ISSN 2229-5518

Structural Reliability of RCC buildings subjected to seismic loads

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1. Introduction

Reliability Analysis is a vital ingredient for a successful structural design. It assists the Engineer to consider all possible structural uncertainities by calculating the probabilities of failure during the analysis, design, construction and life span of structure. Therefore a well known methodology of reliability analysis has to be adopted to evaluate the seismic performance of reinforced concrete buildings. The lateral displacement of a building during an earthquake has an important impact on its structural performance. Estimation of seismic hazard in any region needs the complete data of previous earthquakes with a uniform magnitude scale. Dynamic structural analysis is used to confirm that building designs are capable of meeting the intended performance standards. The total drift is limited by different seismic codes . In order to design safe structures, The Indian code for seismic design IS1893 (part 1)(2002) has stated that the storey drift in any storey due to the minimum specified design lateral force, with partial load factor of 1.0 shall not exceed 0.004 times the storey height. Therefore the total drift of the building should not exceed a drift limit of 0.004 times the building height. Different softwares are available to perform nonlinear static analysis like ETABS, SAP, ADINA etc which can be used for calculating the total drifts . The reliability index β is typically used to measure the reliability of the building , by assessing the total drift of the building. This approach has made it possible to reduce the probability of failure of building structures. . The reliability index of a structure increases when the probability of failure reduces.

While a lot of research has been done in the field of reliability , limited studies addressed the use of reliability index to calculate the reliability of buildings based on their total drifts in different seismic zones of India. This paper develops a reliability index approach to calculate the reliability of tall buildings subjected to seismic loads. The dynamic response of a building was obtained using the models of three buildings having different L/B ratios. These buildings were subjected to the time history data of twenty different earthquakes and their total displacement was recorded. A reliability range is developed for safe structures subjected to seismic loads in the four seismic zones of India .

2. Method Formulation

In order to develop a reliability range, three different buildings were modeled in a well known structural software called ETABS. These buildings having different L/B ratios. ie Building 1 (L/B =1.19), Building 2 (L/B =1.44) and Building 3 (L/B = 1.72) were used. All the buildings are thirty storied with 3 m as the floor to floor height. Therefore the total height of these buildings is 90m .

These buildings were modeled for twenty actual earthquakes and analysed in the four seismic zones of India . The drifts thus obtained were tabulated and the safety margin curve was plotted. Reliability Index is than calculated based on the total drift obtained from these structures.A building fails when the total drift of a building is more than the allowable drift. The margin of safety of a building is given by the following equation:

$M = \triangle - \delta$ -- (1)

where $\triangle$ is the allowable drift given by the equation

$\triangle = H_T * D_1$ -- (2)

H_T is the total building height and D_1 is the drift index as specified by the code (0.004)

δ is the actual total displacement of the building.

Hence the probability of failure is given by the following equation :

$p_f = P(M<0)$ -- (3)

$= \varnothing\left(\frac{0-\mu_M}{\sigma_M}\right)$

Where $\varnothing$ is the standard normal cumulative probability distribution function

μ_M is the mean value of M

s_M is the standard deviation of M

Therefore $pf = \varnothing\left(\frac{-\mu_M}{\sigma_M}\right)$ --- (4)

The reliability index is obtained by the equation :

$b = \left(\frac{\mu_M}{\sigma_M}\right)$ -- (5)

3 Data used :

The following are the plans of the buildings that were used:

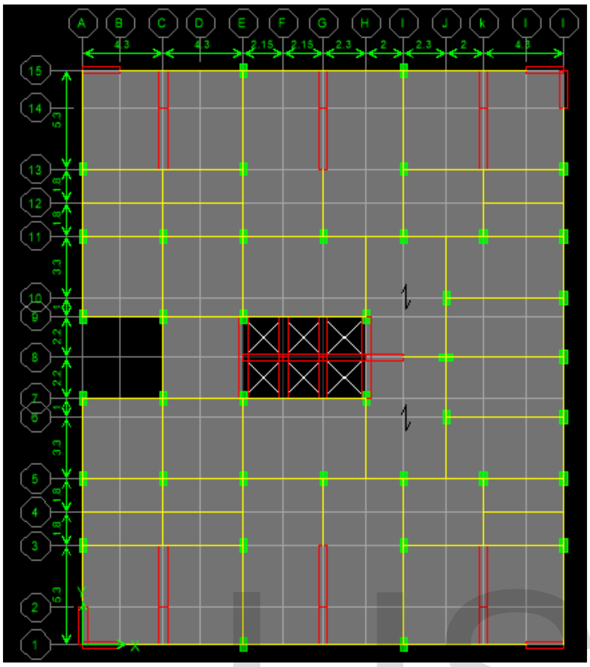


Fig 1: Building 1

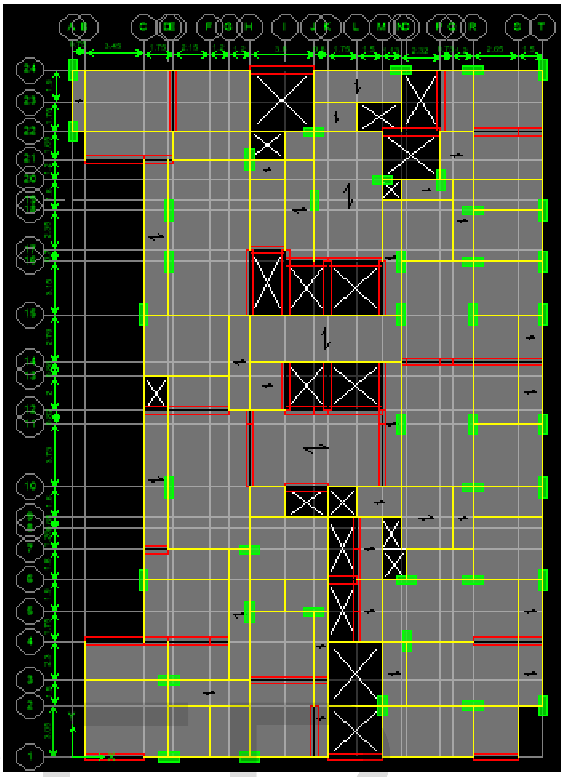


Fig 2: Building 3

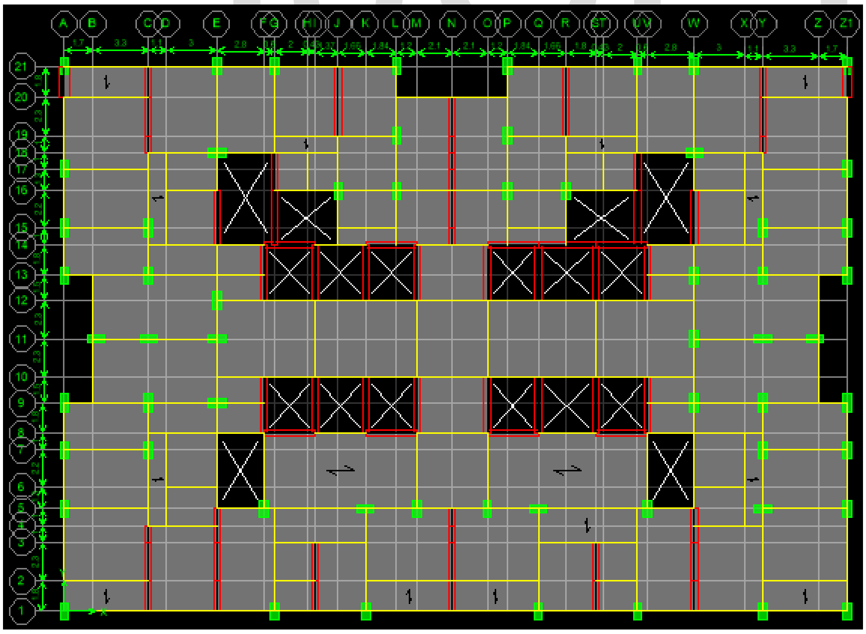


Fig 3: Building 2

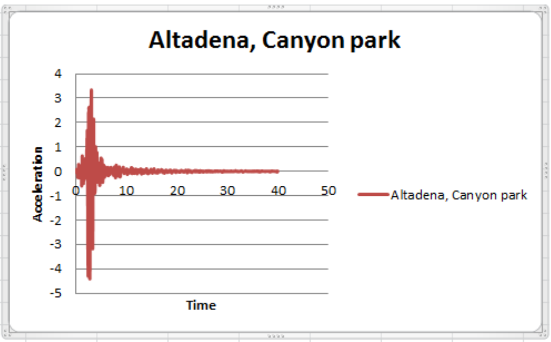
For the purpose of determining seismic forces, IS1893, Part 1 (2002) has classified the country into four seismic zones as given below:

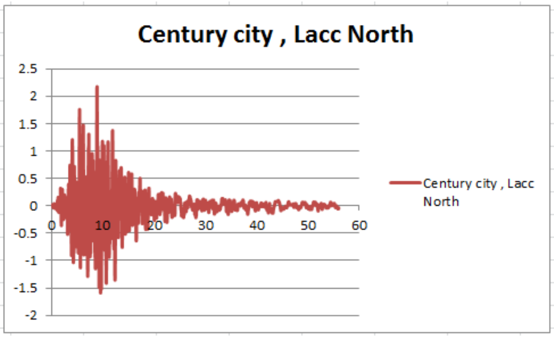
ISSN 2229-5518

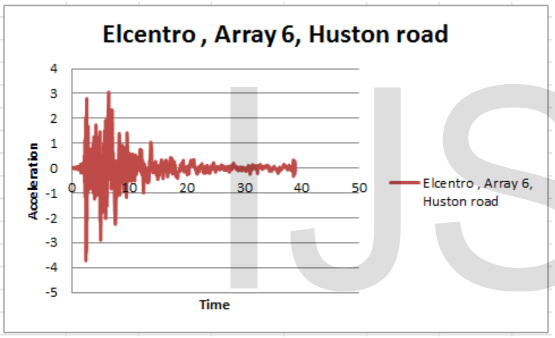
Seismic zone	II	III	IV	V
Seismic Intensity	Low	Moderate	Severe	Very Severe
Zone Factor	0.10	0.16	0.24	0.36

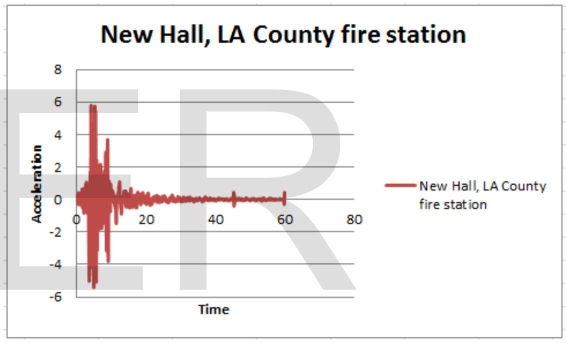
Table 1: Values of zone factors as per the code.

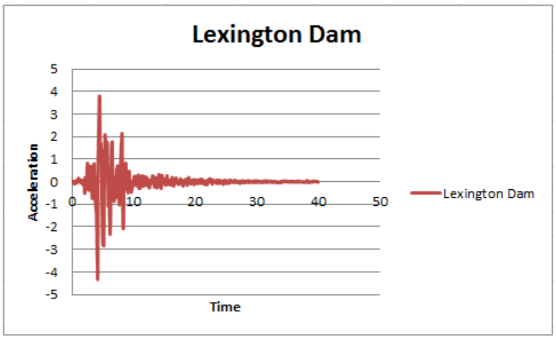
The time history data of the following earthquakes of magnitude lying in the range of 5 to 7.5 on the richter scale were used.

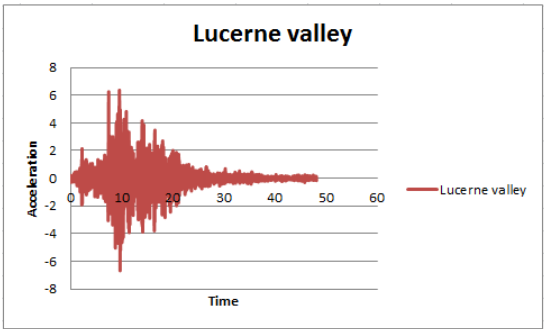


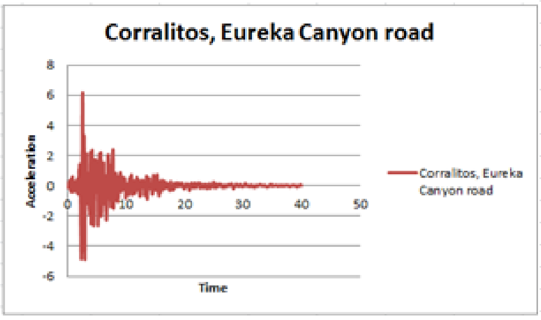


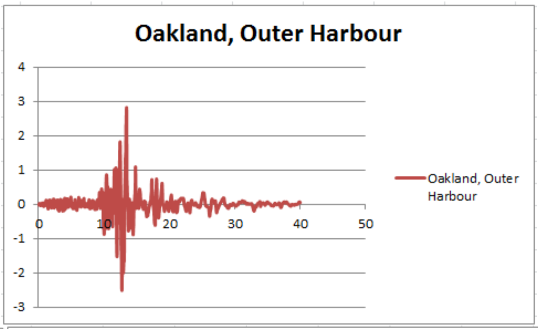


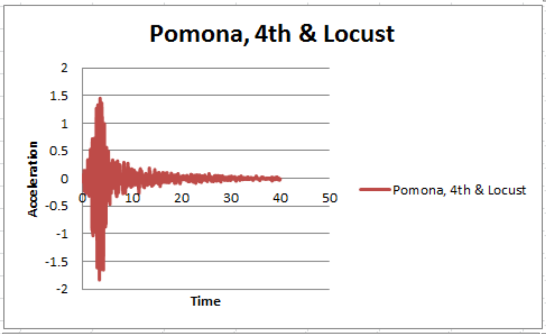


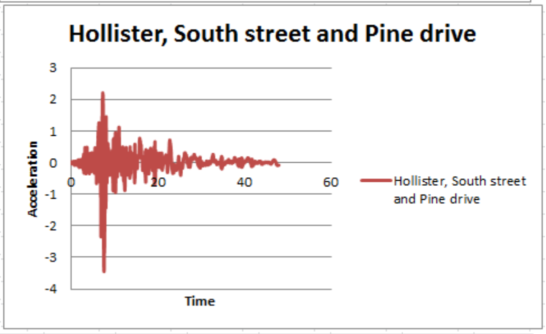


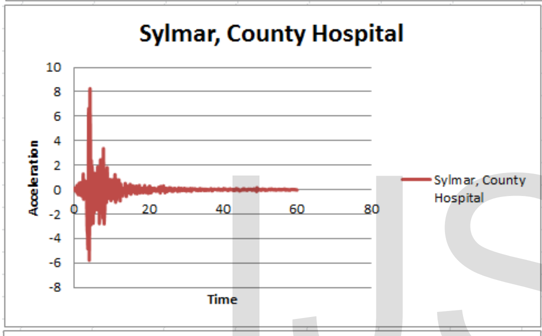


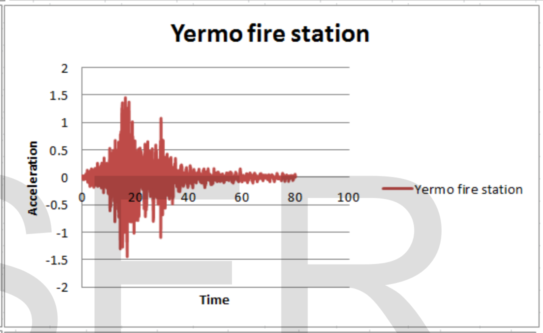

Corralitos, Eureka Canyon road
Acceleration
Time
Corralitos, Eureka Canyon road

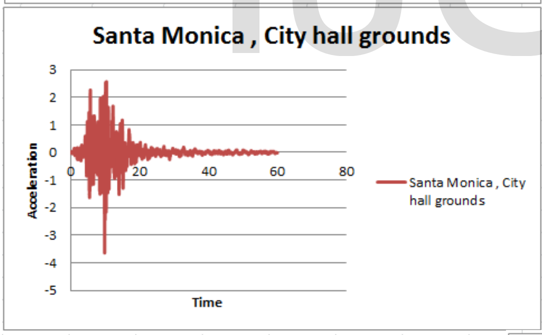

Oakland, Outer Harbour
Oakland, Outer Harbour

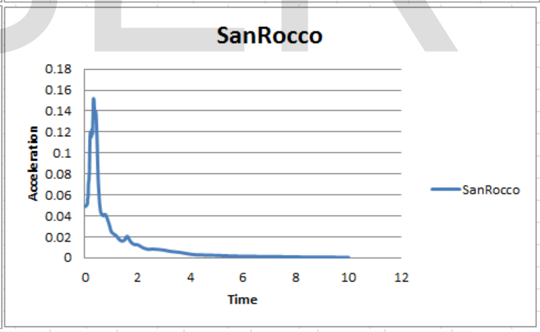

Pomona, 4th & Locust
Acceleration
Time
Pomona, 4th & Locust


Hollister, South street and Pine drive
Acceleration
Time
Hollister, South street and Pine drive

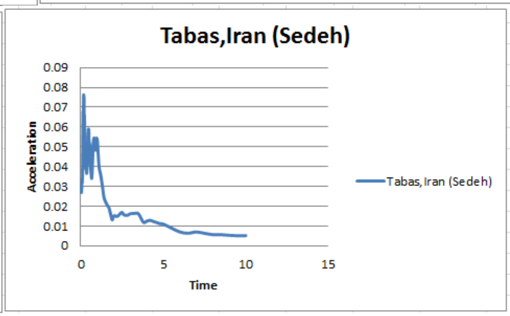

Sylmar, County Hospital
Acceleration
Time
Sylmar, County Hospital


Yermo fire station
Acceleration
Time
Yermo fire station


Santa Monica , City hall grounds
Acceleration
Time
Santa Monica , City hall grounds


SanRocco
Acceleration
Time
SanRocco


Kozani,Greece(Larisa)
Acceleration
Time
Kozani,Greece(Larisa)


Tabas,Iran (Sedeh)
Acceleration
Time
Tabas,Iran (Sedeh)

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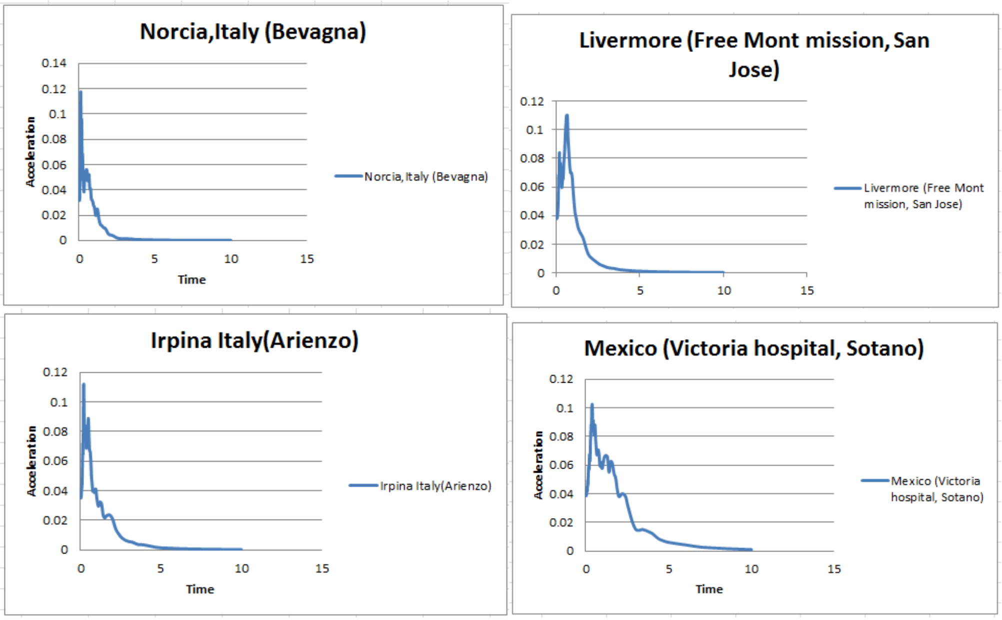

Fig 4: Time history data of earthquakes

The following data was used in the analysis of the structures:

Cross section of beams: 300mmx600mm/700mm.

Grade of Concrete : M50

Steel : Fe500

The following cross sections of columns and shear walls were used for the buildings:

		S_2 Zone			S_3 Zone			S_4 Zone			S_5 Zone		
	Floor Level	Column Sections (mm)	Shear Wall Sections (mm)		Column Sections (mm)	Shear Wall Sections (mm)		Column Sections (mm)	Shear Wall Sections (mm)		Column Sections (mm)	Shear Wall Sections (mm)	
			x	**y**		**x**	**y**		**x**	**y**		**x**	**y**
Building 1	26th to 30th	400 x 700	350	450	400x800	350	450	500x900	350	450	500x1200	350	450
	21st to 25th	400 x 700	350	500	400x800	350	500	500x900	350	500	500x1200	350	500
	16th to 20th	500 x 800	400	550	500x900	400	550	600x1000	400	550	600x1400	400	550
	11th to 15th	500 x 800	450	600	500x900	450	600	600x1000	450	600	600x1400	450	600
	5th to 10th	600 x 900	500	650	600x1000	500	650	700x1200	500	650	700x1600	500	650
	1st to 5th	600 x 900	500	700	600x1000	500	700	700x1200	500	700	700x1600	500	700
Building 2	26th to 30th	500 x 1000	350	400	500x1000	350	400	500x1500	350	400	500x1750	350	400
	21st to 25th	500 x 1000	450	450	500x1000	450	450	500x1500	450	450	500x1750	450	450

	16th to 20th	600 x 1300	500	450	600x1200	500	450	600x1600	500	450	600x1850	500	450
	11th to 15th	600 x 1300	550	500	600x1200	550	500	600x1600	550	500	600x1850	550	500
	5th to 10th	700 x 1500	600	550	700x1400	600	550	700x1700	600	550	700x1950	600	550
	1st to 5th	700 x 1500	600	600	700x1400	600	600	700x1700	600	600	700x1950	600	600
Building 3	26th to 30th	500 x 1200	450	450	500x1350	450	450	500x1450	450	450	500x1650	450	450
	21st to 25th	500 x 1200	500	500	500x1350	500	500	500x1450	500	500	500x1650	500	500
	16th to 20th	600 x 1300	550	500	600x1450	550	500	600x1550	550	500	600x1750	550	500
	11th to 15th	600 x 1300	600	550	600x1450	600	550	600x1550	600	550	600x1750	600	550
	5th to 10th	700 x 1400	650	600	700x1550	650	600	700x1650	650	600	700x1950	650	600
	1st to 5th	700 x 1400	650	600	700x1550	650	600	700x1650	650	600	700x1950	650	600

Table 2: Cross sections of columns and shear walls

4 Results and Discussion

The following values of displacements were recorded in the topmost storeys of the buildings in the different seismic zones of India.

		S2 Zone					
		Building 1		Building 2		Building 3	
Sr No		dx	dy	dx	dy	dx	dy
1	Altadena	0.17	0.15	0.17	0.25	0.24	0.2
2	Century City	0.25	0.4	0.26	0.5	0.4	0.34
3	Elcentro	0.27	0.34	0.28	0.51	0.51	0.43
4	Newhall	0.26	0.07	0.25	0.26	0.29	0.23
5	Lexington	0.12	0.15	0.11	0.25	0.23	0.21
6	Lucerne	0.03	0.52	0.06	0.51	0.27	0.17
7	Corralitos	0.19	0.24	0.19	0.31	0.26	0.23
8	Oakland	0.21	0.17	0.21	0.27	0.26	0.21
9	Pomona	0.21	0.13	0.21	0.25	0.32	0.21
10	Hollister	0.32	0.17	0.31	0.34	0.43	0.31
11	Sylmar	0.28	0.16	0.27	0.33	0.41	0.26
12	Santamonica	0.36	0.03	0.36	0.24	0.46	0.29
13	Yermo	0.28	0.39	0.38	0.63	0.6	0.37
14	SanRocco	0.18	0.19	0.23	0.26	0.12	0.12
15	Greece	0.27	0.25	0.23	0.24	0.24	0.18
16	Iran	0.13	0.19	0.14	0.15	0.14	0.12
17	Norcia-Italy	0.12	0.14	0.15	0.17	0.09	0.08
18	Livermore	0.24	0.34	0.27	0.3	0.33	0.26
19	Irpina-Italy	0.2	0.23	0.21	0.24	0.15	0.13
20	Mexico	0.24	0.33	0.24	0.27	0.23	0.18

Table 3: Deflections of the buildings in the S_2 Zone

		S_3 Zone					
		Building 1		Building 2		Building 3	
Sr No		dx	dy	dx	dy	dx	dy
1	Altadena	0.18	0.1	0.19	0.16	0.25	0.32
2	Century City	0.26	0.48	0.29	0.44	0.39	0.51
3	Elcentro	0.23	0.3	0.28	0.32	0.5	0.64
4	Newhall	0.28	0.27	0.29	0.06	0.26	0.35
5	Lexington	0.11	0.1	0.11	0.15	0.2	0.32
6	Lucerne	0.12	0.75	0.22	0.52	0.22	0.24
7	Corralitos	0.2	0.28	0.23	0.27	0.25	0.35
8	Oakland	0.23	0.16	0.25	0.2	0.26	0.32
9	Pomona	0.21	0.09	0.25	0.16	0.34	0.31
10	Hollister	0.34	0.17	0.39	0.28	0.45	0.47
11	Sylmar	0.27	0.16	0.32	0.25	0.41	0.38
12	Santamonica	0.4	0.37	0.45	0.15	0.51	0.44
13	Yermo	0.25	0.39	0.29	0.41	0.62	0.55
14	SanRocco	0.09	0.11	0.22	0.25	0.14	0.16
15	Greece	0.33	0.33	0.27	0.32	0.14	0.23
16	Iran	0.11	0.17	0.17	0.21	0.19	0.16
17	Norcia-Italy	0.14	0.21	0.15	0.18	0.06	0.09
18	Livermore	0.23	0.31	0.32	0.35	0.21	0.19
19	Irpina-Italy	0.15	0.2	0.23	0.28	0.19	0.18
20	Mexico	0.2	0.3	0.3	0.37	0.16	0.14

Table 4: Deflections of the buildings in the S_3 Zone

		S4 Zone					
		Building 1		Building 2		Building 3	
Sr No		dx	dy	dx	dy	dx	dy
1	Altadena	0.12	0.05	0.21	0.19	0.35	0.28
2	Century City	0.2	0.37	0.33	0.52	0.52	0.54
3	Elcentro	0.38	0.16	0.3	0.42	0.45	0.59
4	Newhall	0.08	0.21	0.35	0.11	0.32	0.16
5	Lexington	0.22	0.07	0.12	0.2	0.42	0.28
6	Lucerne	0.49	0.73	0.25	0.71	0.62	0.27
7	Corralitos	0.08	0.2	0.27	0.31	0.35	0.39
8	Oakland	0.04	0.1	0.3	0.23	0.31	0.29
9	Pomona	0.09	0.07	0.28	0.21	0.3	0.26
10	Hollister	0.1	0.12	0.46	0.22	0.39	0.46
11	Sylmar	0.15	0.11	0.38	0.28	0.54	0.25
12	Santamonica	0.07	0.35	0.53	0.15	0.28	0.23
13	Yermo	0.38	0.3	0.28	0.46	0.56	0.44
14	SanRocco	0.17	0.23	0.27	0.27	0.19	0.24
15	Greece	0.46	0.46	0.27	0.29	0.2	0.34
16	Iran	0.21	0.27	0.17	0.2	0.27	0.23
17	Norcia-Italy	0.19	0.24	0.15	0.17	0.09	0.13
18	Livermore	0.44	0.56	0.33	0.33	0.39	0.33
19	Irpina-Italy	0.23	0.3	0.23	0.26	0.27	0.27
20	Mexico	0.33	0.43	0.3	0.34	0.23	0.22

Table 5: Deflections of the buildings in the S_4 Zone

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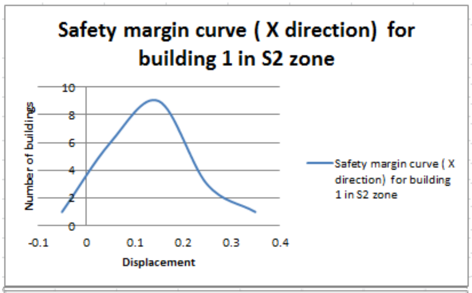
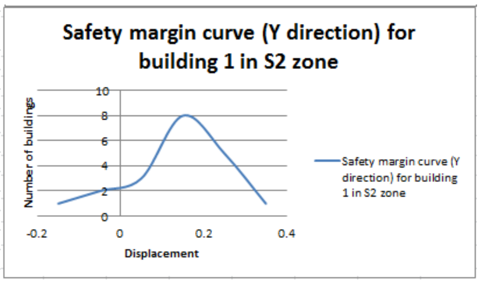
		S5 Zone					
		Building 1		Building 2		Building 3	
Sr No		dx	dy	dx	dy	dx	dy
1	Altadena	0.16	0.34	0.16	0.12	0.37	0.27
2	Century City	0.48	0.26	0.24	0.29	0.56	0.46
3	Elcentro	0.38	0.11	0.49	0.26	0.74	0.58
4	Newhall	0.05	0.26	0.12	0.25	0.64	0.48
5	Lexington	0.23	0.04	0.28	0.14	0.3	0.26
6	Lucerne	0.55	0.64	0.64	0.71	0.68	0.15
7	Corralitos	0.09	0.25	0.09	0.21	0.25	0.36
8	Oakland	0.07	0.08	0.18	0.18	0.2	0.27
9	Pomona	0.06	0.11	0.26	0.24	0.17	0.25
10	Hollister	0.08	0.24	0.18	0.25	0.22	0.36
11	Sylmar	0.12	0.19	0.2	0.21	0.36	0.23
12	Santamonica	0.14	0.62	0.28	0.29	0.25	0.22
13	Yermo	0.36	0.32	0.49	0.26	0.29	0.36
14	SanRocco	0.2	0.32	0.29	0.28	0.23	0.34
15	Greece	0.47	0.47	0.46	0.51	0.27	0.46
16	Iran	0.35	0.43	0.27	0.3	0.37	0.35
17	Norcia-Italy	0.3	0.34	0.23	0.25	0.11	0.19
18	Livermore	0.58	0.49	0.57	0.62	0.46	0.4
19	Irpina-Italy	0.37	0.47	0.34	0.37	0.43	0.31
20	Mexico	0.35	0.4	0.46	0.5	0.26	0.27

Table 6: Deflections of the buildings in the S_5 Zone

The margin of safety is calculated from these values and the safety margin curve in the x and y direction is plotted. The mean and standard deviation of these values is than calculated and is used to find the reliability index.





S2 Zone (Building 1)

μ x = 0.1435

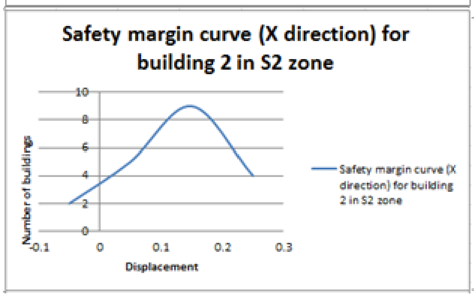
μ y = 0.1305

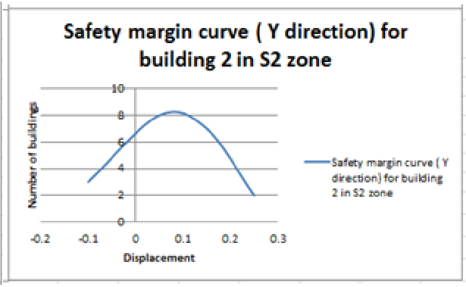
σ x = 0.0757

σ y = 0.119

β x = μ x/ σ x = 1.90

β y = μ y/ σ y = 1.09





S2 Zone (Building 2)

μ_x = 0.1335

μ_y = 0.046

σ_x = 0.0764

σ_y = 0.0892

$\beta_x = \mu_x / \sigma_x$ = 1.75

$\beta_y = \mu_y / \sigma_y$ = 0.42

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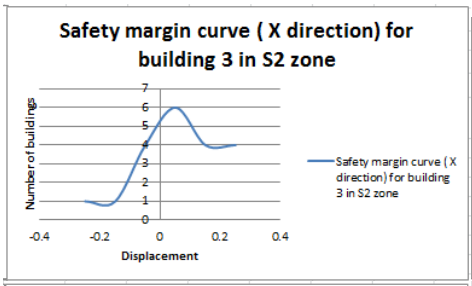
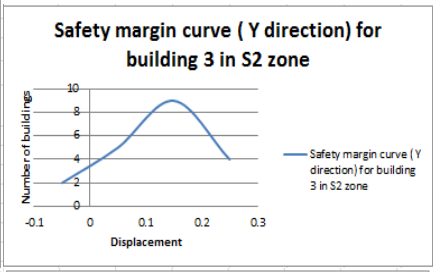




S2 Zone (Building 3)

$\mu_x = 0.061$

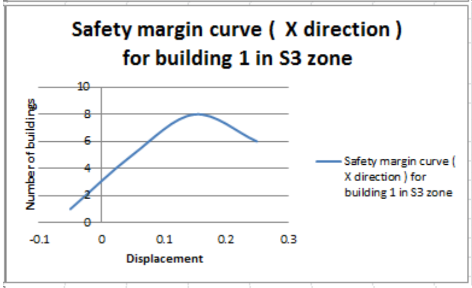
$\mu_y = 0.1335$

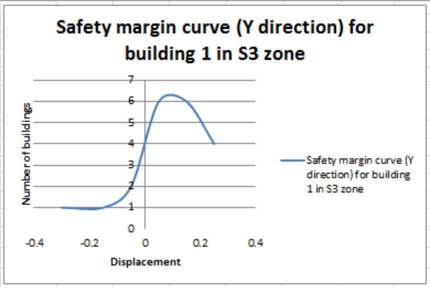
$\sigma_x = 0.131$

$\sigma_y = 0.087$

$\beta_x = \mu_x / \sigma_x = 0.46$

$\beta_y = \mu_y / \sigma_y = 1.54$





S3 Zone (Building 1)

$\mu_x = 0.1435$

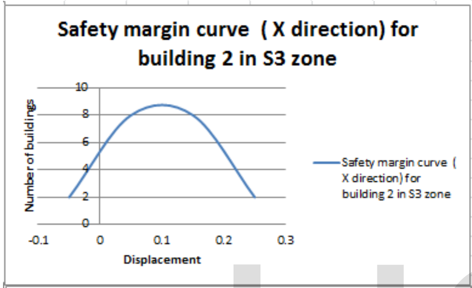
$\mu_y = 0.0975$

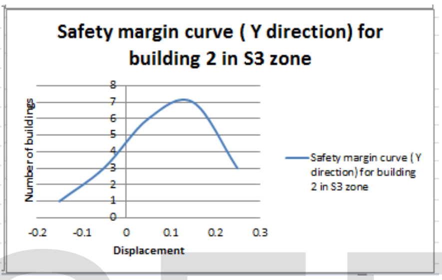
$\sigma_x = 0.0815$

$\sigma_y = 0.154$

$\beta_x = \mu_x / \sigma_x = 1.76$

$\beta_y = \mu_y / \sigma_y = 0.63$





S3 Zone (Building 2)

$\mu_x = 0.099$

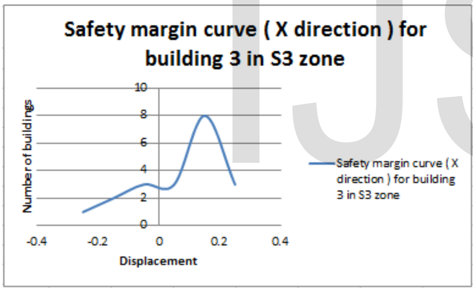
$\mu_y = 0.094$

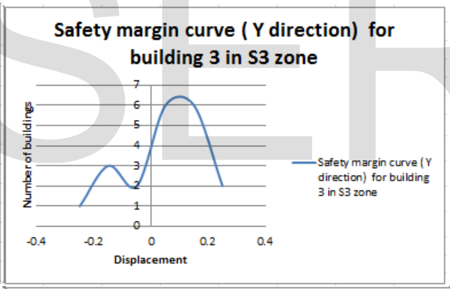
$\sigma_x = 0.077$

$\sigma_y = 0.12$

$\beta_x = \mu_x / \sigma_x = 1.29$

$\beta_y = \mu_y / \sigma_y = 0.77$





S3 Zone (Building 3)

$\mu_x = 0.0725$

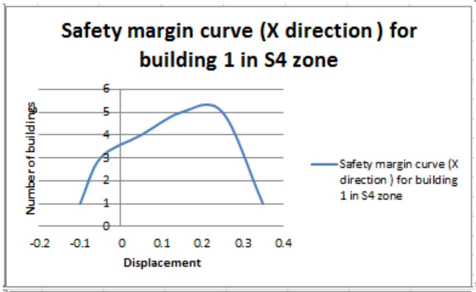
$\mu_y = 0.0425$

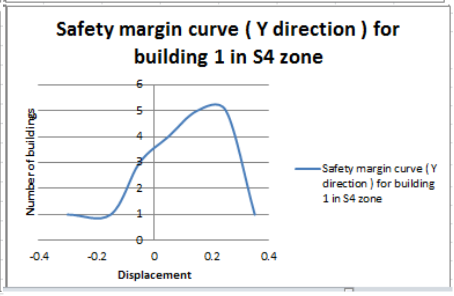
$\sigma_x = 0.149$

$\sigma_y = 0.164$

$\beta_x = \mu_x / \sigma_x = 0.49$

$\beta_y = \mu_y / \sigma_y = 0.26$





S4 Zone (Building 1)

$\mu_x = 0.1385$

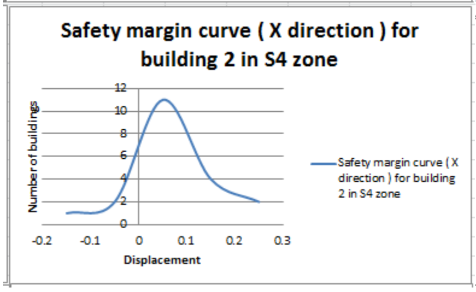
$\mu_y = 0.935$

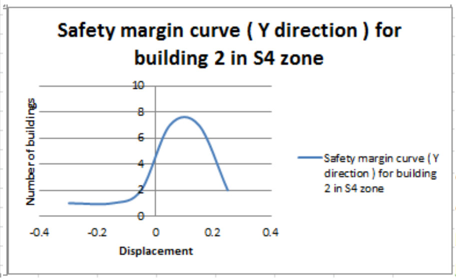
$\sigma_x = 0.139$

$\sigma_y = 0.174$

$\beta_x = \mu_x / \sigma_x = 1.0$

$\beta_y = \mu_y / \sigma_y = 0.54$





S4 Zone (Building 2)

$\mu_x = 0.071$

$\mu_y = 0.0665$

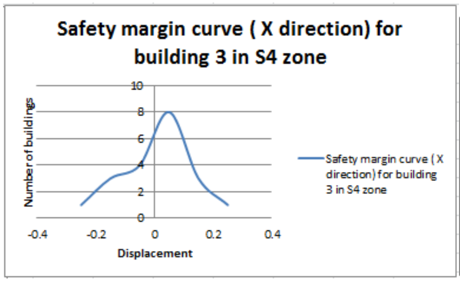
$\sigma_x = 0.094$

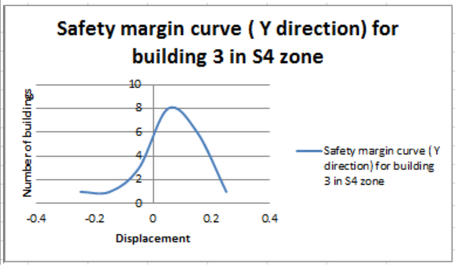
$\sigma_y = 0.1393$

$\beta_x = \mu_x / \sigma_x = 0.75$

$\beta_y = \mu_y / \sigma_y = 0.48$

ISSN 2229-5518





S4 Zone (Building 3)

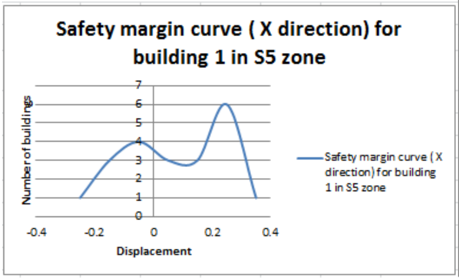
$\mu_x = 0.0075$

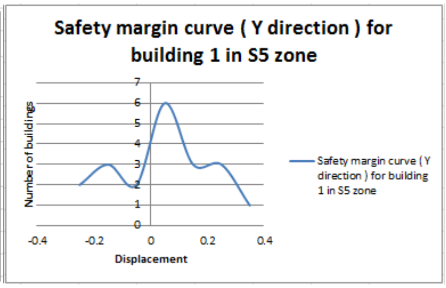
$\mu_y = 0.05$

$\sigma_x = 0.16 \quad \sigma_y = 0.125$

$\beta_x = \mu_x / \sigma_x = 0.132$

$\beta_y = \mu_y / \sigma_y = 0.43$





S5 Zone (Building 1)

$\mu_x = 0.0905$

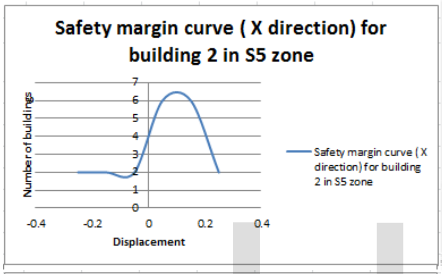
$\mu_y = 0.041$

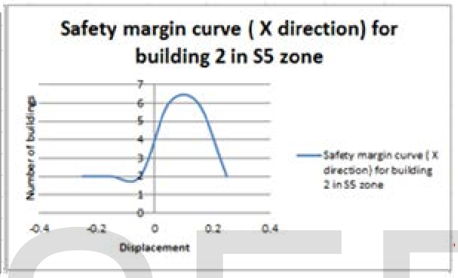
$\sigma_x = 0.168$

$\sigma_y = 0.166$

$\beta_x = \mu_x / \sigma_x = 0.54.$

$\beta_y = \mu_y / \sigma_y = 0.25.$





S5 Zone (Building 2)

$\mu_x = 0.0485$

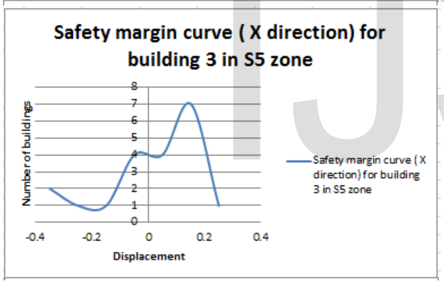
$\mu_y = 0.048$

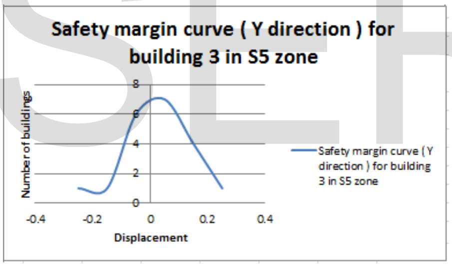
$\sigma_x = 0.152$

$\sigma_y = 0.152$

$\beta_x = \mu_x / \sigma_x = 0.32$

$\beta_y = \mu_y / \sigma_y = 0.32$





S5 Zone (Building 3)

$\mu_x = 0.002$

$\mu_y = 0.0315$

$\sigma_x = 0.172$

$\sigma_y = 0.106$

$\beta_x = \mu_x / \sigma_x = 0.012$

$\beta_y = \mu_y / \sigma_y = 0.30$

Fig 5 : Safety margin curves in X ad Y directions

The above values are than tabulated as folllows:

Seismic zone	Building model	Reliability Index βx	Reliability Index βy
S_2	Building 1	1.90	1.2
	Building 2	1.75	0.52
	Building 3	0.46	1.54
S_3	Building 1	1.76	0.63
	Building 2	1.29	0.77
	Building 3	0.49	0.26
S_4	Building 1	1.0	0.54
	Building 2	0.75	0.48
	Building 3	0.06	0.43
S_5	Building 1	0.54	0.25
	Building 2	0.32	0.32
	Building 3	0.011	0.3

5 Conclusion:

The paper develops a range of reliability index for the different seismic zones of India. It suggests that the building can be considered reliable if its reliability index lies within the following range:

S_2 zone: 0.46 to 1.90

S_3 zone: 0.26 to 1.76

S_4 zone: 0.06 to 1.0

S_5 zone: 0.011 to 0.54

The range is developed based on the time history data of actual earthquakes lying in the range of magnitude 5 to 7.5 on the richter scale. It is observed that the reliability index is higher for buildings having lower L/B ratio and vice versa. It is also observed that reliability index is higher in the lower seismic zones and lower in the higher seismic zones.

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