Effects of Infill Walls and Floor Diaphragms on the Dynamic Characteristics of a Narrow-Rectangle Building

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Abstract

Most buildings in Singapore are lightly reinforced concrete structures which are manly designed for gravity loading only, because Singapore is an island country located in a low to moderate seismic region. The dynamic properties of a typical high-rise residential building with a long, narrow rectangular floor plan are studied using both experimental and numerical methods. The effects of the brick infill walls and the flexible diaphragms on the dynamic characteristics of the building are discussed in detail. The results from the ambient vibration tests are correlated with the numerical results of three different finite element models with different levels of sophistication. They include a bare frame model, a frame model with brick infill walls, and a frame model with both brick infill walls and flexible diaphragms. The dynamic properties of the third model match very well with the measured results in terms of both the natural frequencies and the mode shapes. The correlation results

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demonstrate the respective effects of the brick infill walls and the flexible diaphragms on the dynamic characteristics of the narrow-rectangle building structure.

Keywords: Correlation, Ambient vibration, Brick infill walls, flexible diaphragms

Introduction

With the rapid development of computer hardware and software, computer simulation using the finite element (FE) method has become the most popular way in building structural analyses. However, one question is always being asked: whether an FE model is accurate enough to represent the physical system? One of the best ways to test the adequacy of an FE model is to conduct full-scale tests on the real structure under study, and then correlate the test results with the numerical results obtained from the FE model. Among the several testing techniques available, the full-scale ambient vibration test is frequently used to assess the structural dynamic characteristics of a building.

Singapore is a small island country located off the southern tip of the Malay Peninsula. The country is famous for its excellent public housing program; more than 80% of the population lives in the high-rise apartments constructed by the government (HDB, 2002). In order to meet the large demand on the public housing, the public residential buildings have been constructed in a rather similar way. They share some typical geometries and shapes with a similar structural system. Because Singapore is located in a neither seismic active nor strong wind region, the British concrete design code BS8110 (BSI, 1987) is adopted in the construction industry. Therefore, all the public high-rise residential buildings are typically of lightly reinforced concrete structures. There has been interest in knowing the dynamic performance of such structures when subjected to local ground tremors (Pan, 1995 & 1997). A full-scale ambient vibration test on a typical high-rise residential building was therefore carried out (Phang, 2000, Goh, 2000), and the correlation analysis between the measured results and the numerical results obtained from finite element analyses are reported in this paper. Because of the long, narrow rectangular shape of the building, the behaviors of flexible floor diaphragms were observed during the measurements. Therefore, the effects of diaphragm flexibility are considered for the correlation analysis. In addition, because of the impact of the brick infill walls on the lateral stiffness, the brick infill walls are also included in the numerical models.

Literature reviews

In order to make the FE modeling of a building possible and cost effective, many assumptions are made in order to simplify the modeling process. Among them, one is to ignore the non-structural elements in a structural model, and another is to assume the floor diaphragms behave rigidly.

The infill partition wall in a frame structure is one type of non-structural elements which is normally ignored in a simplified FE model. However, the effects of infill walls on the structural properties of a building have been recognized by engineers and studied for a long period of time (Ghassan, 1998). The infill partition walls are supposed to increase the building stiffness. They may also introduce some undesirable effects on the building performance, such as enhancing the soft storey mechanism and causing short column effects. The efforts of trying to include masonry infill panels in FE models date back to as early as the 1950s. There are generally two approaches: micro-modeling and macro-modeling for local and global responses, respectively. The micro-modeling is to simulate the infill panels using detailed meshes to study the stress and strain distributions within a local region. The macro-modeling uses a single finite element to represent the infill panel and study its effects on the global structural properties of a building, such as the building frequencies and base shear forces. The original idea of macro-elements was from Holmes (1961) who proposed replacing the infill by an equivalent pin-joined diagonal strut of the same material with a width of one-third of the infill's diagonal length. After that, much research effort has been on the better estimation of the characteristics of the compression struts. Recently, Saneinejad and Hobbs (1995) proposed an "equivalent strut model" for masonry frames with infill by accounting for elastic and plastic behaviors of infilled frames considering the limited ductility of infill materials. Based on this method, Madan et al (1997) suggested a hysteretic model and its control parameters to represent masonry infill panels in nonlinear analyses of frame structures. Later, Dolsek and Fajfar (2002) formed an idealized force-displacement curve for the masonry infill panels using the results of pseudo-dynamic tests. FEMA-356 (FEMA, 2000) also gave the guidelines on modeling the masonry infill, which models the infill as a compression strut. An alternative way of macro-modeling is to model the infill panels using plane elements. During the small deformation stage, the separation between the infill panels and the frame elements may not have been initiated, and the infill panels are still in full contact with the frame elements. Therefore, the plane elements would be a good approximation for the infill panels in such cases. Chaker and Cherifati (1999) suggested that plane stress finite elements provide a better representation of the in-plane initial stiffness of the infill panels under the small strain condition. Since the building reported here was only subjected to small strains during the ambient vibrations, the plane stress elements were thus used to simulate the infill walls in the correlation analysis in this paper.

Even though building's floor diaphragms play a critical role in distributing and redistributing the lateral forces to the vertical structural elements of lateral load resistance, it is a common practice in the numerical simulation of buildings to model the floor diaphragms as a rigid horizontal plate to reduce the computational efforts. Therefore, with the rigid diaphragm assumption, the lateral force resisted by an individual vertical element is proportional to its lateral stiffness. However, this simplification may cause errors in the analyses, when the building has a special shape, such as a long, narrow rectangle floor plan with a large length/width aspect ratio, which is the case for the typical high-rise residential building studied in this paper. Goldberg and Herness (1965) first studied the dynamic properties of long and narrow buildings in the 1960's. They showed that for a multistory building with n identical floors and m identical frames, the $m \times n$ frequencies and mode shapes could be obtained by separately solving a typical frame problem and a typical floor problem. They also showed that the eigenvalues of the building were simply the square roots of all possible sums of the squares of a frame frequency and a floor frequency, and that the corresponding eigenvectors of the building were the tensor product of the eigenvectors of the frame problem and the floor problem. Later, Jain (1984) did a further study to show that the modal participations in structural responses of ideal buildings with uniformly distributed stiffness and masses were zero for the modes which were composed from the higher deformation modes of floors. Both Button et al (1984) and Dolce et al

(1992) studied the effects of flexible diaphragms on non-uniform building structures. They concluded that the flexible diaphragms would affect the buildings in two ways: one is the dynamic characteristics of the buildings such as natural frequencies, and the other is the lateral load distributions to the vertical elements. However, all these studies were based solely on the numerical analysis results. Correlation analysis between the numerical results and the field measurements has not been reported at all to date for buildings with flexible diaphragms.

Building Descriptions

The structure studied in this paper is a typical 15-storey, reinforced concrete (RC) residential building. The overall height of the building is 42.8 m with the first storey of 3.6 m and the others 2.8 m. Figure 1 shows a typical floor plan of the building. The dimensions of the floor plan are 94.5 m in the longitudinal direction and 11 m in the transverse direction. The typical thickness of the floor slabs is 125 mm. The main lateral force resistant system of the building is a dual system which consists of RC frames and shear walls. No clear symmetry can be observed from the building drawings. The frame system consists of a series of two-bay frames spanning in the transverse direction. The frames are spaced at about 3 m along the longitudinal direction. The typical column sections are 0.3 m by 1.2 m for the first three stories, and 0.3 m by 0.9 m for the upper stories with the larger dimension along the transverse direction. The typical beam size is 0.3 m by 0.5 m. Figure 2 shows the details of a typical beam-column joint.

The wall system is made up with the three staircases located towards the two ends and the middle of the building. They are encircled in Figure 1 as parts A, B, and C. The thickness of the wall panels is 0.2 m. The walls are also aligned mainly along the transverse direction. Therefore, the longitudinal direction appears to be the softer direction. The partition walls inside the frames are made of bricks. The building accommodates eight units of apartments per floor, and the corridor is at one side of the building. The partition walls along the corridor are only half-height to provide the large openings for windows. The ground floor is an open area reserved for public usage.

Instrumentation and Experimental Results

The structural dynamic characteristics of the building are determined by a series of full-scale ambient vibration tests at the field. Eight uni-axial accelerometers were placed at different levels of the building along each of the three staircases to capture the lateral modes in the vertical plane. Additionally, seven accelerometers were placed along the corridor of the 15th storey to record the modal properties of the building in the horizontal plane. The locations of the accelerometers are marked using pentagons as shown in Figure 1. In this study, the parameters within the range of 0.1 Hz to 11.0 Hz were extracted since the building's structural response is mainly in the low frequency range. The higher frequency signals recorded on site are mainly of machineries and interference of random noise.

Figures 3 and 4 show one typical frequency response functions (FRFs) for the transverse and longitudinal directions, respectively, derived from one set of recorded data. The lower resonant frequencies in the FRFs are relatively easy to identify. The FRF curves peak at the frequencies of 1.23 Hz, 1.38 Hz, 1.80 Hz and 3.07 Hz. In the frequency range above 3.5 Hz, the signals are noisier. The resonant peaks above 3.5 Hz are thus identified via engineering judgments, and are expected to be subject to some errors. Table 1 shows the frequencies of the first 10 natural modes identified in the field tests, where T1 represents the first mode in the transverse direction and L1 the first mode in the longitudinal direction. It is interesting to note that the fundamental mode of 1.23 Hz of the building is in the transverse direction, even though the stronger directions of columns and walls are aligned along the transverse direction. The supposedly softer longitudinal mode appears as the third global building mode of 1.80 Hz.

Figures 5 and 6 show the 3D and plan views of the mode shapes of the building along the transverse direction, respectively. It can be seen that the first mode (1.23 Hz) is a lateral translational mode in the transverse direction, and that the second mode (1.38 Hz) is the lateral-torsional mode. The fourth mode of 3.07 Hz shows clearly diaphragm deflections. The phenomenon suggests that the diaphragms of this building behave flexibly and that the conventional rigid diaphragm assumption may not be valid for this case. The global building modes can be viewed as the combination of the frame modes and the diaphragm modes. For instance, the fourth global mode of 3.07 Hz is the combination of the first frame mode and the second diaphragm mode, as discussed in the work by Jain (1984).

Correlation Analyses

Three finite element models with different levels of sophistication were constructed to simulate the actual building. They are 1) the bare frame model with rigid diaphragms, 2) the frame model with brick infill partition walls and rigid diaphragms (the B/R model) and 3) the frame model with both brick infill walls and flexible diaphragms (the B/F model). The accuracy of the models is examined by comparing their modal properties with the field-measured modal properties. The results are presented in the following sections.

Bare Frame with Rigid Diaphragms

As part of the normal practice, the building was first modeled as a bare frame model, including all the lateral force resistant structural elements, like shear walls, columns and beams, while ignoring the non-structural elements, such as infill partition walls. The floor slabs are assumed to behave rigidly. The masses of the non-structural elements and the floor diaphragms are assigned to the beams. Figure 7 shows the 3D view of the bare frame model. Figure 8 shows the three views on the coordinate planes of the first four mode shapes of the model. As shown, the fundamental mode of the model is in the longitudinal direction with the frequency of 0.7 Hz. It is followed by the two rotational modes in the transverse direction with the frequencies of 1.0 Hz and 1.1 Hz, respectively. It is agreed with the original observation that the frame structure is softer in the longitudinal direction.

However, it is hardly possible to correlate the modal properties of the bare frame model with the building properties obtained form the ambient vibration tests, in terms of both natural frequencies and mode shapes. As shown in the previous section, the experimental results show that the fundamental mode of the building is in the transverse direction, instead of the longitudinal direction shown by the bare frame model. Table 2 shows the comparison of the natural frequencies of the bare frame model and the instrumental results. Table 3 shows the percentage of errors in frequencies of the FE model relative to the instrumental results. The errors for the first transverse and longitudinal modes are -17.1% and -60.6%, respectively, which are not acceptable. Thus, the finite element model needs major modifications in order to capture the real dynamic characteristics of the building.

Frame Model with Brick Walls and Rigid Diaphragms (B/R Model)

It can be seen from the comparison results shown in the previous section, if the first mode frequency of the finite element model (f = 0.7 Hz) can be increased, while at the same time, keeping the transverse mode frequencies less affected, the correlation between the numerical results and the instrumental results will improve. In this case, the brick infill walls appear to play this role, because most of the brick wall panels are aligned in the longitudinal direction of the building. Thus, the brick wall panels were added to the bare frame model. All the brick walls along the corridor are modeled as half-height plane stress elements to account for the large openings at the upper part of the walls. The 3D view of the new model (the B/R model) is shown in Figure 9.

Table 2 shows the natural frequencies of the model. The first four mode frequencies are 1.29 Hz, 1.35 Hz, 1.75 Hz and 5.23 Hz. Figure 10 shows the three views on the coordinate planes of the corresponding mode shapes. The brick walls increase the model frequencies dramatically (Table 2). For example, the first longitudinal mode frequency is increased from 0.71 Hz to 1.75 Hz, accounting for 146% of increase. As anticipated previously, compared with the bare frame model, the increase of stiffness in the longitudinal direction is greater than that of the transverse stiffness. The first two modes of the new model are now both lateral modes in the transverse direction. The first longitudinal mode appears only as the third global mode of the model and is coupled with a rotational mode shape. It shows that the non-structural elements have contributed significantly to the lateral stiffness, even changing the direction of the fundamental mode of a building. In this case, the fundamental mode of the building is shifted from the longitudinal direction to the transverse direction by including the brick infill walls.

The correlation between the natural frequencies of the B/R model and the measured frequencies of the building is generally much better than the bare frame model. As shown in Table 3, the maximum error of the first three mode frequencies is only 4.9%. However, by comparing the natural frequencies, it can be found that those modes which show up in the field measurement between 2.0 Hz and 5.1 Hz are completely uncorrelated with the numerical model. All of these modes show diaphragm deflections according to the experimental results (Figures 5 & 6).

Frame Model with Brick Walls and Flexible Diaphragms (B/F Model)

In order to improve the B/R model, the rigid diaphragm assumption of the B/R model is relaxed, and the floor slabs are added explicitly to the model using shell elements. Figure

11 shows the 3D view of the new model including both the brick infill walls and the floor diaphragms (the B/F model). The natural frequencies of the B/F model are also shown in Table 2. Figure 12 shows the mode shapes of the first four modes of the B/F model. The first four natural frequencies are 1.24 Hz, 1.33 Hz, 1.69 Hz and 2.93 Hz. They are associated with the mode shapes in the transverse, transverse, longitudinal and transverse direction, respectively, which are now consistent with the experimental results.

The matching of the natural frequencies between the B/F model and the experimental results is very good. The maximum error for the first 10 modes is only 6.7% (Table 3). Having added the floor slabs, the numerical model can simulate those modes with diaphragm deformations, e.g. the fourth mode of the building. On the other hand, the first three modes of the model, where the diaphragms behave rigidly, are less affected by relaxing the rigid diaphragm assumption. Their frequencies decreased only slightly: 1.6% for mode 1, 1.5% for mode 2 and 3.4% for mode 3.

Besides the modal frequencies, the first four mode shapes also match quite well by comparing Figures 5 & 6 with Figure 12. The further mode shape analyses are conducted by calculating the modal assurance criterion (MAC) values using the following formula:

$$MAC(\psi_a, \psi_e) = \frac{(\{\psi_a\}^T \{\psi_e\})^2}{(\{\psi_a\}^T \{\psi_a\})(\{\psi_e\}^T \{\psi_e\})} \tag{1}$$

where ψ_a is the mode shape of the numerical results, and ψ_e is the mode shape of the instrumental results. An MAC with value close to the unity indicates a good correlation between the paired mode shapes. The MAC values calculated by pairing the vertical frame mode shapes of the first three measured modes with the first 10 numerical modes are shown in Table 4. In the table, the prefix "E" represents experimental results and "A" represents analytical results. The MAC values from pairing the first three measured modes and the first four numerical modes are very high and close to the unity. This means that they all have a similar mode shape vertically, i.e. the first mode of the frame structure. From the fifth mode onwards, the higher frame modes appear in the numerical model, which makes the corresponding MAC values very low, less than 0.1, except the ninth mode. After examining the ninth mode shape of the numerical model, it is found that the ninth mode is the combination of the first frame mode and the third diaphragm mode. This confirms the combination theory associated with a uniform frame structure (Goldberg & Herness, 1965 and Jain, 1984). Thus, it can be concluded that the correlation between the vertical frame mode shapes of the numerical model and the field measurement is relatively good.

Table 5 shows the MAC values by pairing the horizontal floor mode shapes. The MAC values between mode E1 to E3 and mode A1 to A12 are not as close to the unity as those of the vertical frame modes (Table 4). The MAC values for E1 – A1, E2 – A2 and E3 – A3 are 0.96, 0.83 and 0.79, respectively. They are still acceptable. The MCA value of E4 – A4, which both have clear diaphragm deflections, is very high 0.99 indicating that the mode shapes match well with each other. The table shows that the B/F model can capture the deformation of the flexible diaphragms very well.

Conclusions

A full-scale ambient vibration test was carried out for a typical high-rise residential building. The results are compared with the numerical results calculated from three different finite element models. The models are: 1) Model 1 – a rigid-diaphragm model with only bare frames and shear walls, 2) Model 2 – the rigid-diaphragm model amended by adding the brick infill walls (the B/R model), and 3) Model 3 – Model 2 amended by relaxing the rigid-diaphragm assumption (the B/F model). The following observations and conclusions can be drawn from the study:

1. The typical residential building has its fundamental natural mode of 1.23 Hz in the transverse direction, even though the layout of the structural elements of the building suggests that the transverse direction is the stiffer direction. Because of the large aspect ratio of the floor plan, the diaphragms of the building behave flexibly, which can be seen from the diaphragm deformations shown in some of the measured planar mode shapes of floors.
2. In this case, the numerical model with the rigid-diaphragm assumption and consists of only bare frames and shear walls can't simulate the instrumental results well in terms of both the natural frequencies and the mode shapes. In particular, the numerical model shows the fundamental mode in the longitudinal direction, while the experimental results show that in the transverse direction.

3. Adding the brick partition walls increases the natural frequencies of a building. In this case, because almost all of the brick walls are aligned along the longitudinal direction, the stiffness in the longitudinal direction is increased dramatically, from 0.71 Hz to 1.75 Hz. Thus, the longitudinal direction becomes the stiffer direction, and the fundamental mode of the building switches to the transverse direction, which is consistent with the observation made during the ambient vibration tests. The modal frequencies and the mode shapes of the model with the brick infill walls match well with some of the building dynamic characteristics measured. Therefore, in order to achieve a good correlation between the numerical and the experimental results, the non-structural brick infill walls need to be included in the model. However, the model so obtained still can't re-produce the modes with floor diaphragm deformation.
4. The B/F model can capture both the vertical frame modes and the horizontal floor diaphragm deformation modes. Both the modal frequencies and the mode shapes of the model match the experimental results well. It can be seen that the rigid diaphragm assumption is not valid in this case. In order to simulate the building behavior correctly, the diaphragm flexibility needs to be included explicitly in the numerical model.
5. The good correlation between the numerical results and the field measurements suggests that the plane stress elements can model the brick infill walls well in the small strain situation, and that the floor slabs are well simulated by the shell elements.

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Table 1 First ten natural frequencies (Hz) from the measurement

Mode	1	2	3	4	5	6	7	8	9	10
Freq	1.23	1.38	1.80	3.07	4.79	5.00	5.09	5.70	6.16	7.56
Direction	T1	T2	L1	T3	T4	T5	L2	T6	T7	T8

Note: "T" reprents transverse direction, "L" represents longitudinal direction

Table 2 First ten natural frequencies (Hz) of the FE models

Mode	T1	T2	T3	T4	T5	T6	T7	T8	L1	L2
Field	1.23	1.38	3.07	4.79	5	5.7	6.16	7.56	1.8	5.09
Bare Frame	1.02	1.09	4.57	4.93	10.31	11.08	-	-	0.71	2.26
B/R Modal	1.29	1.35	5.23	5.69	11.24	12.06	17.29	19.07	1.75	5.39
B/F Modal	1.27	1.33	2.93	4.83	5.08	5.79	6.57	7.92	1.69	5.37

Note: "T" reprents transverse direction, "L" represents longitudinal direction

Table 3 Errors (%) of the frequencies of the FE models relative to the measurement

Mode	T1	T2	T3	T4	T5	T6	T7	T8	L1	L2
Bare Frame	-17.1	-21.0	48.9	2.9	106.2	94.4	-	-	-60.6	-55.6
B/R Modal	4.9	-2.2	70.4	18.8	124.8	111.6	180.7	152.2	-2.8	5.9
B/Fmodal	3.3	-3.6	-4.6	0.8	1.6	1.6	6.7	4.8	-6.1	5.5

Note: "T" reprents transverse direction, "L" represents longitudinal direction

Table 4 MAC values of the mode shapes in the vertical plane

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
E1	0.98	0.98	0.98	0.99	0.03	0.03	0.06	0.01	0.77	0.04
E2	0.98	0.98	0.98	0.99	0.04	0.03	0.07	0.02	0.78	0.04
E3	0.97	0.97	0.97	0.98	0.06	0.05	0.10	0.04	0.78	0.05

Note: "E" represents experimental results, "A" represents analytical results

Table 5 MAC values of the mode shapes in the horizontal plane

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
E1	0.96	0.03	0.02	0.02	0.03	0.71	0.35	0.00	0.05	0.02
E2	0.03	0.83	0.83	0.06	0.44	0.02	0.59	0.25	0.01	0.22
E3	0.03	0.80	0.79	0.03	0.87	0.24	0.57	0.03	0.19	0.38
E4	0.05	0.00	0.00	0.99	0.14	0.10	0.05	0.79	0.03	0.02

Note: "E" represents experimental results, "A" represents analytical results

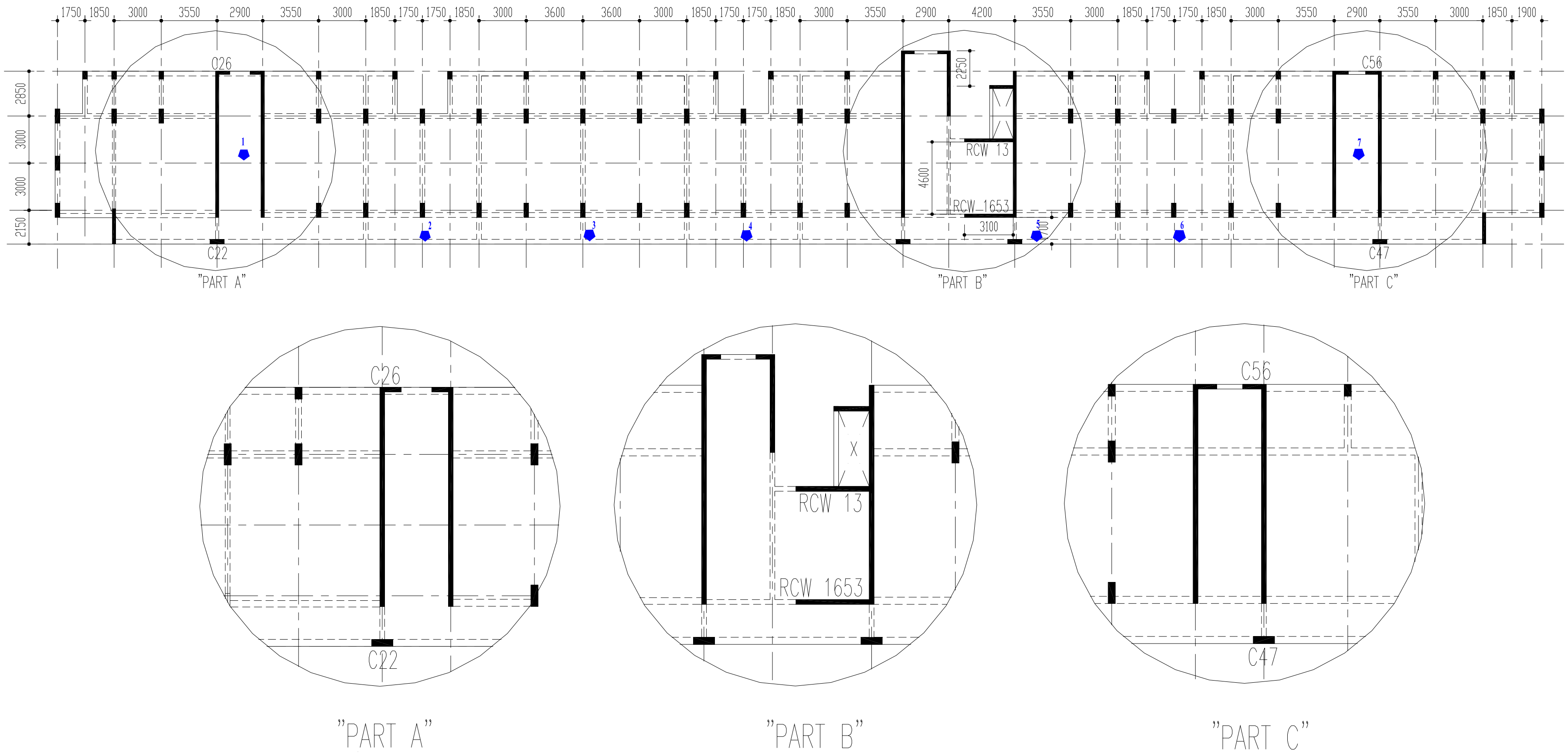

Figure 1 Typical plan of the building

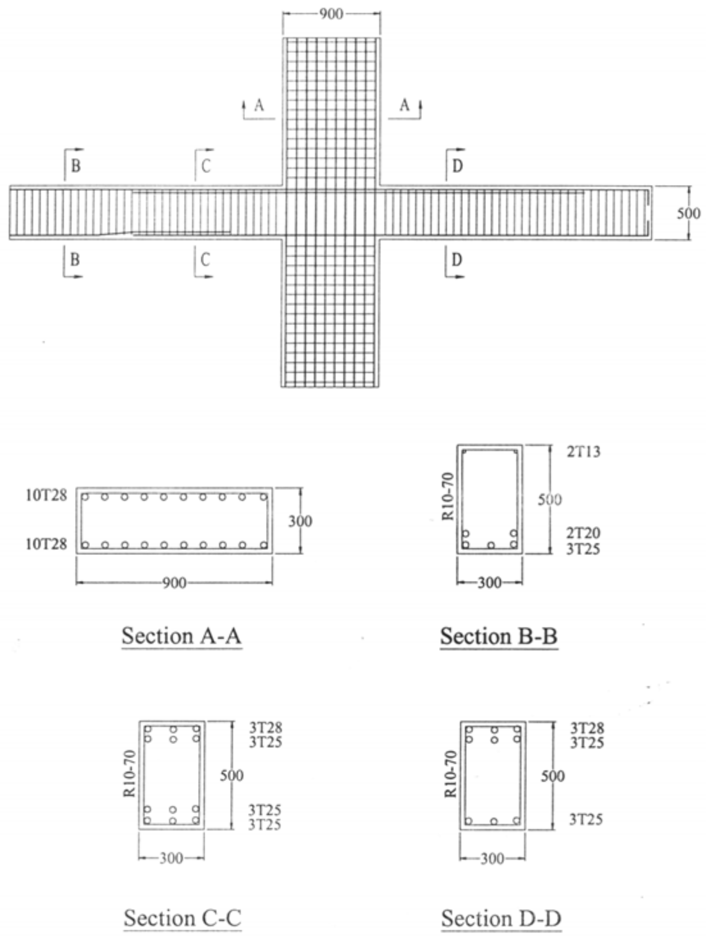

Figure 2 Details of a typical beam-column joint

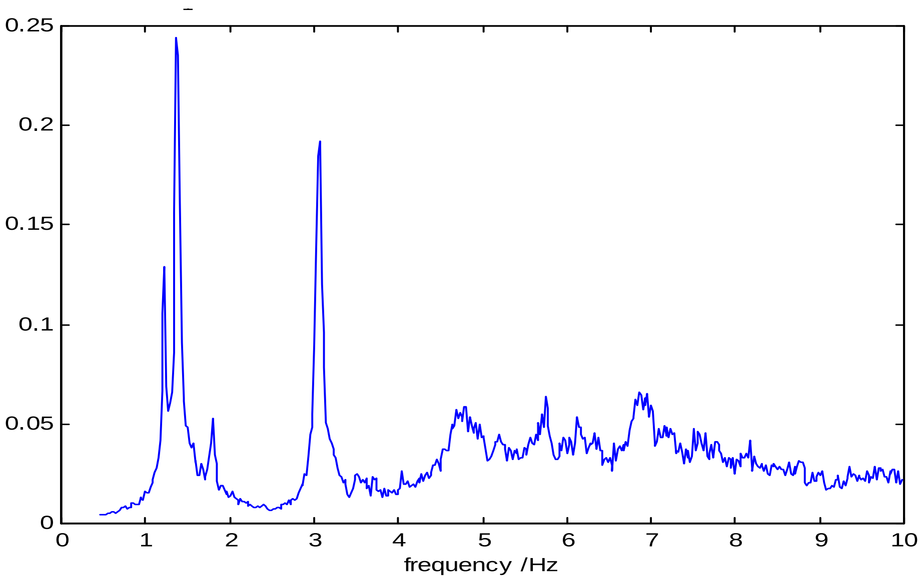

Figure 3 Frequency response function in the transverse direction

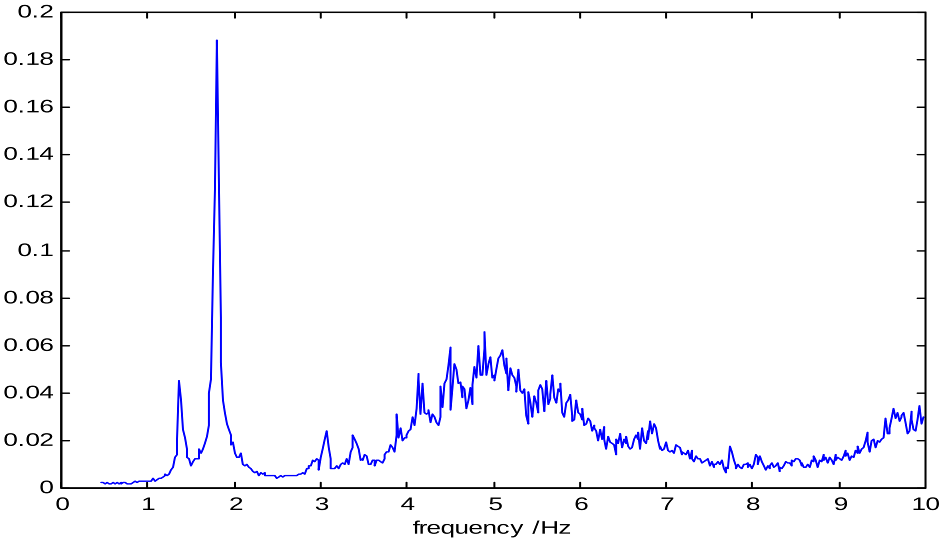

Figure 4 Frequency response function in the longitudinal direction

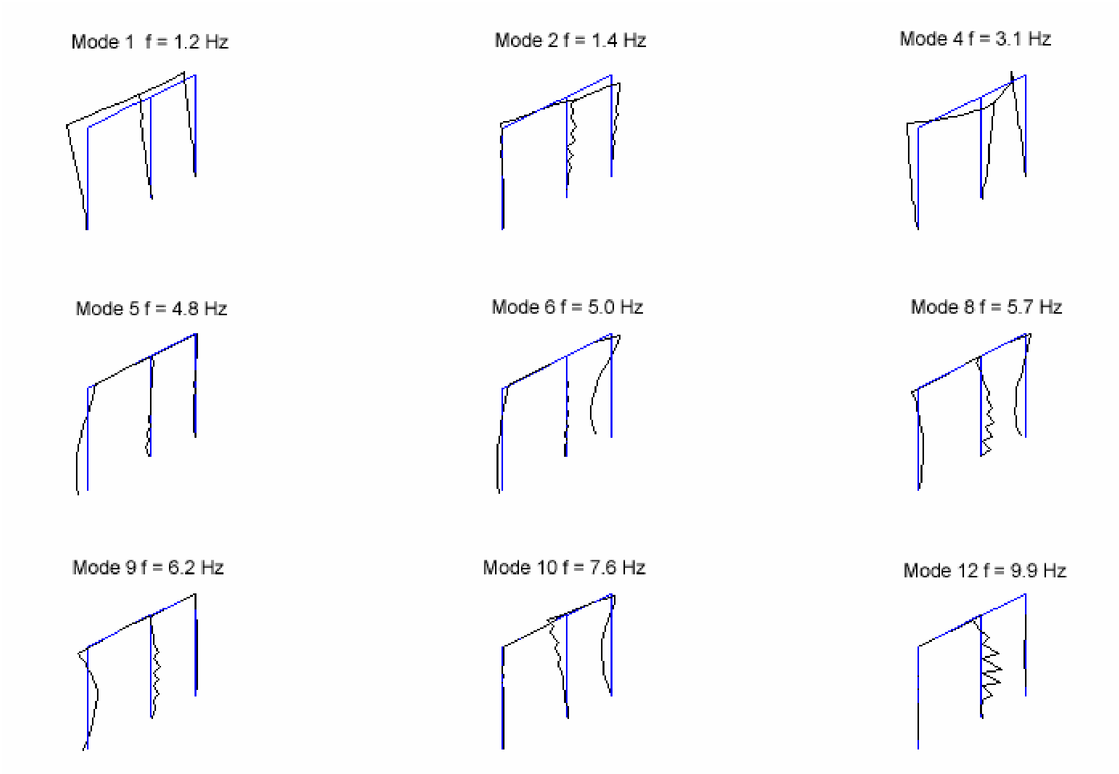

Figure 5 Frame mode shapes along the transverse direction in the vertical plane from one measurement

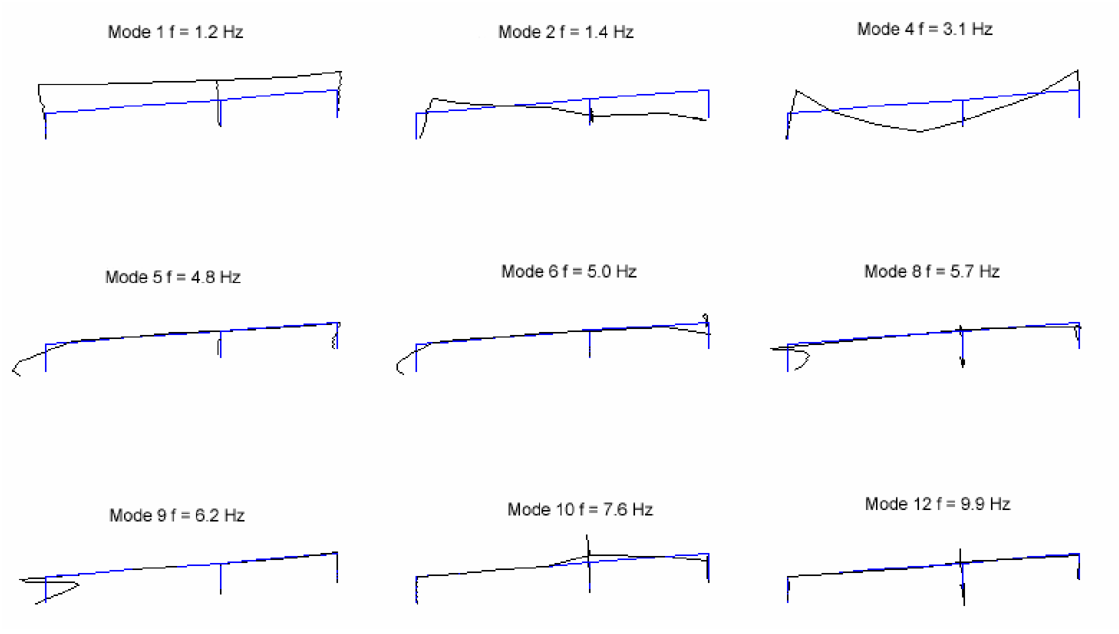

Figure 6 Floor mode shapes along the transverse direction in the horizontal plane from one measurement

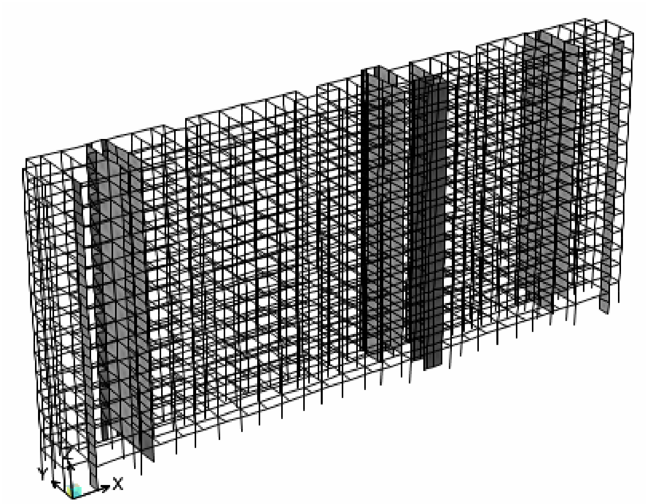

Figure 7 3D view of the bare frame model

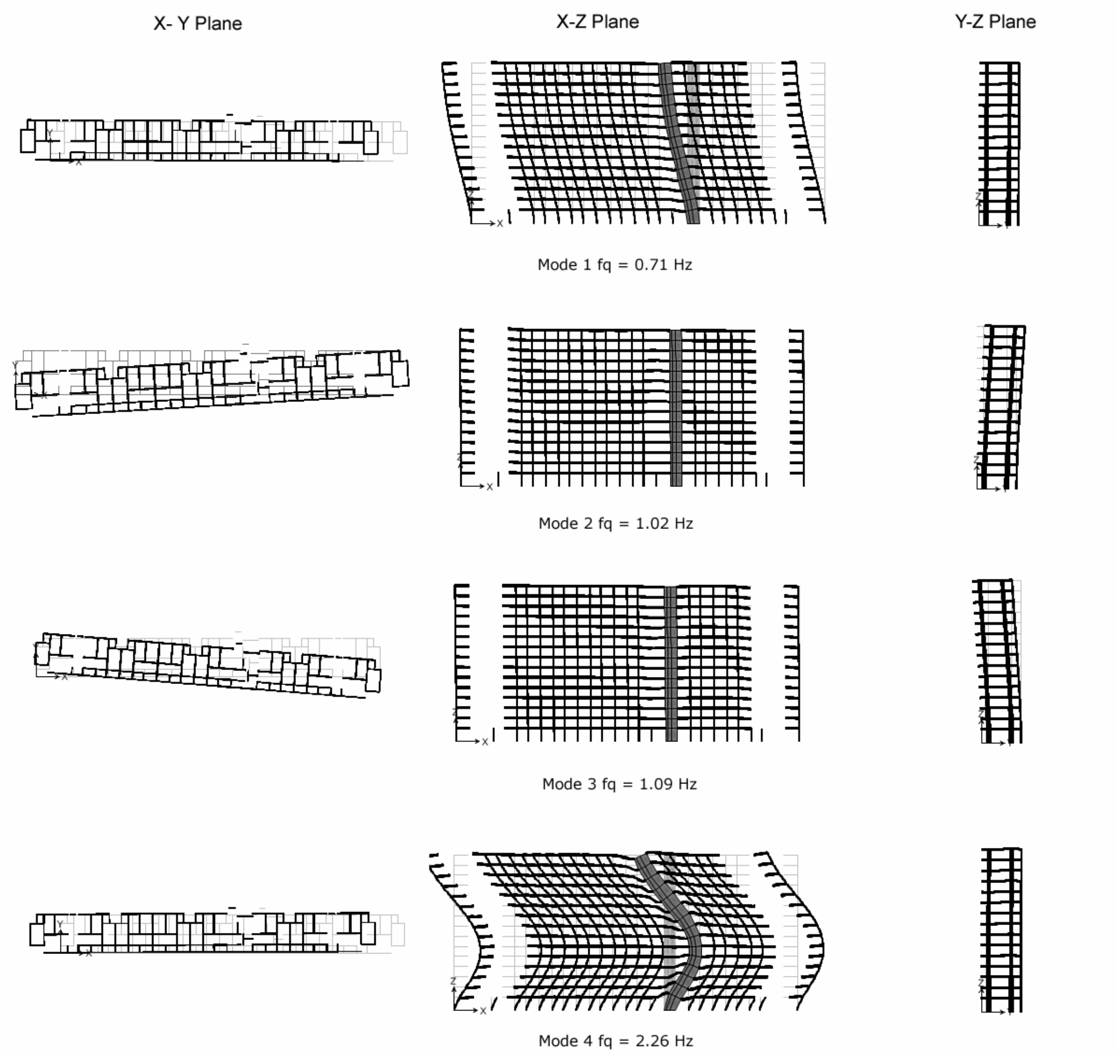

Figure 8 First four mode shapes of the bare frame model

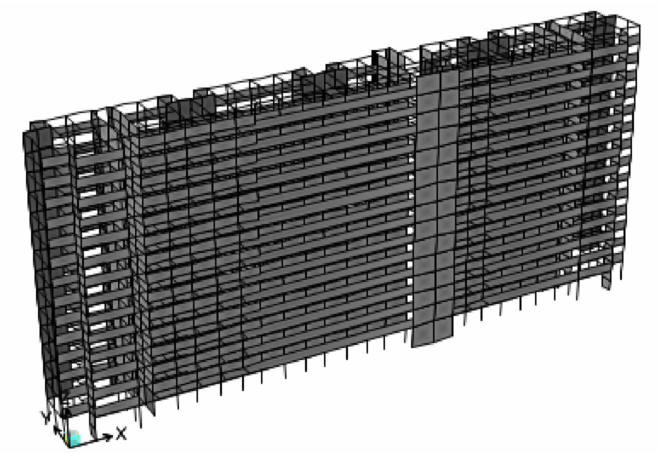

Figure 9 3D view of the frame model with partition walls

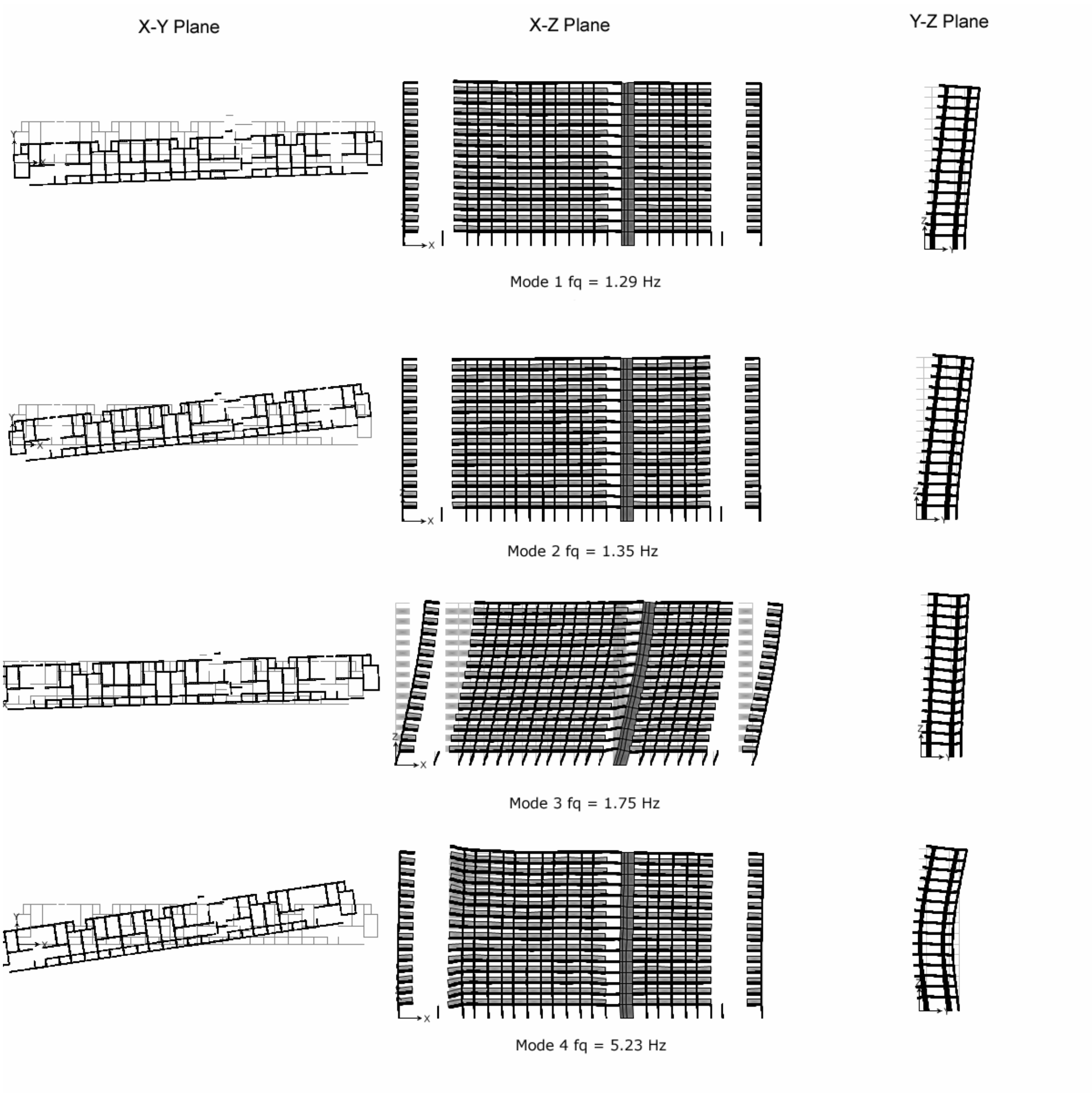

Figure 10 First four mode shapes of the frame model with brick walls

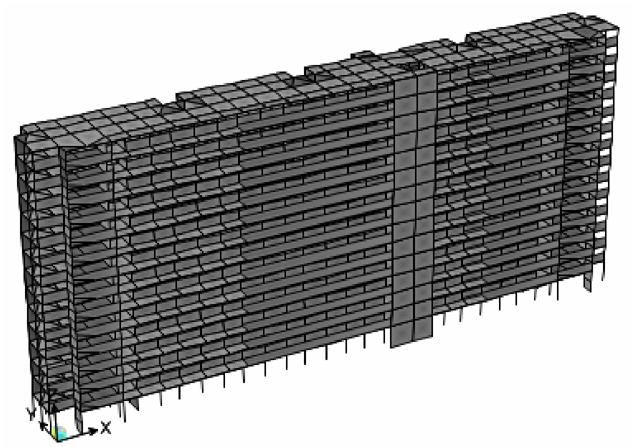

Figure 11 3D view of the model with both brick walls and flexible diaphragms

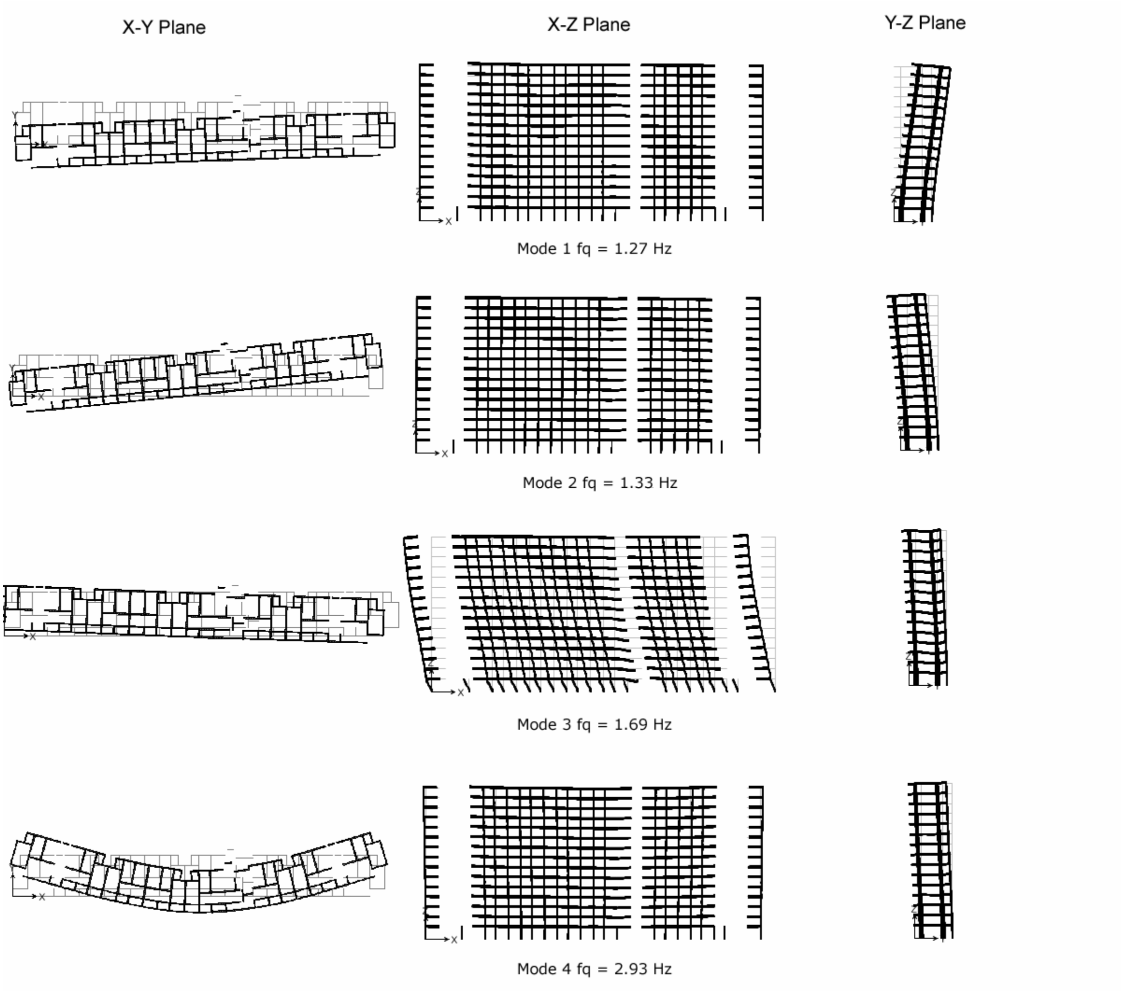

Figure 12 First four mode shapes of the frame model with brick walls and flexible diaphragms