The analysis for prediction of a central distribution crack for RDE Pressure Vessel by Fuzzy Neural Network

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Abstract. Many investigations were conducted on some material which used in Reactor, especially for Pressure Vessel. BATAN is designing Reactor Daya Experimental (RDE). The material to be used needs to be tested first. The fracture toughness has reflected the strength of the material. The center of crack distribution is a phenomenon of a failure material. The localization for the crack detection of RPV is necessary analyzed. The characteristic of distribution crack propagation is necessary predicted. The Fuzzy Neural Network (FNN) is an efficient prediction for detection of the center location measured for distribution data. Beside that the analysis of the resistance material can calculate by fracture mechanic analysis use Stress Intensity Factor (SIF) value through J-Integral calculated. The material SA 516-70 stainless steel is used for the main body in RDE Pressure Vessel. It is necessary to analyze the resistance that material. The center measured reflecting the characteristic of data distribution. The objective of this study is to analysis the center of crack location RDE Pressure Vessel by FNN. The strength of fracture mechanic calculated by SIF calculation through J-Integral with some crack ratio value. The resistance material SA516-70 was analyzed by comparing between SIF value and fracture toughness that material. The prediction centered value of crack distribution in fracture mechanic was evaluated for the phenomena of resistance material of SA 516-70 stainless steel which used for RDE Pressure Vessel.

Keywords: Distribution Crack, Fracture mechanics, Pressure Vessel, RDE, J-integral, Stress Intensity Factor, FNN

1. Introduction

In Experimental Power Reactor (in Indonesian, abbreviated as RDE), Reactor Pressure Vessel (RPV) is categorized as a safety-related component. The RPV is under an extreme circumference, under high load, high temperature, and neutron exposure. This condition induces material degradation and could lead to material fracture. The material used in manufacturing RPV plays an important role in term of component integrity. The poor material property causes the phenomena of material failure, especially in brittle fracture mode. A fracture of material is initiated by the crack occurrence. To evaluate the severity of crack, fracture mechanic analysis is applied. In fracture mechanic, the Stress Intensity Factor (SIF) is value effect of the material resistance parameter. Assessment is needed to determine the integrity of the material. The SIF value is determined through J-Integral calculation. The
phenomena of fracture mechanics are reflected in the crack distribution. The center of crack distribution is one way to determine the model of the materials fails.

The model with some parameters sometimes it is difficult to predict the center value of data distribution. In here clustering is one method to predict the center measured by crack distribution The ratio crack is a comparison of depth crack and width crack. The centering of crack distribution which still allowed may use clustering in relation to detection the resistance of the material. The centering parameter is the main characteristic of data distribution.

The clustering is a tool for centering problem. The clustering is one method to predict the center measured for one or more group data distribution. In here clustering is an efficient prediction for the measured center of crack distribution through SIF values. The ratio crack is a comparison of depth crack and width crack. The centering of crack distribution which still allowed may use clustering in relation to detection the resistance of the material.

The fracture toughness is one of parameter value limit for the resistance material. The phenomena of fracture mechanics are reflected in the crack distribution. The information on the prediction center of crack distribution is one way to determine the model of the failure of the materials. For the analyzed detection localization crack may use clustering.

The effects of temperature on microstructure and mechanical properties were analyzed for SA 508 GR. 4N steel[1]. The SIF for mode-I fatigue crack was determined by using finite element analysis[2]. After that, 3-D SIF was calculated for coplanar crack arrays and ring cracks in spherical pressure vessel[3]. The prospect and limitation of a tool fracture mechanics were reviewed for failure analysis[4]. The simple method has used to calculate the SIF for complex 3-D cracks at a notch[5]. The SIF for semi-elliptical cracks with high aspect ratio was computed by using the tetrahedral finite element[6]. The SIF was calculated for embedded elliptical cracks in cylindrical and spherical vessels[7]. In other respects, the retail items were grouping by using K-means clustering[8]. The cluster analysis of residential smart meter is measured by K-means method[9]. Additionally, the cluster analysis of acoustic emission activity within wood material was used for monitoring crack tip propagation[10]. The cyclic testing time for components of automotive suspension system utilizing was reducing the wavelet transform and the Fuzzy C-Means[11]. Besides that, the primary loop confinement and pressure boundary system were analyzed for the HTR-10[12]. The modified cuckoo optimization algorithm has detected for the crack of cantilever Euler-Bernoulli beam[13]. The mechanical fracture of PWR pressure vessel was evaluated and modeling based on the neural network[14]. The optimal crack ratio has analyzed for PWR pressure vessel cladding using Genetic Algorithm[15]. The Design has studied of a Straight Tube Bundle Steam Generator for Experimental Power Reactor Straight Tube bundle steam generator for experimental power reactor[17].

In case, the studies mentioned above, the analysis center of distribution crack of the fracture mechanic with J-Integral calculation and SIF of material SA 516-70 stainless steel haven’t been performing. Those material use for RDE Pressure Vessel. Based on the previous studies, the crack detection of the fracture mechanic for beam structures has analyzed. The prediction of the center measured by the crack distribution hasn’t been performed. Those are needed to know the center measured of the crack location which causes the failure material with the SIF value. The ratio crack is by looking at the aspect of comparison of depth and crack width.

The objective of this study is to predict analysis a fracture mechanic through J-Integral and SIF calculation with a crack ratio of material SA 516-70. The center of crack propagation has predicted by FNN. The SIF value has compared with fracture toughness value for evaluating material resistance. The crack distribution has detection for RDE Pressure Vessel material and the SIF value. The centered measure of crack distribution was predicted by clustering of the SIF value through J-Integral.

2. Theory

2.1. Fracture Mechanics
Fracture mechanics is the study of the mechanical behavior of cracked materials subjected to an applied load. The process of rupture is due to the displacement of nucleation and growth of cracks. It is assumed the crack propagation is a crack distribution. One of the types of crack is the semi-elliptic. The crack distribution and the semi-elliptic crack are described in Figure 1[6].

![Figure 1. The semi-elliptic crack in 3-D](image1)

The crack introduces a discontinuity in the elastic body such that the stresses tend to infinity as one approaches the crack tip r. The distribution crack in 3-D with crack-tip shown in Figure 2.

![Figure 2. The distribution crack in 3-D with crack-tip [15](image2)]

The stress intensity factor, $K_I$, is a fracture mechanic parameter to predict the stress value near the tip of a crack caused by a load. The value of Stress Intensity Factor is governed by stress level, crack geometry and material geometry. The fracture toughness is a value of material resistance from fracture mechanics. In the crack analysis, Stress Intensity Factor is compared to fracture toughness $K_{IC}$. The stability of crack propagation distribution could be determined by comparing the value of $K_I$ and $K_{IC}$. Since the value $K_I$ is greater than $K_{IC}$, it means that the material structure is not a safe condition[14].

The energy release rate can be expressed as a path-independent line integral, called the J-integral. To analyze the relationship among Stress Intensity Factor, crack ratio, and fracture toughness, J-Integral may calculate in numerically or finite element. In elastic-plastic fracture mechanic, J-integral was used to evaluate the crack. The value of J-Integral was evaluated around crack front in the form of the stress value. The problem is difficult to estimate the prediction optimization of ratio crack. The cladding pressure vessel is assumed by the cantilever beam. The J-Integral in 3-D especially is expressed in equation 1[13,15].

$$J = 1.8624x^2 - 3.95x^3 - 16.375x^4 - 37.226x^5 + 76.81x^6 - 126.9x^7 + 172x^8 - 143.97x^9 + 66.56x^{10}$$ (1)
where \(x\) is a crack ratio in range \(0 < a/h < 1\) where \(a\) is the depth of crack and \(h\) is the depth or thickness of the beam\[13,15\]. The optimization of J-Integral can be shown the optimization of the ratio of \(a/h\) bound.

After obtaining a J-integral value, the SIF can be calculated using equation 2 \[14,15\],

\[
K_I = \sqrt{\frac{E}{1-\nu}} J
\]

where \(E\) is Young's modulus, \(\nu\) is the value of Poisson ratio, \(J\) is the value of the J-Integral.

The fracture toughness, \(K_{IC}\), is a material property which describes the ability of a material containing a crack to resist fracture. Each of material has a different characteristic fracture toughness. This value gets from some research in the experiment. Critical crack size in the material was determined by comparing the value of SIF and the value of material’s fracture toughness. If the SIF still less than with the Fracture Toughness value, it means the material still has resistance against fracture\[14,15\].

2.2. Clustering

Clusters are made such that objects in the same cluster are very similar, and objects in different clusters are very distinct. There are several clustering techniques and measures of similarity to create the clusters. Additionally, cluster evaluation determines the optimal number of clusters for the data using different evaluation criteria. Cluster analysis organizes data into groups based on similarities between the data points.

The function partition data into \(k\) mutually exclusive clusters, and returns the index of the cluster to which it has assigned each observation. The clustering operates on actual observations (rather than the larger set of dissimilarity measures) and creates a single level of clusters. The distinctions mean that is often more suitable for large amounts of data.

The training data \(\{ (x_i, y_i)\} x_i \in X, y_i \in Y, i = 1,2,\ldots,l\} grouping into M clusters. Every cluster represents a rule \(R_m\) where \(m = 1, 2, \ldots, M\). Thus a neural network with n input units, hidden layers and M output units might be applied to train on the pre-defined clusters. For testing, an arbitrary pattern \(x\) is presented to the trained neural network. Every output unit \(m\) will return a degree to which extend \(x\) may fit the antecedent of rule \(R_m\) \[8-11\]. An example of data clusters and their centers for simple two-dimensional data are shown in Figure 3 \[16\],

![Figure 3](image)

**Figure 3.** Data clusters and their centers for simple two-dimensional data \[16\]

A fuzzy inference model consists of situation and action pairs where conditional rules described in if-then statements are generally used. The task of adapting fuzzy systems for a one-line application
involves neuronal improvements of fuzzy inference systems and fuzzy of neural network systems. In this way, we can exploit the complementary nature of fuzzy inference systems and neural network systems. The combination of the two systems is called an FNN system, can be accomplished through clustering of numerical data. A fuzzy inference model based on subtractive cluster and the model can be used to predict the center of crack distribution[9].

The architecture of the fuzzy neural network is following [11];

It $x_i(k)$ is $A_j(k)$ AND... AND $x_i(k)$ is $A_i(k)$ then $\bar{y}_i(k)$ is $f_i(x_i(k),...,x_i(k))$ and $x_i(k)$ is the input variable of fuzzy inference models. In Subtractive clustering is defined as a function of euclidian distance to all another data point in equation 3,

$$P(k) = \sum_{j=1}^{N} e^{-\frac{||x(k) - x(j)||^2}{s^2}}, \text{ } k = 1,2, ..., N$$ (3)

Each data point is revises by the following equation 4,

$$P(k) = P(k) - P_i(l)\sum_{j=1}^{N} e^{-\frac{||x(k) - x(j)||^2}{s^2}}, \text{ } k = 1...N$$ (4)

The sixth cluster center of acquired data is revised by the following equation 5,

$$\bar{y}_i(k) = \frac{\sum_{i=1}^{n} A_i(x(k))f_i(x(k))}{\sum_{i=1}^{n} A_i(x(k))}$$ (5)

where

$$A_i(x(k)) = e^{-\frac{||x(k) - x(j)||^2}{s^2}}$$

3. Methodology

Semi-elliptic surface cracks in reactor pressure vessel wall were analyzed under 3-dimensional model using stress intensity factor and J-integral parameters. The stress intensity factor values depend on crack geometry, especially the ratio between crack depth and crack surface length. In this study, J-integral calculations of crack for sample RDE Pressure Vessel were modeled as a beam with semi-elliptic surface crack as shown in Figure 4. The type of material is used SA 516-70 stainless steel. The sample geometry has a height of 1150 mm, an inner radius 4200 mm and a thickness 80 mm, respectively [17]. The Poisson ratio ($\nu$) was 0.29 and Young’s modulus (E) is $200 \times 10^3$ MPa[12].

Figure 4. The sample geometry in 3-D with semi-elliptic surface crack[14]
The chemical composition of SA516-70[12], shown in Table 1.

Table 1. The composition of elements chemical carbon steel SA 516-70

| Element | Weight (%) |
|---------|------------|
| C       | 0.10/0.22  |
| Si      | 0.60       |
| Mn      | 1/1.7      |
| P       | 0.03       |
| S       | 0.03       |
| Ni      | 0.30       |
| Cr      | 0.30       |
| Mo      | 0.08       |
| Al      | 0.02       |
| Cu      | 0.30       |
| v       | 0.02       |

The parameter inputs are a crack ratio. In this case, as material properties, Poisson ratio and Young’s modulus were given. The calculation results for the stress intensity factor value obtained according to the J-Integral equation. In order to evaluate the J-integral calculations were performed by varying crack ratio. The J-integral calculations were performed in numerically used equation 1 depends on the crack ratio in the certain range. After then, the SIF for AISI 516 grade 70 is calculated from the J-Integral value used material properties (the Poisson ratio and modulus Young’s) in equation 2. The centered measure of crack distribution uses the SIF value which takes from calculated some crack ratio. The SIF value use for determined a center measured by crack distribution. This calculated use clustering method from function facility in MATLAB. The flow diagram of the steps shown in Figure 5.

![Figure 5](image-url)
4. Results and Discussion
The crack ratio $a/W$ (crack depth to surface crack length) were varied between 0.05 and 0.99. In general, the crack ratio optimum takes from 0.05 until 0.6 [15]. The calculation of J-Integral and SIF is shown in Table 2. The J-integral value depends on crack ratio value. The SIF value is obtained from the J-Integral value with equation 2. By determining SIF with various crack geometry, a relationship can construct between crack ratio, J-Integral, and SIF. The SIF value use for determined a center measured by crack distribution calculated. This use clustering method. The certain range of parameter crack ratio and the output of J-Integral and SIF value are expressed in Table 2.

| Crack Ratio | J-Integral | SIF (MPa m$^{1/2}$) |
|-------------|------------|----------------------|
| 0.05        | 0.0040     | 29.7362              |
| 0.07        | 0.0073     | 39.9893              |
| 0.09        | 0.0109     | 48.8924              |
| 0.11        | 0.0144     | 56.0662              |
| 0.13        | 0.0170     | 61.0014              |
| 0.15        | 0.0182     | 62.9602              |
| 0.17        | 0.0169     | 60.7347              |
| 0.19        | 0.0123     | 51.8487              |
| 0.21        | 0.0034     | 27.0489              |
| 0.23        | -0.0112    | 49.3598              |
| 0.25        | -0.0325    | 84.2314              |
| 0.27        | -0.0620    | 116.3902             |
| 0.29        | -0.1013    | 148.7193             |
| 0.31        | -0.1518    | 182.0861             |
| 0.33        | -0.2154    | 216.8636             |
| 0.35        | -0.2937    | 253.2400             |
| ...         | ...        | ...                  |
| 0.59        | -3.1083    | 823.8557             |

From Table 2 shown for crack ratio 0.05, 0.07 until 0.59, the J-Integral are 0.0040, 0.0073 until -3.1083. The trend of J-integral value with a certain range of crack ratio could be seen in Figure 6.
For crack ratio 0.05 until 0.59, the SIF value are getting 29.73, 39.98 until 823.85 MPa $\sqrt{m}$. For crack ratio 0.23, the SIF Value is 49.35 MPa $\sqrt{m}$. For crack ratio 0.25, the SIF value is 84.23 MPa $\sqrt{m}$. Those still less than the fracture toughness. The fracture toughness of material stainless steel of that material is 100 MPa $\sqrt{m}$. It means this material still safe[14]. But for crack ratio 0.27, the SIF value is 116.39 MPa $\sqrt{m}$. Those greater than the fracture toughness of that material. This material will fracture. The trend of SIF value in the certain range of that crack ratio shown in Figure 7.

![Figure 7. SIF with some Crack Ratio](image)

The center measured of distribution crack shown in Figure 8. The crack distribution divided into three clusters. In the first cluster shown the crack ratio is 0.17 and the SIF value is 60.73 MPa$\sqrt{m}$. In the second cluster shown the crack ratio is 0.37 and the SIF value is 291.31 MPa$\sqrt{m}$. Finally in the third cluster shown the crack ratio is 0.53 and the SIF value is 659.17 MPa$\sqrt{m}$.

![Figure 8. The center measured SIF of Crack Distribution](image)
Conclusion
The strength of resistance material SA516-70 for design RDE Pressure Vessel has been analyzed. The analyzed fracture mechanic for material SA 516-70 was a calculation by J-Integral and SIF with some crack ratio value. The resistance material SA516-70 was analyzed by comparing between SIF value and fracture toughness that material. The prediction of the center crack location has calculated by FNN. The crack distribution divided into three clusters. The center measured of crack distribution for each cluster are (0.17;60.73 $MPa\sqrt{m}$), (0.37;291.31 $MPa\sqrt{m}$) and (0.53;659.17 $MPa\sqrt{m}$)

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