Research on a Method for Selecting Fatigue Monitoring Points for Welding Structure of Rail Vehicles Based on Structural Stress Method

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***Abstract*—Selecting fatigue monitoring points for welding structure in a PHM system or a fatigue bench testing for rail vehicles is a complex and difficult problem. In this paper, a method for selecting fatigue monitoring points for welding structure based on structural stress method is proposed. Firstly, static strength method is selected to obtain the weak points of the welded structure. Secondly, the structural stress method with the standard load spectrum and the actual load spectra is used to achieve more fatigue weak points, and the cumulative damage ratio of various weak points are calculated as well. A selecting procedure is then used to determine the ultimate locations of the fatigue monitoring points based on the fatigue weak points above. Finally, a rail vehicle is taken as an example to verify the method. The result shows that the position of the fatigue monitoring points for the complex welded structure of rail vehicle can be obtained effectively by the method.**

Keywords-structural stress method; load spectra; fatigue monitoring point

I. INTRODUCTION

The welded joints of the welded structures of rail vehicles are subjected to alternating loads during long-term operation. They are one of the weakest parts that are most prone to fatigue damage. The large-scale welded structures, such as high-speed trains and railway wagons, have numerous welds (up to several hundred) which are different types and arbitrary direction. Choosing monitoring points of these structures for PHM system and fatigue bench testing is a complex and difficult problem. In traditional methods, fatigue monitoring points usually are selected manually by calculating static strength of the welded structure finite element model to get weak areas or from practical and accumulated experience. These methods which have not an effective fatigue assessment method are easy to cause inaccurate selection, missed selection or multiple selections. Furthermore, if there are a large number of welds and several calculation conditions in a large-scale complex welded FE model, the determination of weak points will be very time-consuming and error-prone because of the manual way. In addition, the traditional standard fatigue assessment methods such as IIW standard and BS standard are very difficult to determine fatigue weak areas of practical industry complex welded structures due to their limited joint types. All these problems directly affect the health monitoring effect and fatigue assessment results of rail vehicle welding structure. Therefore, to study the selection method for fatigue monitoring points of welded structures has great research significance and practical engineering significance.

Scholars have finished a lot of research on the selection method of fatigue monitoring points. L. Molent compared the fatigue monitoring point data obtained by the fatigue monitoring system with the results of the fatigue experiment, and verified that the selection of the fatigue monitoring point is correct [1]; Hongsheng Yan used fatigue spectra analysis with linear cumulative damage theory to evaluate the fatigue life of the structure and provides a method for the selection of fatigue monitoring points[2]; Lianhui Jia obtained the structure's structural stress response with external load by finite element analysis. Based on this, the fatigue monitoring points are selected [3]; Haohui Zhang calculates the structural strength by the spectral analysis method and the stress concentration factor method. The cumulative damage ratio is taken to consider the position as the index to obtain the optimal arrangement of the fatigue monitoring points [4].

The structural stress method which became the ASME standard in 2007 and can figure out the stress concentration areas from arbitrarily curved welds provides an effective method for obtaining fatigue monitoring points of complex welded structures [5]. The feature of the method compared to the traditional welding fatigue assessment method is that it uses a main S-N curve to predict the welding fatigue life. Furthermore, this method solved the two weld fatigue assessment problems: the sensitivity of the finite element mesh size and the difficulty of selecting the S-N curve corresponding to different welded joints types.

Based on structural stress method, this paper obtains the weak points and calculates their damage ratio. In order to get the final locations of the fatigue monitoring point, combing

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static strength weak points of welded structure, the selecting program is used to choose ultimate position of fatigue monitoring points by considering the damage level and the location information.

II. STRUCTURAL STRESS METHOD

Weld fatigue failure generally occurs at weld toe of the welded joint and extends along the direction of plate thickness [6]. The stress distribution in this position is shown in Fig. 1. The stress in the direction of the thickness of the weld is nonlinear here. The main stress σ_z at the toe of the welds is determined by the sum of the membrane stress σ_m , the bending stress σ_b and the nonlinear peak stress σ_n . The main stress acting on the fatigue performance is defined as the structural stress σ_s , which can be expressed as:

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

In the formula: t is plate thickness; f_y is the linear force per unit length of the welding line; m_x is the moment of unit length line on the welding line.

$$\begin{Bmatrix} F_{y1} \\ F_{y2} \\ F_{y3} \\ \vdots \\ \vdots \\ F_{yn} \end{Bmatrix} = \begin{bmatrix} \frac{l_1}{3} & \frac{l_1}{6} & 0 & 0 & \cdots & 0 \\ \frac{l_1}{6} & \frac{(l_1+l_2)}{3} & \frac{l_2}{6} & 0 & \cdots & 0 \\ 0 & \frac{l_2}{6} & \frac{(l_2+l_3)}{3} & \frac{l_3}{6} & 0 & 0 \\ 0 & 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \ddots & \ddots & \frac{(l_{n-2}+l_{n-1})}{3} & \frac{l_{n-1}}{6} \\ 0 & \cdots & \cdots & 0 & \frac{l_{n-1}}{6} & \frac{l_{n-1}}{3} \end{bmatrix} \begin{Bmatrix} f_{y1} \\ f_{y2} \\ f_{y3} \\ \vdots \\ \vdots \\ f_{yn} \end{Bmatrix} \tag{2}$$

In practical finite element model, the weld was divided into $n\text{-}1$ elements. The linear forces f_i is calculated by（2）from the nodal forces F_i and the element edge length l_i. The corresponding line moments m_x can be calculated identically.

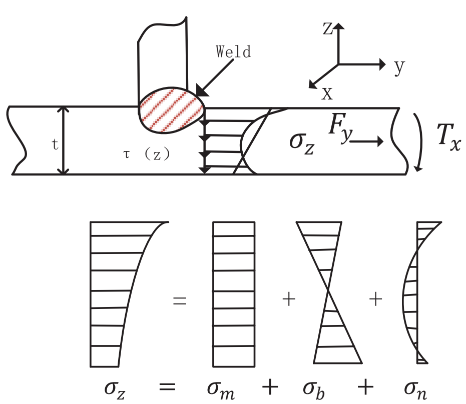


Figure 1. Stress distribution at the weld toe

TABLE I. MAIN S-N CURVE PARAMETER TABLE

Statistic	Related Parameters	
	C	***H***
median +2σ -2σ +3σ -3σ	19930.2 28626.5 13875.8 31796.1 12492.6	-0.32

Every node structural stress σ_s can be calculated according to (1).

Structural stress reflects the stress concentration caused by external load and is considered as the driving force of crack propagation. Based on the principle of fracture mechanics, in order to better express the correlation of welded structures, the structural stress method introduces a new stress, namely "equivalent structural stress" [7]. The introduction of this parameter takes into account not only the influence of joint shape and plate thickness size, but also the influence of stress concentration problem. The variation range of the equivalent structural stress is:

$$\Delta S_s = \frac{\Delta \sigma_s}{t^{\frac{2-m}{2m}} \cdot I(r)^{\frac{1}{m}}} \tag{3}$$

In the formula: ΔS_s is the change range of equivalent structural stress; $\Delta\sigma_s$ is the range of structural stress; t is the thickness of the plate; I(r) is the dimensionless constant of the bending ratio ($r = \Delta\sigma_b / \Delta\sigma_s$); m is the crack growth index, generally m = 3.6.

With the equivalent structural stress variation range ΔS_s as the parameter, the formula is fitted and corrected by the data obtained from a large number of fatigue experiments [8], and the calculation formula of welding fatigue life is finally obtained:

$$N = \left(\frac{C}{\Delta S_s}\right)^{\frac{1}{h}} \tag{4}$$

N represents fatigue life; C and h are experimental constants of s-n curve (Table Ⅰ); A single S-N curve can be obtained by this formula, which is the main S-N curve.

III. SELECTION OF FATIGUE MONITORING POINTS BY STRUCTURAL STRESS METHOD

In order to select the monitoring position of the rail vehicle welding structure, the method of selecting the weak point method proposed is shown as Fig.2.

A. Load spectra selection

Through applying the standard load spectra and the measured load spectra to the finite element model, the structural stress method is used to evaluate the life and damage

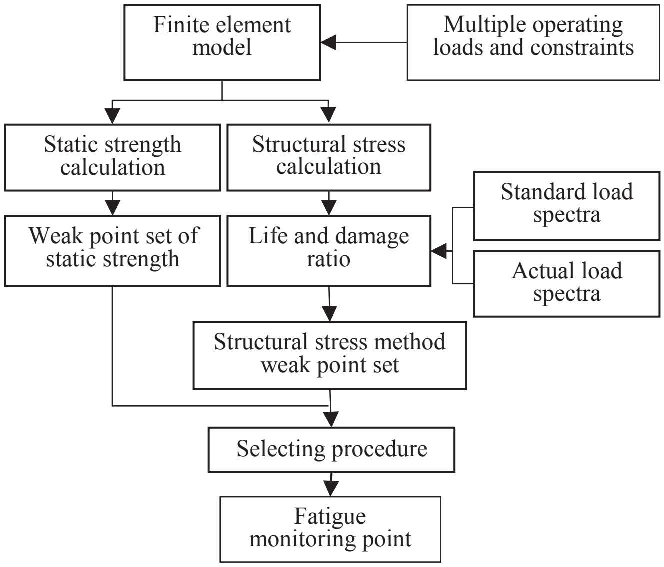


Figure 2. Fatigue monitoring point selection process

ratio of the welded structure, and then the weak points are achieved.

The standard load spectra refers to the standard-based load spectra and is suitable for fatigue assessment of rail vehicles, such as the US AAR load spectra for railway wagons [9]. The actual load spectra is the actual load gathered from the vehicle body running on the actual line. The content of the actual load spectra needs to cover many actual information when the vehicle is running, such as running on the main line, entering and exiting the side line, entering and exiting the vehicle section and other working conditions.

B. *Determine the location of stress concentration and the selection of monitoring points*

The steps to select the fatigue point of the welded structure based on the structural stress method are as follows:

1)Establish a finite element model of the welded structure.

2)Extracting the nodal forces and moments of the weld toe line in the finite element result, then calculate the structural stress according to (1).

3)Converting structural stress at each node into equivalent structural stress.

4) Load spectra is applied to the model.

5)Refer to Table 1 to confirm the relevant parameters of the main S-N curve, and calculate the variation range of the equivalent structural stress according to (2).

6)Fatigue life of each node is got according to (3). According to Miner cumulative damage theory, the damage ratio of each node is calculated.

7)Sort by accumulated damage ratio. Select the nodes with large damage ratio(large damage) as the weak points.

After applying the standard load spectra and the measured load spectra respectively, the accumulated damage is got through the calculation of the structural stress under multiple calculation conditions. The weak points come from relatively large damage ratio are obtained to form the weak nodes set. It is also necessary to consider that the large stress points in the FE static strength calculation of the welded structure under multiple calculation conditions are added into the total weak nodes set.

C. *Selection of fatigue monitoring points*

It is necessary to select points from weak nodes set as the fatigue monitoring points. Therefore, the positions of all weak points are considered, and the finally selected weak points become the fatigue monitoring points.

According to (5), the distance d_{ij} between weak points set is compared to determine whether it is less than the reference distance. If it is less than the reference distance, the point with high damage ratio will be retained as the fatigue monitoring point, and the point with low damage ratio will be deleted. Until all the weak points are judged, the selected point is the location of fatigue monitoring point.

$$d_{ij} = | p_i - p_j | \qquad (5)$$

p_i denotes the coordinates of the i weak point and the coordinates of the j weak point of p_j.

IV. THE METHOD IMPLEMENTATION AND EXAMPLES

A. *Fatigue monitoring point selection software implementation*

Using C++ language and OpenSceneGraph as the graphics engine, the fatigue monitoring point selection program named MPS is implemented which is shown in Fig. 3. Through the finite element reading module of the program, the nodal forces and nodal moments of the weld toes from Ansys calculation result file are directly read. The structural stress and the weak point node set are obtained according to the method of chapters above.

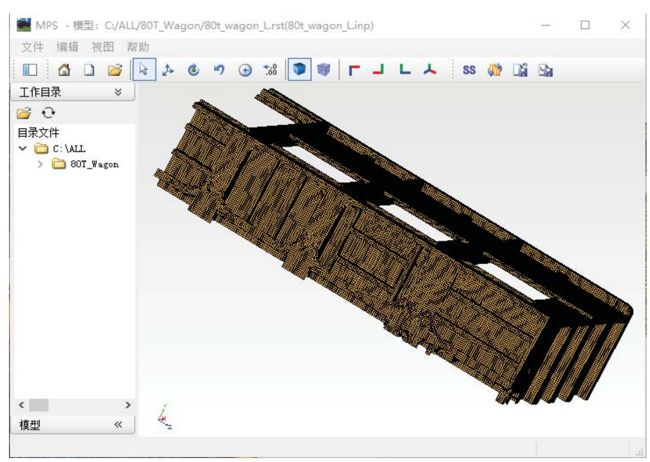


Figure 3. *Monitoring point selection （MPS） program user interface*

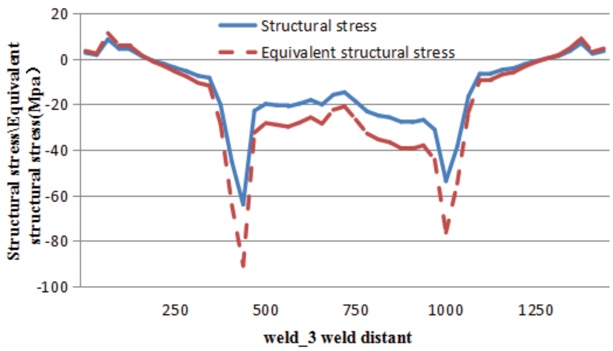


Figure 4. *Structural stress curve*

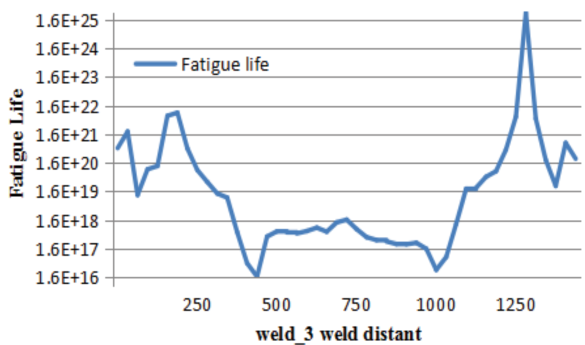


Figure 5. *Fatigue Life curve*

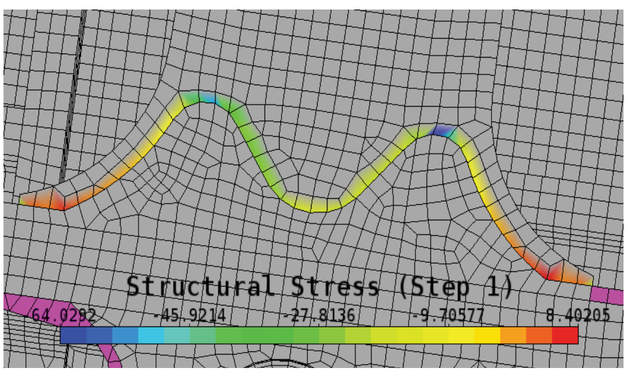


Figure 6. *Structural stress nephogram*

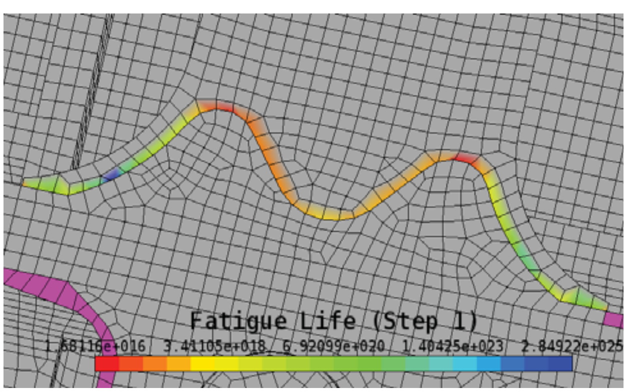


Figure 7. *Fatigue life nephogram*

After the calculation, structural stress and fatigue life can be achieved and are shown by nephogram and curve ways from MPS program (Fig.4-7.) With the results, continuous distribution of stress concentration and fatigue life are obtained. Based that, all welds weak points are selected directly and easily.

B. *Selection of fatigue weakness points*

Taking five calculation conditions of a railway freight car as an example, the finite element model of the car body is shown in Fig.8. The model consists of 129605 nodes, 142389 elements and 242 welds. In this paper, the MPS program is used to calculate the node set of fatigue weakness.

After the finite element model is established, the ANSYS calculation results is obtained. After loading the AAR load spectra and the actual load spectra and multiple working conditions, structural stress, fatigue life and damage ratio results are listed and arranged from high to low by their accumulated damage values. The high accumulated damage points are chosen as weakness point set. After calculation, 26 stress weak points of weld structure are obtained automatically by the MPS program. Combining with 31 weak points from FE static stress calculation, 57 total weak points as a total weak point set is obtained. 27 weak points as monitoring points are achieved by the selecting procedure from the total weak point set at the end. The MPS program which provides a quick and convenient selection method improves the selection efficiency of weak points.

C. *Fatigue monitoring point arrangement*

Typical monitoring points of 27 monitoring points are shown in the Fig.9 and relevant information is shown in Table II. All these selected monitoring points are recommend to be the real monitoring points in PHM system and fatigue bench testing. This selecting monitoring points method has been preliminarily applied to vehicle fatigue test of CRRC Qiqihaer Rolling Stock Company.

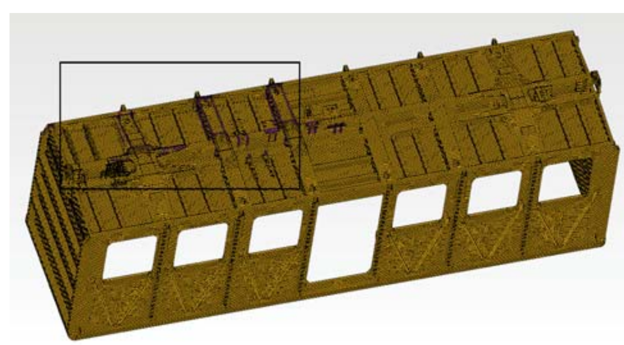
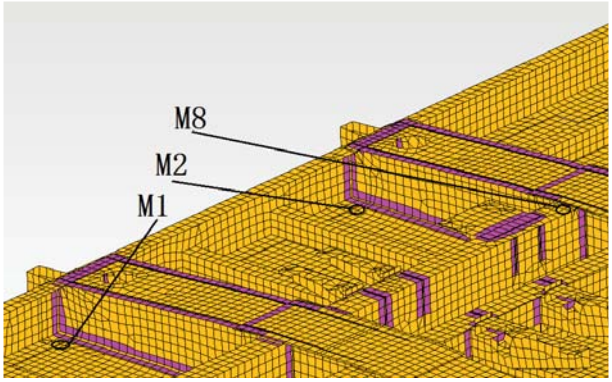
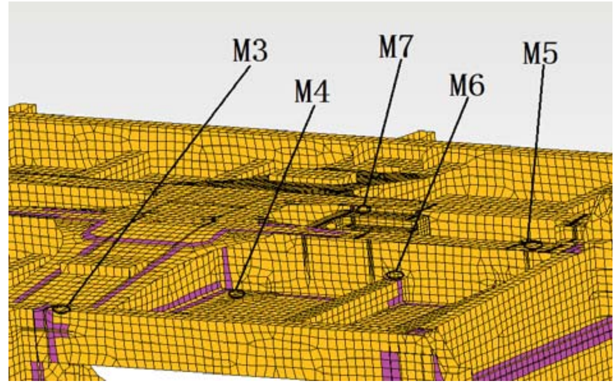


Figure 8. *Finite element model of railway freight car body*



(a)3 typical monitoring points



(b)5 typical monitoring points

Figure 9. *Positions of the fatigue monitoring points*

TABLE II. TYPICAL FATIGUE MONITORING POINTS SELECTION RESULT

Monitoring point number	Related Parameters			
	Working condition	**Weld joint unit number**	**Node number**	**Location**
M1	5	115	315282	Inside of the large beam
M2	5	73	313594	Inside of the large beam
M3	5	44	307175	Pillow beam chassis intersection
M4	4	38	324514	Girders and middle beams intersection
M5	2	198	354716	Inside of the middle beam intersection
M6	3	22	351049	Small beam and middle beam intersection
M7	3	183	352291	Inside of the middle beam intersection
M8	1	103	350732	Large beam and middle beam intersection

V. CONCLUSION

In this paper, a method of selecting monitoring points based on structural stress method is put forward for rail vehicles PHM system and fatigue bench test. The following conclusions are obtained: the fatigue weak points of welded structure of rail vehicle can be found out quickly by using structural stress method. Suitable fatigue monitoring point can be obtained by considering the static strength weak points, considering the position factor and using the selecting program to consider the cumulative damage ratio and position of the weak points. The practical example shows that this method can obtain selection in high efficiency in large amount of welds and multi-load conditions for complex welding structure.

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