Reliability analysis of girth welds by using finite element simulations with uncertain material properties

Cheng Qian¹, Jin Xiao Meng¹, Yi Ren¹, Bo Sun¹, Qiang Feng¹, De Zhen Yang¹* and Zi Li Wang¹

¹ School of Reliability and Systems Engineering, Beihang University, Beijing, China

E-mail: dengzhenyang@buaa.edu.cn

Abstract. This research proposes a reliability simulation method combining the finite element simulation technology and stress-strength model to predict the structural reliability of girth welds with the following steps. Firstly, a group of finite element simulations of the girth welds are carried out considering uncertainties of elastic moduli in the weld and core barrel materials. Then the maximum von-Mises stresses over the welds are extracted from those simulations to generate the stress distribution. Finally, through a stress-strength model, the structural reliability of the girth weld is calculated by assuming its yield strength following a Normal distribution. In addition, via the proposed method, influences factors such as temperature, pressure and the uncertainty level among the elastic modulus on the weld reliability are discussed in detail.

1. Introduction
The structural reliability is of paramount importance for girth welds which are used in, for instance, core barrels, pipelines, and pressure vessels for the connection and sealing purposes. Fatigue crack growth [1][2][3] and Stress Corrosion [4][5][6] in the girth welds are common causes to lead to the weld leakage. Besides, overstrains resulted from inadequate material strength [7][8] and stress concentration [9][10] under extreme conditions can be key issues especially for those girth welds in large diameter barrels. Moreover, differences between thermal expansion coefficients of the solder and base materials and improper welding process will also result in weak spots in girth welds. In summary, these above failure modes are major concerns to the reliability of these welds.

In practice, material parameters of the girth welds are measured with a number of uncertainties because of the random crystalline structures and stochastically distributed micro-pores. Traditional methods to analyze the reliability of the girth welds is usually based on costly experiments. This makes the model accuracy highly dependent on the size of experimental data. On the contrary, application of simulation technology in reliability avoids complex operation in research and therefore reduces time and cost to a large extent. For instance, finite element simulation based methods are widely applied in structural analysis of the girth welds for calculation of stress, strain, stress intensity factors, etc. [1][11][12]. However, most of the existing numerical reliability researches are performed deterministically without considering the stochastic features of the welds material parameters well [13][14]. In the recent years, the probabilistic fracture mechanics (PFM) approach is increasing utilized to evaluate the structural reliability of reactor pressure vessels by introducing the uncertainty.
to the structure as a whole \cite{15,16,17}. However, the spatial uncertainty of material properties has not been taken into account carefully yet.

In this paper, a numerical simulation method to model the reliability of the girth welds is developed by using finite element technology with the consideration of incorporating uncertain material properties. The uncertainties of elastic moduli of the weld and core barrel materials over the girth weld structure are particularly considered in the proposed method. The remainder of this paper is organized as follows. A description of the proposed reliability simulation method is presented in Section 2. In Section 3, the effects of three factors, i.e. width of root face, coolant temperature and pressure, on stress distribution over the weld are discussed. And the effects of coolant temperature and material dispersion on the weld reliability are discussed as well. Finally, the concluding remarks from this study are drawn in Section 4.

2. Modelling

The main flowchart of the proposed method for reliability analysis of the girth welds is shown in Figure 1. It contains four steps, including sampling parameters from given distributions, finite element simulation, Kolmogorov-Smirnov test and reliability prediction with the stress-strength model, respectively.

![Flowchart of the proposed reliability simulation method](image)

**Figure 1.** Flowchart of the proposed reliability simulation method.

The 2D girth weld numerical model is developed from a practical used weld in a core barrel provided in literature \cite{18}. This girth weld is in a typical double U butt joint shape and attached to the core barrel on its upper and lower sides. Material parameters of both weld and core barrel are provided in Table 1. And geometric parameters used in the girth weld model are provided in Table 2 and illustrated in Figure 2.

**Table 1.** Material parameters used in the finite element model. [18]

| Component | Material | Parameters                  |
|-----------|----------|-----------------------------|
| Weld      | 308 steel| Elasticity modulus [Pa] 1.79E11 |
|           |          | Poisson ratio [-] 0.247     |
|           |          | Density [kg/m³] 7930        |
|           |          | Thermal expansion coefficient [°C] 1.620E-5 |
|           |          | Working Temperature [°C] 300 |


| Component        | Material | Parameters              |                  |
|------------------|----------|-------------------------|------------------|
| Core barrel      | 304 steel| Elasticity modulus [Pa]  | 1.92E11          |
|                  |          | Poisson ratio [-]       | 0.247            |
|                  |          | Density [kg/m³]         | 7930             |
|                  |          | Thermal expansion coefficient [1/℃] | 1.707E-5 |
|                  |          | Working Temperature [℃] | 300              |

Table 2. Geometric parameters of the girth weld.

| Geometric parameter | Design value |
|---------------------|--------------|
| Inner diameter [mm] | 3397.25±3.18 |
| Thickness [mm]      | 50.8         |
| Bevel angle [°]     | 20           |
| Groove angle [°]    | 40           |
| Root opening [mm]   | 0            |
| Root face [mm]      | 3.2          |
| Root radius [mm]    | 6            |

Figure 2. Geometric parameters used in the girth weld model

For introducing material uncertainties caused by arbitrary defects, the girth welds model is divided into 100 areas as shown in Figure 3. The elastic moduli of these areas are assigned randomly by calculations using a Normal distribution with the mean values and standard deviations shown in Table 3 [19][20].
Figure 3. The girth weld numerical model divided into 100 areas.

To fit the real operating conditions inside the core barrel of a reactor, the following boundary conditions are set:

1) In the y direction, constraints on all freedoms are applied to the upper boundary of the weld.
2) A coolant pressure with a value of 1.55E7 Pa is applied at the left and right boundaries of the weld.
3) A gravity load induced by the core barrel with a value of 7.39E6 Pa is applied at the lower boundary of the weld.
4) The temperatures of all joint parts in the girth weld model are assumed equal to the coolant temperature since the core barrel is totally submerged in coolant.

Furthermore, in order to consider uncertainties existing in materials of the girth weld model, input variables including elasticity modulus and yield strength are assumed to follow certain Normal distributions in which the mean and standard deviation values are referred from literature [20], respectively. These distribution parameters are provided in Table 3, and used to generate the stochastically distributions of elastic moduli of the weld and core barrel materials, and yield strengths of the weld, respectively.

Table 3. Input variables and distribution. [20]

| Variable         | Unit | Distribution | Mean      | Standard deviation |
|------------------|------|--------------|-----------|--------------------|
| Elastic modulus  | Pa   | Normal       | Weld: 1.79E11 | 9E9                |
|                  |      |              | Core Barrel: 1.92E11 | 1.65E8            |
| Yield strength   | Pa   | Normal       | 1.65E8    | 2.17E7             |

With the finite element simulation, the maximum von-Mises stress over the girth weld model can be obtained. In corresponding to the uncertain inputs of elastic modulus, and inner diameters, the statistical distribution based on maximum von-Mises stresses calculated from one hundred finite element simulations using the Monte Carlo method. Such a distribution is assumed to follow the shape of a Normal distribution, which can be determined by using the Kolmogorov-Smirnov testing model, as shown in Eq. (1).

\[ D = |\text{Data}(x) - \mathcal{N}(x)| \]  

in which \( \text{Data}(x) \) and \( \mathcal{N}(x) \) indicate the distribution of the maximum von-Mises stress and the corresponding Normal distribution respectively, and \( D \) indicates the difference in between them. The maximum \( D \) values (i.e. \( D_{\text{max}} \)) should be less than its critical threshold \( D_{0.05} \) under a confidence \( \alpha \) equalling to 0.05, as described in Eq. (2).

\[ D_{\text{max}} < D_{0.05} \]  

Afterward, by using the stress-strength model as shown in Eq. (3), Eq. (4) and Eq. (5), the reliability of the weld can be calculated.

\[ R = \int_{-\infty}^{\beta} \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}u^2} du \]
The von-Mises stress distribution over the girth weld obtained from a deterministic finite element simulation of the girth weld model. Stress concentrations are observed at both the root face and weld toes. Effects of the width of root face on those stress concentrations are evaluated and shown in Figure 4. Increase of the root face width results in a decrease on the maximum von-Mises stress at the root face from 64.5 MPa to 60.7 MPa but an increase on the maximum von-Mises stresses at weld toes. And it is found that the maximum von-Mises stresses at the root face are always higher than those at the weld toes. However, as the weld surface is a main bourgeois area more susceptible to create corrosions, the weld toes where the von-Mises stresses are much higher than the other areas become risky areas to fail. Under this circumstance, the failure probability will be further enhanced with the increase of the root face because of an increasing maximum von-Mises stresses at the weld toes. This results in an opposite conclusion that the reliability of the girth weld will drop with the increase of the root face. Therefore, careful cautions should be taken to weigh the pros and cons when trying to optimize the weld reliability with a proper width of root face.

\[
\mu = \frac{2(\mu_1-\mu_2)}{\sqrt{\sigma_1^2+\sigma_2^2}} \quad (4)
\]

\[
\beta = \frac{\mu_1-\mu_2}{\sqrt{\sigma_1^2+\sigma_2^2}} \quad (5)
\]
in which \( R \) indicates reliability of the girth weld, \( Z \) indicates the difference between stress and strength, \( \mu_1 \) and \( \mu_2 \) indicate mean of stress and strength, respectively, \( \sigma_1 \) and \( \sigma_2 \) indicate standard deviation of stress and strength, respectively.

In practical operation of a reactor, the yield strength of the girth weld will decline sharply with the temperature rise. The yield strength descent curve with temperature in this model is based on the literature and different yield strength is chosen according to the temperature and curve in every simulation [20].

3. Results and discussions

Figure 4 shows the von-Mises stress distribution over the girth weld obtained from a deterministic finite element simulation of the girth weld model. Stress concentrations are observed at both the root face and weld toes. Effects of the width of root face on those stress concentrations are evaluated and shown in Figure 4. Increase of the root face width results in a decrease on the maximum von-Mises stress at the root face from 64.5 MPa to 60.7 MPa but an increase on the maximum von-Mises stresses at weld toes. And it is found that the maximum von-Mises stresses at the root face are always higher than those at the weld toes. However, as the weld surface is a main bourgeois area more susceptible to create corrosions, the weld toes where the von-Mises stresses are much higher than the other areas become risky areas to fail. Under this circumstance, the failure probability will be further enhanced with the increase of the root face because of an increasing maximum von-Mises stresses at the weld toes. This results in an opposite conclusion that the reliability of the girth weld will drop with the increase of the root face. Therefore, careful cautions should be taken to weigh the pros and cons when trying to optimize the weld reliability with a proper width of root face.

Coolant pressure in the reactor pressure vessel is also an important control parameter for a reactor during work. In the power operation mode, coolant pressure can reach up to 1.55E7Pa which is in the same order of magnitude with the gravity load induced by the reactor core. When the reactor changes among different working conditions, coolant pressure will simultaneously change and thus alter the von-Mises stress distribution over the girth weld. Therefore, it is necessary to investigate the influence of coolant pressure on von-Mises stress concentrations of the weld.
According to the saturation temperature curve of water, the minimum pressure of coolant is 1E7Pa at the temperature of 310 °C. In our simulations, the coolant pressure is changed from 1E7Pa to 2.1E7Pa with an interval of 2.75E6Pa at the temperature of 310 °C for investigating the influence of coolant pressures on the von-Mises stress distribution over the girth weld. The simulation results are shown in Figure 6. It can be seen that maximum von-Mises stresses of both the upper and lower weld toes increase along with the rise of the coolant pressure. As shown in Figure 7, the x directional stresses on the weld toes are significantly enlarged during the increase of the pressure of the coolant. On the contrary, this increase of coolant pressure makes the maximum von-Mises stress of root face declined, causing a reduction on the x directional stresses on the root face.

Figure 6. Effect of the coolant pressure on stress concentration.

The last important influence factor on the stress concentrations of the girth weld is coolant temperature. The thermal-mechanical stress caused by the mismatch between thermal expansion coefficients of the weld and core barrel materials is usually the root cause for the stress concentrations. Figure 8 shows von-Mises stress profiles in the vicinity of the root face obtained by simulations under the coolant temperatures of 100°C, 200°C, 250°C and 300°C, respectively. It can be seen that the von-Mises stress undergoes a significant increase with the increment of the coolant temperature from 100°C to 300°C. Furthermore, according to the simulation results in correspondence to the coolant temperature from 100°C to 300°C, the maximum von-Mises stresses of the upper weld toe and root face are plotted in terms of the coolant temperature, as shown in Figure 9. Both of them increase in a linear manner with the increase of the coolant temperature.
Figure 8. Calculated von-Mises stress profiles around the root face area, when the coolant temperature is (a) 100℃; (b) 200℃; (c) 250℃; (d) 300℃.

Figure 9. Effect of the coolant temperature on the maximum von-Mises stresses.

By introducing the uncertainties of elastic moduli of the weld materials provided in Table 3 and the inner diameter of the girth weld model, in total one hundred simulations are carried out under the coolant temperature of 310℃. The calculated maximum von-Mises stress distribution follows a Normal distribution as shown in Figure 10. The distribution of the yield strength is then calculated with the parameters provided in Table 3 and plotted in Figure 10 as well. Then by using Eqs. (3) to (5), the reliability of the girth weld is calculated as 0.9998.
Figure 10. Distribution of maximum von-Mises stress and yield strength.

In reality, standard deviations of elastic moduli of the weld and core barrel materials might be a stochastic value depending on their internal defects and impurities. In this study, these standard deviations are discretized in a range from 7E9 Pa to 3E10 Pa. Then the weld reliabilities are calculated by using the proposed reliability simulation method, and plotted in . It can be seen that the reliability gradually decreases with an increase of the standard deviation of elastic modulus. This is might because that a higher standard deviation of elastic modulus gives a high probability where the maximum von-Mises stress of the weld is greater than its yield strength, and therefore lower the weld reliability.

Figure 11. Effect of the standard deviation of elasticity modulus on the weld reliability.

Figure 12. Effect of the coolant temperature on the weld reliability.

With the maximum von-Mises stresses calculated from simulations under different coolant temperatures, reliabilities of the girth welds are further calculated and plotted in Figure 12. The reliability of the weld begins to decline rapidly when the coolant temperature exceeds 310℃ with an ever-increasing rate in terms of the coolant temperature.

4. Conclusions

In this paper, a finite element simulation based method is proposed for predicting structural reliability of the girth weld which is used in a reactor core barrel. In this proposed method, the material uncertainties are introduced by considering elastic moduli of the weld and core barrel and inner parameter of the weld structure follow certain Normal distributions, respectively. In this way, the distribution of the maximum von-Mises stresses of the girth weld model is obtained from one hundred
Monte Carlo simulations. And then the weld reliability is calculated from by using the stress strength interference model.

With the proposed model, effect of the width of root face on the von-Mises stress distribution and structural reliability of the girth weld is firstly analysed. And then, effect of the coolant pressure on von-Mises stress concentrations over the girth weld model is discussed as well. An increases of coolant pressure can reduce the maximum von-Mises stress at the weld toe but increase the maximum von-Mises stress at the root face. Furthermore, effects of the coolant temperature on the weld reliability are investigated. There is a turning point for the coolant temperature over which the weld reliability begins to degrade obviously. The weld reliability begins to a significant reduction when its surrounding coolant temperature is higher than 310°C. In the end, effects of standard deviation of elastic moduli of the weld and core barrel materials on the weld reliability are studied. According to the simulation results, the weld reliability reduced gradually with an increase of standard deviation of the elastic modulus. This is to say, materials with a large deviation of elastic moduli should be avoided for getting a high structural reliability of the girth weld.

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