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EXPERIMENT ON A SMART TEST SYSTEM FOR HIGH-RISE STEEL TOWER STRUCTURES WITH AUTOMATIC DAMAGE DIAGNOSIS FUNCTIONS

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ABSTRACT

The experiment and the integrated technology of a smart test system for high-rise steel tower structures with automatic damage diagnosis functions for three types of damage are presented in this paper. The identification methods of three types of structural damage, which are the instability of major structural components, bolt looseness at flange assembling joints and fatigue crack initiation at welded joints of a high-rise tower structure, are established and implemented. Meanwhile, the experimental verification of the smart test system for high-rise steel tower structures with automatic damage diagnosis functions for these types of damage is performed. Experimental investigation shows that the smart test system for high-rise steel tower structures works well and it can diagnose the three types of structural damage of the tower structure accurately and automatically and provide detailed analysis data for remote monitoring.

KEYWORDS

Smart test system, tower structure, automatic damage diagnosis, instability of major component, bolt looseness, fatigue of welded joint.

INTRODUCTION

High-rise steel tower structures are a kind of widely used engineering steel structures. Wind-induced disaster investigation and simulation analysis of the high-rise steel tower structures indicated that under the long-term wind excitation, the instability of major structural components, bolt looseness at flange assembling joints and fatigue crack initiation at welded joints of high-rise tower structures are the three dominant structural damage types, having a great influence on wind resistance capacity and even causing the structure to collapse. Therefore, it is of significance to study the smart test system for high-rise steel tower structures with automatic damage diagnosis functions to ensure the safety and normal performance of the high-rise steel tower structures.

Sporadic research of damage identification of high-rise steel tower structures has been carried out worldwide. However, the development of diagnostic methods and the integrated technology of smart high-rise steel tower structures with automatic damage diagnosis functions for the three types of damage in this paper are exclusive. The experiment and the integrated technology of a smart test system for high-rise steel tower structures with automatic damage diagnosis functions for the three types of damage are presented in this paper. The three types of structural damage identification methods and their implementation techniques are also established. Meanwhile, the experimental verification of the smart test system for high-rise steel tower structures with automatic damage diagnosis functions for the three type of damage is conducted. Experimental investigation shows that the smart test system for high-rise steel tower structures works well and it can diagnose the three types of structural damage of the tower structure accurately and automatically and provide detailed analysis data for remote monitoring.

INTEGRATION OF SUBSYSTEMS TO A SMART TEST SYSTEM

Integration of Subsystem

The test system is integrated with five subsystems, i.e. sensor network and data acquisition, database management, automatic damage identification, wireless transmission and human-computer interaction. The system software is developed with the LabView platform based on virtual instrument technology produced by American National Instrument Company. The overall integration of the test system is shown in Figure 1.

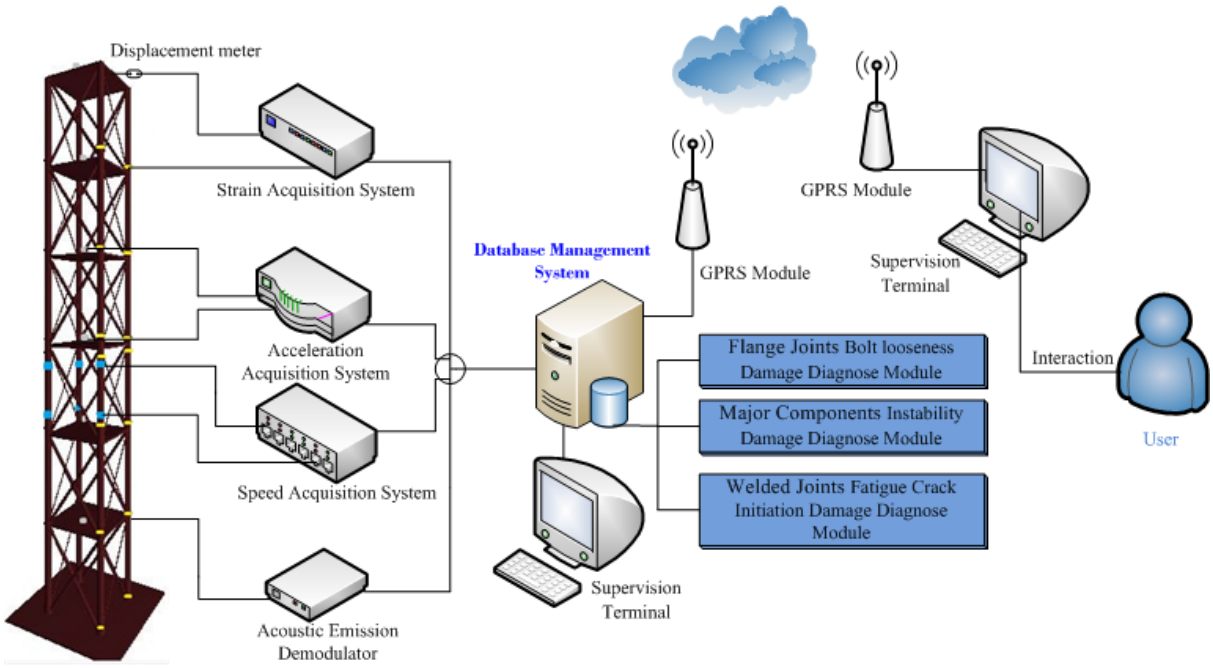


Figure 1. The diagram of the system configuration

The sensor network and data acquisition subsystem consists of sensor networks and data acquisition instrument. The sensor networks are constructed by resistance strain gauges, accelerometers, speed and acoustic emission sensors. The signals coming from resistance strain gauges and speed sensors are collected using DH3817 acquisition instrument with 1394 fire wire protocol. The accelerometer signals are collected using TMR7200 acquisition instrument from Tokyo Institute with TCP / IP protocol. The signals of acoustic emission sensor are collected using acoustic emission conditioner with TCP / IP protocol. The database management subsystem includes real-time database and damage identification database. Both of them are realized with an open source database SQLite. The automatic damage identification subsystem includes Flange Joints Bolt Looseness Damage Diagnosis Module, Major Components Instability Damage Diagnosis Module and Welded Joints Fatigue Crack Initiation Damage Diagnosis Module. The identification algorithm of each module has been established by the authors before. The wireless transmission subsystem includes wireless sending and receiving modules with GPRS. The human-computer interaction subsystem includes four components: parameter settings of sensors and acquisition instruments, visualization and transformation of the 3D model of test high-rise structures, test data displaying in real-time, process data displaying and results visualization for automatic damage identification sub-modules.

Workflow of Test System

The workflow of the test system is implemented automatically. Firstly, the information collected by the sensor networks is converted into digital signals through the acquisition instruments. Secondly, through communication protocol, the real-time data collected by acquisition software modules are stored into the real-time database after digital filtering process. And then, damage automatic identification subsystem extracts real-time data from the real-time database of back-end database server. The automatic damage identification algorithms are called through LabView and MATLAB interface program. After the damage identifications are completed, the results are stored into database, and at the same time test reports are generated. Finally, the diagnosis results are synchronously transmitted to the remote monitoring terminal or specified mobile phone users through wireless sending modules with GPRS. The test system software uses multi-thread technology to ensure the real-time

performance of the response of interface user events, the collection of sensor data, the use of diagnostic algorithms and the storage of data so that the whole system runs automatically.

IDENTIFICATION OF THREE TYPES OF STRUCTURAL DAMAGE OF TOWER MODEL

Identification for Instability of Major Components

Since instability of major components of a tower structure is elastic-plastic instability, the element axial stiffness reduces gradually and the member can still bear some external load after elastic-plastic instability occurs. Consequently, axial stiffness of the major member of the tower can be selected as a reasonable buckling damaged index.

In this paper, two-step diagnosis method to identify the instability damage of major components of tower structures is presented. The first step of diagnosis is used to find the possible instability regions of the tower. The second step of the proposed method is used to identify locations of instability of major components of the tower.

Identification of Possible Instability Region of the Tower

Under laboratory conditions, an initial displacement is imposed to the top of the tower structure, and damped free vibration of the structure is generated by releasing the initial displacement. Accelerometers are installed at every nodal floor of the tower to measure the acceleration response, from which the change status of the wavelet packet (WPT) energy curvature distributed along the tower height can be obtained. The change ratio of WPT energy curvature of the *i*th frequency band at the *k*th nodal floor is defined as the damaged index (QU, *et al.* 2012)

$$ECCR_{j,k}^{i} = \left| \frac{EC_{j,k}^{i,d} - EC_{j,k}^{i,u}}{EC_{j,k}^{i,u}} \right| \text{(k=1,2,…,n)} \tag{1}$$

in which superscript *u* and *d* stands for the original undamaged and damaged tower, respectively. According to the change ratio of WPT energy curvature of the *i*th frequency band at every nodal floor, the possible regions which contain instability components can be identified.

Location Identification of Instability of Major Members

The initial displacement excitation method, the same as before, is also adopted to obtain the tower model vibration with the first bending mode or the first torsional mode in the second step. Speedometers are installed at each end of the major components located at the possible instability region diagnosed from the first step to measure the velocity response of each end of major components. The layout of installed speedometers is shown in Figure 2.

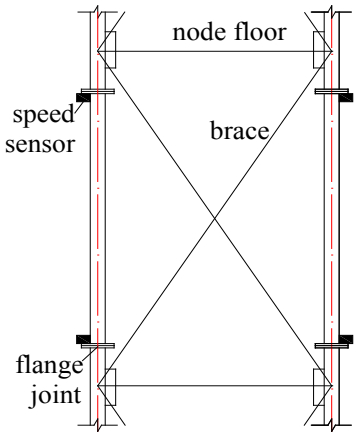


Figure 2. Layout of installed speedometers

The displacement can be calculated by simple integral operation of the measured velocity response. Then, the normalized modal responses and the change ratio of modal strain energy of all components, which includes both damaged and undamaged ones, can be obtained. Furthermore, the upper limit of change ratio with confidence

probability is also derived.

$$Index_j = MSECR_j - \mu \tag{2}$$

in which

$$MSECR_j^i = \left| \frac{MSE_j^{i,d} - MSE_j^{i,u}}{MSE_j^{i,u}} \right| \tag{3}$$

$$\mu = \overline{X} + \frac{S}{\sqrt{ne}} t_{\frac{\alpha}{2}}(n-1) \tag{4}$$

Apparently, if $Index_j \geq 0$, the jth member has damage at the confidence level $(1-\alpha)\%$, otherwise the member is considered as undamaged.

Location Identification of Bolt Looseness at Flange Joints

The studies demonstrate that the bolt looseness has a great effect on the bending rigidity of flange joints, which can be calculated from the longitudinal strain sensor at the outside of flange joints, as shown in Figure 3. Therefore, under the free vibration the longitudinal strain response at the outside of flange joints can be selected as a reasonable damaged index of the bolt looseness of flange joints. As shown in the theoretical analysis and the experimental results, the damaged index is local and sensitive to the bolt looseness (QU, *et al.* 2011).

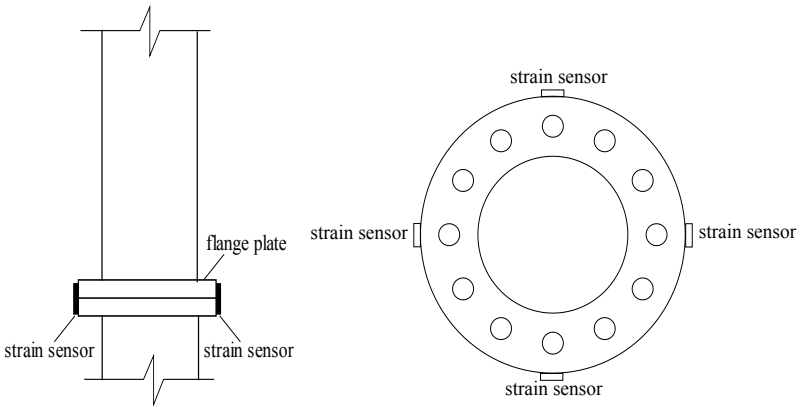


Figure 3. Locations of strain sensors at a flange joint

According to the difference of the longitudinal strain response of the undamaged and damage structures, the damage index vector can be defined as follows:

$$\{E\} = \begin{bmatrix} \Delta\varepsilon_1 \\ \vdots \\ \Delta\varepsilon_i \\ \vdots \\ \Delta\varepsilon_n \end{bmatrix} \tag{5}$$

$$\Delta\varepsilon_i = \frac{\varepsilon_i^d / y_0^d - \varepsilon_i^u / y_0^u}{\varepsilon_i^u / y_0^u} \tag{6}$$

in which $\varepsilon_i^{d(u)}$ is the damaged and undamaged peak longitudinal strains, respectively, of outside flange joints after a complete cycle of the free vibration; $y_0^{d(u)}$ is the imposed initial displacement excitation of damaged and undamaged status. Apparently, the defined damage index vector has the characteristic of (1) independent of the initial displacement excitation; (2) sensitive to the bolt looseness at flange joints; and (3) a substantial change at

the damage locations of the flange joints.

Identification for Fatigue Crack Initiation of Welded Joints

Considering that fatigue crack initiation first occurs at the weld toe under the vibration, the acoustic emission sensors are installed at the weld ends to directly detect the transient elastic waves generated by rapid energy release of the weld cracking (Jia, 2012) as shown in Figure 4.

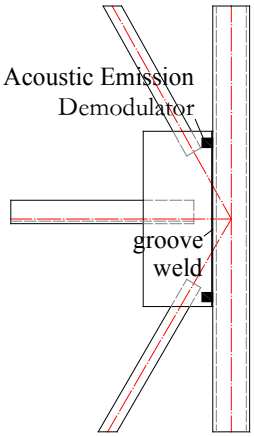


Figure 4. Layout of installed acoustic emission sensors

The acoustic emission sensors are sensitive to the fatigue crack initiation and can be used to detect the fatigue crack initiation of the welded joints of the tower structure.

EXPERIMENT ON SMART TEST SYSTEM FOR HIGH-RISE STEEL TOWER STRUCTURES

General Description

The overall integration of the test system has been shown in Figure 1. A tower model of 6 floors, with the depth-width ratio 9:1, is designed as the test model as shown in Figure 5. The vertical members are made of seamless steel tube with 32 mm external diameter. The inclined web members are made of round steel bar with 6 mm diameter. The vertical members of the model are in conjunction with flange joints, and the intersection of the vertical and inclined web members are in conjunction with rectangular welded gusset plate.

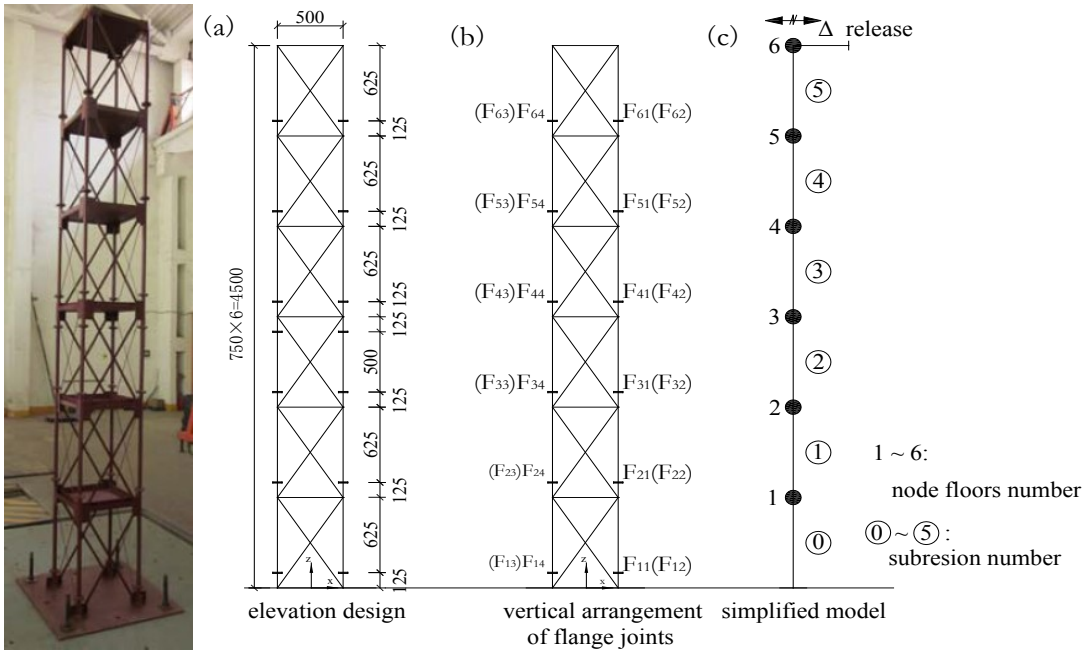


Figure 5. Test model

The three types of structural damage previously mentioned are simulated in the model test. The instability damage of the vertical major component is simulated by replacing one vertical major member with a smaller cross section seamless steel tube of 20 mm external diameter. Bolts looseness is tested by twisting off two symmetrically arranged bolts at the scheduled flange joints (each flange joint has 6 bolts). The crack initiation of welded joints is tested by the cyclic loading at fatigue testing machine for simplification.

Test Results of High-Rise Steel Tower Structure

For the high-rise steel tower structure with the smart test system as shown in Figure 1, the sensor networks are constructed by accelerometers, speedometers, resistance strain gauges, displacement sensor and acoustic emission sensors. Six accelerometers are installed at each nodal floor of the six floors tower, and six speedometers are installed at each end of the major components located at the possible instability damaged region (because only six speedometers are available in our laboratory, and actually eight speedometers should be installed at each end of the four major components in one floor). Twenty-four strain gauges are installed at twelve flange plates located at one side of vibration direction. One displacement sensor is only installed at the top of the tower model. Two acoustic emission sensors are installed at one welded joint.

A total of four cases are investigated in the experiment. However, only the test results of 'undamaged case' and 'cases' in which instability of the major components and bolt looseness of flange joint occur simultaneously are presented in this paper. Firstly, the free vibrations of undamaged and damaged structure are generated by releasing different initial displacements, and the vibration information collected by the sensor networks is stored into the real-time database. Then, damage automatic identification subsystem extracts real-time data from the real-time database of back-end database server. Finally, the calculation of damage index is carried out based on the experimental data, and the following results are obtained:

Detection of Possible Instability Region

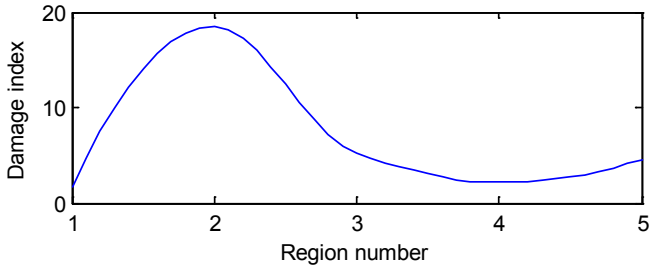


Figure 6. Detection results for possible regions of instability damage of major members

It can be seen from Figure 6 that the change rates of energy curvature at the second region is significant. Thus, the instability damage events may exist in third floor of the tower.

Location Identification of Instability of Major Components

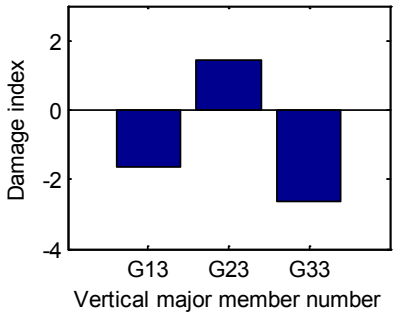


Figure 7. Detection results for damaged member location

Figure 7 demonstrates that the damage index of member G23, the second component in third floor, is larger than zero, indicating that the corresponding damaged members is accurately detected.

Damage Identification of Bolt Looseness at Flange Joints

It can be seen from Figure 8 that the damage index has obvious mutation information at F32、F34、F44 flange joints and at other locations it is relatively small. The results indicate that bolt looseness damage occurs at the F32、F34、F44 flange joints.

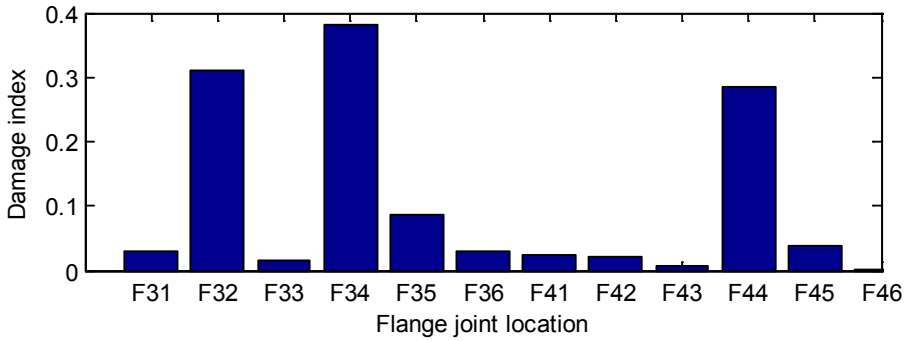


Figure 8. Detection results for bolt looseness location of flange joints

Fatigue Crack Initiation Diagnosis of Welded Joints

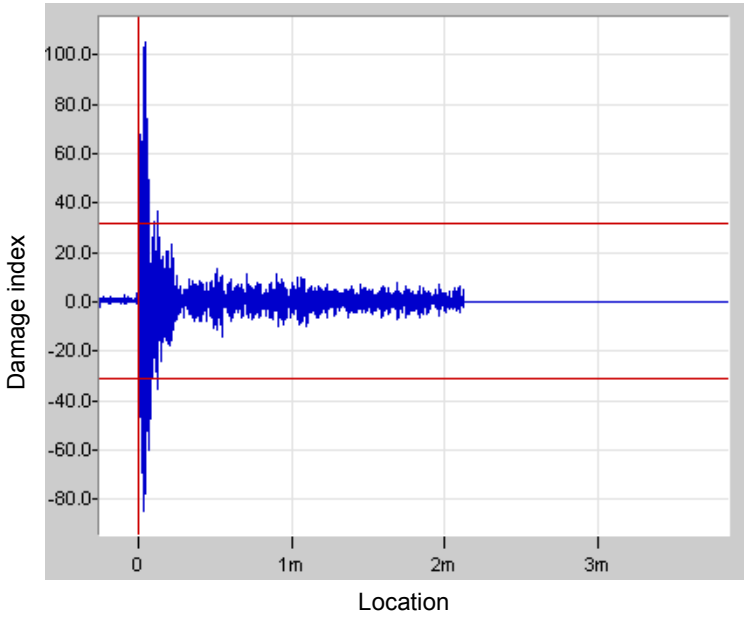
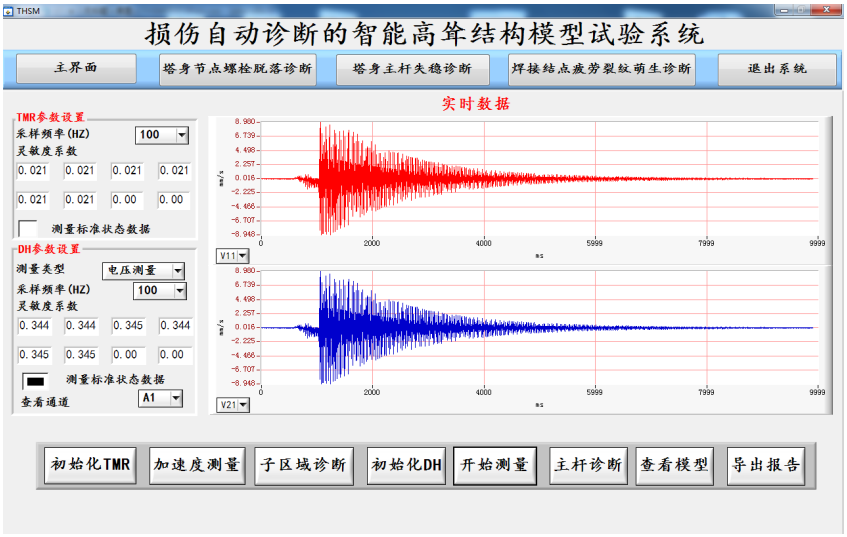


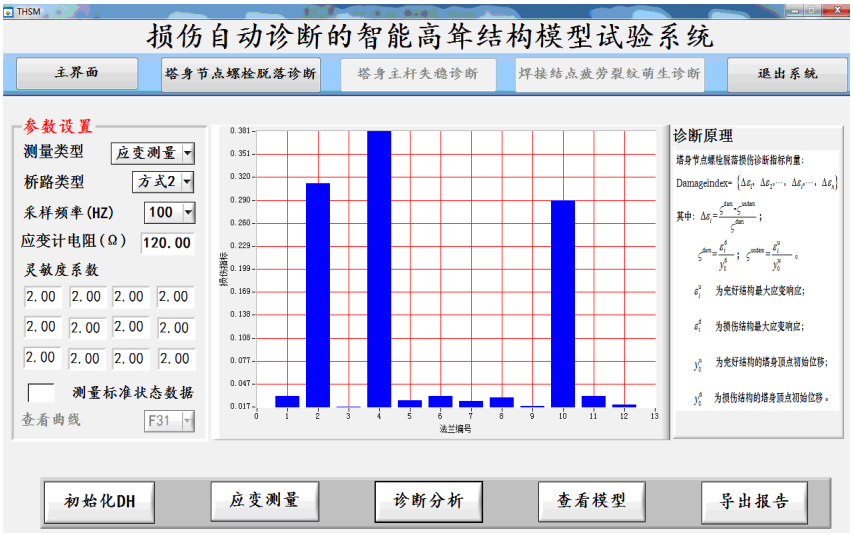
Figure 9. Damage index of fatigue crack initiation of welded joints

It can be seen from Figure 9 that the regional impact event captured by acoustic emission sensors is observed in the fatigue test. Apparently, the smart test system for the high-rise steel tower structure can be used to detect the fatigue crack initiation of the welded joints.

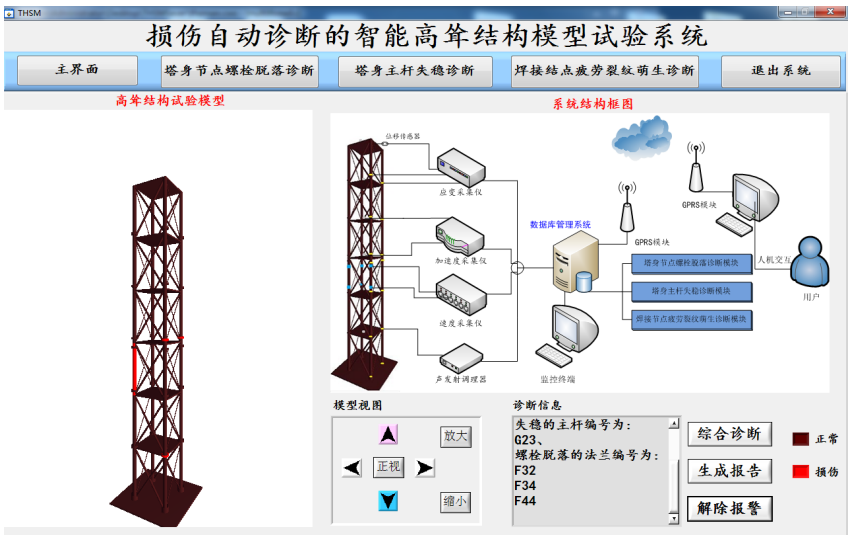
The smart test system for high-rise steel tower structures has a good screen display ability of the sensor network, signal acquisition and damage index on the remote human-computer interface as shown in Figure 10.



(a) Illustration of the sensor network signal acquisition



(b) Illustration of the diagnosis results



(c) Illustration of the diagnosis locations at the test model

Figure10. Remote human-computer interaction interface

It can easily visualize and inform the remote users of the damage locations at which the damage of major components, flange joints or welded joints may occur.

ACKNOWLEDGEMENTS

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