MODAL IDENTIFICATION OF LARGE-SCALE LOW-RISE BUILDINGS THROUGH MICROTREMOR MEASUREMENTS

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Abstract

The demands of anti-seismic performance for a structure are rising from being not collapse during an earthquake to being repairable, and recently the trend even moves to the damage evaluation for low-rise buildings and non-structural components. The dynamic analysis for low-rise buildings becomes more important because of both the safety consideration and other economical demands. For low-rise buildings, standard structural design laws generally require static loading analysis only. The large-scale property makes it questionable to apply rigid floor assumption as well as lateral-torsional independent assumption to this kind of structures, because complex dynamic properties are expected. Additional factors such as expansion joints, large spaces, atria and other components make it even harder to understand the actual dynamic characteristics of such buildings.

One of the practical ways to understand the dynamic nature of its kind is vibration measurement. This paper tries to reveal the general dynamic property by applying microtremor measurement to six commercial buildings which have different characteristics individually. The natural frequencies and the corresponding modal shapes are evaluated by singular value decomposition of power spectra density matrices of outputs in the frequency domain (FDD method). The natural frequencies are evaluated by Random Decrement (RD) method as well to confirm the consistency among system identification results. A course array of accelerometers in the application of the FDD method is proposed to obtain global modal shapes of a structure with a limited number of sensors. In fact, only eight sensors were used to obtain the modal amplitudes at more than 50 locations in each building during the measurement process.

The adapted method obtains the global modal shapes of a structure with a limited number of sensors and the general dynamic properties of large-scale low-rise commercial buildings are revealed through microtremor measurements: (1) The first natural frequency does not match the corresponding design value/approximated value even though it is identified under microtremor; (2) Lateral-torsional coupling property is obvious when investigating modal shapes at edges of each floor, particularly for L-shaped structures; (3) Expansion joints divide the area even under microtremor and lead to local inconsistent local modes around them; (4) Large inconsistent amplitudes are likely to occur at large spaces such as food courts and theaters; (5) The sub-structures such as parking lots have its own modal shapes, causing the interaction with the main building by connecting bridges; (6) local inconsistent modes are also identified around atria and skylights, exhibiting unexpected functions; and (7) the identified damping ratios of six buildings for lower modes vary from 1% to 2%, which are quite regular from the engineering viewpoint of structural design.

The information will be used in the development of a new method that can effectively identify the building damage shortly after an earthquake in the further research.

Keywords: large-scale low-rise building; modal identification; microtremor; lateral-torsional coupling

1. Introduction

This paper reports dynamic properties of large-scale low-rise buildings through microtremor measurement and system identification. Compared with high-rise buildings, the large-scale low-rise buildings often have relatively irregular shapes and several larger atria in the building plans. For low-rise buildings, standard structural design laws generally require static loading analysis only. As a result, their actual dynamic properties have not been understood well so far.

Six commercial buildings were selected to extract general dynamic nature from large-scale low-rise buildings that have different characteristics individually. The multi-setups of accelerometers in the application of the system identification can obtain global modal shapes of a structure with a limited number of sensors. For each building, about more than 50 spots were selected to measure acceleration microtremor [1]. Simultaneous measurements at 6-8 spots were repeated by fixing one accelerometer at a certain reference spot. The reference spot was used to integrate local modal shapes obtained by the simultaneous measurements into the global modal shapes of the structure.

The modal identification results reveal general dynamic nature of the large-scale low-rise commercial buildings in Japan. In the buildings with L-shaped plans, the first lateral vibration mode stimulates the torsional vibration, and the coupled modal amplitude becomes larger at the edges of the structure. The influences of expansion joints, atria and skylights are confirmed even under microtremor. Rigid-floor assumption is not satisfied near large atria and skylights. The large spaces such as food court and theater hall have larger modal amplitudes than other small spaces. In addition, the first natural frequency under microtremor does not match the corresponding design values, but the damping ratios of lower modes are at normal level.

2. Modal Identification Methods

Natural frequencies and the corresponding modal shapes can be identified by singular value decomposition of power spectra density matrices of outputs in the frequency domain [2]. This modal identification is generally called as FDD (Frequency Domain Decomposition) method. The method can be applied to output-only system identification when it is assumed that excitations input to a structure are white noises and the modal damping ratios are small. An advantage of the FDD method is to separate nearly closed modes clearly, which is useful for a structure with lateral-torsional coupled modes. However, the method can be applied to a set of simultaneously measured structural responses in its traditional use. This needs microtremor records at many desired locations to identify the modal shapes.

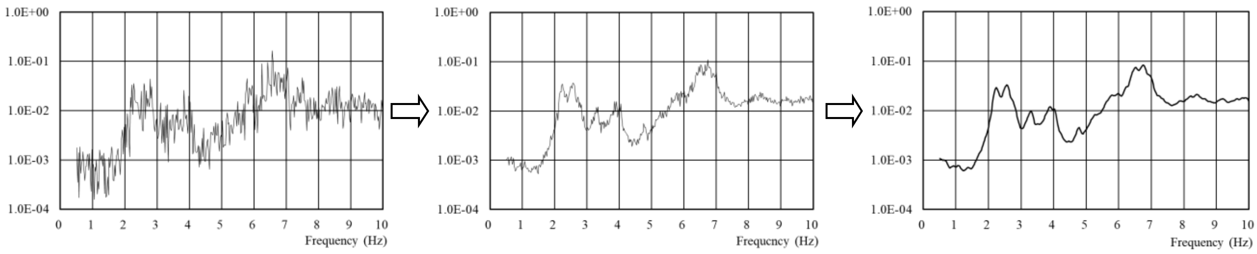
To obtain global modal shapes of a structure with a limited number of sensors, simultaneous measurements at 6-8 spots were repeated by fixing one accelerometer at the reference spot. The reference spot was selected around the center of top floor because the modal amplitude there might be relatively larger. The reference spot is used to integrate local modal shapes obtained by the simultaneous measurements into the global modal shapes of the structure. The FDD method can find vibration modes at frequencies where the power spectra density matrices of microtremors in the frequency domain have local peaks. The peak frequencies are evaluated as natural frequencies and the corresponding left singular vectors express the modal shapes.

$$\left.\begin{aligned}\phi_A &= [\phi_0, \phi_1, \phi_2, \dots, \phi_7, 0, 0, \dots, 0] \xRightarrow{normalized} [1, \phi'_1, \phi'_2, \dots, \phi'_7, 0, 0, \dots, 0] \\ \phi_B &= [\phi_0, 0, 0, \dots, 0, \phi_8, \phi_9, \dots, \phi_{14}] \xRightarrow{normalized} [1, 0, 0, \dots, 0, \phi'_8, \phi'_9, \dots, \phi'_{14}]\end{aligned}\right\} \xrightarrow{Assembled} \phi_{AB} = [1, \phi'_1, \phi'_2, \dots, \phi'_7, \phi'_8, \phi'_9, \dots, \phi'_{14}]$$

Fig. 1 – Integration of local modal shapes into global modal shape in application of FDD method

Fig.1 shows an application example when two sets of simultaneous measurements A and B find the same peak frequency. ϕ_A is the modal shape vector through Measurement A, and ϕ_B is the modal shape vector through Measurement B. Each component in the modal vectors is the modal amplitude at each measurement spot. First, both the modal shape vectors are normalized by the modal amplitudes at the reference spot. Next, these vectors are assembled as the global modal shape.

At each simultaneous measurement, the recording time was up to 20 to 30 minutes with a sampling frequency of 200Hz, since the first natural frequencies in low-rise buildings are relatively higher than ones in middle/high-rise buildings. In a simultaneous measurement, its singular value distribution in the frequency domain was averaged by using 20 windows in the time domain. Each window is 20.48s or 40.96s long responding to 4096 or 8192 data set in the discrete time. Finally, the averaged distribution curve was smoothed through repeating Hanning Window five times. The averaging and smoothing are useful to identify natural frequency more easily. Microtremor included noise because it was recorded during shopping stores in the buildings were open for business.



(1) Original singular values (2) Averaged singular values (3) Smoothed singular values

Fig. 2 – Averaging and smoothing effects in the first singular values by FDD method

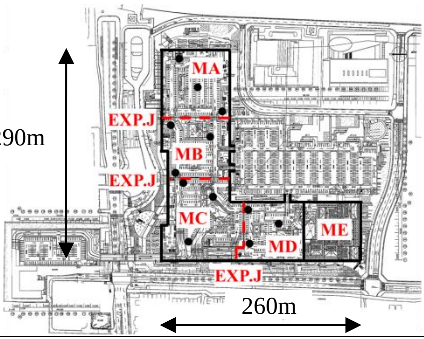
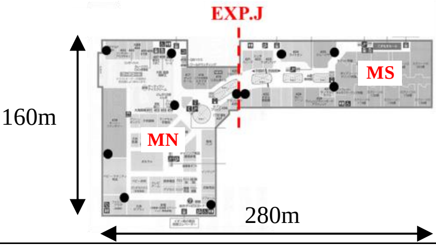
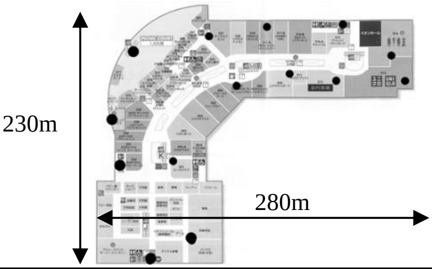
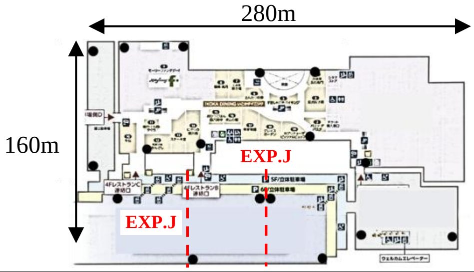
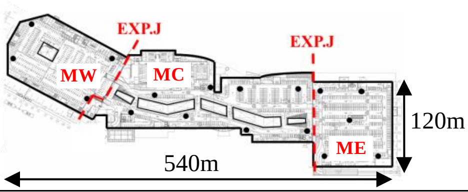
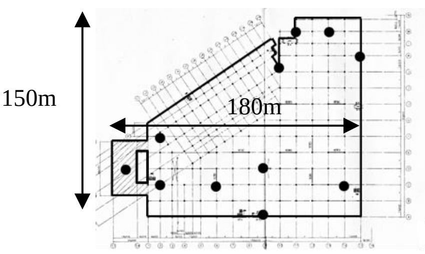
Modal damping ratios in the lower vibration modes were evaluated by applying the Random Decrement (RD) method [3] to microtremor recorded at one measurement spot on the roof floor. First, microtremor records were bandpass filtered to specify the target frequency. The filter width was determined on the singular value distribution obtained by the FDD method. To obtain a natural frequency and the corresponding damping ratio, an AR model was applied to a quasi-free vibration response made by the RD method. The natural frequency by the RD method was compared with the corresponding natural frequency by the FDD method to confirm the consistency between both the identification methods.

3. Objective Structures

Table 1 shows six large-scale low-rise commercial buildings that are named as A, B, C, D, E and F respectively. These buildings are characterized by planar view with size, structural frame material, story, heights and expansion joint (EXP.J). These structures vary from 180m to 540m long with 2 to 6 stories. Buildings A, B, C and D have L-shaped plans. From a viewpoint of EXP.J, Building A has three joints only at the roof floor, and Building B has one joint at each floor to separate the whole structure into two sub-structures. Building D has two joints only in the parking sub-structure. Building C has no joints. Most buildings have atria in shopping area, and only Building E has skylights on the roof. All the buildings use the roof floor for car-parking and air conditioner facilities. In figures of all the buildings, the horizontal line represents *x*-direction, and the perpendicular line represents *y*-direction.

Sub-sections 4.1 to 4.6 describe the dynamic properties for these individual buildings. Section 5 extracts the general dynamic nature of the large-scale low-rise commercial buildings based on the modal identification results in Section 4. Fig.2 shows the averaging and smoothing effects in the first singular value distribution, indicating a simultaneous measurement in *x*-direction of Building A.

Table 1 – Objective structures

Name	Geometric characters	Planar view
A	Frame: S (Steel) Plan: L-shape, 260m by 290m Height: 25m Shopping area: 3 stories with atria Parking area: 4th (Roof) floor Expansion joint (EXP.J): 3 only at roof floor	
B	Frame: S Plan: L-shape, 280m by 160m Height: 29m Shopping area: 4 stories with atria Parking: 5th & 6th (Roof) floors EXP.J: 1 at each floor through whole building	
C	Frame: SRC (Steel-framed reinforced concrete) & S Plan: L-shape, 280m by 230m Height: 25m Shopping area: 3 Stories with atria Parking area: 4th-6th (Roof) floors EXP.J: None	
D	Frame: SRC & S Plan: L-shape, 280m by 160m Height: About 40m Shopping area: 4 stories with atria Parking area: Beside shopping sections connected by contact bridges EXP.J: 2 only in parking area	
E	Frame: S Plan: 540m by 120m Height: 14m Shopping area: 2 stories with atria & skylights Parking area: 3rd (Roof) floor EXP.J: 2 at each floor through whole building	
F	Frame: SRC & S Plan: Trapezoid, 180m by 150m Height: About 24m Shopping area: 3 stories with atria Parking area: 4th -6th (Roof) floors EXP.J: None	

4. Modal Identification Results

4.1 Building A: L-shaped steel structure with expansion joints at roof only

For the convenience of description, naming the areas divided by expansion joints MA, MB, MC and MD as shown in Table 1. The first global lateral modes for *x*-direction and *y*-direction are almost identical, at 2.22Hz and 2.23Hz respectively [4]. Red lines show modal amplitudes at measurement spots, and red arrows mean global movements of the building. The first lateral mode in each direction clearly couples with torsional components. The first torsional mode is found at 2.57Hz. The designed first natural period is 0.69s, corresponding natural frequency is 1.45Hz and it is around 65% compared with the identified value. The identified damping ratios in the lateral and torsional modes vary around 2%.

The other typical modes in *x*-direction are (1) at 3.30Hz, local mode at roof floor of MA part influenced by EXP.J; and (2) at 3.85Hz, torsional mode. In *y*-direction, the typical modes include (1) at 3.42Hz, local mode by EXP.J; (2) at 3.52Hz, local mode in MA part; and (3) at 3.85Hz, local mode similarly influenced by EXP.J.

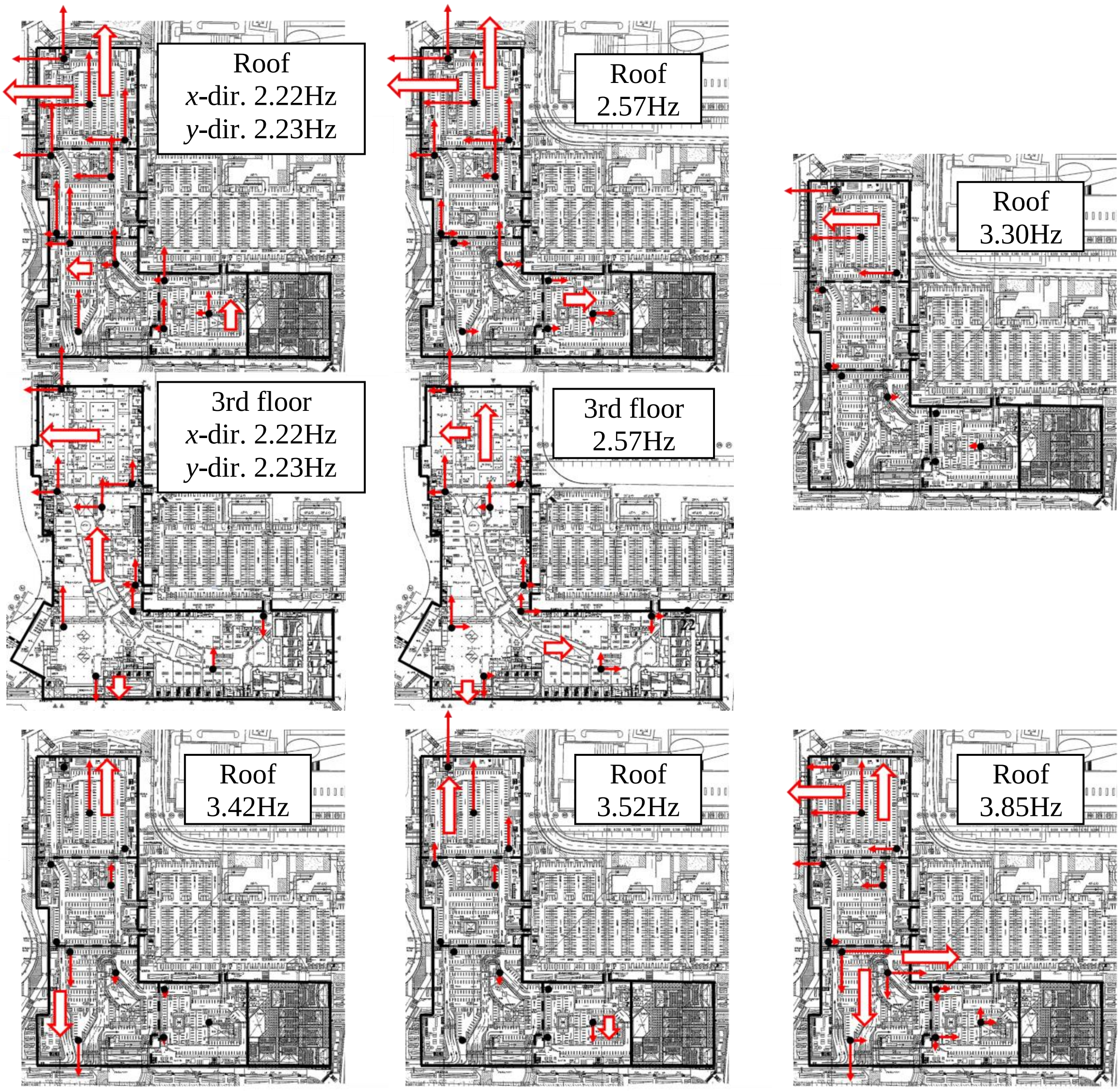


Fig.3 – Modal shapes of Building A

4.2 Building B: L-shaped steel structure with expansion joints throughout whole building

The first global mode in *x*-direction is identified at 1.50Hz, and the first global torsional mode is at 1.92Hz [5]. However, the cutting through EXP.J makes it difficult to identify the general global modes of the structure in *y*-direction because it divides the building into MN and MS parts. Since the designed first natural period is not available, the approximated period according to its height is around 0.87s, the corresponding natural frequency is around 83% to the identified value. The identified damping ratios for lower mode are around 2% as well.

The typical other local modes in *x*-direction are (1) at 2.17Hz, independent first lateral modes for MS and MN parts; and (2) at 3.99Hz, local torsional mode for MS. The typical local modes in *y*-direction are (1) at 1.38Hz, first lateral mode for MS, it is coupled with torsional components and the amplitudes are particularly large near the theater; and (2) at 1.54Hz, first lateral mode for MN. The other local torsional modes are (1) at 1.54Hz for MS; and (2) at 2.60Hz for MS (3rd floor and above) and MN (5th and 6th floors).

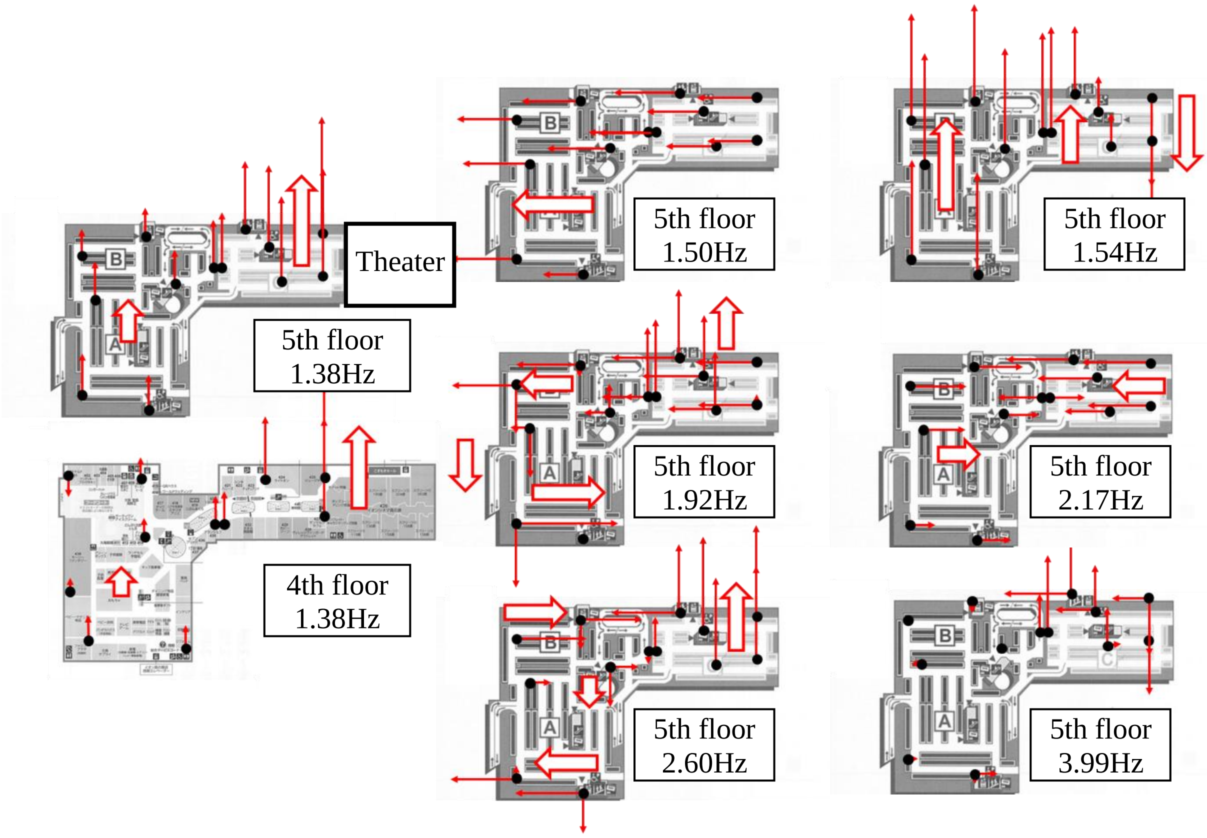


Fig.4 – Modal shapes of Building B

4.3 Building C: L-shaped SRC structure with no expansion joints

The parking lot is built above the shopping mall, and the inconsistent horizontal stiffness leads to many local modes at the parking lot. The first lateral mode of roof in both directions occurs at 1.51Hz while the first global lateral modes of the three-floor parking lot are at 2.45Hz in *y*-direction and at 2.88Hz in *x*-direction. And the first global lateral modes of the building are at 3.17Hz in *y*-direction and at 3.58Hz in *x*-direction, both modes are coupled with torsional components. The approximated natural frequency of this structure would be around 2Hz, 19% lower than the identified value when comparing with the first mode of parking lot. The identified damping ratios corresponding to the global lateral modes are around 1%. Local torsional modes are identified, yet the global torsional mode is not. The typical local torsional modes are found at 4.36Hz, 4.92Hz and 5.76Hz. The local modal amplitude is large at food court on the 3rd floor at 5.76Hz.

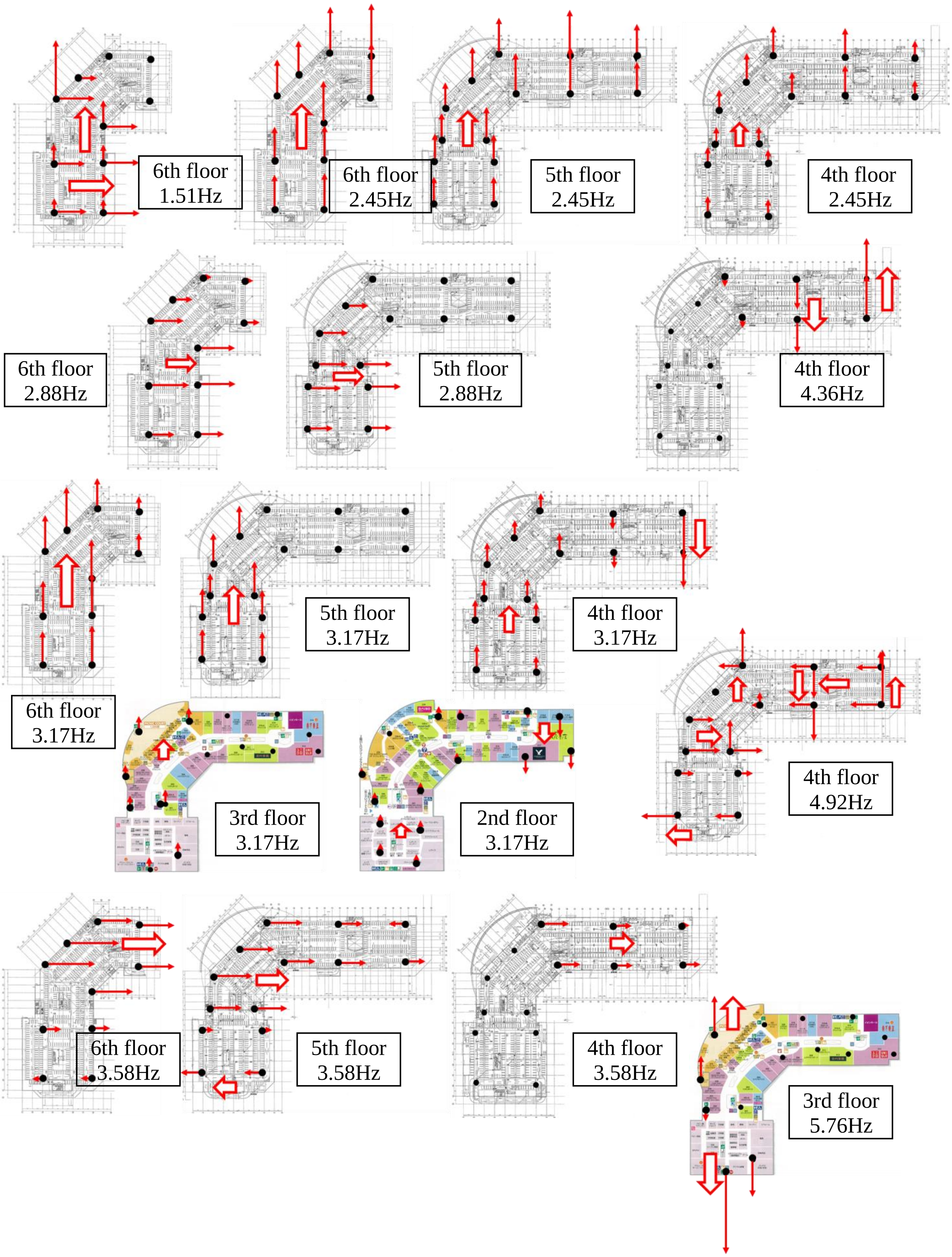


Fig.5 – Modal shapes of Building C

4.4 Building D: L-shaped SRC structure with no expansion joints and attached with parking lots

Building D does not have obvious global lateral modes because the parking lot is connected with the main structure and there would be interaction between them. Some of the parking lot floors are in the middle of the two floors of main building, which means the floors of main building and parking lots are not at the same height level. But the first global torsional mode can be found at 2.80Hz as shown in Fig.5. The identified damping ratios in the lower modes vary from 1% to 2%.

The typical local modes are (1) at 1.83Hz, lateral mode for the left part; (2) at 2.08Hz, local lateral mode in parking lot, dragging the attached entrance of shopping moll moving with it; (3) at 2.39Hz, the local torsional mode at 4th floor; (4) at 2.71Hz, torsional mode at the 4th floor, causing the parking lots twisting around the EXP.J; (5) at 4.63Hz, torsional mode at 4th floor where the right part and the left part have independent torsion in *x*-direction. The approximated first natural period according to its height is around 0.8, 1.25Hz to corresponding first natural frequency, 32% lower than the identified lowest natural frequency.

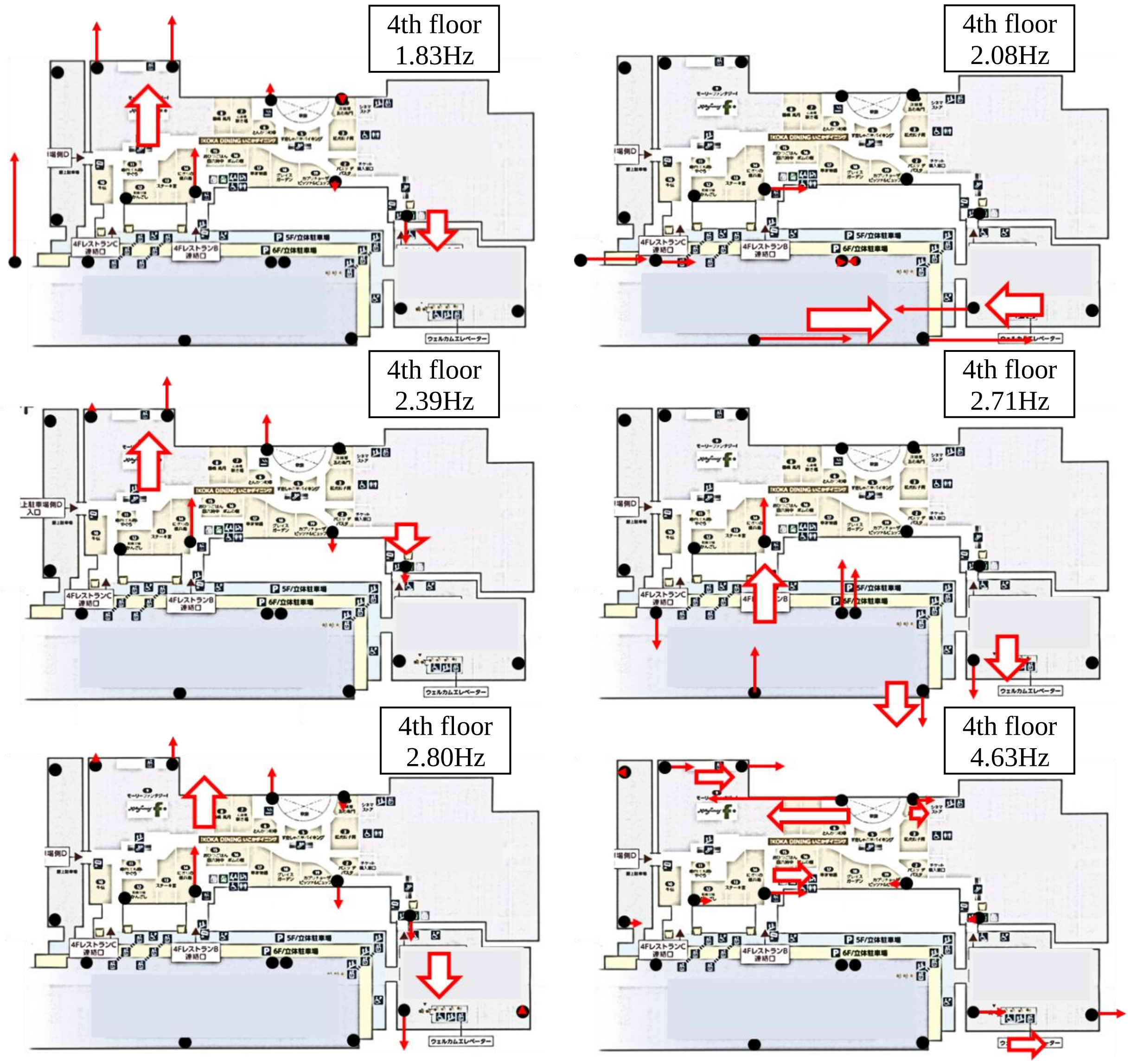


Fig.6 – Modal shapes of Building D

4.5 Building E: Steel structure of big length-width ratio and large atria

This structure is divided by EXP.J into three parts, MW, MC and ME, respectively [6]. There is no clear sign of global torsional mode or global lateral mode in the both horizontal directions. The first *x*-direction lateral modes are observed at 1.47Hz for MC and ME and at 2.09Hz for MW. The first *y*-direction lateral modes are found at 1.25Hz for ME, at 1.47Hz for MC and at 1.84Hz for MW. The local torsional modes occur at 1.84Hz for MC and ME. Lots of local modes are identified around skylights and atria such as: (1) local lateral-torsional coupling modes around skylights in MC at 2.71Hz and 3.56Hz in *x*-direction; (2) inverse vibration along atria in MC at 5.42Hz in *x*-direction; (3) local torsional modes around atria in MC at 4.15Hz, 5.37Hz and 5.71Hz. The approximated first natural frequency based on its height is 2.4Hz, around 113% to 190% compared with the identified local first natural frequency. The identified damping ratios corresponding to the global lateral modes are around 1%.

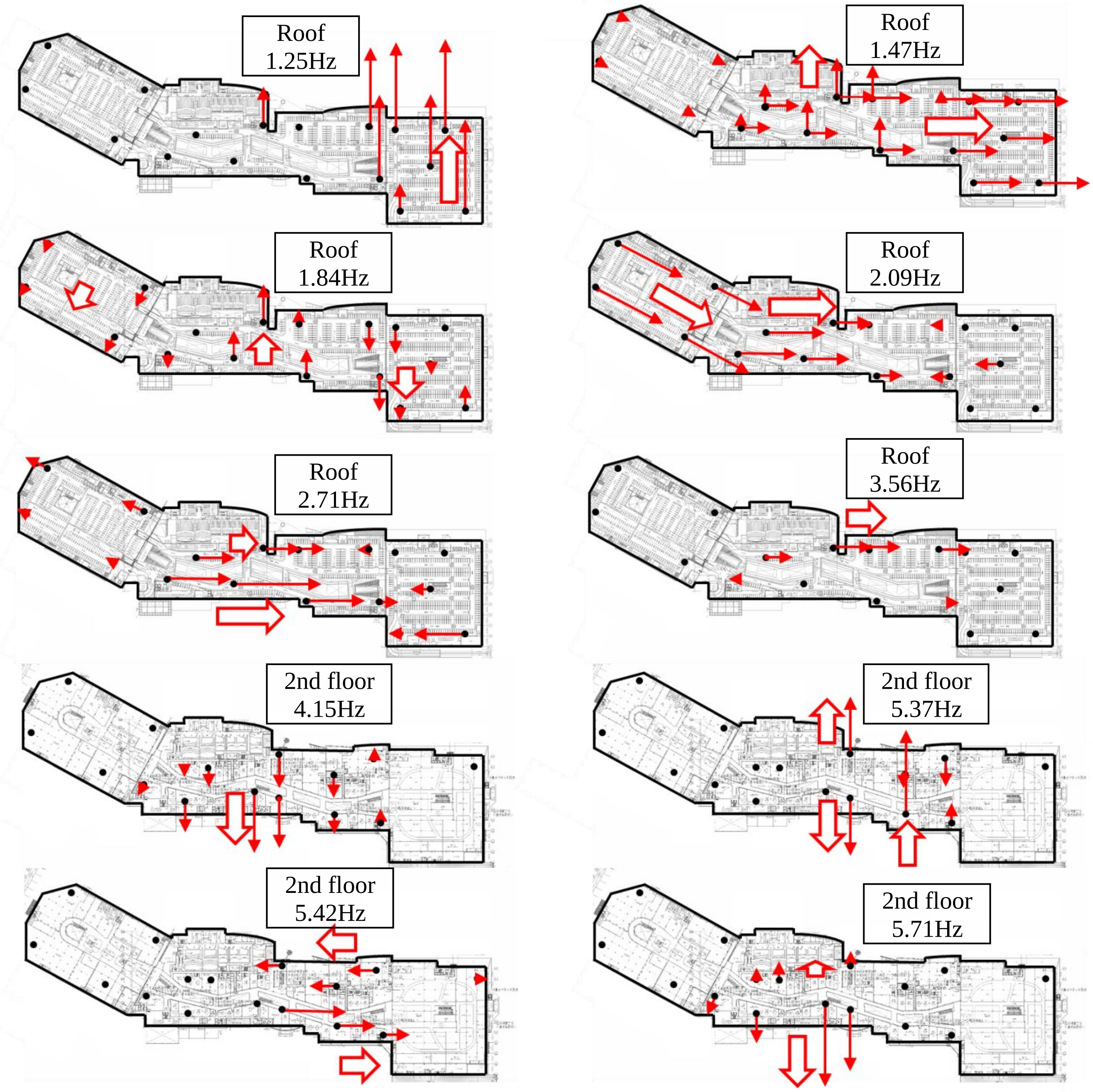


Fig.7 – Modal shapes of Building E

4.6 Building F: Trapezoid-shaped steel structure with no expansion joints

Building F is selected because it has regular geometrical characteristic, it makes a good comparison with the previous five buildings. The first natural frequency in *x*-direction is 2.44Hz and the influence of atrium at 3rd floor is obvious [5]. The first natural frequency in *y*-direction is 2.74Hz and the global torsional mode occurs at 3.39Hz, since there is no EXP.J and the shape of the building is relatively regular. The designed first natural frequency is 1.67Hz, around 32% lower than the identified result. The damping ratio for the first lateral mode and torsional mode is around between 1.5% and 2%. Inverse local modes are found at 4.28Hz.

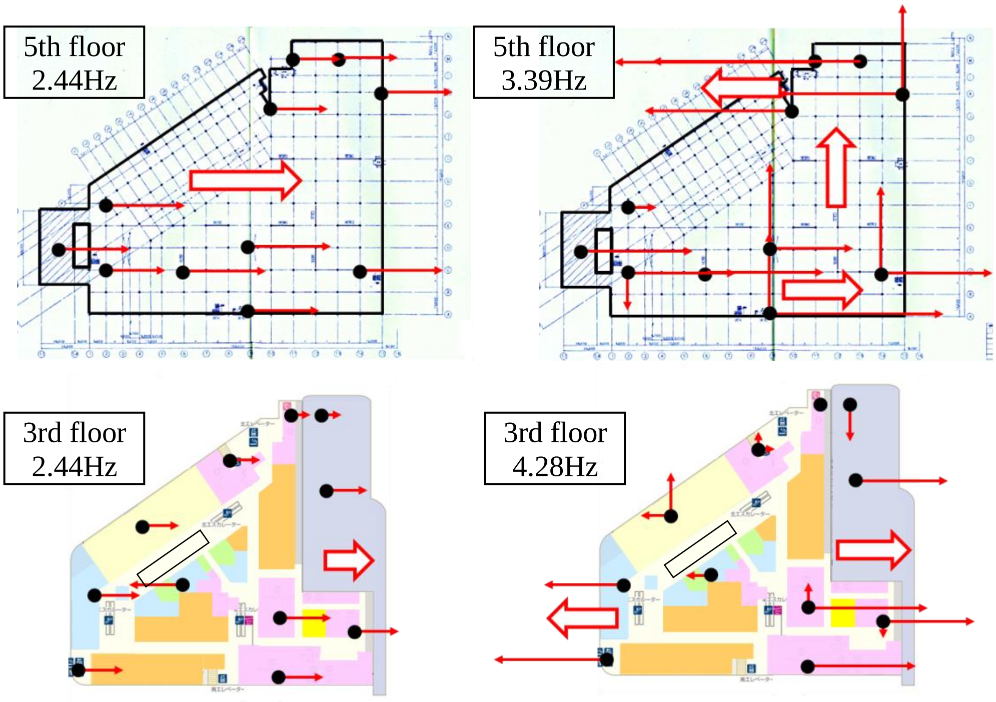


Fig.8 – Modal shapes of Building F

5. Dynamic Property Analysis

Section 5 summarizes the dynamic properties of six buildings including natural frequencies, damping ratios and modal shapes. Compared with the medium/high-rise buildings, the identified damping ratios are at normal level, around 1-2%. However, the natural frequencies and modal shapes have some typical characteristics different from other buildings.

Natural frequency differences

The identified first global and/or local lateral natural frequencies are generally higher than the designed values except for Building E. In general, the higher values seem to be affected mainly by the fact that actual dead and live loads are smaller than the designed loads. During the microtremor measurement that lasts around one day for each building, it is obvious that the mass is time changing and it is different in the morning from that in the afternoon because the customers are flexible and it can be expected to change a lot comparing the weekend situation with weekday situation. The variance is considered indirectly by averaging and smoothing the singular value distribution in the frequency domain.

Lateral and torsional coupling

One of the major characteristics of large-scale structures is irregular shape. The irregular shape like L-shape often leads to the eccentric of mass center and stiffness center, leading to the lateral-torsional coupling character. The large-scale property would expand it to a considerable level, which means such property would be obvious at the edges of structure. This is supported by lots of identification results. The torsional property occurs regardless of local mode or global mode, and it is generally observed on all six identified structures.

The influence of expansion joints

The expansion joints separate an area into small areas and many local modes happens at those small areas. The typical local modes around expansion joints include (1) opposite lateral modes around expansion joints; (2) lateral modes on one side and torsional modes on the other side; and (3) local torsional modes with opposite direction. This property means that it is difficult to use one sensor to summarize the mode shape of one floor when expansion joints are installed. The modal shapes are more uniform in Building F because there are no expansion joints and the shape is relatively regular.

Local modes of large spaces

The local modes caused by expansion joints often have relatively even modal amplitude in the separated sub-structures. However, the local modes of large spaces such as movie theater and food court are particularly large, because those places tend to have more flexible floor with less partition walls. This property further challenges the rigid floor assumption. The uneven local modes for one integrated floor regardless of the influence of expansion joints simply cannot be considered to be rigid.

Influence of sub-structures

One of the structures, Building D, has a sub-structure for car parking and it is connected to the main building by bridges. The difference of natural frequencies between the main structure and the sub-structure leads to coupled, interacted and complicated local modal shapes as the connection result. The modes of the sub-structure would drag the main structure, and they lead to local modes around the connecting bridges. In return, the main structure would influence the sub-structure as well. Although the actual influence of connecting bridges under large earthquakes might be different from the microtremor situation, the identification result should be considered in future structural design.

Atria and skylights effect

The function of expansion joints is to divide a large space into small pieces with simple dynamic properties, and it is expected to have opposite vibration around expansion joints. The similar phenomenon can be observed around atria and skylights as well. There would be opposite direction modes around atria in the shopping area and skylights at roof. This property indicates that local modes can be made unconsciously, thus it is important to apply system identification to the existing building. There would be unexpected dynamic properties and complex modal shapes around those irregular locations.

6. Conclusions

This paper investigates the dynamic properties of six large-scale low-rise commercial buildings with different shapes by using microtremor measurements. It reveals several common characteristics of these structures through the system identification results. The approach of sensor deployment is useful to overcome the situation where the total measurement location number exceeds the sensors amount at hand in the application of the FDD method. This strategy is to measure the microtremor of the building piece by piece instead of recording them all together. The multi-setups of sensors make it possible to use eight sensors to obtain the modal shapes at about more than 50 locations within two days. Microtremor included noise because it was recorded during shopping stores in the buildings were open for business. The averaging and smoothing were useful to evaluate modal properties easily. The dynamic characteristics of large-scale low-rise commercial building are summarized as follows:

1. The identified first global natural frequencies of six building do not match to their designed/approximated values. The reason is that the mass of a structure including customers, goods and cars is different from the designed value and changing from time to time, and it also explains the variance of identification result. The variance is considered indirectly by averaging and smoothing the singular value distribution in the frequency domain.

2. The lateral-torsional coupling phenomenon is observed in all six buildings, particularly in the L-shaped structures and the long rectangular structure. This property would greatly influence the modal amplitude at edges of structure. It means that the sensor is supposed to be placed at those edges to capture this kind of property in the measurement.
3. Local inconsistent and sometimes opposite modes are observed around expansion joints, it means the general assumption of rigid floor is improper for this kind of structure, also indicating that it is difficult to capture the mode shape tendency of one floor by using single sensor, the deployment of sensor should be based on the distribution of expansion joints.
4. Large local modes are identified at large spaces such as food court and movie theaters, and the distribution of modal amplitude indicates that rigid floor assumption is improper for this kind of building. The previous sub-conclusions 3 and the later sub-conclusion 6 also suggest this statement from other perspective.
5. The interaction between main structure and sub-structure is reflected by the modal shape that global modes at one building would lead to local modes in the other. And this kind of interaction should be considered if trying to analyze two structures independently.
6. The inconsistent modal shapes are observed around atria and skylights, which should be considered in structural design. It makes it harder to use one representative location to represent the whole area.
7. The identified damping ratios in lower modes vary from 1% to 2%. The difference in damping ratios between steel structures and SRC structures is unclear under the microtremor measurements. Unlike the natural frequency, the damping ratio is very sensitive to sensor location and the identification process itself thus the variance is larger than that in natural frequency. This corresponds to the well-known experience from the past research.

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