Recent Trends in Civil Engineering and Built Environment Vol. 2 No. 1 (2021) 362-371

RTCEBE

Homepage: http://publisher.uthm.edu.my/periodicals/index.php/rtcebe
e-ISSN :2773-5184

Effect of Vertical Irregularity(Lower level) of 5-Storey Laboratory Steel Tower using Modal Parameters

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DOI: https://doi.org/10.30880/rtcebe.2021.02.01.039
Received 30 January 2021; Accepted 28 April 2021; Available online 30 June 2021

Abstract: Building multi-story high-rise structure buildings is now common with incredibly limited areas, as open floor structures are by far the most common type of urban architecture. Vertical irregularity is frequently used by designers around the world to place car parks, swimming pools or outdoor areas as it strengthens the buildings' architectural values. A modal analysis then be carried out using STAAD Pro to evaluate the natural frequency nd mode shapes of a 5-storey steel tower model which based on a real steel tower installed at the UTHM Jamilus Research Centre. Based on the previous laboratory findings performed using accelerometer sensors and EFDD analysis, the modal analysis output was verified. 4 parametric studies were performed using STAAD Pro modal analysis to establish vertical irregularities by eliminating the beams at the lower level of the steel tower model. The natural frequency of the bare frame steel tower were f_1=f_2=5.55Hz and f_3=7.21 Hz with the comparable difference of less than 10% compare to Faizul(2019). The steel tower experienced translation on mode 1 and 2 while torsional on mode 3.

Keywords: Vertical Irregularity, Dynamic Characteristics, Modal Analysis

1. Introduction

Multi-storey high-rise frame building designs is now popular due to excessive limited spaces with vertical irregularity at lower level becoming more common [1]. Sometimes referred as soft storey, it was described as an unconventional building structure constructed according to a certain functional purpose [2]. The NEHRP code mentioned that a structure with ratio with one quantities between adjacent storeys which exceed it minimum values (70-80% for soft storey, 80% for weak storey) is defined as irregular [3].

There are different types of vertical anomalies such as soft storey, vertical geometric irregularity(set-backs) and weak storey [4].A set-backs structure was made by two parts which are lower base part with several bay and upper part with less bays [4]. Both soft storey and set-backs structure have irregular design in vertical condition and building type [5]. Based on the findings on the previous study to find the impact of dynamic study of setbacks and soft storey, concluded that structural

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behaviour was influenced by the presence of irregularity as it was observed between normal structure [6].

Modal analysis is the study of structural dynamic features that can be used to determine the irregular construction's natural frequency and mode shape. In addition, in the assessment of building conditions, natural frequency and mode shape are the most widely used criteria for dynamic characteristics. The overall stiffness can be represented by natural frequency which is low natural frequency is small structural stiffness while very fragile structure, high natural frequency is known to have large structural stiffness and very hard structure [7]. In addition, mode shapes correspond to the configuration of the building deformation design as it reacted according to its natural frequency [8].

1.1 Problem Statement

The most common design structure for a modern style construction is the one with irregularity. Nevertheless, the demand of the modern style makes the construction of high architectural value buildings which lead to changes in the irregularity of the structure, such as apartments, hospitals and workplaces, does not achieve the necessary serviceability [9].

According to Salunkhe and Kanase [10], building vertical irregularity is one of the factors causing huge number of structural failures. Buildings with vertical anomalies are one of the causes of structural collapse that leads to loss of life [11]. According to Bansal & Gagandeep [12], The existence of such a factor will contribute to such structural effects, such as dynamic structure and irregular structure displacement. Building behaviour is a crucial component of maintaining successful and safe construction design in which the dynamic characteristics of a building in an unusual structure configuration are analysed in a very critical way [13].

The analysis of modal analysis is one of the important methods for analysing dynamic characteristics [14]. After the advent of the digital analyzer, the analysis modal analysis has evolved continuously and has become a popular activity in order to find structure modes since the late of 1900 [15].The previous study by Qin-sheng et al. [16], the natural frequency and mode shapes of the model is obtained by undergoing an analysis study. According to Chandravashi & Mukhopadyay [14], modal analysis can forecast the complex behaviour of the system under many different situations by using the method as it can generate several useful infromations and critical data for structure strengthening during the design phases.

1.2 Objective

This paper aims to determine the dynamic characteristics of the steel tower in four vertical irregularity conditions using modal analysis and to analyse the influence of vertical irregularity on the relationship between dynamic characteristics (natural frequency and mode shapes).

2. Methodology

2.1 Stage 1: Description of structure

The listing of the dimensions of the 5-storey steel tower located in Jamilus Research Centre (JRC) Laboratory UTHM was carried out. The material properties of steel tower elements used was mild steel grade S275. A square hollow section with a dimension of 77mm x 77mm x 1000mm and 3mm thickness of beams and columns was used to assembled the steel tower with four based connectors connected at the bottom of steel tower. 10mm and 25mm diameter bolts were used to lock and tighten up the connector plate at the joints. The configurations of the steel tower were as shown in Figure 1.

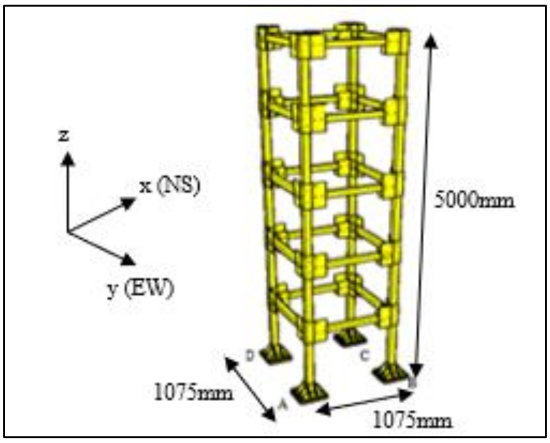

Figure 1: 5-storey steel tower in JRC laboratory

2.2 Stage 2: Modal analysis

2.2.1 Steel tower modelling using STAAD Pro

The dimensions of steel tower listed in Stage 1 was used to key in into the script of the STAAD.Pro editor to produced the steel tower model. Then, the steel tower model was assigned with the detailing as shown in Table 1.

Table 1: Steel tower model detailing [17].

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

2.2.2 Partial moment release

After that, partial moment release in STAAD Pro was used to apply the principle of partially rigid on the modelled steel frame. It is where the structure tend to sway and where structure torsion occurs. Moment release from level 2 to level 5 was added to the beams and columns. A percentage of the partial moment release added to the start-end of the beams and columns. The higher the percentage of partial moment release added to a beam, the lower the percentage decrease in beam bending moment. So, 28% of partial moment was assigned to the start-end part of beams while 80% of partial moment was assigned to the start-end part of the columns of steel tower. This percentage values was used by the method of trial-and-error as the natural frequency result needed to be comparable according to Khairul [18].

2.3 Stage 3: Output modal analysis

2.3.1 Result verification

The analysis model modal analysis was carry out on the steel tower model developed with STAAD Pro software as it was to indicate the moment resisting frame of the actual steel tower. The natural frequency and shape of the mode will be compared with the findings of previous laboratory experiments using accelerometer sensors and EFDD analysis. The output natural frequency of steel tower modal analysis were f_1=f_2=5.55Hz and f_3=7.21Hz while the natural frequency from Khairul [18] laboratory outcomes were f_1=5.24Hz, f_2=5.49Hz and f_3=7.23Hz.

2.3.2 Four parametric studies of vertical irregularitites at lower level

This research intended to study the dynamic characteristics of the steel tower in four vertical irregularity conditions. Two different types of steel tower configurations were the model of the bare steel tower and four parametric studies of lower level irregularities. The beams were removed part by part to indicate vertical irregularity at the lower level starting from one beam, two beams, three beams and four beams. Every beam removed was followed by an analysis of dynamic characteristics.

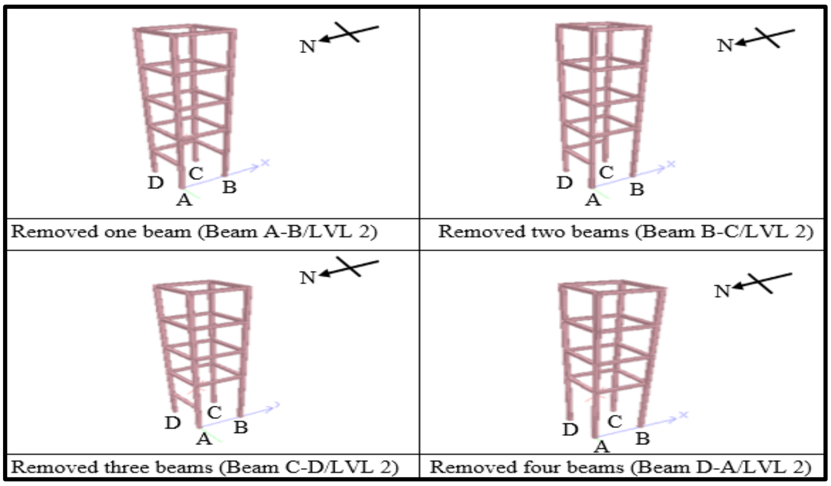

Figure 2: Parametric study of irregularity at lower level .

2.3 Stage 3: The relationship between vertical irregularities and the dynamic characteristics

2.3.1 Vertical irregularity cases vs natural frequency

From the frequencies of the first three modes of the irregular steel tower, the natural frequency of irregular beam configurations at the lower level were calculated. Natural frequency graphs were arranged to observed the trendlines according to the mode form. By using the Equation 2.1 and 2.2, the relationship between the vertical irregularity cases vs natural frequency was constructed by calculating the percentage difference of bare frame and irregularity cases.

Percentage difference for frequency of bare frame (%)
(**Error! No text of specified style in document.**.1)

$$[(f_{modal\ analysis} - f_{previous\ laboratory\ testing}) / f_{previous\ laboratory\ testing}] \times 100\%$$

Percentage difference for frequency of irregular cases (%)
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$$[(f_{irregular\ cases} - f_{bare\ frame}) / f_{bare\ frame}] \times 100\%$$

2.3.2 Vertical irregularity cases vs mode shapes

STAAD.Pro modal analysis also able to generate the mode shapes patterns in 3D view which shows the difference between the bare frame and the vertical irregularities at the lower level was according to its deflection plane. Futhermore, three mode shapes were produced from where translation occurred on mode 1 and 2 while mode 3 experienced torsional mode.

3. Results and Discussion

3.1 Result verification on the natural frequency of bare frame

This verification of the results was carried out by comparing the natural frequency of the modal analysis with Khairul [18] laboratory experiments. The natural frequency of bare steel tower were extract from STAAD Pro with f_1=f_2=5.55Hz and f_3=7.21Hz while the natural frequency of Khairul [18] result were f_1=5.24Hz, f_2=5.49Hz anf f_3=7.23Hz. The percentage difference between both study was calculated and tabulated into Table 2.

Table 2: Percentage difference between modal analysis and EFDD analysis

Mode	1	2	3
Modal analysis method frequency (Hz)	5.55	5.55	7.21
Previous laboratory frequency (Hz) [18-19]	5.24	5.49	7.23
Percentage difference (%)	5.6	1.1	0.3

The percentage between the modal analysis and Khairul [19].were f_1=5.6%,f_2=1.1% and f_3=0.3% respectively The frequency values in the modal analysis f_1 and f_2 were found higher compared to previous laboratory study. Meanwhile, the lower percentage difference for f3 was due to the small comparable difference between the output of modal analysis and previous laboratory study. The frequency data was accepted since the percentage difference between both analysis was less than 10%[20].

3.2 Natural frequency of vertical irregularity

After that, four irregualrity cases was applied to the bare steel frame model by using STAAD Pro software. Based on the output result, it clearly shows that the natural frequency were decreasing as the irregularity cases was applied to the bare frame as revealed in Figure 3. Karakale[21] mentioned that the declining of natural frequency of an irregular structure may affected by the addition and reduction of components on the structure.

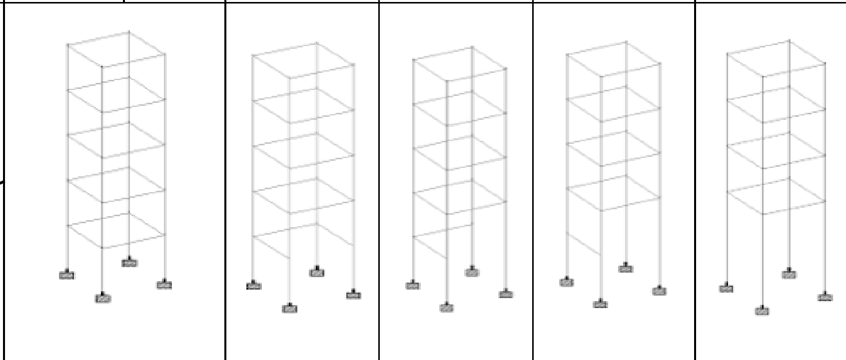
Mode	Previous Studies	Bare Frame	Irregularity case 1	Irregularity case 2	Irregularity case 3	Irregularity case 4
N						
1(Hz)	5.24	5.54	5.32	5.31	5.11	5.11
2(Hz)	5.49	5.54	5.55	5.34	5.32	5.11
3(Hz)	7.23	7.21	7.12	7.03	6.93	6.81

Figure 3: Natural frequency of steel tower according to irregularity cases at lower level.

The natural frequency of all the irregular cases was plotted into three scattered graph to observed the R2 values. This method was used to find the coeffiecient of determination by using several equations such as logarithm quadratic and linear. Figure 4 shows the linearity of decreasing natural frequency. The r-value for all the three modes was considered strong linear relationship as it was over 0.7(70%). Moore et al.,[22] said that when the r-value is more than 0.5, it was consider as strong. The R2 values increase as the modes increase. Largest R2 value occurred on the 3rd mode with 0.99(circled).The coefficient of determination was found very strong as it exceeded the value of 1.00 [23].

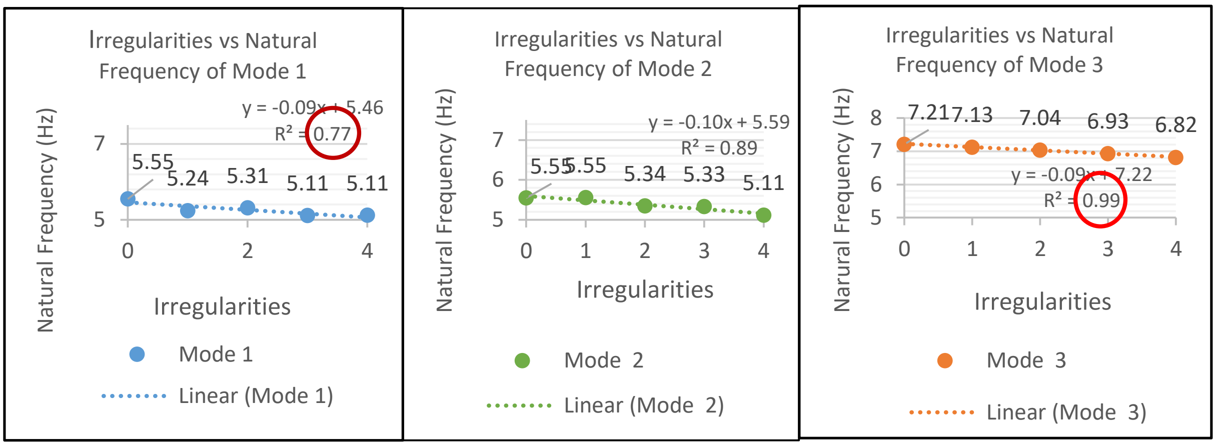
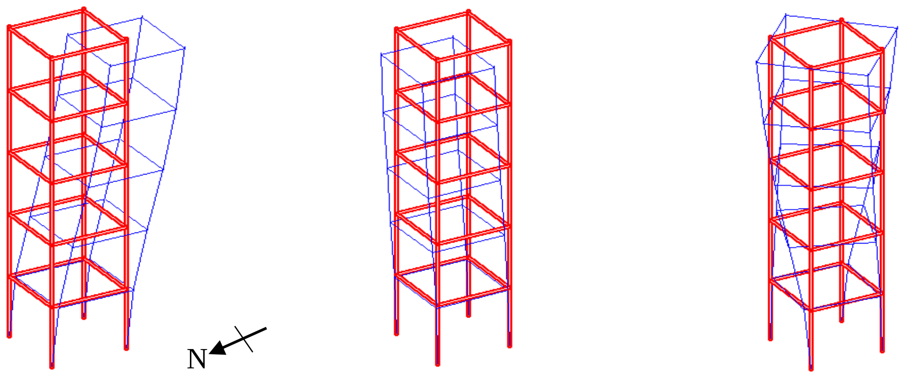


Figure 4: Natural frequency vs. Irregularity cases according to modes

It was observed that there was only a slight difference of natural frequency of the 5-storey steel tower from the bare frame configuration using the modal analysis. The steel tower model was designed according to the similar beam and column elements, thereby making it solid and rigid. The vertical irregularities parametric study of removing beams at the lower level revealed the variations of natural frequencies.

3.3 Mode shape of steel tower

The first three modes of bare steel tower were extracted from STAAD Pro modal analysis. It was found that 1st mode translated on the North-South(NS) direction, 2nd mode translated on the East-West(EW) 3rd mode torsion in both NS and EW directions as in Figure 5.

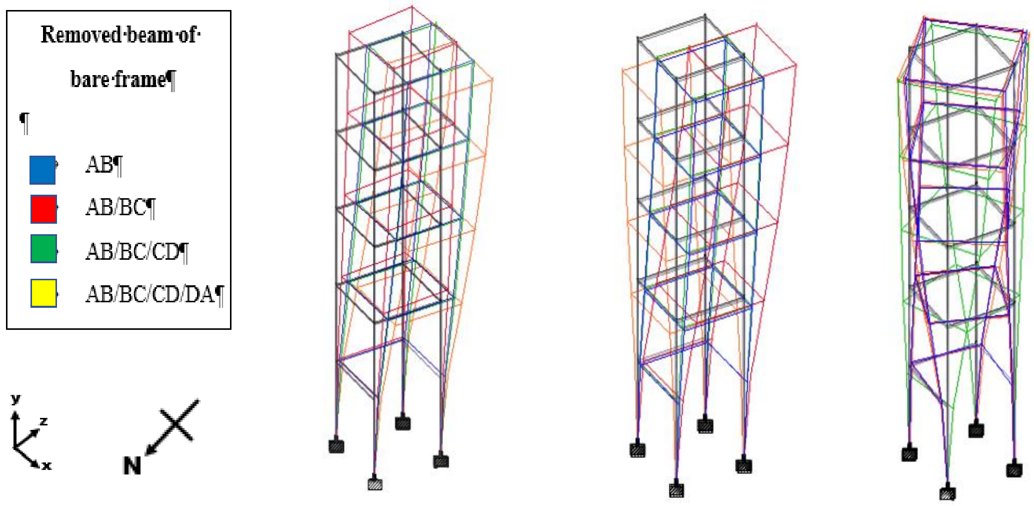


1st mode: 5.55Hz (Translation mode) | 2nd mode: 5.55Hz (Translation mode) | 3rd mode: 7.21Hz (Torsional mode)

Figure 5: Bare steel tower mode shape

The overlapping modes of vertical irregularities under multiple cases can be referred in Table 3. The deformation mode of the modelled steel tower in all cases tend to translate on both X(NS-direction) and Z(EW-direction) axis but according to Murty et al.,[24] the mode shapes tend to translated on both X and Z axis actually translated more on its dominant axis.

Table 3: Overlapping mode shapes of steel tower



Irregularities at lower level	Mode Shape 1	Mode Shape 2	Mode Shape 3
Bare frame case	5.55Hz	5.55Hz	7.21Hz
Irregularity case 1	5.32Hz	5.55Hz	7.12Hz
Irregularity case 2	5.31Hz	5.34Hz	7.03Hz
Irregularity case 3	5.11Hz	5.32Hz	6.93Hz
Irregularity case 4	5.11Hz	5.11Hz	6.81Hz

It was found on the 1st mode that the deformation mode of irregularity case 1, 2 and 3 tend to translated only on the NS-directions while the bare frame and irregularity case 4 translated in between the NS and EW directions. Similar mode shapes pattern also occurred on the 2nd mode as the irregularity 1,2 and was assigned where it only translated on a particular axis which was in the EW-direction. The bare frame and irregularity case 4 of the 2nd mode also had the similar deformation modes translated between the EW and NS directions. The effect of removing one beam, two beams and three beams at lower level showed that the deformation mode of the steel tower tend to only translated on their particular axis. The similar pattern of deformation modes of the bare frame and irregularity case 4 was due to the same structural configurations of removed beams at the lower level. On the 3rd mode, it was observed the similar deformation mode persisted in each irregularity cases. These conditions arose when the 3rd mode tend to torsion in the form of NS and EW directions. Table 4. shows the summary of the deformation mode behaviour of the steel tower.

Table 4: Summary of the deformation mode behaviour of the steel tower.

Mode	Type of irregularity case	Mode shape
1	Irregularity case 1, 2 and 3	Translated only in NS direction
	Bare frame and irregularity case 4	Translated between NS and EW direction
2	Irregularity case 1, 2 and 3	Translated only in EW direction
	Bare frame and irregularity case 4	Translated between EW and NS direction
3	All cases	Torsional in NS and EW direction

4. Conclusion

From this study, the steel tower model natural frequency for bare frame case are f_1=f_2=5.55Hz, f_3 and 7.21Hz while the natural frequency of the MRF when all the vertical irregularities was applied were f_1=f_2=5.11Hz and f_3=6.82Hz. As the vertical irregularities were added to the steel frame,natural frequency changes according to its parametric studies. It can be inferred that vertical irregularities at the lower level of steel tower were conducted with 7.93% for the first and second modes, followed by 5.41% for the third mode the natural frequency pattern can be seen decreasing. The linear reduction in the percentage outcome was also assisted by the linearity of R^2 value. From this analysis, the steel tower natural frequency decreased along with the removed beam members at lower level.The change in steel tower configurations was observed had alter the dynamic characteristics in terms of both natural frequency and mode shapes. Similar deformation shapes translated along the NS and EW direction in both frame configurations are seen in the 1st and 2nd mode, while the 3rd mode appears to twist in the NS and EW directions. The displacement of the beam component from the structure suddenly changes, in terms of its overriding frequency, the complex features of the configuration of the structure.

Acknowledgement

The author would like to thank Faculty of Civil Engineering and Built Environment, University of Tun Hussein Onn Malaysia (UTHM), for the technical support and facilities.

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