Reliability Analysis of Clamp Welding Defects Based on Finite Element Simulation

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Abstract. Cracking and failure of clamp is a common problem in the maintenance of power grid, which seriously threatens the safety of power grid electrical transmission. Therefore, based on the finite element analysis method, the static strength check and reliability analysis are firstly carried out to evaluate the structural safety of the defect-free clamp. Secondly, SINTAP was used to evaluate clamps with planar defects, and Paris formula was used to predict the fatigue crack growth life. The results show that the clamp with planar welding defects can also meet the requirements under severe working conditions due to its good plastic reserve and toughness. The crack depth \( a \) of the welding defect significantly affects the safety of the clamp structure, and the crack feature \( a/c \) also has a certain impact on the safety. However, when the crack depth \( a \) is less than a certain value, no fatigue fracture will occur.

1. Introduction

Clamp is an important fixture in overhead transmission lines and distribution lines of power grid, which is used to connect transmission wires and basic power equipment, bear and transmit mechanical and electrical loads [1]. Cases of clamp cracking or failure occur from time to time, which can lead to interruption of electrical transmission and serious economic losses. For this reason, researchers have carried out defect detection and failure mechanism research. For instance, literature [2] introduced one failure case of the clamp. Through component spectrum analysis and material mechanical property test, it was believed that the main reasons for cracking were loose casting material, improper material strength selection and water vapor infiltration into the joint. In literature [3], scanning electron microscopy and other detection methods were used to analyze the microstructure and metallographic structure of the clamp fracture, and it was believed that the welding defects in the clamp structure were the main cause of the fracture, while the extension of welding defects under alternating stress finally caused the fatigue fracture of the clamp.

In the welded structure, welding defects will cause the effective bearing area to decrease, resulting in stress concentration and a large reduction in bearing capacity of the structure. Welding defects can be divided into planar defects (crack, non-fusion, non-penetration, etc.), volumetric defects (porosity, slag inclusion, etc.) and forming defects (edge bite, dislocation and angular deformation, etc.), among which planar defects have the highest impact on structural strength. Planar defects on the influence of the fracture depends on the size, direction, location of defects and defect edge sharp degree [4]. The defect which has surface perpendicular to the direction of stress, or located on the surface of the...
structure, near the surface, and the front of the very sharp crack, has the greatest impact on the strength of welded structure. Welded structures subjected to alternating load, impact load, or stress corrosion often result in brittle fracture [5].

Therefore, this article classifies the clamps with a certain degree of volume defects as “non-defective clamps”, and focuses on the reliability analysis and safety assessment of the clamps with planar defects. The SY-185/25A device clamp is used as research object. Based on the finite element analysis method, the dangerous parts of the clamp structure can be determined, the fatigue crack propagation life of the clamp defect can be predicted and finally, the structural reliability of device clamp can be assessed.

2. Modeling and Analysis

2.1. Force Model of Device Clamp

In order to simulate the natural environment service status of device clamps, three representative working conditions were selected. Condition 1: No wind, no ice-covered environment; Condition 2: Continuously distributed high wind, no ice-covered environment (wind speed is 20 m/s, which is a class 8 gale); Condition 3: Continuously distributed wind, ice Environment (wind speed is 10 m/s, which is a class 5 strong wind; ice thickness is 10 mm).

Based on the actual status of device clamps when in service, a simplified working model is established. The force model of the device clamp at the suspension point with the bus down-conductor is shown on the left side of figure 1. The horizontal force $F_{sx}$ is the force of the clamp received from the bus down-conductor in horizontal direction. The vertical force $F_{sy}$ is the force of the clamp received from the bus down-conductor in vertical direction. The wind direction force $F_{sz}$ is the force of the clamp received in the direction perpendicular to the vertical plane. $F_S$ is the combined force of $F_{sx}$, $F_{sy}$, and $F_{sz}$, and it is also the axial force of the bus down-conductor at the suspension point. The description of the wires is shown on the right side of figure 1. The horizontal force $F_{mx}$ is the force on the wire in the axial direction, the vertical force $F_{my}$ is the force on the wire in the vertical direction, and the wind force $F_{mz}$ is the force on the wire in the vertical plane direction.

![Force analysis schematic diagram of the equipment clamp.](image)

2.2. Reliability Analysis of Defect-Free Clamps

PDS Technology (Probability Design System) is a module based on the theory of reliability design and calculation of mechanical structure provided by ANSYS software, which combines the finite element method and probability design method to analyze. The reliability analysis steps of clamp structure based on the module are as follows:

(1) The analysis files used to establish the cycle include: defining element and material properties, parametric modeling, meshing, loading, solving and post-processing.

(2) Extract the maximum stress value and the maximum deformation value of the clamp. According to the structural failure criterion of mechanical reliability theory, the limit state function $Z(X)$ is defined:
\[ Z(X) = \sigma_s - \sigma_{\text{max}} \quad (1) \]

In equation (1), \( X \) is the random input variable vector, \( \sigma_s \) is the material strength limit of the component, and \( \sigma_{\text{max}} \) is the maximum stress value of the component. When \( Z(x) < 0 \), the structure is in failure state, and the probability of \( Z(x) < 0 \) is the structure’s reliability; when \( Z(x) = 0 \), the structure is in critical state; when \( Z(x) > 0 \), the structure is safe, and the probability of \( Z(x) > 0 \) is the structure’s reliability. Two limit state functions \( Z_n(X) \) and \( Z_{0.2}(X) \) are defined here, which respectively represent the difference between the tensile strength limit, the conditional yield strength and the maximum stress value, as shown in equations (2) and (3).

\[ Z_n(X) = \sigma_n - \sigma_{\text{max}} \quad (2) \]
\[ Z_{0.2}(X) = \sigma_{0.2} - \sigma_{\text{max}} \quad (3) \]

2.3. Reliability Analysis of Clamps with Incomplete Penetration Defects

In this paper, the crack is normalized to a semi elliptical surface crack on a finite width plate, as shown in figure 2, a/c value is used to represent the crack characteristics. At the same time, because the above analysis shows that the defect mostly bears the tensile and compressive stress perpendicular to the defect plane direction, it is evaluated according to the mode I crack.

![Schematic diagram of normalized crack.](image)

Using SINTAP/FITNET technology to evaluate the safety of clamp structure of equipment with incomplete penetration, according to the available data of material tensile properties and the degree of mismatch between weld and base metal in the structure, the first grade is determined. According to the failure evaluation curve equation given in SINTAP/FITNET, the failure evaluation curve of clamp welding joint can be obtained [6].

In this paper, the influence of secondary stresses such as residual stress and environmental thermal stress in welding process is ignored, and only one stress is considered. Using the finite element software ANSYS/Workbench to linearize the equivalent stress treatment, the membrane stress and bending stress on the path can be obtained in the treatment results. Select the stress condition of equipment clamp under condition 3 for evaluation and calculation. According to the results of finite element calculation, membrane stress \( \sigma_m = 2.7336 \text{ MPa} \), bending stress \( \sigma_b = 1.4412 \text{ MPa} \).

According to the following formula, calculate the load ratio of the surface crack defects with semi ellipse, and calculate the abscissa (applicable a/B<0.8) as follows:

\[ L_s = \frac{1}{(1-\xi)^2\sigma_{0.2}} \left[ g(\xi) \cdot \frac{\sigma_n}{3} + \sqrt{\left( \frac{g(\xi) \cdot \sigma_n}{3} \right)^2 + (1-\xi)^2 \sigma_m^2} \right] \quad (4) \]

\[ \xi = \begin{cases} \frac{ac}{BW}, & W \leq B+c \\ \frac{ac}{B(c+B)}, & W \geq B+c \end{cases} \quad (5) \]
The fracture ratio $K_i$ is calculated by the mode I stress intensity factor $K_i \ (0 \leq a/c \leq 1, \ 0 \leq \theta \leq \pi, \ W > 2c)$ at the defect tip and the fracture toughness of the material $K_c$ as follows:

$$K_i = \frac{K_1}{K_c}$$  \hspace{1cm} (7)

where

$$K_i = 0.4 \sigma_{0.2} \sqrt{B}$$  \hspace{1cm} (8)

$$K_1 = \frac{\sqrt{\pi a}}{E(k)} \cdot F \cdot (\sigma_m + H \sigma_b)$$  \hspace{1cm} (9)

The maximum value of $K_i$ is at $\theta = 0$, and the stress intensity factor of crack tip at $\theta = 0$ is used as the critical point for priority evaluation. The fracture ratio $K_i$ can be obtained by calculating the values of incomplete penetration defects $K_i$ corresponding to different characteristic sizes a and c.

Next, according to Paris formula, the fatigue life $N$ of clamp crack can be estimated as follows:

$$N = N_f - N_0 = \frac{1}{C} \int_{\sqrt{K_0}}^{\sqrt{K}} \frac{1}{(\Delta K)^n} d\Delta K$$  \hspace{1cm} (10)

$$\Delta K = \Delta K_i = \frac{\sqrt{\pi a}}{E(k)} \cdot F \cdot \Delta \sigma$$  \hspace{1cm} (11)

$$\Delta \sigma = \Delta \sigma_m + H \Delta \sigma_b$$  \hspace{1cm} (12)

where, $C$ and $n$ are the values obtained by the material according to the fatigue crack growth rate test: for the clamp aluminum alloy material, take $C = 2.6 \times 10^{-10}, \ n = 3$. The amplitude of the stress intensity factor $\Delta K$ is determined by the primary stress, i.e. dynamic stress; the geometric factor $F$, parameter $H$ and parameter $E(k)$ are calculated by the crack size parameter [7], and the calculation method is limited by the length. Please refer to the relevant literature for the calculation method; $\Delta \sigma$ is the stress amplitude at the evaluation point; and $\Delta \sigma_m$, $\Delta \sigma_b$ are the membrane stress amplitude and bending stress amplitude calculated by the linearized primary stress amplitude respectively. According to the safety evaluation results, the critical crack size ac of the defect is about 4.5 mm when $a/c = 0.25$ [7].

3. Results and Analysis

3.1. Finite Element Analysis of Static Strength of Equipment Clamp

The static strength finite element analysis results of flawless SY-185/25A equipment clamp under three working conditions are shown in table 1, and the partial enlarged drawing and total deformation nephogram of the equipment clamp under working condition 3 are shown in figures 3 and 4.

| Table 1. Calculated value of stress and strain. |
|-----------------------------------------------|
| Mechanical property                           | Condition 1   | Condition 2   | Condition 3   |
| Maximum equivalent strain                      | 1.33E-5       | 3.21E-5       | 3.72E-5       |
| Maximum equivalent stress /MPa                | 2.61          | 6.41          | 7.43          |
| Maximum deformation /mm                       | 0.0092        | 0.0111        | 0.0201        |
Figure 3. Partial enlarged drawing of equivalent effect force of equipment clamp under condition 3.

Figure 4. Cloud chart of total deformation of equipment clamp under condition 3.

In conclusion, the finite element analysis results of the static strength of the clamp under three working conditions show that the equivalent stress values at the corner of the clamp terminal board and the weld area are large, which belong to the dangerous area. With the change of the resultant force of the bus down lead of the clamp, the position of the maximum equivalent stress point changes along the circumference direction of the crimping pipe. However, the maximum equivalent stress under the three working conditions is less than the yield strength and tensile strength of the material, so the structural strength of the flawless equipment clamp is safe.

3.2. Safety Assessment of Clamps with Incomplete Penetration Defects

Take the values of a and c of different crack sizes to calculate the corresponding coordinate values of the evaluation points. The calculation results are shown in Table 2 below.

| Crack characteristics | a (mm) | Lr   | Kr   | (Lr, Kr)       |
|-----------------------|-------|------|------|---------------|
| Semi elliptical surface crack a/c=0.25 | 1     | 0.1177 | 0.4714 | (0.1177, 0.4714) |
|                       | 2     | 0.1388 | 0.6667 | (0.1388, 0.6667) |
|                       | 3     | 0.1704 | 0.8165 | (0.1704, 0.8165) |
|                       | 4     | 0.2111 | 0.9428 | (0.2111, 0.9428) |
|                       | 4.5   | 0.2304 | 1.0000 | (0.2304, 1.0000) |
|                       | 4.8   | 0.2384 | 1.0328 | (0.2384, 1.0328) |
| Semi elliptical surface crack a/c = 0.5 | 1     | 0.1141 | 0.4024 | (0.1141, 0.4024) |
|                       | 2     | 0.1282 | 0.5691 | (0.1282, 0.5691) |
|                       | 3     | 0.1494 | 0.6970 | (0.1494, 0.6970) |
|                       | 4     | 0.1748 | 0.8048 | (0.1748, 0.8048) |
|                       | 4.5   | 0.1856 | 0.8536 | (0.1856, 0.8536) |
|                       | 4.8   | 0.1895 | 0.8816 | (0.1895, 0.8816) |

The coordinates of different crack size evaluation points are plotted on the failure evaluation curve, as shown in figure 5.

It can be seen from the above analysis that when a/c = 0.25, the coordinate of evaluation point a = 4.5 mm is just outside the failure evaluation curve area, that is, the clamp structure will have brittle fracture, and the critical crack size is about 4.5 mm; when a/c = 0.5, the result shows that the evaluation point without structural fracture, that is, the structure is safe when a < 4.8 mm; when the crack size a is the same, the evaluation point coordinate of a/c=0.25 is more than the evaluation point of a/c = 0.5. The coordinate is closer to the failure evaluation curve, that is, the smaller the a/c value is, the less safe the structure is. At the same time, the larger the crack size a is, the more the coordinate of
the corresponding evaluation point moves to the peripheral area of the failure evaluation curve, that is, the larger the $a_i$ is, the less safe the structure is, and the crack size significantly affects the safety of the structure. In addition, it is easy to know that the abscissa value of the evaluation point is far less than the $L_r$ limit value, that is, the plastic reserve of the clamp material is better, but the toughness is relatively poor.

![Failure assessment point curve.](image)

**Figure 5.** Failure assessment point curve.

### 4. Conclusion
In this paper, SY-185/25A equipment clamp is taken as the research object, static strength analysis and structural reliability analysis under three natural working conditions are carried out by using finite element software. Aiming at the clamp with incomplete welding defects, based on the structure integrity assessment technology of SINTAP/FITNET, the safety assessment of standardized semi elliptical surface cracks is carried out according to the first level assessment level. It can be concluded as follows:

1. According to the static strength analysis, the weld area is the dangerous part of the clamp structure, and the reliability analysis proves that the flawless clamp structure is reliable under the severe ice and snow and strong wind environment;
2. The clamp material has good plasticity reserve and toughness. Even if there are some defects, the clamp can meet the use requirements under more severe working conditions;
3. The crack depth $a$ of the clamp with incomplete penetration defects can significantly affect the safety of the structure, and the crack characteristic $a/c$ has a certain influence on the safety of the structure;
4. Paris formula is used to estimate the fatigue crack growth life. The results show that even if there are some defects, when the crack depth $a$ is less than a certain value, the fatigue fracture will not occur.

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