Nonlinear Static Analysis of R.C.C. Building by Using Procedure- A as Per ATC- 40

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Abstract—*Performance based seismic design (PBSD) is appropriate way of controlling seismic damage. This approach used in building construction for improving the performance of building. PBSD is of two types that are displacement based and forced based design process. Capacity spectrum method is the most widely accepted displacement based method. PBSD emphasizes on performance than strength and check the performance of building by calculating performance point. Performance point is calculated by using different methods, ATC-40 report published by Applied Technology Council (USA) gives three different procedures for finding performance point namely procedure A, B and C. Procedure A is the most direct and formulae based while procedure B is simplified assumption based. In procedure B post yield slope is taken to be constant and it used in software packages like SAP2000 and ETABs. Procedure C is purely graphical method and not useful for computer programming. The current study involves theoretical steps for calculating performance point and evaluates the performance point of building by using analytical steps of Procedure- A. For validating the results of software same capacity spectra consider as input in Procedure- A (Analytical Analysis) and calculate the performance point. The Procedure- A is mostly formulae based so by developing an Excel Sheet Program the results are calculated and compare with other procedure. This program also helps to check the exactness of performance point.*

Keywords: *Performance point, Performance Based Seismic Design, Pushover, R.C.C building, Capacity spectrum, Demand spectrum.*

1. INTRODUCTION

Performance-based seismic design (PBSD) philosophy is approximate way to control efficiently the seismic damage on the structure and ensure the predictable and safe performance. Performance-based Seismic Engineering (PBSE) is an approach of PBSD. Due to the recent advances in seismic hazard assessment, PBSE methodologies, experimental facilities, and computer applications, PBSE has become increasing more attractive to developers and engineers of buildings in seismic regions. It is safe to say that within just a few years PBSE will become the standard method for design and delivery of earthquake resistant structures. In order to apply PBSE effectively and intelligently, one need to be aware of the uncertainties involved in both structural performance and seismic hazard estimations [3]. Up to now, the philosophy

of performance-based seismic design has been sufficiently developed. In several countries, seismic design is in the process of fundamental change, with the emphasis changing from "strength" to "performance" [4, 5].

The historical reviews of papers explain the PBSD and from that scope of study is introduced. The previous researchers use mostly the computer based methods of calculating Performance point by using software SAP and ETAB. The guideline of ATC- 40 [1] is more helpful for this study that provides the steps of calculating the performance point. Sigmund A. Freeman [4] & [5] used nonlinear static analysis to determine building capacity and an elastic response spectrum to represent the earthquake demand capacity curve and demand curve in ADRS format; superimpose this two curves and calculate the response of the structure, Chopra and Goel [8] uses an inelastic design response spectrum as the demand curve in the capacity spectrum method. Developed new methods that also give similar results to ATC-40, Farzad Naeim [7] decide performance objectives such as life safety, collapse prevention, or immediate occupancy are used to define the state of the building and provides a basic understanding of the promises and limitations of performance based seismic engineering, Dalal Sejal P. [9] Presented updated literature review of the Performance-based Seismic design (PBSD) method, Dr. Bindhu [6] and Dr. Rehan A. Khan [3] *et.al* work on performance based seismic design. The research has shown that the Capacity Spectrum Method can be used for a variety of uses such as rapid evaluation technique for a large inventory of building. In proceeding, we will focus on analytical calculation of determination of performance point of the building by using procedure– A of ATC-40. The results of Procedure- A are correlates with Procedure- B (*i. e.* software method) [2]. Which is done in previous work [2] and that validate by this work.

2. PBSD APPROACH

This study is based on analytical method of finding performance point. Building model, material properties and structural elements used in the present study are same as procedure- B (Previously Studied) [2].

## 2.1 Calculating Performance Point Using Procedure- A

This is the most direct application of the concepts and relationships described in Procedure- A. It is truly iterative, but it is formula-based and easily can be programmed into a spreadsheet. It is more an analytical method. The general steps for calculating performance point are given bellow;

1. Develop the 5 percent damped (elastic) response spectrum appropriate for the site using the procedures provided in the ATC- 40 [1]
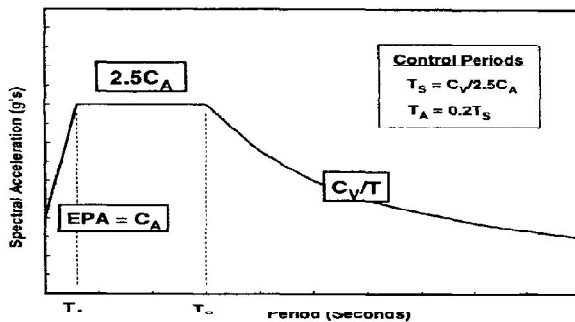

Fig. 1: Construction of a 5% damped elastic response spectrum (Demand Curve) (Source, ATC- 40, 4.4.3.3)

2. Transform the capacity curve into a capacity spectrum as described in Section 8.2.2.1.1 [1] using equations 8-1, 8-2, 8-3 and 8-4 of ATC- 40[1]. Plot the capacity curve on the same chart as the 5% damped response spectra as shown in Fig. 2.
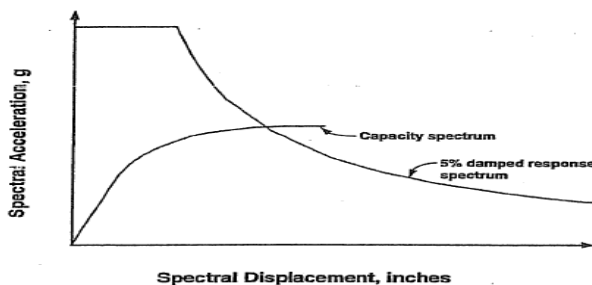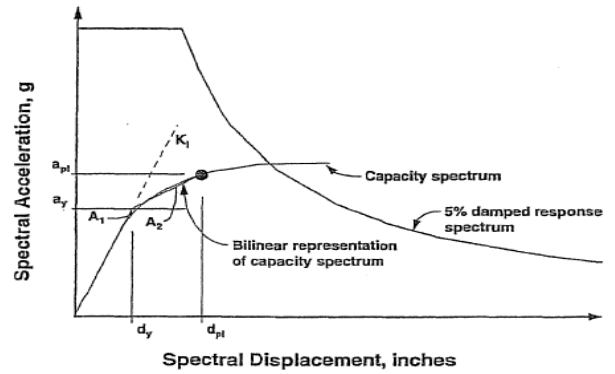

Fig. 2: Capacity spectrum procedure after step 2 (Source, ATC- 40, 8.2.2.1.1)

3. Select a trial performance point, a_{pi}, d_{pi} as shown in Fig. 3.
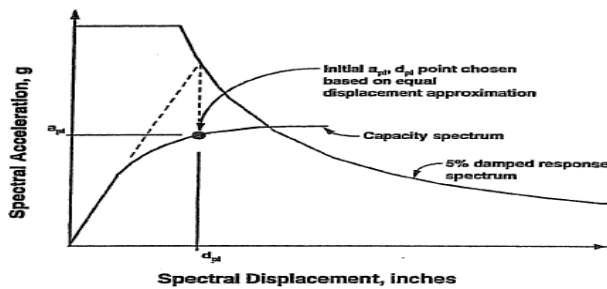
Fig. 3: Capacity spectrum procedure after step 3 (Source, ATC- 40, 8.2.2.1.1)

4. Develop a bilinear representation of the capacity spectrum using the process described in Section 8.2.2.1.1 [1] and illustrated in Fig. 4. The result of this step is illustrated in Fig. 4.

Fig. 4: Capacity Spectrum procedure after step 4 (Source, ATC- 40, 8.2.2.1.1)

5. Calculate the spectral reduction factors as given in equations 8-9 and 8-10. Develop the demand spectrum using the process illustrated in Fig. 5. Draw the demand spectrum on the same plot as the capacity spectrum as shown in Fig. 5.
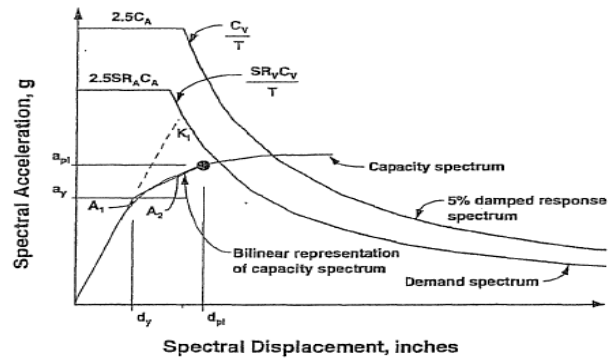
Fig. 5: Capacity spectrum procedure after step 5 (Source, ATC- 40, 8.2.2.1.1)

6. Determine if the demand spectrum intersects the capacity spectrum at the point, a_{pi}, d_{pi}, or if the displacement at which the demand spectrum intersects the capacity spectrum, d_i, is within acceptable tolerance of d_{pi}. The acceptable tolerance is illustrated in Fig. 6.

7. If the demand spectrum does not intersect the capacity spectrum within acceptable tolerance, then select a new a_{pi}, d_{pi} point and return to step 4.

If the demand spectrum intersects the capacity spectrum within acceptable tolerance, then the trial performance point, a_{pi}, d_{pi}, is the performance point, a_p, d_p, and the displacement, d_p, represents the maximum structural displacement expected for the demand earthquake.
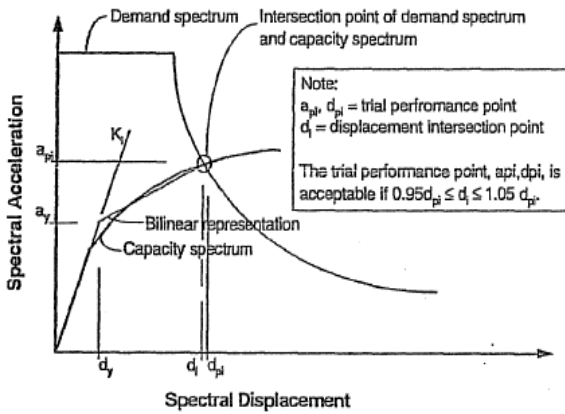
Fig. 6: Intersection point of demand and capacity spectrums within acceptable tolerance (Source, ATC- 40, 8.2.2.1.1)

3. BUILDING MODEL

At present the six storied rectangular and four storied square plan symmetrical R.C.C. buildings are taken for study. Which are exactly similar with building model consider in software analysis (i.e. in geometry, material properties and loading are same). Capacity spectrum procedure- A is applied on the same building models.

3.1 Material Properties

1. Grade of concrete used is M 25

2. Grade of reinforcing steel Fe-415

3. The modulus of elasticity (*Ec*) of concrete is taken as, *Ec* = 5000 $\sqrt{fck}$ MPa

3.2 Structural Elements

1. Slab Thickness is 0.12 m

2. Live load on all floors is 4 kN/m^2

3. Live load on roof is 1.5 kN/m^2

4. Density of concrete is 25 kN/m^3 Soil type II (Medium soil)

6. Zone factor for zone IV is 0.24

7. Importance factor of buildings is 1.5

8. Response reduction factor is 5

Table 1: Building dimension data

	Building Type	Dimension		Floor to Floor Height	Bay width in	
		Column	Beam		X-direction	Y-direction
1	Rectangular Plan Building	0.35 m X 0.35m	0.25 m X 0.35 m	3 m	3.5 m	3 m
2	Square Plan Building	0.35m X 0.35 m	0.4 m X 0.5 m	3.75 m	5 m	5 m

4. Analytical calculation for Procedure- A

The analytical calculation are done by using the excel sheet programming which reduces the time and give the accuracy more than hand calculation.

1. Develop the 5 percent damped (elastic) response spectrum appropriate for the site using the Fig. 1 and using the following formulae

$$T_S = \frac{C_V}{2.5 \times C_A},$$

$$T_A = 0.2 \times T_S$$

(1)

2. Biliniearity concept:- for that initial point (a_y, d_y) = (0.162, 0.015) and (0.1925, 0.023) are consider from the capacity spectrum curve of rectangular and square plan building respectively. Other trial point (a_{pi}, d_{pi}) is consider from end point on capacity spectrum and that reduces iteratively up to A_1 equal to A_2. The buildings are same so the capacity spectrum of both building obtained from software analysis are considered as input in Procedure- A. The capacity spectra of both building in S_a - S_d format are shown below,
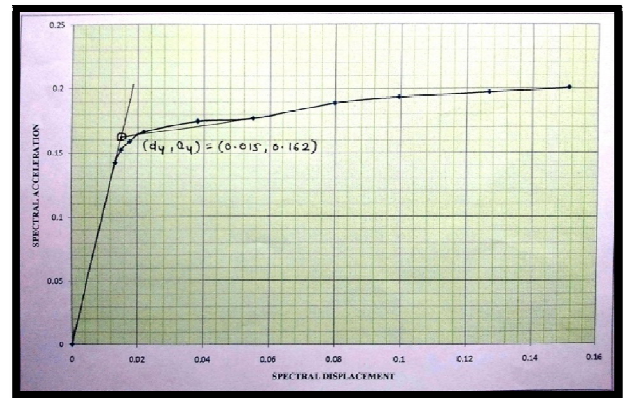
(a)
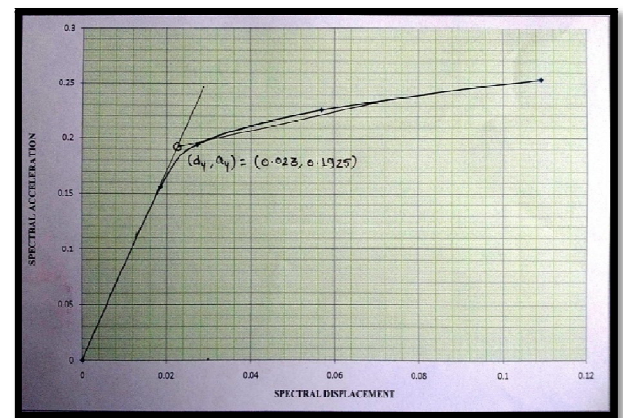
(b)

Fig. 7: Consideration of Initial Point (a_y, d_y) of Bilinear System on Capacity Spectrum for Rectangular (a) and Square Plan Building (b) [10]

3. Considering Building Type- B for that the value of k is calculated from following formula.

k = It is a factor based on the expected behavior of primary elements, for type B building it is written as

$$k = 0.845 - \frac{0.446\,(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} \qquad (2)$$

4. Equivalent viscous damping is calculated from following equation,

$$\beta_0 = \frac{63.7\,(a_y d_{pi} - d_y a_{pi})}{a_{pi} \times d_{pi}} \qquad (3)$$

5. From the values of β_0 effective equivalent viscous damping (β_{eff}) is calculated as

$$\beta_{eff} = k \times \beta_0 + 5 \qquad (4)$$

6. Spectral reduction factors SR_A and SR_V are calculated as

$$SR_A = \frac{3.21 - 0.68\,\ln(\beta_{eff})}{2.12},$$

$$SR_V = \frac{2.31 - 0.41\,\ln(\beta_{eff})}{1.65} \qquad (5)$$

7. Calculation of corresponding time period for each point of (a_{pi}, d_{pi}) given by

$$T = 2\pi \times \left(\frac{d_{pi}}{a_{pi}}\right)^{\frac{1}{2}} \qquad (6)$$

8. Period (Ts) where the damped spectrum changes from the const. acceleration to const. velocity range.

9. Spectral acceleration on the 5% damped spectrum for $T > T_S$ is written as

$$S_{a5\%} = \frac{C_V}{T} \qquad (8)$$

And when $T <= T_S$

10. From 5% damped spectral acceleration calculate the Spectral displacement for 5% damping,

$$S_{d5\%} = \frac{T_i^2}{4\pi^2} \times S_{ai} \times g \qquad (10)$$

11. Reduced demand spectrum is obtained by using the following equations,

$$S_a = SR_V \times S_{a5\%},$$

$$S_d \text{ at } T_S = S_a \left(\frac{T}{2\pi}\right)^2 \qquad (2) \qquad (11)$$

12. After that the difference between $(a_{pi} - S_a)$ and $(d_{pi} - S_d)$ is calculated when the sign changes +ve to -ve sign in between the performance point is obtained. By iterating in between two rows where the sign changes in that rows iteration done by excel sheet got the performance point of the building. The calculated performance point is check by $\pm 5\%$ of trial point (a_{pi}, d_{pi}).

The above all calculations are done by excel sheet programming. Excel sheets of both the building are shown as bellow and the difference between $(a_{pi} - S_a)$ and $(d_{pi} - S_d)$ closer to zero, at that exact performance point is about to obtained. Then that procedure is considered as more accurate for calculating the performance point.

Where,

k = It is a factor based on the expected behavior of primary elements, for type B building it is written as

k = (0.845 - (0.446(ay*dpi - dy*api)/(api*dpi))+5)

ßo % = Equivalent Viscous Damping

ßeff % = Effective Equivalent Viscous Damping

SRA = Spectral reduction factor in the constant accleration range

SRV = Spectral reduction factor in the constant velocity range

T_s = Period where the 5% damped spectrum changes from the const. Accleration to const. velocity range

$$T_s = \frac{SR_V C_V}{2.5 \times SR_A C_A} \qquad (7)$$

T = T_eff = Corresponding period

$$S_{a5\%} = 2.5 \times C_A \qquad (9)$$

Yellow color cell and row indicate the calculated performance point and their check by Excel Sheet Program Pink color row indicate the check of accuracy for procedure- B

Table 2: Excel sheet of rectangular building

CALCULATION OF PERFORMANCE POINT BY USING PROCEDURE- A OF ATC- 40																	
Work Name: Finding out The Performance point of Rectangular Plan Building.																	
From Graph of capacity spectrum where A1= A2		Trial performance point and capacity spectrum		Building Type B							T >= Ts	T>= Ts		when value changes sign in that performance		min. limit of Sa	max. Limit of Sa	min. limit of sd	max. Limit of Sd
				k	ßo %	ßeff %	SRA	SRV	T= Teff	Ts	Sa 5%	demond spectrum						
ay	dy	api = Sa	dpi = Sd									Sa	Sd	api-Sa	dpi-Sd	5% of api	5% of api	5% of dpi	5% of dpi
0.162	0.015	0.200435	0.150999	0.52882896	45.1571636	28.880416	0.4354003	0.56430477	1.740305	0.518424	0.229845	0.129702492	0.097712	0.07073251	0.05328679	0.190413	0.21045675	0.143449	0.15854895
0.162	0.015	0.196861	0.126657	0.53079944	44.8757308	28.820013	0.4360719	0.56482502	1.608273	0.518103	0.248714	0.140479847	0.090382	0.05638115	0.03627467	0.187018	0.20670405	0.120324	0.13298985
0.162	0.015	0.193489	0.099386	0.53889673	43.7192343	28.560152	0.4389771	0.56707569	1.437009	0.516725	0.278356	0.157848847	0.081079	0.03564015	0.01830663	0.183815	0.20316345	0.094417	0.1043553
0.162	0.015	0.18897	0.079766	0.54652392	42.6298801	28.298249	0.4419321	0.56936487	1.30268	0.515341	0.307059	0.174828825	0.073797	0.01414117	0.00596912	0.179522	0.1984185	0.075778	0.0837543
0.162	0.015	0.176974	0.054866	0.55867008	40.8951033	27.846871	0.4470896	0.57336034	1.116406	0.512971	0.358293	0.205430812	0.063688	-0.02845681	-0.0088223	0.168125	0.1858227	0.052123	0.0576093
0.162	0.015	0.174775	0.037871	0.60825223	33.8135262	25.567153	0.474486	0.59458396	0.933338	0.501245	0.428569	0.25482047	0.055216	-0.08004547	-0.0173446	0.166036	0.18351375	0.035977	0.03976455
0.162	0.015	0.166207	0.021719	0.7183143	18.0938995	17.997107	0.5871021	0.68182636	0.724804	0.464537	0.551874	0.376281944	0.04917	-0.21007494	-0.0274514	0.157897	0.17451735	0.020633	0.02280495
0.162	0.015	0.158774	0.017381	0.77484114	10.0204466	12.764254	0.6973014	0.7671964	0.663396	0.440095	0.602958	0.462587317	0.050639	-0.30381332	-0.0332585	0.150835	0.1667127	0.016512	0.01825005
0.162	0.015	0.152309	0.014978	0.81727735	3.95949075	8.2360021	0.8378348	0.87606596	0.628766	0.418252	0.636166	0.557323719	0.054807	-0.40501472	-0.039829	0.144694	0.15992445	0.014229	0.0157269
0.162	0.015	0.142183	0.013234	0.84235408	0.37790406	5.318329	0.9781188	0.98474227	0.611712	0.402709	0.653903	0.643925617	0.059935	-0.50174262	-0.0467008	0.135074	0.14929215	0.012572	0.0138957
0.162	0.015	0.184	0.07	0.54789752	42.4336957	28.249316	0.4424872	0.56979491	1.236703	0.515084	0.323441	0.184294897	0.070112	-0.0002949	-0.0001122	0.1748	0.1932	0.0665	0.0735
0.162	0.015	0.184988	0.069718	0.55038132	42.0789465	28.159466	0.443509	0.57058651	1.230909	0.514611	0.324963	0.185419612	0.069881	-0.00043161	-0.0001627	0.175739	0.1942374	0.066232	0.0732039
		performance point		1 represent the lower value in api and dpi.															
		api1 =	0.176974	dpi1 =	0.054866	(Sa-api)1=	-0.028457	(dpi-Sd)1=	-0.0088223										
		api2 =	0.18897	dpi2 =	0.079766	(Sa-api)2=	0.0141412	(dpi-Sd)2=	0.00596912										
		Sa =	0.18498771		Sd =	0.06971751													

Table 3. Excel sheet of square building

CALCULATION OF PERFORMANCE POINT BY USING PROCEDURE- A OF ATC- 40																	
Work Name: Finding out The Performance point of Square Plan Building.																	
From Graph of capacity spectrum where A1= A2		Trial performance point and capacity spectrum		Building Type B							T >= Ts	T>= Ts		when value changes sign in that performance		min. limit of Sa	max. Limit of Sa	min. limit of sd	max. Limit of Sd
				k	ßo %	ßeff %	SRA	SRV	T= Teff	Ts	Sa 5%	demond spectrum						
ay	dy	api = Sa	dpi = Sd									Sa	Sd	api-Sa	dpi-Sd	5% of api	5% of api	5% of dpi	5% of dpi
0.1925	0.023	0.253396	0.109118	0.60019082	34.9648988	25.985611	0.4692787	0.59054993	1.31575	0.503368	0.304009	0.17953253	0.077311	0.07386347	0.03180727	0.240726	0.2660658	0.103662	0.1145739
0.1925	0.023	0.253407	0.109084	0.60023483	34.9586133	25.983377	0.4693062	0.59057129	1.315517	0.503357	0.304063	0.1795709	0.0773	0.0738361	0.03178419	0.240737	0.26607735	0.10363	0.1145382
0.1925	0.023	0.253411	0.109065	0.60025656	34.9555097	25.982274	0.4693199	0.59058184	1.315392	0.503351	0.304092	0.179591167	0.077294	0.07381983	0.03177115	0.24074	0.26608155	0.103612	0.11451825
0.1925	0.023	0.226277	0.056905	0.64584102	28.4449036	23.370886	0.5032953	0.61690223	1.005496	0.49029	0.397814	0.245412218	0.061717	-0.01913522	-0.0048122	0.214963	0.23759085	0.05406	0.05975025
0.1925	0.023	0.194703	0.027094	0.78265415	8.9045527	11.969185	0.7179301	0.78317725	0.747955	0.436353	0.534792	0.418836648	0.058283	-0.22413365	-0.0311894	0.184968	0.20443815	0.025739	0.0284487
0.1925	0.023	0.155898	0.018503	0.84868394	-0.526159	4.5534573	1.0279231	1.0233251	0.690758	0.398211	0.579074	0.592580935	0.070331	-0.43668294	-0.0518284	0.148103	0.1636929	0.017578	0.01942815
0.1925	0.023	0.23	0.064	0.63199864	30.4219429	24.226627	0.4917606	0.6079664	1.057672	0.494522	0.378189	0.229926146	0.063979	7.3854E-05	2.0551E-05	0.2185	0.2415	0.0608	0.0672
0.1925	0.023	0.231863	0.063766	0.63558611	29.9095616	24.010102	0.4946402	0.61019721	1.051487	0.493447	0.380414	0.232127291	0.063839	-0.00026429	-7.268E-05	0.22027	0.24345615	0.060578	0.0669543
		performance point		1 represent the lower value in api and dpi.															
		api1 =	0.226277	dpi1 =	0.056905	(Sa-api)1=	-0.019135	(dpi-Sd)1=	-0.0048122										
		api2 =	0.253411	dpi2 =	0.109065	(Sa-api)2=	0.0738198	(dpi-Sd)2=	0.03177116										
		Sa =	0.23186266		Sd =	0.06376616													

4. RESULTS AND DISCUSSIONS

The performance point find out by analytical method (*i. e.* Procedure- A) and by software SAP2000 (*i. e.* Procedure- B) is given bellow,

Table 4: Performance point of both the buildings

Building Type	Procedure- B		Procedure- A	
	S_a x g m/ sec²	S_d meter	S_a x g m/ sec²	S_d meter
Rectangular Plan	0.184	0.070	0.184988	0.069718
Square Plan	0.230g	0.064	0.231863	0.063766

Table 5: Calculation of SR_A and SR_V at Performance Point by Procedure- A (referring Table 2 and Table 3)

Building Type	Sa	Sd	SRA	SRV
Rectangular plan building	0.1889	0.0798	0.44193	0.569365
	0.1849	0.0697	?	?
	0.1769	0.0549	0.44708	0.573360
Square plan building	0.2534	0.1091	0.46932	0.590582
	0.2319	0.0638	?	?
	0.2263	0.0569	0.50329	0.616902

For structural behavior Type- B given minimum allowable SR_A and SR_V values are 0.44 and 0.56 respectively. The calculated SR_A and SR_V at Performance Point by Procedure- A for rectangular building are,

$SR_A = 0.445008 > 0.44$ *i.e.* ok

And $SR_V = 0.571615 > 0.56$ *i.e.* ok [1].

Similarly; the calculated SR_A and SR_V at Performance Point by Procedure- A for square building are

$SR_A = 0.473789 > 0.44$ *i.e.* ok

And $SR_V = 0.593847 > 0.56$ *i.e.* ok. (As per ATC – 40, Table 8.2)[1].

Table 6: Effective damping ($ß_{eff}$) values and maximum allowable limits (referring Table 2 and Table 3)

Procedures	Calculated $ß_{eff}$ at Reduced Response Spectra		Maximum Allowable $ß_{eff}$ for Building Type- B
	Rectangular Building	Square Building	
Procedure- B	28.2 %	23.5 %	29 %
Procedure- A	28.1595%	24.0101 %	29 %

$ß_{eff}$ at Reduced Response Spectra (*i.e.* at performance point) less than 29% that shows analyzed $ß_{eff}$ was within limit as per ATC-40.

5. CONCLUSIONS

The performance of reinforced concrete building was investigated using the Capacity Spectrum Method Procedure- A. As a result of the work that was completed in this study, the following conclusions were made:

1. The results obtained by Procedure- B (*i.e.* by software analysis) and by Procedure- A are nearly equivalent with difference of results is less than $\pm$1 % but results obtained by Procedure- B. Hence the conventional software package based on Procedure- B is found to be performing satisfactorily.

2. A very small difference is found in the results obtained from SAP2000 vs.14 and Excel Sheet program of Procedure- A (*i.e.* less than $\pm$ 1 %). This is due to the fact that SAP2000 is based on Procedure- B. In Procedure- B, a simplifying assumption is made. That is post yield slope remains constant

is made. This assumption is concluded to be the source of this difference.

3. The results of Procedure- A and B are nearly same so that validate the results of one method with other method. Because both the procedure gives results in the range of less than $\pm$ 1 %.

4. The Excel Sheet Program made for Procedure- A reduces the too much complications, calculations, iterations and interpolation work so it save the time of user and this program is validate by procedure- B for both the building.

5. Procedure- B is not transparent if user used software for it. So for beginner Procedure- A is the best Procedure than Procedure- B.

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