

A Study on Pushover Analysis Using Eurocode Based Capacity Spectrum Method

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Abstract— The performance of a structural system can be evaluated by resorting to non-linear static analysis. This involves the estimation of the structural strength and deformation demands and the comparison with the available capacities at desired performance levels. Seismic evaluation of existing structures and of the proposed design of new structures can be done based on Non-linear Static procedure (NSP) popularly known as Pushover Analysis (PA). Generally, Capacity Spectrum Method (CSM) refers to procedures described in ATC-40 and FEMA 440. The method of Eurocode 8 (EC8) is considered to be a Target Displacement approach. However, the Optional iterative procedure mentioned in EC8 is a CSM based one, and is investigated here. The conventional PA is restricted to single mode response. The method is valid for low to mid-rise buildings where the behavior is dominated by fundamental vibration mode. It is of significance to take into account of higher mode effects in pushover analysis of tall buildings. The present paper attempts to adopt the conventional PA method as well as Consecutive Modal Pushover (CMP) procedure on a structure modeled using the software package of SAP2000. Since no commercial package has facilities for conducting CMP or the Optional Iterative Procedure of EC8, the procedure for determining Performance Point is programmed in VISUAL BASIC (VB) Script and embedded in MS-Excel. The procedures for determining Performance Point according to the Optional Iterative Procedure of EC8 was developed. The study includes modeling of a typical realistic building and determination of performance point for each method by using the developed VB script code. The verification of results is done by comparing results with the Non linear time history (NL- THA) analysis.

Keywords— *CMP; CSM; N2 method; Eurocode 8; Pushover Analysis; SAP2000; RC Building; Seismic Analysis*

I. INTRODUCTION

Pushover analysis (PA) also known as Nonlinear Static analysis Procedure (NSP) is a simple method for prediction of non linear behavior of the structure under seismic loads. PA is a performance based methodology where it necessitates in the determination of a performance point from the two estimated quantities namely; seismic demand and seismic capacity. Seismic demand gives a description of the earthquake effects where as seismic capacity shows the ability of the structure to resist these earthquake effects. PA can be done using software packages such as SAP2000, ETABS and STAAD Pro, which provides the facility to conduct the procedure. In general, NSP or PA is a technique in which the structure is subjected to a monotonic incremental lateral load which approximately represents the relative inertia forces generated at centers of masses for each storey. The structure is thus gently “pushed”,

resulting in the formation of cracks, yielding, hinge formations and finally failure of various structural components. This increment of load continues for a predetermined displacement limit. Always, Nonlinear Dynamic Analysis Procedure (NDP) or Non Linear Time History Analysis (NL-THA) gives a more realistic solution for seismic assessment, where its accuracy depends on the input such as the modeling of the structure and the ground motion characteristics. But the procedure is more complex compared to NSP and hence recommended for the estimation of the maximum response of the structural model.

The paper attempts to conduct the Consecutive Modal Pushover Analysis (CMP) using user developed code based on the optional iterative procedure of EC8, which is a CSM based N2 method. The maximum base shear values are compared with the corresponding values from NL-THA for verifying the results. The developed program was coded in VISUAL BASIC (VB) Script and embedded in MS Excel.

II. METHODOLOGY

The methodology for the present study consists of three stages. First, a structure is modeled using SAP 2000. Then the PA of the structure is done using the facility available in SAP 2000 and the pushover curve is obtained. Third, the performance point is obtained using the developed program and is compared with NL-THA results.

A. Modeling of the structure

The structure considered for the investigation is an eight storey hospital building, with tower room at roof level (Fig. 1). The plan area of the building is 24m x 12m (Fig. 2). All beams along longitudinal direction (longitudinal frames) and along transverse direction (cross frames) are assigned with geometric properties of 0.23m x 0.50m and 0.23m x 0.60m, respectively. All sub beams are assigned with a property of 0.23m x 0.40m and the slab thickness is taken as 0.1m. A cross-section of 0.30m x 0.60m is assigned to columns, with fixed supports at base and the typical floor height is 3.6m. In the structure modeled, P-M-M hinges were inserted to column elements since P-M2-M3 interaction surface can describe the yielding of a column under combined axial, strong-axis, and weak-axis bending. Similarly flexural hinges were assigned to the beam elements [6]. Medium soil condition was assumed as the site condition of the structure.

B. Determination of Pushover Curve using SAP 2000

A load combination (where DL- Dead load; LL- Live load or Imposed load) of $1.0DL + 0.25LL_{\leq 3kN/m^2} + 0.5LL_{>3kN/m^2}$ is

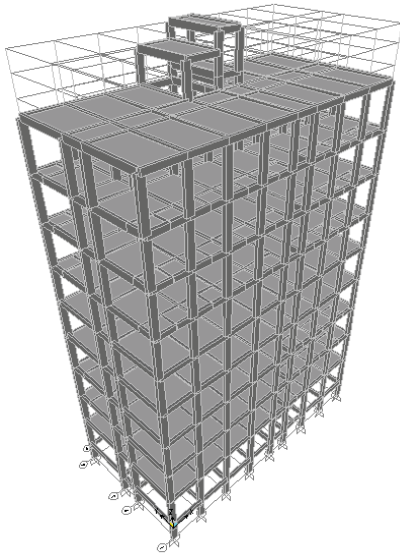


Fig. 1. 3D extruded view of the building model created in SAP 2000.

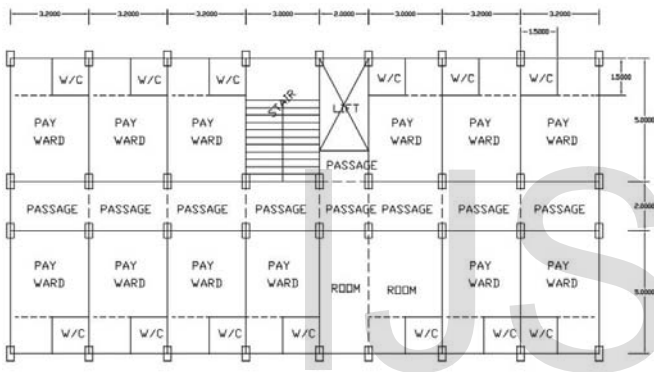


Fig. 2. Typical floor plan of the building.

TABLE I. TABLE SHOWING BASE SHEAR V/S ROOFTOP DISPLACEMENT APPLIED ON THE STRUCTURE ALONG Y DIRECTION

Step	Displacement (m)	Base Force (kN)
0	0	0
1	-0.001926	543.146
2	-0.007649	1742.245
3	-0.008834	1867.018
4	-0.012405	2010.878
5	-0.021779	2187.3
6	-0.06537	2595.896
7	-0.081666	2658.411

considered for the non linear static analysis of the structure in the gravity direction. Response spectra of medium soil as given in IS1893 (Part 1): 2002 is considered for the analysis.

The PA is done in both longitudinal and transverse directions (designated as Push X and Push Y) based on modal loads. The pushover curve obtained from the analysis of the structure is shown (Fig. 3) with rooftop displacement in the negative direction. Since the effective time period of the building was below 2.2s; we have to consider two stages PA for executing the CMP procedure [2] in SAP2000.

For conducting CMP procedure using SAP 2000; the PA is to be continued as explained: consider Push Y1 be the first stage PA. The 2nd stage PA (Push Y2) is analyzed as a continuation of Push Y1 and Push Y3 a continuation of Push Y2. The summation of the corresponding displacement increment values gives the target displacement (δ_i or δ_{rt}) of the structure.

III DEVELOPMENT OF THE PROGRAM BASED ON OPTIONAL ITERATIVE PROCEDURE OF EUROCODE 8 (N2 METHOD)

In this method, seismic demand is determined from inelastic spectra and depends on the period of the idealized equivalent Single Degree of Freedom (SDOF) system. The transformation from the Multi Degree of Freedom (MDOF) system to an equivalent SDOF system is based on the assumption of a time-invariant displacement shape [5, 7]. The procedure of EC 8 based N2 method adopted for programming is as follows:

- The initial Acceleration Displacement Response Spectrum (ADRS) of demand is formed for 5% damping as explained in CSM method [3].

For developing the S_a - S_d graph, the spectral displacement, S_d corresponding to each point of the Response Spectra (Initial RS) (S_a/g vs. T); the following relation is used.

$$S_d = \frac{T^2}{4\pi^2} S_a \tag{1}$$

where, S_a is the spectral acceleration and T is the time period. The corresponding S_d and S_a values in response spectra are converted to those of the corresponding equivalent SDOF system by dividing both with the participation factor, Γ .

- A characteristic non linear force (Base shear, V_b) displacement (rooftop displacement, Δ_{rt}) relationship of the MDOF system is determined and using (2) and (3), Transformed Base shear, F^* and corresponding rooftop displacement, d^* is calculated for the corresponding Equivalent Single Degree of Freedom system.

$$F^* = \frac{F_b}{\Gamma} \tag{2}$$

$$d^* = \frac{d_n}{\Gamma} \tag{3}$$

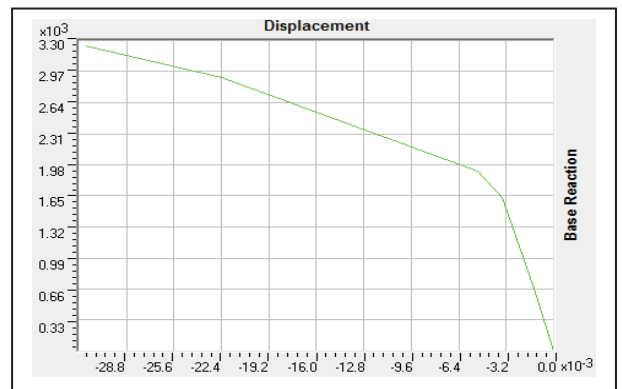


Fig. 3. Pushover curve from SAP 2000 for PA along Y direction.

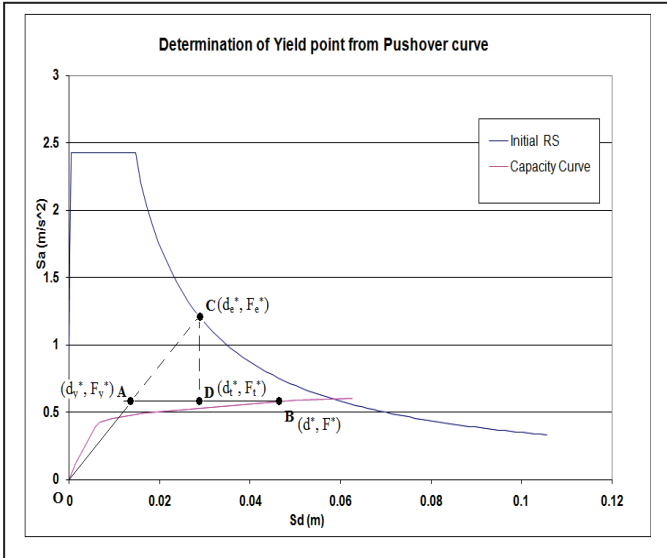


Fig. 4. Determination of yield and target displacement point from capacity curve and demand curve.

- For each point on the converted pushover curve, the yield points (F_y^*, d_y^*) are determined by equivalent bilinear representation (idealized elasto-perfectly plastic) on equivalent Pushover curve $(F^* \text{ vs. } d^*)$, by (4) where $F_y^* = F^*$ and $A_{tot} = \text{Area beneath the pushover curve up to B}$, where 'B' is the point under consideration.

$$d_y^* = 2 \left(d_m^* - \frac{A_{tot}}{F_y^*} \right) \tag{4}$$

In fig. 4, the point 'B' marks the point under consideration, (d^*, F^*) and the point 'A' marks the corresponding yield point, (d_y^*, F_y^*) . Thus effective time period of the structure correspond to point 'B' is, (where m^* is the equivalent mass of the structure)

$$T^* = 2\pi \sqrt{\frac{m^* d_y^*}{F_y^*}} \tag{5}$$

- The equivalent pushover curve in $F^* \text{ vs. } d^*$ is converted into corresponding acceleration and displacement $(S_a \text{ vs. } S_d)$ capacity curve using (6) with $S_d = d^*$.

$$S_a = \frac{F^*}{m^*} \tag{6}$$

- The intersection ordinate (shown by 'C' (d_c^*, F_c^*)) of the initial stiffness line with Initial ADRS of demand line (Initial RS) is found out. Then based on the following condition the target displacement, (d_t^*) which is marked as the point 'D' in fig. 4) for the corresponding point 'B' under consideration is determined. Let μ_s and R_s be the displacement ductility ratio and response reduction factor (equal to F_c^*/F_y^*) of the ordinate marked by B in fig. 4.

For $T^* < T_c$:

$$\mu_s = (R_s - 1) \frac{T_c}{T^*} + 1 \tag{7}$$

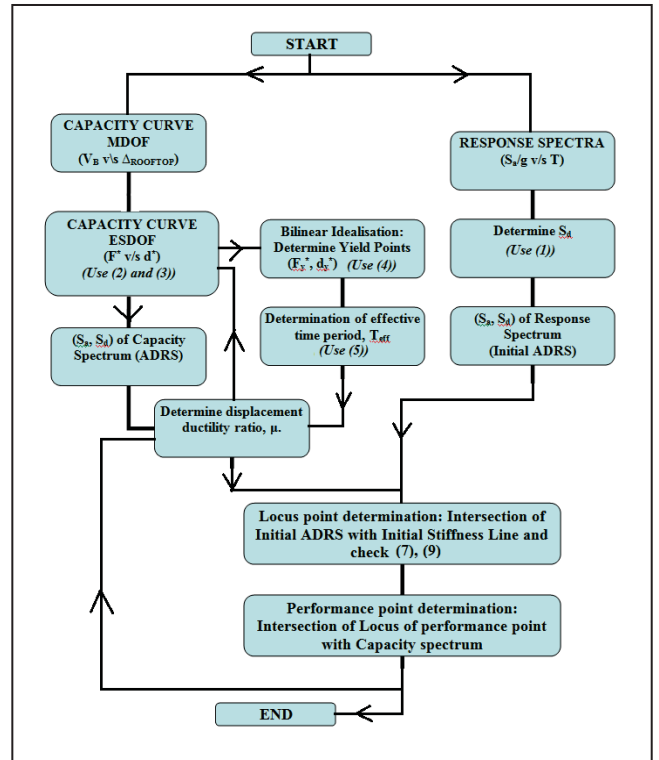


Fig. 5. Flowchart of the program based on the procedure of N2 method.

$$d_t^* = \mu_s d_y^* \tag{8}$$

For $T^* \geq T_c$:

$$d_t^* = d^* \tag{9}$$

where, T_c is the corner time period, which is the time period at which the response spectrum switches from its constant acceleration plot (flat portion) to its constant velocity plot (downward sloping portion). Also $F_t^* = F_y^*$ (fig. 4).

Thus a locus is obtained and the intersection point of the locus line with capacity spectrum gives the performance point.

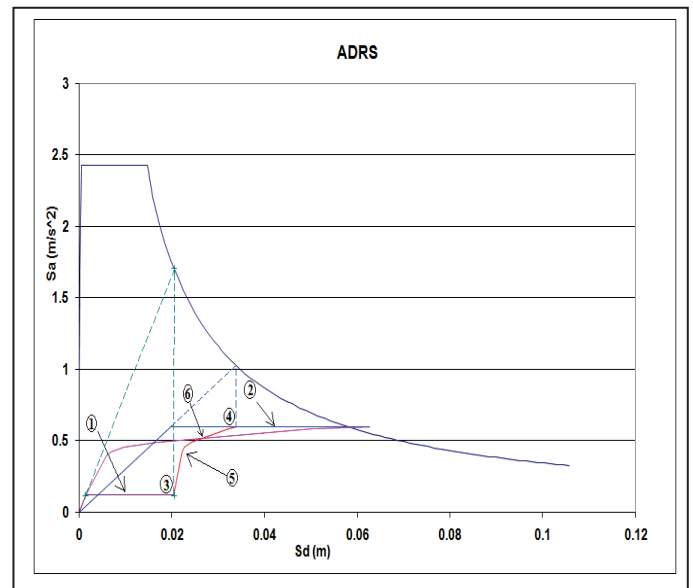


Fig. 6. Determination of Performance point in N2 method.

- Thus for each point on the Pushover curve, from the 1st to nth point, a probable Target Displacement with ordinates (d_t^* , F_t^*) is determined. A line is drawn, connecting these points in sequence, and is referred to as the locus of the Performance point. The intersection point of the locus with capacity spectrum gives the performance point. This is explained in Fig. 6, where '1' marks the bilinear curve of 1st point and '2' is the bilinear curve of nth point on the pushover curve; '3' is the target displacement for 1st point and '4' is the target displacement for nth point; '5' is the locus of Performance Point, connecting target displacements of each point from 1st to nth; '6' is the Performance Point obtained by the intersection of locus of Performance Point with Pushover curve. Note that point '3' lies at a displacement beyond that of its point on the capacity curve while point '4' lies at a displacement within that of its corresponding nth point. The performance point is that point on the capacity curve where actual displacement is equal to the estimated target displacement.
- The initial response spectra can be reduced using the reduction factor R_μ , which is related to displacement ductility ratio, μ as shown.

For $T < T_c$:

$$R_\mu = (\mu - 1) \frac{T}{T_c} + 1 \quad (10)$$

For $T \geq T_c$:

$$R_\mu = \mu \quad (11)$$

Thus S_a values are reduced, to obtain the reduced spectra in ADRS plot. It should be noted that the construction of these spectra is in fact not needed in the computational procedure. They just help for the visualization of the procedure. The reduced demand curves are shown plotted in fig. 8 and fig. 9.

IV. CONSECUTIVE MODAL PUSHOVER ANALYSIS

The pushover loads applied on the structural model is taken from the SAP2000 analysis results. Then, the processing of the values as per N2 method of EC is done with combination of CMP procedure. As per CMP procedure if value of $\delta_{rt} = 0.1310m$ then value of displacement increments u_{r1} and u_{r2} are 0.1059m and 0.0251m. Thus the maximum response corresponding to u_{r1} and u_{r2} is to be calculated.

Here, an assumption is done such that the performance point corresponding to u_{r1} and u_{r2} values are determined and these values will be considered as the maximum response, r . In SAP 2000, direct facility for conducting CMP is not presently available. Using the program developed as explained in the coming section, the CMP can be performed as per below procedure.

A. Procedure of CMP

The procedure of CMP consists of PA with a displacement control at the top of the building. The PA is implemented according to the following sub-steps until the total target displacement at the roof; δ_t is reached [2].

- The first PA is implemented using inverted triangle load pattern for medium-rise buildings and uniform force distribution for high-rise ones until the control node at the roof sways to predefined total target displacement, δ_t .
- The second PA is performed in two stages. In the first stage, nonlinear static analysis is implemented using invariant lateral forces according to $s_1^* = m\phi_1$ until the displacement increment at the roof reaches $u_{r1} = \beta_1\delta_t$, where $\beta_1 = \alpha_1$, where β_1 is the damping value and α_1 is the effective modal mass ratio for 1st mode.
- The second stage of analysis starts from stressed and deformed state at the last step of the previous stage. Therefore, in the second stage, the analysis continues with lateral forces according to $s_2^* = m\phi_2$ until the displacement increment at the roof reaches $u_{r2} = \beta_2\delta_t$, where $\beta_2 = 1 - \alpha_1$.
- The third analysis in the CMP is a three-stage consecutive modal pushover analysis. It is only performed for buildings having a period of 2.2 sec or more. The first stage is exactly the same as the first stage in two-stage consecutive modal pushover analysis. After the first stage, the nonlinear static analysis continues with lateral forces according to $s_2^* = m\phi_2$ until the displacement increment at the roof reaches $u_{r2} = \beta_2\delta_t$, where $\beta_2 = \alpha_2$.
- Thereafter, the third (last) stage of three-stage modal pushover analysis is carried out using lateral force distribution according to $s_3^* = m\phi_3$ until the displacement increment at the roof reaches $u_{r3} = \beta_3\delta_t$ where $\beta_3 = 1 - \alpha_1 - \alpha_2$.
- Calculate the peak value of the desired responses for PA described above.

V. NON LINEAR TIME HISTORY ANALYSIS

For verification of the CMP results, a Non Linear Time History Analysis (NL-THA) is done on the same structural model. The NL-THA is done with accelerograph (Fig. 7) generated based on IS 1893 [8] Response spectra. The accelerograph compatible with Response spectra of IS 1893 (Part1): 2002 was created using the computer program created for the generation of Spectrum compatible Time History data [9].

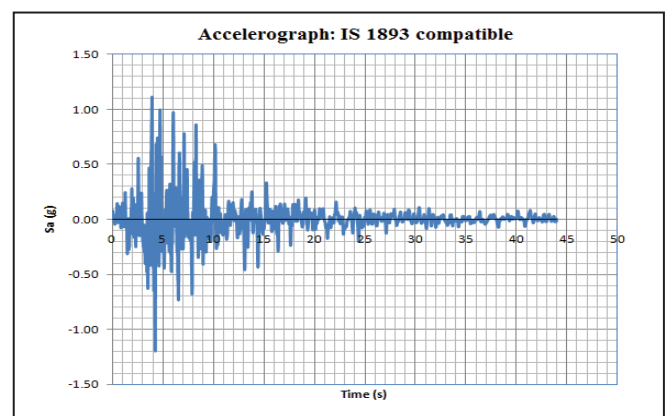


Fig. 7. Accelerograph compatible with IS 1893(Part 1)- 2002 Response spectra.

SAP 2000 uses Hilber-Hughes-Taylor method for NL-THA. From the NL-THA, the maximum base shear of the structure is obtained as 2049kN.

VI. DISCUSSION OF RESULTS

In this study, the seismic demand is applied independently in X and Y directions, consequently two separate analyses are performed with respect to each direction. The response spectrum of Medium soil, Zone III [8] is considered for the seismic demand, assuming that the damping due to soil structure interaction is negligible (damping taken as 5%).

N2 method is simpler and on processing the PA along Y direction, the ordinates (S_d , S_a) of performance point is obtained as {0.0266, 0.0531g} (fig. 8). The corresponding base shear (maximum) is calculated as 2306kN. However, no performance point is obtained for the corresponding analysis in X direction, exposing the weakness of the structure along the longitudinal direction.

With the CMP analysis done as explained in [2], the values of the base shear for each consecutive pushes in Y direction are as shown in table III. From the NL-THA, the maximum base shear of the structure is obtained as 2049kN, while, from the CMP analysis of the structure, the performance point is obtained as {0.0266, 0.0531g} (fig. 9), from which, the corresponding value of maximum base shear is 2306kN.

TABLE II. PUSHOVER CURVE CAPACITY- N2 METHOD - ALONG Y DIRECTION OBTAINED BY THE AUTHOR

Step	S_d Capacity (m)	S_a Capacity (m/s^2)	T_{eff} (s)	μ	T^* (s)
0	0	0	0		
1	0.0015	0.1227	0.6893	1	0.689
2	0.0059	0.3936	0.767	1.0638	0.744
3	0.0068	0.4217	0.7963	1.1309	0.749
4	0.0095	0.4542	0.9092	1.4141	0.765
5	0.0167	0.4941	1.1551	2.0125	0.814
6	0.0501	0.5864	1.837	2.8626	1.086
7	0.0626	0.6005	2.029	3.1707	1.139

TABLE III. TABLE SHOWING BASE SHEAR V_b VS $\Delta_{ROOFTOP}$ FOR EACH CONSECUTIVE PUSH

$\Delta_{rooftop}$ (m)	V_b (kN)			
	Push Y1	Push Y2	Push Y3	Total PushY
0	0			0
-0.0019	543.146			543.146
-0.0076	1742.245			1742.245
-0.0088	1867.018			1867.018
-0.0124	2010.878			2010.878
-0.0218	2187.3			2187.3
-0.0654	2595.896			2595.896
-0.0817	2658.411	0		2658.411
-0.0817		1.477		2659.888
-0.0824		18.976	0	2677.387
-0.0825			2.796	2680.183
-0.0825			10.81	2688.197
-0.1098			779.241	3456.628
-0.1311			1208.999	3886.386

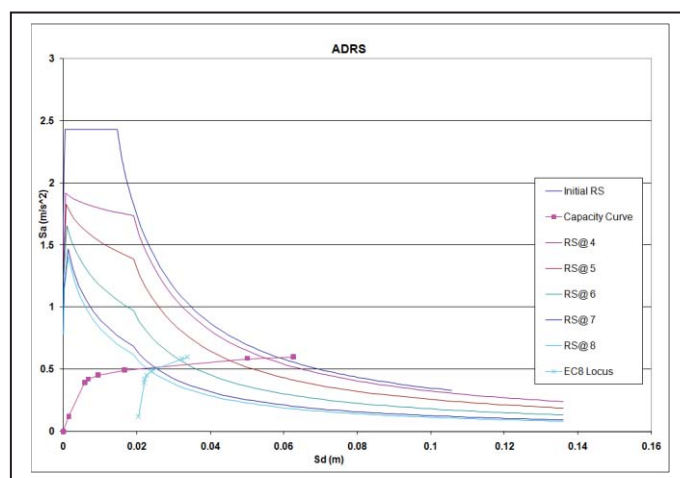


Fig. 8. ADRS plot obtained for PA along Y direction using N2 method.

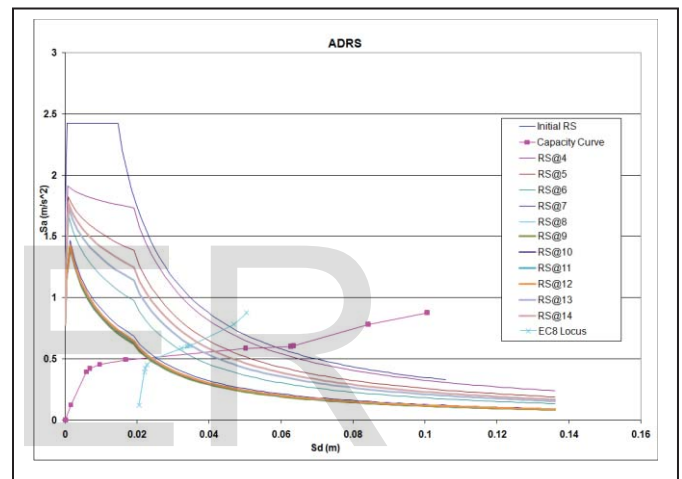


Fig. 9. ADRS plot obtained for PUSHY (PUSHY1+ PUSHY2 + PUSHY3) along Y direction using N2- CSM method and CMP procedures.

VII. SUMMARY & CONCLUSION

The following conclusions can be drawn from the study conducted:

- As CSM method was mostly defined for the American based Pushover methods (such as ATC 40 method [3] and FEMA440 method [4]) and very little material could be found where the CSM procedure has been extended to the Eurocode Method with simple approach fit for routine application, a CSM program has been developed for the EC8 based N2 method, which is also not available in common analysis packages such as SAP2000. The inputs of the program developed are the Pushover Curve ordinates from the PA results and the ordinates of the Response Spectra. The developed program calculates the Performance point from the input details for the structure.
- The CMP procedure is performed using the program developed and can be considered to be advantageous for processing the building response (V_b vs. $\Delta_{rooftop}$) analyzed in packages such as SAP 2000 or STAAD Pro

as well as general Finite Element packages such as ANSYS or ABAQUAS. The results obtained are verified on the same model and the maximum response is obtained.

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