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Effects of Vertical Irregularity at Upper Level of 5-Storey Laboratory Steel Tower Using Modal Analysis

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Abstract: Buildings with vertical irregularity at upper level often amaze people with its esthetical design and unique appearance. The increment of population and urbanization force the engineers to come out with safe and unique building designs occupied with its multi-functional spaces uses. However, irregular building design build up from complex dynamic behavior compared to regular buildings design. Therefore, a study was conducted to determine the effects of vertical irregularity at upper level of 5-storey laboratory steel tower using modal analysis via STAAD.Pro software. The dynamic characteristics of steel tower was investigated in terms of predominant frequencies and mode shape. The results of bare frame (control tower) were compared to previous laboratory testing for verification purpose before implement the four cases of irregularity on the steel tower. The first three predominant frequencies of bare frame and irregular cases were arranged according to their modes. The frequencies of bare frame were f_1 and f_2 = 5.55Hz, and f_3 = 7.21Hz with percentage difference less than 10% from previous study. There were 3 type of mode shapes experienced by the steel tower which were translational for mode 1 and 2, and torsional for mode 3. Hence, vertical irregularities could be considered a risk for a building compared to regular building design.

Keywords: Vertical Irregular, Modal Analysis, Staad.Pro, Dynamic Characteristics

1. Introduction

Irregular structure design has either mass, stiffness, or geometric regularity which is not uniform all over the structure. Modern infrastructures often designed in different types of vertical irregularities. In developed countries and metropolitan cities, these structures are more important as they enhance the aesthetic nature and improve living conditions. These structures have become more complex from an architectural point of view, with irregular shapes, geometry, mass, stiffness, and vertical irregularities, etc.

Soft storey can be defined as an irregular building structure that was constructed according to architectural decisions for a certain function requirement. It is also known as weak storey [1]. The

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location of soft storey in a building could be various depends on the function such as leisure use, parking or merchant use. The soft first and last story are the examples of building irregularity.

Irregular structures translated like an inverted pendulum under substantial ground shaking for example footsteps, machineries, and wind that demand for ductility concentrated on the soft floor. As a consequence, these structures tend to have inadequate stability and are prone to damage. As gravity takes over, columns that experienced full axial gravity force drift without extra support which could result to the collapse of the building if the safety in designing been ignored [2].

Nowadays, vertical irregularity is a common design build for modern type of buildings. Many buildings were built with irregular configurations, and low stiffness structure in line as it functions such as office, apartment, hospital and factory. During an earthquake, irregular structures with vertical irregularities tends to experienced severe damage resulting from discontinuity in geometry, mass and stiffness. The ground motion could bring more damage to the building with irregular geometry. Behaviour of tall building was an important component to ensure efficient and secure building design [3]. Therefore, it was undeniable that study of dynamic characteristic of a building was very important in order to understand building behaviour under irregular structure arrangement. Modal analysis has become a common method for detecting the vibration modes for a machine or structure because each structure vibrates at its resonant frequency with high vibration amplitude. In order to improve its strength and reliability at the design stage, it was essential to study the modal analysis, such as frequency and mode shape characteristics of the structure in different operational circumstances [4]. Therefore, a modal analysis was conducted to study the dynamic characteristics of the irregular beam arrangements at upper level of a 5—storey steel tower using STAAD.Pro software. Four irregular arrangements on the steel frame were modelled for their predominant frequencies and mode shapes.

The objectives were to determine the dynamic characteristics of steel tower under multiple cases of vertical irregularity using modal analysis and to investigate the relationships between vertical irregularity and the parameters of dynamic characteristics such as frequency and mode shape.

The significances were to design the irregular steel tower using modal analysis for an alternative analysis method on the relationship between multiple cases of irregular steel tower and its dynamic characteristics. Besides that, it also could assess the dynamic characteristics of irregular steel tower at upper level based on their relationship on predominant frequency and mode shape.

2. Literature review

Previous study was conducted on a 10-storey building with two different irregularity by using an equivalent static method from IS 1893-part 1: 2002 [3]. Another research using CSI-ETABS program to study the damages resulted from different plan irregularities, during seismic actions of different scales in Mexico [5]. The researches were tabulated in Table 1.

Some of the elements in dynamic characteristics of buildings consist of frequency and mode shape. The dynamic characteristics can be used to determine the structure appearances by computing the analytical models to interpret the performance of the structure [6]. In addition, the reactions of building toward ambient excitations during drawing plan or re-evaluation period can be estimate by their frequency and mode shape patterns of the building [7]. Moreover, there was a study stated that frequency could gave impact in structural health monitoring techniques, which it could be used to identify the physical harms on buildings [8].

Each building has its own natural or also known as predominant frequencies. A single-story building have the natural periods at about 0.1 seconds, thus, if the building shake at 1 reciprocal, it is equivalent to 0.1 seconds = 10 Hertz, or 10 complete cycles [8]. Meanwhile, a building with four floors will contribute about 0.5 seconds time interval [9]. Table 2 shows previous studies on the predominant frequency of building by some researchers.

Table 1: Findings for the past studies of irregular building arrangements

<table>
<tr><th>Author</th><th>Methodology</th><th>Remarks</th></tr>
<tr><td>[3]</td><td>The analysis was analysed using the program CSI-ETABS. To study the effects of irregularities on the frames, the five frames were analysed and their lateral storey deflection, storey drifts and base shears were computed.
Irregularities considered two types:
Vertical irregularities (Stiffness, mass, geometry, discontinuity)
Plan irregularities (torsion, re-entrant corners, diaphragm discontinuity, out of plane offsets, non-parallel systems)</td><td>Frame carry heavy loading tends to suffer maximum deflection signifies it is the weakest and vulnerable</td></tr>
<tr><td>[5]</td><td>Different geometric building shapes in Mexico were modelled in SAP2000, taking one, two and four levels into account to determine the effect of the geometric shape on the seismic behaviour of elastic analysis structures.</td><td>Irregular models of rectangular, T, L and U plans were subjected to a ten characteristics accelerograms to get their elastic deflection. From this study, the more irregular the building, constructions became more vulnerable.</td></tr>
</table>

Table 2: Findings for the past studies of predominant frequency

<table>
<tr><th>Author</th><th>Methodology</th><th>Remarks</th></tr>
<tr><td>[10]</td><td>An eighteen-storey building with 200 mm thickness of shear wall was investigated to resist a tendency to fracture arising from lateral pressure. FDD methods were used in order to acquire singular values of the output response PSD matrix with frequency at a between 0 Hz until 10 Hz. The peak picking techniques utilized to determine frequency until the sixth order of frequency.</td><td>The natural frequency of the building was tabulated in table below.
<table><tr><th>Mode</th><th>Natural frequency (Hz)</th></tr><tr><td>1st</td><td>1.07</td></tr><tr><td>2nd</td><td>1.27</td></tr><tr><td>3rd</td><td>2.44</td></tr><tr><td>4th</td><td>4.98</td></tr><tr><td>5th</td><td>5.47</td></tr><tr><td>6th</td><td>8.30</td></tr></table></td></tr>
<tr><td>[11]</td><td>The full scale of two-floor levels reinforced concrete structure was used throughout the test with 5.3 m length on East-West orientation and 4.3 m length on North-South orientation.</td><td>Validation of frequency between ambient vibration test and force vibration test of the building were tabulated in table below.
<table><tr><th>Mode</th><th>F_v (Hz)</th><th>F_a (Hz)</th></tr><tr><td>1st BM (EW)</td><td>1.83</td><td>1.88</td></tr><tr><td>1st BM (NS)</td><td>2.20</td><td>2.15</td></tr><tr><td>1st TM</td><td>3.18</td><td>3.17</td></tr><tr><td>2nd BM (EW)</td><td>5.67</td><td>6.05</td></tr><tr><td>2nd BM (NS)</td><td>6.50</td><td>6.67</td></tr><tr><td>2nd TM</td><td>9.49</td><td>9.95</td></tr></table></td></tr>
</table>

Mode shapes were formed under certain frequency that was applied on the building. Mode shape of building known as the distortion of shape of building when it oscillates according to their predominant frequency. There are three types of mode shapes in every 3D building which are the motions of structure in X orientation, Y orientation and Z orientation known as torsion, as shown in Figure 1.

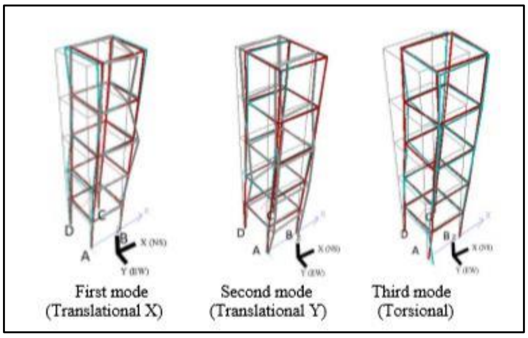


Figure 1: Mode shapes patterns: motions in X orientation, Y orientation and torsion [12].

3. Methodology

3.1 Phase 1: Steel tower detailing

The 5 storey of steel tower in the Jamilus Research Centre (JRC) laboratory, Universiti Tun Hussein Onn Malaysia (UTHM) was built under the Research Grant TIER 1 Phase 1/2017. The components of steel tower were in loose parts which able the user to assemble and dismantle the tower according to project guidelines. All elements (beams, columns and connections) were assembled into a 5-storey steel tower with four base connectors were placed fixed to the floor using four high tension bolts and nuts with diameter of 25mm. The spacing between connectors were 1000mm. The columns and beams were secured with 10mm diameter high tension bolts and nuts to grip the steel tower in position. The steel tower should be fixed in placed as Figure 2 below. In order to model the steel tower for modal analysis, all dimensions of the steel tower were identified to be used in STAAD.Pro software. The detailing needed for STAAD.Pro modelling work are as in

Table 3.

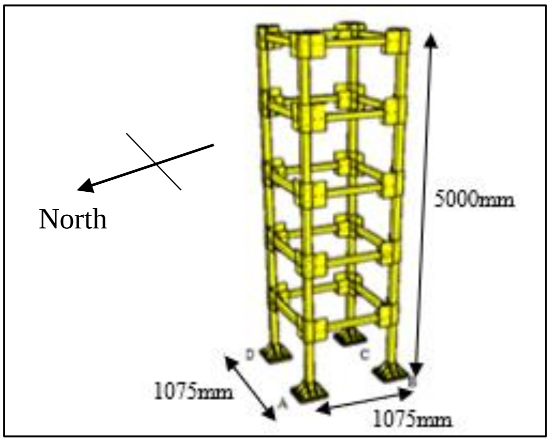


Figure 2: Moment resisting frame of a 5-storey steel tower in JRC

Table 3: Detailing needed for modal analysis [13]

No.		Element
1	Standard	BS EN 1993-1-8:2005 fy: 275×10^{-3} kN/mm^2 λ: 300×10^{-3} E: 205kN/mm^2
2	Beam and column	Square hollow sections (SHS) Steel grade S275 Length = 1000 mm B x H = 77 mm×77mm Thickness 3 mm
3	Connection	Steel grade S275 High tension bolt grade 8.8 with diameter 10mm and 25mm
4	Support	Fixed at base floor
5	Loading	Self weight

3.2 Phase 2: Modal analysis

The steel tower was designed in 3D view using STAAD.Pro software. Some try and errors were done until the output frequency reached the range of previous studies. By implementing this method, it is shown that the high percentage of moment release applied produced low percentage reduction in bending moment of beam. Thus, the percentage of moment release applied to the columns needed to be lower than the percentage apply to the beams. The percentage of moment release that applied in the steel tower was 80% for beam members and 28% for column members. The intermediate and top connectors were assigned with partial moment release to indicate semi-rigid condition at the start and end of every member.

To analyse the dynamic characteristics of steel tower model, the frequency results of bare steel tower model that was constructed in STAAD.Pro software was compared with frequency results from previous laboratory results that were conducted using accelerometer sensors and EFDD analysis. The output frequency results that was used for verification was from bare frame with regular design.

Result verification with previous laboratory testing using ambient vibration test method is essential to avoid errors during selection of predominant frequency of the steel tower. The previous laboratory testing was done by using a real bare frame steel tower located at JRC Laboratory and obtained frequency of the bare frame at f_1 = 5.24Hz, f_2 = 5.49Hz and f_3 = 7.23Hz. This verification was done by comparing predominant frequency value obtained from bare frame of STAAD.Pro modal analysis and previous laboratory tests [14-15] using accelerometer sensors.

The existing bare frame model was modified into four types of vertical irregularities at upper level. The results of frequency and mode shapes of bare frame was set as the reference value for initial design. Another four designs were the irregular beam arrangements at upper level on the five-storey steel tower as shown in Figure 3. The beams were removed one by one accordingly to create the irregular building configuration along with soft storey effect.

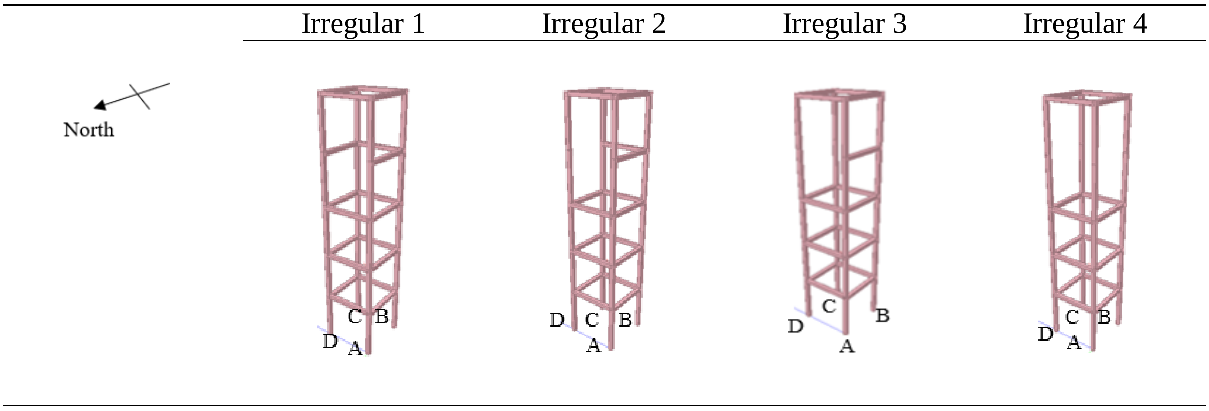


Figure 3: Four types of irregular steel tower conditions at upper level

3.3 Phase 3: Relationship between vertical irregularity and the parameters of dynamic characteristics

A 5-storey steel tower model in STAAD.Pro was analysed to simulate the soft storey effect with irregular beam arrangements at upper level. The model was used for determination of predominant frequency and mode shapes of the steel frame under multiple cases of vertical irregularity.

Predominant frequencies of irregular beam arrangements at upper level of steel tower can be determined from the frequencies of first three modes from each types of irregular steel tower. The predominant frequencies graphs were arranged according to type of trendline used for the best fit trendline. The relationship between irregularities cases and predominant frequencies of the steel tower were established using the percentage difference of frequency for bare frame and irregular cases that were calculated by using Equation 1 and Equation 2 below.

$$\begin{matrix} Percentage\ difference\ for \\ frequency\ of\ bare\ frame\ (\%) \end{matrix} = \frac{f_{modal\ analysis} - f_{laboratory\ testing}}{f_{laboratory\ testing}} \times 100\% \qquad \text{Eq. 1}$$

$$\begin{matrix} Percentage\ difference\ for \\ frequency\ of\ irregular\ cases\ (\%) \end{matrix} = \frac{f_{irregular\ cases} - f_{bare\ frame}}{f_{bare\ frame}} \times 100\% \qquad \text{Eq. 2}$$

STAAD.Pro software could perform 2D and 3D mode shapes in which according to deflection plane that was produced and find the specific trend or pattern between the variation on the bare frame and the vertical irregularities at upper level. There were three predominant mode shapes for irregular steel tower were generated from STAAD.Pro software where mode 1 and 2 experienced torsional mode while mode 3 experienced rotational mode.

4. Results and Discussion

The output results were obtained from modal analysis of 5 storey steel tower in JRC Laboratory, UTHM in term of its predominant frequency and mode shapes under multiple cases of vertical irregularity. The application of irregular cases in steel tower configurations able to change the predominant mode of frequencies. The relationship of irregular cases versus predominant frequency and relationship of irregular cases versus tower mode shapes were also discussed detail.

4.1 Predominant frequencies of bare frame and result verification

Result verification of predominant frequency from modal analysis method is vital to ensure the accuracy of data for the dynamic characteristics of the steel frame. This data verification was conducted by comparing predominant frequency value from modal analysis method and previous laboratory testing. The results of predominant frequencies were obtained from modal analysis by using STAAD.Pro software. The software produced three main modes where each mode had their own predominant frequency of the bare frame. The first three modes of predominant frequencies of steel bare tower were 5.55 Hz, 5.55 Hz, and 7.21 Hz. Two previous laboratory tests were selected to verify the predominant frequencies from modal analysis method. From previous studies, the frequencies data for control tower were the same where the first three predominant frequencies of bare frame (control tower) were at 5.24 Hz, 5.49 Hz and 7.23 Hz as tabulated in Table 4. These predominant frequencies were identified by placing accelerometer sensors at selected location on the steel tower and analysed by using ARTeMIS software.

The percentage difference of predominant frequencies from each type of mode were calculated for frequency data from modal analysis method and previous laboratory tests. The first, second and third percentage difference according to their mode were 5.6%, 1.1% and 0.3% respectively. For the first and second mode, the frequency values in modal analysis method were higher compared to previous laboratory tests which made the percentage difference increased. Meanwhile, the percentage difference for third mode was decreased due to lower value of frequency in modal analysis method compared to previous laboratory tests. Overall, the frequency data was acceptable since the percentage difference was less than 10% [16]

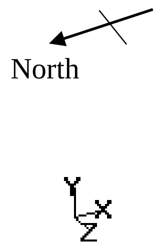
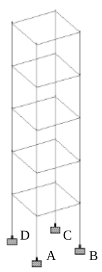
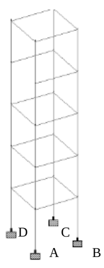
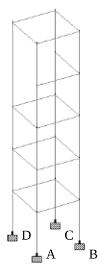
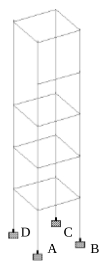
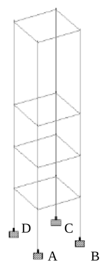
Table 4: Percentage difference for frequency data

Mode	1	2	3
Modal analysis method frequency (Hz)	5.55	5.55	7.21
Previous laboratory frequency (Hz) [14-15]	5.24	5.49	7.23
Percentage difference (%)	5.6	1.1	0.3

4.2 Predominant frequencies of multiple cases of vertical irregularity

The steel tower modelling was modelled with multiple cases of vertical irregularities. There were four types of vertical irregular cases conducted at upper level of the steel tower. By using modal analysis method, the predominant frequencies for each vertical irregular case were organised in Table 5 below.

Table 5: Predominant frequencies for vertical irregular cases

Mode	Bare frame	Irregular 1	Irregular 2	Irregular 3	Irregular 4
					
1	5.55 Hz	5.47 Hz	5.60 Hz	5.48 Hz	5.63 Hz
2	5.55 Hz	5.68 Hz	5.61 Hz	5.74 Hz	5.63 Hz
3	7.21 Hz	7.31 Hz	7.41 Hz	7.52 Hz	7.64 Hz

The frequencies were categorised according to their modes. Trendline was applied in the scattered plot data as the best fit line to predict future values based on current data [17]. Mode 1 and 2 shows the fluctuation in frequencies data for irregular cases. These fluctuations were caused by the removal of beam members at upper level. Meanwhile, an increasing scattered data can be seen for mode 3. The consistent increasing pattern was resulted from the constant rotational moving patterns for irregular mode 3.

The R^2 value indicates how well the information fits a trendline based on a statistical model, whether in line or curve shape. The determination coefficient of R^2 was an assortment of values from $0 \leq R^2 \leq 1.0$ [18]. R^2 value closed to 1.0 shows the regression line was a linear tabulation while if R^2 nearest to 0 indicate that the line is a non-linear. The R^2 value was obtained based on the best trend line that fits the deflection curve perfectly [12]. Four types of trendlines were applied to identify the best fit line for all mode. Based on the range of R^2 value in Table 6, the strength of linear relationship of predominant frequency of irregular cases and mode shape in mode 1, 2 and 3 can be determined. The justification of the trendlines were tabulated in Table 7.

Table 6: The strength of trendline relationship based on R2 value [18]

R^2 value	Indication
1.00 - 0.8	Very strong
0.79 - 0.6	Strong
0.59 - 0.4	Medium
0.39 - 0.2	Weak
0.19 - 0.00	Very weak

Table 7: R2 value justification

Type of trendline	Mode	Justification	Remarks
Linear	1	0.144	Very weak
	2	0.216	Weak
	3	0.998	Very strong
Exponential	1	0.142	Very weak
	2	0.218	Weak
	3	0.999	Very strong
Polynomial 2nd order	1	0.300	Weak
	2	0.501	Medium
	3	0.999	Very strong
Polynomial 3rd order	1	0.318	Weak
	2	0.511	Medium
	3	1.0	Very strong
Polynomial 4th order	1, 2, 3	1.0.	Very strong

From the justification table, it can clearly understand that all trendlines fit for mode 3 for every irregular case. This was cause by the steady increasing scattered data plotted for mode 3. Meanwhile, the best fit trendlines for all modes was polynomial 4th order which means the modes were non-linear trend. All scattered data lies on the trendline thus resulted to perfect R^2 value (1.0).

By referring to the predominant frequency from bare frame, the percentage differences of irregular cases were calculated and tabulated in Table 8. The first three predominant frequencies of bare frame were at 5.55 Hz, 5.55 Hz and 7.21 Hz. The percentage difference of the first and second mode of predominant frequency experienced increase and decrease (fluctuation) value. However, an increasing value of percentage difference can be seen at the third mode of predominant frequency.

Table 8: Percentage difference of irregular cases of steel tower

Irregular cases	Mode shape	Predominant frequency (Hz)	Percentage difference (%)
1	1	5.47	-1.44
	2	5.68	2.34
	3	7.31	1.39
2	1	5.60	0.90
	2	5.61	1.08
	3	7.41	2.77

3	1	5.48	-1.26
	2	5.74	3.42
	3	7.52	4.30
4	1	5.63	1.44
	2	5.63	1.44
	3	7.64	5.96

It is found that, by using modal analysis method, there were only small significant change in predominant frequency of the 5 storey steel tower from the bare frame configuration. The structure was built with the same elements for beam and column, thus created a strong and rigid steel tower. Unfortunately, the removal of beams at upper level showed an insignificant variation in predominant frequencies.

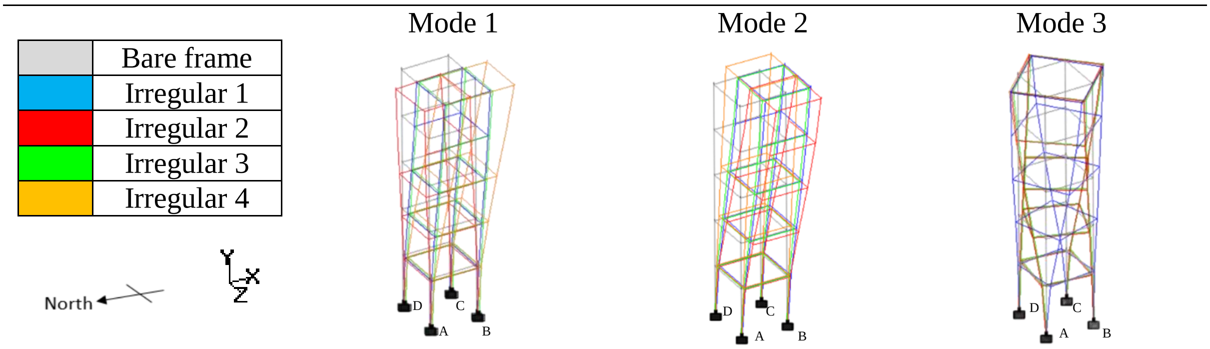
4.3 Steel tower mode shape

Irregularity shows a great effect on the deflection shapes. It is expected that the effect of vertical irregularities was reduced and weakening the stiffness of the tower, based on the reductions of predominant frequency [19]. Mode shapes of the steel tower were generated based on the first three predominant frequencies of the structure. From analysis of the STAAD.Pro software, the mode shapes from bare frame and irregular cases were extracted. Translational deformation shape for the first two modes of bare frame found translated along North-South (NS) and East-West (EW) direction. Meanwhile, translational deformation shape for the third mode of bare frame was translated in rotational mode where it twisted in both North-South (NS) and East-West (EW) direction.

The deformation mode shape for steel tower under multiple cases of irregularity in the overlapped of mode shapes that were illustrated in Figure 4. Irregular case 1 and 3 translated along EW direction for mode 1 and NS direction for mode 2. Both irregular cases had opposite mode shape patterns than bare frame. The mode shape patterns acted synchronized along with the frequency data.

The removal of beam members at level 4 had changed the structure configuration, thus resulted in changes of mode shape. For irregular case 2 and 4, both designs had mode shape patterns translated at the same directions as bare frame. For mode 1 and mode 2, both cases had translated in both NS and EW direction. Meanwhile, irregular case 1 and 3 experienced opposite translation mode for mode 1 and 2 than bare frame. Mode 1 for irregular case 1 and 3 translated in one direction only which was EW direction while mode 2 translated in NS direction. Mode 3 for every irregular case remained the same mode shape pattern. These situations happened when all cases experienced rotational mode in NS and EW direction.

Table 9 shows the summary of translation and rotation direction based on mode shape of irregular cases according to the modes.



	Mode 1	Mode 2	Mode 3
Bare frame	f = 5.55Hz	f = 5.55Hz	f = 7.21Hz
Irregular 1	f = 5.47Hz	f = 5.68Hz	f = 7.31Hz
Irregular 2	f = 5.60Hz	f = 5.61Hz	f = 7.41Hz
Irregular 3	f = 5.48Hz	f = 5.74Hz	f = 7.52Hz

Irregular 4	f = 5.63Hz	f = 5.63Hz	f = 7.64Hz

Figure 4: Overlapped mode shape for all irregularity cases

Table 9: Mode shape of irregular cases according to modes

Mode	Type of irregular case	Mode shape
1	Irregular 1 and 3	Translation in 1 direction (EW)
	Bare frame, irregular 2 and 4	Translation in 2 direction (NS and EW)
2	Irregular 1 and 3	Translation in 1 direction (NS)
	Bare frame, irregular 2 and 4	Translation in 2 direction (NS and EW)
3	All cases	Torsional

5. Conclusions

The first objective was successfully achieved which is to determine the dynamic characteristics of steel tower under multiple cases of vertical irregularity using modal analysis. The dynamic characteristics of steel tower was focused on predominant frequency and mode shapes of four irregular cases which related to the second objective.

The second objective was to investigate the relationships between vertical irregularity and the parameters of dynamic characteristics such as frequency and mode shapes. The predominant frequencies for bare frame were f_1 and f_2 = 5.55Hz, and f_3 = 7.21Hz. the percentage difference of frequency for four irregular cases from bare frame were less than 6% which only resulted to small significant change in predominant frequency of the steel tower. The frequencies of irregular cases were analysed using various type of trendlines that can be determine the best fit line using R^2 values as indicator. There were fluctuations in frequencies data occurred for mode shape 1 and 2 that only could be fit in polynomial 4^{th} order trendline. These fluctuations were cause by the irregularity of beam members at upper level. The other trendlines produced very weak to medium mode shape of frequency relationship for mode shape 1 and 2. However, mode 3 produced very strong frequency relationship due to increasing linear for every irregular case. In the meantime, polynomial 4^{th} order trendline created the best frequencies distribution for mode 1, 2 and 3 because it managed to join all scattered data in one curve line. A simple conclusion can be drawn where the frequency of structure increased along with the removal of beam members. Predominant frequency of structure is related to the lateral dimension of structure such as building height. The removal of beam member from the structure abruptly alters the dynamic characteristics of the structure configuration in terms of its predominant frequency. The steel tower experienced three predominant mode shape which were translation for mode 1 and 2, while torsional for mode 3.

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