Structural Health Monitoring of High-Rise Structure Using Different Dynamic Properties

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Abstract: In this study, while monitoring the structural health of a tall building, it covers and exemplifies how sensor placements should be, updating the digital model, continuous tracking, and event-based tracking. Pre-engineering of the structure was carried out, and the system was analyzed with ground accelerations at different levels. According to the results of this analysis, by giving priority to the floors where the stiffness changes are experienced, sensors were placed on the floors determined, and on-site readings were done. With the data taken from the accelerometers, the structure was followed continuously, and the trend lines of the structure were determined. The behavior of the building was observed under single events, and it was checked whether the trigger levels given for the structure were exceeded with a sample earthquake. The performance of a high structure created in the model was determined under possible earthquake records. In light of the actual acceleration records obtained thanks to the accelerometers placed in this building, the structure was constantly monitored, the structure behavior under the influence of the earthquake was recorded, and the dynamic properties of the building were realistically reported.

1 INTRODUCTION

It is known that our country is on an active seismic belt and is always at risk considering its building stock. This situation shows the necessity of determining the performances of the structures and building them according to these performances. The Turkish Building Earthquake Regulation, which entered into force in 2018, made it necessary to design according to the implementation of the structures. It is essential to examine whether the structure behaves as designed under the influence of different forces and to conduct engineering studies of the structure according to the determinations made.

Structures are exposed to various ambient vibrations and effects such as temperature, strong wind, heavy rains, and strong ground motion. A building health monitoring system is used to gather information about worn-out structures and to understand their behavior. With the help of sensors placed on buildings in the building health monitoring system, vibrations monitored in real-time and numerical quantities such as acceleration, velocity, and displacement can be obtained. If the data is used, it is possible to determine the damage conditions and control whether the trigger levels given for the structure are exceeded. Based on the physical change values recorded by pre-engineering studies, interpretations can be made about the mechanical behavior of the structure.

Many researchers have studied building a health monitoring system for a long time. Considering the studies on structural health monitoring, analytical studies on existing structures and experimental studies on shaking tables appear. 21st century The developments in structural health monitoring and technology in the early days caused significant progress in both the number and content of real-world applications related to structural health monitoring

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and brought laboratories to the real world (Tekdemir, 2020).

Kırkpınar (2010) monitored a twenty-six-story high-rise built with a core shear wall system in Istanbul with sixteen accelerometers and obtained the natural oscillation frequencies and mode shapes of the structure by system diagnostic method. The real-time data obtained were compared with the finite element model results, and time-history analyses were performed under the earthquake records. The finite element model update applied based on the mode values defined in this study has played a significant role in determining the earthquake load demand on the building.

The data obtained from the shaking table tests carried out with earthquake recorders were analyzed using definition methods in the time and frequency domain. Results were obtained in practical application (Alçık & Beyen, 2015). In the experiment, accelerometers were placed on the model at floor levels, and various filters were applied to the vibration data obtained.

When the numerical analysis results were compared with the model, it was seen that the experimental data were consistent (Durgun, 2013). Thirty-six accelerometers were used to monitor the vibrations of the cast-reinforced Green Building located on the Massachusetts Institute of Technology campus and to measure the building's translational, torsion, and vertical responses. Comparisons were made between seven field measurement data sets taken from the building. This building has an identifiable soil-structure interaction behavior, and the ground motion had significant effects on the building response (Sun & Büyüköztürk, 2017).

2 MODEL BUILDING AND METHODOLOGY

2.1 High-Rise Building Model

Within the scope of the article, a forty-four-story high building with an eleven-floor basement and thirty-three floors above ground is examined. The structure studied has a total height of 190.67 m, Figure 1.

2.2 Dynamic Behavior of the Building with Pre-Engineering Studies

It is expected that the structure will be damaged at various levels as a result of earthquakes. The structural health monitoring system is more concerned with the level of damage to the building than the data it will provide on whether the damage limits have been exceeded. In structural health monitoring systems, it is necessary to monitor the vibrations occurring in the structure in order to be able to interpret what levels the structure reaches in the region up to its elastic limits.

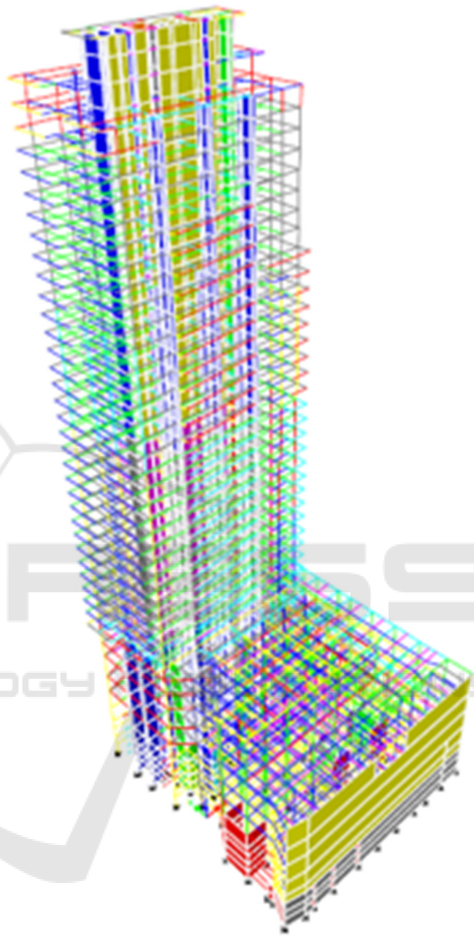

Figure 1: High-rise Building Model.

In this article, elastic analysis was performed by simulating a single component of the Kobe earthquake to the design spectrum at seven different levels, from the earthquake level, which is very difficult to be felt by people, to a certain percentage of the design earthquake, in order to express the ground movements at various levels, all of which, except the design earthquake, are expected elastic behavior in terms of the structure.

By using the scaling method in the frequency domain, it is possible to obtain records that broadly match the design spectrum (Özdemir, Fahjan. 2007). By scaling the 0.32 g acceleration level frequency domain using the original earthquake record of the Kobe earthquake, the acceleration spectrum for this acceleration record and the design spectrum for the 0.32 g acceleration level according to TBDY 2018 was created (Figure 2, Figure 3)

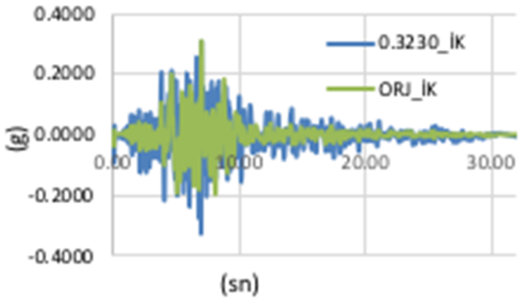

Figure 2: Original and scaled earthquake recording for 0.32 g acceleration level.

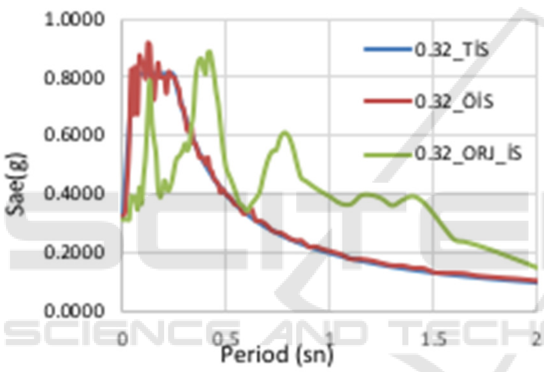

Figure 3: Original acceleration spectrum, scaled acceleration spectrum, and design acceleration spectrum for 0.32 g acceleration level.

The general characteristics of the structure can be determined from small ground movements where it is not damaged at all to large ground movements where it is heavily damaged. For this reason, target-based spectra were created considering different acceleration levels. These spectra were designated as trigger levels, and each was scaled similarly. The acceleration spectra generated are given in Figure 4. The acceleration-time graphs created for acceleration levels other than the original acceleration level are shown in Figure 5.

The displacement values found by the analyzes for different acceleration levels are given in Figure 6 and Figure 7. When these data are examined, gradually decreasing displacement values for all floors have been obtained from the analyses made for different acceleration levels from 0.1 g acceleration level to 0.0005 g acceleration level.

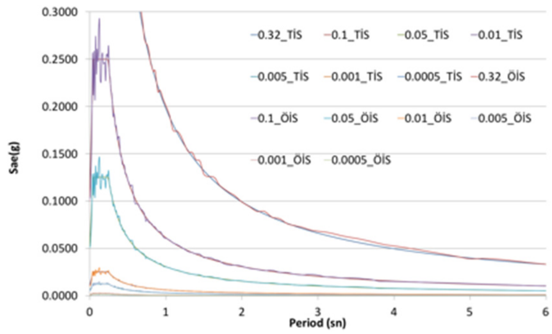

Figure 4: All scaled acceleration and design spectra.

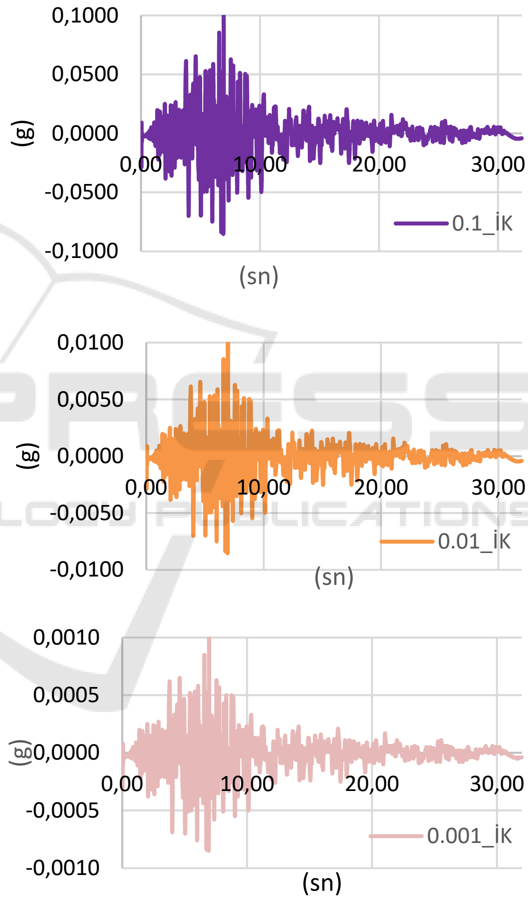

Figure 5: Scaled acceleration records.

In Figure 8 and Figure 9, acceleration values read at all building floors for different acceleration levels are given. For all acceleration levels, increasing acceleration values are seen from the foundation to the top of the structure.

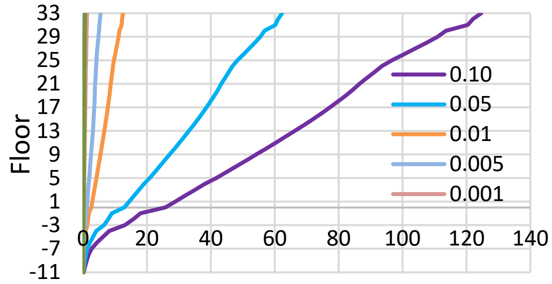

Figure 6: Floor displacements in the x-direction.

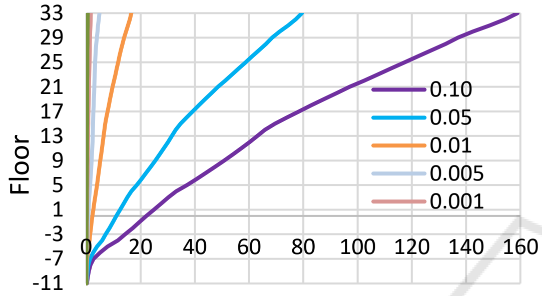

Figure 7: Floor displacements in the y-direction.

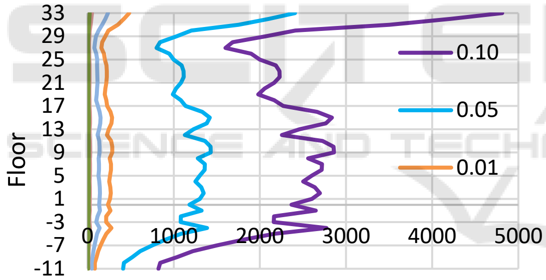

Figure 8: Acceleration in x-direction.

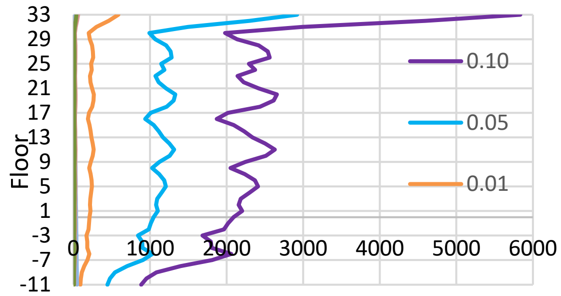

Figure 9: Acceleration in y-direction.

As a result of the analysis, the relative story drift graphs of the building are presented in Figure 10 and Figure 11. In these graphs, it is seen that there are severe changes in some floors along the height of the building. It is observed that the floors where these value accumulations are experienced are the regions where the ductile frame system consisting of columns and beams undergoes profound rigidity changes. The mass stiffness, wall thicknesses, or plan dimensions change.

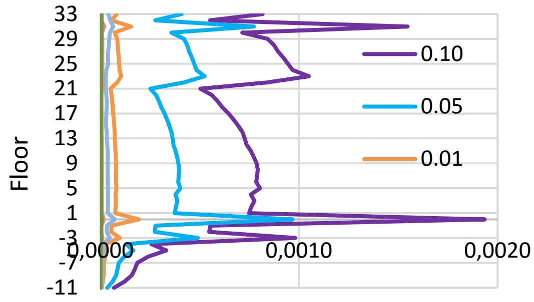

Figure 10: Drift ratios (mm) in the x-direction.

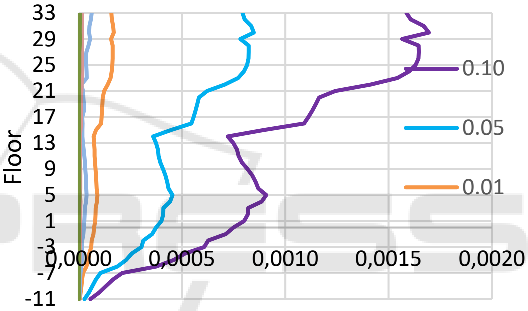

Figure 11: Drift ratios (mm) in the y-direction.

3 STRUCTURE SENSOR LAYOUT

The building health monitoring system, which provides data on the building, shows the changes and ensures that the damage detection methods are applicable and the technical characteristics of the related hardware. The excellent planning of its placement in the building provides reliable data from the system.

Modern design and manufacturing regulations have made it mandatory to place and properly monitor this equipment for some particular building types. For this reason, in parallel with TBDY 2018, the Structural Health Monitoring System Directive (YSIS Directive 2019) was prepared and put into effect for the establishment, maintenance, continuous monitoring, and reporting of structural health monitoring systems for buildings classified as high-rise buildings and defined by their unique conditions.

In buildings that are planned to be continuously monitored in real-time, firstly performing numerical analysis for the placement of the hardware and considering the floors where there are changes in the height of the building, which can be considered necessary in terms of building dynamics, as intermediate monitoring zones ensure healthy monitoring of the building (Çelik, Taşkın, Peker and Güneş, 2019).

The correct placement of sensors is related to the parameters to be measured and monitored. The parameters to be followed can be listed as translation modes in the horizontal x and y directions, torsion modes (around the vertical axis), rotations of the rigid structure around the foundation (around the x and y axis), vertex displacement, floor displacements, and interstory translation ratios. The displacements at the apex are critical for modal analysis due to their contribution to higher-order modes, so sensors must be placed on the structure's top floor. A uniaxial sensor should be placed at one point on the mezzanine floors where the critical stiffness changes. A biaxial accelerometer should be placed at a second point, leaving a specific opening. Accelerometers with vertical axis should be placed on the basement floor to follow the rigid structure's rotations around the foundation (Dinçer, Aydın, & Gencer, 2015).

With the analyses made as a result of preliminary engineering studies, It has been determined that the floors where there are severe changes in building dynamics along the building height are the floors where damage or possible disturbances can be seen. Considering Figure 10 and Figure 11 above, accelerometer placements were made on the floors where the stiffness changes and the value accumulations of the building are experienced. An example image of accelerometer placements is given in Figure 12.

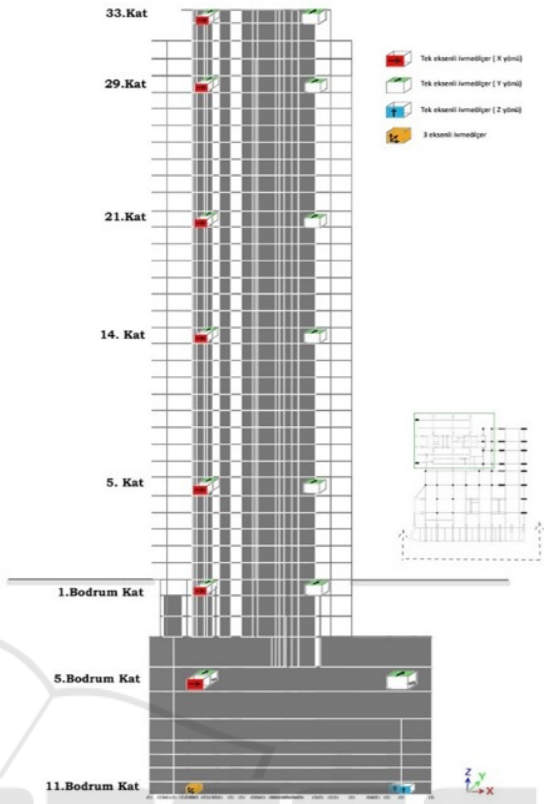

Figure 12: Locations of the sensors.

The vibration records taken from the structure are used for updating the model. The numerical model of the structure is arranged as closely as possible and the mass, stiffness, and damping values are updated most realistically by simulating many structure modes.

The structural stiffnesses and elasticity modules of this structure continued to shift until the results received from the numerical model and the values read on-site were in agreement with one another. By paying attention to the predominant frequencies, it was determined that it was adequate for the difference in value before and after the upgrade to fall within the percentage range of 5 to 10%. (Beyen, 2017). Table 1 presents the frequency values that were acquired following the update to the model and that were read on-site.

4 RESULTS

4.1 Model Update with Recorded Acceleration Data

The model update process integrates the results obtained by the correct definition of the building behavior with the data obtained from the field most consistently. While updating the structure, the reference behavior data, the correct selection of the parameters to be updated, and the model calibration process affect the resulting model.

Table 1: Model frequencies (Hz) read in situ and after the model update.

Modes	In-situ Records	After Update	Difference
1st Mode	0.354	0.338	%4.50
2nd Mode	0.354	0.341	%3.67
3rd Mode	0.488	0.446	%8.60

4.2 Build Trend, Trigger Level, and Reporting in Continuous Events

Continuous monitoring is a method that covers the data obtained from the past to the present and estimates the data that can be obtained in the future. While the building's health is constantly monitored, reports on dynamic properties such as displacement, acceleration, and speed are made using the data taken at specific intervals.

While structural health is constantly monitored, changes in the dynamic properties of the structure and changes in damping values are followed. In the process, the trend line was created by following the frequency value changes of the structure. This trendline can have a horizontal or downward slope, and a downward-sloping trend line indicates wear in the structure. By estimating the change in that trend line and determining whether it is acceptable, it is possible to predict how long it will continue to follow the structure.

Since the building has no experience, it starts to experience seasonal changes and wear caused by people and equipment. With the increase in long-term use of the structure, its period becomes longer due to increased damping or mass.

The structure was analyzed according to its stiffness before wear, the section stiffness of the structure with the model updated, and the cracked section stiffnesses according to TEC 2018, and the structure modes were obtained. As a result of the analyzes made, the frequency values of the structure are given in Table 2, Table 3, and Table 4 below.

Table 2: Model frequencies obtained before an earthquake.

Modes	Frequencies (Hz)
1st Mode	0.314
2nd Mode	0.388
3rd Mode	0.414

Table 3: Model Frequencies of the Structure After Update

Modes	Frequencies (Hz)
1st Mode	0.338
2nd Mode	0.341
3rd Mode	0.446

Table 4: Model Frequencies According to TEC 2018 Cracked Section Stiffness of the Structure

Modes	Frequencies (Hz)
1st Mode	0.185
2nd Mode	0.235
3rd Mode	0.240

Vibration recordings were taken every month from June 2017 to September 2020 for both the X and Y directions of the structure using accelerometers. The records taken formed a trend line in the process. The structure's frequency values and the modes' changes during the recording period were examined. It can be said that the structure behaves as predicted if the values read and monitored are within limits set. The trend may damage the frequency values' structure outside the determined limit values. For this reason, continuous monitoring is critical to determine the structure's trend in the coming years.

According to Figure 13, the first mode start frequency for our structure's X direction is 0.36, and according to Figure 14, the second mode start frequency for our structure's X direction is 0.50. Examining the frequencies of these two modes reveals that the structure is stable because the slope connecting the peaks of the value changes occurs at a level that is comparable to what is considered appropriate. Variations in temperature throughout the year and shifts in the building's mass are two potential contributors to shifts in frequency values.

Subsequently can be seen that the third Mode starting frequency for the X orientation of the structure is 1.92, and it can also be seen that a trend line with a downward slope is formed. Both of these observations can be found in Figure 15. Because the structure has not yet reached a conclusion regarding the third mode, the tendency should be adhered to.It can be seen in Figure 16 that the first mode start frequency for our construction in the Y direction is 0.36, and it can be seen in Figure 17 that the second mode start frequency for the Y direction is 0.53. When the fluctuations in the frequency values are taken into account, both the increases and the reductions in value are stable.

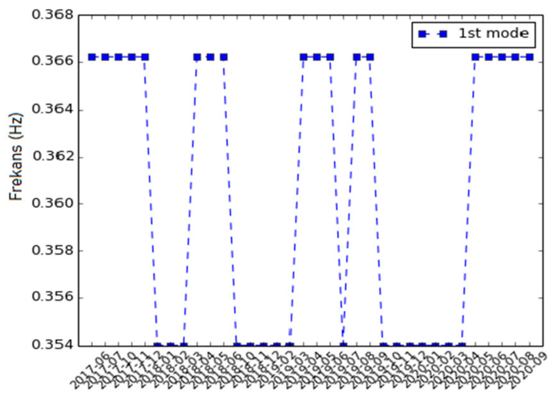

Figure 13: Structural Frequency Values Read to the X Direction Sensors for the first mode.

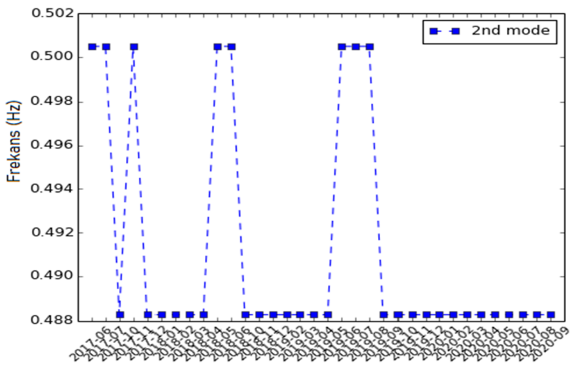

Figure 14: Structural Frequency Values Read to the X Direction Sensors for the 2nd Mode.

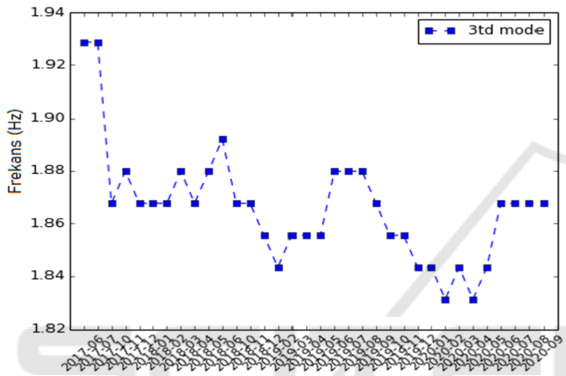

Figure15: Structural Frequency Values Read to the X Direction Sensors for the third mode.

Figure 18 illustrates that there has been a gradual decline over time in the third mode frequency for the Y orientation of the structure, with the slope falling between 1.56 and 1.50. The third phase of the build exhibits a moderately steep decline of 3% throughout its progression.

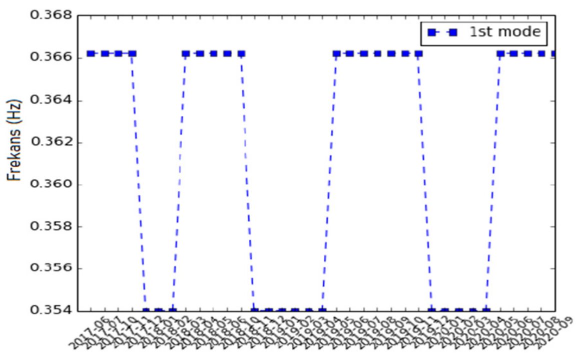

Figure 16: Structural Frequency Values Read to the Y Direction Sensors for the first mode.

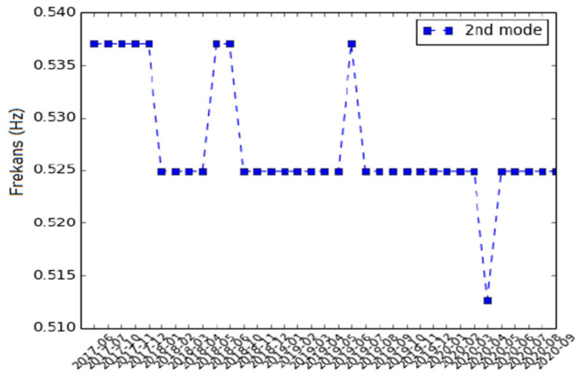

Figure 17: Structural Frequency Values Read to the Y Direction Sensors for the second mode.

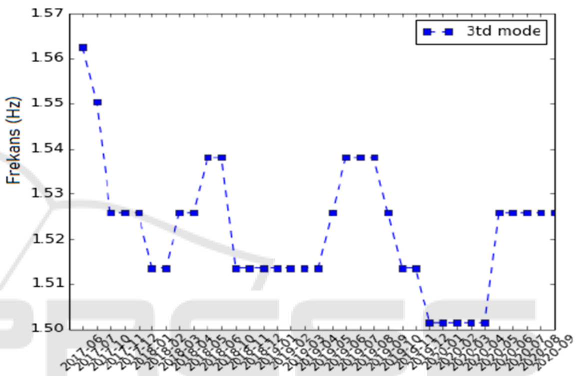

Figure 18: Structural Frequency Values Read to the Y Direction Sensors for the 3rd Mode.

5 CONCLUSIONS

In this study, pre-engineering studies of the structure were made, and numerical analyzes of the structure were made with ground accelerations at different levels. According to the results of this analysis, sensors were placed, and on-site readings were done by giving priority to floors where stiffness changes were experienced, wall thicknesses, or plan dimensions were changed. The structure was continuously monitored with the vibration data obtained from the accelerometers, and trend lines were determined. The changes in the frequency values of the building during the recording period were examined. It has been observed that the values read and monitored are within the limits set, and the structure behaves as predicted.

With the introduction of building health monitoring into TBDY 2018, the use of this system in the new building stock is expected to increase. As time passes, it will be possible to establish and implement the building health monitoring system in high-rise buildings and all low-rise and specialty buildings. Thus, it will be possible to evaluate the behavior of the building through numerical data and to have information about the damage status of the building.

The technical equipment needed for building health monitoring is being provided with lower costs with the help of technological developments. Suppose the preliminary engineering work of the building is carried out. In that case, it is possible to make comments that will not cause discussion, based on healthier data about the state of the building, with a minimum of building health monitoring sensors at the top and ground point.

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