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Frequency variation in construction stages and model validation for steel buildings

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Abstract. This study aims to monitor the variation of modal frequencies of steel buildings during their construction sequence. In this respect, construction of a steel building is followed by vibration based measurements. The monitored building is a three-story educational building within a building group whose structural system consists of steel moment resisting steel frames and eccentric braces. Five different acceleration measurements in two perpendicular directions are taken on five different construction stages, starting from the erection of the columns and beams ending with the completion of the construction. The recorded measurements are transferred into frequency domain and the dominant frequencies for each case have been determined. The change in the dominant frequencies is evaluated with the existing construction stages and performed constructional works between the stages. The last measurement, performed on the building in service, revealed the first two dominant frequencies as mutual in X and Y direction, showing that these dynamic modes are torsional modes. This result is investigated by numerical analysis performed with finite element model of the building constructed for design purpose. Lower frequencies and different mode shapes are determined from numerical analysis. The reason of lower frequencies is discussed and the vibration survey is extended to determine the effects of an adjacent building. The results showed that the building is in strong relation with an adjoining building in spite of a designed construction joint.

Keywords: steel buildings; vibration survey; numerical modeling; dynamic analysis

1. Introduction

Steel buildings are rarely constructed in Turkey due to lack of steel workmanship and high construction cost. In parallel, the number of studies performed for steel buildings is less than that of performed for reinforced concrete buildings. One important research opportunity was obtained when three buildings of Istanbul Medeniyet University were decided to be built by steel structural system. The middle building of the three, constructed in a row, but separately is used to search the variation of the modal frequencies of steel buildings during their construction stages first.

The method, used in this study is named as Ambient Vibration Survey (AVS) or Operational Modal Analysis. The technique is employed for the investigation of different problems for different structures (Gentile *et al*. 2015, Aras *et al*. 2011, Gül and Çatbaş 2011, Macdonals and Daniel 2005, Sevim *et al*. 2012, Chellini *et al*. 2010). More relevant to the presented study, Astroza

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et al. (2016) applied the method to investigate the effects of the construction processes and nonstructural components on the modal properties of a five-story reinforced concrete building constructed in a laboratory. Besides, in an earlier study, Torkamani and Ahmadi (1988) analyzed ambient vibration measurements taken on three different construction stages of eighteen-story building. They studied the added effect of nonstructural elements on dynamic frequencies and mode shapes. For this reason, AVS can be classified as a well-known and a reliable method.

However, the application in steel structures is not plenty but the recent studies are promising. Shakib and Parsaeifard (2011) applied ambient vibration survey to a 19-story steel building and compared the experimentally and numerically obtained modal periods. In another study, Türker and Bayraktar (2011) used vibration analysis for the investigation of effects of different type of braces into the dynamic behavior of steel buildings. They used roughly ½ scaled, three-story steel building in the laboratory and determined its modal properties for its bare phase (without bracing) and four different braced phases, namely, X type, Λ type, V type and K type braces by operational modal analysis. Later on, over the same test setup the modal damping in steel buildings was discussed by Kudu *et al*. (2015). Performed in laboratory, over ½ scaled test specimens, all of these studies have contributed to the scientific problems not answered before. In this respect, vibration based surveys can be used in different test setups in scientific investigations. However, use of this technique over real buildings can give more realistic and meaningful results.

By the completion of the constructional works in September 2015, four vibration measurements have been taken from the same point by a single two-directional accelerometer. An additional measurement was taken seven month later from the completion of the construction. Thereby modal frequencies of the final building are determined and the variation of vibration frequencies is observed and evaluated with the performed works during the construction.

The results of the last measurement enable estimation of mode shapes of the constructed building. These experimentally obtained modal properties are inspected by numerical investigations over the finite element model of the building. Thereby performance check for the numerical model constructed for design purpose in SAP2000 (2015) is also aimed. Comparison of the numerical and experimental results showed that the numerically estimated mode shapes are different from experimentally obtained real mode shapes. Moreover, numerically estimated modal frequencies are lower than those obtained experimentally. The poor performance of the numerical model is discussed and as the most suspicious parameter in the torsional behavior of the existing building, the effect of adjacent building is investigated by additional vibration analysis. It is seen that the torsional behavior of the studied building is caused by the adjacent building although a separation line exists between two buildings.

2. The studied building and applied methodology

As a new established state university, Istanbul Medeniyet University owned a new campus area at the heart of the Asian side of Istanbul. In order to meet the building need for its educational purposes, steel constructional system is preferred for the construction of its temporary buildings due to high construction speed and recycling rates. In these respects, a 10000 m^2-building complex has been designed and constructed in the south campus of the university (see Fig. 1).

This study is performed in Building-B (in total 2060 m^2) which is the most regular building in the complex. It is a three-story building with plan dimensions of 23.5 m by 29 m. Maximum bay length is 9 m and the story height is 4.2 m for each story. The building' structural carrying system is designed as a combination of moment resisting frames and eccentric braces applied on two bays in X direction and one bay in Y direction. The slab system of the building is composite slab formed by arched steel shell and reinforced concrete. The foundation of the building contains the piles and single footings connected by link beams. Fig. 2 illustrates the buildings' structural carrying system with the used terminology through this study.

From the left hand side, the structural system of Building-B is completely separated from Building-A, but there is a passage aisle between them. The structural system of this aisle is connected to Building-A. From the right hand side Building-B has no connection.

In order to monitor the variation of the dynamic properties of the constructed steel building vibration measurements are taken during its construction. One two-directional accelerometer, containing Colibrys type sensor was located on the third story to collect vibration data. The linear full acceleration range of each sensor is ± 3 g and its noise level is 0.3 μgrms/√Hz. Accelerations were measured with 200 data per second and for each set 30 minutes records were taken.

The obtained measurements were analyzed by using Matlab computer program (2012). Basically the frequency domain representation for each measurement was obtained with "fft" function of the software. The data was analyzed as a whole without windowing. The number of discrete Fourier transform point was specified according to the length of data and it is 2^{18} = 262144. Thereby dominant frequencies and their power were revealed. No filtering was applied to to the data. Presentation of the frequency domain analyses between 0 and 15 Hz is deemed to be adequate for the intended purpose.

Fig. 1 View of the building complex of Istanbul Medeniyet University

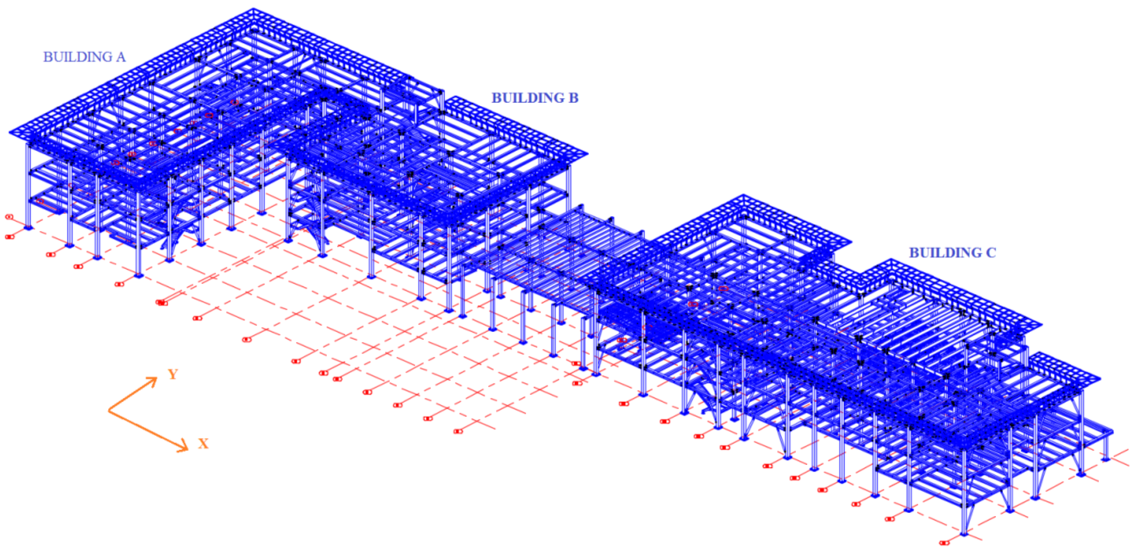


Fig. 2 Structural system of the buildings and used terminology

Fig. 3 Details of the separation, construction joint (A, B: View of the separation during the construction, C: view of the separation in the building in use)

3. Vibration analyses on different construction stages

Construction stages of a steel building can be summarized as the erection of the column and beam elements, addition of braces, tightening the bolts, forming the slab system and addition of the partition walls and other finishing, including HVAC (Heating, Ventilating and air conditioning) and communication cables. Although it seems that stages are successive in the construction site, when a higher construction speed is required, they can be accomplished together in order to use the available sources effectively, as in the studied building's construction. Hence, some structural works increasing the modal frequencies and some others decreasing them are performed together. For this reason, in this study, the author defined the construction stages in detail.

Secondly, the prediction of the dynamic parameters by operational modal analysis is very difficult and may be misleading for an uncompleted structure because the boundary conditions cannot be visualized. Therefore, the author preferred to compare the first dominant frequencies in each direction instead of interpreting other frequencies.

Finally, the temperature is shown as a parameter affecting the vibration frequency (Saisi *et al*. 2015). However its effect is limited on the vibration frequencies, compared to those caused by main structural alterations. For this reason, the effect of temperature was neglected in this study. Within the explained basis five different construction stages with the performed vibration surveys are explained as shown.

3.1 Vibration analysis on the first stage

The first vibration measurements were performed on 27.02.2015. The columns and the beams including slab girders of the building were erected except a few beams. However, the bolts on the connections were not tightened yet. Even there were no bolts on the most of the joints. There was no bracing in the structural system yet. Fig. 4 shows the building on the first stage with the location of measurement. Note that a few beams were still missing including the one connected to the measurement point in X direction.

The accelerometer was placed by using a crane basket. During the measurements the other constructional works were in progress but there were no significant force or vibration effect on the building except the wind and motor way traffic. Fig. 5 shows the FFT of the signals. Many peaks on the FFT spectrums in X and Y directions were detected. This shows that the location of the measurement is vibrating independent from the other members. The first peak in X direction was identified on 1.35 Hz while it was on 1.1 Hz in Y direction.

Fig. 4 The building on the first stage (A: general view, B: connection detail, C: accelerometer in the measurement)

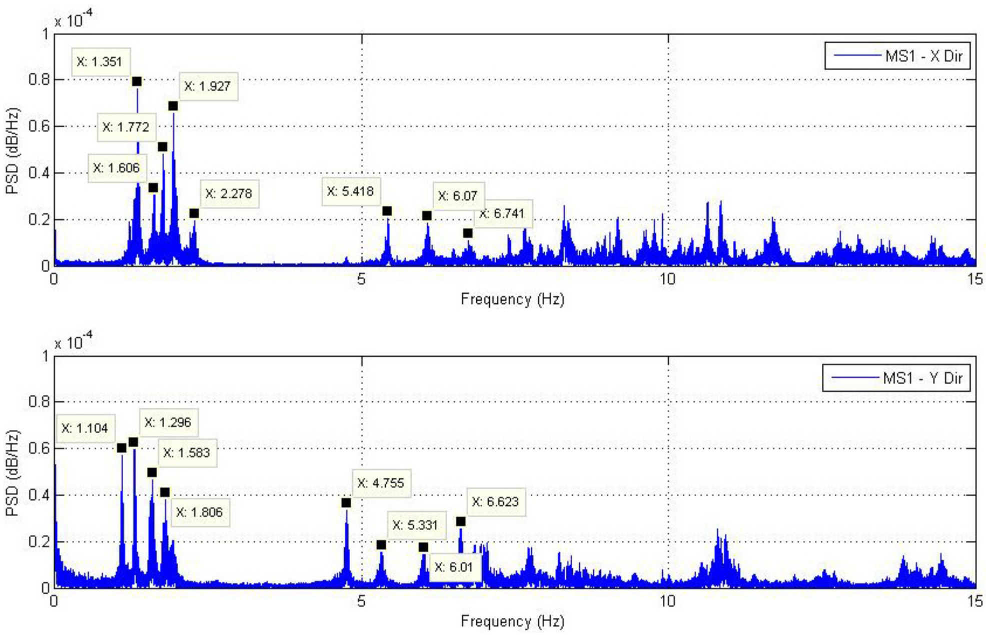


Fig. 5 Dominant frequencies in X and Y directions for the first stage

3.2 Vibration analysis on the second stage

The second vibration measurements were performed on 03.04.2015. In addition to the first stage of the construction, the torqueing of the column-beam joints were completed, braces on a bay in X direction were placed without torqueing. The plates of composite slabs on the first and second floors were placed. Fig. 6 shows the building on the second stage.

Fig. 7 shows the FFT of the signals taken on this stage. The first peak in X direction is seen on 1.71 Hz showing the increased rigidity. In Y direction the first dominant frequency is increased to 1.89 Hz. The increase in the frequency is obviously the result of torqueing of the bolts in the joints.

Fig. 6 The building on the second stage (A: general view, B: braces, C: accelerometer in the measurement)

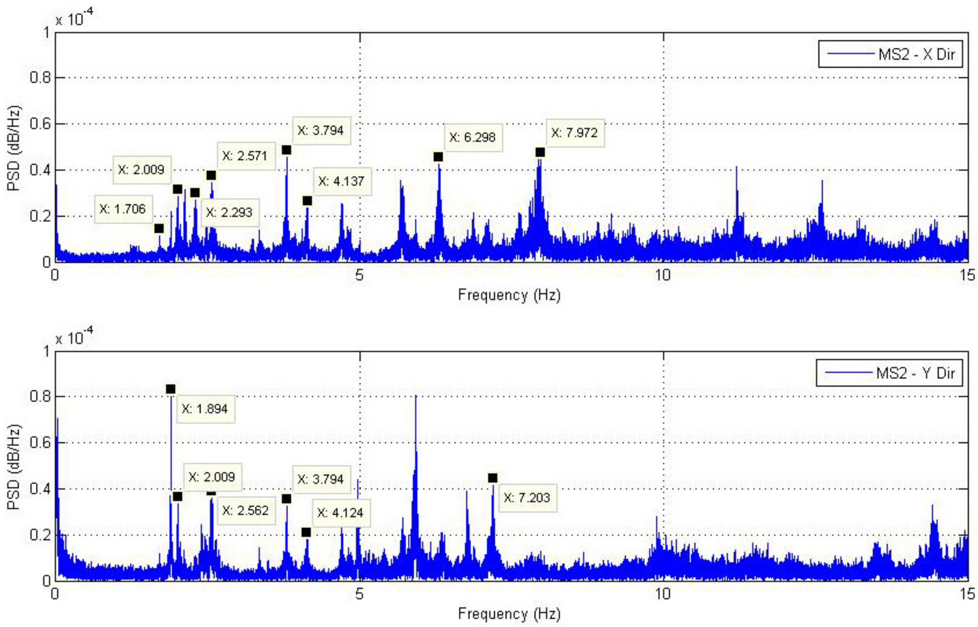


Fig. 7 Dominant frequencies in X and Y directions for the second stage

3.3 Vibration analysis on the third stage

The third measurement was taken on 13.04.2015. All structural elements were placed. Only the torqueing the bolts of braces in Y direction were not done yet. Composite slabs of the building were also completed. Fig. 8 shows the details in the building on the fifth stage.

Fig. 9 shows the FFT of the measured vibrations. The dominant frequency in X and Y directions are determined around 1.51 Hz. The obtained frequencies are less than those on the second stage. Formation of the composite slabs increases the structural mass and decreases the

Fig. 8 The building on the third stage (A: general view, B: accelerometer in the measurement, C: completed concreting of the top floor)

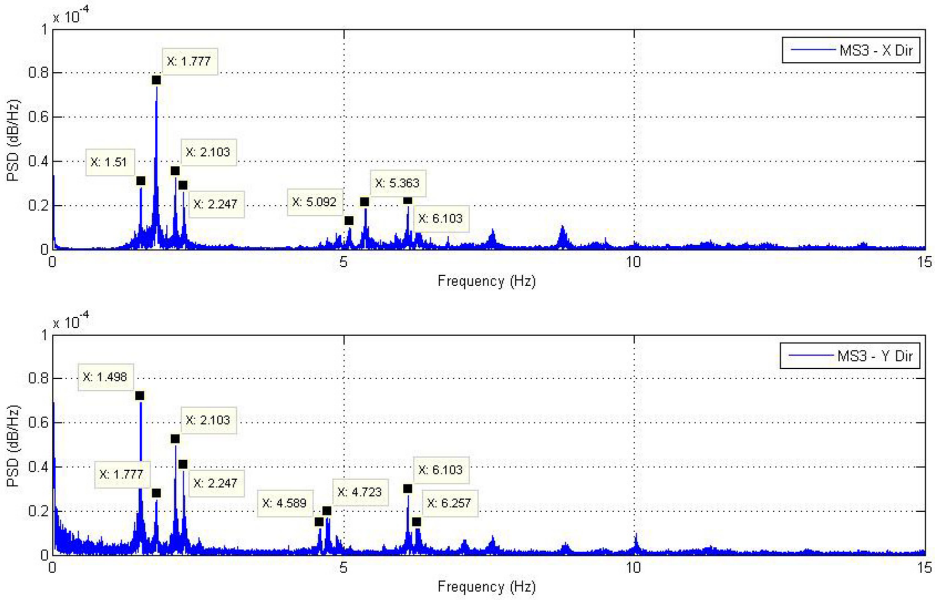


Fig. 9 Dominant frequencies in X and Y directions for the third stage

vibration frequency as compared to the building on the second stage. The further dominant frequencies in each direction have the same values with different power magnitudes. This shows that in this stage the building general behavior is torsional.

3.4 Vibration analysis on the fourth stage

The fourth measurement was taken on 05.05.2015. In this stage the torqueing of the braces was completed. The steel frames of the partition walls and the masonry walls were also formed

Fig. 10 The building on the fourth stage (A: composite slab after concrete pouring, B: accelerometer in the measurement, C: braces in Y and X directions on the ground floor)

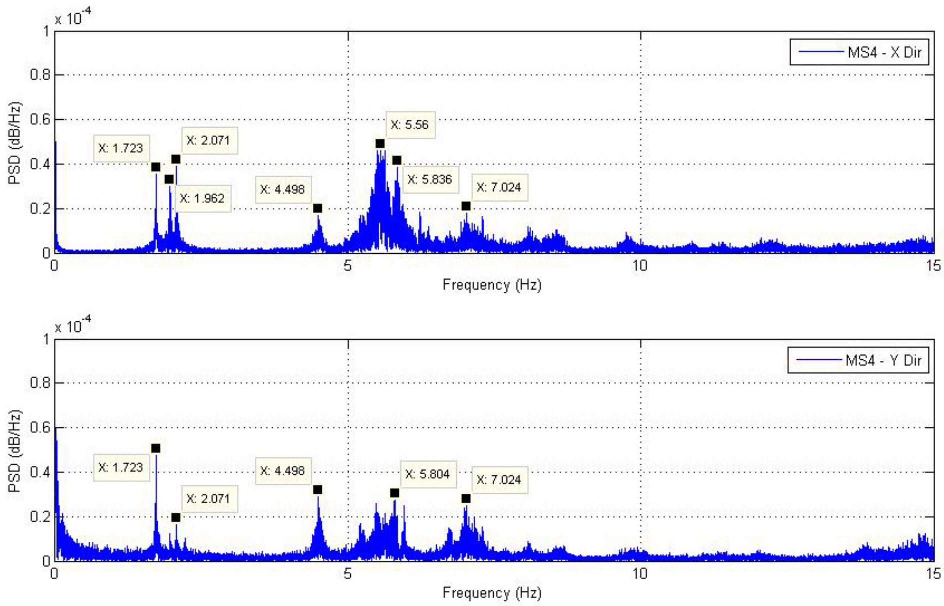


Fig. 11 Dominant frequencies in X and Y directions for the fourth stage

completely. Fig. 10 shows the details in the building on the fourth stage.

Fig. 11 shows the FFT of the measured vibrations. The obtained frequencies are more than those on the third stage showing the stiffness increase in both directions (1.72 Hz in both directions) as a result of brace activation by torqueing.

3.5 Vibration analysis on the fifth stage

The fifth measurement was taken on 18.03.2016 when the building had been in use for seven months as an academic center. Fig. 12 shows the completed building.

Fig. 13 shows the FFT of the measured vibrations taken from the same location shown on the previous stages on the third floor of the building. Two mutual frequencies in both directions are

Fig. 12 Building is in use on 18.03.2016

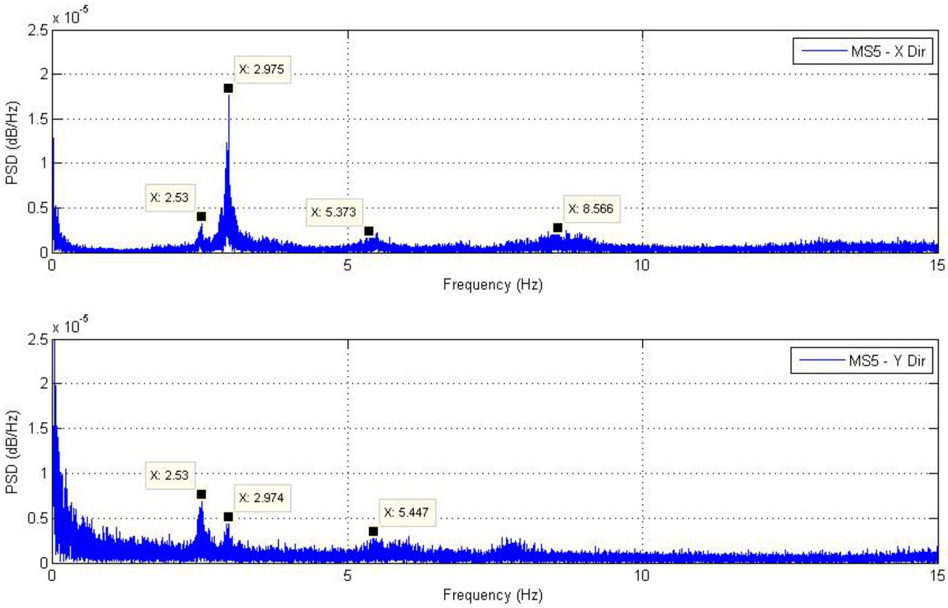


Fig. 13 Dominant frequencies in X and Y directions for the fifth stage

identified and these mutual frequencies indicate that the building's first two modes govern the torsional behavior.

The structural carrying system of the building is not symmetrical in both directions due to bracings. For this reason torsional modes can be expected. At this point, numerical analysis is helpful to see the effects of unsymmetrical brace configuration in torsional behavior.

4. Numerical model of the building and dynamic analysis

Numerical dynamic analysis of the building is performed with the finite element model of the building, constructed in the design stage with SAP2000 computer package. Frame elements are used for the structural columns, beams, girder and braces whereas shell elements are used for the composite slab system. Fig. 14 shows the constructed numerical model of the building.

Eigen value analysis is performed. Table 1 shows the dynamic properties of the building. Some of the modes are formed by movement of individual elements in which global dynamic behavior cannot be presented. As a result, the mass participation of these modes is very small (Mode 4, 5 etc). It is seen that, after nine modes 96% of the total mass is accounted. The first three modes of the building represent the global behavior of the building. The first mode is obtained as the movement of the building in Y direction (1.36 Hz). The second mode is the movement of the building in X direction (1.54 Hz) and the third mode is a pure torsion (1.81 Hz). The further four modes with smaller mass participation values represent the partial movement of slab hangovers and they are not important for the overall structural behavior. Finally modes 8 and 9 represent important dynamic modes with active masses. Fig. 15 shows the first three and ninth mode of the building.

Comparison of the experimental and numerical modes shows that the numerical model estimates the modal frequencies with smaller values of frequency for all modes. Moreover determined mode shapes are not consistent with the experimentally estimated results. In that respect the difference on the between the experimental and numerical findings should be evaluated.

Lower frequencies, estimated by numerical analysis are the effects of under estimated stiffness and overestimated mass values due to the well-known relationship specified in Eq. (1). A numerical model of a building, constructed for design, has some discrepancies from constructed real building stemming from, assumption, simplification and idealization. Related to this study,

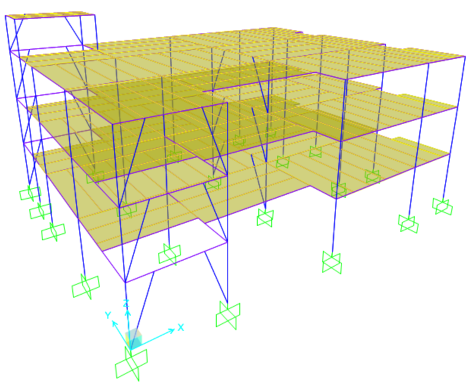
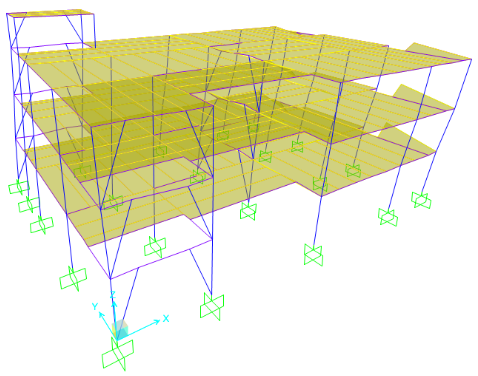


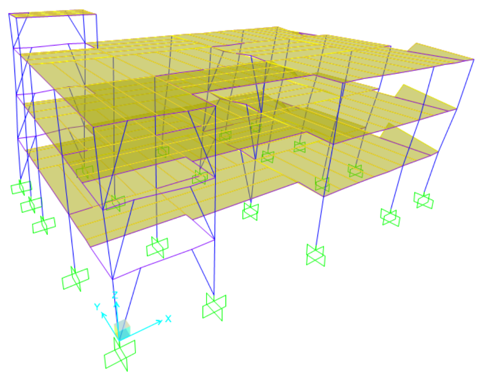
Fig. 14 Numerical model of the building

Table 1 Numerically obtained modal frequencies and mass participations

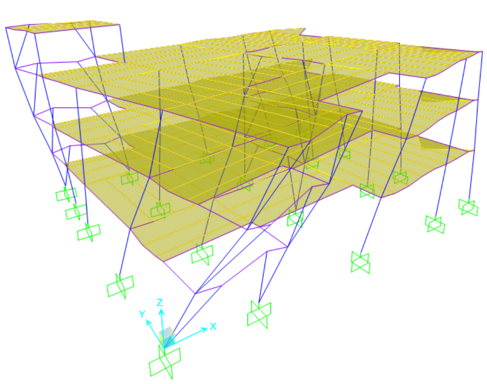
Mode	Frequency	Period	Mass participation		Sum of mass participation	
	Hz	Sec	X	Y	X	Y
1	1.361	0.735	0.001	0.718	0.001	0.718
2	1.545	0.647	0.857	0.003	0.859	0.721
3	1.809	0.553	0.003	0.125	0.861	0.846
4	4.230	0.236	0.000	0.013	0.861	0.859
5	4.337	0.231	0.000	0.000	0.861	0.859
6	4.337	0.231	0.000	0.004	0.861	0.864
7	4.420	0.226	0.000	0.000	0.861	0.864
8	4.664	0.214	0.000	0.089	0.862	0.953
9	5.078	0.197	0.108	0.001	0.969	0.954
10	5.451	0.183	0.000	0.000	0.969	0.954
11	5.457	0.183	0.000	0.000	0.970	0.954
12	5.982	0.167	0.000	0.011	0.970	0.965



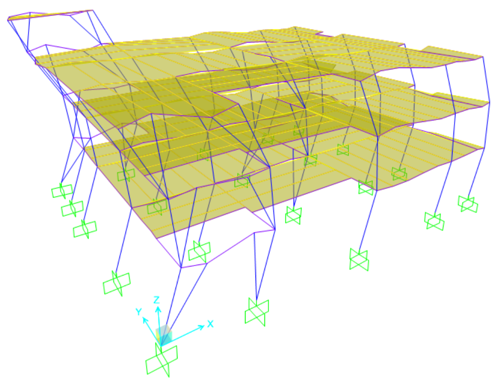
(a) Mode 1: Movement in Y direction



(b) Mode 2: Movement in X direction



(c) Mode 3: Torsional mode



(d) Mode 9: Movement in X direction

Fig. 15 Numerically obtained mode shapes one of the most important parameters which the numerical model does not contain is the stiffness effects of partition walls in the building. Since the numerical model does not include the partition wall it underestimates the stiffness of the building. As a result, it gives lower modal frequencies than those in real building, determined experimentally.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{1}$$

Another issue is about the design load values assigned into the numerical models. Design loads should always be such great values that the structure should not be exposed to them. In that respect, the existing loading is less than that in numerical model. In other words, the overestimated loading, such as self-weight and live load cause an increase in mass and thereby underestimate the frequency of the building.

The experimentally obtained torsional behavior is the second real phenomenon that estimated wrongly by the numerical model. A parameter exist in the real construction but is not accounted in numerical model can cause the mode shape difference between the experimental and numerical survey. The most important fact about the real building may be the Building-A which adjoins the studied building from its left hand side. Although these two building are separated structurally, the aisle between them can provide a connection between them and in low level vibrations these two buildings can affect each other. In a previously completed study, Morassi and Polentarutti (2011) have been faced with the similar disagreement between the experimental and numerical dynamic properties of two seven-story buildings which are separated by 20 cm seismic joint. Their analyses revealed the coupling of two buildings through the seismic joints. In that respect, the next stage is devoted to the investigation of the coupling between Building-A and Building-B.

5. Investigation of effects of Building-A on the dynamic behavior of Building-B

Structural effects of Building-A on Building-B is investigated by vibration analysis again. Vibration measurements were taken on 25.03.2016, from three locations shown in Fig. 16. As it is seen, Point-a is located on Building-A, Point-b is located in Building-B and Point-c is on the aisle between Building-A and Building-B. As can be seen in Fig. 3 –B, the aisle is structurally separated from Building-B and connected to Building-A.

Fig. 17 shows the FFT presentation of the records taken from three points shown in Fig. 16. Careful look on the determined dominant frequencies reveals that in X direction points a, b and c have the same values while in Y direction they are close to each other. The aisle connects two buildings in X direction for this reason definitely it supplies a better connection effect along with this direction. This means that structurally separated aisle is somehow connected to the Building-B.

Estimation of the dynamic properties of a building correctly in design stage is important since the seismic loads are dependent on these properties. The concept of response spectra, which many seismic design codes uses to estimate the design loads, can show the relation between the period of the building and target spectral acceleration. Obviously, wrongly determined modal frequencies or periods can cause serious deficiencies. The studied building was designed according to Turkish Earthquake Code (2007) by using the response spectra specified according to seismic region and soil conditions (Fig. 18). The numerically determined modal frequencies of the building (1.36 Hz – 1.81 Hz) show that the effective spectrum coefficient which is related to the spectral acceleration was derived from the flat plateau of the response spectrum which is in between 0.2 second and 0.9 second (5 Hz – 1.1 Hz). When the real modal frequencies (2.5 Hz – 3 Hz), derived from operational modal analysis are interpreted with the response spectra, it is seen that, the spectrum coefficient is again coincide the flat plateau of the response spectrum. As a result, it can be concluded that due to the wide flat plateau of the response spectrum used in the design stage, wrongly estimated dynamic frequencies do not cause a change in the design spectral acceleration for the studied building. Minor increases can be expected in the design internal forces of the structural members due to the torsional behavior of the building but they were not investigated since a detailed safety assessment is out of the concern of the presented study.

Fig. 16 Measurement points to investigate the building interaction

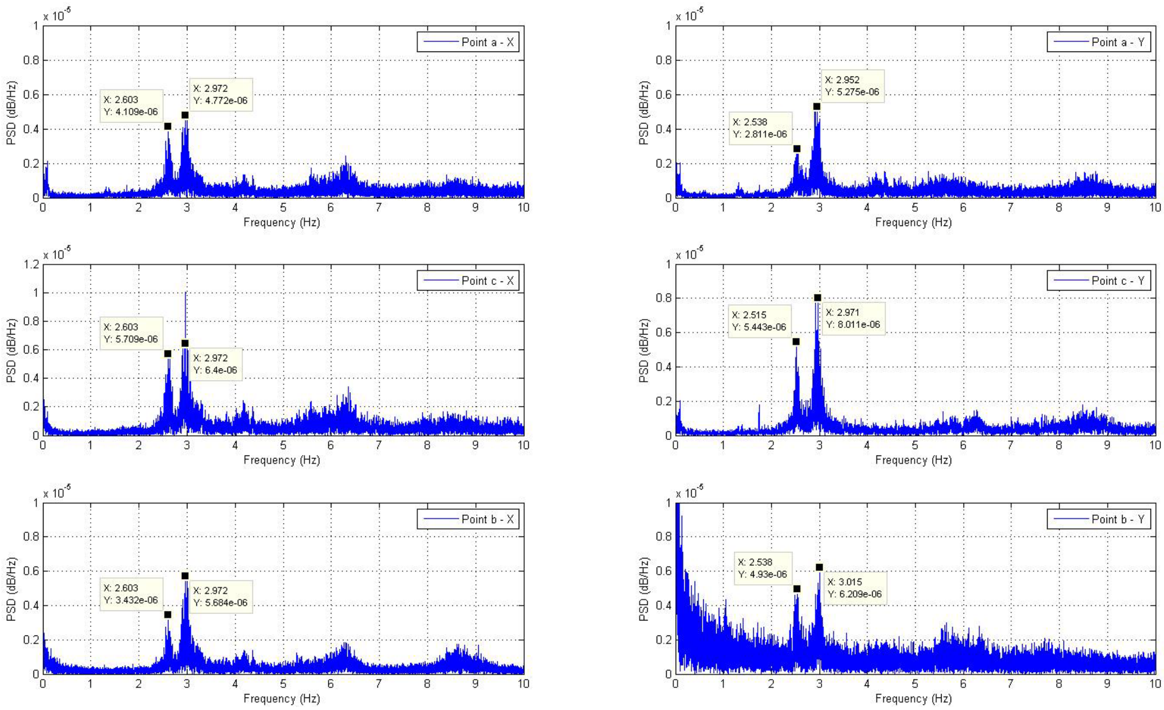


Fig. 17 Dominant frequencies on point a, b, and c in X and Y directions

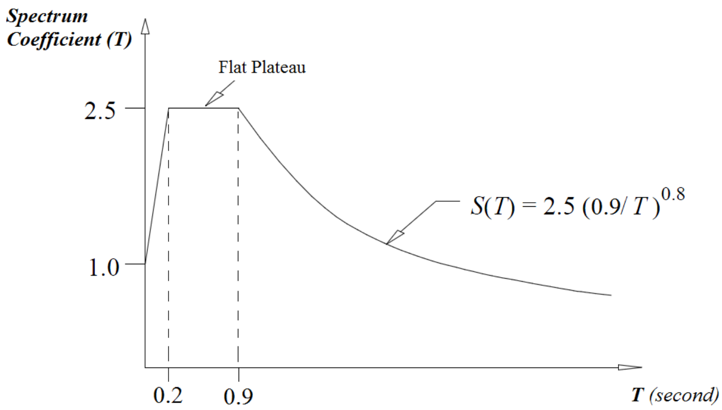


Fig. 18 Response Spectra, used in the design of the studied building

6. Conclusions

In this study, simple vibration analyses have been applied to a steel building during its construction period to monitor the variation of its dynamic properties. Evaluation of dominant frequencies determined in five different construction stages revealed that:

- In the first stage, i.e., columns and beams are erected without torqueing many peaks on the FFT spectrum have been determined showing the independent vibration of the measurement point.
- Second stage measurements indicated the frequency increase, thus, stiffness increase due to torqueing of the bolts in connections.
- In the third stage, formation of rigid floor systems in every story provided the general building behavior. Mutual frequencies in X and Y direction are the sign of torsional behavior.
- As the result of braces completion stiffness increase were observed in both directions. The mutual frequencies in X and Y direction are the sign of torsional modes in the building.
- Dynamic analysis performed on the completed building has given the first two subsequent modes of the building as torsional modes with 2.53 Hz and 2.97 Hz frequencies.

Numerical analysis has been performed with mathematical model of the building constructed in SAP2000. Eigen value analysis showed that:

- The first mod is the simple movement mode in Y direction with a frequency of 1.36 Hz, the second mode is the simple movement mode in X direction with a frequency of 1.54 Hz and the third mode is the torsional mode with a frequency of 1.81 Hz.
- Total participating mass with these three modes is about 85% of the total mass.
- The effects of the wrongly estimated modal frequencies on the seismic safety of the building were also discussed. It was concluded that, since the both numerically and experimentally obtained modal frequencies are on the flat plateau of the response spectra, the spectral accelerations does not change. In that respect, the wrongly estimated modal frequencies did not cause a seismic safety problem for the studied building.
- The difference between the numerically and experimentally obtained frequencies forced to

judge the existing condition of the building and to investigate the reason of torsional behavior.

Higher frequencies obtained from the experimental analysis are most probably the effect of partition walls exist in the real building but not included into the numerical model. Secondly the loads, accounted for design purposes are always more than the existing values and overvalues in loads in the numerical model can also decrease numerically obtained frequencies. The adjoining building (Building-A) to the studied building (Building-B) is seen as the most suspicious reason for the torsional behavior although a structural separation was used between two buildings. Vibration measurements were taken from two buildings and the aisle connecting them. It is seen that:

- Dominant frequencies of Building-A, Building-B and aisle are the same in X direction which is the aisle direction.
- Dominant frequencies of Building-A, Building-B and aisle are almost the same in Y direction.
- Finally it is concluded that, Building-A has altered the mode shapes of Building-B completely in spite of the separation line.

Acknowledgments

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