

Equivalent Lateral Load Method vs. Response Spectrum Analysis Which Way is Forward

Samir H. Helou¹ and Ibrahim Muhammad²

¹ Lecturer at An-Najah National University- Palestine
Email: shhelou {at} yahoo.com

² Lecturer at An-Najah National University- Palestine

ABSTRACT---- *In earthquake prone zones like the region in which Palestine is situated, structures have to resist added forces induced on them as a result of member distortions caused by the ground motion on which they rest. The response is attributed to the inherit properties of the structure itself, the nature of the exciting motion as well as the particular foundation system of the structure.*

The present study aims at clarifying the prudent technical approach for the structural analysis and design for seismic action in compliance with pertinent code requirement; namely that of the IBC and the UBC. Of the recognized three dimensional standard methods of seismic analysis of multistory structures are the Equivalent Lateral Load method and the more sophisticated Response Spectrum Method. The later is better known as the Modal Analysis procedures both methods form the foci of the present study. Other methods are available but they are beyond the scope of the following discourse. Examples that illustrate the difference and the limitations of the two prime methods are presented in addition to the study of the effect of various seismic parameters that include, inter alias, height, topology and the vertical distribution of stiffness and mass on the overall structural response. Moreover, prevalent structural systems which include the locally popular yet essentially adverse practice of adding unreinforced facade masonry walls to framed reinforced concrete structures is briefly alluded to.

Keywords- Equivalent lateral load method, response spectrum, UBC97, IBC, base shear

1. INTRODUCTION

The Equivalent Lateral Load method is essentially a simplified static approach that involves the judicious application of an equivalent lateral load along the height of the building at the floor levels. the Response Spectrum method is substantially more sophisticated. The fundamental objective is to evaluate the strength demand imposed by the seismic action on structures on one end and to quantify the structure's capacity to counteract those demands on the other end. It is of interest to remember at the onset that the adoption of the Response Spectrum method is hitherto an accepted method of analysis; however it does not relieve the designer from carrying out the obligatory Equivalent Lateral Load method. The necessary parameters for any seismic structural analysis and design undertaking include Zoning, Site Characteristics, Structural Occupancy, Structural Topology, Structural System and Height

The popularity of the Equivalent Lateral Load method stems from the fact that it requires modest understanding of the structure being analyzed or the nature of the spectral data or the mathematics involved in the more elaborate mode superposition in the Response Spectrum dynamic analysis. The following study presents a comprehensive numerical comparison between the two methods of analysis. Towards the turn of the century the UBC code was replaced by the IBC; the procedure in each is slightly different albeit the general logic remains virtually unchanged.

2. THE EQUIVALENT LATERAL LOAD METHOD

In seismic analysis loads, are historically taken as equivalent static accelerations modified by certain factors depending on the seismicity of the location, soil properties and the natural frequencies of the structure and the intended use. The formulas are developed for regular structures which enjoy reasonable distribution of mass and stiffness and lead to decoupling of lower modes. The method of analysis is obviously limited by stringent constraints that include but are not limited to height, weight,

occupancy and the relevant seismic zone category. In such a procedure, once the base shear is evaluated for a certain structure its vertical distribution along the height of the structure is accomplished in a manner that resembles the first mode of a vertical cantilever. The scenarios where this logic is applicable are limited to the following:

- Structures in design category A
- Structures in Seismic Design category B and C except for light framed structures
- For regular structures that have a period $< 3.5 T_s$ and are in design category D, E and F
- For irregular structures in D, E and F but with horizontal irregularity type 2, 3, 4 and 5 and $T < 3.5 T_s$.
- In irregular structures in Seismic Design Category D, E, and F but with vertical irregularities of type 4, 5a and 5b and $T < 3.5 T_s$.
- Light framed construction in occupancy I & II, more than 3 stories high, occupancy III & IV, more than 2 stories high and regular light frame structures with $T < 3.5 T_s$ in Seismic Design Category D, E, and F.

In accordance with the IBC, the necessary data pertaining to the seismic action include the Seismic Importance Factor, I and Structural Occupancy, the Mapped Spectral Response Accelerations S_s and S_1 , the Site Class, the Spectral Response Coefficients, S_{D_s} and S_{D_1} , the Seismic Design Category, Seismic Response Coefficient, C_s and the Response Modification Factor.

Based on UBC97, the base shear is calculated by the following formula

$$V = \frac{C_v I}{RT} W \quad \text{UBC97 30-4}$$

But the total design base shear shall not exceed the following:

$$V = \frac{2.5 C_a I}{R} W \quad \text{UBC97 30-5}$$

The total design base shear shall not be less than the following:

$$V = 0.11 C_a I W \quad \text{UBC97 30-6}$$

In addition, for seismic zone 4, the total base shear shall not also be less than the following:

$$V = \frac{0.8 Z N_v I}{R} W \quad \text{UBC97 30-7}$$

The period is calculated

$$T = C_t (h_n)^{\frac{3}{4}}$$

Where:

Z= seismic zone factor,

I= importance factor,

R= numerical coefficient representative of the inherent over strength and global ductility capacity of lateral force resisting systems,

C_a=acceleration seismic coefficient,

C_v= velocity seismic coefficient,

N_v= near source factor,

W= the total dead load and portions of other loads

C_t= 0.0731 for reinforced moment resisting frame and h_n is the height in meters.

Once the base shear is quantified the lateral distribution follows after determining an additional force applied at the top when certain conditions exist. This addition force, F_t shall be determined from the formula:

$$F_t = 0.07TV \leq 0.25V \text{ for } T > 0.7 \text{ seconds}$$

$$F_t = 0.0 \text{ for } T \leq 0.7 \text{ seconds}$$

Therefore the total base shear, V is:

$$V = F_t + \sum_{i=1}^n F_i$$
$$F_x = \frac{(V - F_t)w_x h_x}{\sum_{i=1}^n w_i h_i}$$

Where:

F_x = design seismic force applied to level x

W_x = that portion of weight, W located at or assigned to level x

W_i = that portion of weight, w located to or assigned to level i

h_x, h_i = height in meters above the base to level x and i

The storey shear is distributed in proportion of the stiffness of the supporting frames. The rather new IBC code specifies a significantly different procedure. It should be noted that in the static approach the formulations do not accommodate horizontal neither vertical irregularities

3. THE RESPONSE SPECTRUM METHOD

The Response Spectrum method is heavily based on computers and on improved structural analysis techniques. Here the force distribution is based on the natural modes of vibration. It is a more precise method and requires the determination of a Response Spectrum from measured seismic activity data. The Response Spectrum curve is a plot of the maximum spectral value versus period. The data of the seismic activity is reduced to the determination of a plot of seismic action versus natural frequency; this could be displacement; acceleration or velocity; however, the most typical is the acceleration. The plot has two characteristic periods; they are T_s and T_o. Detailed information from the structural model obtained from geometric decomposition gets coupled with the corresponding spectral values for each specific mode of vibration. In order to guarantee that the majority of the structural mass is included in the analysis; the code sets the acceptable mass participation at 90%. Independent results are combined to determine the general response of the overall structure. Since building structures enjoy closely spaced band of frequency values, the Complete Quadratic Combination method is given the edge over the SRSS.

The Response Spectrum is a function of period and damping ratio; it is developed for a single degree of freedom harmonic oscillator in order to develop equations for displacements, velocity and acceleration; the values are the maximum absolute values from the equations. It can be noticed that spectral acceleration drops exponentially with increasing period after leaving the plateau region, this means that for structures with low first frequencies the resulting spectral accelerations can be quite low. Structures with high fundamental frequencies fall either within the sharp initial linear region or within the plateau region.

The Response Spectrum procedure is obligatory for structures that are high in elevation with vertical or horizontal irregularity of stiffness, mass or geometry. These are some of the conditions that are clearly mentioned in codes of practice.

The following is the procedure briefly outlined:

- Determine S_S and S_1 short period spectral acceleration and 1 second period spectral acceleration
- Determine Site Classification
- Based on S_S and S_1 Determine site amplification coefficients F_a and F_v from ASCE 7-05
- Determine S_{MS} and S_{M1}
- $S_{MS} = F_a S_S$
- $S_{M1} = F_v S_1$
- Determine design S_{DS} and S_{D1}
- Maximum considered earthquake spectral acceleration is reduced by 1/3
- $S_{DS} = 2/3 F_a S_S$
- $S_{D1} = 2/3 S_{M1}$

Calculation of the Design Response Spectrum follows a standard procedure.

4. THE MATHEMATICAL MODELS

Two regular yet common framed reinforced concrete building are selected. Both have a 7 meter span and 3 bays in the Y-direction and a 5 meter span with 4 bays in the X-direction. The isometric view of the models is shown in Figures 1 and 2; the structures are assumed to have a total fixity at base. However, one model is comprised of 5 identical floors while the other is comprised of 15. For comparison purposes the plans of the models are structurally modified in order to amplify the irregularity induced. The structures are modeled using Etabs Software of Computers and Structures Incorporation. The seismic data is selected in harmony with local geotechnical conditions. [Soil: soft rock, S_e type in accordance with UBC 97 provisions. Site class C in accordance with IBC 2009. Zone factor $Z = 0.2$ in UBC 97, $C_a = 0.24$; $C_v = 0.32$; $\Omega = 2.8$; $R = 5.5$ Due to lack of a map of spectral accelerations of S_1 and S_S , the following is assumed $S_1 = 1.25 Z$; $C_d = 4.5$; $S_S = 2.5 Z$, and a 5% damping ratio [Amendment No. 3 to SI 413 (2009)].

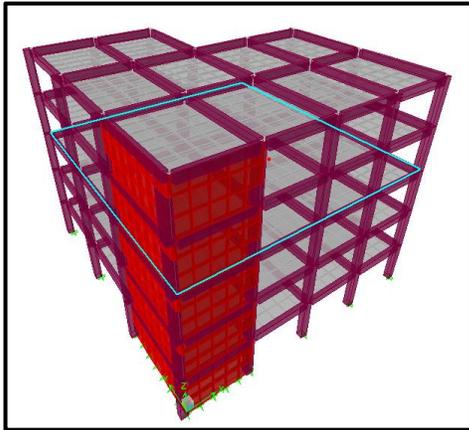


Figure 1: The Irregular 5-Story Bldg.

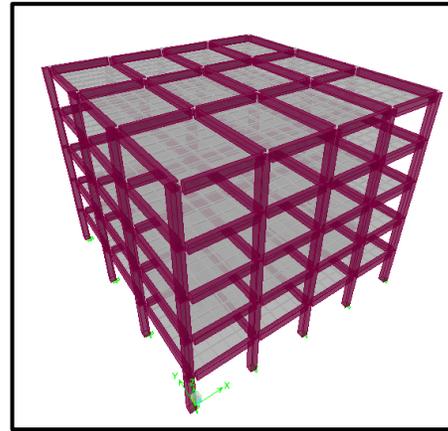


Figure 2: The Regular 5-Storey Bldg.

With the above data and in accordance with the UBC procedure the following is obtained:

The period is given by:

$$T = C_t(h_n)^{\frac{3}{4}} = (0.0731)(5 \times 3.5)^{0.75} = 0.625 \text{ seconds}$$

The base shear is:

$$V = \frac{C_v I}{RT} W = \frac{(0.32)(1)}{(5.5)(0.625)} = 0.0931W \quad \text{UBC 97 30 - 4}$$

$$V = 3243.7 \text{ kN}$$

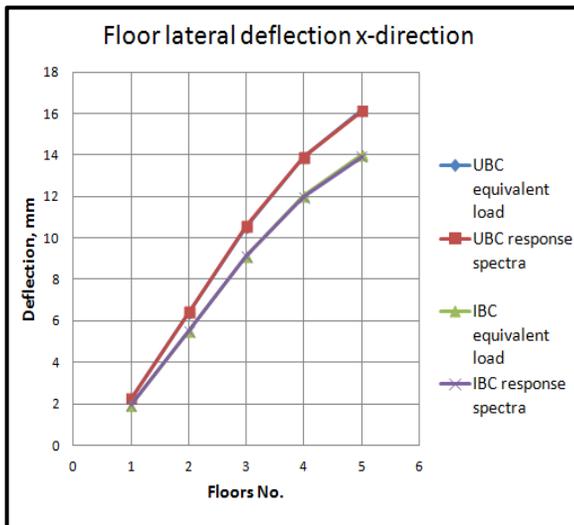


Figure 3: Floor Lateral Deflection, 5-Storey Bldg

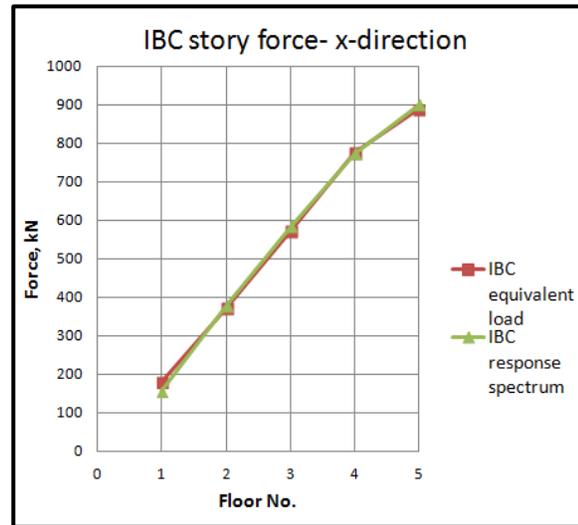


Figure 4: Story Forces, 5-Storey Bldg

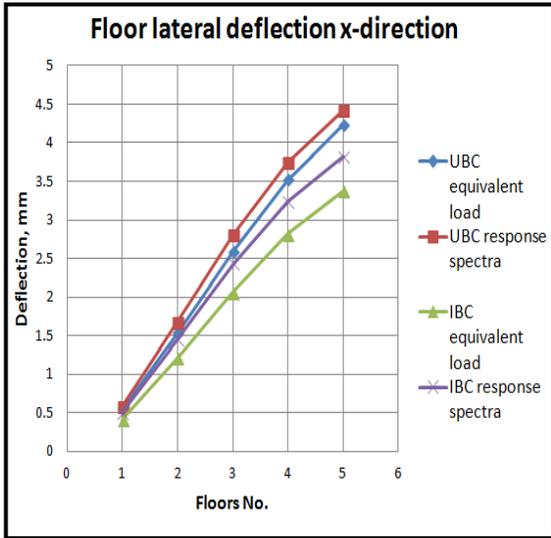


Figure 5: Floor Lateral Deflection, 5-Storey Irregular Bldg

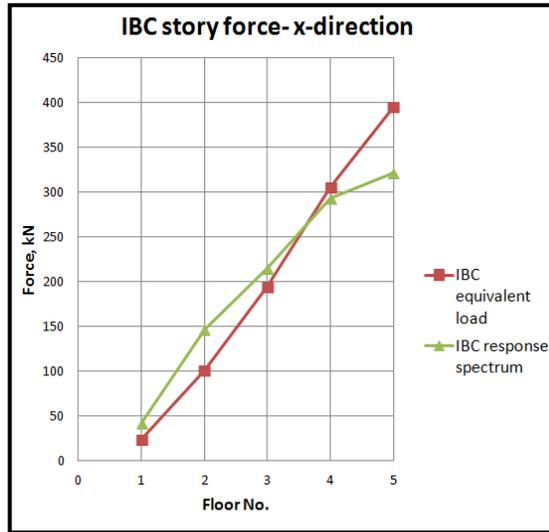


Figure 6: Story Forces, 5-Storey Irregular Bldg

For the 15-Storey regular the following and following similar calculations lead to the following in accordance with the UBC 97. The period is given by:

$$T = C_t(h_n)^{\frac{3}{4}} = (0.0731)(15 \times 3.5)^{0.75} = 1.43 \text{ seconds}$$

The base shear is given by:

$$V = \frac{C_v I}{RT} W = \frac{(0.32)(1)}{(5.5)(1.43)} = 0.0407W \quad \text{UBC 97 30-4}$$

$$V = 0.0407 \times 104523.75 = 4254 \text{ kN}$$

However in accordance to the IBC

$$T_a = C_t(h_n)^x = 0.0466(52.5)^{0.9} = 1.65 \text{ seconds} \quad \text{ASCE 7-10 (12.8-7)}$$

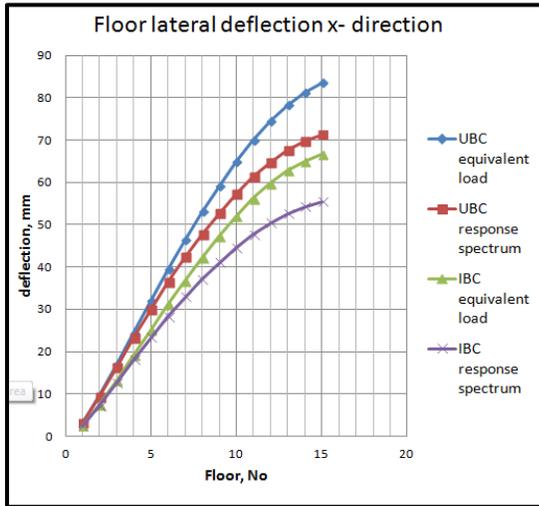


Figure 7: Floor Lateral Deflection 15-Storey Regular Bldg.

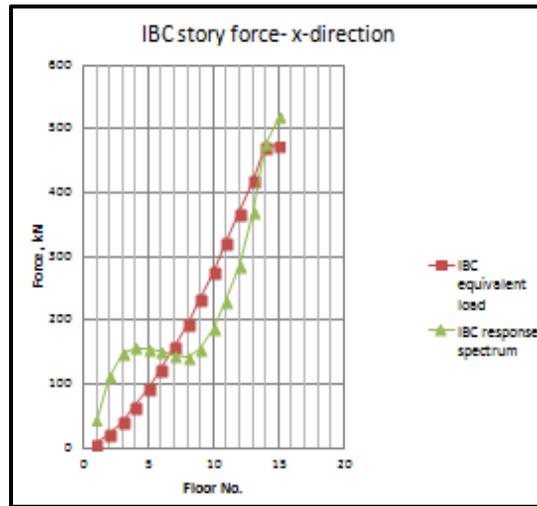


Figure 8: Story Forces 15-Storey Regular Bldg. 15- Storey Regular Bldg.

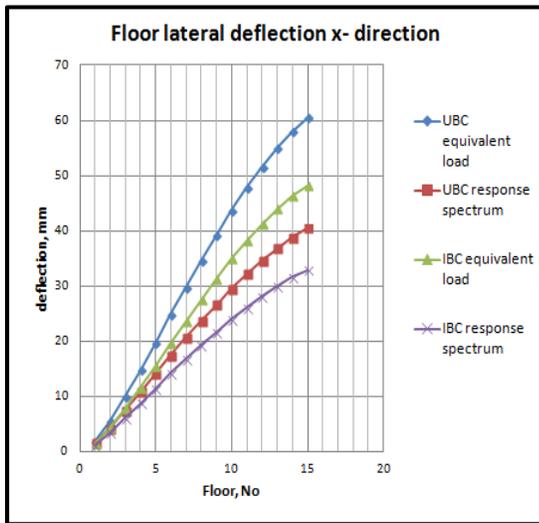


Figure 9: Floor Lateral Deflection, 15-Storey Irregular Bldg.

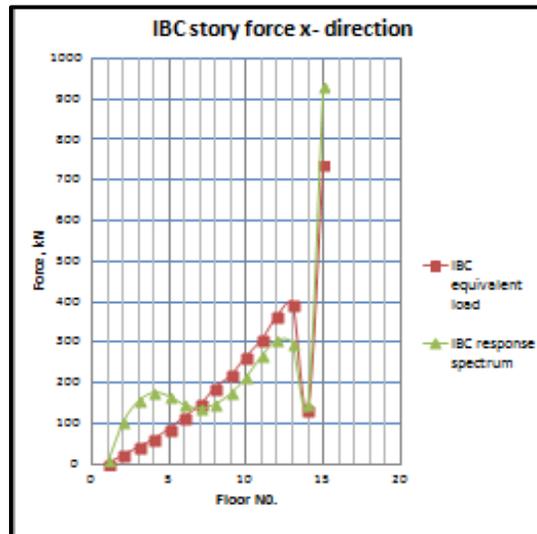


Figure 10: Story Forces, 15-Storey Irregular Bldg.

5. RESULTS AND CONCLUSION

Scrutinizing the above figures that focus on the lateral deflection as an indicator of structural behavior it is easily observed that the Equivalent Lateral Load Method gives conservative results relative to the Response Spectrum Method. This is manifested in both in regular and in irregular buildings albeit that the difference is more pronounced in the later. The order of difference increases substantially with increasing height. This observation is irrespective of irregularity. However the deviation is quickly amplified within the irregularity domain.

Tables 1 to 4 below show the geometric decomposition results for the 4 different structures. Scrutinizing the geometric decomposition results which include mass participation, modal participation as well as the frequency distribution for the four models, it is noticed that in the 5-storey regular structure a 90% of the total mass is secured from the initial very few modes. Torsion modes have no significance. However, for the 5 story irregular structure the situation changes. Frequencies become spaced within a narrower band, more eigenvector are required to guarantee 90% modal mass participation and the torsion modes become of considerable significance. This implies that for irregular structures there is no predominant mode signifying that the inertia force is well distributed over a number of vibration modes.

The question therefore is never which way to go in seismic analysis and design undertakings. Since the static analysis is an obligatory initial step then the question amounts to whether to continue with the elaborate dynamic analysis. This is indeed necessary, as has been shown above, even in the case of symmetric structures but of increased elevation. Furthermore, plan symmetry is not the important matter, because unsymmetrical floor plans may be brought closer to regularity with judicious distribution of shear walls. Another attribute to consider is the closeness of the eigenvalues. For irregular structures these are narrowly spaced. Finally it is to be noted that masonry infill walls have an adverse effect of lowering the fundamental frequency while shear walls wisely located help tone the system to behave closer to a regular one. Masonry walls add mass with little, if an, contribution to stiffness.

Table 1: The Case of the 5-Storey Regular Structure

Mode	Period	UX	UY	UZ
1	1.193648	0	83.2225	0
2	1.08944	83.945	0	0
3	0.9543	0	0	0
4	0.380425	0	10.3853	0
5	0.352391	10.2205	0	0
6	0.307236	0	0	0
7	0.213645	0	4.0126	0
8	0.20265	3.7436	0	0
9	0.175414	0	0	0
10	0.145962	0	1.8358	0
11	0.142349	1.6315	0	0
12	0.121737	0	0	0

Table 2: The Case of the 5-Storey Irregular Structure

Mode	Period	UX	UY	UZ
1	0.986037	27.1231	28.8366	0
2	0.588376	42.4655	28.7159	0
3	0.357902	3.9435	4.0019	0
4	0.250577	6.633	18.7326	0
5	0.198518	1.3068	0.9122	0
6	0.163069	11.9233	9.2425	0
7	0.137487	0.8899	0.9292	0
8	0.111909	0.1754	0.2088	0
9	0.097563	2.053	2.4887	0
10	0.089108	1.9082	3.6474	0
11	0.080365	0.8123	0.7935	0
12	0.070824	0.0393	0.0674	0

Table 3: The Case of the 15-Storey Regular Structure

Mode	Period	UX	UY	UZ
1	3.463663	0	83.5087	0
2	3.163478	83.4518	0	0
3	2.70096	0	0	0
4	1.088422	0	8.0963	0
5	0.993782	8.4615	0	0
6	0.849938	0	0	0
7	0.623896	0	3.288	0
8	0.566168	3.3069	0	0
9	0.497197	0	0	0
10	0.442182	0	1.7431	0
11	0.403697	1.6881	0	0
12	0.354162	0	0	0

Table 4: The Case of the 15-Storey Irregular Structure

Mode	Period	UX	UY	UZ
1	2.758852	25.7397	34.4477	0
2	2.225406	44.9144	26.7901	0
3	1.189814	2.6553	8.4536	0
4	0.983758	5.2725	7.6902	0
5	0.622555	8.3816	6.1001	0
6	0.541208	0.7901	1.2724	0
7	0.398217	0.8633	0.844	0
8	0.289971	0.3117	0.2817	0
9	0.286246	2.8416	3.0861	0
10	0.27288	2.077	3.9307	0
11	0.236729	0.2999	0.329	0
12	0.19334	0.253	0.2074	0

6. REFERENCES

- [1] American Society of Civil Engineers, "Minimum Design Loads for Buildings and Other Structures, ASCE/SEI 7-10", Reston, VA, 2010
- [2] American Concrete Institute, " Building Code Requirements for Structural Concrete, ACI 318-08 and Commentary", Farmington Hills, MI, 2008
- [3] International Code Council, "International Building Code, IBC 2009 ", Washington, D.C. 2009
- [4] International Conference of Building Officials, "Uniform Building Code, volume 2, UBC 97", California, 1997
- [5] James K. Wight and James G. McGregor, "Reinforced Concrete Mechanics and Design", Fifth edition, Pearson International Edition, 2009
- [6] S. K. Ghosh, Ph.D. and Pro Dasgupta, Ph.D., P.E., " Seismic Design using Structural Dynamics", S. K. Ghosh Associates Inc., 2014