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# Dynamic Characteristics Evaluation on Portable Steel Frame due to Mass Irregularities

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**Abstract:** Application of irregular mass configuration in modern design era of buildings is unavoidable in order to serve various building functionality. The effect of mass irregularities was investigated on 5-storey portable moment resisting steel tower (PostFrame), against its dynamic behaviour. PostFrame was designed at five meter height and assembled on the strong floor in Jamilus Research Centre laboratory, UTHM. The predominant frequencies and mode shapes were determined on bare frame, uniform mass frame and mass irregularities' frames. A total of four steel blocks at 800 kg were placed in uniform, ascending and alternating orientations on the first to fourth level of the PostFrame. Ambient vibration testing (AVT) was conducted using uni-axial accelerometer sensors. The sensors were aligned in bi-axial horizontal directions with respect to the North-South (NS) and East-West (EW) directions. ARTeMIS processing tool and Frequency Domain Decomposition (FDD) methods were used in the analysis of dynamic behaviour. Comparative findings were made between bare frame and mass action frame. Two translation mode shapes and torsional mode were illustrated by respective three predominant frequencies. Significant reduction of predominant frequency showed up to 37.79% between bare frame and frame with ascending mass orientation.Uniform mass orientation shows at the lowest percentage discrepancy percentage compared to others. Even though some changes have be found in predominant frequencies, but comparable mode shapes illustration were observed from all three predominant frequencies from all frame configurations.

**Keywords:** Mass irregularity, ambient vibration testing, predominant frequency, mode shape

## 1. Introduction

Current trend of irregular building configurations are expressively growth due to high demand of building's serviceability and functionality. Irregularities arrangements are existed when non-equal weight, force and flexibility allocated either discretely or simultaneously applied on the buildings [1]. A building is supposed to be a regular when the configuration is nearly symmetrical about the axis but classified as irregular when it lacks symmetry and discontinuity in the geometry, mass or elements which resists load [2]. In addition, mass irregularity through the elevation exist when it has unexpected mass modification in certain floor levels [3]. An irregular building is also defined as the building for

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which the difference appearing in any of the properties such as stiffness, strength or mass between two consecutive floors is above a specified limit [4].

The building with regular geometry, weight and rigidity in both plan and elevation is much less damaging compared to irregular configurations [5]. In presence scenario, the excessive dynamic loads such as earthquake may induce damage or collapse on structures that usually begins at fragility parts on structure [6]. This fragility could occur due to building irregularities which classified under rigidity, weight applied on each floors and building geometry [7]. In contrast to aleatory unpredictability, when it is created by unexpected room rearrangement which involved with heavy machinery that may alter the existing dynamic behaviour of the structure. These may lead to building structures with irregular distributions in mass, stiffness and strength along the height of building [8].

Building behaviour and vulnerability of buildings are highly dependent on its dynamic characteristics. Irregularities may also cause a building to behave into non-uniform behaviour that brings twisting action. Irregularities of mass distributions from the dead weight of floor building and actual weight of partition and equipment in vertical or horizontal planes, may create irregular response and complex dynamics characteristics [9], and initiating vulnerable potential to the structural members and connections. For instance, stress concentration will start to be accumulated at discontinued point such as windows and door opening, changes in shapes of wall or connection between any separate parts of a building mass that must be studied to avoid for potential damage [10].

Various findings were given from previous researchers on the effect of mass irregularity on a structure. Based on previous research given by James [11], mass irregularity could affects the response of the floor accelerations and inter-storey drifts within a flexural structure. The author added, as the 5% and 10% mass shift is being added the current mass at different floors, each shift gives a different structural response when the structure undergoes earthquake excitation. In that circumstance, the natural period of the structure could be shifted to trigger the potential of site-structure resonance potential. Besides, the shifted mass could also causes the structure to become more flexible and induces larger interstorey drift demands [11]. Different finding contributed by Naveen et al. [12], when the presence of irregularity does not always amplifies the response and perhaps at certain combinations of irregularities it brings down the structural response. According to Azghandi et al. [13], mass vertical irregularity with concentration in the lower half of the structure is the most vulnerable (21% reduction in collapse resistance of the structure), whereas the stiffness irregularity with distribution in the top and bottom parts of the structure is the least affected. As reported by Karavasilis et al. [14] from Azghandi et al. [13], the effect of mass vertical irregularity on the distribution of demands over the height of a plane steel moment frame had found that, the location of irregularity is an essential parameter in performance assessment of such structures.

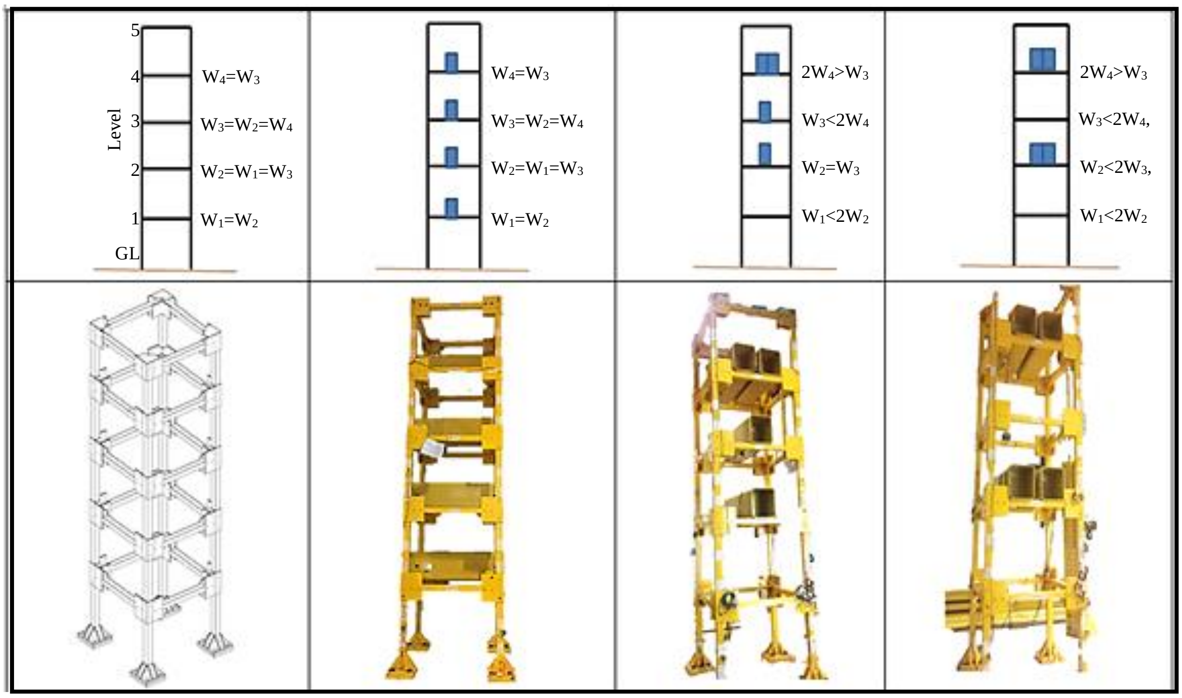
In this research, ambient vibration testing has been performed on 5-storey portable moment resisting steel tower. The height of tower was five meter. It was constructed on the strong floor in JRC laboratory, UTHM. The main objective of this research is to examine and quantify the dynamic characteristics of the built steel tower in terms of natural frequencies against the effect of vertical mass irregularity. Besides, the relative storey displacement amplitude (or inter storey displacement amplitude) were also observed for identification of displaced and weak level due to the abrupt changes of mass along their height. These parameters are important not only for current investigation, but future monitoring and assessment at different application of vertical irregularities applied on this PostFrame.

## 2. AVT and Mass Irregularities

PostFrame was designed based on fix sizes of column, beam and slotted connectors. All column-beam elements are able to be assembled and dissembled without destruction. The elements of beam and columns were designed using 77 mm × 77 mm square hollow with 1000 mm length of sections and 3 mm thickness. The connectors were designed and customized for the base, intermediate and roof (top level) connections. All components were made by S250 of steel grade is used. High tension bolt of grade 8.8 with diameter 10 mm and 25 mm was used to fasten all connectors to the elements. By assembling all elements and connectors components, this PostFrame was fixed to the strong floor in JRC laboratory for ambient vibration testing.

Vertical irregularities could be formed by irregular mass, stiffness and geometry along the height a building [13]. To define mass irregularities on a structures, a specific mass (W) ratio at effective mass of any storey more than 150% of the effective mass of an adjacent storey ($W_i < 1.5W_a$) were recommended by most code of practices and guidelines such as IS 1893:2016 (Part I) [15], NZS 1170.5 [16], ASCE/SEI 7-16 [17], NEHRP (2000) [18], UBC [19] etc. Additional characteristics was described in Poncet [b], when the structure has a weight irregularity if the mass of any storeys are more than 150% of the adjacent storey, and a dynamic analysis procedure must be used if the structure is more than 20 meter in height or has a fundamental period longer than 0.5 sec (2 Hz). The author had added the exception of mass irregularity consideration can be accepted if the storey drift of a structure at any storeys is less than 130% the storey drift at the storey above based on 2003 IBC [20]

To evaluate the effect of mass irregularities on the PostFrame using ambient vibration testing, a few mass configurations were considered as illustrated in Fig. 1. Uniform mass steel block was applied on each level of PostFrame excluding the ground level and root top. Each steel block has 200 kg of mass. For mass irregularity configurations, consideration of 200% effective mass discrepancy between adjacent storeys (top and bottom) was chosen on this research. These masses were orientated in ascending and alternating orientations.




**FRAME 1** Bare Frame | **FRAME 2** Uniform Mass | **FRAME 3** Ascending Mass | **FRAME 4** Alternating Mass

**Fig. 1 - Mass irregularities ratios and mass orientations**

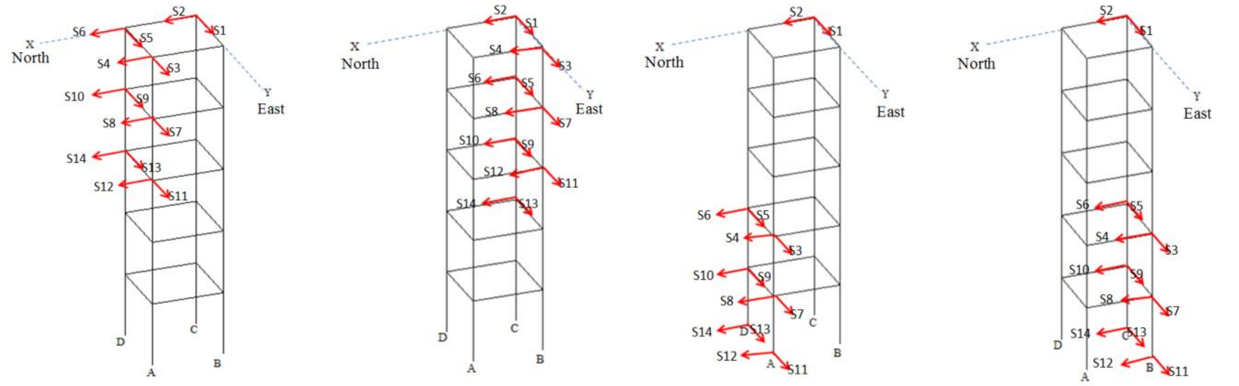
Ambient vibration testing is carried out using accelerometer sensors types KS48C with voltage sensitivity of 1 V/g and measurement range of ± 5g (see Fig. 2(b)). 14 channels of accelerometers were used to record the ambient vibration signals in bi-axial horizontal directions which were NS (in line to X-axis) and EW (in line to Y-axis). The sensors were connected to the data acquisitions system namely IMC data logger (see Fig. 2(a)).


**Fig. 2 - (a) Data acquisition station; (b) Bi-axial alignment of accelerometer sensors**

Fig. 3 shows the orientation of uni-axial accelerometer sensor which aligned in respective X-Y axes. The breakdown of ambient vibration measurements in Table 1 is required to complete the 3D mode shapes illustration without neglecting any one of 24 joints of the PostFrame. Two sensors were remained on the upper level of steel tower as the reference sensors in respective NS and EW directions. 100 Hz of sampling frequency was taken for 15 minutes of ambient vibration recording. All vibrations records were computed into Fourier series which automatically done in ARTeMIS extractor software based on classical method of FDD. As recommended by SESAME (2014) guideline [21], all short period disturbances such as transient, machinery, bad weather condition etc. must be minimized for good and quality ambient vibration signal records during the recording [22].

Validation of the origin natural frequencies (or predominant frequencies) of the PostFrame from the output of FDD method in ARTeMIS extractor were made against seismometer instrument and Fourier Amplitude Spectra (FAS) analysis. 4-units of Lennartz tri-axial seismometer with 1 Hz eigenfrequency sensors were connected to CityShark II data logger which operated by 12 volts of direct current. Similar ambient vibration recording parameters were applied, (100 Hz of sampling frequency and 15 minutes recording of length).

To distinguish the origin peak frequencies of the PostFrame against any spurious peak frequencies which could be participated from the intrusion of ground response or nearby structures, overlapping protocol on the frequency spectrum between the adjacent structures (JRC buildings) and ground surface (soil) are performed [24]. Strong ground amplification from soft soil profile may significantly contaminate the frequency response of the measured structure and causes inaccurate selection of the predominant frequency [25], [26]. Seismometer sensor were also placed on several locations such as JRC building (on ground floor), ground surface (on soil) and adjacent multi-storey reinforced concrete (RC) building (on roof top). All ambient vibration records from seismometer sensor were analyzed using GEOPSY software based on Fourier Amplitude Spectra (for structure) and Horizontal to Vertical Spectra Ratio (HVSR) (for ground only). Detail analysis with regards to FAS and HVSR methods are discussed in [23]-[26]



**1st Measurement (M1)** **2nd Measurement (M2)** **3rd Measurement (M3)** **4th Measurement (M4)**

**Fig. 3 - Vibration sensors arrangements**

**Table 1 - Breakdown of ambient vibration measurements**

| Measurement No. | S1 | S2 | S3 | S4 | S5 | S6 | S7 |
|---|---|---|---|---|---|---|---|
| **M1** | C/5 | A/5 | D/5 | A/4 | D/4 | A/3 | D/3 |
| **M2** | C/5 | B/5 | C/4 | B/4 | C/3 | B/3 | C/2 |
| **M3** | C/5 | A/2 | D/2 | A/1 | D/1 | A/GF | D/GF |
| **M4** | C/5 | B/2 | C/2 | B/1 | C/1 | C/GF | C/GF |

## 3. Results and Discussion

### 3.1 Validation of Predominant Frequencies

Verification protocol was made between both seismometer and accelerometer findings. Peak frequencies from FAS and Power Spectral Densities (PSD) spectrum were compared for discrepancy percentages. Three significant peak frequencies were found from the Fourier spectrums outputs of ARTeMIS extractor and GEOPSY softwares. Fig. 4 shows the sample of PSD spectrum obtained from the FDD methods which taken from Frame 1 (bare frame).

The discrepancy percentage between PSD peak frequencies spectrum and FAS spectrum (1st $f_o$ = 5.22 Hz, 2nd $f_o$ = 5.41 Hz and 3rd $f_o$ = 7.15 Hz) was found between 0.38% to 1.46% (refer to Table 2). These ranges are acceptable, and it is comparable to prior study conducted by Ditommaso et al. [27] when the author had obtained less than 1.4% of discrepancy percentage.

An empirical relationship of $F_o = 11.533\ H^{-0.453}$ (by taking H = 5 meter) derived from several low rise to medium rise reinforced concrete buildings in UTHM from previous project also found closer prediction for the first mode of frequency of Frame 1 at 5.56 Hz.

Besides, it was found that the peak frequency of ground surfaces (soil) from the HVSR curves ($F_o$ = 1.64 Hz) and the FAS curves of adjacent structure (JRC ground floor at 1.48 Hz and adjacent multi-storey RC tower at 3.31 Hz) unable to give any significant frequencies perturbations against the origin frequencies of the PostFrame.

### 3.2 Effect of Mass Irregularity on PostFrame Dynamic Behavior

Three significant modes of frequencies were identified from the PSD spectrums under bare frame and mass irregularities on the PostFrame as illustrated in Fig. 5. Identical pattern of predominant frequency distributions are given for all cases of bare frame and mass actions. The predominant frequencies of bare frame indicate the highest, but significant reduced after withstanding 800 kg of mass. This finding was agreed the general relationship of $f_o = 1/2\pi\ (K/M)^{0.5}$ when the mass acted on a structure at constant stiffness will reduce their natural frequencies.

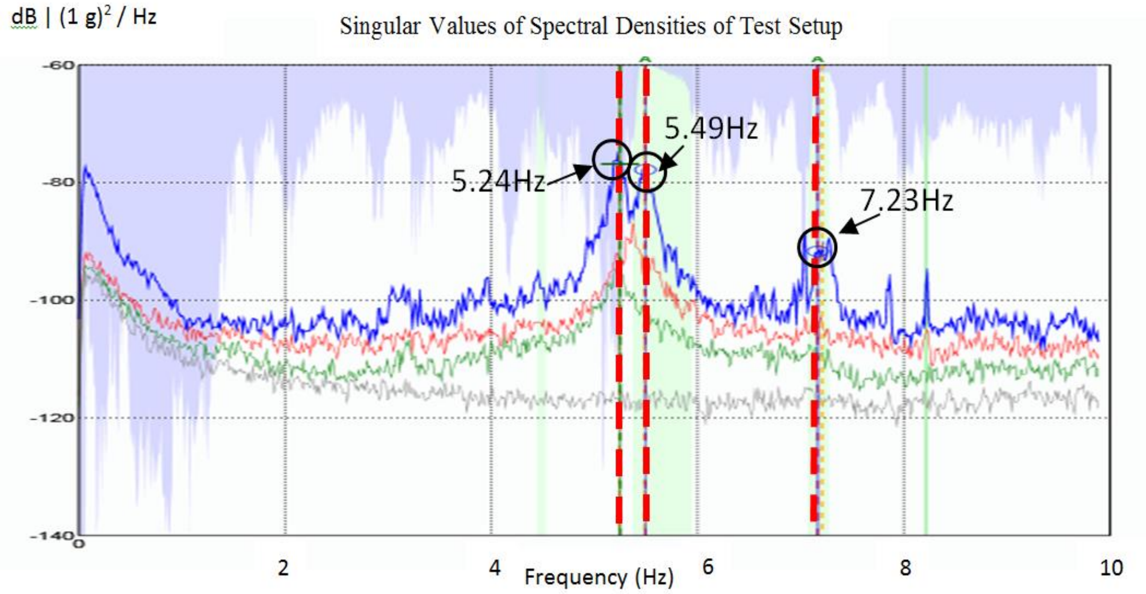



**Fig. 4 - PSD of bare frame (Frame 1) from FDD method used**

**Table 2 - Comparison predominant frequencies obtained by accelerometer and seismometer sensors**

| Mode | Predominant frequencies by accelerometer (Hz) | Predominant frequencies by seismometer (Hz) | Percentage difference (%) |
|---|---|---|---|
| First (x-x direction) | 5.24 | 5.22 | 0.38 |
| Second (y-y direction) | 5.49 | 5.41 | 1.46 |
| Third (torsion) | 7.23 | 7.15 | 1.11 |

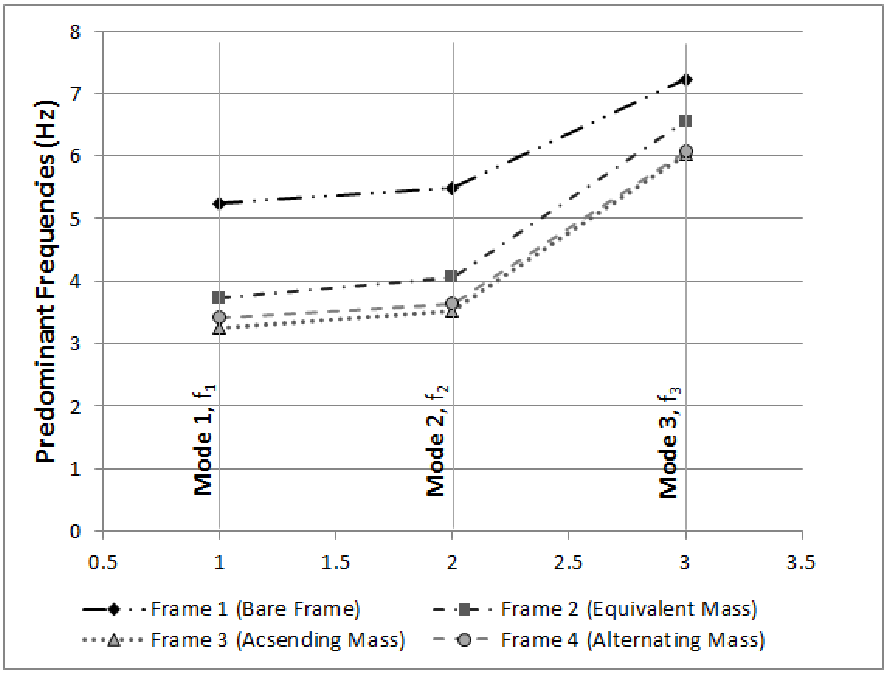



**Fig. 5 - Distribution of predominant frequencies of all frames**

To quantify the effect of these mass orientations and their mass irregularity effect on the PostFrame, Table 3, Table 4 and Table 5 show the discrepancy percentage and standard deviation of respective mode of frequencies. Frame 3 indicates the highest percentages of discrepancy, followed by Frame 4 and Frame 2. From these percentages, it was found that the effect of mass irregularity can be distinguished in all modes of natural frequency. Even though at higher predominant frequencies, the effect of mass irregularities is reduced but their percentages (Frame 3 and Frame 4) are remain higher if compared to the uniform mass configuration (Frame 2). The standard deviation (Stdev) is calculated to investigate the variations among mass action frames between all modes of frequencies. However, slight different of Stdev found between $f_1$, $f_2$ and $f_3$ which explain identical trend of dynamic behavior of all frames.

Mass irregularity in ascending orientation is discovered to produce the lowest predominant frequency compared to other frames configurations. It was agreed by Darshan and Shruthi [28], when the peak frequencies on upper floor levels with massive support loading may exhibits the lowest values. Serious attention must be emphasized in the application of excessive mass application especially when involves to seismic design. The resonance effect could be triggered, at similar oscillation frequency between ground and structure if excessive reduction of predominant frequency is occurred on the structure due to the excessive mass abruption.

**Table 3 - 1st predominant frequencies of all frame configurations**

| | Frame 1 (Bare Frame) | Frame 2 | Frame 3 | Frame 4 |
|---|---|---|---|---|
| **Mode 1, $f_1$** | 5.24 Hz | 3.73 Hz | 3.26 Hz | 3.42 Hz |
| | | 28.82% | | |
| | | | 37.39% | |
| | | | | 34.73% |
| | | Mean = 3.47 Hz and Stdev = 0.24 | | |

**Table 4 - 2nd predominant frequencies of all frame configurations**

| | Frame 1 (Bare Frame) | Frame 2 | Frame 3 | Frame 4 |
|---|---|---|---|---|
| **Mode 2, $f_2$** | 5.49 Hz | 4.06 Hz | 3.53 Hz | 3.64 Hz |
| | | 26.05% | | |
| | | | 35.70% | |
| | | | | 33.70% |
| | | Mean = 3.74 Hz and Stdev = 0.28 | | |

**Table 5 - 3rd predominant frequencies of all frame configurations**

| | Frame 1 (Bare Frame) | Frame 2 | Frame 3 | Frame 4 |
|---|---|---|---|---|
| **Mode 3, $f_3$** | 7.23 Hz | 6.56 Hz | 6.02 Hz | 6.07 Hz |
| | | 9.27% | | |
| | | | 16.74% | |
| | | | | 16.04% |
| | | Mean = 6.22 Hz and Stdev = 0.30 | | |

Fig. 6 shows the deformation behaviours of respective frames. The first and second mode shapes were translated in the NS and EW directions (translational mode shape). Meanwhile, the third mode shape pattern was deformed in twisting mode in both directions (torsional mode shape). Even though the mass orientations are different between Frame 1, Frame 2, Frame 3 and Frame 4, but their translational and torsional mode shapes are identical.

Heavier mass of the upper storeys exhibits to the maximum deflection on the upper level. Likewise to all frames, the highest deflection amplitude was observed on the top storey. It is reducing when reach to the ground level.

Determination of relative displacement analysis at each level could benefit in vulnerability assessment especially in identification of excessive displacement at specific joint or weak storey. Excessive relative storey displacement is obviously observed at the mid-height of the portable steel tower. Uniform mass orientation produces the least relative displacement amplitude compared to the other mass irregularities. However, alternating mass orientation showed the weakest distribution of maximum relative displacement in translational and torsional mode shapes.

Inconsistent trend of maximum relative displacement amplitudes were observed on Frame 1 and Frame 2 under torsional mode shape. However, opposite illustrations were given by Frame 3 and Frame 4. This inconsistency could be strongly influenced by unprecise steel fabrication of slotted connectors. Additional gap between elements (beam and column) at respective connector connections may allow the joint to freely displaced especially under irregular mass orientations.

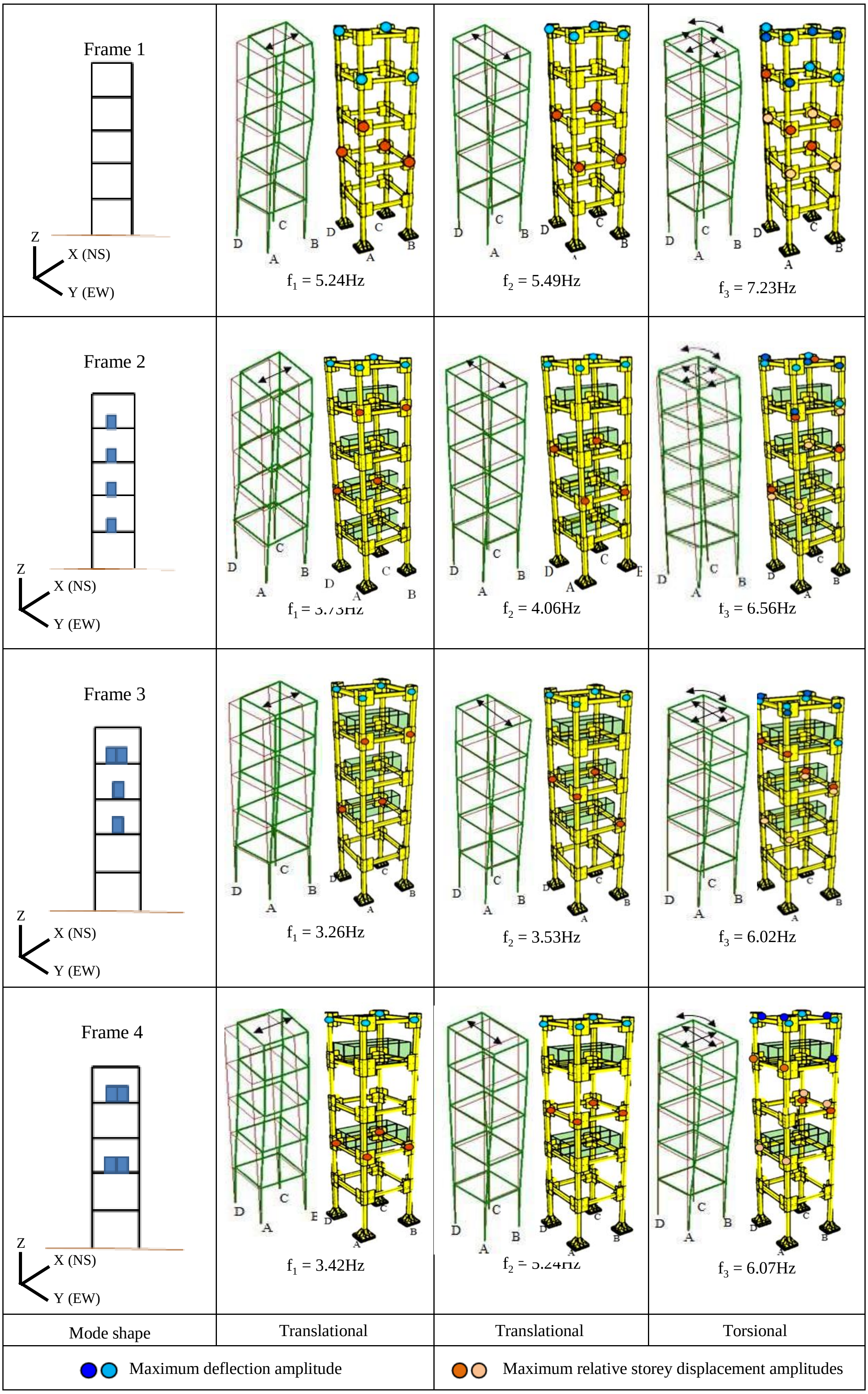



**Fig. 6 - Mode shapes, the maximum deflection amplitudes and the maximum relative floor displacement amplitudes of PostFrame**

## 5. Conclusions

Configurations or mass arrangement is important to be considered for safety and serviceability of buildings especially when exposed to dynamic loads or ambient excitations. It is clearly showed that, the predominant frequencies have significantly reduced under uniform mass and irregular mass configurations. The effect of mass irregularity on the PostFrame should not be neglected when the reduction of natural frequency could reach 25% (from the $1^{st}$ mode), 33% (from the $2^{nd}$ mode) and 75% (from the $3^{rd}$ mode) if compared to the predominant frequencies of the uniform mass orientation. From the mode shape illustrations, the maximum displacement amplitude occurred at top level and start reducing to the ground. Uniform mass distribution shows the least relative displacement amplitude due to identical distribution of mass on each level. In contrast to relative displacement amplitude, when the maximum relative displacement amplitudes were accumulated at mid-height levels. Even though the modes shapes among all predominant frequencies are almost comparable, excessive storey displacement are quite significant to ascending mass irregularities compared to the other frames' configurations.

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