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Vibration test and reinforcement analysis of some steel structure workshop building

The crane of some single-storied steel structure mold workshop runs under load, causing obvious vibration of an adjacent two-storied steel structure office building along the crane running direction. Vibration test was done by using CRAS random signal and vibration analysis system DH-5922. As test results reveal, in case of cantilever brake, the office building resonates with the mold workshop, with a resonant frequency of 3.3 Hz; for the office building, the maximum vibration velocity is 2.26 mm/s, and the maximum vibration level is 105.72 dB, neither meeting ambient vibration requirements of the office area. In this regard, plans to reinforce the office building stiffness were proposed, and the reinforcement effect was simulated by using FEM (finite-element method) midas. As simulation results reveal, the plan to add a cross brace is more conducive to the vibration damping of office building than the plan to expand the sectional area in the resonance direction. As results of acceptance testing after reinforcement show, for the office building, the fundamental frequency increases to 4.2 Hz; there is not resonance with the mold workshop any longer; the maximum vibration velocity decreases to 0.49 mm/s by 75%; the vibration level decreases to 82.38 dB by 22%. All of these values meet ambient vibration requirements of office area. The building stiffness was well improved. The proposed solution can be used as reference for the vibration test and problems solving of similar items.

Keywords: *Single-storied steel structure workshop, office building, resonance, cross-bracing reinforcement.*

1. Introduction

Steel structure is a very important structure in civil works. As a result of structural steel, it has outstanding advantages over other structures: light with strong material; safe and reliable with elastic and tough material; easy to process or make, convenient for construction, highly industrialized; economical [1]. Consequently, steel structure is widely used in such civil works as industrial and civil construction, for example, single-storied or multi-storied industrial steel structure workshops.

However, during production in steel structure workshops, most of machines produce varying degrees of vibration. Due to poor knowledge of dynamic characteristics of machinery, such vibration may cause local/global strong vibration, approximate resonance, or even resonance of adjacent buildings [2]. Production or office work is seriously endangered as a result of inadequate consideration of big vibration sources in regional layout and plant layout, which was universal. In view of the evaluation criteria and limits of the vibration of the workshop, the scholars have done the relevant research. Treadgold [3] proposed the stiffness standard of floor vibration design as early as 1828. Smith [4] and other scholars [5-7] studied the effects of wood floor vibration on human comfort. The control range of the allowable vibration trace value of the anti vibration index is put forward by Mao [8].

In view of the big problem, Gao [9] discussed the characteristics of the vibration frequency distribution and the influence factors of the vibration amplitude according to the data of the factory building. Xing [10] used the finite element method to analyze the dynamic response of the hydropower plant, and discussed the vibration frequency, the vibration displacement response and the size of the vibration stress. Hu [11] tested the vibration displacement and acceleration of the multi-storey building, and discussed the effect of vibration on the building structure and the measures to reduce the vibration. In addition, some scholars [12-14] have analyzed the vibration response of the powerhouse and the Viaduct with the ANSYS finite element simulation and the field measured data.

Hazards of vibration shall be handled depending on circumstances so as to restore production and office work to normal. Based on an actual project, we did a vibration test of some steel structure workshop vs an adjacent office building and reinforced the workshop and building, in the hope of reference for similar projects.

2. Project overview

For automation line unity workshops of some mold company, the building safety degree is II. The mold workshop is a

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single-storied workshop, with a story height of 11.30m. The beam top elevation of vibrating crane is 7.81m; the adjacent mezzanine auxiliary room is a two-storied steel structure office building with an overall height of 9.00m; the first storey is overhead with a height of 5.65m, and the second storey is for office work purpose with a height of 3.35m. Fig.1 shows the steel column layout and the number of mold workshops and office buildings; Table 1 sets out sectional dimensions of all types of columns. The upper structure of mold workshop and office building is steel truss. Steel structure (steel column, steel beam and crane beam) uses Q345B steel as the main material, and foundation is single foundation under column. The mold workshop has a total of 12 types; the office building has 7 types. Among them, No. 9, 10, 11, 12 steel columns of mold workshop are connected to the foundation of No. 13, 14, 15, 16 steel columns of office building respectively.

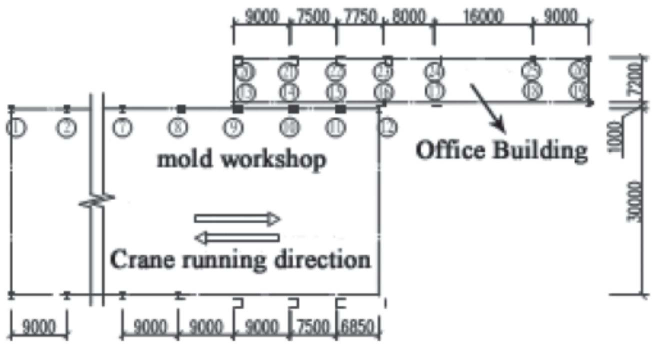

Fig.1 Floor plan and number of mold workshop and office building's steel columns

TABLE 1: PIN-SECTIONAL DIMENSIONS OF EACH STEEL COLUMN

Number of columns	Cross section size (mm)
13,14,15,16	H400×340×10×14
17,18,19	H600×250×10×14+400×280×10×12
20,21,22,23,26	H300×300×10×14+400×280×10×12
24,25	H300×300×10×14

As owners reflect, when the crane in mold workshop runs, the office area on the second floor of office building vibrates obviously along the crane running direction, influencing the office environment seriously. To solve this problem, all members and pipelines connecting structure workshop and office building are ever disconnected, but the problem is still not solved. Then, we conducted the vibration test analysis of this steel structure.

3. Vibration test

3.1 PURPOSE OF VIBRATION TEST

We tested vibration parameters such as vibration frequency and horizontal amplitude of mold workshop and office building by using vibration analysis system DH-5922 and velocity/acceleration transducer DRA-101C/941. We analyzed causes of poor vibration.

3.2 SETTING AND TESTING OF THE VIBRATION SOURCE

Vibration source testing has two parts: crane running vibration test and fundamental frequency test.

The crane running vibration test went first. We set measuring points on the crane beam of No. 12 column and at the middle parts of No. 15, 16, 23 columns. According to the usage feedback and site survey, a preliminary view was that office building vibration resulted from the starting and braking of a 20t crane in mold workshop when lifting a weight of 20t or so. Vibration was the most obvious when the weight was located at 1/4 of a beam close to one side of office building. The test required that the 20t crane in mold workshop should lift the maximum weight (the load is 17t actually in testing) under normal working condition to 1/4 of a beam close to one side of office building and that the crane should run in a straight line. An operator drove the crane from far to near distance and then from near to far distance. Due to ground limitation, the crane started at No. 5 column and braked at No. 7 column; started at No. 7 column and braked at No. 9 column; started at No. 9 column and braked at No. 11 column; then, returned to No. 5 column. In this period, the crane started and braked 6 times.

The fundamental frequency test went second. We adopted pulsing for dynamic testing of the mold workshop and office building. We used velocity/acceleration transducer DRA-101C/941 put in advance at the middle part of No. 15 of mold workshop and office building to measure the vibration of small and irregular structure caused by various external factors. Then, we made a spectrum analysis and finally obtained the dynamic characteristic (inherent vibration frequency) of office building steel structure.

4. Result analysis

4.1 ANALYSIS OF CRANE VIBRATION TEST

Test results showed that braking had the biggest influence on office building, so we analyzed vibration caused by braking only from the standpoint of amplitude. Table 2 gives analysis results.

We can know from Table 2:

(1) Amplitude changes of office building crane depend on running conditions. Far from the office area of office

TABLE 2: THE MAXIMUM AMPLITUDE OF THE FIRST TEST LIST

Route	5—►7	7—►9	9—►11	11—►9	9—►7	7—►5
Upper of 12 columns	0.16	0.21	0.25	0.28	0.225	0.11
Middle of 16 columns	0.06	0.07	0.09	0.08	0.09	0.06
Middle of 23 columns	0.06	0.08	0.09	0.09	0.11	0.06
Middle of 15 columns	0.12	0.07	0.09	0.11	0.09	0.05

Notes: In this table, 5—►7 means that the crane starts at No.5 column and brakes at No.7 column. The rest can be deduced from this

Table 3: Each indicators maximum for 9⟶11 process

Test project	Middle of 16 columns	Middle of 23 columns	Middle of 15 columns
Acceleration (mm/s^2)	153.80	306.12	298.91
Speed (mm/s)	2.02	2.26	1.91
Displacement (mm)	0.09	0.09	0.09

building, the amplitude is small, 0.06mm; near to the office building, the amplitude is great, 0.09mm.

(2) Except that maximum amplitude measured at the middle part of No. 15 column is twice as great as that measured at the middle part of the other two columns (No. 16 column or No. 23 column) in case of 5⟶7, amplitude values at the middle parts of No. 16, 23 and 15 columns are very close and almost equal, which suggests that the office platform just moves horizontally without distortion.

The representative process 9⟶11 was selected for analysis. Table 3 shows maximum indicators.

Seeing from Table 3, the vibration acceleration at the middle part of each column goes beyond the limit of worrying people ($150mm/s^2$), and the vibration velocity is much higher than the allowable value of office area (1.0mm/s) .

4.2 Analysis of fundamental frequency test

For the fundamental frequency test, we acquired 40 minutes of data and analyzed them by using DHDAS-5920 dynamic signal acquisition and analysis system FFTreal-time spectrum. Fig.2 shows analysis results.

It is obvious from Fig.2 that thefundamental frequency of office building is 3.3Hz. The vibration frequency of mold workshop at crane braking can be calculated according to Fig.3.

It can be seen from Fig.3 that 4 consecutive troughs correspond to time points 0.90s, 1.21s, 1.51s, 1.81s respectively. We can obtain the vibration period of mold workshop is 0.30s. Thus, the vibration frequency is 3.3Hz, equal to the fundamental frequency of office building, so resonance is produced [15-16].

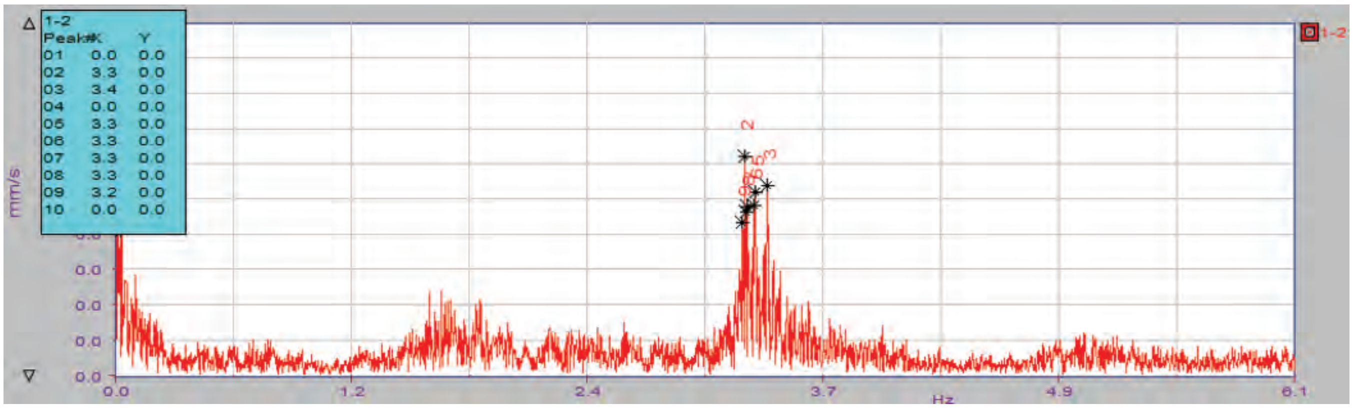

Fig.2 FFTin real-time spectrum analysis chart on the 15th central column

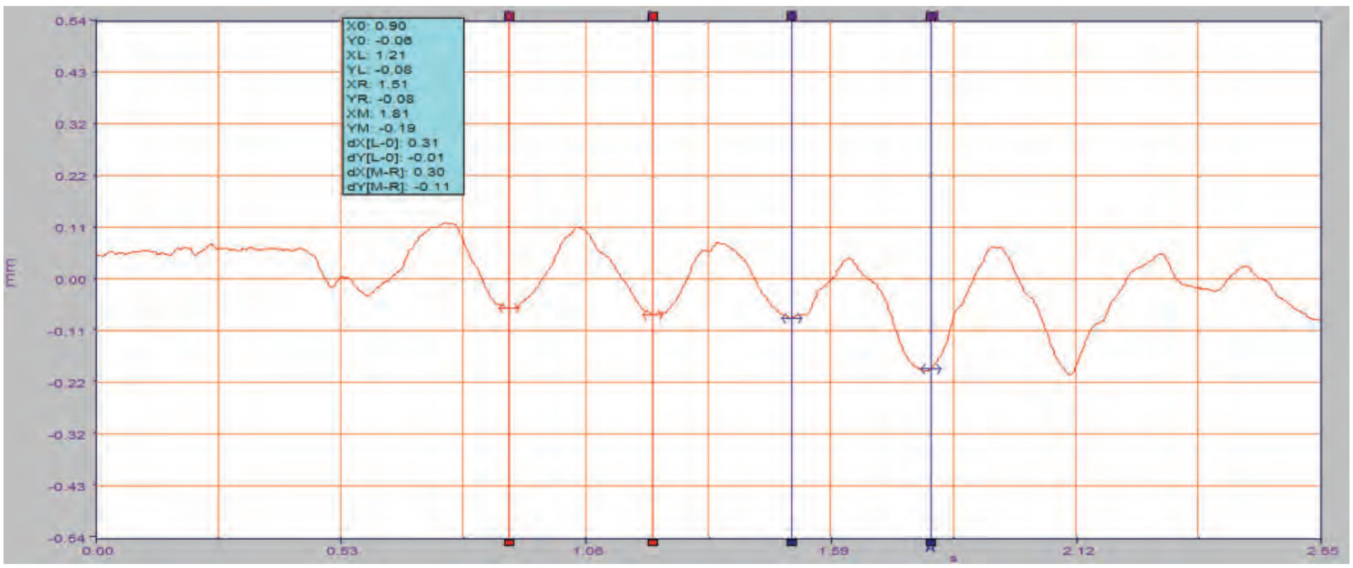

Fig.3 Vibration displacement map on the 12th upper part pillar in the crane when the brakes

5. Vibration solution

There are a variety of methods to handle resonance: keeping a long distance; adjusting equipment layout; reinforcing the stiffness of foundation or steel structure, etc. According to characteristics of this project and owner requirements, we chose the method to reinforce the local and global stiffness in the light of low cost construction convenience. To attain the expected effect, we used FEM for reinforcement simulation and comparison of plans and finally obtained reasonable reinforcing measures.

5.1 Model profile

As stated in the design documents relevant to the mold workshop and office building, C30 concrete of floor slabs in the model C30 has an elasticity modulus of 3×104MPa, a Poisson's ratio of 0.2, a density of 2,500kg/m^3; Q345 steel in the model has an elasticity modulus of 2.08×105MPa, a Poisson's ratio of 0.3, a density of 7,800kg/m^3; Q235 steel in the model has an elasticity modulus of 2.06×105MPa, a Poisson's ratio of 0.3, a density of 7,800kg/m^3. Fig.4 shows the model built by using large-scale finite-element method midas.

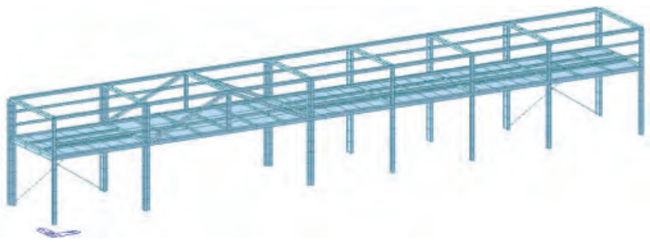

Fig.4 The structural model before reinforced

We analyzed the inherent vibration characteristic of office building model and extracted the first 3 orders of modal frequency. The 1st order of inherent vibration frequency is 2.61Hz, corresponding to vibration along X direction, and this value is close to the actual inherent vibration frequency. The 2nd order corresponds to back and forth vibration. The 3rd order corresponds to twisting vibration, irrelevant to this study, so we did not analyze it.

5.2 Contrast of plans for reinforcement

Taking usage convenience into full consideration, we intended to use following plans for reinforcement:

(1) Adding a cross brace: There was a tie rod between Nos. 13 and 14 columns and a tie rod between Nos. 18 and 19 columns. However, their stiffness is too low to bear a pressure. To achieve the rectification effect, we removed the original tie rods and added a cross brace between Nos. 13, 14, 15, 16 columns and Nos. 18, 19 columns. This cross brace has a 2×110×8 sectional dimension and is made of Q345B steel.

(2) Expanding the sectional area in X direction: Expand the sectional areas of No. 13~26 columns in X direction so as to reinforce the stiffness in X direction. Table 4 gives sectional dimensions.

Table 4: Sectional size comparison list before and after reinforced the X-direction section

Before reinforced	After reinforced
H600×250×10×14+400×280×10×12	H600×250×10×14+2×400×280×10×12
H300×300×10×14+400×280×10×12	H300×300×10×14+2×400×280×10×12
H400×300×10×14	H400×300×10×14+2×400×280×10×12
H300×300×10×14	H300×300×10×14+2×400×280×10×12

Table 5 gives calculation and analysis results.

Table 5: Comparison list before and after analog reinforcement

Reinforcement form	Original structure	Add cross	Increase the cross section of X direction
Frequency (Hz)	2.61	4.23	2.97
Amplitude (mm)	0.56	0.09	0.45
Acceleration (mm/s^2)	106.4	17.1	85.5
VL (dB)	96.5	80.6	94.6
Whether or not to meet the level of a person's level of vibration (<83 dB)	No	Yes	No

Learning from Table 5, the first plan (adding a cross brace) can increase the stiffness of original structure significantly and decrease the vibration acceleration and velocity greatly; it can increase the vibration frequency of office building to 4.23Hz and make it much different from the vibration frequency of mold workshop 3.3Hz (2.6Hz in the model). Seeing from the calculation of horizontal allowable vibration level, reinforcement can satisfy office work requirements. Through calculations, the vibration frequencies of the 2nd and 3rd vibration models are 4.26Hz and 4.70Hz respectively, both are much different from the vibration frequency of mold workshop 3.3Hz, which proves that after reinforcement the office building does not resonate with the mold workshop. This plan needs a low construction cost and a short construction period. Thus, it is chosen.

6. Acceptance testing of reinforcement effect and analysis

6.1 Acceptance testing

This acceptance testing has two parts: the first part is crane running vibration test, and the second is fundamental frequency test. Points for acceptance testing are the same with test positions before reinforcement. To complete the impacts of load weight variations and different weight positions on office building vibration, we detailed the crane running vibration test into 7 conditions:

(1) Condition 1: The weight is fully loaded and 1/4 of span close to a

side of office building;

(2) Condition 2: The weight is fully loaded and located at the middle of span;

(3) Condition 3: The weight is fully loaded and 3/4 of span close to a side of auxiliary room;

(4) Condition 4: The weight is fully loaded and 1/4 of span close to a side of auxiliary room;

(5) Condition 5: The weight is half loaded and located at the middle of span;

(6) Condition 6: The weight is half loaded and 3/4 of span close to a side of auxiliary room;

(7) Condition 7: The crane runs under no load.

For the fundamental frequency test, the method is the same with that used before reinforcement.

6.2 Selection of most unfavourable condition

Table 6 gives statistical results of the vibration velocity of office building under 7 conditions.

Seeing from Table 6, the maximum vibration velocity of office building occurs under Condition 1. For this reason, we chose Condition 1 as the most unfavourable condition for contrast before and after reinforcement.

6.3 Contrast before and after reinforcement under most unfavourable condition

To compare the reinforcement effect, we chose the maximum acceleration under Condition 1 for contrast before and after reinforcement, as shown in Fig.5.

Seeing from Fig.5, through office building reinforcement, the maximum acceleration of No. 12 column under Condition 1 is 631.74 mm/s^2, decreasing by 10.8% from 708.11 mm/s^2; the maximum acceleration of No. 15 column decreases from 298.91 mm/s^2 to 20.84 mm/s^2 (7.0% of the original value). It proves adding a cross brace decreases the vibration acceleration of office building significantly where the vibration acceleration of crane varies not much.

We chose the maximum velocity under Condition 1 for the contrast before and after reinforcement, as shown in Fig.6.

Seeing from Fig.6, through office building reinforcement, the maximum velocity of No. 12 column under Condition 1 is 11.94 mm/s, increasing by almost 1 time from 6.25 mm/s; but

TABLE 6: SEVEN CONDITIONS' OFFICE BUILDINGVIBRATION VELOCITY STATISTICS

Condition	5→7	7→9	9→11	11→9	9→7	7→5
Condition 1	0.30	0.46	0.50	0.28	0.45	0.39
Condition 2	0.30	0.30	0.49	0.39	0.43	0.41
Condition 3	0.28	0.29	0.36	0.30	0.35	0.30
Condition 4	0.30	0.17	0.46	0.17	0.35	0.36
Condition 5	0.22	0.31	0.46	0.38	0.17	0.24
Condition 6	0.20	0.22	0.15	0.22	0.22	0.12
Condition 7	0.14	0.17	0.25	0.17	0.28	0.17

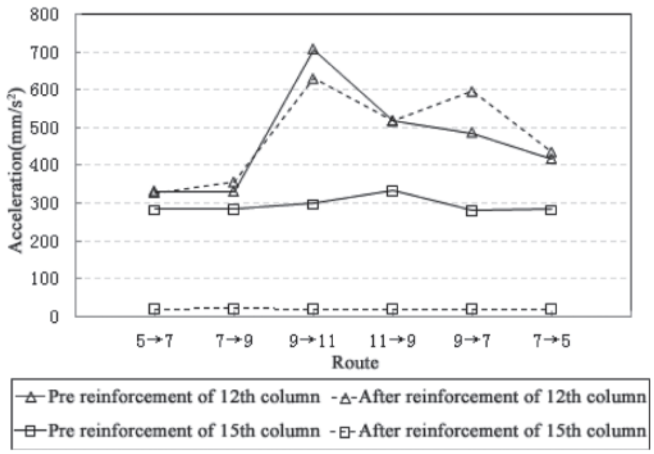

Fig.5 Acceleration graph comparing 12 pillar with 15 pillar before and after reinforced

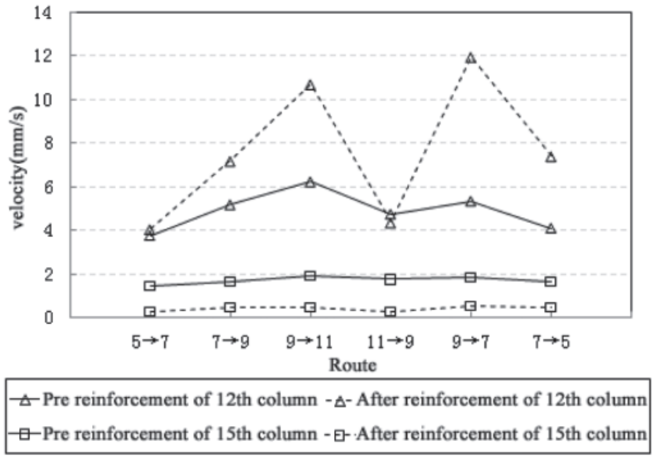

Fig.6 Speed graph comparing 12 pillar with 15 pillar before and after reinforced

the maximum velocity at the middle part of No. 15 column decreases by 25.7% from 1.91 mm/s to 0.49 mm/s. It proves, adding a cross brace decreases the vibration velocity of office building significantly where the vibration velocity of crane increases. And the maximum velocity is lower than the allowable vibration velocity of office area (1.0mm/s), which meets vibration velocity requirements for office work.

We chose the maximum amplitude under Condition 1 for the contrast before and after reinforcement, as shown in Fig.7.

Seeing from Fig.7, through office building reinforcement, the maximum amplitude of No. 12 column under Condition 1 is 0.31mm, close to the original value 0.28mm; but the maximum amplitude at the middle part of No. 15 column decreases significantly from 0.12mm to 0.05mm (41.7% of the original value).

6.4 Analysis of fundamental frequency

For the fundamental frequency test, we acquired 40 minutes of data and analyzed these data by using DHDAS-5920 dynamic signal acquisition and analysis system FFT real-time

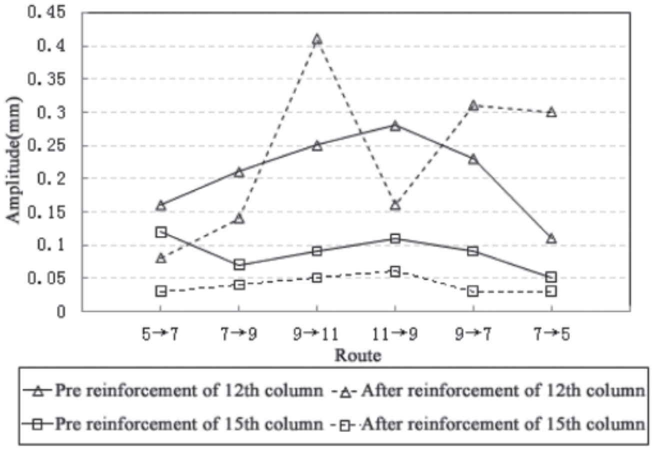

Fig.7 Displacement graph comparing 12 pillar with 15 pillar before and after reinforced

TABLE 7: COMPARISON LIST BEFORE AND AFTER THE ACTUAL REINFORCEMENT

Reinforcement form	Original structure	Simulated add cross	After the actual reinforcement
Frequency (Hz)	3.3	4.23	4.2
Amplitude (mm)	0.09	0.09	0.05
Acceleration (mm/s^2)	298.91	17.10	20.84
VL(dB)	105.51	80.60	82.38
Whether or not to meet the level of a person's level of vibration (<83 dB)	No	Yes	Yes

spectrum. Then, we obtained the fundamental frequency of office building 4.2Hz, which is close to the simulation calculated value 4.23Hzand different from thevibration frequency of mold workshop. Thus, resonance with the mold workshop is not produced any longer.

6.5 ANALYSIS OF ACCEPTANCE TESTING

Table 7 gives the comparison between data measured before and after reinforcement and calculated data based on the model built by using midas.

Seeing from Table 7, through reinforcement, the vibration frequency, amplitude, acceleration and VL of office building were reduced obviously. Simulation calculated data are close to data measured after reinforcement, except for a big deviation in amplitude. This big deviation is associated with the difference between the pseudo-static method used for testing or simulation and actual conditions. As analysis results show, both allowable vibration velocity and allowable vibration level meet office work requirements, and reinforcement measures attain the effect of vibration damping.

7. Conclusions

(1) The vibration frequency at braking obtained through site vibration test was equal to the fundamental frequency of office building, so resonance was produced. This is the major immediate cause of the vibration velocity and vibration level of office area is much higher than that of the allowable values.

(2) In case where the building resonates, if the vibration source can hardly be eliminated, then relevant construction measures can be taken into change in the inherent vibration frequency and to eliminate conditions for resonance. In this paper, a cross brace is added to enhance the global stiffness and inherent vibration frequency of office building greatly so as to eliminate resonance and attain allowable indicators of office area.

(3) FEM midas was used for numerical simulation of measures for reinforcing the office building. Through comparison of different plans, the preferred plan for reinforcement was chosen, providing reasonable guidance on engineering reinforcement design. As revealed by post-reinforcement measured results, both vibration velocity and vibration level meet office work requirements, which validates the rationality of midas model. The model can be used as reference for similar projects.

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Continued on page 448