Integrity Assessment of Cracked Pressure Vessel with Considering Effect of Residual Stress Based on Failure Assessment Diagram Criteria

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ABSTRACT

During the period of its operation, a pressure vessel may experience excessive loading which can cause crack defects. Integrity analysis needs to be carried out to evaluate the feasibility operation of that cylindrical pressure vessel with defects. In this paper, integrity assessment of cracked pressure vessel under internal pressure and tensile residual stress was conducted based on failure assessment diagram criteria. This criteria applied widely and adopted in API 579-1/ASME FFS-1 2007 Code. There are three assessment levels provided in code. Level 1 and 2 assessment performed using analytical calculation while Level 3 assessment is conducted using finite element method. On a case study, failure criteria for the integrity analysis is based on the Failure Assessment Diagram (FAD), that distinguish safe and unsafe region based on two failure criteria, namely brittle fracture and ductile fracture. This diagram is built using finite element method with the assumptions of both Linear Elastic Fracture Mechanics (LEFM) and Elastic Plastic Fracture Mechanics (EPFM). Based on Level 1 assessment, the pressure vessel under study is not recommended to be operated, whilst based on Level 2 and 3 assessments the pressure vessel is considered acceptable. This study concludes that Level 1 and 2 analysis provide more conservative results when compared with level 3 analysis. Failure Assessment Diagram for Level 3 analysis relatively more conservative at elastic-plastic region (0.4≤Lr≤1), but less conservative at plastic collapse region. Parametric studies performed with increasing operating pressure and size of defects. Based on analysis, failures of the pressure vessel occur at pressure of 403 psi and an aspect ratio of 0.18 for analysis with including the effect of tensile residual stresses. Meanwhile, if the analysis is done by ignoring the effect of residual stress, pressure vessel failed at pressure of 589 psi and leak when aspect ratio reaching 0.42.

KEY WORDS: *Integriy Analysis; Failure Assessment Diagram; J-Integral; Cylindrical Shell; Residual Stress.*

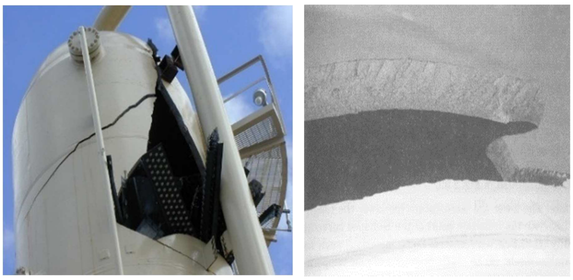
NOMENCLATURE

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

1.0 BACKGROUND

Pressure vessels are static mechanical device that used for maintain pressure and temperature of working fluid to be different with ambient temperature. In industry, pressure vessel can be categorized as high risk equipment. Failure of this equipment can be endanger the environment and have major impact to overall process in industry. Therefore, the use and maintenance of pressure vessel is strictly controlled based on code and regulations stated by government or companies.

Crack or crack like flaw is a kind of defect that can be occurred in pressure vessel. Crack can be found in manufacturing, installation, and operating process. During its operation, pressure vessel subjected to primary load, such as internal pressure, and secondary load, such as seismic load, wind load, weight load, hydrostatic load, etc. These combine of load will increase state of stress in equipment, and if plastic failure occurred, crack or crack like flaw can be appeared in the material. Corrosion attack is another source of crack. If a corrosive material combines with high stress region, stress corrosion cracking can be appeared. This type of crack should be inspect and analyze carefully to prevent sudden failure of equipment. Figure 1 show a collapse pressure vessel due to crack defect.



(a) (b)

Figure 1: Mode of failure due to brittle fracture as an effect of crack defect; (a) fail at vertical vessel (b) surface of brittle failure due to crack [1].

Failure Assessment Diagram is a criteria used in assessment of mechanical equipment containing crack. This method introduced firstly by Ainsworth[2] and applied generally in several Code, i.e. API 579-1/ASME FFS-1 2007, SINTAP, FITNET, BS 7910, R6 Method, and PD 6493 [3]. In API 579, integrity of cracked pressure vessel can be assessed using three level of assessment. Conservatism and complexity of analysis for each assessment level as show in Figure 2. To provide more accurate result of assessment, Level 3 should be held by competence engineer in field of structural integrity [3]. The used of FAD criteria was applied by Tipple [4] to determine feasibility operation of pressure vessel containing crack at intersection between nozzle and shell. Using this criteria, remaining life of pressure vessel can be predicted analytically and numerically. Not only for crack, FAD criteria also can be used for assessment of notched components [5] and high temperature fracture [6].

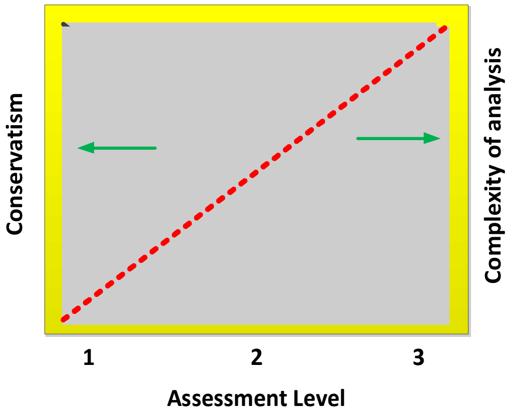


Figure 2: Complexity and conservatism of three level assessments in API 579.

In pressure vessel, residual stress has a major impact to failure of pressure vessel. Residual stress can be emerged in welding process and installation of the equipment. Residual stress become a serious threat due to unknown and unpredictable state of stress in the region of shell. In API 579, effect of residual stress on integrity of cracked pressure vessel is considered. Several investigation also conducted by researcher in this field. Jeyakumar [7] using finite element analysis to predict failure pressure of cylindrical pressure vessel containing welding residual stress. Firstly, elastic-plastic finite element is used to predict failure pressure of cylindrical shell without containing residual stress. Then a thermo-mechanical finite element is preformed to investigate the effect of residual stress to reduction of failure pressure. Another researcher, Cannas et.al. [8] study the residual stress in aluminum alloy numerically. To validate his numerical result, experimental method using blind hole technique was performed to investigate the influence of residual stress to strain hardening of material.

This paper aimed at investigate the use of Failure Assessment Diagram (FAD) criteria stated in API 579 code in integrity assessment of cracked pressure vessel with considering effect of residual stress in the equipment. There are two kind of FAD constraint which will be used here, namely FAD Level 2 (generate based on given equation in Code) and FAD Level 3 (generated using numerical analysis). Conservatism degree for each diagram will be investigated and applied to integrity assessment of cracked pressure vessel with and without considering effect of residual stress. Finally, for certain size of crack, failure pressure and failure mode of pressure vessel can be predicted from the diagram.

2.0 METHODOLOGY

2.1 *J*-Integral

In order to generate specific Failure Assessment Diagram (FAD) which depend on material and geometry of crack and cylinder, finite element simulation need to be conducted. Finite element simulation is used to determine the value of stress intensity factor around crack front based on mode of applied load to the crack. Several finite element method were developed and applied widely in commercial finite element software, i.e. displacement method, virtual crack closure method, and *J*-integral method. The last one is preferred to be used in finite element due to its ability to apply in both region of fracture analysis, namely linear elastic and non-linear elastic-plastic fracture mechanics. To build FAD, both of the fracture analysis need to be conducted separately. In two dimensional case, *J*-Integral is define as follow [9].

$$J = \int_{\Gamma} \left(W dy - T \frac{\partial u}{\partial x}\, ds \right) \qquad (1)$$

Where

$$W = W(x, y) = W(\varepsilon) = \int_0^{\varepsilon} \sigma_{ij} d\varepsilon_{ij} \qquad (2)$$

Γ in Eq. (1) 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.

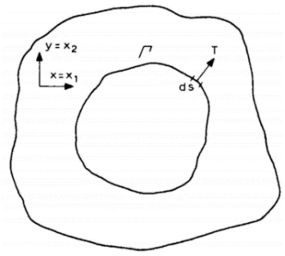
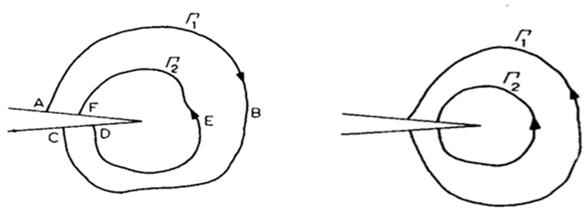


Figure 3: Definition of *J*-Integral Method [9].



(a) **(b)**

Figure 4: J-Integral contour around crack front: (a) close contour with zero value, (b) two contour with same integral value [9].

The concept of mathematical integral in abovementioned equation is used to get the solution of energy release rate at crack tip. *J*-Integral value which is defined along path or contour around crack is used to get number of potential energy (*V*) were changed during crack extension (∂a) process. Then, the value of *J*-Integral can be defined as follow [9].

$$J = -\frac{\partial V}{\partial a} \qquad (3)$$

For elastic materials,$-\partial V/\partial a = G$, hence *J*=*G*. Then, Eq.(4) and Eq.(5) are used to get the value of Mode I Stress Intensity Factor for cases of plane stress (Eq.4) and plane strain (Eq.5).

$$J_I = G_I = \frac{K^2}{E} \qquad (4)$$

$$J_I = G_I = \frac{K^2}{E}\,(1 - v^2) \qquad (5)$$

For a case of surface crack, the value of stress intensity factor are various along crack front. In some cases, maximum value is found at maximum depth whereas in some cases it's found at surface of the wall. Raju and Newmann [10] was derived an equation (Eq.6) for semi-elliptical crack at internal side of cylindrical shell. Geometry factor (F) is function of crack and cylinder size and usually provided in code or crack handbook. To define the shape of ellipse, Q is calculated based on elliptical integral of second kind (Eq.6) and empirically can be calculated using Eq.(8) and Eq.(9). In this paper, the value of stress intensity factor is derived from numerical method based on *J*-Integral calculation.

$$K_I = \frac{pR_i}{t}\sqrt{\frac{\pi a}{Q}}\,F\left(\frac{a}{c}, \frac{a}{t}, \frac{Ri}{t}, \theta\right) \qquad (6)$$

$$Q = \int_0^{\frac{\pi}{2}} \left(1 - \frac{c^2 - a^2}{a^2} \sin \emptyset^2\right) d\emptyset \qquad (7)$$

$$Q = 1 + 1.464 \left(\frac{a}{c}\right)^{1.65} \quad untuk \quad \frac{a}{c} \leq 1 \qquad (8)$$

$$Q = 1 + 1.464 \left(\frac{c}{a}\right)^{1.65} \quad untuk \quad \frac{a}{c} > 1 \qquad (9)$$

2.2 Failure Assessment Diagram

Failure Assessment Diagram criteria is used when deterministic method is carried out rather than probabilistic method to assess feasibility operation of pressure vessel. Deterministic method is used with constant parameter as input whereas probabilistic method is applied with considering uncertainty of input parameter in analysis [11]. In application, both of the method can be compared to enhance the result of analysis.

API 579/ASME FFS-1 Code has outlined a procedure for assessing the integrity of damaged pressure vessels through Fitness For Service (FFS). As explained previously, a more detail and accurate analysis can be carried out using Level 2 or Level 3. In Level 2 assessment, the knowledge of loading, vessel dimensions, vessel mechanical properties, crack dimensions and other information lead to the *Load Ratio*, L_r, and *Brittle Fracture Ratio*, *Kr*. The Code provides with the tabular data for limited range variations of cylindrical shell dimensions (i.e. thickness to internal radius ratio, *t/Ri*), crack size (i.e. crack depth to wall thickness ratio, *a/t*, and crack aspect ratio, *a/c*). An equation (Eq.10) also provided in this level to generate Failure Assessment Diagram(FAD) that serves as a criterion to separate between SAFE or UNSAFE condition. On the other hand, a procedure to calculate the coordinate of the *Plastic Collapse Ratio* and *Brittle Fracture Ratio* are calculated and placed on the FAD as abscissa and ordinate, respectively, from which the damage condition of the vessel can be assessed.

In assessment process, exact value of stress intensity factor is used to determine the position of assessment point of existing crack in the diagram. The abscissa and ordinate point of assessment point can be calculated using Eq.(11) and Eq.(12), respectively. Simplification of procedure in creating failure assessment diagram is show in Figure 5. The scheme diagram is developed from procedure outlined in API 579 Code.

$$f_1(L_R) = \left[1 - 0{,}14{L_r}^2\right]\left[0{,}3 + 0{,}7\exp(-0{,}65(L_r)^6)\right] \qquad (10)$$

$$K_r = \frac{K_I}{K_J} \qquad (11)$$

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \qquad (12)$$

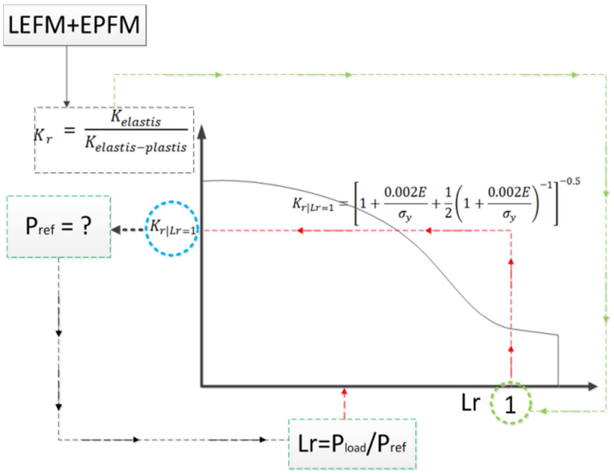


Figure 5: Scheme diagram to generate specific FAD using finite element simulation.

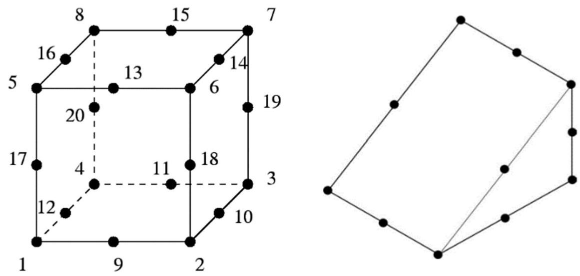
The abovementioned equations only applicable if there is no residual stress in the material. If residual stress is exist, API 579 Code provide Eq.(13) and Eq.(14) to be used. Plasticity interaction factor (ϕ) is used here due to plastic deformation and current residual stress which take place in material.

$$K_r = \frac{K_I^P + \phi K_I^{SR}}{K_{mat}} \qquad (13)$$

$$L_r = \frac{\sigma_{ref}^{SR}}{\sigma_y} \qquad (14)$$

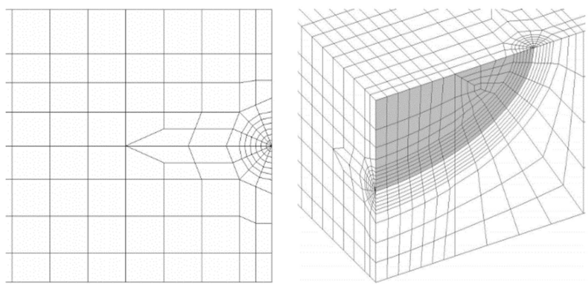
2.3 Finite Element Modelling

Finite element analysis based on *J*-Integral, an energy-based method, is used here. The advantage of this method is can be used for both linear and non-linear fracture analysis. Crack-tip element which recommended to be used are isoperimetric brick type (20 or 27 node) [3,11]. Spider-web mesh with concentrated element at crack tip is used. First ring of mesh is using wedge element (Figure 6.b) and next ring is using brick element (Figure 6.a). Typical design of mesh which recommended by several literature [3,11] as shown in Figure 7.



(a) (b)

Figure 6: Type of element to be used in finite element simulation: (a) element brick with 20 nodal (b) element wedge at crack tip[11].



(a) (b)

Figure 7: Typical design of 3D crack mesh: (a) spider web mesh design with element concentration at crack tip, (b) 3D brick element with isoperimetric 20 node [11]

Dimension of pressure vessel and size of crack which will be analyzed in finite element simulation are shown in Table 1. ASTM SA-516 material is used and its mechanical properties as shown in Table 2. Internal pressure is applied at crack face and increased gradually in order to investigate maximum value of stress intensity along crack in the region of linear elastic and non-linear plasticity. In plasticity analysis, Ramberg-Osgood model, generated using Eq.(15) - Eq.(17), is used to generate stress-strain curve of material [11]. Generated stress-strain curve of ASTM SA-516 material is shown in Figure 8. Figure 9 show the solid model of pressure vessel, and position of crack in shell side as illustrated in Figure 10. In simulations, semi elliptical crack is modeled in full length (Figure 11.a) and spider web mesh was generated, as shown in Figure 11.b.

$$\varepsilon_{us} = 100 \cdot \left(\varepsilon_r - \frac{\sigma_u}{E} \right) \quad (15)$$

$$n = \frac{Ln(\varepsilon_{us} / 0.2)}{Ln(\sigma_u / \sigma_y)} \quad (16)$$

$$\varepsilon = \frac{\sigma}{E} + 0.002 \cdot \left(\frac{\sigma}{\sigma_y} \right)^n \quad (17)$$

Table 1: Dimension of pressure vessel and crack to be assessed and modeled in finite element analysis.

No	Variabel (symbol)	Value	Unit
1	Internal radius(*Ri*)	60	*in*
2	Length of cylinder (*L*)	200	*in*
3	Thickness of cylinder (*t*)	1	*in*
4	Crack length (*2c*)	3.2	*in*
5	Crack depth (*a*)	0.2	*in*

Table 2: Material specification of ASTM SA-516 Gr.70 .

Mech. Properties	Unit (ksi)	Unit (MPa)
Tensile strength	70-90	485-620
Yield strength	38	260
Elongation (8 in)	17 %	
Elongation (9 in)	21 %	

σ (Ksi)	ε
0.0	0.00000
7.6	0.00025
15.2	0.00050
22.8	0.00079
30.4	0.00136
32.4	0.00164
34.3	0.00202
36.2	0.00254
38.1	0.00324
41.4	0.00504
44.8	0.00795
48.2	0.01256
51.8	0.01964
55.7	0.03021
59.9	0.04558
64.6	0.06736
70.1	0.09741
76.7	0.13779
84.7	0.19062

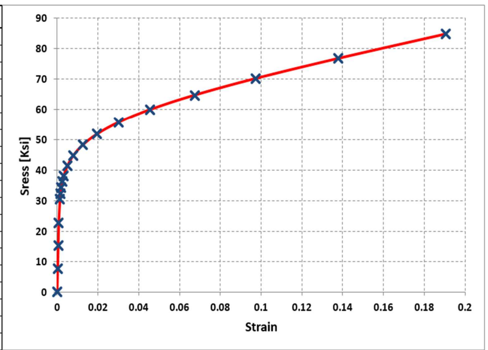


Figure 8: True stress-strain curve of ASTM SA-516 Gr.70 which generated using Ramberg-Osgood formula.

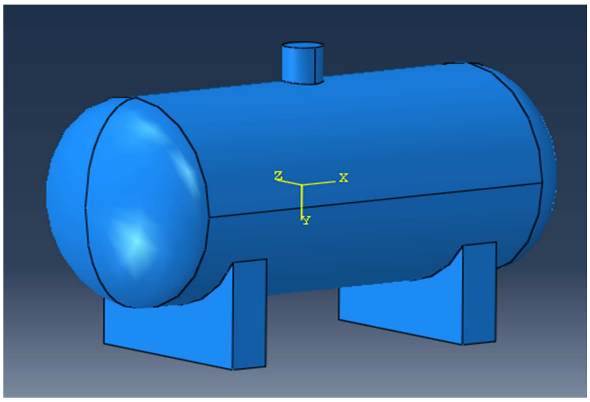


Figure 9: Solid model of cylindrical pressure vessel which containing crack at longitudinal weld joint.

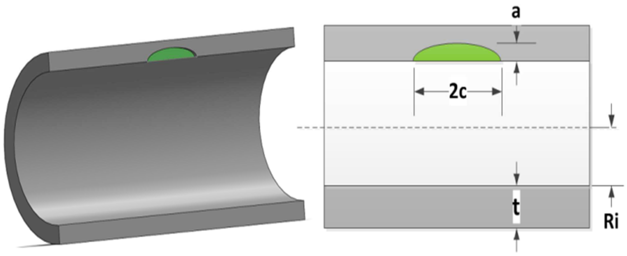
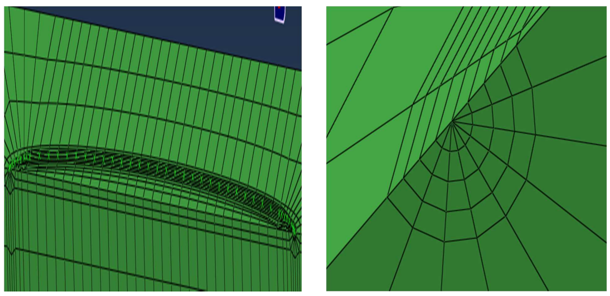


Figure 10: Position of semi-elliptical crack at inside surface of cylindrical shell.



(a) (b)

Figure 11: Typical of meshing near crack area: (a) node along semi-elliptical crack front, (b) spider web mesh near crack front.

3.0 RESULTS AND ANALYSIS

3.1 Validation of the Results

Numerical results were resulted from this research then compared directly with the results of stress intensity factor which is calculated using API 579 Code. API 579 Code only provide required tables and an equation to calculate the value of Stress Intensity Factor *(K_I)* for certain geometry of crack and shell. Therefore, the value of *J*-Integral resulting from finite element simulations need to be converted into Stress Intensity Factor *(K_I)* using Eq.(4). Finite element software was used to solve the *J*-

Integral solution of 45 nodal position along crack front. The position of each nodal and meshing that used in this simulation is shown in Figure 11.Validation was take for a case of semi elliptical crack with position at inner wall of the shell. A cylindrical shell with thickness ratio (t/R_i)=0.0167, and a crack with (a/t)=0.2 and (a/c)=0.125was modeled here (all ratio is calculated from data in Table 1).

The results of energy release rate (*J*-Integral) of semi elliptical crack along crack front can be seen in Figure 12. Figure 13 showed a comparison between the values of K_I resulting from finite element simulations with K_I provided by the API 579 Code. A good agreement is shown with the value of Sum Square Error (SSE) equal to 0.624 (Table 4).

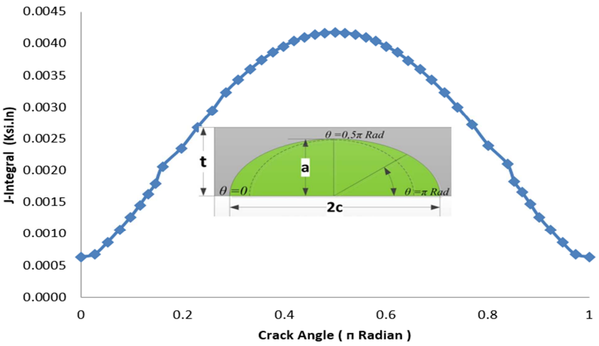


Figure 12: Results of finite element simulations in form of energy release rate (*J*-Integral) along crack front.

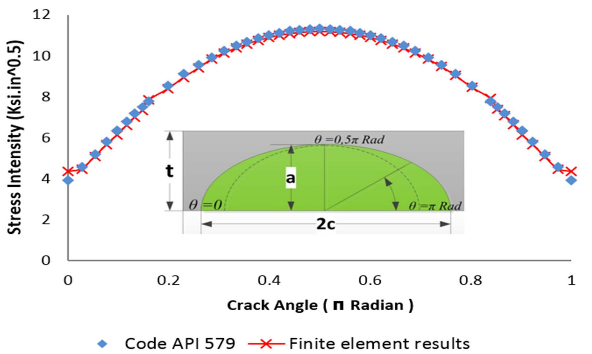


Figure 13: Validation of finite element results to stress intensity solutions which provided by API 579.

Table 3: The value of K_I resulted from FE simulations and API 579 Code (half symmetry, Nodal No. 1-23).

Nodal No.	Crack Angle (π rad)	FEM Results (ksi.in^0.5)	API 579 (ksi.in^05)	SSE
1	0	4.3555	3.9447	0.1688
2	0.0271	4.4884	4.5708	0.0068
3	0.0529	5.0888	5.2132	0.0155
4	0.0765	5.6603	5.8100	0.0224
5	0.0978	6.1486	6.3448	0.0385
6	0.1157	6.5907	6.7825	0.0368
7	0.1321	6.9938	7.1682	0.0304
8	0.1470	7.3295	7.5074	0.0317
9	0.1608	7.8673	7.8079	0.0035
10	0.1981	8.3997	8.5571	0.0248
11	0.2300	8.9671	9.1236	0.0245
12	0.2587	9.4050	9.5725	0.0280
13	0.2850	9.8490	9.9378	0.0079
14	0.3098	10.142	10.240	0.0095
15	0.3333	10.384	10.492	0.0116
16	0.3558	10.589	10.702	0.0127
17	0.3776	10.762	10.876	0.0131
18	0.3988	10.896	11.018	0.0149
19	0.4195	11.006	11.132	0.0159
20	0.4399	11.089	11.218	0.0167
21	0.4601	11.148	11.279	0.0174
22	0.4800	11.182	11.317	0.0181
23	0.5000	11.194	11.332	0.0192
				SSE=0.6241

3.2 Assessment of Level 1 & 2

In assessment Level 1, screening criteria is applied based on screening curve which provided in API 579. There is no analysis of residual stress effect can be involved in this level. Based on assessment in this level, for an internal longitudinal crack with 3.2 inch length, maximum permissible crack length is only up to 0.2 inch (Table 4). It means, with current defect, pressure vessel is not acceptable to continue for operation.

Different results may be exist in the next level of assessment. Increasing level of assessment means decreasing conservatism degree of the results. In level 2, a failure assessment diagram is started to use as failure criteria. Failure assessment diagram slope is created based on given equation provided in Code and literature [3,11]. The results of assessment in this level are provided in Table 5 and Table 6. Then, data of assessment point can be plotted into diagram to measure acceptance of crack defect at current dimension. In Figure 14, FAD Level 2 and assessment point for each analysis are plotted together. From the diagram, all of the assessment point are in safe region area. It can be concluded that pressure vessel is acceptable for continue operation. The effect of residual stress also investigated in this level. The results show that there is a significant effect of residual stress in increasing value of *Kr* coordinate. It means, a cracked pressure vessel will fail with brittle fracture rather plastic collapse. To improve accuracy of the analysis, assessment can be continue to level 3 which is using finite element method.

Table 4: The result of level 1 crack assessment.

Crack length *(inch)*	Maximum permissible crack length *(inch)*
3,2	0,2

Table 5: The result of level 2 assessment without considering effect of residual stress.

Crack angle (θ)	*Lr*(Max=1,420)	*Kr* (Max=0.961)
0°	0,321	0,045
90°	0,321	0,131

Table 6: The result of level 2 assessment with considering effect of residual stress in analysis.

Crack angle (θ)	*Lr*(Max=1,420)	*Kr* (Max=0.961)
0°	0,485	0,274
90°	0,485	0,789

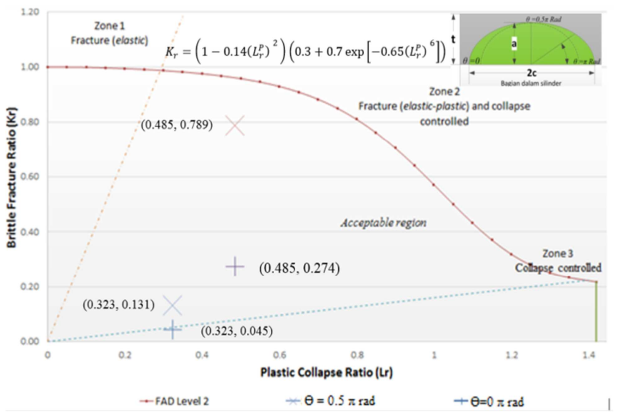


Figure 14: FAD Level 2 of pressure vessel containing crack with including effect of residual stress in analysis.

3.3 Assessment Level 3

Finite element method was used in this level to examine the value of stress intensity factor along crack front. In this level, maximum stress intensity factor resulted from finite element analysis is used to build FAD Level 3.To build FAD, two kind of finite element analysis need to be conducted, namely Linear Elastic Fracture Mechanic (LEFM) and Elastic Plastic Fracture Mechanic (EPFM). The analyses were taken separately and 10 step of increased pressure were simulated gradually. The internal pressure was chosen to accommodate resulted stress take place in elastic and plastic region of shell material. The result of *J*-Integral for 10 step of increased internal pressure can be seen in Figure 15. *J*-Integral value increased as increasing value of internal pressure whether in LEFM or EPFM analysis.

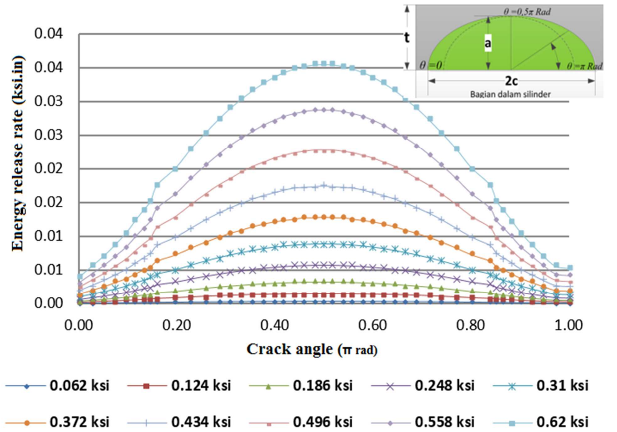


Figure 15: *J*-Integral result along crack front for 10 step of increased internal pressure for LEFM analysis.

J-Integral result then converted into stress intensity factor using Eq. (4) for linear elastic analysis and using Eq.(5) for elastic plastic analysis. For all simulations were carried out in this paper, maximum value of stress intensity factor occurred at Ө=90° or equal to 0.5 π radian (Figure 16). In order to constructing FAD diagram, only maximum value of stress intensity factor or the most critical point need to be used in analysis. It means, FAD diagram only created for nodal No.23 (Table 3) or at the deepest position of crack in the wall side.

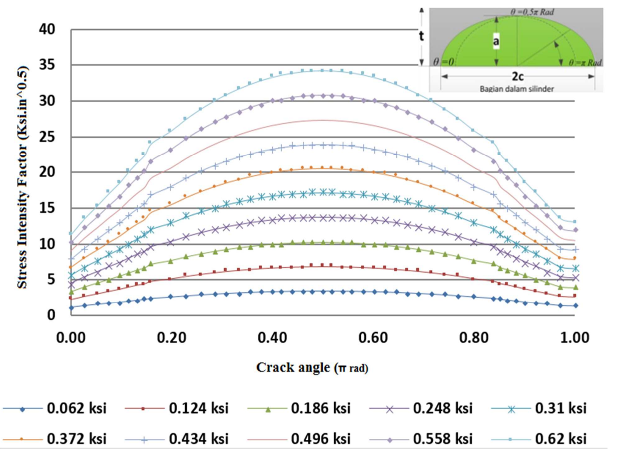


Figure 16: Stress intensity factor along crack front for 10 step of increased internal pressure for LEFEM analysis.

In FAD procedures (Figure 5), iteration process were conducted to find out collapse pressure of cylinder under elastic and elastic-plastic conditions. Using both of assumption, the value of energy release rate and stress intensity factor increase with variations of internal pressure. But, in the case of LEFM, finite element simulation can be carried out only up to yield strength of material (38 ksi) which can be reached when applied internal pressure equal to 0.62 ksi. Then, data of stress intensity factor for internal pressure greater than 0.62 ksi is inferred using extrapolation equation. For the finite element analysis using second assumption, EPFM, large deformation algorithm involved within the software. Nonlinearities of material data in the area of plasticity generated using the Ramberg-Osgood equation (Eq.17). in this kind of simulation, internal pressure increased gradually up to 20 step. A close iteration step need to be refined in the area of nonlinearities, as shown in the Figure 17.

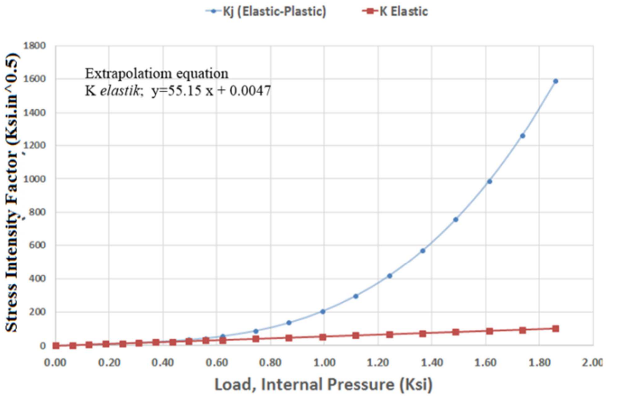


Figure 17: Stress intensity factor with increased of internal pressure under LEFM and EPFM assumption.

By using numerical data as provided in Figure 17, a failure assessment diagram can be constructed using Eq.(11) and Eq.(12). Detail of numerical data in creating the diagram is shown in Appendix 1. A good agreement is showed between FAD Level 2 which generated using Eq. (10) compared to FAD Level 3 which generated using finite element analysis. As shown in Figure 18, the generated curve tend to more conservative in collapse controlled area whereas less conservative in mixed or elastic-plastic region. In other words, it means acceptance region of curve is wider in mixed region and narrower in plastic collapse region.

After failure criteria is stated, assessment point for certain size of crack (Table 1) was assessed. Finite element simulation is used to determine the value of stress intensity factor. The simulation results then converted into *Kr* as ordinate and *Lr* as abscissa of the diagram. The result coordinate of the assessment is shown in Table 7 and Table 8. Then, assessment coordinate can be plotted into Figure 18. From diagram, it can be seen clearly that there is a different result between assessment point using Level 2 and Level 3. The result of level 3 tend to less conservative or in other word more optimistic rather than that one resulted from Level 2 analysis.

Table 7: Assessment point for Level 3 analysis without considering effect of residual stress.

Crack angle (*θ*)	*Lr*(Max=1.420)	*Kr* (Max=0,989)
0º	Not critical	Not critical
90º	0,311	0,09

Table 8: Assessment point for Level 3 analysis with considering effect of residual stress.

Crack angle (*θ*)	*Lr* (Max=1.420)	*Kr*(Max=0,989)
0º	Not critical	Not critical
90º	0,311	0,728

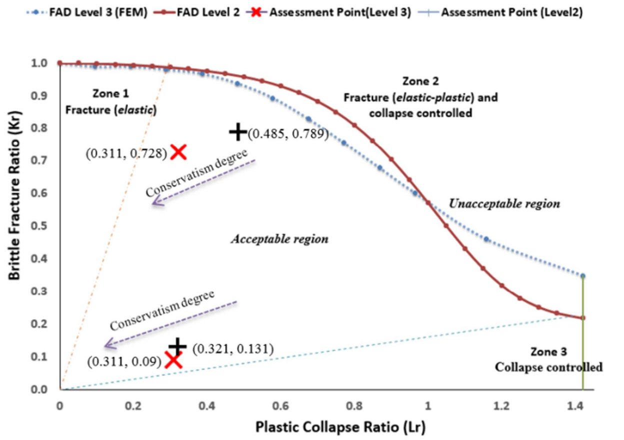


Figure 18: Comparison between the result of integrity assessment of cracked pressure vesselin Level 2 and Level 3.

3.4 Parametric Study

Parametric studies were carried out in order to obtain failure pressure of pressure vessel with and without considering effect of residual stress. In Figure 19, increased internal pressure was applied to certain size of crack (Table 1). Based on simulation results, pressure vessel will be fail at 589 psi if there is no residual stress effect including in analysis. If residual stress take into account in analysis, pressure vessel will be fail at lower internal pressure, i.e. at 403 psi.

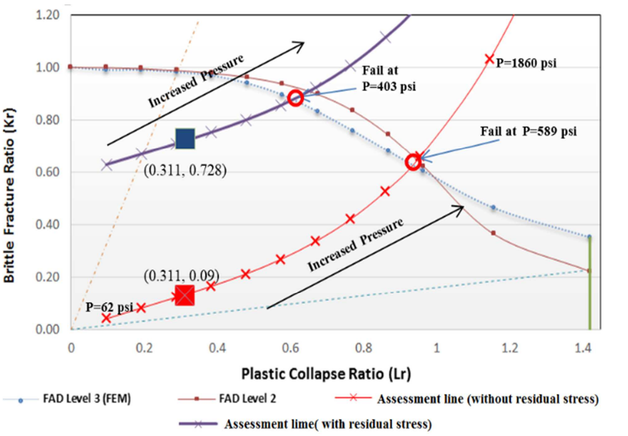


Figure 19: Parametric study with increased internal pressure of pressure vessel.

In another case, parametric study were conducted to a pressure vessel with variation of crack size. In this simulations, internal pressure remain constant at 0.2 ksi and temperature 40 °F. Dimension of crack, in form of aspect ratio, is increased in simulations. From Figure 20, it can concluded that failure of pressure vessel with including residual stress effect occur when aspect ratio (a/c) of crack reach 0.18. If residual stress is neglected in analysis, leakage of pressure vessel occurred when aspect ratio of crack equal to 0.42.

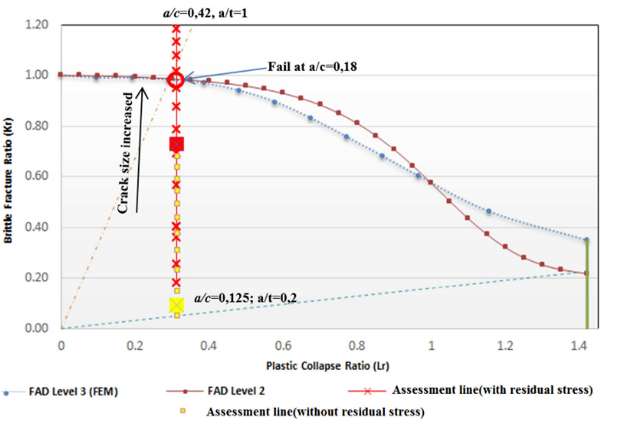


Figure 20: Parametric study with increased size of crack in pressure vessel.

4.0 CONCLUSION

This research describes the usage of three levels assessment in integrity analysis of cracked pressure vessel. Failure assessment diagram was used as criteria which is distinguish safe and unsafe region based on two failure criteria, namely brittle fracture and ductile fracture. FAD can be generated using general equation given in code or by using finite element simulations.

In this research, finite element study with assumptions of linear elastic and elastic plastic fracture mechanics were carried out systematically to generate slope equations of FAD. Moreover, assessment point for a case of crack in pressure vessel was investigated using three level of assessments. Based on the results of this research, the following conclusions can be made:

1. Based on Level 1 assessment, the pressure vessel under study is not recommended to be operated, whilst based on Level 2 and 3 assessment the pressure vessel is considered acceptable. This study concludes that Level 1 and 2 analysis provide more conservative results when compared with level 3 analysis
2. Failure Assessment Diagram (FAD), which are generated using finite element simulations, tend to have a limited acceptance area in elastic-plastic region ($0.4 \leq Lr \leq 1$). Meanwhile, in the area toward plastic collapse region ($Lr > 1$), this curve tend to more optimistic or wider acceptance area.
3. Based on analysis, failure of the pressure vessel occur at pressure of 403 psi and an aspect ratio of 0.18 for analysis with including the effect of tensile residual stresses. Meanwhile, if the analysis is done by ignoring the effect of residual stress, pressure vessel failed at pressure of 589 psi and leak when aspect ratio reaching 0.42.

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