Simulation Effect of Crack Depth and Crack Location on Cylindrical Pressure Vessel

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Abstract. In the present study the problem of calculation of the stress intensity factors (SIF) of semi-elliptical cracks located in the shell and knuckle area of a pressure vessel is numerically solved by 3D Extended finite element method (XEFM) analysis. Crack also will be varied based on crack depth at constant elliptical ratio. The modeling details of the sub-structuring methodology, employed in the analysis, are discussed and the numerical approach is proven to be very efficient for the SIF calculation of pressure vessel semi-elliptical crack. Result of study show that crack with the same geometry, crack located in the shell has more tendency to propagate compare to crack located in the knuckle area. This phenomenon is due to stress at shell is dominated with tensile stress while in the knuckle area, stress is dominated with compressive stress.

1. Introduction
Pressure vessels are widely used in industries and cracks can usually be observed in this type of structures. In addition to manufacturing procedures, environmental effect like corrosion can cause the vessels to be cracked. Several researches have been conducted in order to investigate the behavior of pressure vessels and pipes containing cracks that include geometry and location of crack. Geometry of crack includes the depth of the crack, the width of the crack, the angle of deflection of the crack, the aspect ratio of the crack shape and also the thickness of the pressure vessel itself.

Kurt and Ahyan [1] conducted a crack study on thin-wall pressure vessels (Ro / Ri <0.1) and thick-walled. This research was carried out with variations in crack depth and aspect ratio of crack shape. The results showed that the thicker the pressure vessel, the lower the SIF value. The SIF value is also influenced by the depth of the crack, the crack deflection angle, where the higher the value of the two parameters, the SIF value also rises.

Alizadeh and Dehestani [2] in their research conducted an internal critical pressure simulation on cylindrical pressure vessels that had crack defects. The study was conducted with variations in crack width by analytical and numerical methods of the extended finite element method (XFEM) type. The simulation results show that the critical pressure is affected by the width of the crack where the wider the critical pressure will decrease. Pressure vessels are also more susceptible to failure by external cracks than internal cracks of the same crack length and width.

For other geometries, for example coating thickness on pressure vessels, Eskandari et al [3] do crack analysis on round pressure vessels coated with Functionality Graded Material (FGM) type coatings. SIF calculations vary with coating thickness. The results showed that the crack geometry and
coating thickness significantly influence the value SIF. The study was conducted with the finite element method which was validated by the Crack Opening Displacement (COD) analytical method.

In the fracture mechanism there are three modes of plastic deformation, namely Mode I Opening, Mode II Sliding and Mode III Tearing. Related to the relationship of crack geometry and crack deformation modes, Preda et al [4] confirm that mode III has a more significant effect compared to mode II. The study was conducted with variations in depth and width of cracks with pressure vessels subjected to pure tension loads.

Associated with other crack geometry parameters, Yang et al [5] conducted a study related to the effect of the aspect ratio of crack shape with a value of more than one on a cylindrical pressure vessel. Research conducted by the weight function method which is validated numerically and analytically. The simulation results carried out show that the higher the aspect ratio value, the higher the SIF value.

Perl and Bernshtein [6] in their research, simulating the distribution of SIF mode I for various cracks with three-dimensional numerical methods. Simulated variations include the number of cracks, the ratio of crack depth to wall thickness and the degree of crack shape ellipticity. The results obtained indicate that SIF is influenced by these three parameters.

Besides geometry, the location of the crack is also an additional parameter in influencing the strength of the pressure vessel. Ma et al. [7] conducted a cracking study on cylindrical pressure vessels used to refill hydrogen. Crack location is varied in the middle position of the cylinder, structure and shoulder. The results of simulations with numerical methods show that the distribution stress at the middle position of the cylinder is lower than that of the structure and shoulders. This has an impact on the longer fatigue life for cracks in the middle position of the cylinder.

Crack locations on pressure vessels can be in the form of longitudinal cracks and circumferential cracks. Moustabchir et al [8] carried out experimental and numerical research to study how this crack location influences to the sensitivity of crack propagation. The results of experiments with the installation of a strain gauge near the tip of the crack, show that longitudinal cracks are more sensitive to cracking than circumferential cracks.

Research related to the location of cracks relative to wall thickness has been carried out. Livieri and All [9] conducted an SIF analysis on subsurface crack type under surface on round and cylindrical pressure vessels. The method used is a polynomial weight function based on a second order estimate of the Oore-Burns integral in terms of the contour deviation of a disk.

In pressure vessels there are several points of stress concentration, one of which is the angle area between the nozzle and the shell. However, based on research by Liu et al [10] crack propagation velocity is higher in the shell compared to the nozzle inlet angle area. Similar results were also obtained by Murtaza and Hyder [11]. Research carried out by studying the effects of thermal pressure on SIF for cracking angles between the nozzle and the shell.

Diamantoudis and Labeas [12] also conducted research related to SIF in cracks in areas of stress concentration in cylindrical pressure vessels. The crack location to be considered is the angle area between the nozzle and the shell and the connection of the shell with the hemi spherical head. In addition to the location of the crack, the parameters varied are the shape of the crack or the semi-elliptical ratio. For the initial validation, an analysis of the longitudinal cracks in the shell, finite element and analytical based ASME BPVC section VIII Appendix D-Non mandatory fracture mechanics calculations. The results obtained are close to the results of research conducted by Liu et al [10] and Murtaza and Hyder [11] that crack in the corner area between the nozzle and the shell has no significant impact.

This research will focus on cracks in cylindrical pressure vessels with variations in crack depth and crack location. Simulations will be carried out on the shell and knuckle area where research of stress concentration in the knuckle area is relatively limited. The output of the research is to compare and evaluate SIF from simulated crack.
2. Methodology

2.1. Modelling approach
In the course of this study a cylindrical pressure vessel of length $L = 8$ m, radius $R = 1.45$ m, thickness $t = 50$ mm and design pressure $8.25$ MPa with ellipsoidal ends is considered and made from material SA 516 Grade 70. The crack will be simulated crack length variation and location. For case 1, crack will be simulated in the shell with variation in crack depth ($a$): 0.25$t$, 0.4$t$, 0.6$t$ and 0.8$t$ with constant elliptical ratio $(a/c)$ at 0.3. For case 2, crack will be simulated in knuckle area of ellipsoidal head to evaluate effect of crack location to SIF. Figure 1 shows configuration of crack geometry.

An extended finite element method (XFEM) is used for modelling the crack. In comparison with the classical finite element method, the crack geometry in the XFEM need not be aligned with the element edges, which provides more flexibility and versatility in modelling. By using this method, only a single mesh is needed for any crack length and orientation. critical value. Combine with XFEM method, the sub-model cut-section has been used to optimize time consumption during FE modelling where cut section location must be considered to must be sufficiently far from the stress singularity, such that the stress field in the sub-model boundary is completely unaffected by the semi-elliptical crack.

2.2. Verification of the modelling
The finite element analysis has been used to model and simulate crack. The finite element analysis is conducted using Abaqus. A mesh of the pressure vessel considered, comprising of 1,278,962 elements solid elements with mesh size 1 mm at focused area around crack and 20 mm for area far away from crack as shown in Figure 2. The type of the element is chosen as 3D8R that defines as eight nodes and three translational degrees of freedom at each node.

The verification studies are conducted for various values of crack width ($2c$) and ratio crack depth and crack length ($a/c$). Reference for the verification purpose is based on research conducted by Diamantoudis and Labeas [12] that refer to ASME analytic calculation and finite element study. A comparison between the results of the three approaches shows a good agreement, not exceeding a difference of 5%. Result of the verification is shown in Figure 3. This overall agreement observed gives confidence for the use of the present modeling technique in the determination of SIF values of cases I and II.

![Figure 1. Crack geometry model](image-url)
3. Numerical SIF results for semi-elliptical cracks in a pressure vessel
In the present section, results are presented for all two cases considered. The stress intensity factor distributions along the crack front for various cracks geometry and location are presented in Figure 4. The values obtained are normalized according to the SIF Mode I ($K_{IC}$) value for SA 516 Grade 70 based on experimental that conducted by Metha [13]. In his research, the $K_{IC}$ value found for SA-516 Gr. 70 material is 129.37 MPa $\sqrt{m}$.

3.1. Case 1: Semi-elliptical crack located in the shell
The influence of crack’s relative depth on $K_s/K_{IC}$ distribution along a crack of ellipticity $a/c = 0.3$ for $t/R = 0.034$ in the shell area, are presented in Figure 4 respectively. In all these cases as the crack relative depth, $a/t$, increases, $K_s/K_{IC}$ also increase.

Based on stress modelling in the pressure vessel, stress distribution in the shell is dominated with tensile stress. This is aligned with Irwin's theory based on Linear elastic fracture mechanic (LEFM) where SIF is function of crack geometry and stress. With an increase in SIF approaching $K_{IC}$, cracks...
will tend to propagate. Based on simulation, for very deep cracks, certain points on the crack front around its deepest point have $K_I$ that very close to $K_{IC}$.

3.2. Case 2: Semi-elliptical crack located in the knuckle area
The influence of crack’s relative depth on $K_I/K_{IC}$ distribution along a crack of ellipticity $a/c = 0.3$ for $t/R = 0.034$ in the knuckle area, are presented in Figure 4 respectively. Unlike case 1, an interesting phenomenon can be observed at case 2, $K_I$ varies depends on crack depth.

At depth $0.2t$, $K_I$ has value negative, and the negative value increase when crack getting deeper at depth $0.4t$. While at depth $0.6t$, negative $K_I$ decrease. At the deepest crack at $0.8t$, $K_I$ reach positive value. Based on simulation, at depth $0.8t$, certain points on the crack front around its deepest point have $K_I$ that exceeding to $K_{IC}$ that indicates crack has been propagated.

Based on stress modelling in the pressure vessel, stress distribution in the knuckle area is dominated with compressive stress. This compressive stress at knuckle area also confirm by Schneider [14]. Based in his research, circumferential compressive stresses usually occur in the knuckle areas of torispherical and ellipsoidal heads designed to the ASME code [15]. Wrinkling of the heads is occasionally experienced in the knuckle area in the case of heads having relatively large diameter to thickness ratio. So, as the crack becomes deeper, it penetrates through a weaker and weaker compressive stress field that turns tensile stress at a certain point.

Similar result of negative SIF also confirms by Perl et al [16] during his research on effect of compressive residual stress on SIF in a autofrettaged spherical pressure vessel.

![Figure 4. SIF at various crack geometry with constant a/c = 0.3 and crack location at shell and knuckle area](image-url)
4. Conclusion
In this study, SIF in a pressure vessel is affected not only by crack geometry but also crack location. In case 1 where crack located in the shell, as the crack relative depth, a/t, increases, $K_I/K_{IC}$ also increase. Unlike case 1, an interesting phenomenon can be observed at case 2, $K_I$ varies depends on crack depth. At depth 0.2t, $K_I$ has negative value, and the negative value increase when crack getting deeper at depth 0.4t. While at depth 0.6t, negative $K_I$ decrease. At the deepest crack at 0.8t, $K_I$ reach positive value. Based on simulation, at depth 0.8t, certain points on the crack front around its deepest point have $K_I$ that exceeding to $K_{IC}$ that indicates crack has been propagated.

Phenomenon at case 2 is caused by compressive stress that occur in the knuckle area of head. As the crack becomes deeper, it penetrates through a weaker and weaker compressive stress field that turns tensile stress at a certain point. With the same crack geometry, crack located in the shell has more tendency to propagate compare to crack located in the knuckle area.

References
[1] Kurt E and Ayhan O 2019 Three-dimensional mixed-mode stress intensity factors for deflected internal surface cracks in thin and midsize-thick-walled spherical pressure vessels International Journal of Pressure Vessels and Piping 17110-33
[2] Alizadeh E and Dehestani M 2018 Analytical and numerical fracture analysis of pressure vessel containing wall crack and reinforcement with CFRP laminates Journal Thin-Walled Structures 127 210-220
[3] Eskandari H 2017 Three-Dimensional Finite Element Analysis of Stress Intensity Factors in a Spherical Pressure Vessel with Functionally Graded Coating Journal of Solid Mechanics 9 751-759
[4] Predan J, Mocilnik V and Gubeljak N 2013 Stress intensity factors for circumferential semi-elliptical surface cracks in a hollow cylinder subjected to pure torsion Engineering Fracture Mechanics 105 152–168
[5] Yang T, Ini L and Li Q 2013 Weight function method to determine stress intensity factor for semi-elliptical crack with high aspect ratio in cylindrical vessels Engineering Fracture Mechanics 109 138–149
[6] Perl M and Bernshtein M 2012 Three-dimensional stress intensity factors for ring cracks and arrays of coplanar cracks emanating from the inner surface of a spherical pressure vessel Journal of Engineering Fracture Mechanics 94, 71-84
[7] Ma K, Hua Z, Gu C, Zhang Z, Ya S and Yao Y 2019 Effects of crack position on fatigue life of large seamless storage vessels made of 4130X for hydrogen refueling station International Journal of Hydrogen Energy
[8] Moustabchir H, Arbaoui J, Azari Z, Hariri S and Pruncu E 2018 Experimental /numerical investigation of mechanical behaviour of internally pressurized cylindrical shells with...
external longitudinal and circumferential semi-elliptical defects *Alexandria Engineering Journal* **57** 1339–47

[9] Livieri P and Segala F 2016 Stress intensity factors for embedded elliptical cracks in cylindrical and spherical vessels *Journal of Theoretical and Applied Fracture Mechanics* **86** 260–266

[10] Liu R, Huang M, Peng Y, Wen H, Huang J, Ruan C, Ma H and Li Q 2018 Analysis for crack growth regularities in the nozzle-cylinder intersection area of Reactor Pressure Vessel *Annals of Nuclear Energy* **112** 779–793

[11] Murtaza M and Hyder J 2015 The effects of thermal stresses on the elliptical surface cracks in PWR reactor pressure vessel *Theoretical and Applied Fracture Mechanics* **75** 124–136

[12] Diamantoudis T and Labeas N 2005 Stress intensity factors of semi-elliptical surface cracks in pressure vessels by global-local finite element methodology *Engineering Fracture Mechanics* **72** 1299–1312

[13] Mehta V 2016 Evaluation of the Fracture Parameters for SA - 516 Grade 70 Material *IOSR Journal of Mechanical and Civil Engineering* **13** 38–45

[14] Schneider W 1961 Wrinkling of a large thin code head under internal pressure *Bulletin Welding Research Council* **69** 11–13

[15] American Society of Mechanical Engineer 2015 ASME BPVC Section VIII Division 1 Rules for Construction of Pressure Vessel

[16] Perl M, Steiner M and Perry J 2014 3-D stress intensity factors due to autofrettage for an inner radial lunular or crescentic crack in a spherical pressure vessel *Journal of Engineering Fracture Mechanics* **131** 282–295