Weld Fatigue Life Analysis of Truck Mixer Sub-frame Based on Equivalent Structural Stress Method

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Abstract. In order to accurately calculate the fatigue life of the sub-frame weld of the mixer truck during the design stage, fatigue analysis of the weld is carried out by equivalent structural stress method. Through the finite element analysis of the frame, the key weld position is researched. By using the inertial release method, the stress response of the frame under the single excitation of the unit load is obtained. Combined with the basic principle of equivalent structural stress, the stress at the weld position is calculated, and the main S-N curve with a survival rate of 50% is selected to predict the fatigue life of the weld. The results show that the fatigue life of the key weld is $10^{5.803}$ cycles, which fails to reach the design target value. The equivalent structural stress method has the characteristics of grid insensitivity and can better predict the fatigue life of the sub-frame weld of the mixer truck.

1. Introduction
Sub-frame is the key component of concrete mixer truck, which can effectively share the load of chassis, avoid the damage caused by chassis stress concentration and prolong the service life of the truck. The working conditions of the mixer truck are complex, and cracks often occur in the location of the sub-frame seam weld, which is mainly caused by the dynamic cyclic loading during the driving of the truck. Cracking of the sub-frame weld will seriously reduce the service life of the mixer truck, and it will also cause the mixer truck to roll over and other accidents, which will have certain potential safety hazards. Therefore, it is necessary to evaluate the fatigue of the sub-frame weld in the structural design process.

In order to improve the quality of mixer truck and prolong the life, some large automobile manufacturers, institutions and universities have carried out the research on weld life assessment of mixer truck sub-frame in recent years. Gao,Y,D [1] used the multi-body dynamics method to extract the virtual random load spectrum of the whole truck under the B-class road surface. Combined with finite element method and nominal stress method, the fatigue life distribution of the sub-frame and the position where fatigue failure easily occurred were obtained. Li,J,W [2] measured the performance of the sub-frame key points by strain test method. After analysing the test data, the actual random load spectrum number of the frame is obtained, and the fatigue life of the frame is predicted by using the nominal stress method. Xia ,X,W [3] calculated the fatigue life of the frame by adopting the rigid-flexible coupling dynamic method, and compared it with the actual test results. The consistency of test and simulation result is over 90%. He,X,F [4] analysed the transient response of the mixer truck when it was driving on the D-class road surface, and predicted the life of the sub-frame by using the fatigue life estimation theory. Yuan,J,J [5] has carried out static analysis and optimization
under various typical working conditions, and uses the nominal stress method and fatigue cumulative
damage theory to research the life of sub-frame.

In this paper, the fatigue life of seam weld of truck mixer sub-frame is evaluated by equivalent
structural stress method. It provides relevant guidance for the structural design and welding process of
sub-frame, and improves the fatigue life of sub-frame weld. Equivalent structural stress method is a
theoretical method of anti-fatigue design for welded structures, which can predict the fatigue life of
welded structures more accurately than traditional fatigue assessment methods.

2. Basic principle of equivalent structural stress method.
Structural stress is a kind of stress which is directly calculated by the nodal force and bending moment
output by the finite element method, which based on the tangent plane method of free body. It can
represent the stress distribution on the weld toe section and can be used for fatigue assessment of
welded structure[6, 7]. Related studies have verified that the equivalent structural stress method based
on structural stress and main S-N curve has high accuracy in fatigue assessment of welds, and this
method has been widely used in rail transit, shipping and marine industries.

2.1. Definition and calculation of structural stress.
When the welded structure is subjected to external load, the stress distribution at the welded joint is
highly nonlinear, and the nonlinear stress is decomposed into structural stress and nonlinear notch
stress[8]. The cross-sectional stress of weld is shown in figure 1.

\[
\sigma_s = \sigma_m + \sigma_b = \frac{f_y}{t} + \frac{6m_x}{t^2} \tag{1}
\]

Where \(\sigma_m\) is the membrane stress; \(\sigma_b\) is the bending stress; \(\sigma_s\) is the structural stress; \(t\) is the plate
thickness; \(\int_{y_1}^{y_2}\) is the line force; \(m_x\) is the line moment.

The node force and moment of a shell element with two nodes can be obtained as follows;

\[
\begin{pmatrix}
F_{y_1} \\
F_{y_2}
\end{pmatrix} = \begin{pmatrix}
\frac{4}{t} & -\frac{1}{t} \\
-\frac{2}{t} & \frac{4}{t}
\end{pmatrix} \begin{pmatrix}
F_{y_1} \\
F_{y_2}
\end{pmatrix} \tag{2}
\]

\[
\begin{pmatrix}
M_{x_1} \\
M_{x_2}
\end{pmatrix} = \begin{pmatrix}
\frac{4}{t} & -\frac{1}{t} \\
-\frac{2}{t} & \frac{4}{t}
\end{pmatrix} \begin{pmatrix}
M_{x_1} \\
M_{x_2}
\end{pmatrix} \tag{3}
\]

Where \(F_{y_1}, F_{y_2}\) are node force in the y-axis direction of nodes 1 and 2; \(M_{x_1}, M_{x_2}\) are the moment
of nodes 1 and 2 around the x axis; \(f_{y_1}, f_{y_2}\) are linearly distributed forces on the welding line at nodes
1 and 2; \(m_{x_1}, m_{x_2}\) are linearly distributed moments on the welding line at nodes 1 and 2, \(l\) is the length
of the welding line.
\begin{align}
\{\sigma_{s_1} \sigma_{s_2}\} &= \frac{1}{\tau} \left[ \begin{array}{c}
\frac{4}{\tau} \\
\frac{2}{\tau} \\
\frac{4}{\tau}
\end{array} \right] \left\{ \begin{array}{c}
F_{y_1} \\
F_{y_2} \\
M_{x_1} \\
M_{x_2}
\end{array} \right\} + \frac{6}{\tau} \cdot \begin{array}{c}
M_{x_1} \\
M_{x_2}
\end{array}
\end{align}

Where $\sigma_{s_1}, \sigma_{s_2}$ are the structure stress of node 1 and 2.

From the above derivation process, it can be known that the transformation between node force and line force is the core of solving structural stress\(^{10}\). The stress solving process of the structure is shown in figure 2.

2.2. Structural stress grid insensitivity

The calculation basis of structural stress is that the resultant force of nodal forces on the weld toe section is balanced with external forces. The finite element structure model is divided into 50 or 100 elements, and the resultant force of nodal forces is balanced with external forces, so the structure is grid insensitive. Figure 3 shows a T-shaped welding structure. The structure is meshed with 0.5$\text{t}$, $\text{t}$ and 2$t$ respectively, and static analysis is carried out.

In figure 4, it can be seen that the structural stress of the welded toe element node remains unchanged despite the different mesh sizes, while the von-mises stress and the maximum principal stress increase with the decrease of mesh sizes. It shows that the equivalent stress of the structure is grid insensitive.

2.3. Transformation of equivalent structural stress

The basic assumption of fracture mechanics theory is that there are tiny cracks in the weld before fatigue fracture. Combined with Paris crack propagation equation, the structural stress is transformed into stress intensity factor\(^{11}\), and its expression is;

\begin{align}
\Delta K &= \sqrt{\frac{\Delta \sigma_{m} f_m(a/t) + \Delta \sigma_{b} f_b(a/t)}{\pi}}
\end{align}

Where $\Delta K$ is the variation range of stress intensity factor; $a$ is the edge crack depth; $t$ is the plate thickness; $\Delta \sigma_{m}, \Delta \sigma_{b}$ is the variation range of membrane stress and bending stress; $f_m(a/t), f_b(a/t)$ are dimensionless functions of stress intensity factor range when membrane stress and bending stress works alone. Based on Paris life integral formula, the fatigue life calculation formula of weld is obtained as follows;

\begin{align}
N &= \int_{\tau}^{\frac{\tau}{c}} \frac{t^{d_m(\tau)}}{c(M_{k})^{m}(\Delta K)^{m}} = \frac{1}{c} \cdot t^{1-m} \cdot (\Delta \sigma)_{m}^{m} I(r)
\end{align}
Where $M_{kn}$ is the factor coefficient of stress intensity of weld toe notch; $m$ and $n$ are the long and short crack propagation coefficients; $\Delta \sigma_s$ is the structural stress range; $I(r)$ is a correction function of the load ratio $r$. The equivalent structural stress range expression as follows:

$$\Delta S_e = \frac{\Delta \sigma_s}{I(r)^{1/m} t^{2/n}}$$  \hspace{1cm} (7)

$\Delta S_e$ is the equivalent structural stress range. Combined with the engineering fatigue test data, the fatigue life calculation formula based on the principal S-N curve of equivalent structural stress is as follows:

$$N = \left(\frac{\Delta S_e}{C_d}\right)^{-\frac{1}{h}}$$  \hspace{1cm} (8)

Where $C_d$, $h$ are the test constant. Tests prove that if the S-N curve is drawn by the equivalent structural stress variation range and fatigue life, all the fatigue test data will fall into a narrow band, which is similar to a main S-N curve, so that the fatigue life of welded structures can be evaluated by a main S-N curve. Therefore, Formula (8) is usually also called the main S-N curve equation.

3. Static analysis of sub-frame.

3.1. Finite element model

The sub-frame of mixer truck is mainly composed of front device, back device, vertical and horizontal beams. There are many welds in the whole structure. Figure 5 is a schematic diagram of the sub-frame of a mixer truck in the market. No.1-5 weld seam (black bold position in the figure 5.) of the sub-frame is cracked frequently during working, which are the key welds seam position of the sub-frame.

In the finite element analysis process, the effect of suspension stiffness on sub-frame is considered, and the suspension leaf spring is simulated by beam element. The welds are simulated by shell element. The quality of cab, engine, oil tank, reducer, bracket are applied in the analysis. The overall finite element model and weld modelling are shown in figure 6.

![Figure 5. Diagram of sub-frame and key weld seams](image)

3.2. Results of static analysis.

According to the service conditions of the mixer truck, and select relevant typical working conditions to analyse the performance of the sub-frame. All sub-frame components are made of Q355B material, and its yield strength and tensile strength are 463 and 566MPa. The results of frame structure strength analysis under various working conditions are shown in Table 1.
Table 1. Calculation results of sub-frame under 6 working conditions.

| Working Conditions | Max Stress (MPa) | Position of Max Stress |
|--------------------|-----------------|------------------------|
| Bending condition  | 355.8           | Junction of back device left corner and left longitudinal beam |
| Torsion condition  | 405.8           | Junction of diagonal brace and longitudinal beam (No.3 weld) |
| Braking condition  | 314             | Junction of back device left corner and left longitudinal beam |
| Turning condition  | 349.2           | Junction of diagonal brace and back device (No.5 weld) |
| Sloping up condition| 317.8           | Junction of diagonal brace and longitudinal beam (No.3 weld) |
| Sloping down condition| 283.6         | Junction of back device left corner and left longitudinal beam |

It can be seen from the stress results in Table 1 that the maximum stress of the sub-frame is 405.8MPa under torsion condition, which is close to the yield strength of the material and is located at No.3 weld. Figure 7 shows the stress of the sub-frame under torsion condition. For welded structures, fatigue failure often occurs at the weld position in high stress areas. The results of 6 typical working conditions also show that the stress at several key weld positions of the sub-frame of the mixer truck is high, and fatigue cracking failure is likely to occur after long-term operation. The fatigue life prediction and analysis of the sub-frame weld should be carried out in the design stage.

4. Fatigue assessment of sub-frame welds

4.1. Fatigue load spectrum

With reference to ISO 8608 road roughness grading standard, the dynamic analysis of the mixer truck model was carried out, and the B-class random uneven road surface was selected as the simulated road surface. The straight-line driving simulation was carried out at a speed of 50km/h for 30 seconds, and the load time history of the mixer truck frame was obtained. The load spectrum at each connection point between the frame and the front suspension was extracted at an interval of 0.25s. Because the load in X and Y directions was smaller than that in Z direction, only the Z-direction load is extracted, which used to the fatigue analysis. The load spectrum is shown in figure 8.

4.2. Analysis of inertia release

The frame of the mixer truck is in a free state during driving. When the frame is analysed under unit load, it is impossible to determine the constraint of the frame under the condition of failure. Therefore, the inertia release method is used for static analysis to obtain the stress response of the frame structure under unit load. The inertia release analysis is carried out by applying unit load at each joint position between the frame and the suspension, and the stress of the frame under the single excitation of unit load is obtained, as shown in figure 9, which shows the inertia release result of the joint position between the left leaf spring of the front suspension and the frame.
4.3. Weld fatigue analysis results by equivalent structural stress method.

Inertial release analysis of unit load is carried out at different connection positions of the frame, and the stress responses of the frame are different. The process of fatigue assessment of sub-frame welds by equivalent structural stress method as follows: first converting the stress of each connecting position into the equivalent structural stress, then combining the main S-N curve and load spectrum data to analysis, and obtaining the fatigue life of weld under single load spectrum, finally the fatigue life of weld under multiple load spectrum is solved by the principle of fatigue damage accumulation. The basic process is shown in figure10.

Figure 9. Results of inertia release at connection position

Figure 10. Flow chart of fatigue assessment of sub-frame weld

Through the transformation of structural stress of weld element, the overall equivalent structural stress of weld joint under multiple load spectra is obtained. Combined with formula (8), the main S-N curve with a survival rate of 50% is selected to predict the fatigue life of weld. The fatigue life values of each weld are shown in Table 2.

| Weld number | life cycle in survival 50% | target | Meet requirement |
|-------------|---------------------------|--------|------------------|
| 1           | $1 \times 10^6.52$        |        | yes              |
| 2           | $1 \times 10^5.81$        |        | yes              |
| 3           | $1 \times 10^5.803$       | $8.64 \times 10^5$ | no               |
| 4           | $1 \times 10^7$          |        | yes              |
| 5           | $1 \times 10^6.23$        |        | yes              |

From table 2 and figure11, it can find that minimum fatigue life is $10^5.803$ cycles located at the corner of No.3 weld.

Figure 11. Cloud diagram of weld fatigue life of sub-frame

Assuming that the service cycle of the mixer truck is three years, working 8 hours a day and 300 days a year, combined with the load spectrum data, the design service cycle number of the mixer truck is calculated to be $8.64 \times 10^5$. It can be seen that the No.3 weld seam does not meet the minimum requirement of design life. So the sub-frame structure needs to be optimized in order to reduce the structural stress, and improve the fatigue life of the weld.
5. Conclusion.
(1) The structural stress can be obtained by finite element analysis, and the fatigue assessment of welded joints can be completed by using a main S-N curve, and the effects of stress concentration, plate thickness and load mode on fatigue life are considered. Meanwhile, the structural stress is grid insensitive, which reduces the stress calculation error of welded joints. Compared with traditional methods, this fatigue assessment method is simply and accurate.

(2) The multi-body dynamics simulation analysis was carried out for the mixer truck, and the load spectrum data of the mounting position of the frame and suspension were obtained. The inertia release method is used to apply unit load to each connecting position of the frame and suspension, and the stress response of the frame under the single excitation of unit load was obtained.

(3) The fatigue assessment of the key weld position of the sub-frame was carried out by using the equivalent structural stress method, and the results showed that the fatigue life of the No.3 weld was $10^{5.803}$ cycles, which failed to reach the design target value. Therefore, the sub-frame structure should be optimized to improve the structural stress of the weld position.

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