Simulation Research on Defect Detection of Plate Weld Based on Sensitivity Analysis

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Abstract: In order to improve the efficiency of traditional local non-destructive testing method in detecting the defects of large plate welds and obtain the equivalent mechanical parameters of weld defects, a method for detecting plate weld defects based on local vibration area sensitivity analysis is proposed. This method does not need to pay attention to the specific form of the weld defect, and it regards the defect as a reduction in the local Young's modulus. A plate welding model was established in ABAQUS finite element software to simulate the detection process of different defect positions and different defect levels. The results show that the sensitivity matrix constructed with the elastic modulus of 5% change can be applied to the detection of defects with a degree of 3% to 20%. It shows that the proposed method can be used to locate and quantify weld defects with sufficient accuracy.

1. Preface
The welded structure is prone to damage, mainly concentrated in the weld. This is because during the welding process, the surrounding area of the weld is prone to severe physical and chemical changes, thereby reducing the performance of the material. The consequences of such defects may be extremely serious. At present, the welds are mainly detected by ultrasonic\(^{[1][2]}\), ray\(^{[3][4]}\), leakage magnetic field\(^{[5][6]}\), finite element simulation and other methods at home and abroad. In this paper, the finite element simulation method is used to determine the defect location and defect degree in the flat weld. For the defect detection of the dynamic sensitivity method, relevant scholars have done a lot of researches.

Cawley and Adams\(^{[7]}\) determined the exact location of a single defect by exploiting the ratio of any two natural frequencies. Messina\(^{[8]}\) applied the method of locating multiple defects to several truss structures, which is based on the natural frequency sensitivity, and the accuracy of the method is verified by experimental research. Based on the sensitivity of the time domain response to the damage parameters of the damage structure, Law\(^{[10]}\) studied the truss structure and verified it. Yan Wangji\(^{[11]}\) obtained the modal strain energy sensitivity by using the first-order modal information and the method of combining the flexibility matrix, and applied it to the damage detection of the simply supported beam, and the recognition accuracy is high. Literature\(^{[12][15]}\) studied the defect detection method based on flexibility sensitivity. Literature\(^{[16][18]}\) calculated the sensitivity matrix of time domain response to structural damage parameters, and determined the degree of damage by model correction method.

Based on the above research on weld detection and dynamic sensitivity, this paper proposes a method for detecting weld defects based on sensitivity method in the local vibration region. Compared with other detection methods, the proposed method has the following advantages:
(1) A method of detecting in a local vibration region is proposed, so that the signal is less susceptible to interference in a shorter period of the detection process, and because of the small area, the amount of calculation is greatly reduced and the efficiency is improved.

(2) Once the sensitivity matrix is constructed, it is common in each local vibration region, and has strong adaptability and portability.

(3) High detection accuracy, accurate positioning and small error.

2. Basic theory

2.1 Establish sensitivity equation

The weld of the flat model shown in Figure 1 is divided into $n$ units, and the load $F$ is applied at point $i$, and the signal is collected at the corresponding $i'$ point. In this paper, the excitation point corresponds to the measurement point one by one, and they are the same distance from the weld, the acceleration response of the measurement points is a function of the Young's modulus of each weld cell.

$$X_j = X_j(E_1, E_2, \ldots, E_j, \ldots, E_n) \quad j = 1, 2, \ldots, n$$  \hspace{1cm} (1)

If the plate model has only a certain damage in the $j$ unit, the time domain response $X_{id}(t)$ of the lossy plate model at the measurement point $i$ can be expressed as equation (2) using the multivariate function Taylor formula.

$$X_{id}'(t) = X_{iu}(t) + \sum_{j=1}^{n} \frac{\partial X_j(t)}{\partial E_j} \Delta E_j + \frac{1}{2!} \sum_{j,k=1}^{n} \Delta E_j \Delta E_k X''_{j,k} + \cdots$$

\hspace{1cm} \quad j = 1, 2, \ldots, n \hspace{1cm} (2)

Only the $j$ unit has damage, so when $j \neq k$, $\Delta E_j \Delta E_k = 0$, and when $j = k$, $\Delta E_j \Delta E_k = \Delta E_j^2$.

![Figure 1: Plate weld model](image)

$X_{iu}(t)$ indicates the response of the plate model to the point $i'$ in case of non-destructive, $\Delta E_j$ indicates the amount of elastic modulus damage of the $j$ element.

When constructing the sensitivity matrix in this paper, the damage amount $\Delta E_j$ is set to 5% of the normal value. Since the high-order term is much smaller than the first term, the high-order term of the formula (2) is ignored, and the equation (3) is obtained.

$$X_{ij}(t) \approx X_{iu}(t) + \sum_{j=1}^{n} \frac{\partial X_j(t)}{\partial E_j} \Delta E_j$$  \hspace{1cm} (3)

Using the difference form instead of the partial form, equation (4) is obtained.

$$\Delta X_j(t) = X_{ij}(t) - X_{id}(t) = \sum_{j=1}^{n} \frac{X_j(E_j + \Delta E_j) - X_j(E_j)}{\Delta E_j} \Delta E_j$$  \hspace{1cm} (4)
The sensitivity matrix constructed by the difference method is easy to numerically calculate because it does not require an analytical solution. The parameter change set in this paper is 5%, so that the influence of the higher order term and the differential instead of the partial differential can be ignored as much as possible.

Equation (4) is expanded into a matrix form of discrete time points, as in equation (5).

\[
\begin{bmatrix}
\Delta X_i(t_1) \\
\Delta X_i(t_2) \\
\vdots \\
\Delta X_i(t_s)
\end{bmatrix}_{s \times 1} = [S] \times 
\begin{bmatrix}
\Delta E_1 \\
\Delta E_2 \\
\vdots \\
\Delta E_n
\end{bmatrix}_{n \times 1}
\]

Equation (5) is expanded into a matrix form of discrete time points, as in equation (5).

\[
\Delta X_i(t) \text{ indicates the difference in time domain response of the structure in lossy and lossless conditions, } t_k \text{ indicates different sampling moments for the same measurement point, } k = 1, 2, 3, \ldots, s.
\]

The matrix of equation (6) is a sensitivity matrix, in which each column can be regarded as a weight coefficient vector, indicating the degree of influence of different weld units on the time domain response of a single measurement point under a certain parameter change.

\[
S = 
\begin{bmatrix}
\Delta X_i(t_1) & \Delta X_j(t_2) & \ldots & \Delta X_m(t_s) \\
\Delta E_1 & \Delta E_2 & \ldots & \Delta E_n \\
\Delta X_i(t_1) & \Delta X_j(t_2) & \ldots & \Delta X_m(t_s) \\
\Delta E_1 & \Delta E_2 & \ldots & \Delta E_n \\
\vdots & \vdots & \ddots & \vdots \\
\Delta X_i(t_1) & \Delta X_j(t_2) & \ldots & \Delta X_m(t_s) \\
\Delta E_1 & \Delta E_2 & \ldots & \Delta E_n
\end{bmatrix}_{n \times n}
\]

2.2 Solution method of sensitivity equation

For equation (6), the number of flat weld units is much smaller than the number of measurement time points, that is \( n \ll s \), the least squares method can be used to solve the statically indeterminate equations, as in equation (7), and the specific damage information of the structural unit is finally calculated.

\[
\{\Delta E\} = [S^T S]^{-1} S^T \{\Delta X\}
\]

When the sensitivity matrix is seriously ill-conditioned, it can be solved by Tikhonov regularization method, as in equation (8). At the same time, for the determination of regularization parameters, the L curve method\(^{[19]}\) or the generalized cross-checking method will be used.

\[
\{\Delta E\} = [S^T S + \lambda^2 SL]^{-1} S^T \{\Delta X\}
\]

3. Numerical simulation

3.1 Establishment of finite element model

The flat weld model is shown in Figure 2. The excitation uses a three-period Hanning window excitation, which can reduce the frequency side lobes caused by the sudden start and end of the signal, so that the energy is concentrated on the excitation frequency and is easy to measure. The boundary condition is one-sided solid support, the mesh size is 1mm, the analysis time is 4.6μs, and the time step is 1.0E-8s.

The size of the plate is set to 0.3×0.2×0.004m, the size of the weld is 0.002×0.2×0.004m, the elastic modulus of the weld is 206Gpa, the elastic modulus of the weld base material is 235Gpa, and the Poisson’s ratio is 0.3.
3.2 Construction of sensitivity matrix
When an excitation is applied at a certain point in the plate, the vibration wave generated by the excitation will propagate to the surroundings. In a short period of time, since the boundary region has not been affected by the vibration wave, no vibration occurs, and the displacement is equal to zero, which can be equivalent to the fixed boundary condition, therefore, a detection method based on local vibration region is introduced.

The most important thing in the detection of weld defects based on sensitivity analysis is the construction of the sensitivity matrix. In this paper, by controlling the time and step size of numerical simulation to control the size of the local vibration region, thereby the sensitivity matrix of the local vibration region is constructed. The circle in Figure 3 is the local vibration region.

Select five equivalent units near the excitation point, and form a local vibration region, then set the change of the parameters of the five weld equivalent units $i-2, i-1, i, i+1, i+2$ respectively, and sequentially obtain the response of the measurement point $i'$ in both lossy and non-destructive conditions, then the sensitivity matrix can be calculated by using the difference method.

Now select the 10th measuring point, and the 8-12 five equivalent units constitute the local vibration area, and set the parameter change to 5% of the weld elastic modulus, that is 10.3Gpa. The acquired signal is the acceleration response, and the acceleration response of the 10th measurement point under the lossless structure is obtained, then obtain the acceleration response of the 10th measurement point when the five equivalent units in the local vibration region are respectively set to a
certain parameter change (5%). The total time for data sampling at the measurement point is 4.6 μs, which is sampled every 0.01 μs to obtain a sensitivity matrix of 461 rows and 5 columns.

As shown in Figure 4 below, in the local vibration region, the most important influence on the acceleration response of the 10th measuring point is the intermediate weld equivalent unit (equivalent unit 10), and the influence of the equivalent units 9 and 11 is very small, almost only 1/100 of the equivalent unit of No. 10, but the equivalent units of No. 8 and No. 12 have basically no influence on the acceleration response of the measuring point, almost can be ignored, so delete the two columns of sensitivity vectors. The resulting sensitivity matrix has only three columns, and the condition number is equal to 400000. The matrix is seriously ill-conditioned, so it will be solved by Tikhonov regularization.

![Figure 4: Sensitivity matrix in local vibration region](image)

### 3.3 Test results

In order to analyze the effectiveness of the sensitivity matrix based on the local vibration region structure for the weld defect detection in the flat butt weld structure, the model of Figure 2 is used to numerically simulate the single defect and multiple defects, and the defect conditions are set as follows.

1) Working condition 1-6: set the defect degree of unit 4 to 3%, 5%, 6%, 7%, 10%, 20% respectively;
2) Working condition 7-12: set the defect degree of unit 7 to 3%, 5%, 6%, 7%, 10%, 20% respectively;
3) Working condition 13-18: Unit 4 has the same defect with Unit 5 at the same time, and the degree of defect is set to 3%, 5%, 6%, 7%, 10%, 20% respectively;
4) Working condition 19-22: Unit 5 has the same defect with Unit 7 at the same time, and the degree of defect is set to 3%, 5%, 6%, 7%, 10%, 20% respectively;
5) Working condition 23-26: Unit 5 has the same defect with Unit 11 at the same time, and the degree of defect is set to 3%, 5%, 6%, 7%, 10% respectively;
6) Working conditions 27-28: Unit 5 has the different defect with Unit 7 at the same time;
7) Working conditions 29-30: Unit 5 has the different defect with Unit 14 at the same time;
8) Working conditions 31-34: Unit 4 has the different defect with Unit 5 at the same time.

### 3.3.1 Test results of single defect conditions

As shown in Figure 2, the weld equivalent unit has a width of 2 mm and a length of 10 mm. The distance between the excitation point and the measuring point to the nearest side of the weld is 9 mm.

Combined with the conclusions obtained in Figure 4, it can be concluded that when the equivalent unit of No. 4 is defective, only three equivalent units of 3, 4, and 5 have an influence on the
acceleration response of the measuring point No. 4, and the influence of the fourth unit is the largest. Using the constructed sensitivity matrix, and measuring the response of three measuring points of 3, 4, and 5 respectively, then the sensitivity equation is solved. The closest to the actually set defect is the detection result of the most intermediate unit in the local vibration region. Therefore, in the working condition 1, all the equivalent unit measurement points along the entire weld are sequentially detected (here only the equivalent units 2 to 18 are detected, since the equivalent units 1 and 19 are easily affected by the boundary), and the detection result is shown in Figure 5.

Figure 5 The result of point-by-point detection along the weld under Condition 1
Similarly, in the second to sixth working conditions, each measuring point is tested along the entire plat weld, and the test results are shown in Figure 6.

Figure 6 The result of point-by-point detection along the weld under Condition 2~6
Similarly, the degree of defects detected along the weld can also be obtained from the 7th to 12th working conditions, as shown in Figure 7.

Figure 7 The result of point-by-point detection along the weld in unit 7 with varying degrees of defects (Condition 7~16)
From the test results of the twelve working conditions of Figure 5, Figure 6 and Figure 7, it can be concluded that the maximum error occurs in the case where the equivalent unit 4 (or equivalent unit 7)
has 7% defect, and the error is 0.282%. At the same time, it can be seen that the local vibration region sensitivity matrix constructed by the equivalent unit 5% parameter change is used to detect 5% defects, and the detection accuracy is quite high. As can be seen from the figure, there is basically no error. In short, the sensitivity analysis method based on local vibration region is feasible for detecting single defect conditions, can locate specific defect positions, and also can obtain higher detection accuracy.

3.3.2 Test results of double defect conditions

This section will test the double defect conditions, including the fact that the two equivalent units at different positions have the same degree of defects, and the two equivalent units at different positions have the different degree of defects.

As shown in Figure 8(a), it is detected that the two equivalent units in adjacent positions in the weld have the same degree of defects at the same time. It can be seen from the test results that the error is slightly increased compared with the single defect conditions, and the maximum error occurs in the case where the two equivalent units of 4 and 5 have 7% defects at the same time, and the error is 0.286%. The reason why the error increases slightly is because the two adjacent equivalent units have defects at the same time, which have a certain influence on the acceleration response of the respective measurement points. In fact, it can be seen from the conclusion obtained in Figure 4. Figure 8(b) shows the conditions that the two equivalent elements in non-adjacent locations in the weld have the same degree of defects at the same time. It can be seen from the figure that the test results are good. Actually, these double defect condition tests can be regarded as the detection of single defect conditions, because the two equivalent units with defects in the weld are not adjacent, and some are even far away. From the conclusion obtained in Figure 4, what affects the acceleration response of the measuring point is the three consecutive equivalent units centered on the measuring point. The same conclusion can be drawn from the error of the test results and the error of the single defect conditions.

As shown in the figure below, Figure 9 shows the detection results when the equivalent units of two non-adjacent positions have different degree of defects. It can be seen from the results of the test that when two equivalent units have defects at the same time and there is a certain interval, the defects of each other have almost no influence on the response of the respective measurement points, and the error of the test result is basically the same as that of the single defect condition, so it can be regarded as the detection of the single defect condition. Figure 10 shows the detection results when the equivalent units of two adjacent positions have different degree of defects. It can be seen that the error is significantly increased, and the equivalent unit with a large degree of defect has a large influence on the measurement point response of the equivalent unit with a small degree of defect.

![Figure 8](image1.png)

Figure 8  Detection results of condition with double defects: (a) Condition 13–18; (b) Condition 19–26
4. Conclusion
In this paper, the sensitivity matrix based on the local vibration region is used to detect the defects of the weld in the plate weld structure, and the related numerical simulation research is carried out. Firstly, the model of the plate weld structure was established. Then, the sensitivity analysis method was applied to detect 34 kinds of artificial conditions. A method of introducing a local vibration region is described, and a specific detection step in the plate weld structure is described based on the sensitivity analysis method of the local vibration region. The sensitivity matrix is highly adaptable and we only construct the sensitivity matrix once and it can be applied to the detection of various working conditions. The defect positioning accuracy is high and the detection effect is good, which provides a new idea for the detection of the plate weld defects.

However, this method has certain limitations. Firstly, the errors caused by the high-order terms and the difference method are ignored. Secondly, only the defect of the intermediate equivalent unit of each local vibration region can be detected. For non-intermediate equivalent unit, it is not well detected. In addition, it does not detect the area near the edge of the flat structure well because a part of the mechanical waves are reflected back at the boundary, which causes a large interference to the detection result.
Reference

[1] Legendre S, Massicotte D, Goyette J, et al. Neural classification of Lamb wave ultrasonic welding signals using wavelet coefficients[J]. Instrumentation & Measurement IEEE Transactions on, 2001, 50(3):672-678.

[2] Óscar Martín, Manuel López, Fernando Martín. Artificial neural networks for quality control by ultrasonic testing in resistance spot welding[J]. Journal of Materials Processing Technology, 2007, 183(2-3):226-233.

[3] Run-Shi H, Jia-Xin S, Li W, et al. Image Processing of Real-Time Automatic X-Ray Inspection System for Weld Defects[J]. Nondestructive Testing, 2009.

[4] Waltz F M. Automatic segmentation and classification of weld defects by x-ray inspection[J]. Proceedings of SPIE - The International Society for Optical Engineering, 1992, 1823:262-271.

[5] Wild P. Factors Affecting Magnetic Flux Leakage Inspection of Tailor-Welded Blanks[J]. Research in Nondestructive Evaluation, 2006, 17(2):85-99.

[6] Tsukada K, Yoshioka M, Kiwa T, et al. A magnetic flux leakage method using a magnetoresistive sensor for nondestructive evaluation of spot welds[J]. Ndt & E International, 2011, 44(1):101-105.

[7] Cawley P, Adams R D. The location of defects in structures from measurements of natural frequencies[J]. The Journal of Strain Analysis for Engineering Design, 1979,14(2):49-57.

[8] Messina A, Williams E J, Contursi T. Structural damage detection by a sensitivity and statistical-based method[J]. Journal of sound and vibration, 1998, 216(5):791-808.

[9] Law S S, Li X Y, Zhu X Q, et al. Structural damage detection from wavelet packet sensitivity[J]. Engineering Structures, 2005, 27(9):1339-1348.

[10] Law S S, Li X Y. Wavelet-Based Sensitivity Analysis of the Impulse Response Function for Damage Detection[J]. Journal of Applied Mechanics, 2007, 74(2):375-377.

[11] Yan Wangji. Sensitivity of unit modal strain energy and its application in structural damage identification [D]. Central South University, 2008.

[12] Jaishi B, Ren W X. Damage detection by finite element model updating using modal flexibility residual[J]. Journal of sound and vibration, 2006, 290(1-2):369-387.

[13] Zhao Jingwei, Yang Qiuwei, Li Cuihong, et al. Damage identification of beam structures based on flexibility-derived sensitivity [J]. Journal of Mechanical Strength, 2017, 41(6):1450-1456.

[14] Yang Q W. A mixed sensitivity method for structural damage detection[J]. International Journal for Numerical Methods in Biomedical Engineering, 2010, 25(4):381-389.

[15] Lu Z R, Law S S. Features of dynamic response sensitivity and its application in damage detection[J]. Journal of Sound & Vibration, 2007, 303(1-2):305-329.

[16] Fu Wei, Wei Zitian, Lv Zhongrong, et al. Damage identification of plate structure based on sensitivity analysis of time domain response[J]. Journal of Vibration and Shock, 2015, 34(4):117-120.

[17] Tian Hongyan. A Method for Evaluating Railway Bridge Pier State Based on Dynamic Response Sensitivity Analysis[D]. Beijing Jiaotong University, 2014.

[18] Zhan Wei. Research on time domain identification method of structural physical parameters[D]. Nanjing Forestry University, 2010.

[19] Hansen P C, O’Leary D P. The Use of the L-Curve in the Regularization of Discretel11-Posed Problems[J]. Siam J.sci.comput, 1993, 14(6):1487-1503.