been repeated three times to ensure the repeatability of the result. Table 1 shows the result of measurement the dent depth. The deeper of the dent on plate, the value of elastic recovery will decrease. This means the material will become plastic and there was no significant changes in the dent depth.

Table 1. Result Dent Depth Measurement

Specimen	H_0 (mm)	H_r (mm)	*Elastic Recovery*	
			%	Average
4 mm	4.05	3.38	16.54	17.00
	4.01	3.34	16.71	
	4.06	3.34	17.73	
6 mm	6.02	5.38	10.63	10.96
	6.02	5.34	11.30	
	6.03	5.37	10.95	
8 mm	7.99	7.35	8.01	8.04
	8.01	7.34	8.36	
	8	7.38	7.75	

Figure 2 shows a relationship values between maximum dent depth (H0) and dent depth after spring back (Hr). It has a linear trend with the line is increase. Elastic recovery has similar trend but the line will decrease towards deepening dent (figure 3).

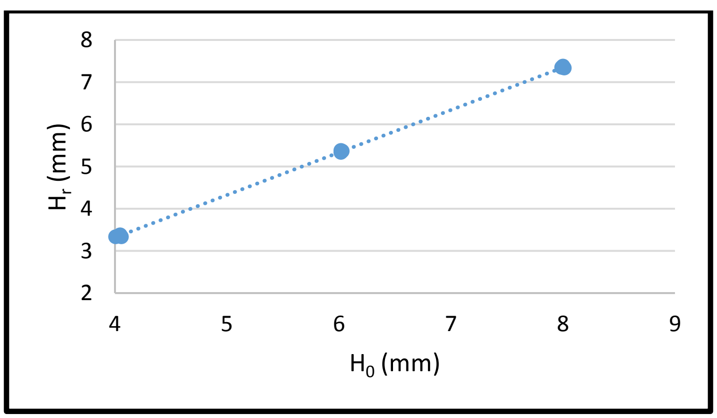

Figure 2. Relation Dent Depth

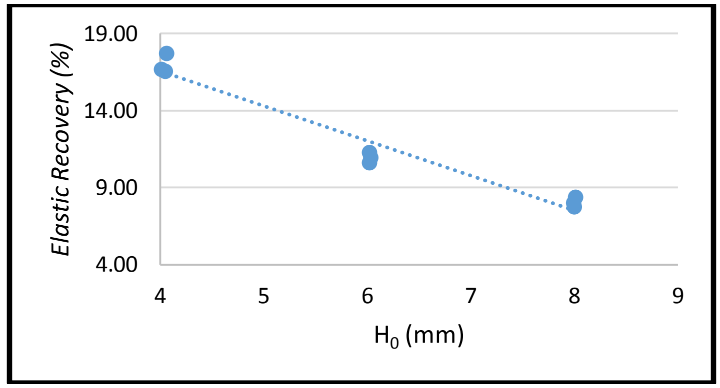

Figure 3. Elastic Recovery

Finite element modeling was conducted to simulate the process of dent and spring back. An eight-node hexahedral solid element, C3D8 of ABAQUS, was used for modeling dent and spring back on plate specimen. Figure 4 shows the modeling of indenter and plate specimen.

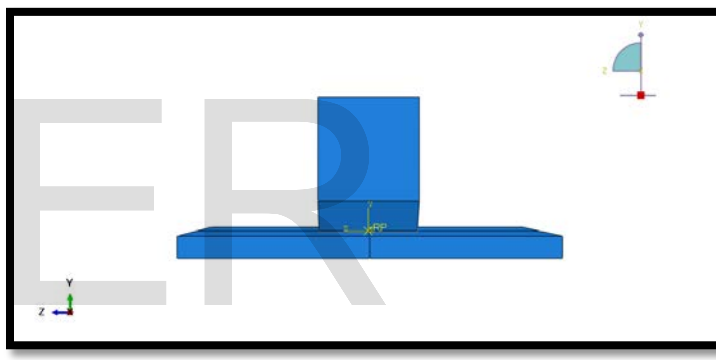

Figure 4. Indenter and Plate Models

Combined hardening between kinematic and isotropic hardening was used to model the behavior of material API-5L-X65 in dent and spring back modeling. The material properties of API-5L-X65 was referred to Akid & Fatoba [3]. The parameters H_0 and H_r as results from the experiment were used to validate the numerical modeling. The value of young's modulus should be changed accordance to the dent depth, therefore the parameter H_0 and H_r of model will be close to H_0 and H_r from experiment. With trial and error to determine the young's modulus, figure 5 shows the young's modulus degradation accordance to the dent depth.

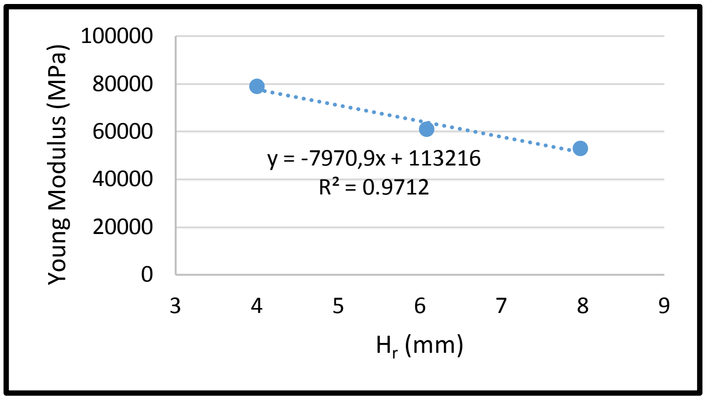

Figure 5. Young's Modulus Degradation

The process of dent caused young's modulus degradation. The deeper of dent depth, the value of young's modulus will decrease (fig. 5). Empiric equation to predict the young's modulus for API-5L-X65 material as presented in figure 5, linear equation as follow

$$E' = -7970,9(H_r) + 113216 \tag{7}$$

Where: E' is the young's modulus degradation

5 XFEM Model

Experimental test in the form of dent resulted the initial crack on the side of the arch dents (fig. 6). Strain gage was attached on crack tip zone. It was used to record the strain on crack tip from propagate until fracture. Tensile tests have been conducted three times to ensure repeatability of the results. Figure 7 shows the average of strain on crack tip from three times test. The maximum strain on crack tip and far field stress on plate were used to validate the finite element modeling of tensile test.

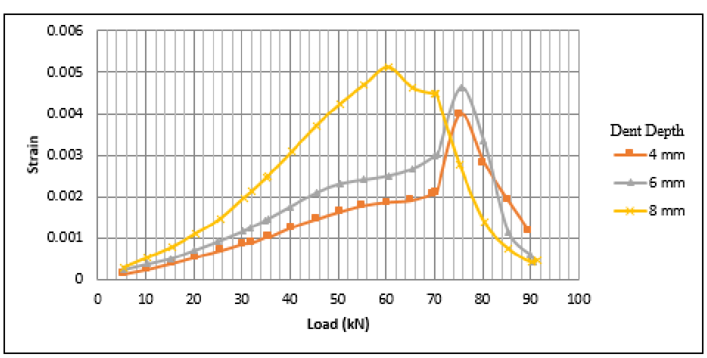

Figure 6. Strain on Crack Tip

To evaluate XFEM result in Abaqus, a stress intensity factor comparison was made against benchmark case. The benchmark case was a wide range of semi-elliptical surface cracks in finite-thickness plates [18]. The stress intensity factor is defined as

$$K_I = \sigma \cdot F\left(\frac{a}{t}, \frac{a}{c}, \phi\right) \cdot \sqrt{\frac{\pi a}{Q}} \tag{10}$$

Where σ is the applied stress, a is the crack depth, Q is the shape factore for an ellipse and F is the geometry facator as function of crack depth, crack length, plate thickness and the parametric angle of the ellipse. The purpose of benchmark XFEM modeling was to determine the meshing technique in crack area. Partition of mesh was more refined near the crack area. The element size for near crack area is 0.25 mm of hexahedron element. Figure 7 shows the mesh configuration near the crack area.

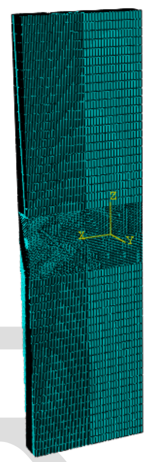

Figure 7. Mesh refinement control

Equation 10 was used to determine the geometry factor from XFEM results. Table 2 shows the comparison of geometry factor results from XFEM model with the reference solution obtained by Newman and Raju in terms of the % relative error.

Table 2. Comparison of Geometry Factor

a/c	**2ϕ/π**	**a/t = 0.5**		
		Newman-Raju	**XFEM Model**	***Error* (%)**
0,4	0	0.988	0.995	0.672
	0.125	0.989	1.045	5.735
	0.25	1.030	1.028	0.159
	0.375	1.095	1.154	5.443
	0.5	1.161	1.182	1.819
	0.625	1.219	1.294	6.128
	0.75	1.263	1.172	7.153
	0.875	1.289	1.196	7.214
	1	1.298	1.405	8.296

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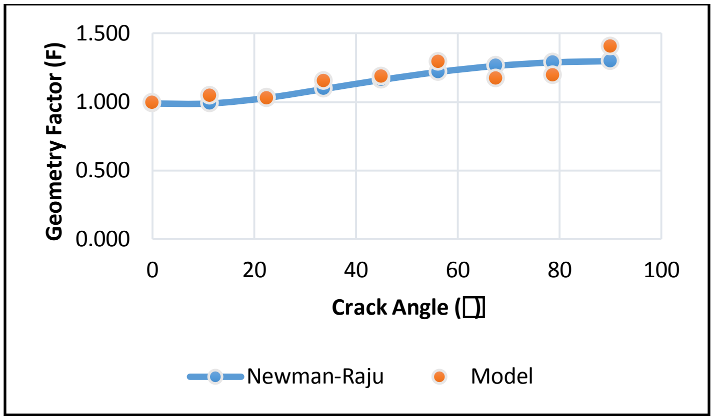

Figure 8. Comparison of Geometry Factor

The highest % relative error was 8.296% and still below 10%. Therefore, the comparisons shows good agremeent with the results published by Newman and Raju, for case a/c = 0,4 and a/t =0,5. The mesh configuration with element size 0.25 mm will be applied to the model dented plate with crack. Figure 9 shows the mesh configuration for XFEM model of dented plate with crack. Deformation of dent shape from spring back analysis is used for XFEM model. On XFEM model, the residual stress from spring back analysis is not applied to model. Therefore, the stress intensity factor from the XFEM modeling is due to external load only. The dimensions of crack are length (2c) 10 mm and the depth of crack (a) 2 mm, with semi-elliptical shape.

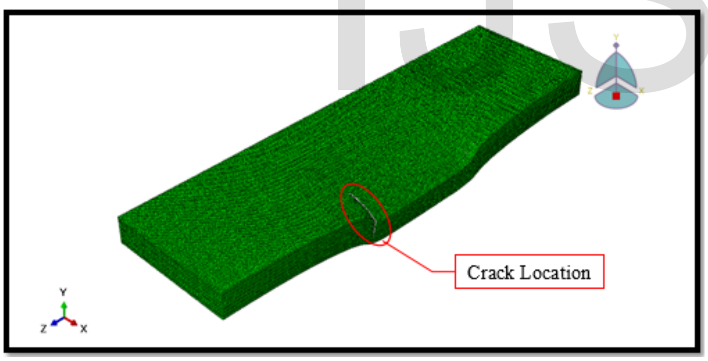

Figure 9. Mesh Configuration on Dented Plate with Crack Model

The result of XFEM modeling was the stress intensity factor (K_I) along the cracked path. Stress intensity factor equation given by Newman and Raju is used to determine the geometry factor of dented plate with crack. The value of geometry factor dented plate with crack is function of angle of the crack path. Figure 10 shows the angle of crack path.

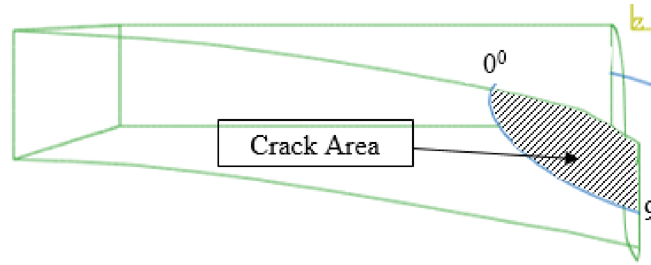

Figure 10. Angle of Crack Path

Figure 11 shows the result of geometry factor along crack path as function of parametric angle (ϕ) and the dent depth. The maximum geometry factor occurs at ϕ = 0^0 and the minimum geometry factor occurs at ϕ = 90^0. The deeper of the dent depth, geometry factor become smaller.

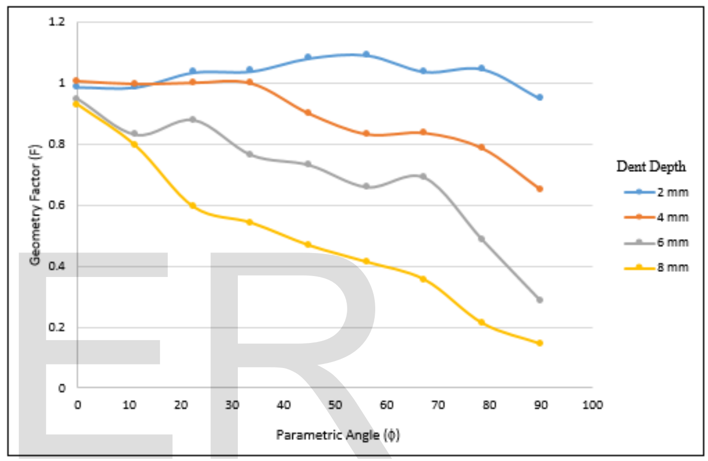

Figure 11. Geometry Factor along Crack Path

Geometry factors for dented plate with semi-elliptical surface crack (a/c = 0.4, a/t = 0.5) as a function of the parametric angle (ϕ) and the dent depth to plate thickness ratio (0 < Hr/t ≤ 2), are given in table 3.

Table 3. Geometry Factor of Dented Plate with Crack

H_r/t	ϕ								
	0	11.25	22.5	33.75	45	56.25	67.5	78.75	90
0	0.988	0.989	1.030	1.095	1.161	1.219	1.263	1.289	1.298
0.5	0.997	0.991	1.062	1.066	1.066	1.055	1.070	1.041	0.957
1	0.989	0.956	1.003	0.963	0.920	0.865	0.858	0.778	0.662
1.5	0.964	0.883	0.851	0.786	0.721	0.651	0.628	0.499	0.413
2	0.923	0.774	0.607	0.536	0.469	0.411	0.381	0.205	0.210

Geometry factor for dented plate could be obtained by equation 11

$$F_{DentedPlate} = \frac{F_{Total}}{F_{NewmanRaju}} \quad (11)$$

Where F_{Total} is geometry factor for dented plate with cracks (table 3) and $F_{NewmanRaju}$ is geometry factor for finite-thickness plate that obtained by Newman and Raju [18]. Table 4 shows the geometry factor for dented plate (a/c = 0.4, a/t = 0.5) as a

ISSN 2229-5518

function of the parametric angle (ϕ) and the dent depth to plate thickness ratio ($0 < H_r/t \leq 2$).

Table 4. Geometry Factor of Dented Plate

H_r/t	ϕ								
	0	11.25	22.5	33.75	45	56.25	67.5	78.75	90
0	1	1	1	1	1	1	1	1	1
0.5	1.009	1.002	1.032	0.973	0.919	0.865	0.847	0.808	0.737
1	1.001	0.966	0.974	0.879	0.792	0.710	0.679	0.603	0.510
1.5	0.976	0.893	0.826	0.718	0.621	0.534	0.498	0.387	0.318
2	0.934	0.782	0.590	0.490	0.404	0.337	0.302	0.159	0.162

6 Geometry Factor of Dented Pipe with Crack

Stress intensity factor equation of surface crack pipe was used to determined geometry factor of dented pipe with crack. The equation is based on API RP 579 [4]. Figure 12 shows crack location on pipe.

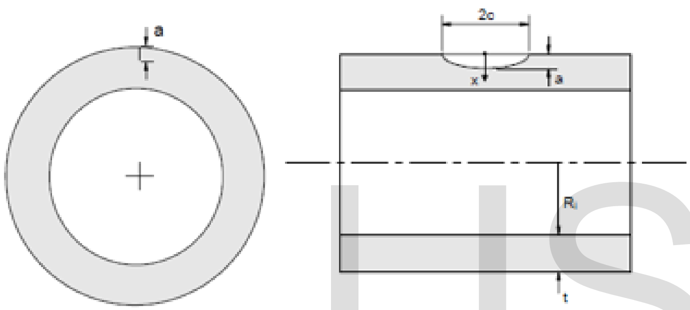

Figure 12. Outside Crack in Pipe

$$K_I = \frac{pR_i^2}{R_o^2 - R_i^2}\left(\begin{array}{l} 2G_0 + 2G_1\left(\frac{a}{R_o}\right) + 3G_2\left(\frac{a}{R_o}\right)^2 + \\ 4G_3\left(\frac{a}{R_o}\right)^3 + 5G_4\left(\frac{a}{R_o}\right)^4 \end{array}\right)\sqrt{\frac{\pi a}{Q}} \quad (12)$$

Where p is the pressure, R_i is the inside radius, R_o is the outside radius and G_0, G_1, G_2, G_3, G_4 are the geometry coefficient. Geometry factor for dented pipe with crack is obtained by multiplied the geometry factor of dented plate with geometry factor of crack pipe. The equation of geometry factor for dented pipe with crack as follow.

$$F_{Arianta} = F_{DentedPlate} \cdot \left(\begin{array}{l} 2G_0 + 2G_1\left(\frac{a}{R_o}\right) + 3G_2\left(\frac{a}{R_o}\right)^2 + \\ 4G_3\left(\frac{a}{R_o}\right)^3 + 5G_4\left(\frac{a}{R_o}\right)^4 \end{array}\right) \quad (13)$$

Where FArianta is the geometry factor of dented pipe with crack as result of this study. The geometry factor for dented pipe with crack plate ($a/c = 0.4$, $a/t = 0.5$) as a function of the parametric angle (ϕ) and the dent depth to plate thickness ratio ($0 < H_r/t \leq 2$), are given in table 5

Table 5. Geometry Factor of Dented Pipe with Crack

H_r/t	ϕ								
	0	11.25	22.5	33.75	45	56.25	67.5	78.75	90
0	2.028	1.993	2.106	2.274	2.436	2.564	2.655	2.715	2.725
0.5	2.046	1.997	2.172	2.213	2.237	2.219	2.248	2.193	2.009
1	2.029	1.926	2.051	2.000	1.929	1.820	1.804	1.638	1.390
1.5	1.979	1.780	1.740	1.633	1.512	1.368	1.321	1.052	0.867
2	1.894	1.559	1.242	1.114	0.984	0.864	0.801	0.433	0.441

Pipeline is a pressure vessel that has thin wall thickness. Equation 12 is for thick wall pressure vessel, therefore the stress intensity equation based on API RP 579 need to be modified. Modified equation 12 for thin wall pressure vessel case as follow.

$$K_I = \frac{pD}{2t}\left(F_{DentedPlate} \cdot \left(\begin{array}{l} 2G_0 + 2G_1\left(\frac{a}{R_o}\right) + 3G_2\left(\frac{a}{R_o}\right)^2 \\ + 4G_3\left(\frac{a}{R_o}\right)^3 + 5G_4\left(\frac{a}{R_o}\right)^4 \end{array}\right)\right)\sqrt{\frac{\pi a}{Q}} \quad (14)$$

Comparison of the stress intensity factor of dented pipe with crack between Yong Bai and Arianta is presented below. The bending moment from Yong Bai equation is neglected, comparison only due to hoop stress that acting on pipeline.

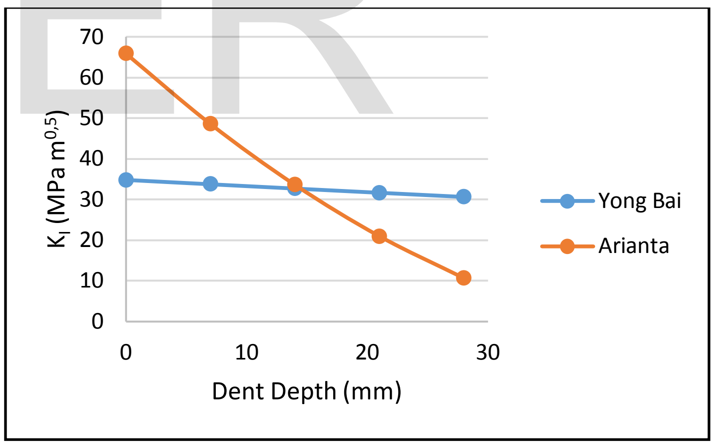

Figure 13. Comparison of Stress Intensity Factor

The stress intensity factors of dented pipe with crack found by Yong Bai and Arianta have a similar tendency to decrease with increasing the depth of dent. Different approach in developing the KI equation of dented pipe with crack, will generate different value between Yong Bai and Arianta. Differrent approach used was; i) the location of the hoop stress and, ii) determination of the geometry factor of dented pipe with crack.

Different approach used to develop the stress intensity factor of dented pipe with crack will produce different result. Different parameters that used to develop the stress intensity factor equation of dented pipe with crack determines the location of hoop stress of dented pipe and the geometry factor of dented pipe with crack.

7 Conclusion

A three dimensional model with XFEM model was used to determine the stress intensity factor of dented plate with crack. The material behavior in model based on experimental test. Dent depth, strain at crack tip and far field stress as result of experimental tests, were used for validation to numerical modeling of dented plate with crack.

Based on XFEM model result due to tensile stress, the presence of a dent on plate the geometry factor become smaller at the deepest point of crack. The geometry factors of dented plate with crack have tendency to be smaller when the dent depth become deeper.

Stress intensity factor equation of outside crack pipe based on API RP 579 was used to determine the geometry factor equation of dented pipe with crack. Comparison of the stress intensity factors of dented plate with crack with Yong Bai have similar trend. It is become smaller when the dent depth deeper. Different approach resulted different slope of the stress intensity factor graph when it was plotted as a function of the dent depth. The geometry factors of dented pipe with crack was limited to $a/c = 0.4$, $a/t = 0.5$ and the dent depth to plate thickness ratio ($0 < H_r/t \leq 2$).

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