Evaluation of the Higher Modes of Vibration on Rigid Response Coefficient and Earthquake Resistance Design of Structures

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Abstract - The effect of the earthquake on a structure depends not only on the peak value of ground acceleration, but also on the size and shape of the building, the arrangement of structural elements, and the presence of mass and stiffness irregularities. Basic modes in irregular structures are often isolated and may not affect the response of other areas of the structure in any significant way. Straight-line fit to semi logarithmic graphs between key frequency f1 & rigid frequency independent of damping are used to derive the empirical expressions for rigid response coefficient. As the study's findings demonstrate, the fundamental mode approach for regular structures & 90% modal mass criteria for the number of modes to be included for dynamic analysis of irregular structures are insufficient. Shear forces are underestimated at the top and bottom levels in numerical instances when the current criterion is used. Elastic seismic analysis of irregular structures can be simplified by the residual mode's ability to simulate dampened periodic response.

A tool MathCAD is used for developing different mathematical models for dynamic analysis and to calculate section capacity of RC and steel sections as per IS Codes.

Further software STAAD.Pro and ETABS is used for modelling and dynamic analysis of real-life structures. The output of both the models is used to verify and validate output and correctness of each other

Keywords - rigid response coefficient, transient response, steady-state response, rigid frequency

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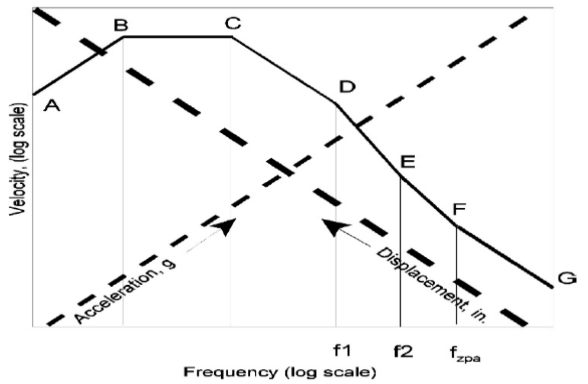
INTRODUCTION

Structures need to be more flexible in order to withstand significant earthquakes, which cause undesired vibrations, deformations and accelerations. When structures are subjected to excessive vibration, it can lead to a variety of negative effects on people and the environment, including human discomfort, energy waste, structural part failure, & transmission of harmful forces and, in the worst case scenario, a collapse. Structures susceptible to dynamic loads, such as earthquakes must be studied in detail in order to eliminate the harmful consequences of vibrations. There's a lot of work to be done by structural engineers today to develop creative design concepts that protect civil engineering structures and their contents. Inelastic cyclic deformations at structural elements' intricately detailed plastic hinge areas may be a source of energy loss in such systems. Recent years have seen a rise in the use of novel methods to improve structural functionality and safety against dynamic loads.

A mode of the structure in an oscillating system, in which all parts of the structure are oscillating with the same frequency. The sum of mass participation in structure vibrations calculated in the modal analysis increases as the number of modes increases. However, to obtain 90-percent mass participation required by codes, it is necessary to consider contribution of large number of eigenmodes, which lengthen calculations and analysis results. The limit of total missing mass could be 10%.

The seismic response of vibration consists of two combinations of two different motions, which are referred in structural dynamics as the damped-periodic motion (also called as simply "periodic") response and the "rigid" response. (In the theory of vibrations, these two parts of motion are referred to as "transient response" and "steady-state response" respectively.) The periodic responses have the frequencies of the oscillators (or individual modes), and the rigid responses have the frequencies of the input motion.



Regions of a broad-banded response spectrum

Figure 1: Broad Spectrum Response Spectrum

Between the end of the region of amplified spectral acceleration, D, and the beginning of the rigid region E, the modal responses consist of both the periodic and rigid components. Appropriate methods, should be used to separate the two components in this transition region. The Gupta method and Lindley-Yow method are considered acceptable.

Gupta separated the periodic and rigid components of a response by a rigid response coefficient α_i.

$$R^2_i = R^2_{Pi} + R^2_{Ri}$$

The periodic response component of *Rpi*can then be expressed as follows:

$$R_{Pi} = [1 - \alpha i2]1/2\ R_i$$

The rigid response component of a modal response, R_{ri}, is defined as follows:

$$R_{ri} = \alpha i\ R_i$$

α_i = rigid response coefficient

With proper selection of key frequencies rigid response coefficient can be idealized as follows:

$$\alpha i\xi = \frac{\ln fi/f1}{\ln fzr/f1} \quad 0 \le \alpha\xi \le 1,\quad f1 \le \text{fi} \le fzr$$

Finally, after calculating the total periodic response, total rigid response, and residual rigid response, an appropriate combination method, should be used to obtain the total response.

Periodic Response of ONE Mode =

$$R_{Pi} = [1 - \alpha i^2]^{1/2}\ R_i$$

Rigid Response of ONE Mode =

$$R_{ri} = \alpha i\ R_i$$

Periodic Response of ALL Modes =

$$R_{PI} = [\textstyle\sum_{i=1}^{n} \sum_{j=1}^{n} \varepsilon_{ij}\ \text{Rpi Rp}j]1/2\ ......$$

for n = number of modes below *fzpa*

Rigid Response of ALL Modes =

$$R_{RI} = \textstyle\sum_{i=1}^{n} \text{R}ri + R_{\text{Missing mass}}$$

OR

$$R_{RI} = R_{\text{Static ZPA}}$$

Complete Response of ALL Modes =

$$R_I = [R^2_{PI} + R^2_{RI}]^{1/2}$$

Combining Effects Caused by Three Spatial Components of an Earthquake:

$$R = [R^2_{IX} + R^2_{IY} + R^2_{IZ}]^{1/2}$$

OR

$$R = R_{IX} + 0.33\ R_{IY} + 0.33\ R_{IZ}$$

RESEARCH METHODOLOGY

The present methodologies used, and recommendations specified by seismic building codes of practice for the seismic analyses of structures, when high frequency modal responses are involved are reviewed. The 90% modal mass criteria defined by design codes in the number of modes measured for analysis are studied with the help of model studies. The effect of the damping ratio on the rigid response coefficient is studied. Regression analysis is conducted for determining rigid frequency and rigid response coefficient. The expressions are validated by comparing output of the model analysis.

The variation of mass throughout the structure when higher modes are truncated is studied. Intense studies are conducted with the help of statistical patterns to study the contributions of the rigid and periodic parts of the response and modal mass corresponding to the residual mode, by varying the frequencies and mass contribution of the truncated higher modes. The approximate residual mode contribution is determined to the contributions of truncated higher modes.

The modified residual mode method is used for developing a simplified procedure for the design of structures with vertical mass and stiffness irregularity. The method is validated using different model studies. The error is calculated by comparing the calculated responses using 90% modal mass and residual modes with the responses calculated using all modes.

Selection of Structures& data collection

The design model of real-life structures are considered for the study. Total twenty-three structures were modelled using the software. Out of these twenty models are of real-life projects with different seismic zones, different soil type, different materials. These structures include residential, commercial, and industrial. Three models are sample models used for validation purpose with standard database.

The summery table on the software models is as below.

Table 1: Model Summary

Model No	Model ID	Software	Type	X-Dim (m)	Z-Dim (m)	Y-Dim (Ht)	Damping Ratio
1	Validation-Basic	STAAD	RCC	20	15	13.8	0.05
2	SGJ1	STAAD	Steel	15	15	28.18	0.02
3	SGJ2	STAAD	Steel	13.1	109.1	20	0.02
4	RHJ	STAAD	RCC	20	15	13.8	0.05
5	Validation-Scaled	STAAD	RCC	20	15	13.8	0.05
6	SGJ3	STAAD	Steel	9	45	28.78	0.02
7	Marvel	STAAD	RCC	93.77	98.62	53.1	0.05
8	Corporate Park	STAAD	RCC	24.76	56.13	58	0.05
9	Filter Bldg- H	STAAD	RCC	60	30	25	0.05
10	STAD BLDNG	STAAD	RCC	36	21	74	0.05
11	Crusher House	STAAD	Steel	42.3	28.4	29.12	0.02
12	PHB Seismax	STAAD	Steel	94.5	47.6	48	0.02
13	SUB-R2	STAAD	Steel	46.4	36	14.4	0.02
14	OS-14 BFW Pump	STAAD	Steel	36	6	14.2	0.02
15	Pipe Stanction	STAAD	Steel	9	4	12.5	0.02
16	Pipe Support Tank	STAAD	Steel	3.65	20.27	12.39	0.02
17	Room-MEC-1	STAAD	Steel	2	2	11.475	0.02
18	Block 24 DU	ETABS	RCC	24.814	14.908	44.415	0.05
19	Block 48 DU	ETABS	RCC	21.936	24.81	44.415	0.05
20	FINAL MODEL G+26	ETABS	RCC	21.85	22.6	86.85	0.05
21	G+12_Final_1	ETABS	RCC	73.075	21.05	44.2	0.05
22	INTERNS GONDA	ETABS	RCC	46.85	14.92	30.15	0.05
23	OFFICER'S QTRS (G+14)	ETABS	RCC	23.8	20.9	50.25	0.05

Methods & tools for analysis

Dynamic analysis is carried out by developing programme in MathCAD and validating it with professional structural analysis software STAAD.Pro and ETABS. Seismic analysis is carried out for each model in following Steps-

- Structural configuration
- Section and Material Properties
- Member Specification
- Define Support condition
- Load Definition and Load Calculation
- Cut of Mode shapes
- Seismic Analysis using Response Spectra

Dynamic analysis of all the models were carried out for different variable factors. An earthquake force is applied in both (X and Z) horizontal directions. The output of the results isanalyzed on the basis of following parameters.

Results of analysis are investigated for following Parameters:

- RC & Steel Structures
- Damping
- Results at 90% modal participation
- Results upto 99% - 100 % modal participation
- Number of Mode Shapes at 90% & 100 % modal participation
- Natural Period (Natural Frequency) at 90% & 100 % modal participation
- Rigid Response coefficient
- Residue Rigid Response
- Base Shear at 90% &upto 99% - 100 % modal participation
- Drift at 90% &upto 99% - 100 % modal participation
- Effect of Soil Type at 90% &upto 99% - 100 % modal participation

RESULTS AND DISCUSSIONS

Illustrative results for Model No.7 are shownbelow.

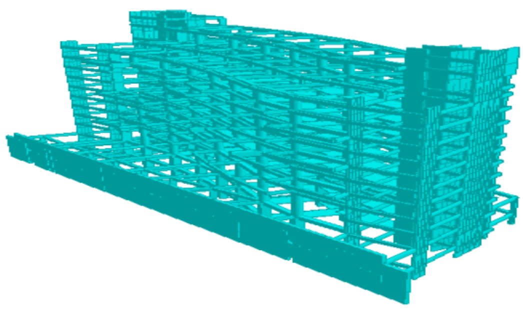


Figure 2: Isometric View- Model No 7

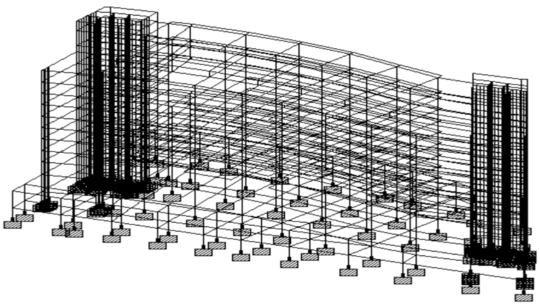


Figure 3: Structural Modelling- Model No 7

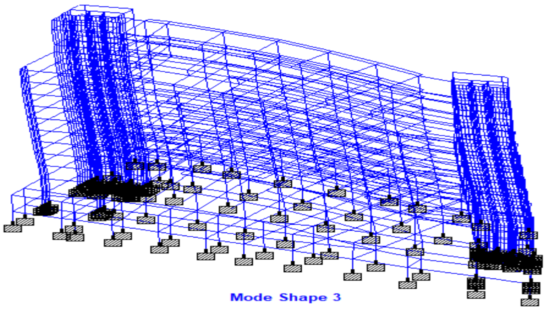


Figure 4: Mode shape 3- Model No 7

Table 2: Modal Analysis- Model No 7

Mode	Freq Hz	Peroid Sec	X%	Y%	Z%		Cuml X%	Cuml Z%
1	0.442	2.26	61.031	0	0.575	Elastic	61.031	0.575
2	0.611	1.637	5.785	0	0.012	Elastic	66.816	0.587
3	0.695	1.439	0.663	0	64.183	Elastic	67.479	64.770
4	1.672	0.598	14.3	0	0.126	Elastic	81.779	64.896
5	2.262	0.442	0.393	0	6.139	Elastic	82.172	71.035
6	2.379	0.42	1.337	0	4.9	Elastic	83.509	75.935
7	3.493	0.286	6.655	0	0.055	Elastic	90.164	75.990
..	..	..	..	..	..	..	..	..
20	13.032	0.077	0.136	0	4.143	Elastic	94.810	92.243
..	..	..	..	..	..	..	..	..
60	43.827	0.023	0	0	0	Elastic	100.002	99.996

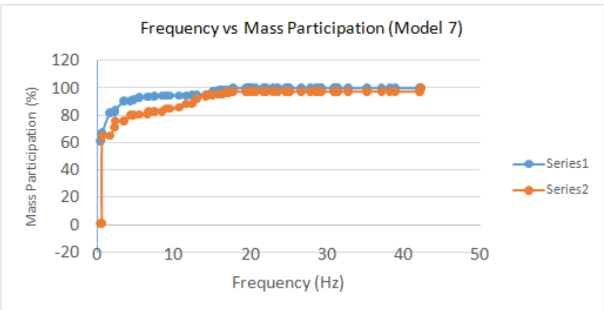


Figure 5: Frequency vs Participation- Model No 7

Table 3: Base Reactions- Model No 7

Reactions	L/C	FxkN	FykN	FzkN	Mx kNm	My kNm	MzkNm
X- Dir	1 EQ IN X	5069.949	29996.196	2586.413	13493.418	136.809	19269.283
Z- Dir	2 EQ IN Z	2634.571	16963.997	4852.207	27260.147	162.722	9187.774

Similarly results of all models are evaluated and summarizedas below.

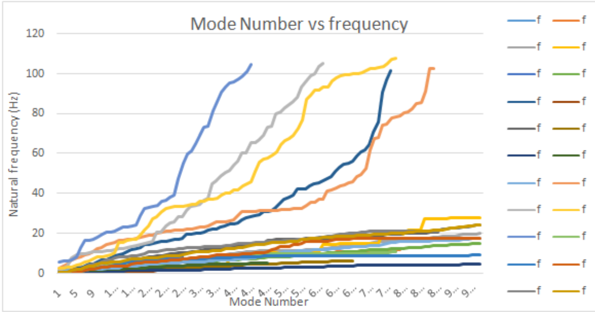


Figure 6: Mode Number - Natural frequency

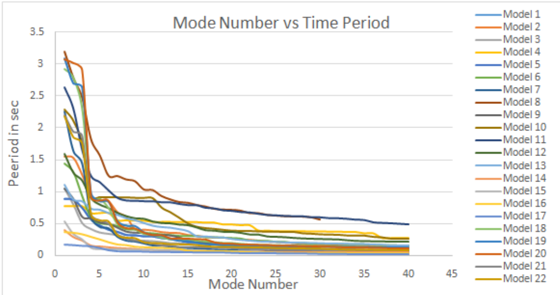


Figure 7: Mode Number -Time Period

- ➢ Performance of steel structures and concrete structures are very well differentiated.
- ➢ Steel structures required higher frequency to reach to desired mass participation.

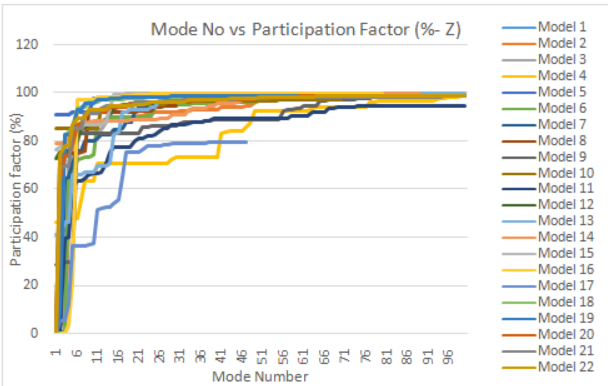


Figure 8: Mode Number – Participation factor

- ➢ Structures with irregular configuration need to consider modes with higher natural frequency.
- ➢ Response of all structures converges at higher frequencies.
- ➢ Convergence both steel structures and concrete structures happens at higher modal frequencies.
- ➢ Residue Rigid Response of steel and concrete structures is similar.

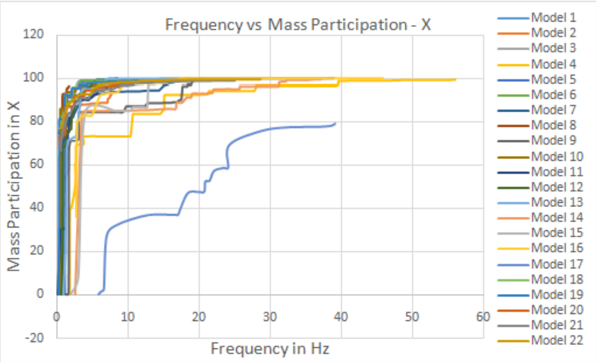


Figure 9 Frequency – Participation factor

- Structural Rigid Response achieved at frequency 33Hz for 5 % damping ratio, which is consistent with CQC Method defined in IS 1893

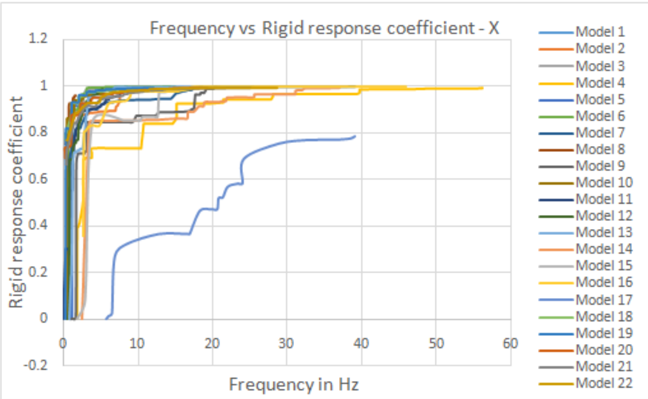


Figure 10: Rigid response coefficient vs Frequency

- Rigid response frequency decreases with increase in damping ratio.
- Rigid Response coefficient for different damping values converges at frequency 33 Hz and above this frequency, the periodic component of the modal response is essentially zero.
- Rigid Response coefficient becomes 1 at 33 Hz frequency for different damping ratios.

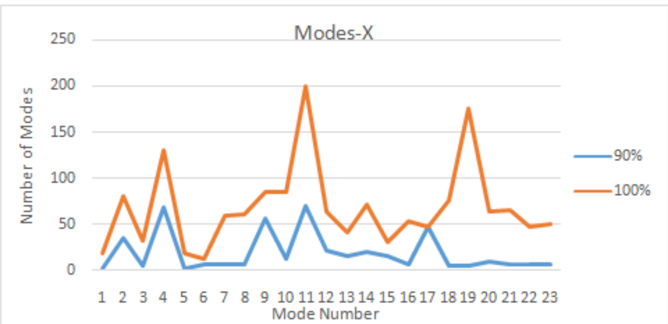
Table 4: Response in X Direction – at 90 % Mass Participation

Model Number	X Direction – at 90 % Mass Participation					
	No of Modes	Frequency (Hz)	Period (sec)	Base Shear (SRSS) kN	Base Shear (CQC) kN	Drift mm
Model 1	2	1.151	0.8688	921	921.7	23.73
Model 2	35	7.116	0.1405	181	248	58
Model 3	5	2.789	0.3586	420.85	420.96	39.18
Model 4	69	15.142	0.0660	1484	1821	19.91
Model 5	2	1.151	0.8688	1391	1391	21
Model 6	6	2.069	0.4833	447	449	47.47
Model 7	7	3.493	0.2863	4302	4365	24.22
Model 8	7	0.803	1.2453	7968	8080	357
Model 9	57	17.134	0.0584	342	356	15.08
Model 10	13	1.475	0.6780	1927	1927	155
Model 11	70	3.764	0.2657	175	500	38.44
Model 12	22	3.108	0.3218	8601	8938	21.79
Model 13	16	3.377	0.2961	1363	1480	27.95
Model 14	20	18.211	0.0549	530	585	2.8
Model 15	16	12.844	0.0779	64	64	2.8
Model 16	7	5.996	0.1668	53	67	5.6
Model 17	47	108.034	0.0093	4.63	5.2	0.955
Model 18	5	1.125	0.8889	1238.93	1391.54	73.745
Model 19	5	1.171	0.8540	3072.22	3342	88.056
Model 20	9	2.385	0.4193	2548.07	2913.65	53.718
Model 21	7	3.12	0.3205	8980.19	9248.62	100.147
Model 22	7	3.124	0.3201	3029.89	3046.78	54.68
Model 23	7	3.182	0.3143	3773.35	3790	40.739

Table 5: Response in X Direction – at 100 % Mass Participation

Model Number	X Direction – at 100 % Mass Participation					
	No of Modes	Frequency (Hz)	Period (sec)	Base Shear (SRSS) kN	Base Shear (CQC) kN	Drift mm
Model 1	19	5.865	0.1705	926	926.5	20.97
Model 2	81	11.672	0.0857	181	248	58.77
Model 3	32	7.626	0.1311	421.17	422.33	39.54
Model 4	130	48.366	0.0207	1405	1790	12.145
Model 5	19	5.865	0.1705	1404	1404	20.92
Model 6	13	3.189	0.3136	456	459.96	47.47
Model 7	59	42.348	0.0236	5075	4849	24.22
Model 8	61	12.311	0.0812	8010	8266	351
Model 9	86	20.203	0.0495	342	358	15.08
Model 10	86	8.459	0.1182	2004	2009	149.65
Model 11	200	7.633	0.1310	176	596	38.44
Model 12	65	10.332	0.0968	8641	9037	21.8
Model 13	42	6.83	0.1464	1365	1514	27.96
Model 14	72	49.457	0.0202	530	530	2.8
Model 15	31	31.813	0.0314	64	64	2.2
Model 16	54	66.63	0.0150	53	67	5.6
Model 17	47	108.034	0.0093	4.63	5.2	0.955
Model 18	77	10.422	0.0960	1280.37	1396.47	80.346
Model 19	176	11.721	0.0853	3177.03	3550.97	98.235
Model 20	65	16.77	0.0596	2605.93	3028.62	59.245
Model 21	66	19.334	0.0517	9115.64	9542.07	111.875
Model 22	47	14.304	0.0699	3052.46	3098.02	60.452
Model 23	51	13.706	0.0730	3811.24	3845.51	45.65

- As the structural irregularity increases, modal mass participation of modes at higher frequency increases.
- Hence effect of higher modes could not be ignored for irregular structural configuration



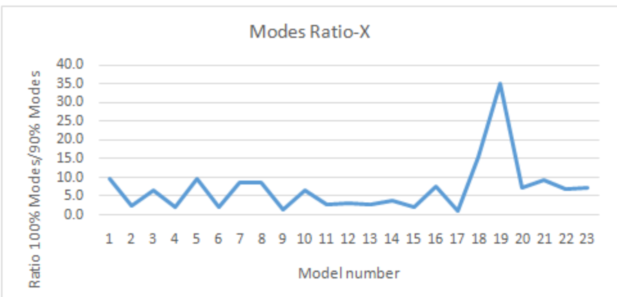
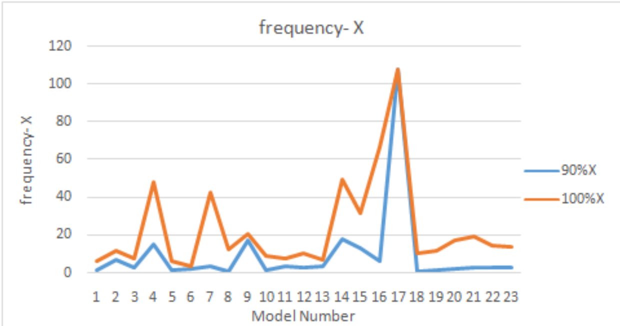


Figure 11: Modal response in X Direction

- Beyond 90% participation factor one need to combine response of very large number of modes at higher frequencies to get complete performance.



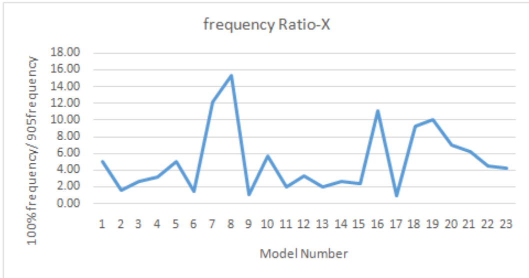


Figure 12: Frequency response in X Direction

- In most of structures 90% modal mass participation is achieved below frequency 33Hz. To get Total response one need to consider response of frequencies higher than 33Hz up to 80Hz. Most of times response at higher modes is rigid.
- Frequency ratio of frequency at 100% mass participation to frequency at 90% mass participation lies between 2 to 10.

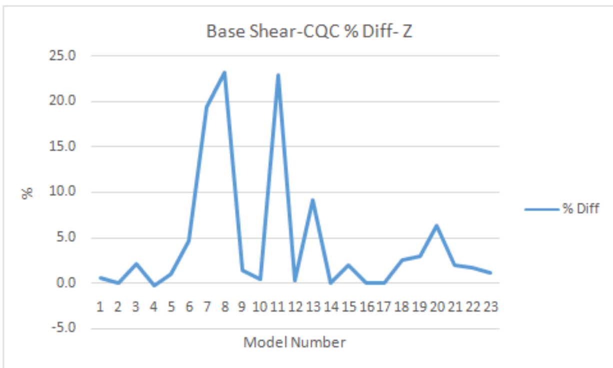


Figure 13: Base Shear Difference

- Error in Base Shear at 90% mass participation and 100% mass participation lies between 3% to 20%. Effect of this error may get amplify in moment at base.

- Ignoring contribution of Residue (Missing) Mass of 1% to 10% at higher frequencies and zero period acceleration as 2.5, the error in response will be in the range of2.5% to 25%.

- The error at higher modal frequencies can be eliminated by considering effect of Residue (Missing) Mass.

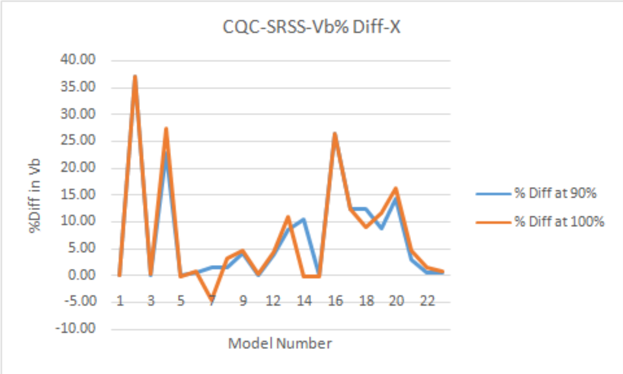


Figure 14: CQC vs SRSS Comparison

- Error in Base Shear at 90% mass participation and 100% mass participation lies between 3% to 20%. Effect of this error may get amplify in moment at base.

- Error in storey shear at 90% Modal mass increases with storey height. The Error can be reduced by adding effect of Residual Rigid Response at higher frequencies.

- SRSS method underestimate Base Shear by 3 to 20% as compared to CQC Method.

- CQC Method is more acceptable method as compared to SRSS Method for modal combination.

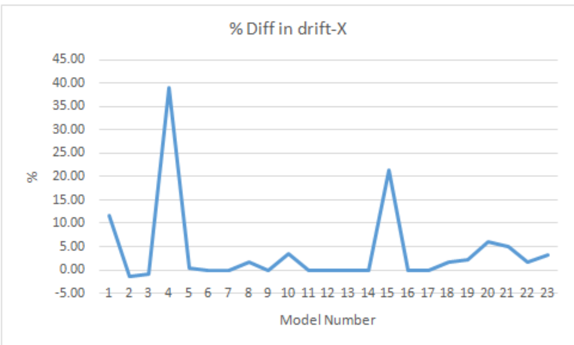


Figure 15: Drift Comparison

- Very little difference is observed between drift at 90% mass participation and drift at 100% mass participation

CONCLUSION

For regular buildings, building rules of practice specify only one mode and 90% seismic mass participation in that mode for regular structures. However, Ub's modal expansion indicates that this method may not always yield the proper answers for all structural parts. Storey shear is underestimated at both the top and bottom levels of the building, according to instances cited in the paper as part of a novel strategy, truncated upper modes are taken into consideration by employing a modified residual mode to calculate the response. This method produces reasonable results in response calculations, as can be seen from the provided examples. Using this method, the pushover analysis of structures can include contributions from higher modes other than first mode, making it elastic.

For regular buildings, first few modes (Modes with lower frequency) have major contribution in overall vibration of the structure and contribution of higher modes (Modes with higher frequency) is considerably very less in overall vibration of the structure.

For Irregular buildings, contribution of first few modes (Modes with lower frequency) is decreases in overall vibration of the structure and contribution of higher modes (Modes with higher frequency) goes on increasing with increase in irregularity of the structure. Hence particularly for structures with large amount of irregularity involved in it, then it is suggested to consider contribution of higher modes in earthquake resistant design of the structure. It is also recommended to perform nonlinear dynamic analysis for high rise structures with large amount of irregularity.

- At lower frequencies response of structure is mainly periodic. Higher frequencies consist of 'periodic' response and the 'rigid' response.

- Gupta Method separates the periodic and rigid components of a response by a rigid response coefficient.

- Rigid response coefficient converges about 90% modal participation.

- No effect of Soil type on frequency and modes shape; but there is effect on base shear. Base shear increases with soft soil.

- SRSS Method underestimate forces by 3% to 20% as compared to CQC Method in combination of closely spaced modes. Complete Quadratic Combination (CQC) Method is more accurate for combination of closely spaced modes.

- Most of Structures reaches to Rigid Response up to frequency 33Hz. At higher frequencies (beyond 33Hz) rigid response is predominate (ZPA) having frequencies that of the input motion.

- Ignoring contribution of Residue (Missing) Mass of 1% to 10% at higher frequencies and zero period acceleration as 2.5, the error in response will be in the range of 2.5% to 25%.

- Rigid Response Error between Modes with 90% modal participation to total response lies between 3% to 20% . This error can be eliminated by considering Rigid Response of Residue Modes of higher modes.

- Structures with irregular configuration, participation of higher frequency modes are more significant. Effect of higher modes could not be ignored for irregular structural configuration.

- To obtain 90-percent mass participation required by codes, it is necessary to calculate a large number of eigenmodes, lengthening calculations. Residue Mode consideration is useful without increasing the number modes.

- For Flexible Structures (Ductile, Tall, Irregular, Steel) to attain 90% participation factor, large number of modes with higher frequency need to be considered. Hence for these structures it is important to consider higher modes with residue mass participation.

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