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# Seismic Assessment of Steel Moment Frames with Irregularity in Mass and Stiffness

**E. Chabokan[1*], I. Faridmehr[2]**

1. M.sc., Candidate, Islamic Azad University, Dezful branch, Dezful, Iran
2. Assistant Professor, Girne American University, Kyrenia / TRNC, Cyprus

Corresponding author: *s.k.k-co@live.com*

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## ABSTRACT

Irregularity, consider to be one of the main reasons of buildings collapse in recent earthquakes. Irregularity also affects the seismic behavior and maximum capacity of structures. The effect of mass and stiffness irregularity was evaluated in this research using static and dynamic analysis. Three frames with 5, 10 and 15 stories with a 20% and 50% increase in mass of the middle stories and a 20% and 50% decrease in the ground level and middle stories were investigated separately. Maximum drift, first mode period, mass participation coefficient, and base shear force were evaluated using a developed program in MATLAB and SAP2000 based on finite element method. The results showed that changes in mass and stiffness causes a maximum increase of shear force by 14% and 5% in short and tall frames respectively. Maximum drift and the longest period in short frame occurred when the stiffness of ground level was decreased by 50 percent. In addition, such irregularity causes around 85% increase in mass participation coefficient in both short and tall frames.

## 1. Introduction

The failure or weakness of structure starts from discontinuity or irregularity. This discontinuity may be in teams of mass, geometry and stiffness of building or structure. Enormous changes in

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stiffness and mass render the dynamic characteristics of these buildings different from the ‘regular’ building. For example, lower stories of residential buildings normally used for business or store accordingly, the mass distribution is change. Setbacks in high-rise structures are common in city centers as result of artistic value or urban regulations. Therefore, it is vital need for structural engineers to have an adequate understanding of the seismic behavior of buildings with irregularity in stiffness, mass or strength along their height. This particular issue has also been acknowledged by current seismic norm and practice e.g. FEMA-356. 2000, Eurocode. 2003 [1,2]. If the mass of each stories is more than 150 percent of the mass of the nearby storeies, the building consider to be irregular and dynamic analysis should be carried out for structures higher than 20 m in height or has a first-mode period longer than 0.5 second. Previous analytical researches on buildings with mass irregularity in height e.g., Ali-Ali and Krawinkler [3] have shown that such irregularity had a limited impact on the seismic behavior of structures. Meanwhile, bracing system and shear wall is often changing or even remove in lower levels for parking or commercial purposes. Stiffness-soft irregularity defines where lateral stiffness of story is less than 70 percent of above story or 80 percent of average stiffness of the three above stories.

The structure irregularity has been investigated by many researchers using numerical and analytical approaches. Valmundsson and Nau [4], Al-Ali and Krawinkler and Chintanpakdee and Chopra [5]. provides in-depth analysis in this particular issue. Valmundsson and Nau mainly consider the adequacy of simplified seismic design recommendation when applied to frames with irregularity in height. Al-Ali and Krawinkler followed by Chintanpakdee and Chopra carried out investigations on the influence of vertical irregularities on the seismic behavior of mid-rise structures. Ko and Lee [6] performed shaking table tests to evaluate the seismic behavior of multi-story scaled RC frame designed according to the Korean seismic regulation, having three types of irregularity at the lower story. Results confirm that lateral deformation at the lower stories of was reduced significantly because of shear wall. Athanassiadou [7] evaluated seismic behavior of some irregular RC structures designed based on EC8. The results showed that the seismic behavior of all frames was satisfactory. In recent years S.Varadharajan and V.K. Sehgal [8] proposed that irregularity in mass has the least effect on structural performance while stiffness irregularity has the most effect. Sarkar et al. [9] recommended new approaches of identifying irregularity in frames, in accordance with dynamic characteristics (stiffness and mass). They proposed regularity index which take into account the changes in stiffness and mass. Ebrahimi Nezhad and Mehdi Poursha [10] have studied seismic evaluation of vertically irregular building frames with stiffness, strength, combined-stiffness-and-strength and mass irregularities. In this study, the effects of different types of irregularity along the height on the seismic responses of moment resisting frames were investigated using nonlinear dynamic analysis. Furthermore, the applicability of consecutive modal pushover (CMP) procedure, using the nonlinear response history analysis (NL-RHA) and Modal pushover analysis (MPA) method for computing the seismic demands of vertically irregular frames is studied. The results show that the CMP and MPA methods can accurately compute the seismic demands of vertically irregular buildings. Jiji Anna Varughese, and Devdas Menon [11] have studied displacement-based seismic design of open ground storey buildings. Open ground storey (OGS) buildings are characterized by the sudden reduction of stiffness in the ground storey with respect to the upper infilled storeys. This study suggests a modification of existing displacement-based design (DBD) procedure by proposing a new lateral load distribution. Salar Manie [12] have studied the collapse response assessment of low-rise buildings with irregularities in plan. Results demonstrate that substantial differences exist between the behavior of regular and irregular buildings in terms of lateral load capacity and collapse margin ratio. Also, results indicate that current seismic design parameters could be non-conservative for buildings with high levels of plan eccentricity and such structures do not meet the target “life safety” performance level based on safety margin against collapse. The adverse effects of plan irregularity on collapse safety of structures are more pronounced as the number of stories increases. A. R. Vijayanarayanan, Rupen Goswami [13] have studied identifying stiffness irregularity in buildings using fundamental lateral mode shape. A simple procedure is presented to estimate storey stiffness using natural period and associated mode shape. Results of linear elastic time-history analyses indicate that the proposed procedure captures the irregularity in storey stiffness in both low- and mid-rise buildings.

According to the literature, mainly base shear and displacement were considered with regards to mass and stiffness irregularity. The present study is motivated by the need to take into consideration the other dynamic characteristics for irregular frames. This research focuses on short and tall frames with mass and stiffness irregularity in height. Three frames with 5, 10 and 15 stories with mass and stiffness discrepancies in middle and ground level stories were analyzed using static, response spectrum and time history methods. In addition, MATLAB was used for parametric study in this research.

## 2. Research methodology and case studies

### 2.1. Case studies specifications

In this research three frames with 5, 10 and 15 stories were designed in SAP2000 according to AISC seismic regulations[14]. The height of frame's storeies and the length of spans were 3 and 5 meters respectively. The frames were considered to be located in hazardous seismic regions and used for residential purposes. The initial frames designed with uniform mass in which the system of frame were intermediate moment frames and the dead and live load were 3 and 1 tons/m2 respectively. Figure 1 shows sections of frames, and Table 1 shows beam and column sections properties.

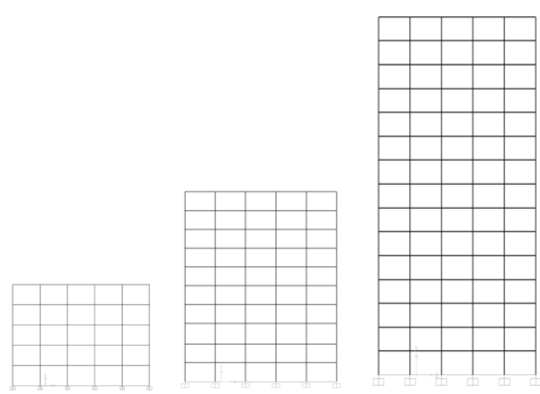


**Fig. 1.** Sections of frames.

**Table. 1**
Beam and column sections of frames.

| Frame type | Story | Column section | Beam section |
|---|---|---|---|
| st5 | 1.2.3 | W12x120 | IPE500 |
| | 4.5 | W8x67 | IPE360R |
| st10 | 1.2.3 | W12x190 | IPE450V |
| | 4.5.6.7 | W10x112 | IPE360R - IPE450V |
| | 8.9.10 | W8x58 | IPE360R |
| st15 | 1.2.3 | W12x230 | IPE500O |
| | 4.5.6 | W12x170 | IPE500O - IPE400R |
| | 7.8.9 | W12x120 | IPE400R |
| | 10.11.12 | W10x112 | IPE400R - IPE360R |
| | 13.14.15 | W8x58 | IPE360R |

## 2.2. Response spectrum and time-history analysis

To perform the seismic analysis of a structure, generally the time-history record is required. Nevertheless, it is not possible to have such records at each and every location. On the other hand, the response spectrum analysis may not carried out only based on the peak ground acceleration 'PGA' as the response of the structure depend upon the frequency content of ground motion and its own dynamic properties. Response spectrum can be interpreted as the locus of maximum response of a SDOF system for given damping ratio. Response spectra thus helps in obtaining the peak structural responses under linear range, which can be used for obtaining lateral forces developed in structure due to earthquake thus facilitates in earthquake-resistant design of structures. Consider a SDOF system subjected to earthquake acceleration, $\ddot{x}_g(t)$ the equation of motion is given by

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = -m\ddot{x}_g(t) \tag{1}$$

where

$m$ is mass, $\ddot{x}(t)$ is acceleration, $c$ is damping factor, $\dot{x}(t)$ is velocity, $k$ is stiffness, $x(t)$ is displacement, $\ddot{x}_g(t)$ is base acceleration. The Eq.1 can be re-written as

$$\ddot{x}(t) + 2\xi\omega_0\dot{x}(t) + \omega_0^2x(t) = -\ddot{x}_g(t) \tag{2}$$

where

$\omega_0$ is frequency $\xi$ is damping ratio, $\omega_d$ is damped frequency

$$\omega_0 = \sqrt{k/m} \qquad and \qquad \xi = \frac{c}{2m\omega_0} \qquad and \qquad \omega_d = \omega_0\sqrt{1-\xi^2}$$

Using Duhamel's integral, the solution of SDOF system initially at rest is given by Agrawal and Shrikhande [15].

$$x(t) = -\int_0^t \ddot{x_g}(\tau) \frac{e^{-\xi\omega_0(t-\tau)}}{\omega_d} ins\omega_d(t-\tau)d_\tau \quad (3)$$

The maximum displacement of the SDOF system having parameters of $\xi$ and $\omega_0$ subjected to specified earthquake motion, $\ddot{x}(t)$, is expressed by

$$|x(t)|_{max} = \left|\int_0^t \ddot{x_g}(\tau) \frac{e^{-\xi\omega_0(t-\tau)}}{\omega_d} ins\omega_d(t-\tau)d_\tau\right|_{max} \quad (4)$$

The relative displacement spectrum is defined as,

$$S_d(\xi, \omega_0) = |x(t)|_{max} \quad (5)$$

Similarly, the relative velocity spectrum, $S_v$ and absolute acceleration response spectrum, $S_a$ are expressed as

$$S_v(\xi, \omega_0) = |\dot{x}(t)|_{max} \quad (6)$$

$$S_a(\xi, \omega_0) = |\ddot{x_a}(t)|_{max} \quad (7)$$

This approach consider only the maximum values of member forces and displacements in each mode of vibration by means of smooth design spectra that are the average of several earthquake motions. Response spectra are curves plotted between maximum response of SDOF system subjected to specified earthquake ground motion and its time period (or frequency).

Direct-integration time-history analysis is a nonlinear, dynamic analysis method in which the equilibrium equations of motion are fully integrated as a structure is subjected to dynamic loading. Analysis involves the integration of structural properties and behaviors at a series of time steps which are small relative to loading duration. The equation of motion under evaluation is given as follows:

$$[M]\{\ddot{u}\} + [K]\{u\} = [M]\{I\}\ddot{u_g} \quad (8)$$

By transforming the equations of motion Eq. (8) from physical coordinates to normal coordinates gives

$$M_n\ddot{y_n} + K_n y_n = L_n \ddot{u_g} \quad (9)$$

where

$$M_n = \{\emptyset_n\}^T[M]\{\emptyset_n\} \quad (10)$$

$$K_n = \{\emptyset_n\}^T[K]\{\emptyset_n\} = \omega_n^2 M_n \quad (10)$$

$$L_n = \{\emptyset_n\}^T[M]\{1\} \quad (12)$$

By dividing Eq.(9) to $M_n$, the equation of motion in each mode can be written as follow

$$\ddot{y}_n + \omega_n^2 y_n = \lambda_n \ddot{u}_g \tag{13}$$

Where $\omega_n$ is the frequency of each mode and $\lambda_n$ is the mass contribution coefficient in that particular mode. The sum of $\lambda_n$ of all structure's modes is 1. By considering damping it was supposed that the shape mode vectors are orthogonal to damping matrix. In this situation by having damping coefficient in each mode, $\xi_n$ , the motion equation can be written as follow

$$\ddot{y}_n + 2\xi_n \omega_n \dot{y}_n + \omega_n^2 y_n = \lambda_n \ddot{u}_g \tag{14}$$

To solve this equation Duhamel integral is normally use. Figure.2 shows the time-history record used in this research where the peak ground acceleration and time of earthquake are *0.18g* and *54.13* second respectively.

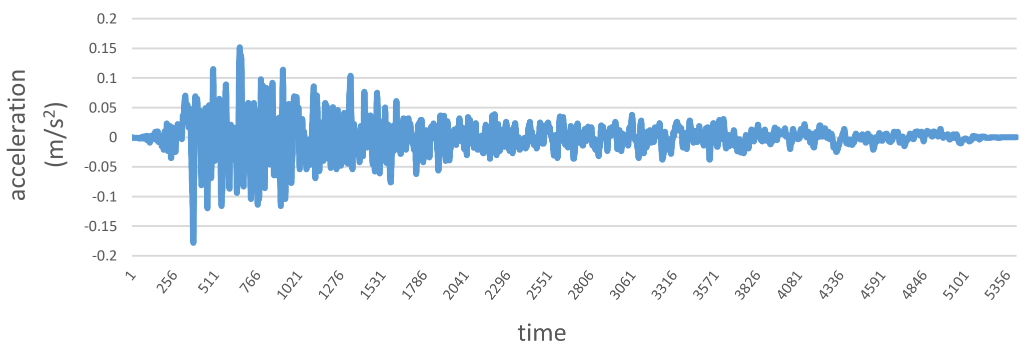



**Fig. 2.** time-acceleration records of earthquake.

## 3. Results and discussion

### 3.1. Base shear

Figure 3 shows that in 5 story frame shear force increases up to 5.3% and 13.5% by increasing the mass of story by 20% and 50% respectively. However, it decreases 4.2% and 10.2% as the stiffness decreases by 20% and 50% respectively. Nevertheless, reduction in the stiffness of middle story does not affect shear force significantly. In fact, 50% increment in the mass of middle story and 50% decrease in the stiffness of ground level has the most effect on shear force in 5 story frame.

Figure 4 indicate that shear force increases in 10 story frame up to 2.7% and 4.8% by increasing mass of middle story by 20% and 50% respectively. 20% reduction in the stiffness of ground level story does not have any significant influence on base shear but by 50% decrease, shear force increases 3.2%. However, shear force decreases 17% and 4.8% by lowering middle story's stiffness by 20% and 50% respectively. Indeed, 50% increase in the mass of middle story has the most effect on the base shear of 10 story frame. Figure 5 representing results of 15 story frame where increasing the middle story's mass by 20% and 50% causes 2% and 4.9% increment in base shear respectively. 20% and 50% reduction in the stiffness of ground level story causes 1.2% and 3.4% increases shear force comparing to the initial frame. But reducing the stiffness of middle story by 20% and 50%, decreases the base shear force by 1.6% and 4.7% respectively. Thus it can be said that 50% mass increment and 50% decrease in stiffness of middle story has the most impact on base shear.

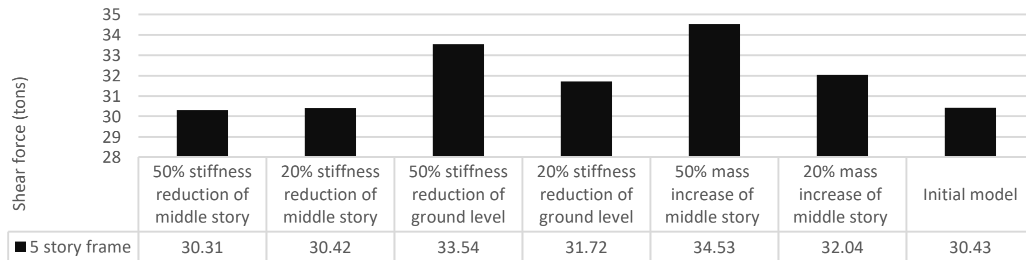



**Fig. 3.** Shear force results of 5 story frame.

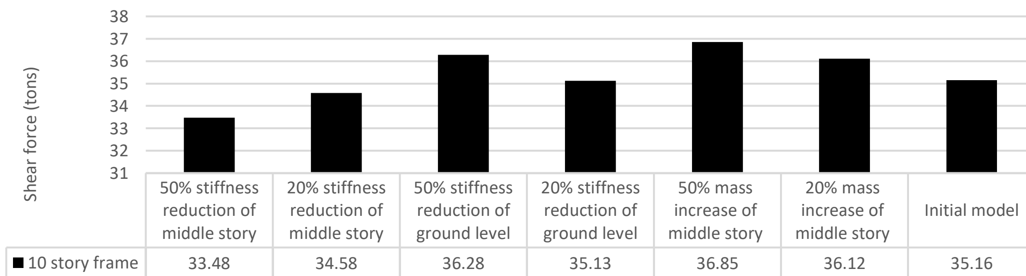



**Fig. 4.** Shear force results of 10 story frame.

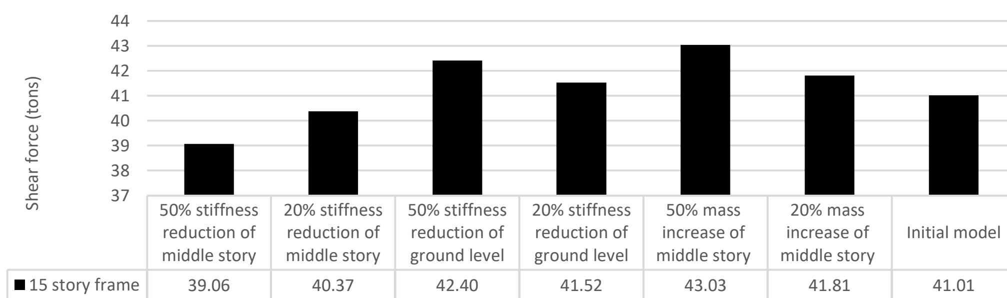



**Fig. 5.** Shear force results of 15 story frame.

## 3.2. Evaluation of mode shapes of frames in response spectrum analysis

According to the mode shape of 5, 10 and 15 story frames, it is found out that variation in the ground level story's stiffness, have significant change while changing the stiffness of middle story lead to less influence as shown in Figure 6 to 8.

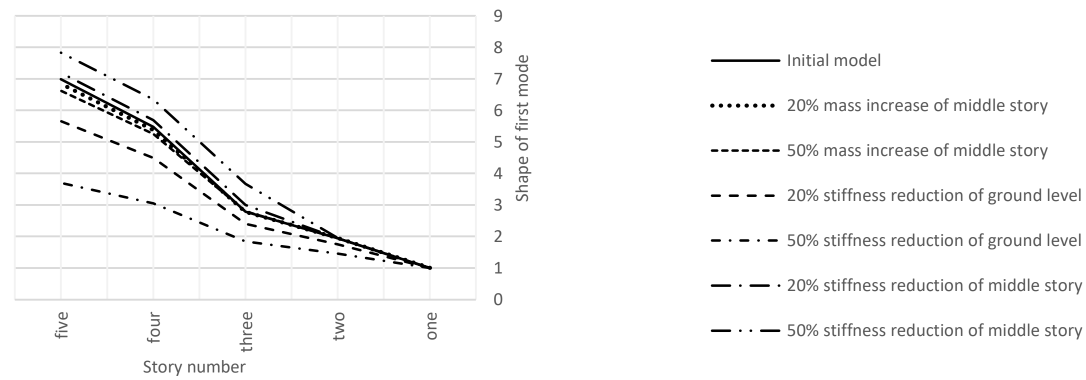



**Fig. 6.** shape of first mode in 5 story frame.

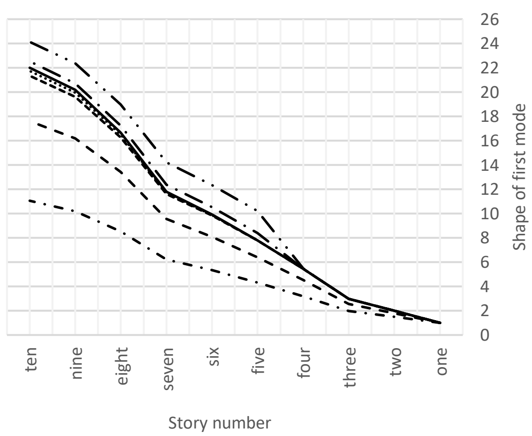



**Fig. 7.** shape of first mode in 10 story frame.

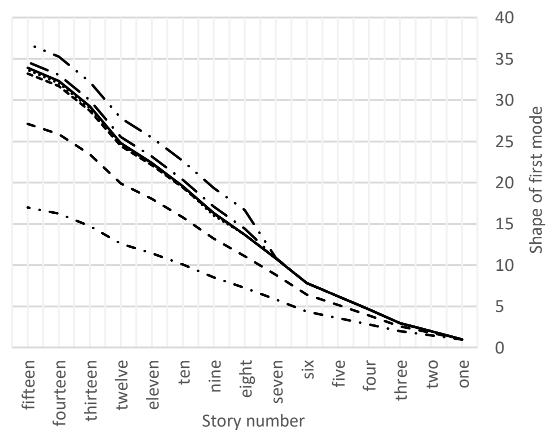
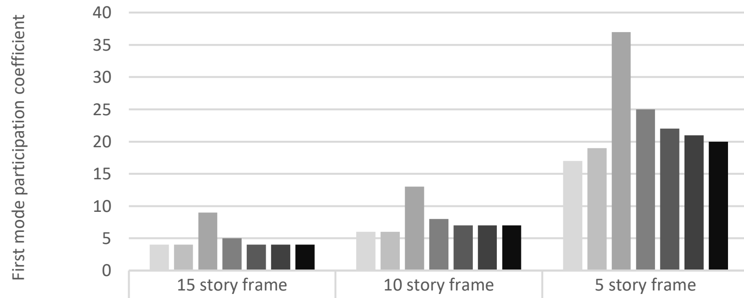



**Fig. 8.** shape of first mode in 15 story frame.

## 3.3. Mass participation of first mode

Figure 9 shows that in 5 story frame 20% and 50% increment of middle story's mass and 20% and 50% stiffness reduction of ground level increases first mode participation. By increasing the stiffness by 50% in ground level, its participation coefficient reaches its maximum of 85%. 20% and 50% reduction of the stiffness of middle story, decreases the participation coefficient by 5% and 15% respectively. In 10 story frame, variation in mass does not affect the participation coefficient of the first mode, but by decreasing the stiffness of ground level by 20% and 50%, the participation coefficient of first mode decreases 14% and 8.5% respectively. Lowering the middle story's stiffness, reduces the first mode's participation coefficient by 14%. Increasing the mass and decreasing the stiffness does not affect the participation coefficient of 15 story frame but 20% and 50% increase in the stiffness of ground level, increases the participation of first mode by 25% and 125%.

Generally, the maximum mass participation coefficient of first mode happens in 5 story frame and as the frame gets taller, the effect of participation of first mode reduces. Also by decreasing the stiffness of ground level to 50%, maximum change in participation coefficient of first mode was observed.

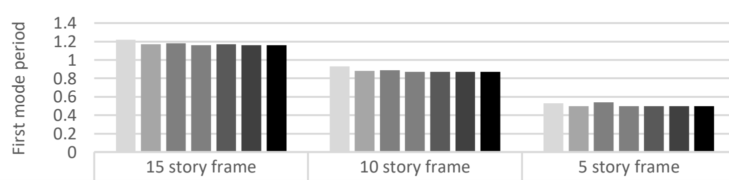



| | 15 story frame | 10 story frame | 5 story frame |
|---|---|---|---|
| Initial model | 4 | 7 | 20 |
| 20% mass increase of middle story | 4 | 7 | 21 |
| 50% mass increase of middle story | 4 | 7 | 22 |
| 20% stiffness reduction of ground level | 5 | 8 | 25 |
| 50% stiffness reduction of ground level | 9 | 13 | 37 |
| 20% stiffness reduction of middle story | 4 | 6 | 19 |
| 50% stiffness reduction of middle story | 4 | 6 | 17 |

**Fig. 9.** First mode participation coefficient of structure.

## 3.4. Evaluation of first mode period of frames

By examining period results of first mode of studied frames in Figure 10, mass variation of middle story and 20% reduction of the stiffness of ground level and middle story does not affect the mode periods of short and tall frames. In 5 story frame, when the stiffness of ground level is reduced by 50%, maximum period of first mode occurs. While in 10 and 15 story frames maximum periods of first mode happens when the stiffness of middle story decreases 50%. In other words, by increasing the frame’s height, the effect of stiffness variation of middle story on first mode’s period increases; And generally as the structure gets taller, first mode period increases as well.

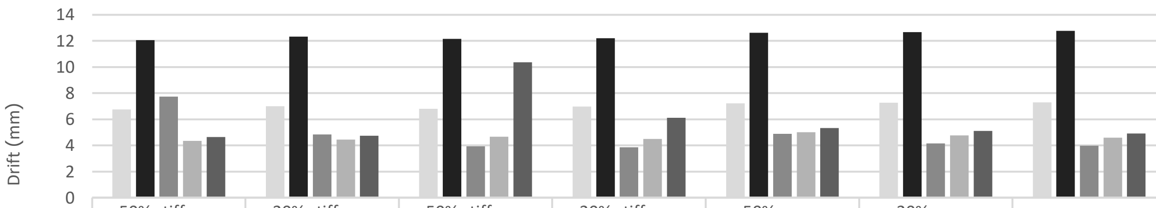



| | 15 story frame | 10 story frame | 5 story frame |
|---|---|---|---|
| Initial model | 1.16 | 0.87 | 0.5 |
| 20% mass increase of middle story | 1.16 | 0.87 | 0.5 |
| 50% mass increase of middle story | 1.17 | 0.87 | 0.5 |
| 20% stiffness reduction of ground level | 1.16 | 0.87 | 0.5 |
| 50% stiffness reduction of ground level | 1.18 | 0.89 | 0.54 |
| 20% stiffness reduction of middle story | 1.17 | 0.88 | 0.5 |
| 50% stiffness reduction of middle story | 1.22 | 0.93 | 0.53 |

**Fig. 10.** First mode period of 5, 10 and 15 story frame story frames.

## 3.5. Evaluation of drift

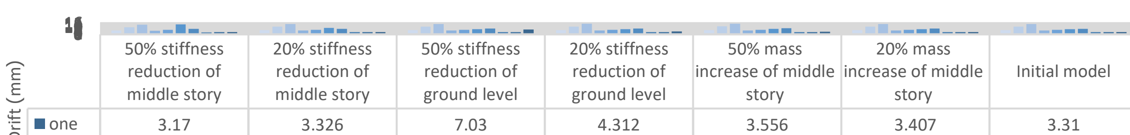
According to the Figure 11 it is observed that increasing the mass of middle story does not have a significant effect on drift. Maximum drift is happened at 4th story. 50% reduction in the stiffness of ground level has the most effect on increasing displacement of stories that maximum value happens at ground level with 111% increment in displacement. According to 2800 regulations, calculated allowed displacement for the stories of 5 story frame is 18.75 mm.




| | 50% stiffness reduction of middle story | 20% stiffness reduction of middle story | 50% stiffness reduction of ground level | 20% stiffness reduction of ground level | 50% mass increase of middle story | 20% mass increase of middle story | Initial model |
|---|---|---|---|---|---|---|---|
| one | 4.64 | 4.75 | 10.37 | 6.12 | 5.33 | 5.11 | 4.92 |
| two | 4.36 | 4.44 | 4.66 | 4.5 | 5 | 4.77 | 4.59 |
| three | 7.74 | 4.85 | 3.92 | 3.85 | 4.9 | 4.14 | 3.99 |
| four | 12.04 | 12.31 | 12.14 | 12.21 | 12.61 | 12.67 | 12.77 |
| five | 6.75 | 7 | 6.81 | 6.977 | 7.21 | 7.27 | 7.3 |

**Fig. 11.** Drift of 5 story frame.

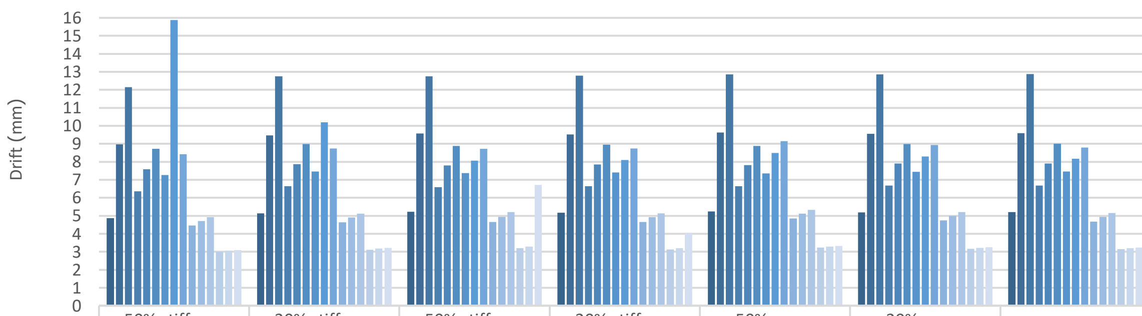
According to the Figure 12 it can be seen that increasing middle story's mass has not a sensible effect on drift. 50% reduction of stiffness of ground level followed by 120% drift increment of ground level has the most influence on the drift of this story. Moreover 50% stiffness reduction of middle story influences on its drift and indeed increases it by 94%. As it can be observed, maximum displacement happened in upper most stories (8th and 9th story). According to the 2800 regulations, allowable displacement of 10 story frame is 15 mm and the value of 8th story's displacement was close to that. Following the presented results, it can be said that if the structure be designed slightly weaker than it is now, it would be still resistance to the earthquake.




| | 50% stiffness reduction of middle story | 20% stiffness reduction of middle story | 50% stiffness reduction of ground level | 20% stiffness reduction of ground level | 50% mass increase of middle story | 20% mass increase of middle story | Initial model |
|---|---|---|---|---|---|---|---|
| one | 3.17 | 3.326 | 7.03 | 4.312 | 3.556 | 3.407 | 3.31 |
| two | 3.113 | 3.267 | 3.403 | 3.373 | 3.5 | 3.348 | 3.258 |
| three | 3.008 | 3.156 | 3.246 | 3.243 | 3.394 | 3.235 | 3.148 |
| four | 7.586 | 7.932 | 8.075 | 8.116 | 8.562 | 8.132 | 7.921 |
| five | 14.15 | 9.126 | 7.389 | 7.428 | 7.901 | 7.463 | 7.286 |
| six | 6.248 | 6.451 | 6.55 | 6.573 | 6.607 | 6.438 | 6.479 |
| seven | 5.305 | 5.496 | 5.604 | 5.615 | 5.679 | 5.506 | 5.56 |
| eight | 13.781 | 14.454 | 14.74 | 14.821 | 15.046 | 14.576 | 14.669 |
| nine | 10.165 | 10.831 | 11.003 | 11.138 | 11.277 | 10.981 | 10.941 |
| ten | 5.531 | 5.942 | 5.99 | 6.112 | 6.146 | 6.028 | 5.968 |

**Fig. 12.** Drift of 10 story frame.

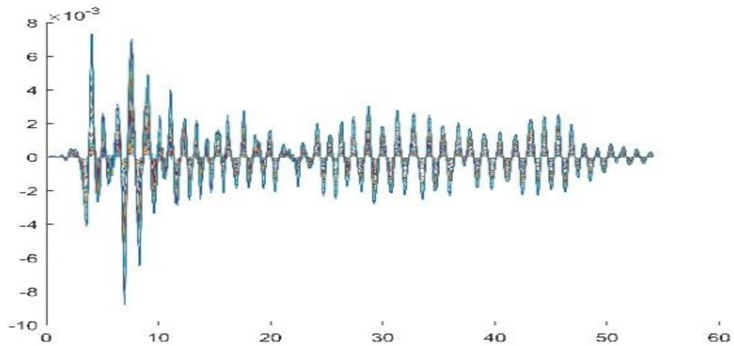
According to the Figure 13, it is observed that mass increment of middle story has not a sensible effect on drift. 50% stiffness reduction of ground level followed by 107% increment of drift in ground level has the most effect on the drift of this story. Moreover 50% stiffness reduction of middle story influences on its drift and indeed increases it by 94%. As it can be observed, maximum displacement happened in upper most stories (13$^{th}$ and 14$^{th}$ story). According to the 2800 regulations, allowable displacement of 15 story frame is 15 mm and the value of 8$^{th}$ story's displacement was close to that.




| | 50% stiffness reduction of middle story | 20% stiffness reduction of middle story | 50% stiffness reduction of ground level | 20% stiffness reduction of ground level | 50% mass increase of middle story | 20% mass increase of middle story | Initial model |
|---|---|---|---|---|---|---|---|
| one | 3.1 | 3.211 | 6.711 | 4.05 | 3.32 | 3.253 | 3.234 |
| two | 3.066 | 3.179 | 3.29 | 3.2 | 3.289 | 3.221 | 3.202 |
| three | 3.002 | 3.115 | 3.193 | 3.13 | 3.23 | 3.161 | 3.138 |
| four | 4.927 | 5.12 | 5.203 | 5.136 | 5.322 | 5.204 | 5.159 |
| five | 4.715 | 4.906 | 4.948 | 4.915 | 5.115 | 4.995 | 4.942 |
| six | 4.464 | 4.646 | 4.656 | 4.65 | 4.858 | 4.742 | 4.681 |
| seven | 8.414 | 8.744 | 8.713 | 8.735 | 9.148 | 8.928 | 8.794 |
| eight | 15.869 | 10.188 | 8.073 | 8.109 | 8.492 | 8.298 | 8.165 |
| nine | 7.266 | 7.456 | 7.367 | 7.41 | 7.35 | 7.436 | 7.462 |
| ten | 8.714 | 8.986 | 8.886 | 8.947 | 8.884 | 8.99 | 9.01 |
| eleven | 7.588 | 7.871 | 7.798 | 7.851 | 7.821 | 7.902 | 7.909 |
| twelve | 6.365 | 6.638 | 6.594 | 6.637 | 6.637 | 6.685 | 6.684 |
| thirteen | 12.143 | 12.744 | 12.761 | 12.78 | 12.858 | 12.864 | 12.87 |
| fourteen | 8.979 | 9.468 | 9.576 | 9.517 | 9.619 | 9.555 | 9.584 |
| fifteen | 4.863 | 5.141 | 5.228 | 5.171 | 5.235 | 5.184 | 5.213 |

**Fig. 13.** Drift of 15 story frame.

An earthquake with a time-acceleration record presented in Figure 14 and an acceleration of 0.18PGA was used in this research. Dynamic analysis of studied models was done using MATLAB. By evaluation the effect of mass and stiffness variation on time history response to displacement in the roof story of a frame, it was observed that minor changes in initial stiffness effects the whole structure's behavior significantly. Considering Table 2, it can be seen that in 5 story frame, increasing mass and stiffness of middle story by 50% causes the most displacement value in the frame. In 10 story frame, by increasing mass, displacement of stories increases as well and by reducing the stiffness, displacement decreases either. By 50% increase of middle story's mass, maximum displacement occurs in the frame. Also in 15 story frame, displacement reaches its maximum value by 50% reduction in the stiffness of ground level and middle story. However, mass increment doesn't have a sensible effect on displacement.




Time (sec)

**Fig. 14.** time history of maximum displacement of roof 15 story with 50% stiffness reduction of middle story.

**Table. 2**
Maximum displacement of roof story in time history analysis(mm).

| | 5 story frame | 10 story frame | 15 story frame |
|---|---|---|---|
| Initial model | 3.11 | 8.56 | 8.16 |
| 20% increase in the mass of middle story | 3.12 | 8.72 | 8.24 |
| 50% increase in the mass of middle story | 3.18 | 8.8 | 8.4 |
| 20% stiffness reduction of ground level | 3.11 | 8.56 | 8.16 |
| 50% stiffness reduction of ground level | 3.03 | 8.16 | 8.64 |
| 20% stiffness reduction of middle story | 3.11 | 8.32 | 8.48 |
| 50% stiffness reduction of middle story | 3.22 | 6.33 | 8.88 |

## 4. Conclusion

The evaluation of Response Spectrum and time history analysis of studied frames with implication of mass and stiffness different distributions indicates:

1. In 5 story frame, increasing mass and decreasing the stiffness of ground level, increases base shear. But reducing the stiffness of middle story does not affect base shear. In 10 and 15 story frames, increasing mass and decreasing the stiffness of ground level increases base shear. However, decreasing the stiffness of middle story lowers the base shear. As the structure is taller, the effect of decreasing the middle story's stiffness on base shear increases comparing to the base frame. But the effect of mass change decreases.

2. In both tall and short frames, the shape number of first mode decreases as the mass in the middle story and stiffness in ground level changes and variation in stiffness of middle story increases first mode number of frame.

3. As the structure is taller, reduction in the stiffness of ground level increases the participation of first mode. This reduction in the middle story has not a significant effect on participation coefficient. Mass changes in short frames increases participation of first mode and the first mode has not a sensible effect in tall structures.

4. Mass variations in middle story does not affect the period of first mode in both tall and short structures. The maximum period in short frames happens in a case that the stiffness of ground level reduces to 50%. This is while this happens to the tall frames when the stiffness of middle story decreases by 50%. Indeed, as the frame gets taller, the influence of changes in middle story's stiffness on the first mode's period increases. And generally by increasing of the height of stories, period of first mode increases.

5. In both short and tall frames, increasing mass of the middle story does not have a sensible effect on drift. 50% reduction of ground level's stiffness has the most influence on drift.

6. By examining the displacement of stories, according to the time history analysis, in 5 story frames, by 50% increment in mass and stiffness reduction of middle story, the displacement increases. In 10 story frames, displacement increases by increasing mass and it decreases by reduction of stiffness. In 15 story frame, mass increment has not a sensible effect on displacement. But by 50% decrease in stiffness of middle and ground level story, displacement reaches its maximum level.

## Nomenclature

| | |
|---|---|
| m | mass |
| $\ddot{x}(t)$ | acceleration |
| $c$ | damping factor |
| $\dot{x}(t)$ | velocity |
| $k$ | stiffness |
| $x(t)$ | displacement |
| $\omega_0$ | frequency |
| $\xi$ | damping ratio, |
| $\omega_d$ | damped frequency |
| $S_v$ | relative velocity spectrum |
| $S_a$ | absolute acceleration response spectrum |
| $\omega_n$ | the frequency of each mode |
| $\lambda_n$ | the mass contribution coefficient in particular mode |

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# Appendix

## Writing code for response spectrum analysis in matlab software

```
syms('wn2')
format short
n_dof=15;
stiff_mat=[53718.2424, 53718.2424, 53718.2424, 31742.60263, 31742.60263, 31742.60263, 15893.51326,
15893.51326, 15893.51326, 11853.55244, 11853.55244, 11853.55244, 5061.07033, 5061.07033, 5061.07033];
mass_mat=[8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8];
stiff_total=zeros(n_dof);
mass_total=zeros(n_dof);
for i=1:n_dof;
for j=1:n_dof;
if j==i;
mass_total(i, j)=mass_mat(i);
if j<n_dof;
stiff_total(i, j)=stiff_mat(i)+stiff_mat(i+1);
end
elseif(j-i)==1;
stiff_total(i, j)=-stiff_mat(i+1);
elseif(j-i)==-1;
stiff_total(i, j)=stiff_total(j, i);
else
```

```
stiff_total(i, j)=stiff_total(i, j);
mass_total(i, j)=mass_total(i, j);
end
end
end
stiff_total(i, j)=stiff_mat(n_dof)
mass_total
matris=stiff_total-wn2.*mass_total;
det_1=det(matris)
dd=det_1;
aa=double(solve(dd));
wn_total2=sort(aa)
wn_total=(wn_total2).^.5;
wn_total=sort((wn_total))
matris_mod_total=[];
fi_total=[];
for i=1:n_dof;
wn2_t_i=wn_total2(i);
matris_mod=double(subs(matris, wn2, wn2_t_i));
matris_mod_total=[matris_mod_total; matris_mod];
[U, R]= eig(matris_mod);
fi_totali=U(:, i);
fi1_to_one=1/fi_totali(1);
fi_totali=fi1_to_one*fi_totali;
fi_total=[fi_total, fi_totali];
end
fi_total
T_total=(2*pi)*(wn_total).^(-1)
num_teif=round((T_total)/0.02);
Teif=xlsread('C:\Soil II - Risk High.xlsx');
for i=1:n_dof;
sd_total(i)=Teif(num_teif(i), 4);
sv_total(i)=Teif(num_teif(i), 3);
sa_total(i)=Teif(num_teif(i), 2);
end
for i=1:n_dof
M(i)=fi_total(:,i)'*mass_total*fi_total(:, i);
end
G=ones(15, 1)
for i=1:n_dof
L(i)=fi_total(:, i)'*mass_total*G
end
for i=1:n_dof
Landa(i)=L(i)/M(i)
end
for i=1:n_dof
```

```
u_1max=0.168*[(fi_total(1, 1)*Landa(1)*sd_total(1))^2+(fi_total(1, 2)*Landa(2)*sd_total(2))^2+(fi_total(1, 3)*Landa(3)*sd_total(3))^2]^.5;
u_2max=0.168*[(fi_total(2, 1)*Landa(1)*sd_total(1))^2+(fi_total(2, 2)*Landa(2)*sd_total(2))^2+(fi_total(2, 3)*Landa(3)*sd_total(3))^2]^.5;
u_3max=0.168*[(fi_total(3, 1)*Landa(1)*sd_total(1))^2+(fi_total(3, 2)*Landa(2)*sd_total(2))^2+(fi_total(3, 3)*Landa(3)*sd_total(3))^2]^.5;
u_4max=0.168*[(fi_total(4, 1)*Landa(1)*sd_total(1))^2+(fi_total(4, 2)*Landa(2)*sd_total(2))^2+(fi_total(4, 3)*Landa(3)*sd_total(3))^2]^.5;
u_5max=0.168*[(fi_total(5, 1)*Landa(1)*sd_total(1))^2+(fi_total(5, 2)*Landa(2)*sd_total(2))^2+(fi_total(5, 3)*Landa(3)*sd_total(3))^2]^.5;
u_6max=0.168*[(fi_total(6, 1)*Landa(1)*sd_total(1))^2+(fi_total(6, 2)*Landa(2)*sd_total(2))^2+(fi_total(6, 3)*Landa(3)*sd_total(3))^2]^.5;
u_7max=0.168*[(fi_total(7, 1)*Landa(1)*sd_total(1))^2+(fi_total(7, 2)*Landa(2)*sd_total(2))^2+(fi_total(7, 3)*Landa(3)*sd_total(3))^2]^.5;
u_8max=0.168*[(fi_total(8, 1)*Landa(1)*sd_total(1))^2+(fi_total(8, 2)*Landa(2)*sd_total(2))^2+(fi_total(8, 3)*Landa(3)*sd_total(3))^2]^.5;
u_9max=0.168*[(fi_total(9, 1)*Landa(1)*sd_total(1))^2+(fi_total(9, 2)*Landa(2)*sd_total(2))^2+(fi_total(9, 3)*Landa(3)*sd_total(3))^2]^.5;
u_10max=0.168*[(fi_total(10, 1)*Landa(1)*sd_total(1))^2+(fi_total(10, 2)*Landa(2)*sd_total(2))^2+(fi_total(10, 3)*Landa(3)*sd_total(3))^2]^.5;
u_11max=0.168*[(fi_total(11, 1)*Landa(1)*sd_total(1))^2+(fi_total(11, 2)*Landa(2)*sd_total(2))^2+(fi_total(11, 3)*Landa(3)*sd_total(3))^2]^.5;
u_12max=0.168*[(fi_total(12, 1)*Landa(1)*sd_total(1))^2+(fi_total(12, 2)*Landa(2)*sd_total(2))^2+(fi_total(12, 3)*Landa(3)*sd_total(3))^2]^.5;
u_13max=0.168*[(fi_total(13, 1)*Landa(1)*sd_total(1))^2+(fi_total(13, 2)*Landa(2)*sd_total(2))^2+(fi_total(13, 3)*Landa(3)*sd_total(3))^2]^.5;
u_14max=0.168*[(fi_total(14, 1)*Landa(1)*sd_total(1))^2+(fi_total(14, 2)*Landa(2)*sd_total(2))^2+(fi_total(14, 3)*Landa(3)*sd_total(3))^2]^.5;
u_15max=0.168*[(fi_total(15, 1)*Landa(1)*sd_total(1))^2+(fi_total(15, 2)*Landa(2)*sd_total(2))^2+(fi_total(15, 3)*Landa(3)*sd_total(3))^2]^.5;
u_1max, u_2max, u_3max, u_4max, u_5max, u_6max, u_7max, u_8max, u_9max, u_10max, u_11max, u_12max, u_13max, u_14max, u_15max
end
for i=1:n_dof
f_1_1max=[mass_total(1, 1)*fi_total(1, 1)*Landa(1)*sa_total(1)]*.42;
f_2_1max=[mass_total(2, 2)*fi_total(2, 1)*Landa(1)*sa_total(1)]*.42;
f_3_1max=[mass_total(3, 3)*fi_total(3, 1)*Landa(1)*sa_total(1)]*.42;
f_4_1max=[mass_total(4, 4)*fi_total(4, 1)*Landa(1)*sa_total(1)]*.42;
f_5_1max=[mass_total(5, 5)*fi_total(5, 1)*Landa(1)*sa_total(1)]*.42;
f_6_1max=[mass_total(6, 6)*fi_total(6, 1)*Landa(1)*sa_total(1)]*.42;
f_7_1max=[mass_total(7, 7)*fi_total(7, 1)*Landa(1)*sa_total(1)]*.42;
f_8_1max=[mass_total(8, 8)*fi_total(8, 1)*Landa(1)*sa_total(1)]*.42;
f_9_1max=[mass_total(9, 9)*fi_total(9, 1)*Landa(1)*sa_total(1)]*.42;
f_10_1max=[mass_total(10, 10)*fi_total(10, 1)*Landa(1)*sa_total(1)]*.42;
f_11_1max=[mass_total(11, 11)*fi_total(11, 1)*Landa(1)*sa_total(1)]*.42;
f_12_1max=[mass_total(12, 12)*fi_total(12, 1)*Landa(1)*sa_total(1)]*.42;
f_13_1max=[mass_total(13, 13)*fi_total(13, 1)*Landa(1)*sa_total(1)]*.42;
```

```
f_14_1max=[mass_total(14, 14)*fi_total(14, 1)*Landa(1)*sa_total(1)]*.42;
f_15_1max=[mass_total(15, 15)*fi_total(15, 1)*Landa(1)*sa_total(1)]*.42;
f_1_1max, f_2_1max, f_3_1max, f_4_1max, f_5_1max, f_6_1max, f_7_1max, f_8_1max, f_9_1max, f_10_1max,
f_11_1max, f_12_1max, f_13_1max, f_14_1max, f_15_1max
V_mode_1max=f_1_1max+f_2_1max+f_3_1max+f_4_1max+f_5_1max+f_6_1max+f_7_1max+f_8_1max+f_9_1m
ax+f_10_1max+f_11_1max+f_12_1max+f_13_1max+f_14_1max+f_15_1max
V_mode_1max
End
```

## Writing code for time-history analysis in MATLAB software

```
syms('wn2');
format short;
n_dof=15;
stiff_mat=[53718.2424, 53718.2424, 53718.2424, 31742.60263, 31742.60263, 31742.60263, 15893.51326,
15893.51326, 15893.51326, 11853.55244, 11853.55244, 11853.55244, 5061.07033, 5061.07033, 5061.07033];
mass_mat=[8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8, 8];
kesai_modal=[0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05];
force_time=xlsread('C:\1.xlsx');
%p=force_time(:, 2:n_dof+1)';
%%% if acceleration on the structure
p_acc=[];
p=force_time(:, 2)';
for kk=1:n_dof;
p_ac=-mass_mat(kk).*p;
p_acc=[p_acc; p_ac];
end
p=p_acc;
%%%%%%%%%%%%%end if
time=force_time(:, 1)';
interval=time(2)-time(1); dt=interval;
stiff_total=zeros(n_dof);
mass_total=zeros(n_dof);
damp_total=zeros(n_dof);
for i=1:n_dof;
for j=1:n_dof;
if j==i;
mass_total(i, j)=mass_mat(i);
if j<n_dof;
stiff_total(i, j)=stiff_mat(i)+stiff_mat(i+1);
end
elseif(j-i)==1;
stiff_total(i, j)=-stiff_mat(i+1);
elseif(j-i)==-1;
stiff_total(i, j)=stiff_total(j, i);
else
stiff_total(i, j)=stiff_total(i, j);
```

```
mass_total(i, j)=mass_total(i, j);
end
end
end
stiff_total(i, j)=stiff_mat(n_dof)
mass_total
matris=stiff_total-wn2.*mass_total;
det_1=det(matris)
dd=det_1;
aa=double(solve(dd));
wn_total2=double(sort(aa))
wn_total=(wn_total2).^.5;
wn_total=sort((wn_total))
matris_mod_total=[];
fi_total=[];
Li_total=[];
khat_total=[];
p_modal_total=[];
Z=[];
for i=1:n_dof;
wn2_t_i=wn_total2(i)
matris_mod=double(subs(matris, wn2, wn2_t_i));
matris_mod_total=[matris_mod_total; matris_mod];
[U, R]= eig(matris_mod);
fi_totali=U(:, i);
fi1_to_one=1/fi_totali(1);
fi_totali=fi1_to_one*fi_totali;
fi_total=[fi_total, fi_totali];
Li=(fi_totali'*mass_total*fi_totali)^.5;
khati=(fi_totali'*stiff_total*fi_totali);
Li_total=[Li_total, Li];
khat_total=[khat_total, khati];
zi=fi_totali/Li;
Z=[Z, zi];
zi_trans=zi';
p_modal=zi_trans*p;
p_modal_total=[p_modal_total; p_modal];
end
fi_total
Li_total;
khat_total;
Z;
p_modal_total;
%% in this segment will calculate all movement
qtt_total=[];
for i_dof=1:n_dof;
stiff=wn_total2(i_dof);
```

```
mass=1;
damp=2*wn_total(i_dof)*kesai_modal(i_dof);
time=[]; p_i=[];
p_i=p_modal_total(i_dof,:);
time=force_time(:, 1)';
k=stiff; %input('individual stiffness=') %input all stiffness
m=mass; % input('individual mass=')% input all mass
c=damp; %2*kesai*wn
qdat=0; q2dat=0; q=0; dqdat=0; dq2dat=0; dp=0; qt=[]; qdatt=[]; q2datt=[]; qt=[0]; qtt=[0];
for i=2:numel(time);
qdat=qdat+dqdat;
q2dat=q2dat+dq2dat;
khat=k+((3/dt)*c)+((6/dt^2)*m);
phat=(p_i(i)-p_i(i-1))+c*(3*qdat+(dt/2)*q2dat)+m*(((6/dt)*qdat)+3*q2dat);
dq=phat/khat;
dqdat=(3/dt)*dq-3*qdat-.5*q2dat*dt;
dq2dat=(6/(dt^2))*dq-(6/dt)*qdat-3*q2dat;
qdatt=[qdatt, qdat];
q2datt=[q2datt, q2dat];
q=q+dq;
qt=[qt, q];
qtt=[qtt, qt];
end
qtt_total=[qtt_total; qt];
end
xtt_total=Z*qtt_total;
F_mass_mode=mass_mat*fi_total*wn_total2*qtt_total;
F_mass_mode=F_mass_mode'
size_F_mass_mode=size(F_mass_mode);
F_storey_mode=zeros(size_F_mass_mode(1), n_dof+1);
for i=n_dof+1:-1:2;
AAA=F_storey_mode(:, i);
BBB=F_mass_mode(:, i-1);
F_storey_mode(:, i-1)=AAA+BBB;
end
F_storey_mode=F_storey_mode(:, 1:n_dof)
V=F_storey_mode(:, 1)
V_max=max(V)
hold on
plot(time, xtt_total)
```