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Tuned mass dampers for human-induced vibration control of the Expo Culture Centre at the World Expo 2010 in Shanghai, China

Xilin Lu, Kun Ding*, Weixing Shi and Dagen Weng

State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China

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Abstract. The Expo Culture Centre is one of the permanent buildings at the World Expo 2010 in Shanghai, China. The main structure has an oval shape and consists of 36 radial cantilever steel trusses with different lengths and inner frames made of concrete-filled rectangular steel tube members. Tuned mass dampers are used to reduce the excessive vibrations of the sixth floor that are caused by human-induced resonance. A three-dimensional analytical model of the system is developed, and its main characteristics are established. A series of field tests are performed on the structure, and the test results show that the vertical vibration frequencies of most structural cantilevers are between 2.5 Hz and 3.5 Hz, which falls in the range of human-induced vibration. Twelve pairs of tuned mass dampers weighing 115 tons total were installed in the structure to suppress the vibration response of the system. These mass dampers were tuned to the vertical vibration frequency of the structure, which had the highest possibility of excitation. Test data obtained after the installation of the tuned mass dampers are used to evaluate their effectiveness for the reduction of the vibration acceleration. An analytical model of the structure is calibrated according to the measured dynamic characteristics. An analysis of the modified model is performed and the results show that when people walk normally, the structural vibration was low and the tuned mass dampers have no effect, but when people run at the structural vibration frequency, the tuned mass dampers can reduce the floor vibration acceleration by approximately 15%.

Keywords: Expo Culture Centre; steel truss; cantilever; human-induced vibration; serviceability; tuned mass damper

1. Introduction

More slender and more aesthetic structures can be designed when high-strength material and innovative structural forms are used. As a result of these design trends, many structures have become more susceptible to vibrations when subjected to human-induced dynamic loads, especially footbridges, cantilever structures and long-span structures. In recent years, a number of structures have experienced human-induced vibration problems (Bachmann 1992, Webster and Vaicaitis 1992, Setareh and Hanson 1992, Occhiuzzi *et al*. 2008), and many researchers have begun to pay more attention to this phenomenon (Bachmann *et al*. 1995, Živanović *et al*. 2005, Ebrahimpour and Sack

*Corresponding author, Ph.D., E-mail: dingkun22@163.com

2005, Pozos-Estrada *et al*. 2011).

Human activities are complicated and can produce a dynamic time-varying force that has components in all three directions: vertical, horizontal-lateral and horizontal-longitudinal. In particular, the vertical component of the force is regarded as the most important of the three forces because it has the highest magnitude. Efforts to determine the vibrational forces generated by human movement and to determine the associated level of vibrational response have been made by many investigators (Mouring and Ellingwood 1994, Kerr and Bishop 2001, Xu and Tangorra 2007). Andriacchi *et al*. (1977) used a force plated to measure single-step walking forces in all three directions. Wheeler (1982) conducted research on the human forces relevant to footbridge dynamic excitation and summarised the work of other investigators related to the different modes of human movement from slow walking to running. Ebrahimpour *et al*. (1996) used a platform equipped with several force plates to obtain continuous walking time histories that have an obvious period. Moreover, the statistical distribution of walking frequencies is important in the determination of the loading associated with walking and the structural analysis under pedestrian loads. Matsumoto *et al*. (1972) investigated a sample of 505 persons and concluded that the frequencies followed a normal distribution with a mean pacing rate of 2.0 Hz and a standard deviation of 0.173 Hz. Bachmann *et al*. (1995) defined typical frequency ranges of 1.6-2.4 Hz for walking, 2.0-3.5 Hz for running, 1.8-3.4 Hz for jumping and 1.5-3.0 Hz for bouncing.

It is well-known that the periodic forces induced by human activities can be represented by a Fourier series (Živanović *et al*. 2005, da Silva *et al*. 2007, Figueiredo *et al*. 2008). Many researchers have performed a number of experiments to quantify the dynamic load factors that are the basis for this most common model of periodic human-induced force (Bachmann *et al*. 1995, Kerr and Bishop 2001, Rainer *et al*. 1988). Živanović *et al*. (2005) summarised the dynamic load factors for single-person forces associated with different human activities that have been reported by different investigators. Because of their specific concept and their ease of use, Fourier series are used by many researchers for simulating human-induced forces.

In addition to the determination of forces induced by human activities, the human perception of vibration is one of the most important research subjects. Allen and Rainer (1976) developed vibration criteria for floors due to footstep loading that were based on the experiences of different investigators with a long-span steel and concrete floor. Murray (1979) suggested a human perception scale for the required damping as a function of the product of the initial displacement and the frequency. Ellingwood and Tallin (1984) presented a serviceability criterion to minimise floor vibration that was objectionable to building occupants. The International Standards Organisation (ISO) (1989) recommends vibration limits in terms of acceleration and frequency. As shown in Fig. 1, a baseline curve is used and different multipliers are used for different occupancies. The American Institution of Steel Construction and the Canadian Institution of Steel Construction published a guideline for the evaluation of steel-framed floor systems and footbridges for vibration serviceability associated with human activities (Murray *et al*. 2003). The reaction of human beings to vibration is a notably complex issue, not only do different people react differently to the same vibration conditions, but an individual exposed to the same vibrations on different days will also likely react differently (Živanović *et al*. 2005). Although researchers from various countries have undertaken a number of experiments, it is always difficult to reach consistent and firm conclusions.

A tuned mass damper (TMD) is a type of passive device with wide applications in the vibration control field. TMD systems are typically effective over a narrow frequency band and must be tuned

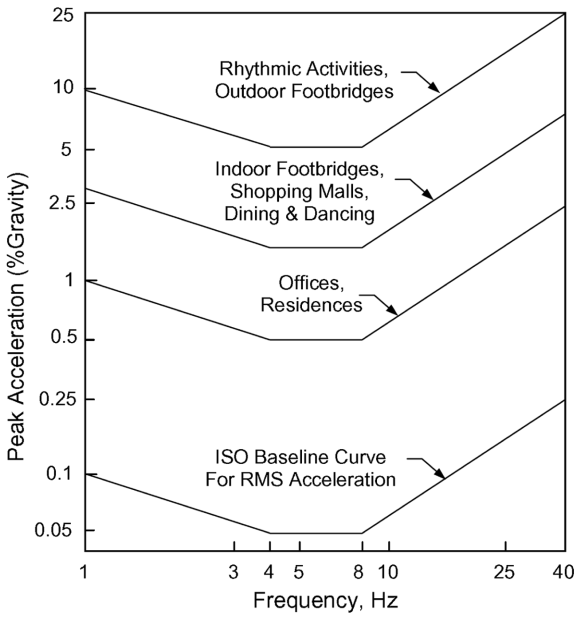


Fig. 1 Peak acceleration for human comfort for vibrations due to human activities

to a particular natural frequency. Thornton *et al.* (1990) used tuned mass dampers to lessen the excessive vibrations of gymnasium floors. Webster and Vaicaitis (1992) used a tuned mass damping system to reduce the steady-state vibrations of the long-span, cantilevered, composite floor system at the Terrace on the Park building in New York City. Setereh and Hanson (1992) reported an investigation of the use of tuned mass dampers for reducing the vibration of an existing floor system induced by rhythmic human activities.

This paper reports an investigation of the vibration sensitivity of the sixth floor of the Expo Culture Centre at the World Expo 2010 in Shanghai, China, and provides details of the analysis and field tests of tuned mass dampers for reducing excessive vibrations.

2. Description of structure

The Expo Culture Centre is one of the most important permanent pavilions at the World Expo 2010 in Shanghai, China. The centre includes a multifunction auditorium with 18,000 seats and a six-story commercial building surrounding it. The main structure consists of the inner frames and 36 cantilever steel trusses of different lengths. The inner frames have 36 concrete-filled steel tubular (CFST) columns distributed around the auditorium at 11.5 m intervals. Circular steel girders are designed to connect the CFST columns for resisting wind and earthquakes. Fig. 2 shows the structural plan of the sixth floor.

The cantilever steel trusses have a length of 20-31 m and are fixed to the CFST columns in the radial direction. The roots of the trusses are at a height of 12 m. All the elements of cantilever trusses including upper chords, lower chords and web members are I-shaped cross-section steel members. Steel beams are designed to connect the adjacent cantilever trusses. For the purpose of controlling the length of the cantilever trusses, five concrete core tubes are included to support part of the cantilever trusses, and transfer trusses are designed to connect those cantilever trusses. The observation deck is situated on the ends of the cantilever steel trusses in the sixth floor. A gathering of a large number of people can easily cause large amplitude vibrations. The details of the cantilever steel trusses and the observation deck are shown in Fig. 3.

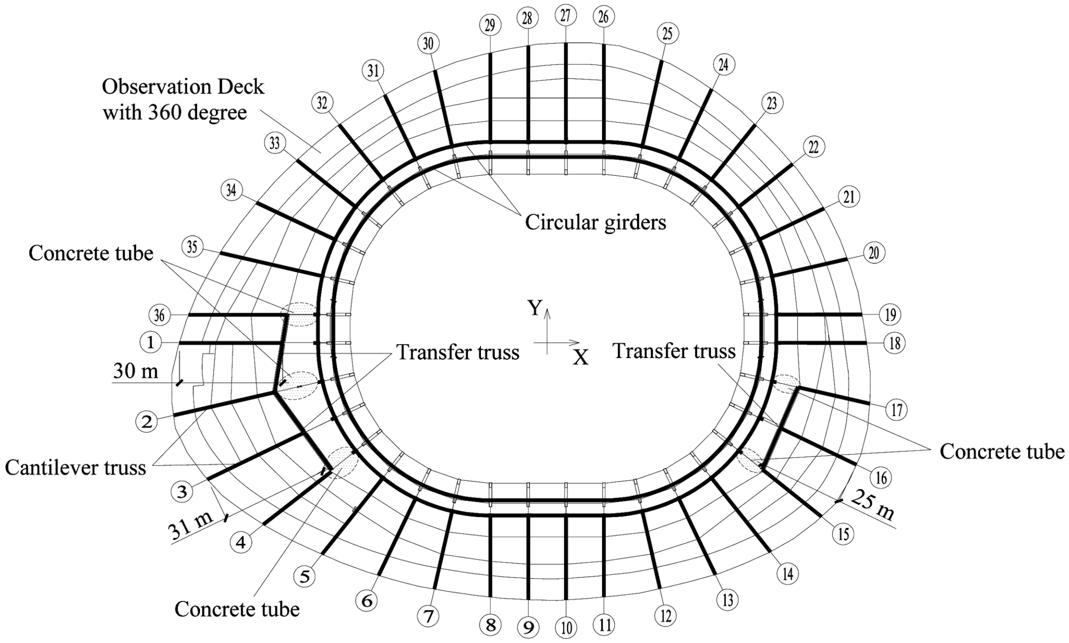


Fig. 2 Structural plan of the sixth floor

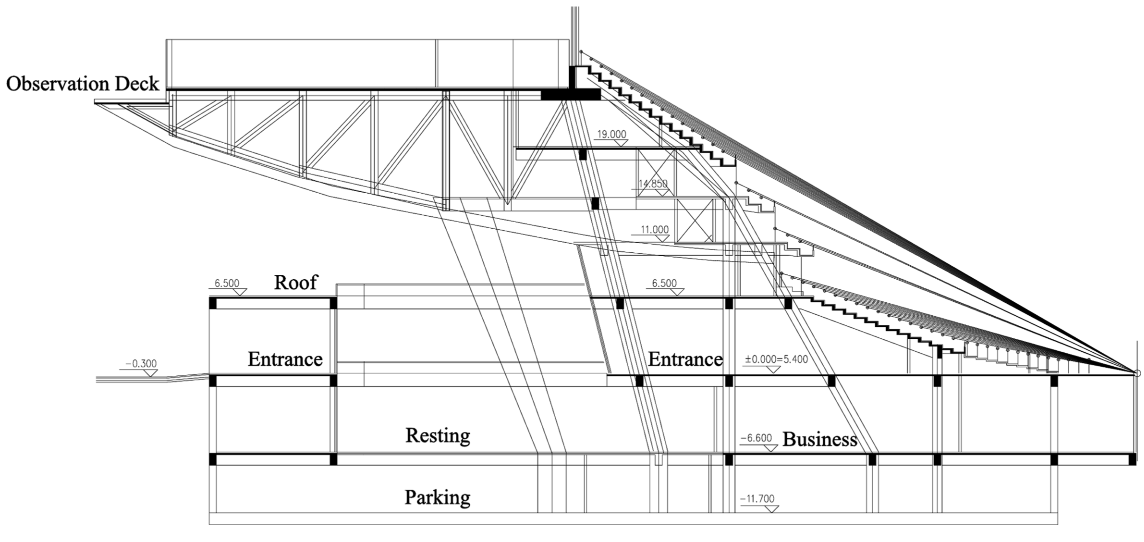


Fig. 3 Details of cantilever steel trusses in profile

3. Structural vibration characteristics analysis

A three-dimensional structural model developed with the computer programme Sap2000 was offered by the design institute. Another three-dimensional model was built with Midas software. The analysis results show that the first mode shape is torsion around the *Z*-axis and that the second and third mode shapes are sway in the *XZ*- and *YZ*-plane, respectively. The higher modes are the vertical vibration of the cantilever trusses, except for a few local vibration effects in individual members. Table 1 gives the first ten frequencies to be calculated by Sap2000 and Midas. The higher modes have the highest tendency to be excited by the movement of people because their frequencies are close to the human walking frequency.

A harmonic response analysis was performed to evaluate the resonance frequency of each cantilever. Vertical sinusoidal loads in the frequency range from 0.01 Hz to 4 Hz and a constant force of 980 N were exerted on the ends of the cantilever trusses, and vertical maximum accelerations were obtained at the same location. The frequency-acceleration response curves showed that most cantilevers have a resonance frequency that varies from 1.96 Hz to 2.28 Hz. The 36 cantilevers were divided into 7 zones according to their architectural function. Table 2 shows the zone limits and the architectural function of each zone. A sinusoidal load was applied to every

Table 1 First ten frequencies of the structure

Modal	Frequency (Hz)	
	Midas	Sap2000
1	0.83	0.81
2	1.65	1.69
3	1.67	1.70
4	1.93	1.97
5	2.07	2.12
6	2.12	2.19
7	2.25	2.28
8	2.46	2.30
9	2.49	2.35
10	2.57	2.49

Table 2 Zone limits and function

Zone	Limits	Function
1	axis 1-4	Two movie theatres, 312 seats
2	axis 5-7	Two movie theatres, 182 seats
3	axis 8-11	Two movie theatres, 283 seats
4	axis 12-18	VIP club
5	axis 19-24	Pub
6	axis 25-30	Restaurant
7	axis 31-36	Pub, Restaurant

node, and a harmonic response analysis was subsequently performed in each zone. The results show that the vertical vibration frequency of the zones is 2.0-2.2 Hz, which is notably close to the range of the individual cantilevers.

4. TMD vibration reducing analysis

Because of the short construction duration for this project, it is impractical to design and manufacture tuned mass dampers on the basis of the field tests after the completion of the structure. Therefore, a great deal of preliminary analysis of the parameters and layout of the TMDs was performed according to the analytical model, and a layout involving 240 tons of TMDs was eventually chosen. The TMDs were produced by GERB Corporation with the following parameters for each TMD: a mass of 4.8 tons, a natural frequency of 2.15 Hz, and a damping ratio of 0.08. Fifty TMDs were selected for reducing vibrations, and they were arranged at the ends of the cantilevers in axes of 1-7, 14-18, 25-30, 33-36. Four TMDs were placed in each axis for 1, 2 and 3 and two TMDs were located in all other axes.

The continuous walking time history curve recommended by the International Association for Bridge and Structural Engineering (IABSE) was used for simulating the load caused by people walking, and a single person was assumed to have a weight of 700 N. Fig. 4 shows the IABSE time history curve at a frequency of 2.0 Hz. The steel design guide series 11, *Floor vibrations due to*

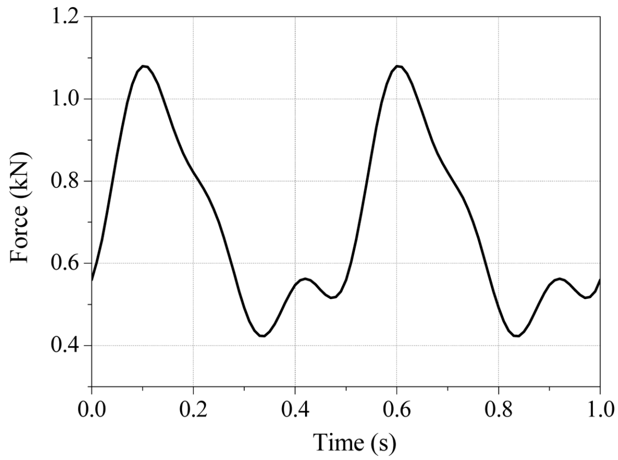


Fig. 4 Walking force shape at a frequency of 2.0 Hz (IABSE)

Table 3 Acceleration limits for civil structure floors

Function	Acceleration Limit
Offices, Residences, Churches	5.0 cm/s^2
Shopping Malls	15 cm/s^2
Footbridge-Indoor	15 cm/s^2
Footbridge-Outdoor	50 cm/s^2

Table 4 Peak acceleration and vibration reduction efficiency of the TMDs

Zone	Frequency	Axis	Peak acceleration without TMDs (cm/s^2)	Peak acceleration with TMDs (cm/s^2)	Reduction efficiency
1	1.93 Hz	1	8.32	4.13	50%
		2	23.59	10.85	54%
		3	39.37	16.23	59%
		4	10.85	4.09	62%
6	2.1 Hz	25	6.01	2.97	51%
		26	10.86	5.47	50%
		27	10.83	5.49	49%
		28	9.88	4.84	51%
		29	7.48	3.45	54%
		30	6.45	2.65	59%

human activity, that is published by the American Institute of Steel Construction (AISC) recommends the acceleration limits under walking excitation that are shown in Table 3. According to the recommended values, 5.0 cm/s^2 was selected for the first control value and 15 cm/s^2 was chosen for the second control value.

Walking excitation was applied to the floor of each zone as an area load. The crowd density was assumed to be 0.74 person/m^2 (approximately equal to the seat density in the cinema), and the walking frequency was equal to the vertical vibration frequency in each area. The analysis results indicated, as shown in Table 4, that the TMDs have an acceleration reduction efficiency of 50% in zones 1 and 6 and of 20-40% in other zones. After the installation of the TMDs, the acceleration of most axes fell below 5 cm/s^2, except for axes 2, 3, 26 and 27; only the vibration response in axis 3 is slightly higher than 15 cm/s^2. Fig. 5 shows a comparison of the acceleration responses with and without TMDs in axis 2 and axis 3.

However, assuming that there may be a discrepancy between the analysis results and the test results, only the TMDs in axes 1-3 and 25-30, totalling 115.2 tons, were installed, which produces a

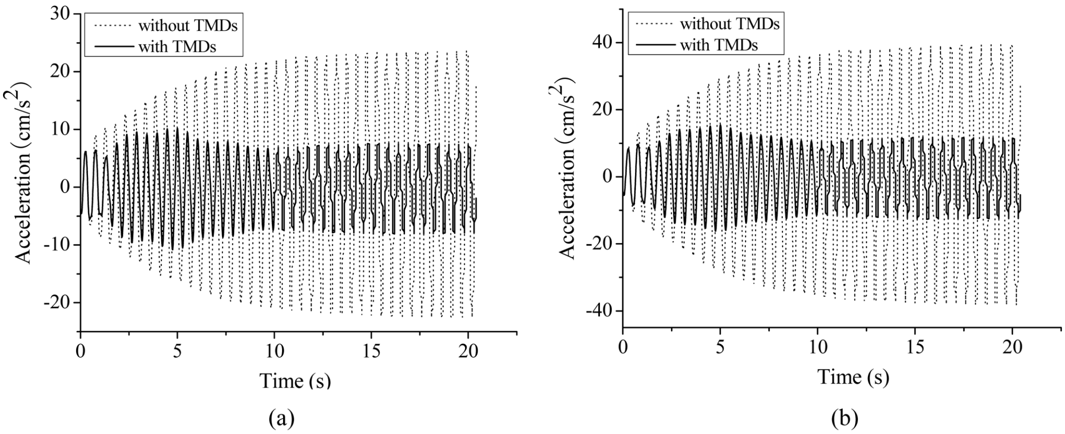


Fig. 5 Comparison of acceleration responses with and without TMDs: (a) axis 2, (b) axis 3

higher acceleration reduction efficiency. Whether or install TMDs in the other axes was decided based on the field test results.

5. Field tests of structural vibration characteristics

To verify the accuracy of the analytical model, field tests of the structure were performed twice at different stages of the construction. The natural frequencies and the measured inherent damping were obtained to assess the significance of the vibrations.

The first experimental measurements were performed after the completion of the main structure. At the time of the tests, the concrete floors had just been poured, and the structure was bare, without surfaces or decorations. Vertical acceleration transducers were placed on the ends of each steel cantilever, and the structural responses to environmental vibrations were recorded with data acquisition instruments. The test results showed that the vertical vibration frequencies range from 3.0 Hz to 5.2 Hz. Using the half-power point technique, the amount of damping was found to be between 1.0% and 3.5%. The analytical model was subsequently modified according to the current load situation and a harmonic response analysis of this model was performed. A comparison of the calculated and tested vibration frequencies is shown in Fig. 6.

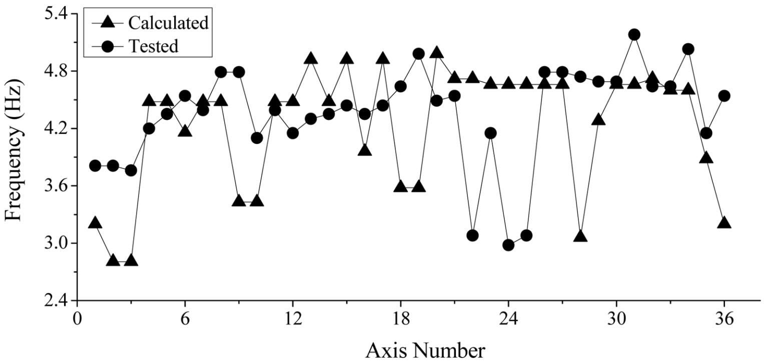


Fig. 6 Comparison of calculated and tested frequencies

(a) (b)

Fig. 7 Appearance of the Expo Cultural Centre under construction at the time of (a) the first test, (b) the second test

Five months later, the second test was performed after the completion of surface finishing and interior decoration. Fig. 7 shows the structural appearance when the two tests were conducted. The second test results showed that the structural vertical vibration frequencies vary from 2.9 Hz to 4.4 Hz and that the measured damping ratio changes from 1.8% to 5.0%.

6. Tuning of mass dampers and vibration testing

Based on the analysis results, tuned mass dampers were designed at a frequency of 2.15 Hz and were installed during the construction process. Four TMDs were placed at each axis for 1, 2 and 3, and two TMDs were located at each axis for 25-30. Because the structural frequencies obtained from the field tests were higher than those calculated in the analysis, measures must be taken to increase the TMD frequency to ensure that the tuned mass dampers can effectively counter human-induced vibrations. In practice, a number of additional springs were placed between the floor and the tuned mass dampers to increase the frequency of the TMDs, so as to achieve a tuning frequency of the real structure.

Following the installation of the TMDs, a series of tests were conducted. A number of accelerometers were installed on the structure and on the tuned mass dampers to measure the level of vibrations under pedestrian loads and to check the performance of the tuned mass dampers. Accelerometers 1 and 2 were placed on the ends and at the middle of the cantilever beams under the concrete floor. The rest of the accelerometers were located on the tops of the tuned mass dampers. Fig. 8 shows the locations of the accelerometers. Fig. 9 shows the tuned mass dampers in the structure. Six people jumped at the ends of the cantilever as a vibration resource and the vibration level of the system was recorded with data acquisition instruments. The results of the tests showed that the tuned mass dampers worked well and that the frequency of the TMDs was approximately 2.9 Hz, which was close to the structural vibration frequency. The damping ratio of

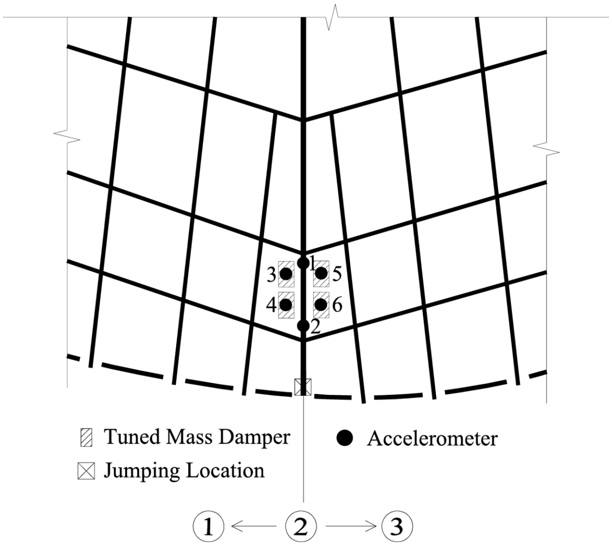


Fig. 8 Location of accelerometers

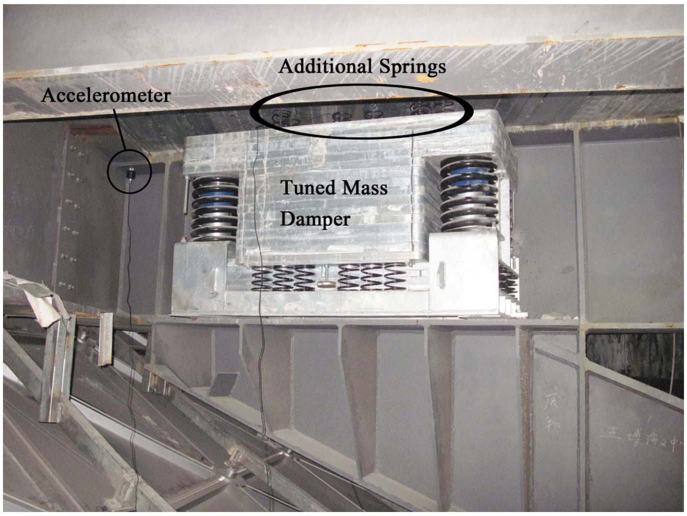


Fig. 9 Tuned mass dampers in structure

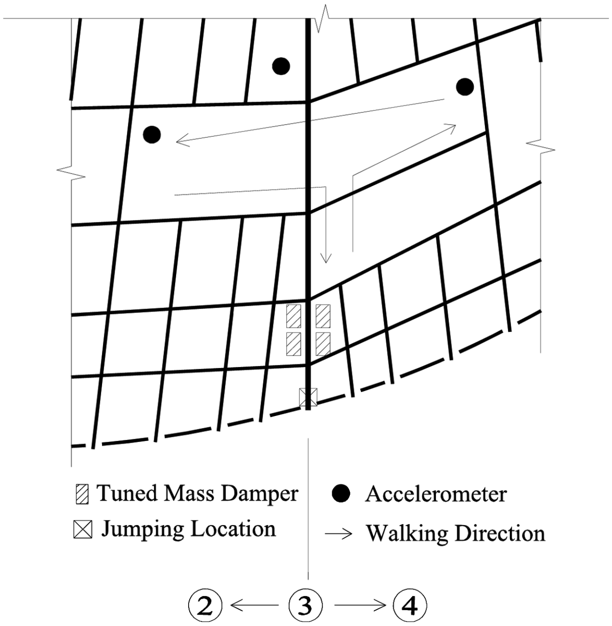


Fig. 10 Location of accelerometers at the entrance of axis 3

the TMDs was approximately 3-5%. The larger vibration acceleration on the tuned mass dampers showed that the TMDs absorbed most of the energy associated with pedestrian loads.

Because the cantilever truss in axis 3 has the longest length of 31 m, additional tests were performed. Three accelerometers were placed at the entrance of axis 3 to measure the vibration level. Two conditions were considered: 11 people walking in the direction of the arrow shown in Fig. 10 to simulate audiences and 4 people jumping consecutively on the observation deck. The test results showed that the vertical peak acceleration was less than 6 cm/s^2 under these two human loading conditions.

According to the test results, the vertical vibration of the floor was notably small when people were walking normally, and it is difficult to cause structural resonance. The tuned mass dampers that were installed in the structure performed well and can reduce the vertical vibration of the floor to a certain extent.

7. Analysis of modified model

According to the above two tests, there is a considerable discrepancy between the vibration frequencies determined from the experimental data and those that were calculated. The reasons may be among the following:

1) The calculated results represented the entire structural vertical vibration frequencies, whereas the test results were the local vibration frequencies of one given cantilever.
2) The distribution of live loads in the analytical model was different from the in-situ conditions. Most of the live loads were not even applied when the tests were performed.
3) The measured frequencies obtained by the environmental vibration method may be slightly greater than the actual frequencies of the structure. Furthermore, the nonstructural components and construction activities greatly affect the test results.

To ensure that the results of the tests and the analysis match, the analytical model was modified after discussion with the structural designers. On the premise of keeping the structure component sizes unchanged, the analytical model was calibrated as follows:

1) Change the steel beam hinge connection to a rigid connection.
2) Reduce the live loads according to the actual situation when the tests were conducted.
3) Ignore the stiffness reduction of the concrete floor in the sixth story in considering the action of long-term loads.

The reanalysis of the modified model was conducted with the finite element programme Sap2000. A comparison of the first ten frequencies of the initial model and the modified model is shown in

Table 5 First ten frequencies of initial model and modified model

Modal	Frequency (Hz)	
	Initial model	Modified model
1	0.81	1.16
2	1.69	1.97
3	1.70	2.04
4	1.96	2.37
5	2.11	2.39
6	2.19	2.41
7	2.27	2.52
8	2.30	2.69
9	2.34	2.75
10	2.49	2.83

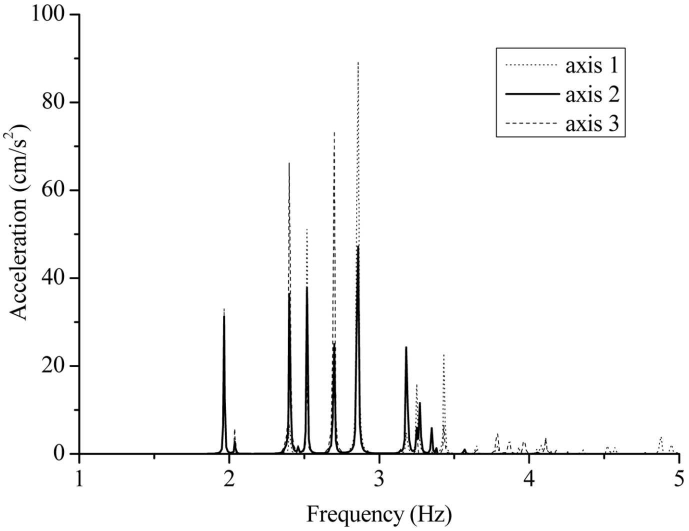


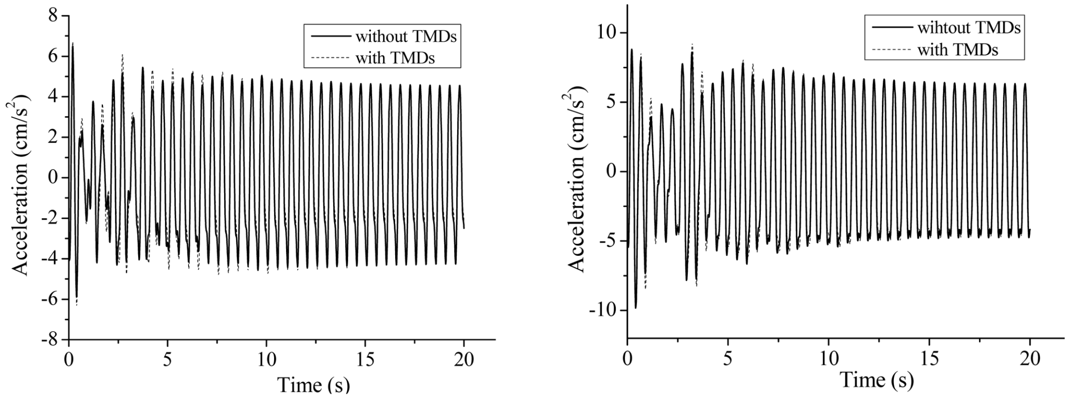
Fig. 11 The frequency-response curves

Table 5. The high-order vertical vibration frequencies of the modified model were closer than those of the initial model to the test results. The differences between the experimental and analytical vertical vibration frequencies were within 15%, which is an acceptable range for engineering applications.

Harmonic response analyses were performed on the cantilevers of axes 1-3 and 25-30, all of which had tuned mass dampers installed. Sinusoidal loads with different frequencies were applied on the ends of the cantilevers, and the maximum acceleration responses at the same point were obtained. The frequency-response curves revealed that the two zones have several vertical vibration frequencies between 2.5 Hz and 3.5 Hz. Fig. 11 shows the frequency-response curves of axes 1-3.

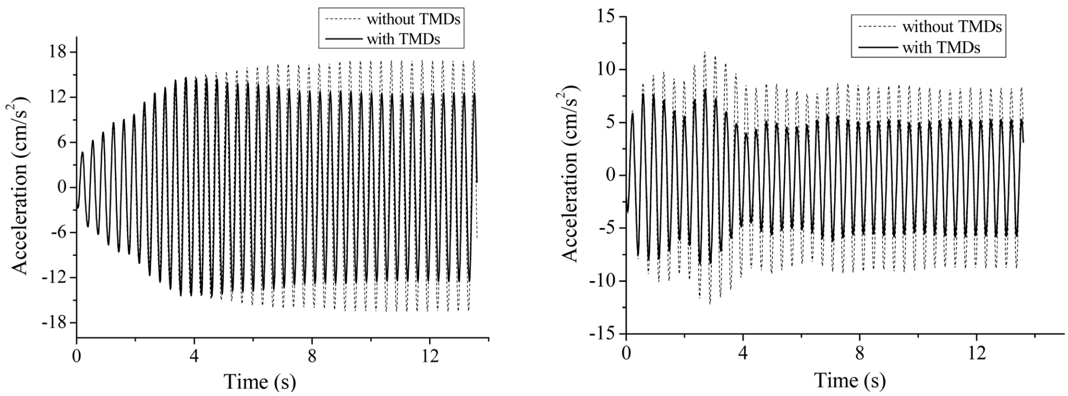
The frequency domain analysis results showed that the vertical vibration frequencies of the structure exceed the normal walking frequency range of 1.6-2.4 Hz, but fall in the centre of the fast-moving or running frequencies (Bachmann *et al.* 1995). The coincidence of the fast-moving frequency and the natural frequency of the structure will result in vibrations with very large amplitudes. Two calculation conditions were thus considered: one condition involves people walking normally at a frequency of 2.0 Hz, and the other involves people moving fast or running at the structural vertical vibration frequency. The frequency corresponding to the peak acceleration response was selected from the frequency-response curve, that is, 2.86 Hz for axes 1-3 and 2.52 Hz for axes 25-30. Also, the parameters of the tuned mass dampers were changed due to the experimental results. As in the aforementioned analysis, an IABSE walking time history curve (Fig. 4) was used as the human-induced force model, and pedestrian loads were applied to the floor as area loads.

The analysis results show that when people walk at a frequency of 2.0 Hz, the vertical vibration acceleration time history curves from before and after the installation of tuned mass dampers nearly overlapped. At the same time, it is noted that a light vibration occurs in the floor and that the peak acceleration responses are less than 8 cm/s^2 under the pedestrian loads. On the other hand, without the tuned mass dampers, the floor vibrations show a visible resonance effect at the structural vertical vibration frequency when people are moving fast or running. After installation of the tuned mass



(a) (b)

Fig. 12 Comparison of acceleration time history curves under a walking load: (a) axis 1, (b) axis 3



(a) (b)

Fig. 13 Comparison of acceleration time history curves under a running load: (a) axis 1, (b) axis 3

Table 6 Vibration reduction efficiency of tuned mass dampers

Frequency	Axis	Peak acceleration without TMDs (cm/s^2)	Peak acceleration with TMDs (cm/s^2)	Reduction efficiency
2.86 Hz	1	16.91	14.64	13.4%
	2	14.59	11.96	18.0%
	3	12.17	8.38	31.1%
2.52 Hz	25	4.24	3.79	10.6%
	26	5.85	5.13	12.3%
	27	5.59	4.93	11.8%
	28	4.73	4.18	11.6%
	29	3.54	3.12	11.9%
	30	2.01	1.73	13.9%

dampers, the resonance phenomenon weakened and the peak acceleration remained below 15 cm/s^2. Figs. 12-13 show a comparison of the acceleration time history curves with and without tuned mass dampers under the two load conditions. Table 6 summarises the vibration reduction efficiency. On average, tuned mass dampers can reduce vertical vibration by 15%.

8. Conclusions

In this paper, an investigation of the use of tuned mass dampers for reducing human-induced vibrations in the Expo Culture Centre at the World Expo 2010 in Shanghai, China was reported. A number of field tests were performed on the structure and on tuned mass dampers to evaluate their performance. The results of the structural characteristics tests showed that the structural cantilevers have several vertical vibration frequencies between 2.5 Hz and 3.5 Hz that exceed the normal human walking frequency but that fall in the centre of the fast moving or running frequency range. After several springs were added on-site, the tuned mass dampers were found to have a frequency of 2.9 Hz and to perform well. Furthermore, the analytical model was calibrated according to the field test results. The results of the analysis of the modified model showed that when people were walking normally, the structural vibrations were low and the tuned mass dampers had no effect, but when people were running at the structural vibration frequency, the tuned mass dampers can reduce the vibration acceleration of the floor by approximately 15%.

Some insight was gained from the analysis and testing of the Expo Culture Centre. As for the dynamic characteristics of a spatial structure with long cantilevers that have several high-order vertical vibration modes, there is a discrepancy between the calculated results and the tested results, and field measurements are required. Because the effectiveness of TMDs is heavily dependent on the tuning ratio between the structural frequency to be damped out and the natural frequency of the auxiliary mass, the design process must follow the field tests of the structural vibration characteristics. The vibration reduction effectiveness of tuned mass dampers is bounded to vibrations sources associated to frequency close to those the TMD have been designed for.

Acknowledgments

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