Damage Identification of General Overhead Travelling Crane Structure Based on Model Updating by Sensitivity

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Abstract: A model based damage identification was proposed by facilitating parameter sensitivity analysis and applied to a general overhead travelling crane. As updating reference data, experimental modal frequency was obtained by operational modal analysis (OMA) under ambient excitation. One dimensional damage function was defined to identify the damage by bending stiffness. The results showed that the model updating method could locate the damage and quantitatively describe the structure. The average error of eigenvalues between updated model analysis and the experimental results was less than 4% which proved the accuracy reliable. The comparison of finite element analysis and the test results of the deflection under the capacity load further verified the feasibility of this method.

Key words: model updating; structure parameterization; damage identification; ambient excitation

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0 Introduction

Engineering mechanical equipments, like large crane, may frequently start and brake, and are always under periodic cyclic loading and large impact. Environmental corrosion and material aging will inevitably lead to structural damage accumulation and resistance attenuation. According to the statistics released by the government, safety accidents related to hoisting machinery accounted for nearly 25% in manufacturing industries of dock, chemical, construction, and automobile, 15% of which are mortal[1]. Just like bridge, reinforced concrete and other civil engineering, the health monitoring, damage identification and condition assessment of crane structure are crucial in the academic and engineering fields.

On the basis of the traditional nondestructive testing (NDT) (such as ray, ultrasound), current health monitoring and damage identification of overhead travelling crane structure has been progressed to online monitoring[2-6]. Crane is being constantly monitored by regular checks on the state parameters to diagnose the health status by NDT sensing system and information processing system (IPS) through corresponding algorithm. In particular, the strain measurement by the resistance strain gauge, structural health monitoring by the fiber grating sensors and the acoustic emission (AE) are more common.

Previously there were many methods proposed to achieve structural damage identification, usually including two kinds of approaches, namely: Digital signal acquisition and processing based and model based[7-9]. The former is commonly characterized in easy implementation and direct diagnosis. It might, however, depend on the location of sensors and face the problem of noise elimination. The latter, represented by finite element (FE) model updating method, has been in-

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creasingly concerned recently, for it could identify the existing damage quantitatively and obtain or even predict the overall dynamic performance of the structure. The online health monitoring stated above is the actually "digital signal acquisition and processing based" but with much more work and findings, while model updating has been applied to the simulation for damage identification of general rod and shell model[10-11]. Since it has made significant headway in recent years, model updating can be applied to more complex engineering structure. It is certainly worth obtaining an improved updated FE model with high-precision for reliably health monitoring large engineering structures.

We presented a parametric FE model updating method based on sensitivity analysis to identify damage of a real general overhead travelling crane with a rated lifting capacity of 5 t. Coordinating FE modeling with modal experiment results, physical parameters of the structure were identified, which indicated the damage quantification. And the more accurate FE model updated succeeded in verifying the deformation in rated load. It can be seen as a positive attempt to introduce "model-based" health monitoring to safety assessment field for large machinery equipment.

1 Model Updating Method

1.1 Characteristics of model updating method

Model updating is essentially a model based method of identifying the undetermined physical parameters of specific operational system or structure. The most striking values or characteristics of this method, for the health monitoring and safety assessment of large equipment such as crane, are listed as follows:

(1) The location and the degree of damage can be quantified by structure parameterization.

(2) Full-scale evaluation of the overall structure can be accomplished. NDT and load test, the most common safety assessment method of crane, are subject to the instrument cost, the test operation difficulty and efficiency. It may only detect damage in partial area, or cannot reflect the structural load capacity completely. The model based parameter identification method would act as a satisfying solution to the integral analysis and assessment of the structure.

(3) The method favors the analysis and comparison of the reinforcement or reconstruction scheme and even the prediction of the structure failure trends. An updated FE model, which is more close to the true structure, can be used to simulate the mechanical properties after modification and maintenance, analyze and compare various reinforced schemes and predict them as well.

1.2 Principle and steps of parametrical model updating

The finite element model updating via design parameters is an optimization problem

$$\min \| \boldsymbol{W}(f) R(\boldsymbol{p})^2, R(\boldsymbol{p}) = \{f_E(\boldsymbol{p})\} - \{f_P(\boldsymbol{p})\}$$

$$\text{s.t.} \quad \text{VLB} \leqslant \boldsymbol{p} \leqslant \text{VUB} \tag{1}$$

where $\boldsymbol{p}$ is the design parameter vector, $\{f_E(\boldsymbol{p})\}$ and $\{f_P(\boldsymbol{p})\}$ denote the identification results of the experiment and the simulation, respectively, $R(\boldsymbol{p})$ is the characteristic parameter (i. e., objective function), VUB and VLB are the upper and the lower limits of $\boldsymbol{p}$, $\boldsymbol{W}(f)$ is the weighted matrix of each characteristic parameter

$$R(\boldsymbol{p}) = \boldsymbol{G}\Delta p \tag{2}$$

where Δp is perturbation of design parameters, $\boldsymbol{G}$ the sensitivity matrix of characteristic parameters to the design parameters.

As can be seen from Eq. (1), the model updating method is an iterative process with steps as follows:

(1) Determine the objective function

Compared with the mode shapes, the advantage of modal frequency in sensitivity analysis is less computation, higher accuracy and better performance in identification. So in this paper, the objective function is the modal frequency identified by the simulation model and the modal experiment. The characteristic residual Rwould is calculated between them.

(2) Model parametrically, calculate the sensitivity matrix $\boldsymbol{G}$ with the design parameters $\boldsymbol{p}_0$, and select the sensitive updating parameters.

According to the structural characteristics and failure modes of the crane, combined with the symmetry of the structure and the similarity of load condition, the parameters of the mechanical properties of the components (material modulus E in this paper) are selected as the parameters to be updated

$$\lambda_{i,q}=\frac{-\boldsymbol{u}_i^{\mathrm{T}}[(\boldsymbol{M}_q)\lambda_i^2+(\boldsymbol{K}_q)]\boldsymbol{u}_i}{\boldsymbol{u}_i^{\mathrm{T}}[2\lambda_i\boldsymbol{M}]u_i} \tag{3}$$

where "T" denotes the transpose, $\boldsymbol{M}_q$, $\boldsymbol{K}_q$ are the first derivative of the mass matrix and the stiffness matrix to the qth parameter, respectively.

As shown in Eq. (3), sensitivity analysis is achieved by the optimization module of the general FE software NASTRAN, which solves the first order partial derivative of objective function to design parameter E based on matrix perturbation. The algorithm, described as semi-analytical method, is more applicable than the traditional analytical method to complex systems, and also more accurate than the finite difference method.

(3) Identify the modal parameters (the modal frequency, modal shape, etc.) of the structure from the simulation and the experiment, respectively.

(4) Iterate by an optimization algorithm until it meets the convergence criteria.

The sequence quadratic programming (SQP) was adopted to optimize parameters by MATLAB command "fmicon" in the paper, which is currently recognized as one of the best algorithms to deal with the problem and medium scale nonlinear programming[12]. The nonlinear optimization problem with equality or inequality constraints is transformed into quadratic programming problems. During the whole updating process, both the sensitivity matrix computation and modal matching problem in solving residual error are of significant importance[13].

2 Parametrical Modeling and Modal Experiment

2.1 FE modeling and simulation

A general overhead travelling crane studied in this paper (as shown in Fig. 1), has the rated lifting capacity of 5 t with 7 150 kg self-weight and A5 work class. Its metal structure, which is characterized by symmetrical welded steel box-girder, comprises the main beam, the tail beam, the walking platform, the handrail, and the operator's cab, etc.

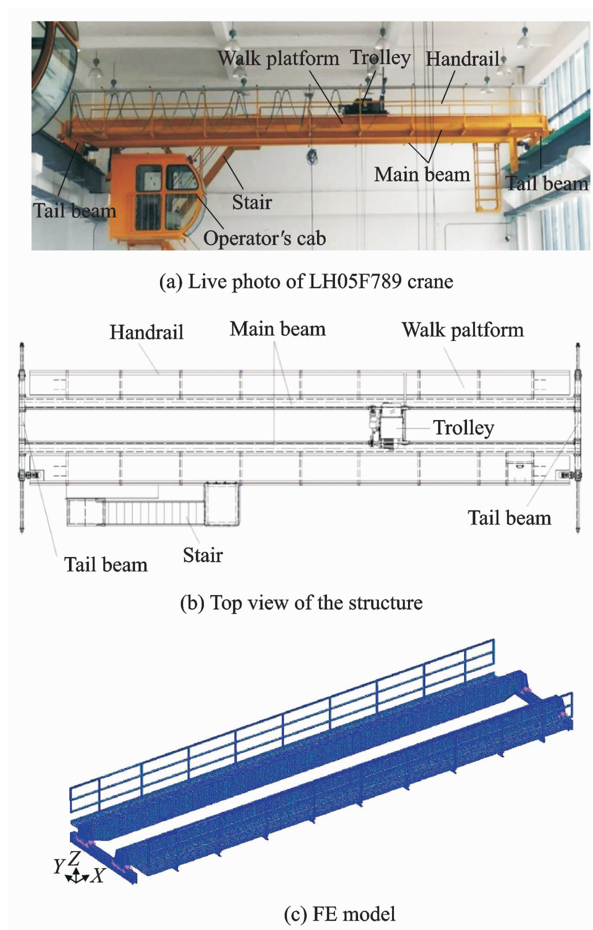


Fig. 1 Actual structure and FE model of LH05F789 crane

The FE model (as shown in Fig. 1(c)) was established by the NASTRAN and meshed by HyperMesh. The upper, the lower and the web plate of the main beam were modeled with the hexahedral element (Hex). The beam stiffener was simplified to beam element (Beam) with L section property coordinating with physical structure. Handrail was represented by quadrilateral plate element (Quad) while the welded relationship between the walking platform and the main beam were simulated by coinciding nodes. The bolt of the main beam and the tail beam took advantage of the beam element and the multi point constraint (RBE2) to simulate the connection and strengthen the area stiffness. The lifting mechanism, the trolley, the operator's cab, the platform and other structures were distributed on the main beam as the lumped mass to ensure that the centroid and the total weight of the model coincide the actual structure. There are totally 60 342 elements and 110 014 nodes in the FE model. The steel material of the structure was defined as isotropic elastic-plastic constitutive relationship.

The frequencies and the mode shapes of 5 modes under the "free to free" boundary condition by FE analysis are presented in Fig. 2. The vertical (Z) and horizontal (X) bending modes are mainly extracted.

2.2 Modal experiment and parameter identification

The sticking points in modal experiment of large crane, especially large-span general overhead travelling crane, can be summarized as:

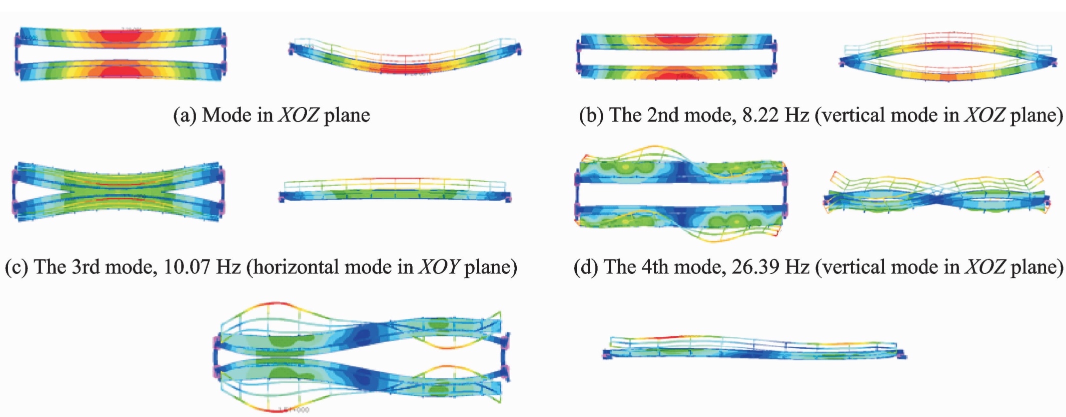
(1) The structure has high flexibility and heavy weight with low modal frequencies.

(2) Traditional hammering excitation can hardly obtain sufficient high energy to excite low order modes and the installation of exciter is inconvenient either.

(3) The working environment of crane is always complex. For example, a crane and some other equipments may run in the same orbit simultaneously, probably leading to plenty of noise of excitation signal that may greatly handicap the test accuracy.

Operational modal analysis (OMA) is a rapid, simple, economical and effective way to obtain structural modal parameters[14], which has been widely applied to the field of ship[15], aircraft[16], civil engineering structures[17] and bridges[18]. The modal parameters can be identified only from the dynamic response of the structure by OMA, which would avoid noise introduced by artificial excitation and make it more consistent with the actual boundary condition and operation environment. Therefore, the modal experiment of large lifting equipment was accomplished by OMA based on ambient excitation in this paper.

The main beam upper plates have been spaced with 14 testing points at each side at intervals of 1.2 m to obtain adequate data for mode shape (as shown in Fig. 3). Seven PCB 356A16-type three-direction acceleration sensors, with 0.3—6 KHz range of testing frequency and 94.5 mV/g sensitivity, acquired the horizontal and the vertical acceleration signal at the same time. The experiment was conducted in four stages: The first testing points were 1—7, the second 8—14, the third 15—21 , the fourth 22—28 in turn.



(a) Mode in *XOZ* plane

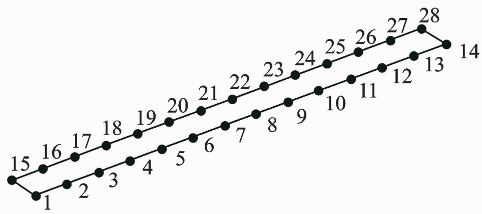
(b) The 2nd mode, 8.22 Hz (vertical mode in *XOZ* plane)

(c) The 3rd mode, 10.07 Hz (horizontal mode in *XOY* plane)

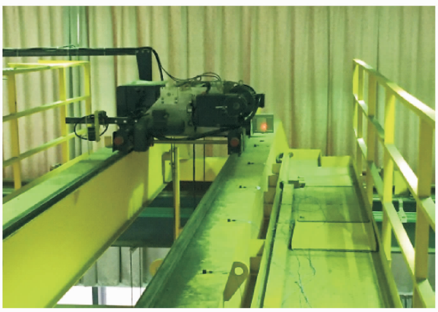
(d) The 4th mode, 26.39 Hz (vertical mode in *XOZ* plane)

(e) The 5th mode, 28.60 Hz (horizontal mode in *XOY* plane)

Fig. 2 Modal analysis results of FE model



(a) Testing point placement of the 1st mode, 7.97 Hz (vertical mode in *XOZ* plane)



(b) The live photo

Fig. 3 Placement of testing points

The input ambient excitation was implemented by keeping the trolley and the cart running intermittently for about 300 s for each testing stage. The sampling frequency is 200 Hz and the spectral line number is 400. Acceleration responses of test reference point (point 3) and all the test points were acquired. In addition, low-pass filtering and rectangular windowing were used to denoise, prevent leakage and improve the recognition accuracy of frequency finally.

Power spectrum method is an effective way to implement the experiment modal analysis (EMA) and parameter identification of real modal structure system with small damping. Self-power spectrum diagram of the response points was taken instead of the magnitude diagram of the overall transfer function[19]. Vertical self-power spectrum of the testing point 3 (reference point) is shown in Fig. 4. The results of modal frequency are listed in the first column in Table 2. A certain degree of frequency error can be found between the simulation and the experiment analyses, while the 4th and the 5th modes were reversed in the appearance order. It is almost certain that parameter settings and structure simplifying introduced some error to FE model and it must be updated.

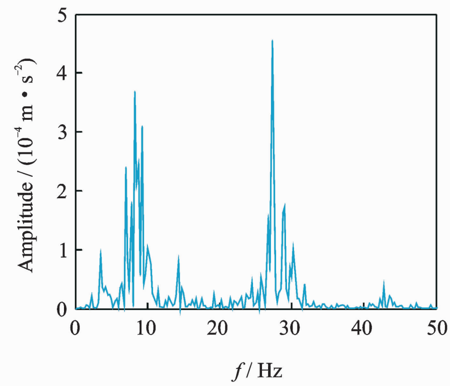


Fig. 4 Self-power spectrum of testing point 3

3 Model Updating and Damage Identification of Crane Structure

3.1 Definition and updating of damage parameters

The damage of beam structure can be interpreted as the decrease of bending stiffness according to the principle of damage mechanics. A one-dimensional function of damage is defined as the ratio of the residual stiffness to the initial stiffness of the structure

$$d_c = 1 - \frac{EI_d}{EI_u} \tag{4}$$

where EI_d is the bending stiffness of damaged cross section of component and EI_u the bending stiffness of undamaged cross section of component.

In this paper, the reduction of Young's modulus, which indicates the stiffness of a material directly, is equivalent to the damage effects

$$E = E_0 (1 - \alpha_E) \tag{5}$$

where E and E_0 are the Young's modulus of the solid element HEX in the updated and the initial FE model, respectively, α_E is a model updated items. When describing the state of structural damage, α_E is synonymous with d_c in Eq. (4), which combine the model updating method with the damage identification.

The metal structure of crane consists of eight parts, which are the left and the right web plates of main beam, the left and the right walking boards, the left and the right handrails, and the upper and the lower cover plates of main beam.

According to structural symmetry and the similarity of component function, parameters aggregate [20] is constructed as

$$\{\boldsymbol{p}\} = \{E11, E12, E13, E14, E21, E22, E31, E32\} \quad (6)$$

The dynamic test experience and the stress distribution from other similar equipments were also taken into consideration. Similar to Ref. [20], eight parameters in $\{\boldsymbol{p}\}$ are classified into three updating groups listed in Table 1 Column 3 and 4 by their respective sensitivity matrix $\boldsymbol{G}$ of modal frequency in Eq. (2) (as shown in Fig. 5). It would significantly improve the computation efficiency of updating iteration.

Table 1 Material constitutive parameters and sensitivity classification

Model parameter	Component	Updating group	Updating parameter	Initial value/GPa
$E11$	Left web plate of main beam	I	$E1$	210
$E12$	Right web plate of main beam	I	$E1$	210
$E13$	Left handrail	I	$E1$	210
$E14$	Right handrail	I	$E1$	210
$E21$	Left walking board	II	$E2$	210
$E22$	Right walking board	II	$E2$	210
$E31$	Upper cover plate of main beam	III	$E3$	210
$E32$	Lower cover plate of main beam	III	$E3$	210

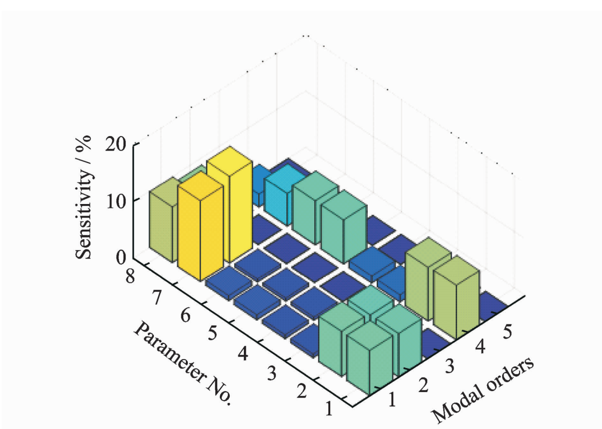


Fig. 5 Sensitivity matrix of 8 model parameter elements to modal frequency

Model updating was iterated by invoking FE analysis results from NASTRAN in engineering software MATLAB. The number of eigenvalues (i. e. model frequencies) obtained by modal experiment is more than that of the parameters to be updated, which signifies an overdetermined equation and the only solution to the parameters.

3.2 Updating and damage identification results

Modal matching situation both in pre-updating and post-updating are indicated in Table 2 and Fig. 6 by model assurance criterion (MAC) values. That the minimum MAC value is 0.843 3 (more than 80%) proves the modal well-matched in iteration.

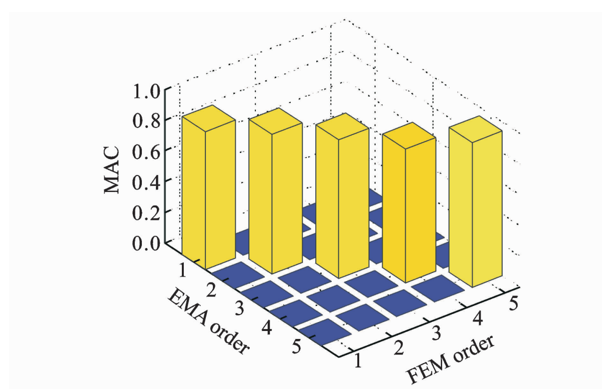


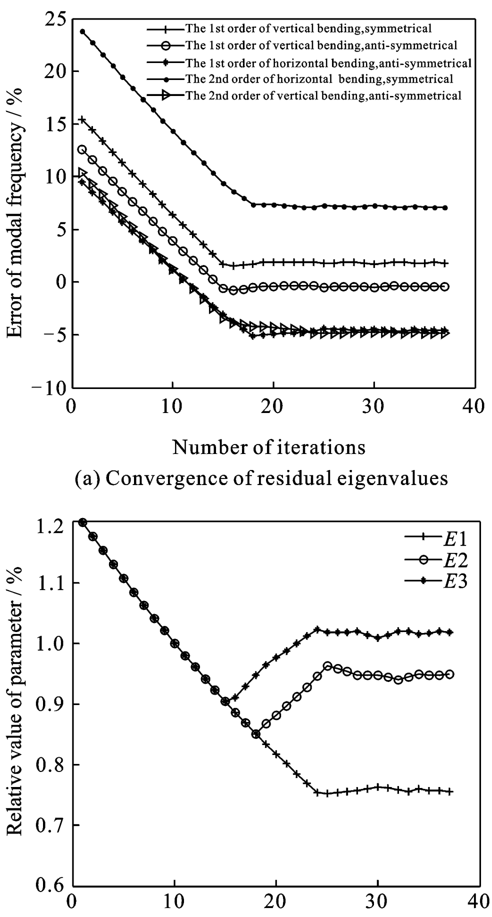
Fig. 6 MAC values of 5 mode shapes

The whole Young's modulus of crane metal structure and the updating parameters, had obvious impact on modal frequency but little on mode shape vectors so that MAC values did not show a clear change in the updating. It has been proved that mode shape updating makes more sense to local damage identification by determining the efficient damage indicator modal strain energy (MSE) of each element[21].

The graph given in Fig. 7(a) is the residuals convergence of the five orders objective function. It shows that the iterative process has been basically stable after step 15 and reached convergence

Table 2 Error comparison results of the model before and after updating

EMA/Hz	Before			After			Mode shape description
	Frequency/Hz	Error/%	MAC	Frequency/Hz	Error/%	MAC	
6.90	7.97	15.44	0.897 7	7.03	1.82	0.897 9	The 1st symmetrical vertical bending
7.30	8.22	12.60	0.908 1	7.27	−0.44	0.908 1	The 1st anti-symmetric vertical bending
9.20	10.07	9.50	0.901 8	8.79	−4.51	0.901 8	The 1st symmetrical horizontal bending
23.10	28.60	23.82	0.843 3	24.76	7.19	0.870 1	The 2nd symmetrical horizontal bending
23.90	26.39	10.40	0.941 5	22.75	−4.80	0.941 7	The 2nd anti-symmetric horizontal bending
Average		14.35			3.75		



(a) Convergence of residual eigenvalues

(b) Convergence of updating parameters

Fig. 7 Updating iteration results of objective function and parameters

at step 35. The errors of eigenvalues are presented in Table 2, which can be seen that the average error has decreased from the 14.35% to 3.75% and the 4th order, the maximum error before updating, fortunately, has decreased from 23.82% to 7.19%. It demonstrates that model accuracy has been improved markedly by updating and the simulation model is almost equal to the experiment model.

Fig. 7(b) shows the convergence of relative value of three groups of material parameters which indicate damage degree. Finally, $E1$, $E2$ and $E3$ converge at 1.015 9, 0.955 0 and 0.757 0 respectively, from the initial value of 1.0 (absolute value 210 GPa). It can be inferred that there is little change in the elastic modulus of walking board. And the material properties of web plate of main beam has even been strengthened because of the presence of the beam stiffeners. Last but not least, the elastic modulus of upper/lower cover plate of main beam has decreased greatly, which shows bending stiffness deteriorated significantly as a result of continuous bending load.

4 Verification of Crane Rated Load Experiment

Checking the midspan vertical static deflection after the rated load experiment is obliged by mandatory national regulation[22], in which the deflection should be less than 1/800 of span for cranes of A4—A6 working class. The rated load experiments have been done for twice. One was in installing supervision inspection (the crane was supposed to be new and undamaged), and the other was during the last periodical inspection (the crane was supposed to be damaged). The comparison of the two experiment results is shown in Fig. 8 (via inspection reports of Nanjing Special Equipment Inspection Institute). And simulation values of the FE model before and after updating are also conflated in the graph to verify the effect of updating model of load capacity.

Fig. 8 shows that:

(1) The deflection simulated by statics analysis of FE model , increases from 9.3 mm before updating to 13.2 mm after. Meanwhile, the results of the two experiments also display the same increasing trend from undamaged 10 mm to damaged 12 mm. This demonstrates that the updated model can reflect the loss of crane structure load capacity resulted from damage accumulation as time goes on.

(2) The deflection error of the simulation result of updated model and the testing value of damaged structure is about 10% which may not be very accurate but acceptable. On the other hand, the simulation value is bigger than the test, maybe it can be concluded that the updated model can indicate the crane's load capacity relatively accurate and slightly more conservative, which would make a wider safety margin in assessment.

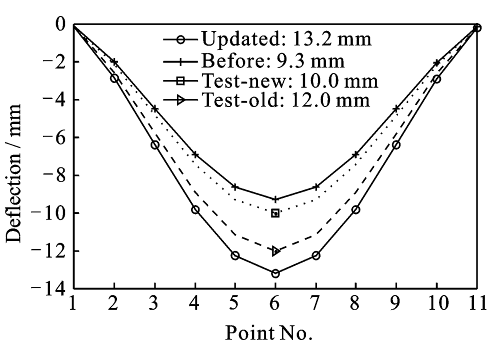


Fig. 8 Comparison of midspan vertical static deflection under rated load

5 Conclusions

(1) The differences in sensitivity of updating parameters to objective function can be used to filter and classify various physical parameters, which can effectively promote the efficiency and rationality of model updating. In addition, the method can prevent updating equations from being unsolvable in case it is difficult to enquire enough experimental modal parameters due to complicated engineering structures, materials, unfavorable working environment and limitation of existing experimental techniques.

(2) Errors between the result of OMA based on ambient excitation and initial FE model analysis is acceptable and updatable. The satisfying result of MAC also illustrates that the OMA method is a wise choice available for the experimental modal analysis of large crane structure.

(3) The improved accuracy of the updated model with a smooth iteration indicates that the model updating method based on SQP can be expected to obtain an optimization process with rapid stable convergence and high accuracy. High precision of simulation models after updating can continue to be applied in safety assessment, structure reinforcement and health monitoring in further.

(4) Localization and quantitative analysis of damage is fulfilled by model updating method, which is proved to be efficient in identifying crane structural physical parameters representing bending stiffness which indicate damage. Comparison of vertical static deflection under rated load further verifies the model accuracy in damage identification. Some problems, however, remain to be answered. For instance, how to construct more scientific damage indicators, which updating objective functions are more reliable than the dynamic response, if model based method could be integrated with online monitoring technology effectively.

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