Failure Prediction of Cracked Pressure Vessel under Fatigue Load Based on API 579 Standard and Finite Element Method

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ABSTRACT

Failure prediction of cracked pressure vessel is analyzed based on crack growth behavior under fatigue loading. The major objective of this study was to investigate and validate the use of commonly used industry standard with finite element method in order to predict failure of cracked pressure vessel. Growing of crack due to fatigue load was analyzed using both analytical and finite element method. In analytical side, API 579 Code is used with involving safety and correction factor which will increase conservatism degree of the results. Pressure vessel with D/t ratio 40, 60, and 80 were taken into analysis. Semi elliptical cracks in longitudinal and circumferential position were included into analysis with ratio a/t=0.3, 0.5, 0.8 and a/c=0.15, 0.125, 0.1. In this paper, there are 84 numerical model were solved numerically and plotted into several curves. Comparisons between API 579 and finite element simulation show that pressure vessel with D/t=40, 60 and 80 have percent error about 2.16 %, 9.32 % and 10.57 %, respectively. This results are reasonable due to several safety factor are included in API 579 analysis. Results of this paper can be used as consideration for make a decision regarding to integrity analysis of pressure vessel.

KEY WORDS: *Fatigue crack growth, failure prediction, pressure vessel, API 579 Standard, Finite element method.*

NOMENCLATURE

API	American Petroleum Institute
K_J	Elastic-Plastic Stress Intensity Factor
K_I	Elastic Stress Intensity Factor
E	Modulus Elasticity
J	Energy Release Rate
v	Poisson Ratio
σ_{ref}	Reference Stress
σ_y	Yield Strength
σ_c	Circumferential Stress
K_r	Brittle Fracture Ratio
L_r	Plastic Collapse Ratio
P_0	Collapse Pressure
P	Internal Pressure
a	Crack Depth
c	Crack Length
t	Thickness
R_i	Internal Radius
L	Cylinder Length

1.0 INTRODUCTION

Pressure vessels are static mechanical equipment which is used widely in industry, vehicle, and any other pressurized equipment. Beside as storage, the main function of pressure vessel is to maintain pressure of working fluid to be different with its ambient. During its operation time, deterioration may be occur to pressure vessel and its accessories. Corrosive fluid, internal or external excessive load, fabrication, and other mechanical damages are the sources of threat which will endanger integrity of pressure vessel. Chemical and mechanical threat bringing on such defect in the pressure vessel, i.e. crack, shell distortions, dent, weld misalignment, creep, blisters, laminations, and metal loss.

Cracks or crack-like flaws are the most dangerous threat which will cause sudden failure in a short time. Failure of cracked structure is analyzed based on fracture mechanics considerations rather than conventional failure theories. In fracture mechanics, failure condition takes place when stress intensity factor of certain crack greater than fracture toughness of material. Stress intensity value is depending on shape and position of crack, loading conditions, and dimension of structure. Crack is found in pressure vessel at any positions and various shape. To simplified the analysis, crack need to be characterized in certain shape and position. Semi-elliptical shape of cracks is commonly found with certain angle, longitudinal, or circumferential positions.

Several researchers were published paper related to integrity analysis of pressure vessel. Akbar and Setiawan [1] was used and developed failure assessment diagram in order to asses integrity of cylindrical shell under static load. Other paper was explained on assessment method and effect of tensile residual stress in the welded joint of vessel [2]. In remaining life prediction, Chong Xu, et.all [3] was used defect failure rate inflection point method. Si ji an Lin, et.all [4] use modification of failure assessment diagram on the basis of failure path and rate. They provide new approach in the study of structural integrity.

The major objective of this study was to investigate and validate the use of commonly used industry standard with finite element method in order to predict failure of cracked pressure vessel. Growing of crack due to fatigue load were analyzed using both analytical and finite element method. In analytical side, API 579 Code is used with involving safety and correction factor which will increase conservatism degree of the results. This paper will make a comparison between the results and it can be used as a consideration for make a decision regarding to integrity analysis of pressure vessel.

2.0 METHODOLOGY

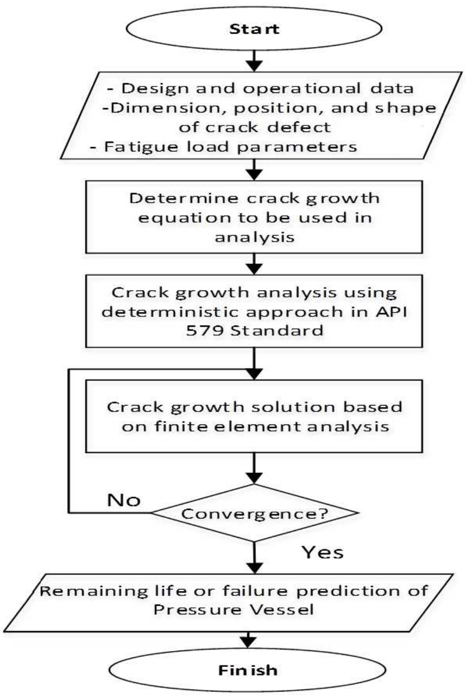

Figure 1: Flow chart of research methodology

In failure prediction analysis of cracked pressure vessel, there are two approaches was used in this research, namely analytical and numerical approach. Analytical calculation was made based on given formula in API 579 Standard whereas numerical approach was conducted using finite element method. Both of the methods then will be compared in terms of accuracy, data provided, difficulties in analysis, and any other aspects. Research methodology that was used in this work is showed in Figure 1.

2.1 Crack Growth in API 579

In API 579 Standard, crack growth of structure which is caused by fatigue load is predicted and modeled using several equations, i.e. Paris Equation, Walker Equation, Trilinear and Bilinear Equation, Modified Forman Equation, NASGRO Equation, and Collipries Equation. Paris Equation, the most famous and simplest crack growth model was used in this research. Paris Equation is provided in Eq.(1) below[5]:

$$\frac{da}{dN} = C\,(\Delta K)^n \qquad (1)$$

where, da/dN = increment of crack growth for given cycle, C= material parameter for fracture toughness, n = material parameter for crack growth modeling, $\Delta K = K_{max} - K_{min}$; if $\Delta K > \Delta K_{th}$ crack growth occurs; otherwise if $\Delta K < \Delta K_{th}$ crack growth does not occur, or da/dN=0.0. In the Code, Fatigue crack growth data is given for ferritic and austenitic steel in air or non-aggressive environment at temperature up to 100° C using Eq. (2). The equation considers to be valid only for material with yield strength less than 600 MPa (87 ksi).

$$\frac{da}{dN} = 8.61\,(10^{-10})(\Delta K)^{3.0}\,(in/cycle) \qquad (2)$$

The threshold stress intensity factor (ΔK_{th}) is used based on mentioned in the Code [5]:

$$\Delta K_{th} = 1.8\ ksi\sqrt{in} \qquad (3)$$

In crack growth analysis using API 579 Standard, a calculation sheet application was built. Parametric study of crack growth was generated using this program. Figure 2 shows screen shoot of main page of the program. As input data, dimension of cylinder and crack on its surface is given in Table 1.

Table 1: Data used for parametric study analysis using API 579

No	Vessel Dimensions			Crack Size			
	D	t	D/t	a	c	a/c	a/t
1	40	1	40	0.3	2	0.150	0.3
2	60	1	60	0.3	2	0.150	0.3
3	80	1	80	0.3	2	0.150	0.3

all dimensions in inch.

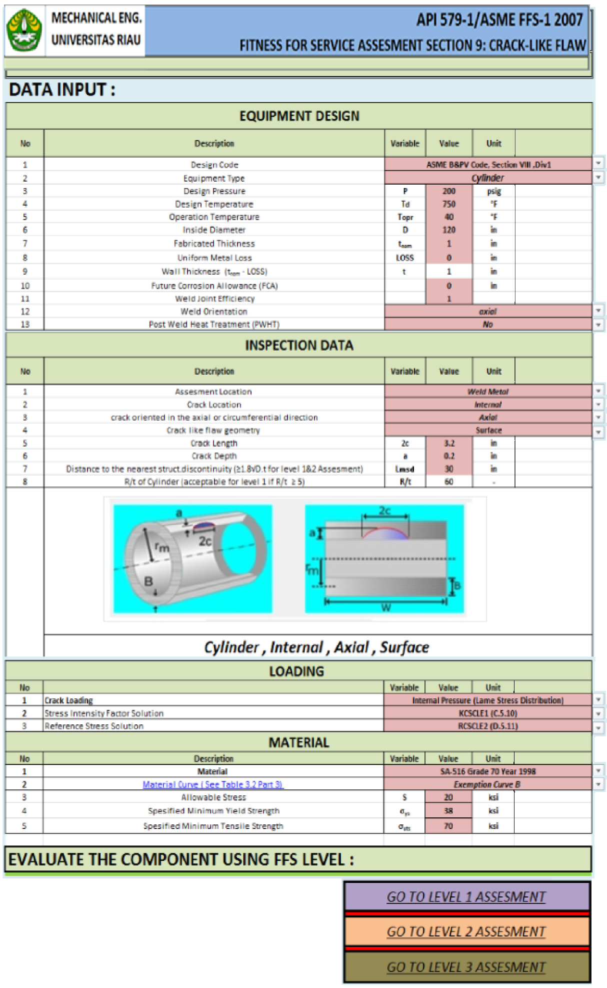

Figure 2: Screen shoot of crack growth calculation sheet program

2.2 Finite Element of Crack Growth

Numerical approach using finite element method can be used to simulate crack growth behavior of vessel material under fatigue load. This method is used widely in the area of fracture mechanics. Parametric study was simulated based on data of vessel dimension and crack size, as shown in Table 5

Table 2: Dimension of pressure vessel and its internal crack to be used in finite element simulations

No	Vessel Dimensions			Crack Size			
	D	t	D/t	a	c	a/c	a/t
1				0.3	2	0.150	0.3
2	40	1	40	0.5	4	0.125	0.5
3				0.8	8	0.100	0.8
4				0.3	2	0.150	0.3
5	60	1	60	0.5	4	0.125	0.5
6				0.8	8	0.100	0.8
7				0.3	2	0.150	0.3
8	80	1	80	0.5	4	0.125	0.5
9				0.8	8	0.100	0.8

all dimensions in inch.

Two models of crack shape that are commonly found in pressure vessel are modeled, namely semi-elliptical longitudinal and circumferential crack. Both of cracks are internal crack or it can be found on inner surface of vessel material. To make it comparable, variation of dimension whether for longitudinal or circumferential crack are kept uniform. Figure 3 shows position of crack to be analyzed in this research.

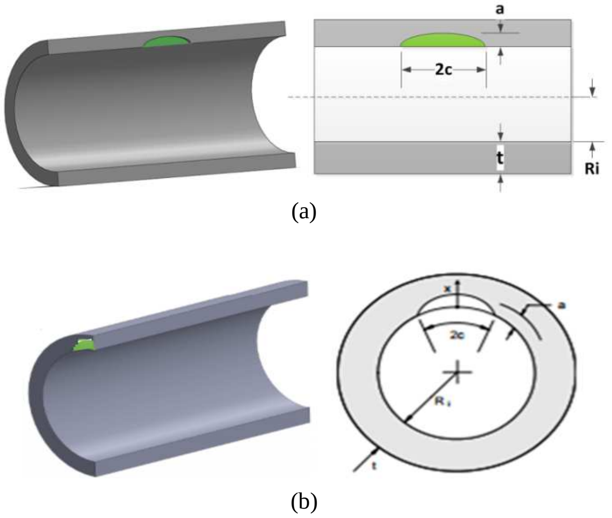

Figure 3: Position of crack in pressure vessel: (a) internal longitudinal crack, (b) internal circumferential crack

In fatigue crack growth simulations, applied internal working pressure is 200 psi (0,2ksi) with constant amplitude remain constant during pressurized and unpressurized of pressure vessel.Finite element method was used based on *J*-Integral approach. Using this method require re-meshing for the model during crack growth.

J-Integral is one of energy method that widely use and adopted in commercial finite element software. Finite element modeling of crack geometry tends to difficult and need special attention on meshing strategy around crack tip. Mesh design for the crack tip region is a spider web mesh with elements concentrated at the crack tip, as shown in the Figure 4. The first ring of elements is made up of quadrilateral degenerated to triangles with several nodes coincident at the crack tip. Isoperimetric bricks elements with 27 nodes is used here. Number of nodes and elements which are used in finite element software provides in Table 3.

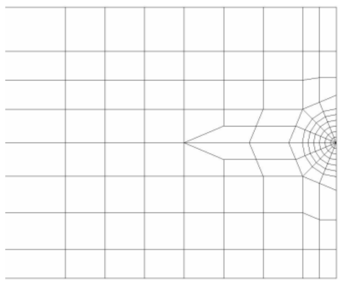

Figure 4: Spider web mesh design with elements concentrated at the crack tip [6]

Table 3: Number of elements and nodes which are used in finite element software

No	D/t	a/c	a/t	Number of Nodes	Number of Elements
1		0.150	0.3	19335	4002
2	40	0.125	0.5	42446	9250
3		0.100	0.8	41941	9180
4		0.150	0.3	27442	5870
5	60	0.125	0.5	42044	9194
6		0.100	0.8	41567	9128
7		0.150	0.3	28564	6026
8	80	0.125	0.5	43250	9362
9		0.100	0.8	42876	9310

In some Code, it is recommended to use a more accurate stress intensity factor calculation using *J*-integral. This method provided a solution to determine value of stress intensity factor either in elastic or elastic-plastic condition based on energy release rate. Another solution is based on displacement method and only available in elastic manner. In two dimensional case, *J*-Integral is define as follow [7]

$$J = \int_{\Gamma} \left(W dy - T \frac{\partial u}{\partial x} ds \right) \qquad (4)$$

where

$$W = W(x,y) = W(\varepsilon) = \int_0^{\varepsilon} \sigma_{ij} d\varepsilon_{ij} \qquad (5)$$

Γ in equation (4) is a close contour with counter clock wise direction, T is traction, $T_i = \sigma_{ij} n_j$, u is displacement in x-axis direction, and ds is an element of Γ. Based on above equations, close contour will have J value equal to zero.

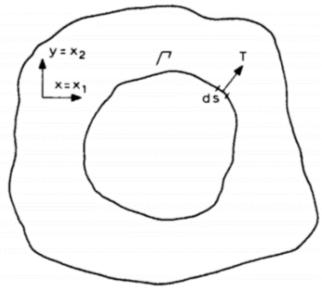

Figure 5:Definition of *J*-Integral Method [8]

3.0 RESULT AND DISCUSSION

3.1 Validation

Numerical model of cracked pressure vessel was validated before used in parametric study. Analytical formula given in API 579 is used to compare with the result of finite element simulation. Figure 6 shows a good correlation between analytical and numerical model with Sum Square Error (SSE) equal to 1.13 or equivalent to average percent error 1.52 %.

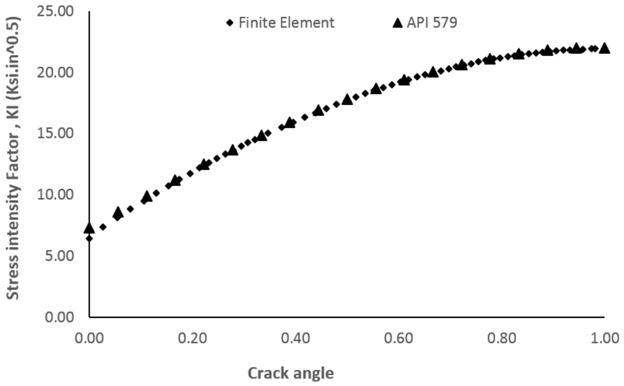

Figure 6: Validation curve for numerical model of cracked pressure vessel with D/t=60, a/t=0.4 and a/c=0.125

3.2 Result of API 579

There are three models of cylinder with same size of crack were investigated using API 579 Standard. Crack growth was calculated based on iteration cycle by cycle using Equation (2). These calculations were done using crack growth calculation spreadsheet that already prepared before (Figure 2).
Table 4 shows the result of iteration in spreadsheet program. Failure of pressure vessel is predicted after certain number of cycle. Iteration process will be stopped when crack growth reaching outer surface of pressure vessel, or in other word if depth of growing crack larger than wall thickness (a≥t). In order to make it comparable with numerical results, number of cycles are provided in two conditions, at a=0.9 in and 1.0 in. Rate of growing crack in depth (a) and length (c) direction are showed in Figure 7 and Figure 8. Pressure vessel with larger D/t tends to fail faster than vessel with small D/t. Increasing value of D/t in a cylinder will causing high longitudinal and circumferential stress in the crack region. At the same time, stress intensity which causing cracks to growth also increased.

Table 4: Failure prediction of pressure vessel using API 579

No	D/t	a/c	a/t	Number of cycle	
				at a=0.9 in	at a=1.0 in
1	40	0.150	0.3	1837000	2143100
2	60	0.150	0.3	584700	682100
3	80	0.150	0.3	298400	255800

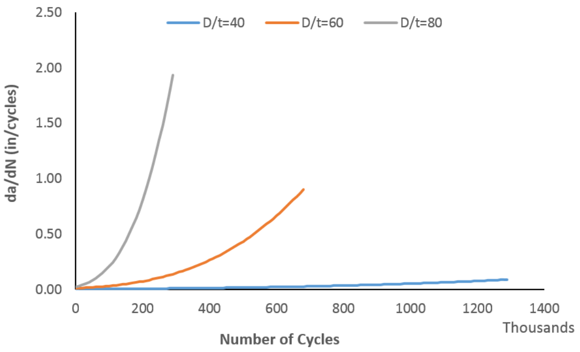

Figure 7: Growth of crack depth for three model of pressure vessel with same crack size

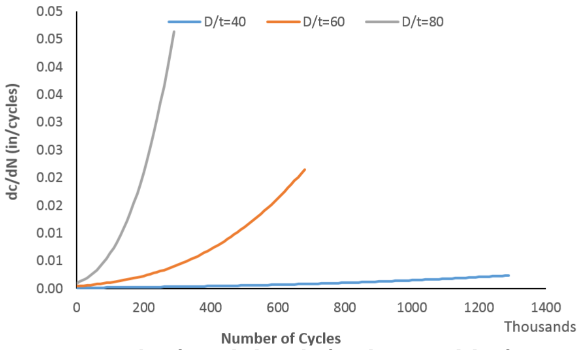

Figure 8: Growth of crack length for three model of pressure vessel with same crack size

3.3 Numerical Results

There are total 84 numerical model were generated in this research. Three variations of initial crack were modeled for three different size of vessel. Stress intensity value for each initial crack in certain vessel was taken every 0.1 inch of increasing depth. In *J*-Integral numerical model, crack face is modeled using a tube with spider web mesh concentered in the center of circles. Due to difficulties in generating the models, growing crack can only modeled up to a/t equal to 0.9. Stress intensity value of 9 initial crack in pressure vessel is showed in Table 5.All of initial crack have stress intensity value greater than stress intensity threshold (K_{th}). It means, all of initial crack will grow when cyclic internal pressure applied to pressure vessel.

Table 5: Stress intensity result for longitudinal crack

No	D/t	a/c	a/t	$K_I$at 0^0 (ksi. $\sqrt{in}$)	K_I at 90^0 (ksi. $\sqrt{in}$)
1		0.150	0.3	1.841	5.147
2	40	0.125	0.5	2.662	8.811
3		0.100	0.8	5.217	18.334
4		0.150	0.3	2.814	7.664
5	60	0.125	0.5	3.902	13.023
6		0.100	0.8	7.809	26.596
7		0.150	0.3	3.709	10.128
8	80	0.125	0.5	5.147	17.241
9		0.100	0.8	10.407	34.760

all dimensions in inch.

For each initial crack in Table 5, simulations were taken for every 0.1 inch of increasing depth. Stress intensity value for same size of initial crack and growing to maximum value in pressure vessel with various dimensions is showed in Figure 9. Each initial crack growing from a=0.3 up to a=0.9. It means, 7 numerical models were investigated for every vessel. Pressure vessel with small value of D/t has the highest fatigue life up to 1.8 million cycleswhereas if D/t reaching 80, fatigue life only 14600 cycles (pressurized and unpressurized). Figure 10 and Figure 11 are stress intensity value for other initial crack (a/t=0.5 and a/t=0.8).Initial crack with a/t=0.8 in pressure vessel with D/t=80 has the lowest fatigue life than the others.

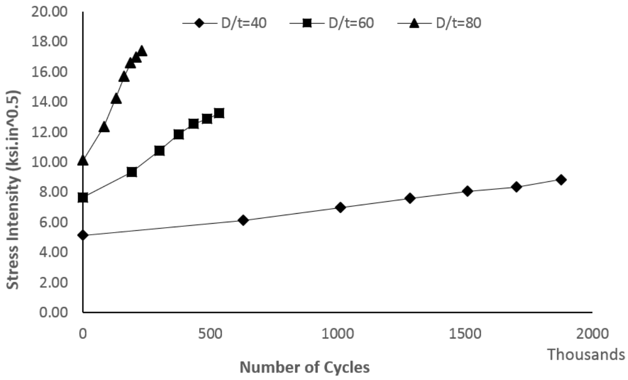

Figure 9: Stress intensity factor during crack growth for initial crack with a/t=0.3 and a/c=0.15

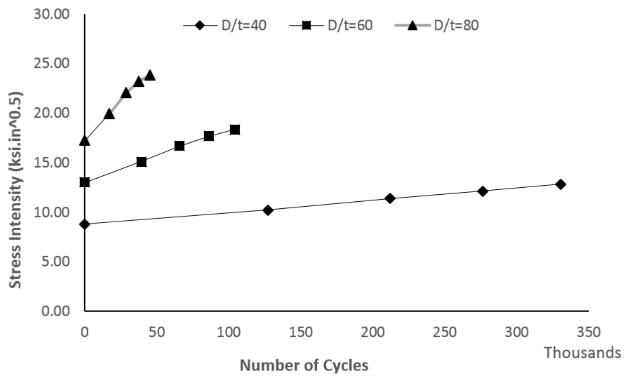

Figure 10: Stress intensity factor during crack growth for initial crack with a/t=0.5 and a/c=0.125

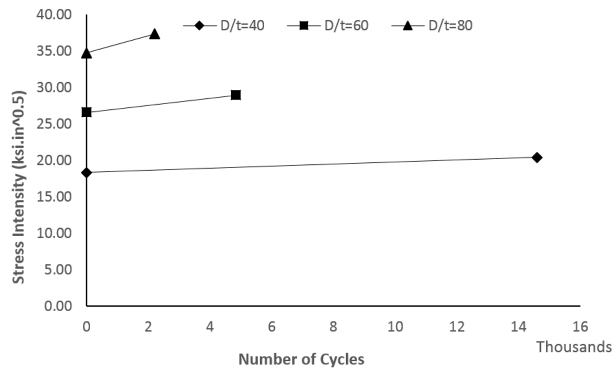

Figure 11: Stress intensity factor during crack growth for initial crack with a/t=0.8 and a/c=0.1

Growth behavior of certain initial crack can be seen in Figure 12 and Figure 13.For same size of initial crack and number of cycle to failure, crack will be growth faster in depth direction rather than in length direction. For a case with a/t=0.3, crack growing up to 200 % in depth direction whereas only 9.15 % in length direction. In Figure 14 and Figure 15, crack growth rate in terms of depth (da/dN) and length (dc/dN) are showed. In this curve, three region of fatigue crack growth can be estimated with the larges region is in the middle of curve or in stable crack growth area.

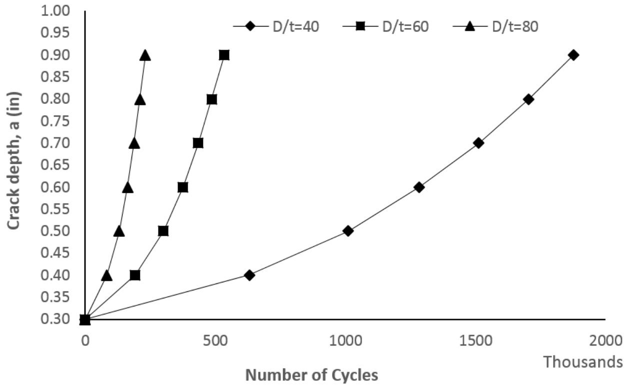

Figure 12: Depth of crack with initial value, a/t=0.3 and a/c=0.15, during crack growth

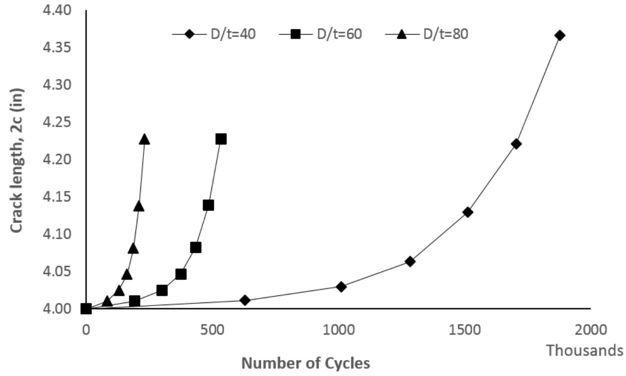

Figure 13: Length of crack with initial value, a/t=0.3 and a/c=0.15, during crack growth

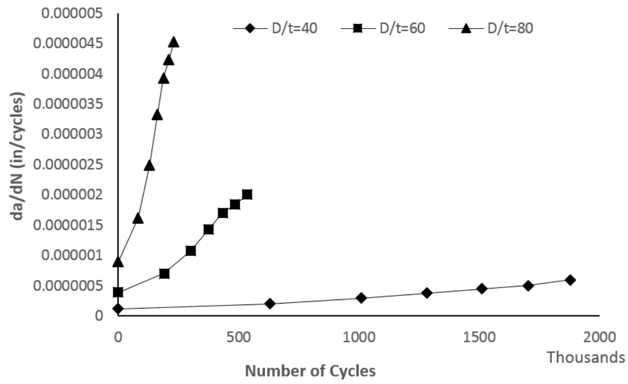

Figure 14: da/dN of crack with initial value, a/t=0.3 and a/c=0.15, during crack growth

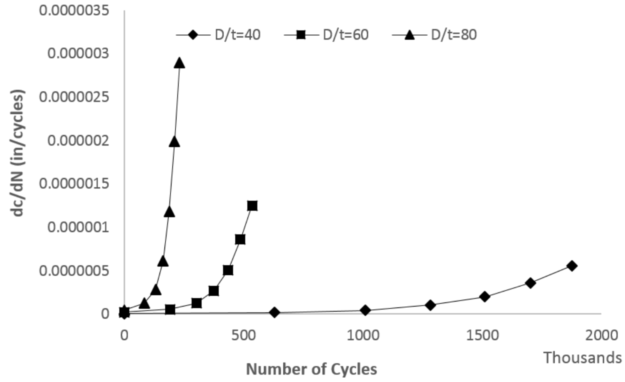

Figure 15: dc/dN of crack with initial value, a/t=0.3 and a/c=0.15, during crack growth

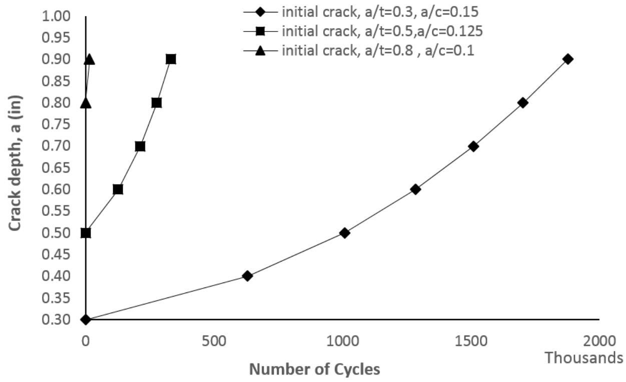

Figure 16: Increasing value of crack depth for various size of crack in pressure vessel with D/t=40

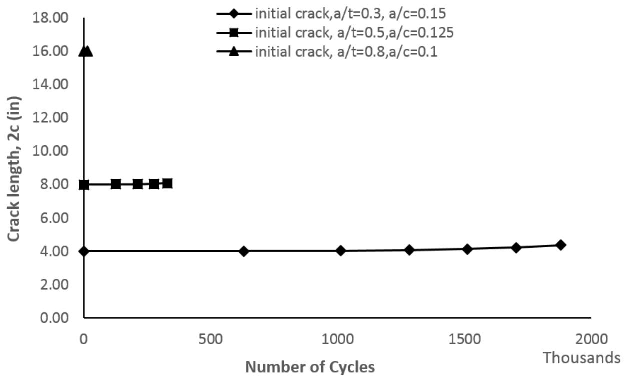

Figure 17: Increasing value of crack length for various size of crack in pressure vessel with D/t=40

Crack growth behavior of semi-elliptical circumferential crack and its effect to integrity of pressure vessel also investigated here. The results of stress intensity value for 9 models of initial crack are showed in Table 6. Stress intensity of crack with initial size a/t=0.3 and a/c=0.15 in pressure vessel with D/t=40 is lower than stress intensity threshold (K_{th}) of material. It means, there is no crack growth occurs for this model. When compared with longitudinal cracks, all value of stress intensity factor for circumferential crack are smaller than stress intensity in longitudinal crack. It means, this type of crack is not threateningintegrity of pressure vessel as longitudinal crack. Figure 18 and Figure 19 show comparison between longitudinal and circumferential position of crack in term of stress intensity and growing crack depth.

Table 6: Stress intensity result for circumferential crack

No	D/t	a/c	a/t	K_I at 0^0 (ksi. $\sqrt{in}$)	K_I at 90^0 (ksi. $\sqrt{in}$)
1		0.150	0.3	0.550	1.594
2	40	0.125	0.5	0.741	2.615
3		0.100	0.8	1.120	4.552
4		0.150	0.3	0.742	2.199
5	60	0.125	0.5	1.080	3.809
6		0.100	0.8	7.290	26.606
7		0.150	0.3	1.030	2.977
8	80	0.125	0.5	1.420	4.998
9		0.100	0.8	1.420	4.998

all dimensions in inch.

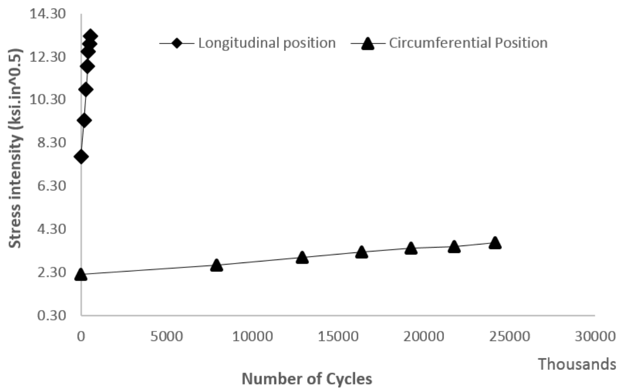

Figure 18: Stress intensity of growing crack with initial size a/t=0.3 and a/c=0.15 in pressure vessel with D/t=60

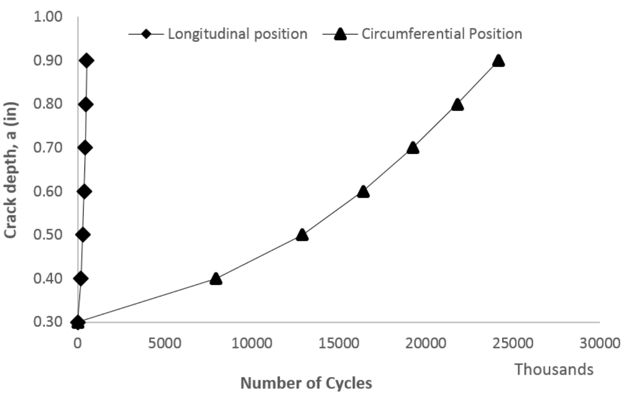

Figure 19: Crack depth of growing crack with initial size a/t=0.3 and a/c=0.15 in pressure vessel with D/t=60

Number of cycles or failure of pressure vessel which is analyzed using API 579 and finite element method are compared in Figure 20. Pressure vessel with D/t=40 has error 2.16 %, D/t=60 has error 9.32 %, and vessel with D/t=80 has error 10.57 %. This results are reasonable due to several safety factor are included in API 579 analysis.

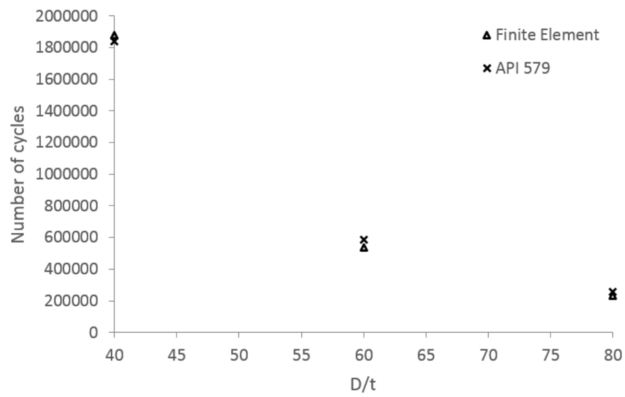

Figure 20: Comparisons of failure prediction API 579 and finite element

CONCLUSION

Failure of pressure vessel can occur due to high stress intensity factor or when depth of crack is same with wall thickness. If stress intensity factor is greater than fracture toughness of material, catastrophic failure will happen. Moreover, If depth of crack growing up to outer surface of vessel, leakage will be found in the shell. In this paper, failure prediction of cracked vessel was analyzed based on calculation using API 579 Standard and finite element method.

There are three cases of pressure vessel with certain initial crack were analyzed using API 579 Standard. Furthermore, nine cases of vessel with three variations of initial crack modeled and solved numerically. It was found number of cycle for each crack growth that will be a remaining life of the pressure vessel. When the results compared, in some cases API 579 give more conservative value rather than numerical analysis. It means, failure prediction using API 579 give large number of cycles rather than using finite element.

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