VOL. 15, NO. 23, DECEMBER 2020 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

EFFECT OF GEOMETRIC CONFIGURATION ON THE SEISMIC RESPONSE OF VERTICALLY IRREGULAR REINFORCED CONCRETE FRAME STRUCTURES

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ABSTRACT

The residential and commercial construction demand is on rise worldwide. This development has introduced more critical engineering and architectural applications and innovations. Soft story buildings or towers are a few common examples of these applications. This study presents an inclusive investigation to study the effect of geometric configuration on the seismic response of vertically regular and irregular reinforced concrete frame structures. The main geometric factors will be slenderness ratio, defined as height to width ratio of the structure, and plan aspect ratio, defined as length to width ratio of the structure. The irregular frames will be introduced with the common real life construction feature known as vertical structural irregularities specifically soft story frame cases. The location of irregularity will vary in three locations in the vertical plane viz. bottom, middle and top. The objective of the investigation is to estimate the seismic demand for each slenderness and plan aspect geometric ratio. The variation in geometric ratios involve five slenderness ratios as 1, 1.5, 2, 2.5 and 3 as well as five plan aspect ratios as 1.2, 2.4, 3.6, 4.8 and 6. Response spectrum analysis is undertaken for the seismic response interpretation using STAAD Pro software employing finite element technique. The results indicate that the increase of regular frame slenderness leads to slight increase in shear response but higher displacements and drift. The increase in plan aspect ratio increases the frames shear response significantly with almost convergent displacements. Also the regular and irregular frames of smaller slender ratios exhibit higher lower-story displacements and drifts than the frames with higher slender ratios. The bottom irregular frames appear to be more vulnerable as compared to frames having irregularity at middle and top level.

Keywords: RC frame seismic response, vertical irregularity, slenderness ratio, plan aspect ratio, soft story.

INTRODUCTION

The seismic behavior of reinforced concrete structures is affected by the ground seismic activity, structural configuration and its geometry, inaccurate structural analysis and design, poor constructions materials and poor construction practices. However, the structural configuration is an important factor and an area of concern and research interest for the dynamic analysis since the very beginning. Within the structural configuration there are numerous parameters that affect the earthquake performance and play an essential role in the behavior of RC frame structures such as slenderness ratio and plan aspect ratios, vertical or horizontal asymmetries or irregularities and building adjacencies. The open story or soft story buildings are typical feature in construction as commonly seen in hotels and plazas (parking lot or lobby floor) which are usually taller than other floors. The increase in height directly reduces the stiffness in those particular floors and hence creates irregularity in the stiffness of structural stories. The past earthquakes like Bhuj earthquake in India, 1999 İzmit earthquake in Turkey, have clearly demonstrated the structural inadequacies of these buildings to resist the ground motion. These open soft story buildings suffered huge damages or even collapsed in certain cases which means no matter what structural precautions and safety measures are considered; the possibility of earthquake damage or even failure is high. This necessitates more analytical investigations and studies. The present study investigates the effect of slenderness ratio and plan aspect ratio on the seismic response of vertically irregular reinforced concrete frame structures with soft story placed at varying vertical plane locations.

LITERATURE REVIEW

Vertical Structural irregularities have been an important research area since early, and design codes are including more than more irregularity cases in every updated version. Arnold [1] stated that building configurations are indispensable because of complications in the seismic design. He prepared a chart form an outline of a building configuration, architectural and structural implications and preferable solution. Moehle [2] carried an experimental study on the Seismic response of four irregular reinforced concrete frames using 6 types of static and dynamic elastic and inelastic analysis procedures. He studied the discontinuities in the vertical plane irregularity type. The experimental cases were presented by discontinuing the structural walls at various levels. He concluded that standard limit analysis and static inelastic analysis deliver good measures of strength and deformation under heavy earthquake motions. Eggert V. Valmundsson [3] studied the seismic response of two-dimensional building frames with 5, 10, and 20 stories with vertical structural irregularities. The irregularities are introduced by changing the properties of one story or floor. Floor-mass ratios ranging from 0.1 to 5.0 are considered, and first-story stiffness and strength ratios varying from 1.0 to 0.5 are included. Time history analysis and equivalent lateral force methods were conducted and compared in compliance with universal building code. He concluded that the mass and stiffness criteria of Uniform Building Code (UBC) result in moderate increases of irregular structures compared to regular structures. Ali and Krawinkler [4] studied the elastic and inelastic seismic behavior of RC structures with mass, stiffness and strength irregularities. The analysis of a 10 story frames indicated that the strength irregularity has the higher roof displacement compared to the other irregularities when considered separately. The combination of the three irregularities has the maximum effect on the roof displacement. Chintanapakdee and Chopra [5] compared the seismic demands for regular and vertically irregular RC frame structures using non liner analytical approaches for a 12 story frames. They noted that combined effect of the strength and stiffness irregularities has the largest influence on seismic response. Aydin [6] evaluated the seismic Equivalent Load Effect (ELF) and time history demands for 5, 10 and 20 story with mass irregularities and concluded that the ELF method overestimates the seismic response compared to time history analysis. Naveen [9] studied the seismic response of 9-story RC building with various vertical and horizontal irregularities, 34 configurations with single irregularity, 20 configurations with combination of irregularities. He found that the mass, stiffness, vertical geometric irregularities have the maximum response in combined irregularities case.

According to the Saudi Building Code [10], every building, and portion thereof, shall be designed and constructed to resist the effects of earthquake loads when it is located in an earthquake prone zone. The building system should include the design codes requirements and specifications for structural irregularities. Intensive analytical procedures must be executed in order to determine the behavior of these structures to make them withstand the lateral load effects. Since the basic effect of soft story is stiffness or strength reduction in the vertical plane of frame structure, it is possible to be introduced in different vertical location of these frames; not necessarily first story, middle or top floors as per the actual situation.

The experimental or analytical studies are limited to only a few cases involving a number of variable parameters. Some investigations take irregularities and independent single cases neglecting the relative change of their behavior to the regular cases scenario. More investigations must be undertaken to observe the seismic behavior of RC frame structures considering major factors such as the geometric configuration. The present paper aims to focus on the effect of geometric configurations on seismic response using response spectrum approach taking into consideration the slenderness and plan aspect ratios of vertically irregular RC frames.

METHODOLOGY

A. Structural Modeling

The main objective of this paper is to study the effect of geometry in structural systems specifically reinforced concrete systems. Accordingly, a total of ten regular geometric configurations have been selected comprising of 5 for slenderness ratio and 5 for plan aspect ratios as given in Tables 1 and 2. These regular frame systems are considered as the reference cases in the comparative study with irregular profile systems which will be the vertically irregular soft story frames. X-axis is represented by the length side. The dead load and live load has been considered as 4 kN/m^2 and 2 kN/m^2 respectively.

Table-1. Slenderness geometric configurations.

Slenderness ratio	Height (m)	Length (m)	Width (m)	Number of stories
3	90	36	30	30
2.5	75	36	30	25
2	60	36	30	20
1.5	45	36	30	15
1	30	36	30	10

Table-2. Plan aspects geometric configurations.

Plan aspect ratio	Height (m)	Length (m)	Width (m)	Number of stories
6	30	180	30	10
4.8	30	144	30	10
3.6	30	108	30	10
2.4	30	72	30	10
1.2	30	36	30	10

VOL. 15, NO. 23, DECEMBER 2020 ISSN 1819-6608
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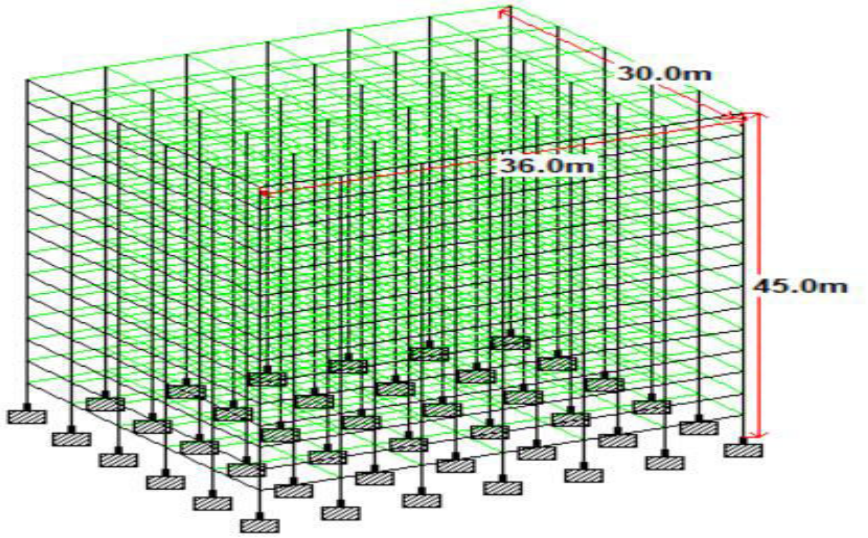

Figure-1. Regular frame geometry with slenderness ratio = 1.5.

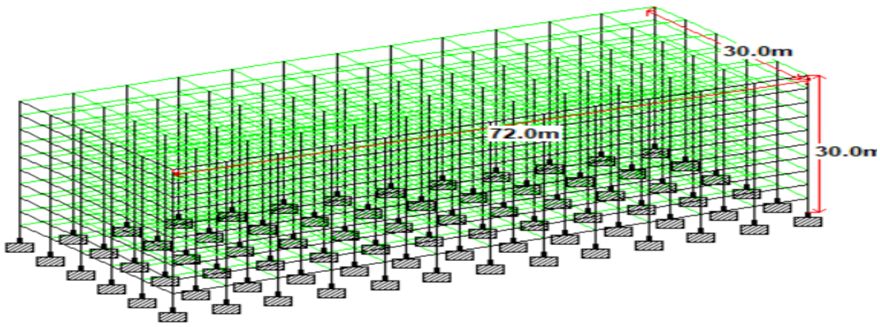

Figure-2. Regular frame geometry with plan aspect ratio = 2.4.

As illustrated in Table-1, slender frames have same plan view but the height varies from 30 m to 90 m as shown in Figure-1 while plan aspect frame lengths range from 36 m to 180 m as shown on Figure-2. The story height is kept as 3m for the regular frames and each bay has a span of 6m in both directions. Bases are fixed and lateral diaphragms are modeled as rigid. The analytical behavior of these reference cases shall determine the risk of vertical irregularities which will be introduced in three vertical plane locations (bottom, middle, top) as discussed earlier. The soft story frame cases are one story less than the regular reference cases and kept as 6 m height shown in Figures 3, 4 and 5.

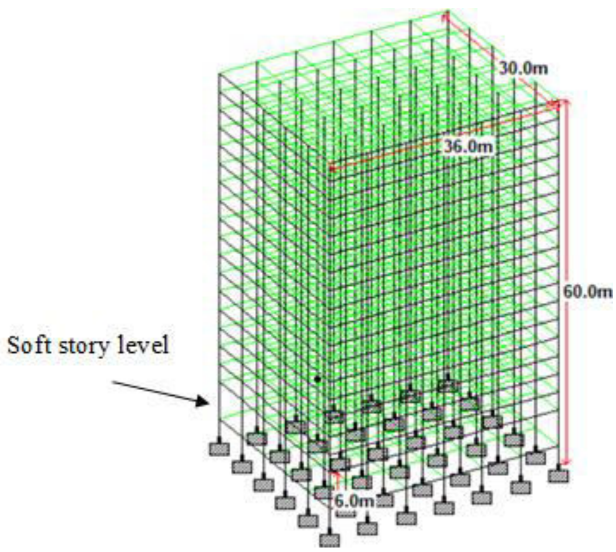

Figure-3. Frame geometry with bottom soft story and slenderness ratio = 2.

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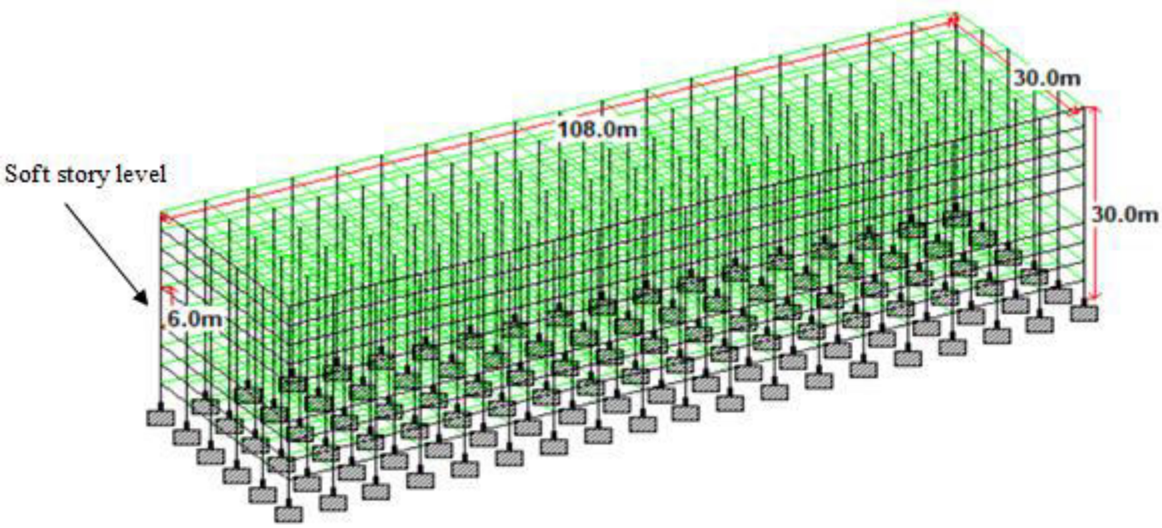

Figure-4. Frame geometry with middle soft story and plan aspect ratio = 3.6.

As shown in Figures 3, 4 and 5 the irregularity is individually located in three vertical positions and the lateral stiffness reduction in this particular soft story is expected to be less than 60% of adjacent stories. Concrete compressive strength for all cases is taken as 27.5 MPa and modulus of elasticity equals 21718.5 MPa. The structural properties are given in Table- 3. All structural elements namely beam and columns are modeled as fixed frame elements and the beam columns joints are assumed as rigid joints.

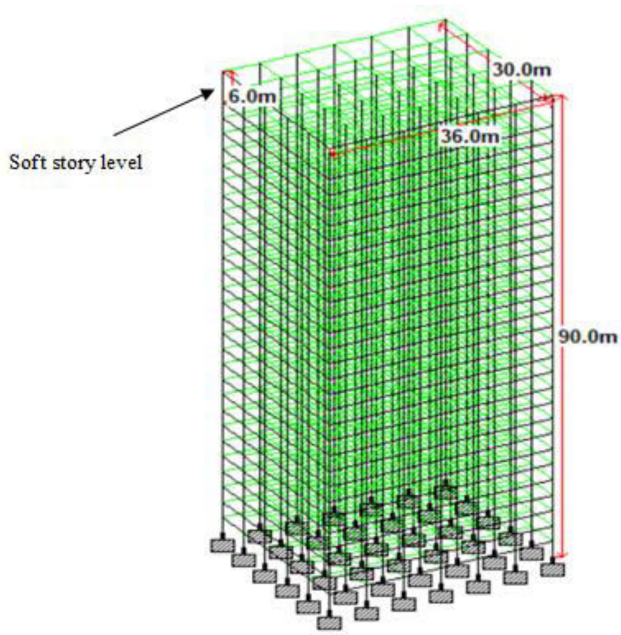

Figure-5. Frame geometry with top soft story and slenderness ratio = 3.

Table-3. General structural properties.

Property	Regular frame	Soft story frame
Beams (width×depth)	**300 mm×600 mm**	**300 mm×600 mm**
Columns	PARs 600 mm×600 mm SR1 600 mm×600 mm SR1.5 650 mm×650 mm SR2 700 mm×700 mm SR2.5 750 mm×750 mm SR3 850 mm×850 mm	PARs 600 mm×600 mm SR1 600 mm×600 mm SR1.5 650 mm×650 mm SR2 700 mm×700 mm SR2.5 750 mm×750 mm SR3 850 mm×850 mm
Story height	3 m	3 m except soft 6 m
Slabs thickness	200 cm	200 cm
Diaphragms	rigid	rigid

B. Structural Analysis Procedure

Response spectrum analysis is used to obtain the seismic response in this study. Design response spectrum development will be according to SBC 2018 [10], which provides a complete guidance for the target response spectrum. The region of study is Haql town in the Kingdom of Saudi Arabia which is considered seismically highly active. The code clearly states that in certain irregularities cases, static analysis is not allowed. The effectiveness of this dynamic approach arises from the structural dynamic concept in which the seismic response interpretation of frame structures depends on the distribution of mass and stiffness, unlike the equivalent static analysis which requires only the heights of the structures.

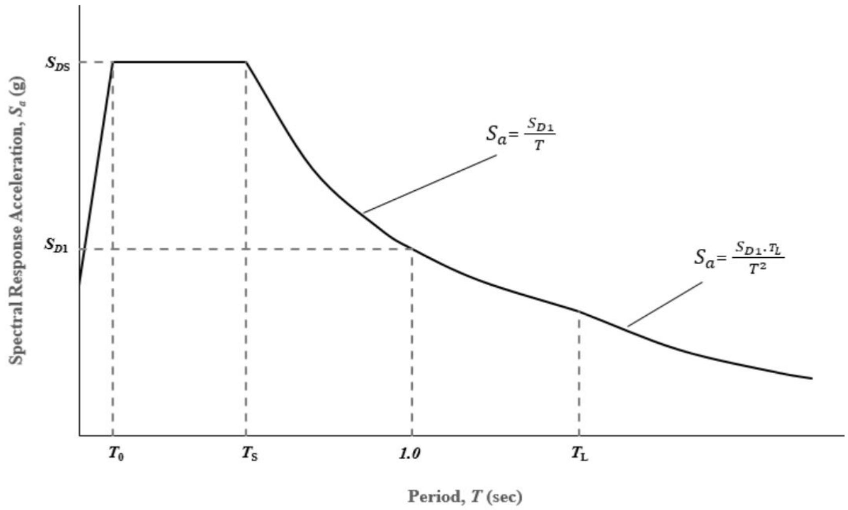

Figure-6. Design response spectrum SBC 2018 [10].

The collection of seismic parameters necessary for the target response spectrum is presented in Table-4. Here Ss is the short period spectral acceleration, S1 represents the long period 1-sec spectral acceleration, TL stands for the long-period transition period in second, R is the response modification Coefficient, I is the importance factor. These coefficients can be selected from the zooning parameters maps provided by the specific design code. The design response spectrum is developed and prepared for the analysis as shown in Figure7 and Figure-8.

Table-4. Spectral parameters.

Ss	S1	TL	Site class	R	I
100	26	6	D	5 (SMRF)	1

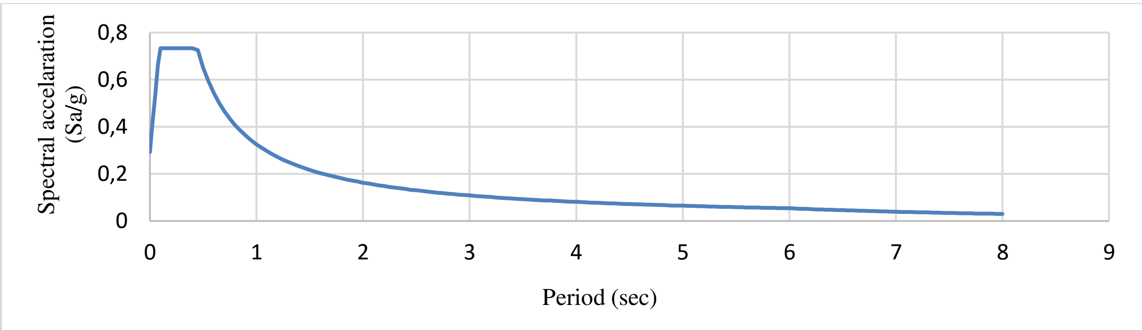

Figure-7. Target acceleration spectrum.

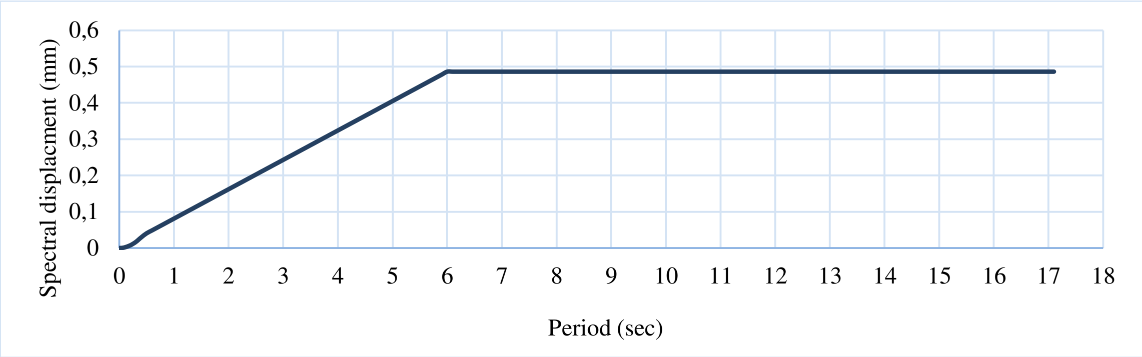

Figure-8. Target displacement spectrum.

RESULTS AND DISCUSSIONS

As stated earlier for the modeling and proposed dynamic analysis STAAD Pro, a finite element analysis based commercial software package capable of incorporating the parametric variation has been used. The study envisages outcomes in form of an appropriate and inclusive investigation in the geometric configuration effect on the seismic behavior of vertically irregular RC frame structures. For the design load combination $1.2D + 1.0E + L$, the parameters of interest include modal periods of vibration, story displacement, story drifts, base shears, and story shear forces.

Modal Fundamental Periods of Vibration (MFPV)

Modal fundamental periods of vibration or natural periods are basically the time taken by single mode to take one complete cycle of oscillation. One of the distinct advantages of dynamic analysis procedures is that these don't only consider one fundamental mode of vibration like in the static procedures but also consist of fundamental mode and additional contributions of various modes. This is what makes it more applicable and preferable for such structural aspects, from which the basis of determination of these periods require more structural details. The fundamental period in static analysis is conducted approximately and empirically, however in response spectrum analysis, modes of vibration are solved mathematically using Eigen solutions and these are directly dependent on the mass and stiffness of the structure, which indicates the reliability and effectiveness of the approach over the static approaches. Ten mode shapes are assigned and the modal fundamental mode is selected for this discussion which is shown in Figures 9 and 10, in which first column represents the MFPV for the regular frame case (i.e. denoted by R) followed by the bottom, middle, and top soft story frames (i.e. denoted by Bot, Mid and Top, respectively). The results indicate significant effect of slenderness ratios in modal behavior compared to plan aspect ratios which shows the opposite where the periods are almost identical no matter how much the plan ratio increases. The bottom soft story has the longer fundamental period overall. This enhancement indicates that the bottom irregularities are less rigid and more flexible than other vertical plane irregularities. For the plan aspect ratios also the bottom irregularities have longer period overall. The middle soft story case shows shorter periods from the bottom and yet higher than the top irregular and regular cases. The top irregular cases have slightly shorter MFPV than the regular frame cases. It is also obvious that for the higher slenderness ratios, the narrower irregularity effect accrues in the modal periods. The time difference between bottom irregularities and regular frame for SR1, SR1.5, SR2, SR2.5 and SR 3 are 0.27, 0.25, 0.25, 0.22, 0.18, and 0.14 seconds respectively. However, plan aspect ratios have the large time difference for all ratios.

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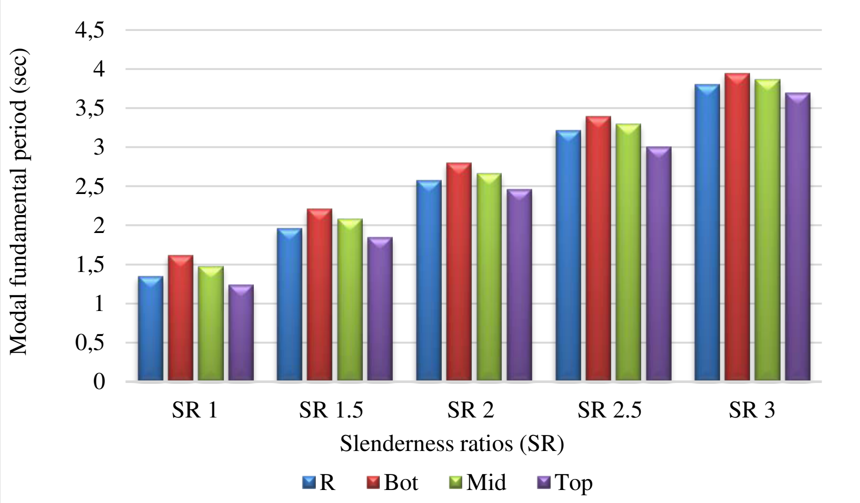

Figure-9. Modal fundamental periods of vibration (MFPV) for frames with varying slenderness ratio.

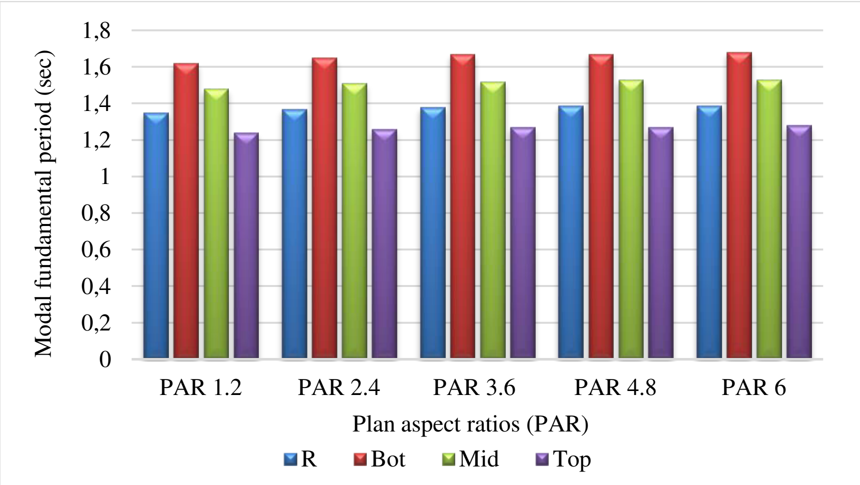

Figure-10. Modal fundamental periods of vibration (MFPV) for frames with varying aspect ratio.

Base Shear

Base shears in earthquake engineering are one of the most vital responses required for any seismic design. The shear responses in dynamic analysis are obtained by combining the shear responses due to all contributing modes. The Complete Quadratic Combination (CQC) combination method is selected for the shear response representation and shown in Figure-11 to Figure-14. It can be seen that for regular frames with varying slenderness ratios, the shears marginally increase by only 4%, despite huge increase on weight and modal periods. Whereas, for regular frames with varying plan aspect ratios, the shear response increases significantly up to 98%. This signifies the effect of plan geometry towards the seismic response. This situation can be clarified by basically summoning Newton's second law of motion on which this entire dynamic analysis is based on. For regular frames with higher slenderness ratios, the modal periods increase, these longer periods will have corresponding less spectral acceleration (Figure-7) even if the weight increased eventually less shear response is expected, however regular frames with high plan aspect ratios have almost equivalent modal periods with narrowing spectral accelerations but their weight significantly increases resulting in higher shear response.

The base shear for frames with vertical irregularities and varying slenderness ratios is shown in Figure-13. It is clear that bottom irregularity suffers significantly lesser shear response with a reduction up to 23.5% in comparison to reference regular frame cases which then progressively increases until reaching higher irregularity shear response for top soft story. This situation is expected since irregular cases have weight less than the reference case also more flexible (greater spectral accelerations). The base shear for frames with vertical irregularities and varying plan aspect ratios is shown in Figure-14. The shear response significantly increases as the plan aspect ratio increases. Furthermore, irregular plan frames tend to diverge for higher ratios which is opposite to how irregular slender frames behave.

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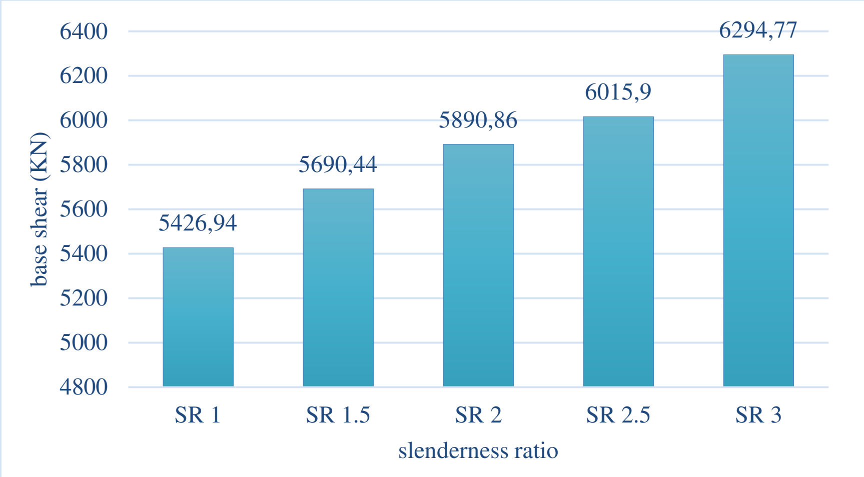


Figure-11. Base shear for regular frames with varying slenderness ratios.

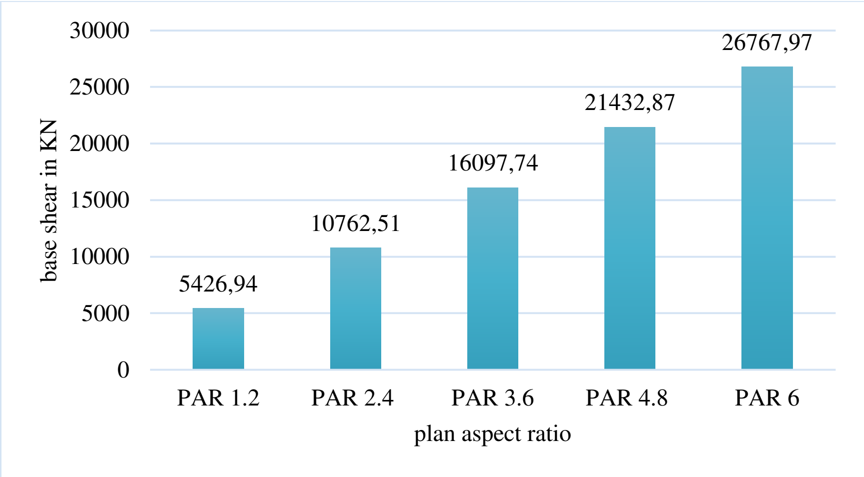
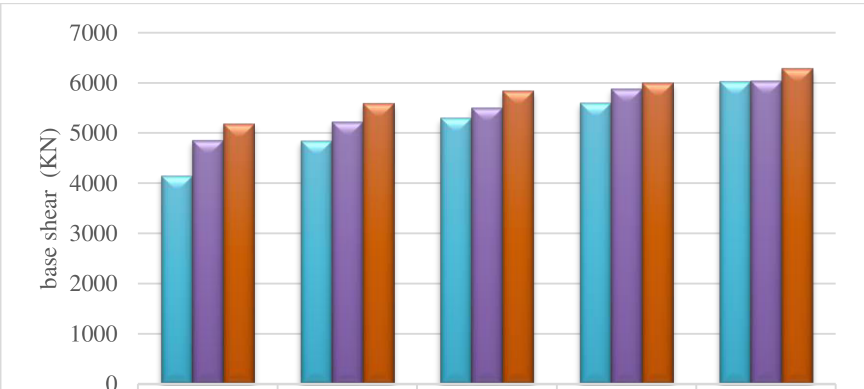


Figure-12. Base shear for regular frames with varying plan aspect ratios.



	SR 1	SR 1.5	SR 2	SR 2.5	SR 3
Bot	4150,48	4849,83	5300,95	5609,01	6029,83
Mid	4858,89	5229,95	5507,65	5884,73	6041,28
Top	5189,05	5591,13	5844,83	6000,18	6291,12

Figure-13. Base shear for frames having bottom , middle and top soft story with varying slenderness ratios.

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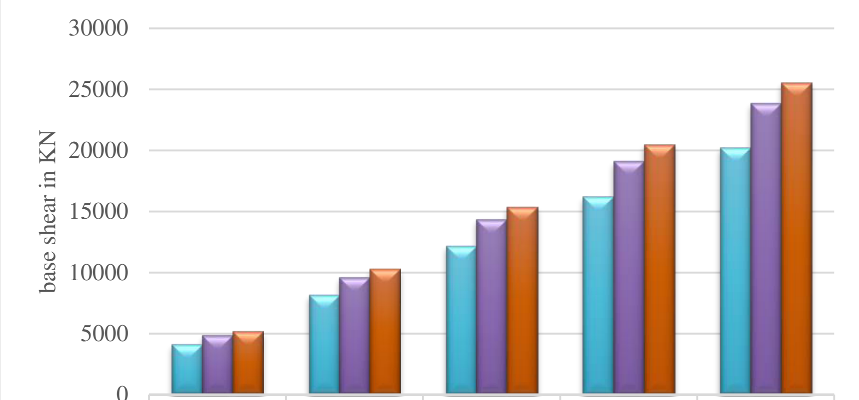

	PAR 1.2	PAR 2.4	PAR 3.6	PAR 4.8	PAR 6
Bot	4150,48	8178,06	12203,96	16229,41	20254,67
Mid	4858,89	9617,05	14374,98	19132,85	23890,69
Top	5189,05	10286,64	15384,13	20481,59	25579,04

Figure-14. Base shear for frames having bottom, middle and top soft story with varying plan aspect ratios.

Story Shears

The story shear for regular frames with varying slenderness ratios is shown in Figures-15 and the story shear for regular frames with varying plan aspect ratios is shown in Figure- 16. It can be seen that lower stories have higher shear response than the upper floors. The smaller slenderness ratios in their lower stories attract story shear almost close to larger slenderness ratios. Further the peak dynamic lateral forces acting on these frames which are the difference between adjacent story shears represent the lateral force acting on that story. For example, the lateral force acting on the top story for SR1 is equivalent to 996.35 kN as a result of the 9th story shear (2176.5 kN) minus the 10th story shear (1180.15 kN) as illustrated in Figure-15. It appears how these story shears are distributed divergently in smaller ratio and more convergent in larger ratios of reference cases. The upper stories of higher slenderness ratios gain less story shears than the frames with lower slenderness ratios. For the frames with plan aspect ratios, shears magnitude is clearly higher in lager ratios than smaller ratios. The results also show that the difference in story shear decreases as the height of building increases.

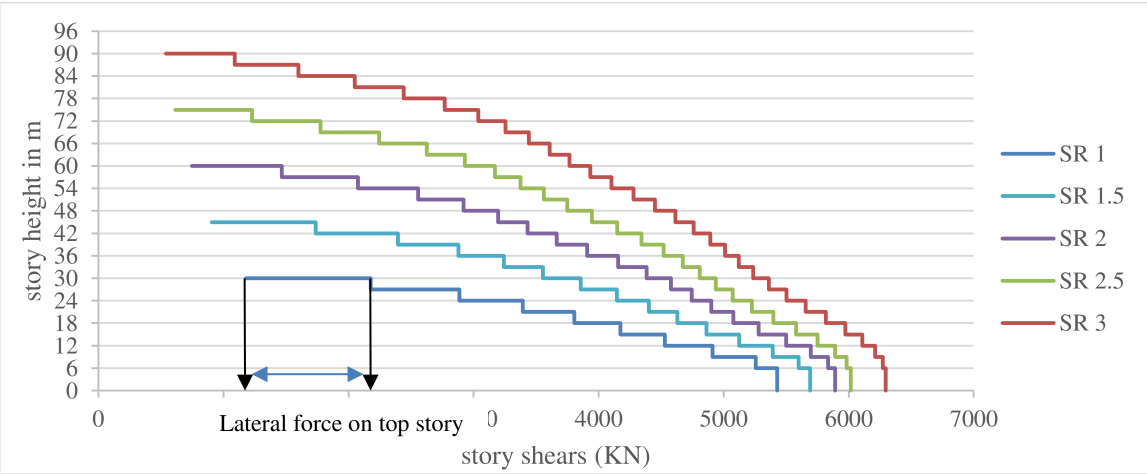

Figure-15. Story shear for regular frames with varying slenderness ratios.

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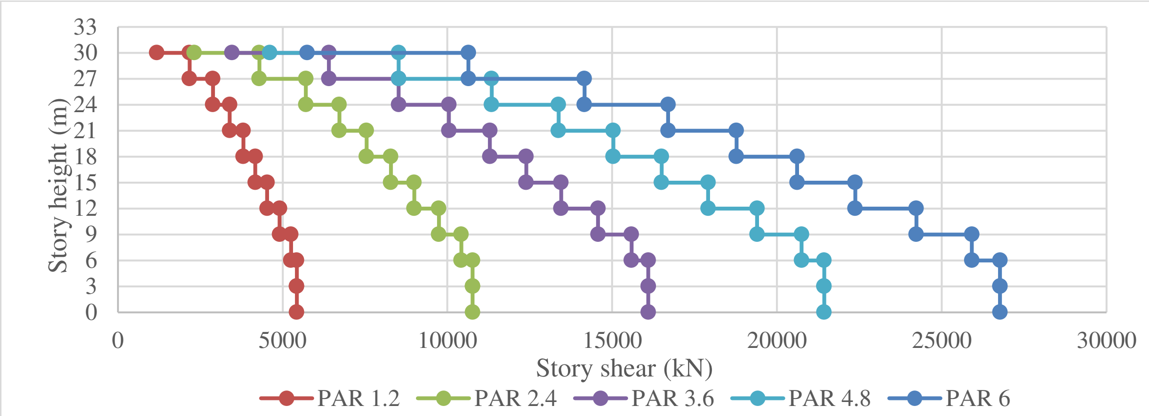

Figure-16. Story shear for regular frames with varying plan aspect ratios.

The story shear values for irregular frames with bottom soft story and varying slenderness ratios are small compared to others as shown in Figure-17. The soft story possesses higher shear than the upper stories. The story shear results for frames having middle soft story with varying slenderness ratios are shown in Figure-18 where irregular story obtains significantly higher shear results. Also, shear results for middle soft story frames are relatively higher than bottom soft cases especially at smaller slenderness ratios. The story shear results for frames having top soft story with varying slenderness ratios are shown in Figure-19 which have the closest shears to the regular reference cases. The top soft story frames tend to behave just like the reference cases except that the top story gained higher shears than typical story.

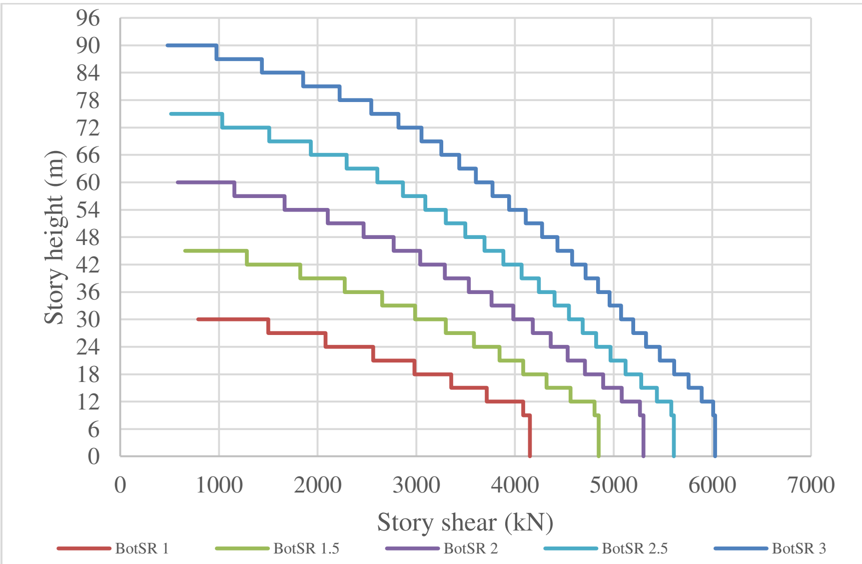

Figure-17. Story shear for frames having bottom soft story with varying slenderness ratios.

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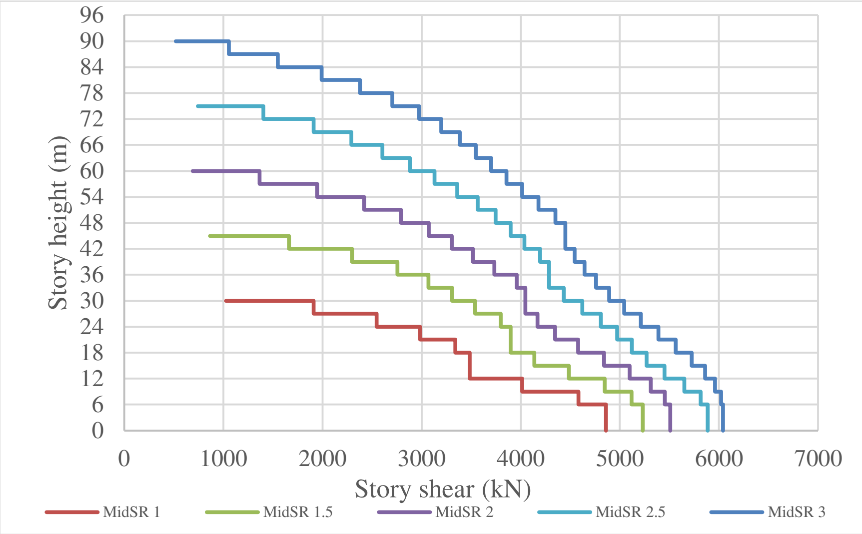

Figure-18. Story shear for frames having middle soft story with varying slenderness ratios.

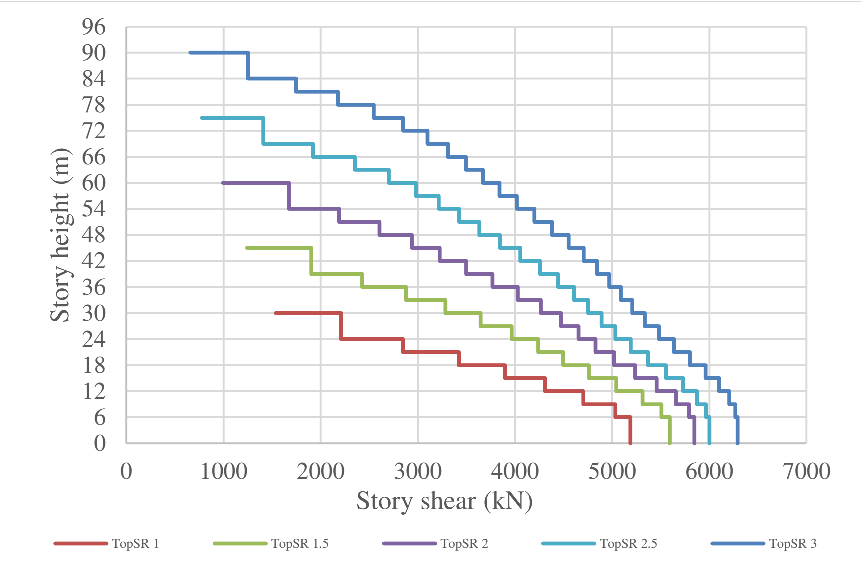

Figure-19. Story shear for frames having top soft story with varying slenderness ratios

The story shear for frames having bottom soft story with varying plan aspect ratios are shown in Figure-20. It can be seen that bottom irregular frames experience significantly less shear than the reference frame whereas the soft stories are observed to gain higher shear. As the plan aspect ratio increases, the story shear varies in similar manner as observed for frames with varying slenderness ratios. The story shear for frames having middle and top soft story with varying plan aspect ratios are shown in Figure-21 and Figure-22 respectively. The story shear variation is observed to follow the same pattern as observed for frame with varying slenderness ratio.

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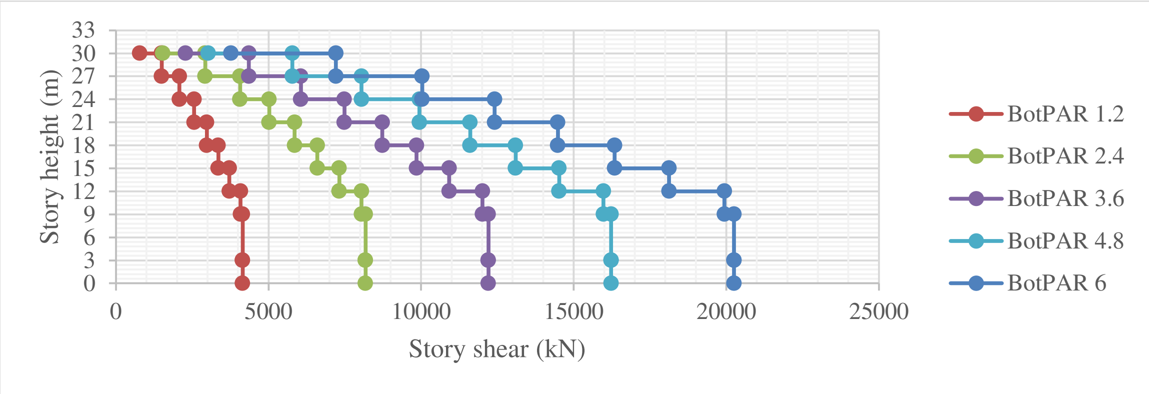

Figure-20. Story shear for frames having bottom soft story with varying plan aspect ratios.

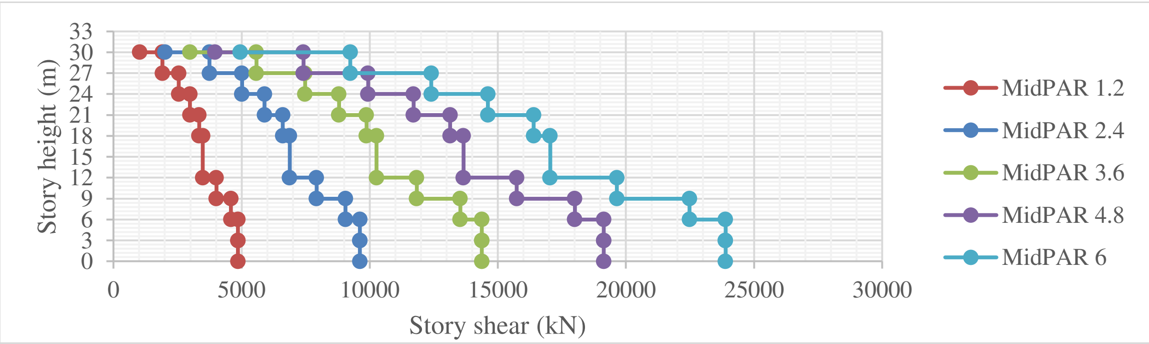

Figure-21. Story shear for frames having middle soft story with varying plan aspect ratios.

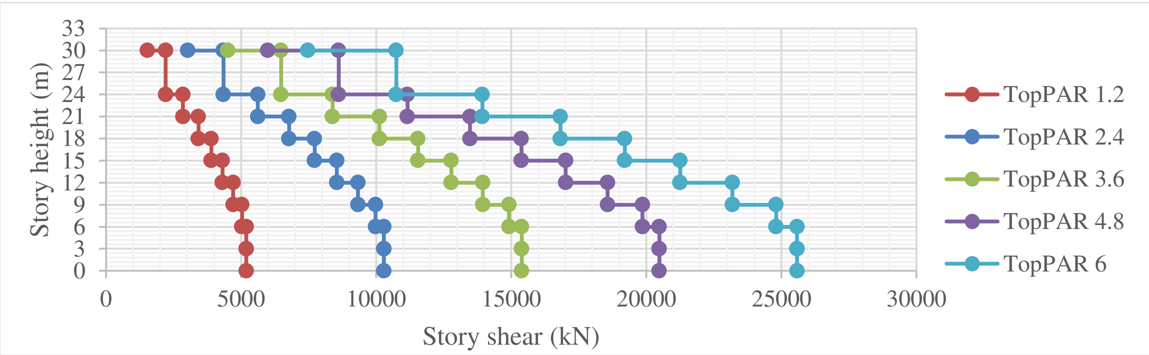

Figure-22. Story shear for frames having top soft story with varying plan aspect ratios.

From the story shear values, it can be concluded that the plan area configurations develop higher story shears than slenderness configurations which has been reported earlier by investigators [1]. These story shears which result in intensive diaphragm forces require structural solution which is not an objective in this study. However, an indication can be achieved on how this situation can intersect with other structural aspects used like horizontal structural irregularities, which means plan aspect configurations can be critical and highly vulnerable if horizontal irregularities are planned especially when combined with the vertical irregularity aspects.

Story Displacements

The story displacement determines the stability of structural elements as well as the damage predictions on nonstructural elements. The story displacement for regular frames with varying slenderness ratios are presented in Figure-23. It has been mentioned earlier that slenderness ratio in some sense maintains an inverse relationship with shear. However, for the displacement this relationship seems to be direct, As can be seen in Figure-11. the top story displacement for SR1 and SR1.5 is 28 and 41 mm respectively with increase of 46.43% and if we recall the base shears for these frames which are 5426.94 kN and 5690.44 kN with an increase of only 4.86%. This response can be justified by recalling the response spectrum component from displacement spectrum along with the acceleration spectrum shown earlier in Figure-7. The target displacement spectrum is shown in Figure-8. It is clear how displacements are directly proportional to periods which indicates how likely displacements will increase for longer periods. In light of the above from Figure-23 it is clear how higher slenderness ratio exhibits higher displacements, also smaller ratios suffer higher first stories displacements than larger ratios, i.e. first story at height of 3 m for SR1, SR1.5, SR2, SR2.5 and SR3 are 2.709 mm, 2.408 mm, 2.156 mm, 1.937 mm and 1.618 mm, respectively. It is also clear how displacements increase almost linearly for low stories.

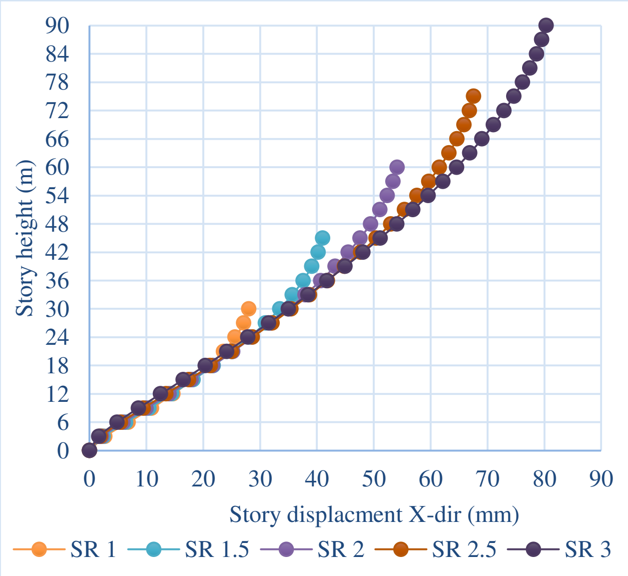

Figure-23. Story displacement for regular frames with varying slenderness ratios.

The story displacement for regular frames with varying plan aspect ratios are presented in Figure-24 and Table- 5. As already explained, displacements are effected by longer vibration periods and the performance of these frames can be predicted since they possess close modal periods of vibration as shown earlier in Figure-10. Therefore, these frames are expected to not trigger spectral displacements (Figure-8) as observed in slenderness configurations. From the Figure- 24 it is clear that plan aspect ratios marginally affect displacements response and are almost close. Higher plan aspect ratios have slightly higher displacements opposite to slender frames for the first story where story displacements of plan aspect ratios of 1.2, 2.4, 3.6, 4.8 and 6 are 2.709 mm, 2.785 mm, 2.813 mm, 2.827 mm and 2.835 mm respectively. It can be fairly concluded that displacements variations are not significant.

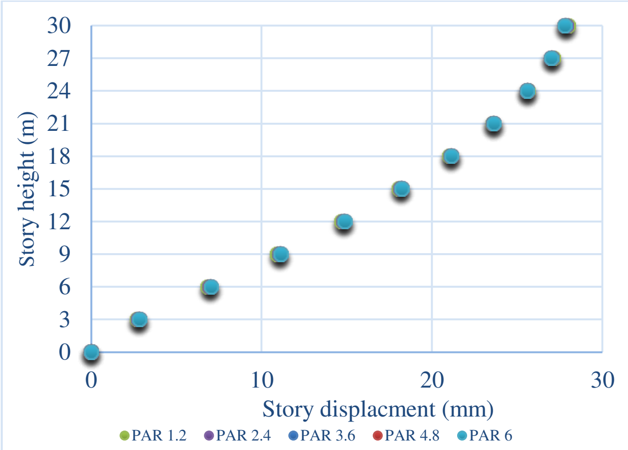

Figure-24. Story displacement for regular frames with varying plan aspect ratios.

For frames having soft stories with varying slenderness ratios/plan aspect ratios, hereto referred as irregular frames, the vertical plane variation affect is summarized in Figure-25 which shows SR1 displacement response of regular and bottom, middle and top soft story cases. Similar behavior is observed for all geometric cases so for brevity the discussion has been confined to only one selected case. Clearly the bottom soft story suffers higher displacements which begins from the soft story level to the top. The pattern is obvious since reference case also suffers higher displacements in its lower stories. The middle soft story performs better than the reference regular case until the soft story and then shifts to higher displacements and surpasses the reference case displacements. The top soft story frame case performs generally better than the reference frame.

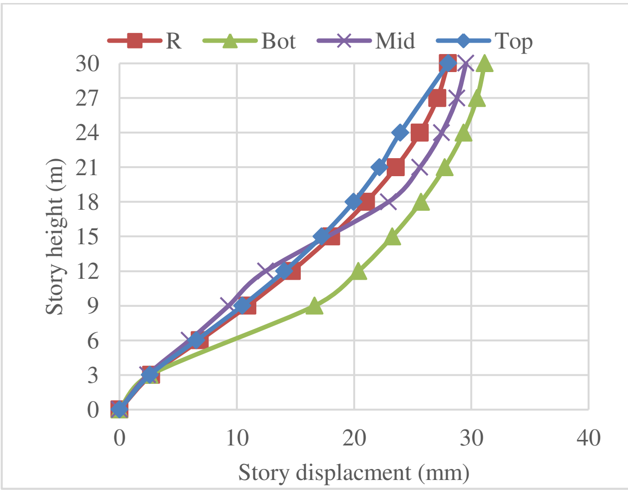

Figure-25. Story displacement for frames with slenderness ratio=1 having vertical irregularities.

The story displacement for frames having bottom soft story with varying slenderness ratios is presented in Figure-26. The bottom soft story undergoes large story displacement as compared to the first story of reference case. It can be seen that at 9 m height second story

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displacement of reference SR1 frame is 10.93 mm whereas at the upper adjacent level of the bottom SR1 frame it becomes 16.65 mm corresponding to an increase of 52%. It should also be noted that higher slenderness ratios have less soft story sway but it does not necessarily mean that percentage difference will be less for higher slenderness ratios. The upper stories seem to perform in a similar manner as the reference upper stories.

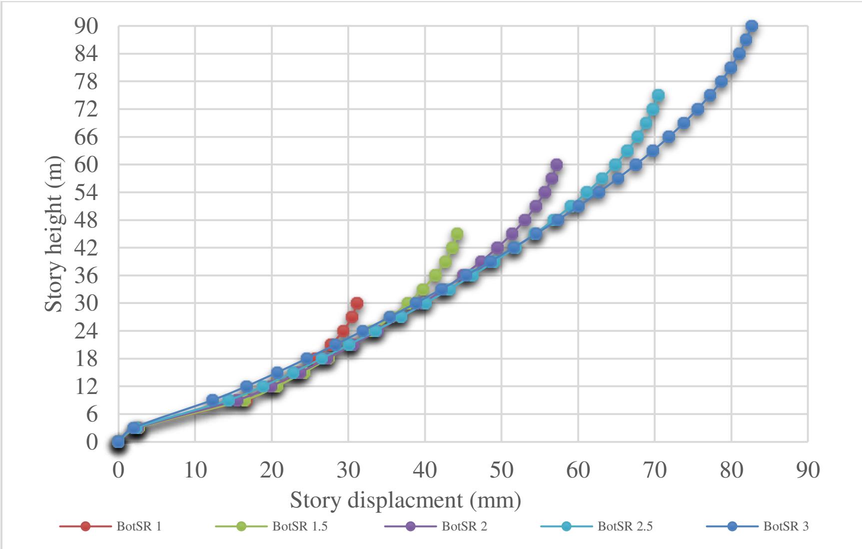

Figure-26. Story displacement for frames having bottom soft story with varying slenderness ratios.

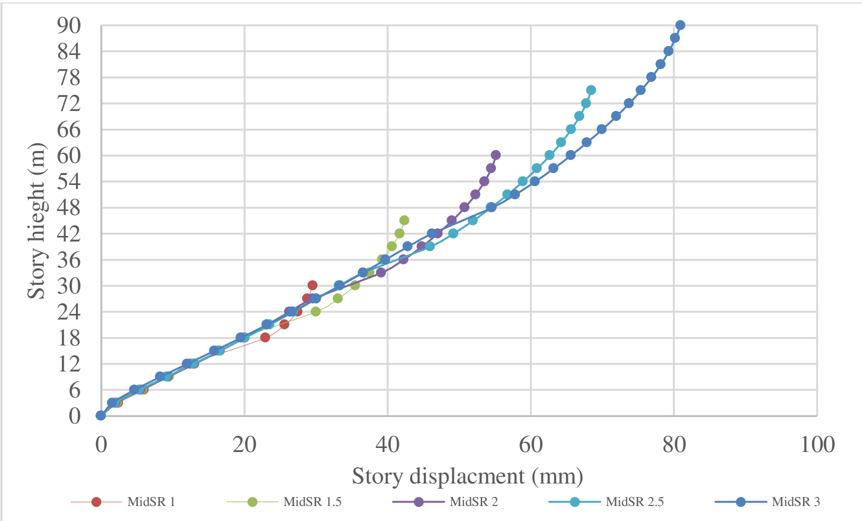

Figure-27. Story displacement for frames having middle soft story with varying slenderness ratios.

The story displacement for frames having middle soft story with varying slenderness ratios is presented in Figure-27. The behavior can be understood by comparison with the reference cases. The 18^{th} story displacements for SR1 reference and middle soft story frames are 21.04 mm and 25.714 mm respectively with increase of 22% which is observed to be less than bottom irregular profile cases. For the upper stories, the displacement patterns are similar to the frames having bottom soft story with varying slenderness ratios.

The story displacement for frames having top soft story with varying slenderness ratios is presented in Figure-28. These frames are observed to have lesser effect of irregularity as illustrated also on Figure-25. It is clear that deformation variation is gradual until the soft story level, beyond which the deformation appears to drift at a higher rate. Furthermore, the top story deformation of reference regular frame and the soft story frames for SR1 are 28.00 mm and 28.04 mm respectively with an increase of 0.1% which is very low in comparison to other irregularity profiles.

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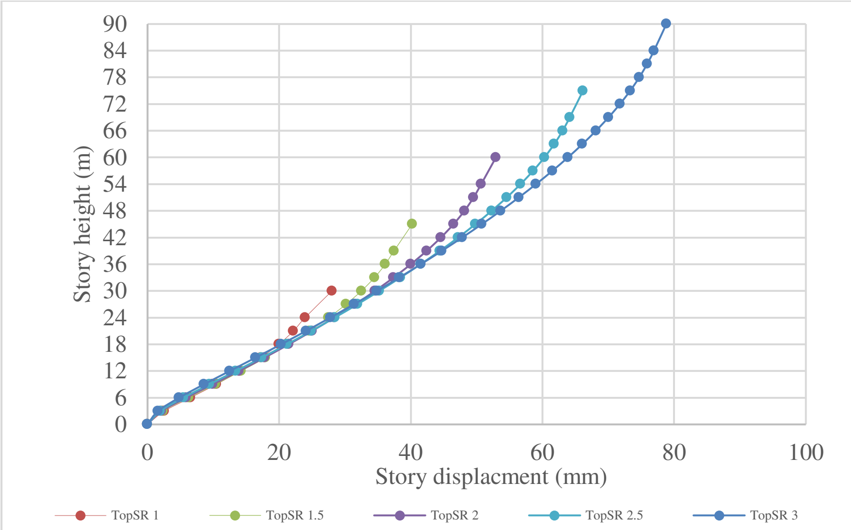

Figure-28. Story displacement for frames having top soft story with varying slenderness ratios.

The story displacement for frames having top soft story with varying slenderness ratios is presented in Figure-28. These frames are observed to have lesser effect of irregularity as illustrated also on Figure-25. It is clear that deformation variation is gradual until the soft story level, beyond which the deformation appears to drift at a higher rate. Furthermore, the top story deformation of reference regular frame and the soft story frames for SR1 are 28.00 mm and 28.04 mm respectively with an increase of 0.1% which is very low in comparison to other irregularity profiles.

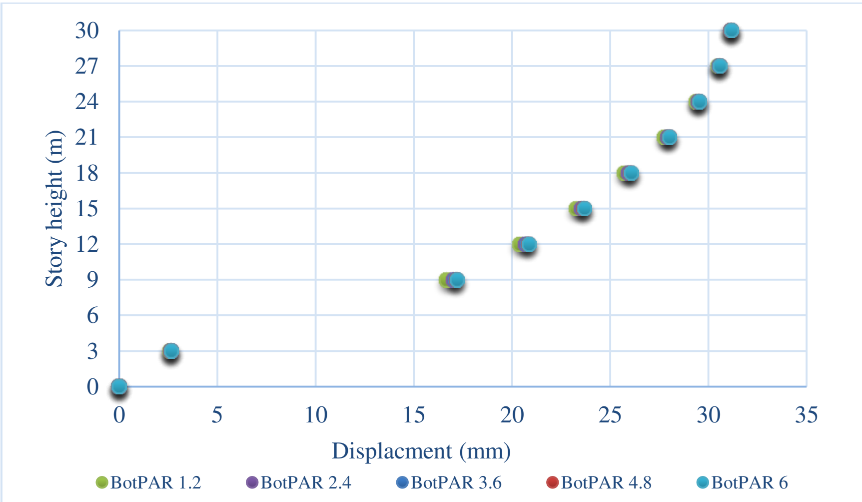

Figure-29. Story displacement for frames having bottom soft story with varying plan aspect ratios.

The story displacement for frames having bottom soft story with varying plan aspect ratios is presented in Figure-29 and Table-6. Similar to frames with varying slenderness ratio, the highest displacement demands appear clearly on bottom soft frame cases. We can see these demands for bottom soft (i.e. 9 m story height) frame cases overlapping around 17 mm this is an increase of 55% relative to reference cases. The top story displacements exceed 30 mm. This overlapping can be justified by the response spectrum attribute for narrow dynamic natural periods even though the significant increase on weight exist yet the modal periods are not as shown earlier. Also the lower stories bottom PAR frames show insignificantly higher displacements demands for larger ratios.

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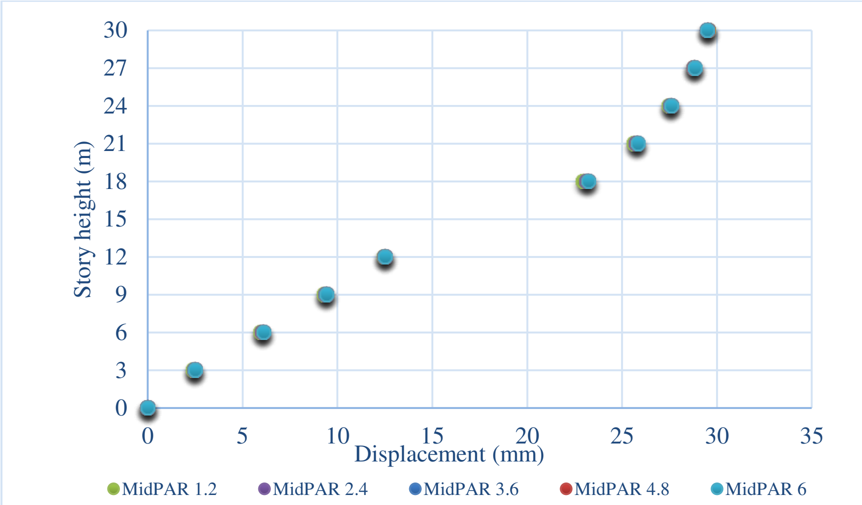

Figure-30. Story displacement for frames having middle soft story with varying plan aspect ratios.

The story displacement for frames having middle soft story with varying plan aspect ratios is presented in Figure-30 and Table-7. Clearly the first stories behave normally until the soft story level where displacements demands shift to around 23 mm, with relative displacement as 8.7% which is less than bottom cases. Also the displacements for different aspect ratios seem perfectly overlapping as expected.

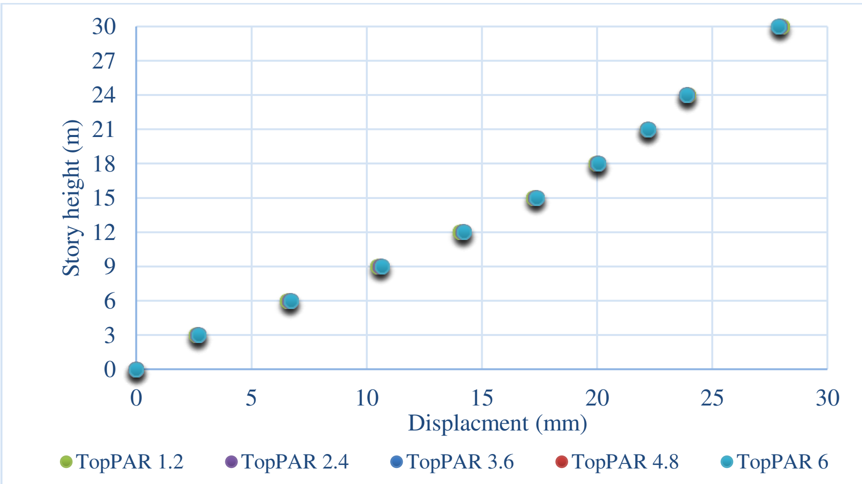

Figure-31. Story displacement for frames having top soft story with varying plan aspect ratios.

The story displacement for frames top soft story with varying plan aspect ratios is presented in Figure-31 and Table-9. The lower stories behave normally same as reference cases then up until the top story level where displacements diverge to around 28 mm which is less than 1% increase compared with the top story response demands in reference case. Again the displacements values almost overlap for the considered plan aspect ratios. It can be seen that effects on account of varying plan aspect ratios are not that significant as observed for varying slenderness ratios. The overlapping is also presented clearly in Table-5 to Table-8.

The story displacement for regular and irregular soft frames with varying plan aspect ratios are presented in Table-5 to Table-8. As shown for regular PAR in Table-5, displacements clearly do not vary as the plan aspect ratio increases, which is opposite to the findings on shear responses. The first 3m story for all ratios are around 2.8 mm with no significant step increase, however, the larger plan configurations tend to demand slightly more displacements than the smaller ratios. The same are observed for bottom soft plan aspect ratios presented in Table-6 although the 9 m story level exhibits higher displacements as shown in Figure-29. The displacement is about 17 mm with no significant change over the plan configurations increase. This pattern is again seen for middle and top levels shown in Table-7 and Table-8 respectively.

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Table-5. Story displacement for regular frames with varying plan aspect ratios.

		Story displacement (mm)				
Story height (m)	**30**	**28.007**	**27.87**	**27.826**	**27.804**	**27.791**
	27	27.115	27.046	27.024	27.013	27.007
	24	25.622	25.608	25.605	25.603	25.602
	21	23.574	23.606	23.619	23.625	23.629
	18	21.04	21.111	21.136	21.149	21.156
	15	18.07	18.169	18.204	18.221	18.232
	12	14.693	14.81	14.851	14.871	14.884
	9	10.93	11.053	11.097	11.119	11.132
	6	6.841	6.955	6.996	7.016	7.029
	3	2.709	2.785	2.813	2.827	2.835
	0	0	0	0	0	0
	PAR	1.2	2.4	3.6	4.8	6

Table-6. Story displacement for frames having bottom soft story with varying plan aspect ratios.

		Story displacement (mm)				
Story height (m)	**30**	**31.148**	**31.148**	**31.151**	**31.154**	**31.155**
	27	30.484	30.542	30.565	30.577	30.584
	24	29.35	29.462	29.503	29.524	29.536
	21	27.749	27.913	27.971	28.001	28.019
	18	25.714	25.926	26.001	26.039	26.062
	15	23.266	23.523	23.613	23.659	23.686
	12	20.374	20.673	20.778	20.831	20.863
	9	16.648	16.99	17.11	17.172	17.209
	3	2.585	2.62	2.632	2.637	2.641
	0	0	0	0	0	0
Bottom PAR		1.2	2.4	3.6	4.8	6

Table-7. Story displacement for frames having middle soft story with varying plan aspect ratios.

		Story displacement (mm)				
Story height (m)	**30**	**29.546**	**29.513**	**29.505**	**29.501**	**29.499**
	27	28.78	28.806	28.818	28.824	28.828
	24	27.478	27.556	27.585	27.6	27.609
	21	25.623	25.751	25.796	25.819	25.834
	18	22.945	23.121	23.184	23.216	23.236
	12	12.46	12.496	12.507	12.513	12.517
	9	9.3	9.379	9.407	9.421	9.43
	6	5.954	6.045	6.076	6.093	6.102
	3	2.398	2.462	2.486	2.497	2.505
	0	0	0	0	0	0
Middle PAR		1.2	2.4	3.6	4.8	6

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The story displacement for regular and irregular soft frames with varying plan aspect ratios are presented in Table- 5 to Table-8. As shown for regular PAR in Table-5, displacements clearly do not vary as the plan aspect ratio increases, which is opposite to the findings on shear responses. The first 3m story for all ratios are around 2.8 mm with no significant step increase, however, the larger plan configurations tend to demand slightly more displacements than the smaller ratios. The same are observed for bottom soft plan aspect ratios presented in Table-6 although the 9 m story level exhibits higher displacements as shown in Figure-29. The displacement is about 17 mm with no significant change over the plan configurations increase. This pattern is again seen for middle and top levels shown in Table-7 and Table-8 respectively.

Table-8. Story displacement for frames having top soft story with varying plan aspect ratios.

		Story displacement (mm)				
Story height (m)	**30**	**28.036**	**27.939**	**27.907**	**27.892**	**27.882**
	24	23.945	23.908	23.897	23.891	23.888
	21	22.179	22.198	22.205	22.209	22.211
	18	19.964	20.023	20.044	20.055	20.062
	15	17.244	17.332	17.363	17.378	17.388
	12	14.063	14.169	14.207	14.226	14.237
	9	10.47	10.585	10.625	10.645	10.657
	6	6.55	6.658	6.695	6.714	6.726
	3	2.592	2.664	2.69	2.703	2.711
	0	0	0	0	0	0
Top PAR		1.2	2.4	3.6	4.8	6

Story Drift

Story drift demand is one of the most critical responses in structural dynamics and serves as criterion for deformations limit. It represents the relative displacements between two consecutive stories. The story drift for regular frames with varying slenderness ratios is shown in Figure-32. It can be seen that first stories for the reference cases undergo higher drifts. Similar behavior has been reported by earlier investigators also such as in Chintanapakdee and Chopra (2004) [5]. The drifts increase significantly on the second and third floor where the maximum drifts are around 4 mm. The lower slenderness ratios are more sensitive and demand more drift than higher ratios i.e. second (6 m height) story drift for SR1, 1.5, 2 are 4.132, 3.957 and 3.76 mm respectively. Thereafter, drift decrease significantly more for lower ratios again for example the story drift for the tenth (30 m height) story are 0.892 mm, 2.519 mm and 3.099 mm respectively. Generally, the upper stories give close values for higher slenderness ratios than the smaller slenderness ratios e.g. the top story drift and its consecutive lower story drift for SR1, 1.5, 2 are 1.493-.891=0.601 mm, 1.143-.743=0.4 mm ,1.012-0.793 =0.221 mm.

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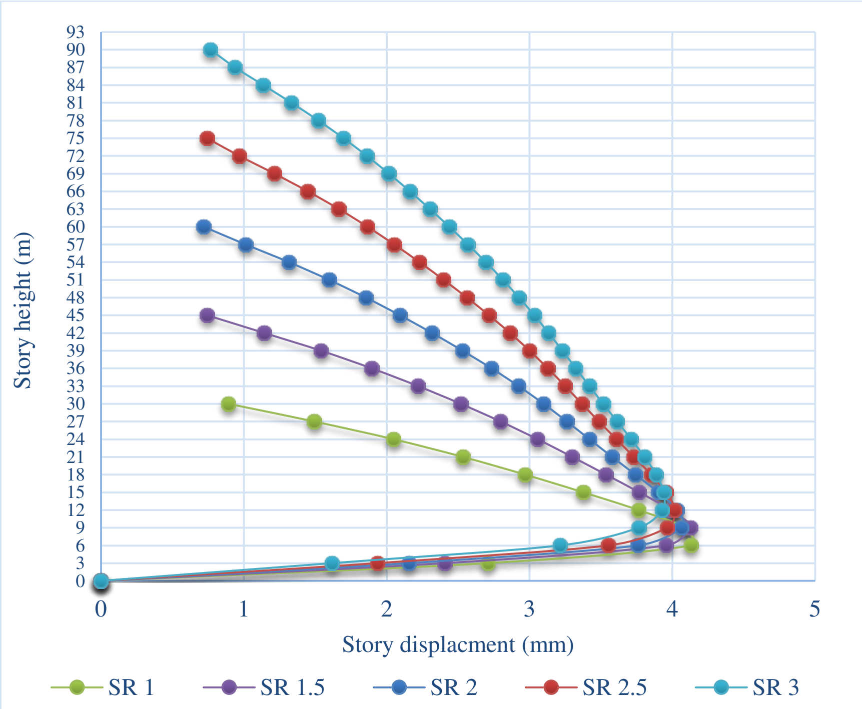

Figure-32. Story drifts for regular frames with varying slenderness ratios.

The story drift for regular frames with varying plan aspect ratios is shown in Figure-33 and Table-9. As mentioned earlier, the displacement results showed minor changes when the plan aspect ratios are varied. Hence, the plan aspect ratios marginally affect story drift response and are almost close with insignificant variations for all ratios where the maximum drift demands are around 4 mm on the second floor. Furthermore, the lower stories of higher ratios have slightly more drift than the smaller ratios and afterwards upper stories tend to demand more story drifts for smaller ratio.

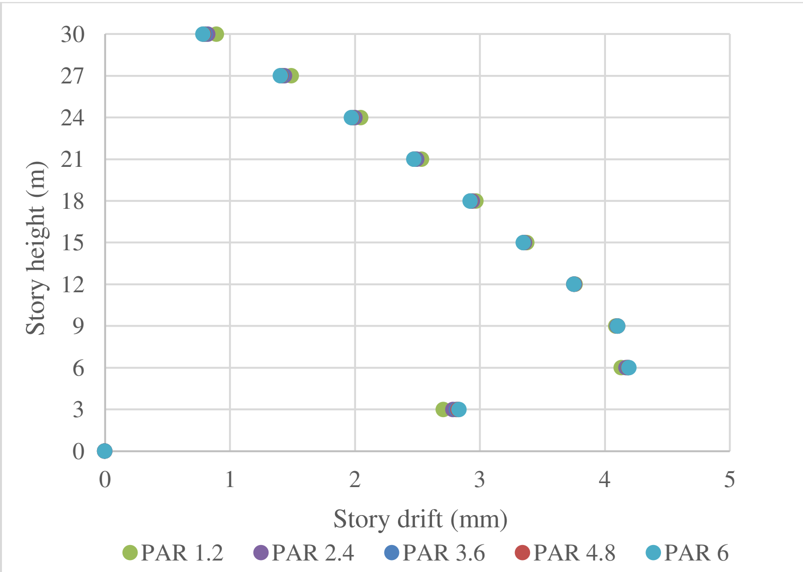

Figure-33. Story drifts for regular frames with varying plan aspect ratios.

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Table-9. Story drifts for regular frames with varying plan aspect ratios.

		Story drift (mm)				
Story height (m)	**30**	**0.892**	**0.824**	**0.802**	**0.791**	**0.784**
	27	1.493	1.438	1.419	1.41	1.405
	24	2.048	2.002	1.986	1.978	1.973
	21	2.534	2.495	2.483	2.476	2.473
	18	2.97	2.942	2.932	2.928	2.924
	15	3.377	3.359	3.353	3.35	3.348
	12	3.763	3.757	3.754	3.752	3.752
	9	4.089	4.098	4.101	4.103	4.103
	6	4.132	4.17	4.183	4.189	4.194
	3	2.709	2.785	2.813	2.827	2.835
	0	0	0	0	0	0
	PAR	1.2	2.4	3.6	4.8	6

The story drift for frames having bottom soft story with varying slenderness ratios is shown in Figure-34. As discussed earlier for displacement response, the frame response is significantly intense as compared to frames with varying plan aspect ratios. The drift demand for frame having bottom soft story for slenderness ratios 1, 1.5, 2 is 14.063 mm 13.85 mm, 13.013 mm. The smaller slenderness ratios demand higher drifts than larger slenderness ratios. The increase in drifts demand is high relative to the reference frames with relative drifts increasing to about 173%. Afterward, drift demands return to the normal behavior. However, the first half drifts are sharply spaced unlike reference cases.

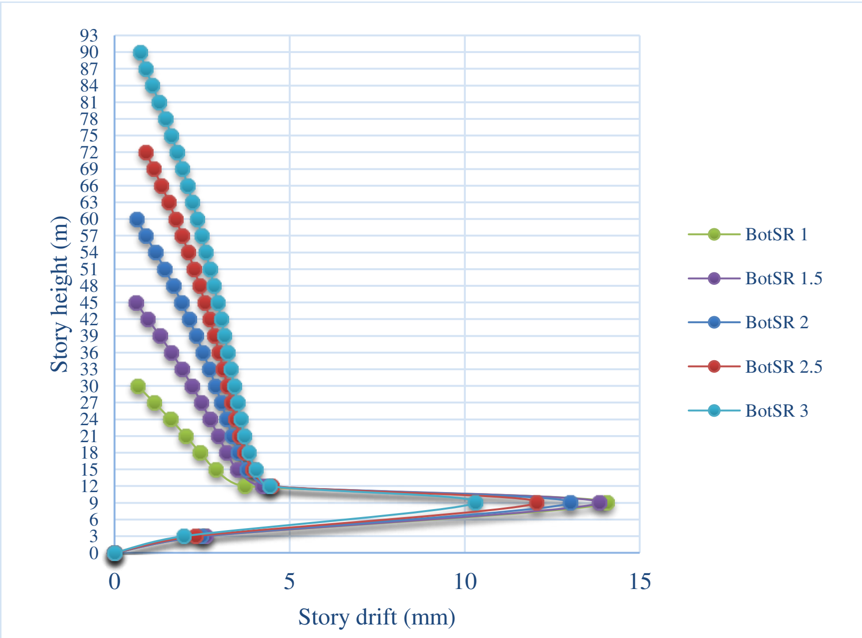

Figure-34. Story drifts for frames having bottom soft story with varying slenderness ratios.

The story drifts for frames having middle soft story with varying slenderness ratios is shown in Figure-35. The stories below the soft story behave normally with the noticeable increase on the first and second stories until the soft story level where drifts exceed 8.385 mm for SR3 frame case. It must be noted that the smaller slenderness ratios experience more drift than larger slenderness ratios and exceed 10 mm for SR1 and SR1.5. Since the corresponding drift for the reference case at that level was 2.927 mm this corresponds to an increase of 186%. The relative drifts to the reference cases become higher for middle soft story slenderness ratio cases. Afterward, upper stories drifts decrease normally and behave similar to regular frames.

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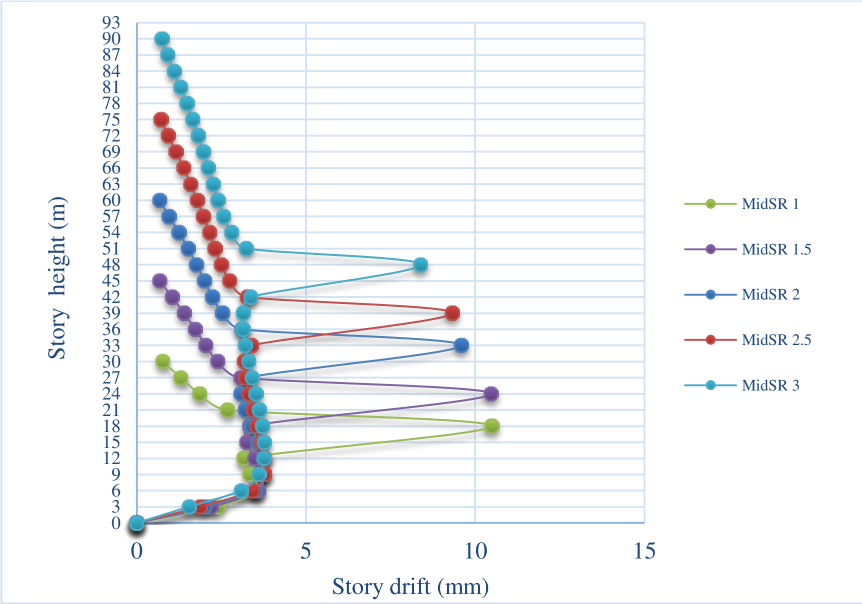

Figure-35. Story drifts for frames having middle soft story with varying slenderness ratios.

The story drifts for frames having top soft story with varying slenderness ratios is shown in Figure-36. As can be seen the demand is the lowest compared to the other irregular profiles with varying slenderness ratios. The stories below the soft story level behave typically as regular profiles and again the smaller ratios appear to demand more drifts than larger ratios. For story drift for slenderness ratio SR 1 is 4 mm. As the slenderness ratio increases it reduces and becomes 2 mm for SR 3. Compared to the reference case it is about 146% for SR3 and 385% for SR1. It can be noted that even though the drift is lower than other irregular profile cases, the relative drifts may be greater in some cases.

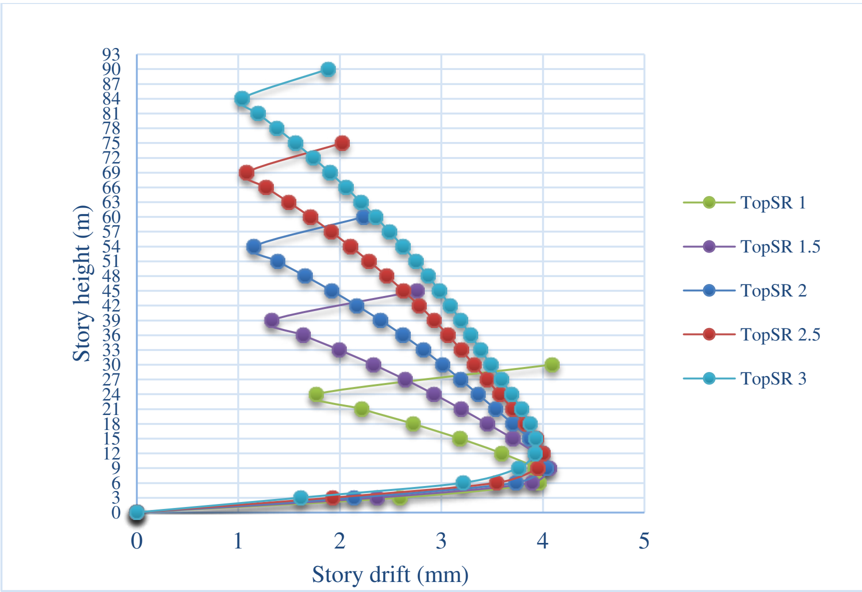

Figure-36. Story drifts for frames having top soft story with varying slenderness ratios.

The story drifts for frames having bottom soft story with varying plan aspect ratios is shown in Figure-37 and Table-10. The effect appears to be minimal. The drifts demand changes slightly as shown on Figure-41. The story drift for bottom story is close to 15 mm with relative drifts around 244% for reference frame with plan aspect ratio = 1.2. The bottom soft story irregular frames have large story drift than middle and the top soft story irregular frames.

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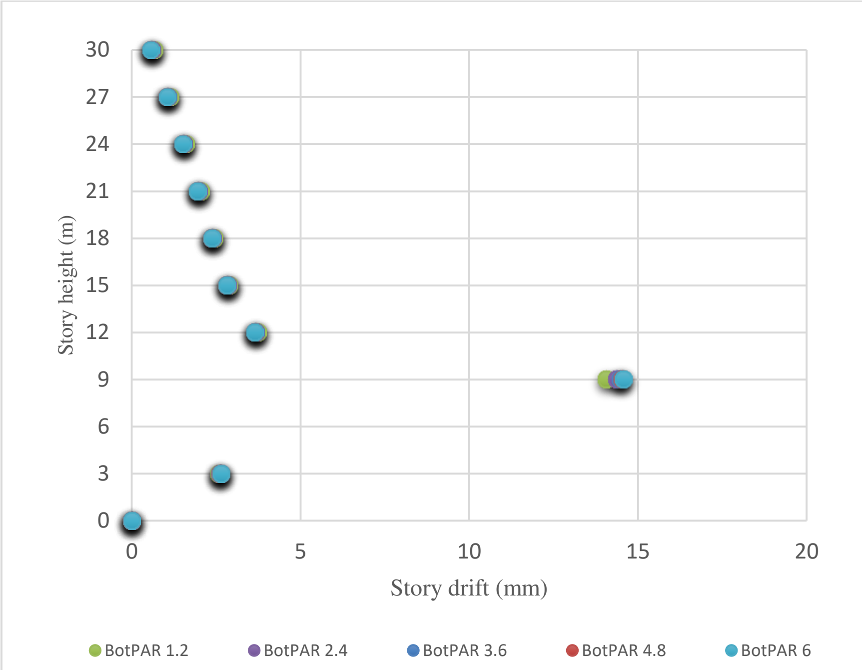

Figure-37. Story drifts for frames having bottom soft story with varying plan aspect ratios.

Table-10. Story drifts for frames having bottom soft story with varying plan aspect ratios.

		Story drift (mm)				
Story height (m)	**30**	**0.664**	**0.606**	**0.586**	**0.577**	**0.571**
	27	1.134	1.08	1.062	1.053	1.048
	24	1.601	1.549	1.532	1.523	1.517
	21	2.035	1.987	1.97	1.962	1.957
	18	2.448	2.403	2.388	2.38	2.376
	15	2.892	2.85	2.835	2.828	2.823
	12	3.726	3.683	3.668	3.659	3.654
	9	14.063	14.37	14.478	14.535	14.568
	3	2.585	2.62	2.632	2.637	2.641
	0	0	0	0	0	0
Bottom PAR		1.2	2.4	3.6	4.8	6

The story drifts for frames having middle soft story with varying plan aspect ratios is shown in Figure-38 and Table-11. The story drift for middle story reaches 266% for reference frame with plan aspect ratio = 6. The, larger plan aspect ratios seem to demand more drifts than smaller ratios which is opposite to slenderness ratios cases.

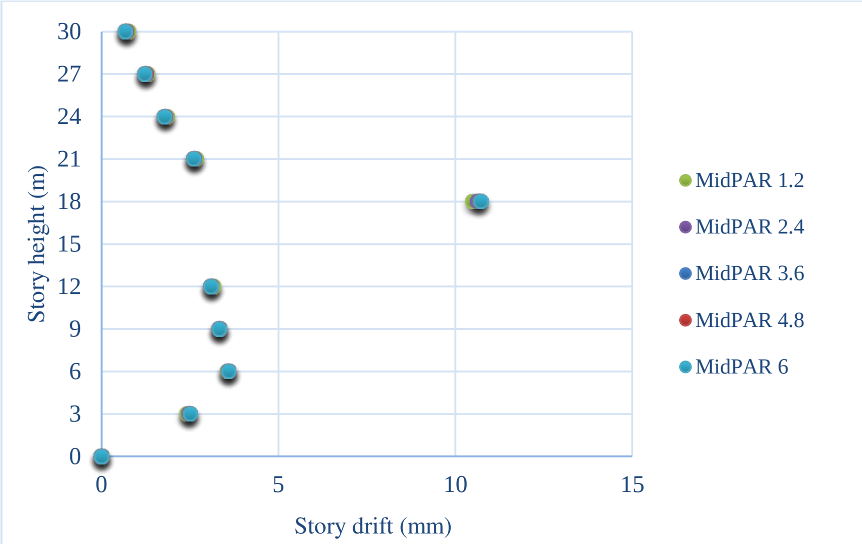

Figure-38. Story drifts for frames having middle soft story with varying plan aspect ratios.

Table-11. Story drifts for frames having middle soft story with varying plan aspect ratios.

		Story drift (mm)				
Story height (m)	**30**	**0.766**	**0.707**	**0.687**	**0.677**	**0.671**
	27	1.302	1.25	1.233	1.224	1.219
	24	1.855	1.805	1.789	1.781	1.775
	21	2.678	2.63	2.612	2.603	2.598
	18	10.485	10.625	10.677	10.703	10.719
	12	3.16	3.117	3.1	3.092	3.087
	9	3.346	3.334	3.331	3.328	3.328
	6	3.556	3.583	3.59	3.596	3.597
	3	2.398	2.462	2.486	2.497	2.505
	0	0	0	0	0	0
Middle PAR		1.2	2.4	3.6	4.8	6

The story drifts for frames having top soft story with varying plan aspect ratios is shown in Figure- 39 and Table-12. These frames have smaller drifts than the bottom's and middle's reaching around 4 mm however the relative drifts reach 385% for reference frame with plan aspect ratio = 1.2 and 409% for reference frame with plan aspect ratio = 6.

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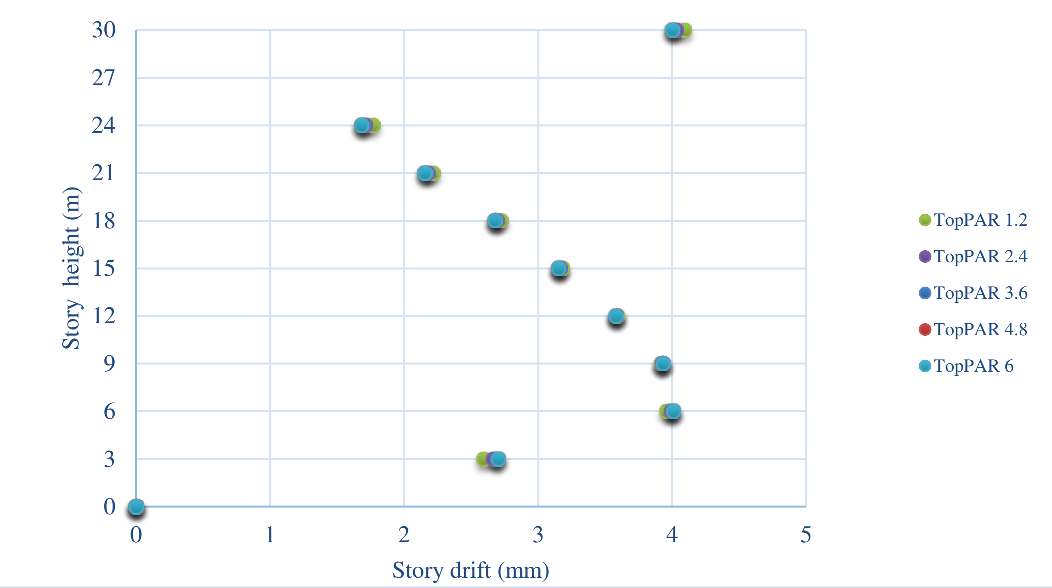

Figure-39. Story drifts for frames having top soft story with varying plan aspect ratios.

Table-12. Story drifts for frames having top soft story with varying plan aspect ratios.

		Story drift (mm)				
Story height (m)	**30**	**4.091**	**4.031**	**4.01**	**4.001**	**3.994**
	24	1.766	1.71	1.692	1.682	1.677
	21	2.215	2.175	2.161	2.154	2.149
	18	2.72	2.691	2.681	2.677	2.674
	15	3.181	3.163	3.156	3.152	3.151
	12	3.593	3.584	3.582	3.581	3.58
	9	3.92	3.927	3.93	3.931	3.931
	6	3.958	3.994	4.005	4.011	4.015
	3	2.592	2.664	2.69	2.703	2.711
	0	0	0	0	0	0
Top PAR		1.2	2.4	3.6	4.8	6

CONCLUSIONS

The investigation is aimed to provide sufficient understanding on the dynamic response of vertically irregular reinforced concrete frame structures and the effect of different geometric configurations specifically slenderness and plan aspect ratios. The outcomes of this study can be categorized under reference regular and irregular configurations.

For the regular frame cases the main conclusions are as follows:

a) The slenderness ratio is directly proportional to natural vibration periods of the structure, and longer periods are expected with increase in slenderness ratio, however plan aspect ratios have almost no effect despite the massive weight increase.

b) The slenderness ratios do not trigger the shear responses as much as it does for plan aspect ratios, so increasing the slenderness ratios may not elevate the shears significantly, however plan aspect ratios increase it significantly. This requires careful attention if certain structural irregularity aspects like horizontal irregularities are planned which directly influence the lateral diaphragm behavior of frames structures.

c) The displacement responses are highly affected by the slenderness configurations, and more displacements are expected when slenderness ratio increases especially smaller ratios which demand higher lower-stories displacements than larger ratios. The plan aspect ratios only marginally affect the response.

d) The story drift demands for both slenderness and plan aspect ratios generally have similar behavior with maximum demand shown on the first two or three floors, however the key finding regarding slender frames is that the first stories of smaller ratios gain higher drifts than larger ratios, while larger ratios plan aspect frames gain slightly more drifts.

For the irregular frame cases the main conclusions are as follows:

a) The frames with bottom soft story for varying slenderness ratio and plan aspect ratio configurations appear more flexible and suffer longer modal periods than frames with middle soft story and top soft story, especially for frames with varying slenderness ratio the fundamental periods significantly increase with larger ratios, whereas for frames with varying plan aspect ratios modal periods are almost identical.
b) The shear demands are lesser on frames with bottom soft story for varying slenderness ratio and plan aspect ratio configurations. In particular, frames with smaller slenderness ratios show diverging trend whereas frames with larger slenderness ratios exhibit converging trend. The frames with smaller plan aspect show convergence and divergence on larger plan aspect ratios.
c) The displacement demands for frames with bottom soft story is the highest among the three irregular profiles, also the relative displacements with respect to the reference cases are higher. Furthermore, the frames with smaller slenderness ratio configurations demand slightly more displacements than frames larger slenderness ratios. The displacement demands for frames with top soft story is lowest among the three profiles. No significant change is noticed in irregular frames with varying plan aspect ratios.
d) The drifts demand for frames with bottom soft story for both slenderness and plan aspect configurations are the highest compared to frames with middle and top soft stories. However, the relative drift is highest for frames with top soft story. Similar to displacements responses, the smaller slenderness ratios exhibit slightly higher drifts than larger slenderness ratios.

REFERENCES

[1] Arnold, Christopher, and Eric Elsesser. 1980. Building configuration: Problems and solutions. Proceedings of the Seventh World Conference on Earthquake Engineering. Vol. 4.

[2] Moehle J. P. 1984. Seismic response of vertically irregular structures. Journal of Structural Engineering. 110(9): 2002-2014.

[3] Valmundsson E. V. & Nau J. M. 1997. Seismic response of building frames with vertical structural irregularities. Journal of Structural Engineering. 123(1): 30-41.

[4] Al-Ali, Ali A. K. and Helmut Krawinkler. 1999. Effects of vertical irregularities on seismic behavior of building structures. John A. Blume Earthquake Engineering Center.

[5] Chintanapakdee, Chatpan, and Anil K. Chopra. 2004. Seismic response of vertically irregular frames: response history and modal pushover analyses. Journal of Structural Engineering. 130.8: 1177-1185.

[6] Ayidin K. 2007. Evaluation of Turkish seismic code for mass irregular buildings. Indian Jl. of Engg. and Mat. Sci. 14: 220-234.

[7] Zhou J., Bu G. & Cai J. 2011. Ductility demand of structures with vertical irregularities subjected to pulse-like ground motions. Journal of Civil Engineering and Construction Technology. 2(12): 268-276.

[8] Rahman S. A. A. A. & Deshmukh G. 2013. Seismic response of vertically irregular RC Frame with stiffness irregularity at fourth floor. International Journal of Emerging Technology and Advanced Engineering. 3(8).

[9] Abraham N. M. & SD A. K. 2019. Analysis of Irregular Structures under Earthquake Loads. Procedia Structural Integrity. 14, 806-819.

[10] Saudi Building Code SBC 301. 2018. Code Requirements, Saudi Building Code National Committee.