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Seismic Performance based Design of Reinforced Concrete Buildings using Nonlinear Pushover Analysis

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***Abstract*—- A performance based design is aimed at controlling the structural damage under the action of earthquake forces, based on precise estimation of proper response parameters. Performance based design using nonlinear pushover analysis involves tedious and intensive computational effort, is a highly iterative process needed to meet designer specified and code requirements. Performance based seismic design evaluates performance of building considering uncertainties in the quantification of potential hazard and assessment of the actual building response. This paper presents an effective computer based technique that incorporates pushover analysis together with pushover drift performance design of RC buildings is carried out. The study begins with the selection of performance objectives, followed by development of preliminary design, an assessment whether design meets performance objectives or not, finally redesign and reassessment, if required, until the desired performance level is achieved. In present study RC framed building example (Designed according to IS 456:2000) analyzed using pushover analysis and redesigning by changing the main reinforcement of various frame elevations at different storey level and analyzing. The pushover analysis has been carried out using SAP 2000, product of computers and structures international. The building is considered as special moment resisting framed building and the main objective of this study is to check kind of performance a building can give when designed as per IS. The best possible combination of reinforcement that is economical, effective and having minimum damage to enable immediate occupancy is determined and is termed as performance based design.**

Keywords— ***Performance based design; Pushover analysis; Virtual work; Performance objectives; Moment resisting framed building.***

I. INTRODUCTION

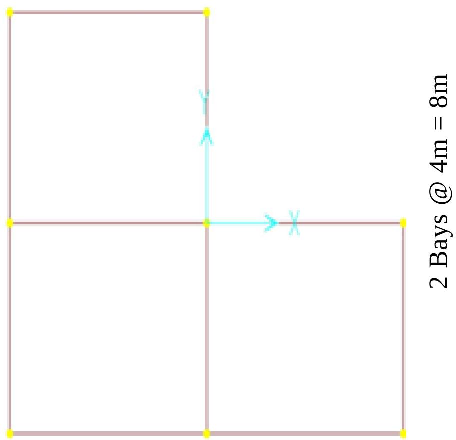
The promise of performance based seismic engineering is to produce structures with predictable seismic performance. From the effects of significant earthquakes (since the early 1980s) it is concluded that the seismic risks in urban areas are increasing and are far from socio-economically acceptable levels, there is an urgent need to reverse this situation and it is believed that one of the most effective ways of doing this is through the development of more reliable seismic standards and code provisions than those currently available and their stringent implementation for the complete engineering of new engineering facilities. The maximum drift of the structure without total collapse under seismic loads is called the target displacement. Pushover analysis is an estimated analysis method where the structure is subjected to different monolithically increasing lateral forces, with a distribution which is height wise invariant, until the target displacement is touched. The nonlinear static analysis procedure requires determination of three elements like capacity, demand and performance. The capacity spectrum can be obtained through the pushover analysis, which is generally produced based on first mode response of structure assuming that the fundamental mode of vibration is predominant response of structure. The demand spectrum curve is normally estimated by reducing the standard elastic 5% damped design spectrum by spectral reduction method. The intersection of pushover capacity and demand spectrum curve defines the 'Performance point' of structure and should be checked using certain acceptability criteria. Pushover analysis comprises of a series of successive elastic analysis, superimposed to estimate a force-displacement curve of overall structure. Pushover analysis can be performed as force controlled and displacement controlled. In force controlled, full load combination is applied as specified and this procedure should be used when the load is known. Also such procedure having some numerical problems that affect the accuracy of results occur since target displacement may be associated with a very small positive or negative lateral stiffness because of development of mechanisms and p-delta effects. Pushover analysis is preferred tool for seismic performance evaluation of structure by the major rehabilitation guidelines and codes because it is conceptually and computationally simple. Pushover analysis allows tracing the sequence of yielding and failure on member and structural level as well as progress of overall capacity of the structure. X.K.Zou et al (2005) presents an effective computer based technique that incorporates pushover analysis together with numerical optimization procedures to automate the pushover drift performance design of R.C. Buildings. Performance-based design begins with the selection of design criteria stated in the form of one or more performance objectives. Each performance objective is a statement of the acceptable risk of incurring specific levels of damage, and the consequential losses that occur as a result of this damage, at a specified level of seismic hazard. Losses can be associated with structural damage, nonstructural damage, or both. They can be expressed in the form of casualties, direct economic costs, and downtime (time out of service), resulting from damage. Methods for estimating losses and communicating these losses to stakeholders are at the heart of the evolution of performance-based design. Once the performance objectives are set, a series of simulations (analyses of building response to loading) are performed to estimate the probable performance of the building under various design scenario events. If the simulated performance meets or exceeds the performance objectives, the design is complete. If not, the design is revised in an iterative process until the performance objectives are met. In some cases it may not be possible to meet the stated objective at reasonable cost, in which case, some relaxation of the original objectives may be appropriate.

II. CASE STUDY DETAILS

A. *Description of the building frame*

In the present study, a G+4 storied unsymmetrical (L-shaped) reinforced concrete building situated in seismic zone IV is considered for the purpose of study.

- Bay span along x-axis : 5m
- Bay span along y-axis : 4m
- Storey height : 3.5m
- No. of floors : G+4 storey
- Size of columns : 450x450mm
- Size of beams : 230x450mm
- Thickness of slab : 150mm thick



2 Bays @ 5 m = 10 m

Fig. *1 Plan of Building*

The regular and relatively simple structure as a design example is considered because it is needed to identify any problems that may arise in applying the proposed structure, and obtain a idea of the relative performance of the structure in case of regular frame buildings.

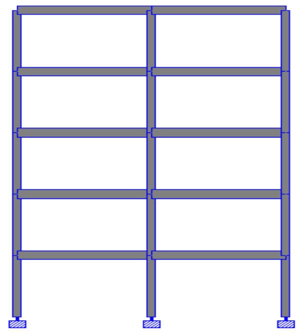


Fig. 2 *Elevation of Building*

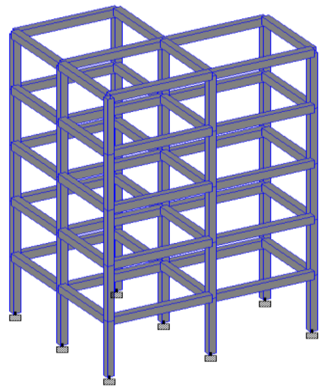


Fig. 3 *3D image of Building*

B. *Loads Considered*

The following loads were considered for the analysis of the Building. The loads were taken in accordance with IS: 875.

- Dead load
  At roof level : 6.950 kN/m^2
  At floor level : 7.450 kN/m^2
- Live load : 3.5 kN/m^2 at all floor levels
- Earthquake load : As per IS-1893 (part-1)2002
- Type of soil : Type-II, medium as per IS:1893

C. *Determination of lateral loads for pushover analysis :*

The maximum design lateral force (Qi) was computed for each storey level and was distributed at each node. The calculation for this force is as follows:

(1) *Calculation of seismic Weight of Structure*

Seismic weight of roof is calculated as under:
Slab = 0.150 x 4 x 5 x 25 x 3 = 225 kN
Beams = 45 x 0.23 x 0.45 x 25 = 116.43 kN
Columns = 0.45 x 0.45 x 1.75 x 25 x 8 = 70.87 kN
Total = 412.31 kN
Seismic weight of one floor is calculated as under:
Slab = 0.150 x 4 x 5 x 25 x 3 = 225 kN
Beams = 45 x 0.23 x 0.45 x 25 = 116.43 kN
Columns = 0.45 x 0.45 x 3.5 x 25 x 8 = 141.75 kN
Total = 483.18 kN
Total Seismic Weight of Building **= 2345.06 kN**

(2) *Calculation of base shear*

The following parameters were taken:

- Zone Factor, Z=0.24
- Importance Factor, I=1.0
- Response Reduction Factor=5.0
- Time Period is calculated from:
  TS = 0.009 h/√d = 0.009x17.5/√10 = 0.498 seconds
- Sa/g = 2.5 (For Medium Soil Conditions)
- A_h = (.24/2) x (1/5) x 2.5 = 0.06
- V_b = 0.06 x 2345.06 = 140.70 kN
- $W_j h_j^2$ = 303842.1
- Now, $Q_i = V_b \, W_i h_i^2 / \sum W_i h_i^2$

Hence, Q5 = (412.31 x 140.70 x 17.5^2) / 303842.1 = 58.47 kN
Similarly, Q4 = 43.85 kN
Q3 = 24.67 kN, Q2 = 10.96 kN, Q1 = 2.74 kN

This load was applied to the structure for pushover analysis. This load is similar to the inverted triangular loading suggested for pushover analysis by ATC-40 as shown in Fig.4

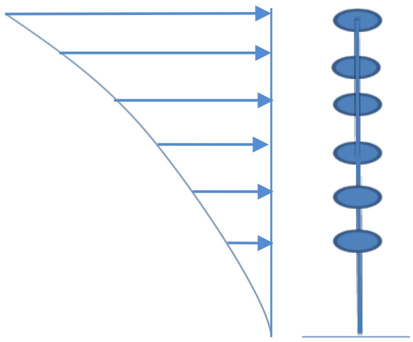


Fig. 4 Applied Inverted Triangular Loading

The building is designed by STAAD.Pro (according to I.S. 456:2000) for Dead Load and Live load case only for getting the reinforcement detail as Shown in Table I.

TABLE I. STRUCTURAL DETAILS (AS PER ANALYSIS AND DESIGN ON STAAD.PRO)

Element	Dimension (m)	Reinforcement are in mm^2
Corner columns	0.45x0.45	904
Mid-face columns	0.45x0.45	1232
Interior columns	0.45x0.45	4926
Beams 1st storey	0.23x0.45	602 (top) 550(bottom)
Beams 2nd srorey	0.23x0.45	600(top) 550(bottom
Beams 3rd storey	0.23x0.45	600(top) 550(bottom)
Beams 4th storey	0.23x0.45	817(top) 632(bottom)
Beams 5th storey	0.23x0.45	720(top) 570(bottopm)

III. PUSHOVER ANALYSIS USING SAP 2000

The following steps are included in the pushover analysis. Steps 1to 4 are to create the computer model, step 5 runs the analysis, and steps 6 to 10 review the pushover analysis results.

1) Create the basic computer model (without the pushover data) as shown in figure 5. The graphical interface of SAP2000 makes this quick and easy task. Assigned sectional properties & applies all the gravity loads i.e. Dead load and Live load on the structure. For changing reinforcement, define frame section from the Define menu.

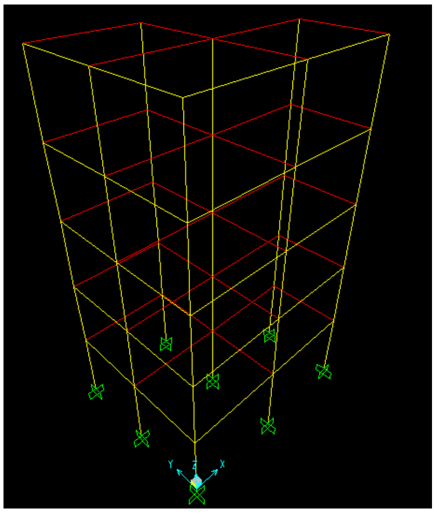


Fig. 5 Basic model in SAP 2000

2) Define properties and acceptance criteria for the pushover hinges. The program includes several built-in default hinge properties that are based on average values from ATC-40 for concrete members and average values from FEMA-273 for steel members. In this analysis, PMM hinges have been defined at both the column ends and M3 hinges have been defined at both the ends of all the beams.

3) Locate the pushover hinges on the model by selecting all the frame members and assigning them one or more hinge properties and hinge locations.

4) Define the pushover load cases. In SAP2000 more than one pushover load case can be run in the same analysis. Also a pushover load case can start from the final conditions of another pushover load case that was previously run in the same analysis. Typically the first pushover load case was used to apply gravity load and then subsequent lateral pushover load cases were specified to start from the final conditions of the gravity pushover. Pushover load cases can be force controlled, that is, pushed to a certain defined force level, or they can be displacement controlled, that is, pushed to a specified displacement. Typically a gravity load pushover is force controlled and lateral pushovers are displacement controlled. In this case a Gravity load combination of DL+0.25LL has been used. This combination has been defined as GRAVITY. The lateral loads have been applied to a case called PUSHPAT.

5) Run the basic static analysis. Then run the static nonlinear pushover analysis.

6) The Pushover curve was made for control nodes at each storey level. This was done by defining a number of pushover cases in the same analysis, and displacement was monitored for a different node in each case.

7) The pushover curve obtained as shown in fig.6. A table was also obtained which gives the coordinates of each step of the pushover curve and summarizes the number of hinges in each state (for example, between IO and LS, or between D and E).

8) The capacity spectrum curve obtained. The magnitude of the earthquake and the damping information on this form can be modified and the new capacity spectrum plot can be obtained immediately. The performance point for a given set of values is defined by the intersection of the capacity curve and the single demand spectrum curve. Also, a table was generated which shows the coordinates of the capacity curve and the demand curve as well as other information used to convert the pushover curve to Acceleration-Displacement Response Spectrum format (also known as ADRS format).See fig.7

9) The pushover displaced shape and sequence of hinge information on a step-by-step basis was obtained.

10) Output for the pushover analysis can be printed in a tabular form for the entire model or for selected elements of the model. The types of output available in this form include joint displacements at each step of the pushover, frame member forces at each step of the pushover, and hinge force, displacement and state at each step of the pushover.

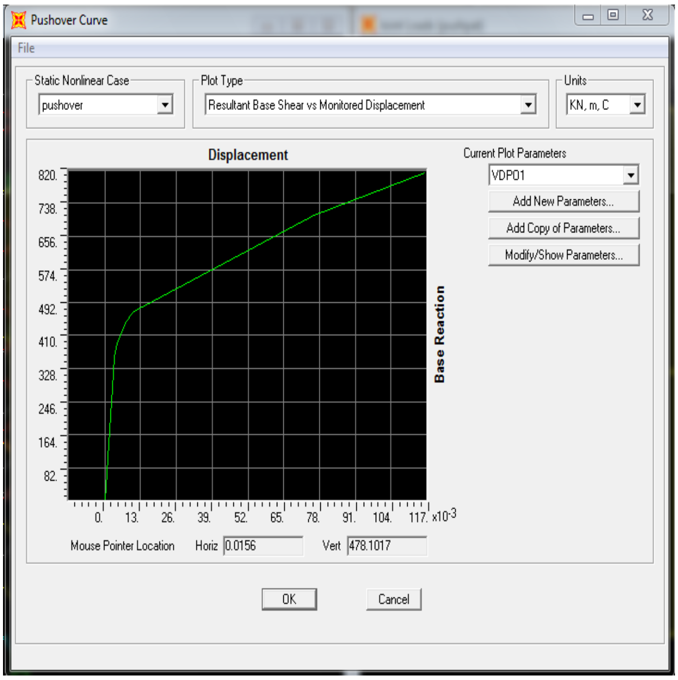


Fig. 6 Pushover curve

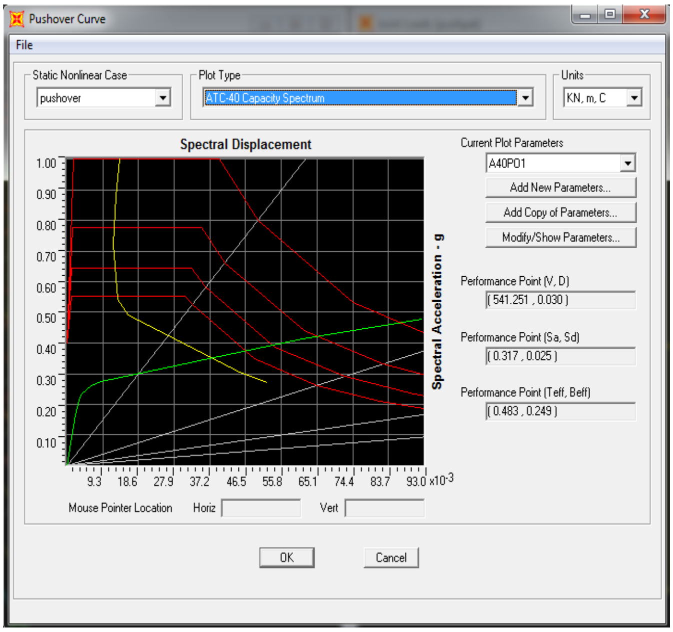


Fig. 7 Capacity spectrum curve

IV. VARIOUS CASES INCORPORATED IN STUDY

To study the effect of change of main reinforcement on the performance of the structure, various cases are made. All beams and columns at a particular story are given same reinforcement. Finally to study the effect of shear walls in structure, shear wall is provided in the basic structure.

To study the effect of change of main reinforcement of various beams and columns on the performance of the structure, various cases are made.

TABLE II. DESCRIPTION OF VARIOUS CASES

Sr. No.	Case no.	Description of cases
1		Basic structure
2	1,2	Increasing reinforcement in beams of 1st storey only
3	3,4	Increasing reinforcement in beams of 2nd storey only
4	5,6	Increasing reinforcement in beams of 3rd storey only
5	7,8	Increasing reinforcement in beams of 4th storey only
6	9,10	Increasing reinforcement in beams of 5th storey only
7	11,12	Increasing reinforcement in corner columns only
8	13,14	Increasing reinforcement in middle columns only
9	15,16	Increasing reinforcement in intermediate (central) columns only

V. ANALYSIS OF RESULTS

A. *Base force*

The base force for the four-storey building with different combination of element reinforcement at various floor levels is presented in Table III. It is observed that with increase in reinforcement of beams only, there is change in the base force varying from 5.24% to -16.6%, which the structure can carry. However, with the increase in reinforcement of storey columns, there is quite an appreciable change in the base force carrying capacity of the structure.

B. *Roof Displacement*

The Roof displacement for the four-storey building with different combination of element reinforcement at various floor levels is presented in Table IV. It is observed that by increasing the reinforcement of beams only, there is a decrease in the roof displacement. The percentage change varies from -6.22% to -34.78%. However, the trends shown by increasing the reinforcement of columns only is a substantial increase in the roof displacement which varies from -0.8% to -37.77%

C. *Pushover Curve*

The Pushover curve is the curve which is plotted between the Base force and Roof displacement. This curve shows the overall response of the structure in case of incremental seismic loading.

The structure is applied an inverted triangular loading. This loading is increased monotonically, in small increments, till there is a failure in the structure at any level. As the loading is increased, a curve between the base force and roof displacement is plotted. This curve is known as the pushover curve.

TABLE III. COMPARISION OF BASE SHEAR

	Cases	**Percentage increase in reinforcement**	**Base shear (kN)**	**Percentage change in Base shear**
Basic structure			815.265	
Beams of 1st storey	CASE 1 CASE2	7.5 15	792.383 737.55	-2.80 -9.53
Beams of 2nd storey	CASE3 CASE4	7.5 15	795.26 756.14	-2.45 -7.25
Beams of 3rd storey	CASE5 CASE6	7.5 15	744.85 726.56	-8.63 -10.88
Beams of 4th storey	CASE7 CASE8	7.5 15	740.25 735.48	-9.20 -9.78
Beams of 5th storey	CASE9 CASE10	7.5 15	722.53 707.83	-11.37 -13.17
Corner columns of all storey	CASE11 CASE12	36.11 50	858.709 879.641	5.32 7.89
Middle columns of all storey	CASE13 CASE14	30.61 50	835.528 719.701	2.48 -11.72
Intermediate (central) columns of all storey	CASE15 CASE16	50 75	797.66 702.14	-2.15 -13.87

TABLE IV. COMPARISION OF ROOF DISPLACEMENT

	Cases	**Percentage increase in reinforcement**	**Roof displacement in mm**	**Percentage change in roof displacement**
Basic structure			116.331	
Beams of 1st storey	CASE 1 CASE2	7.5 15	109.09 82.52	-6.22 -29.06
Beams of 2nd storey	CASE3 CASE4	7.5 15	94.04 90.8	-19.16 -21.94
Beams of 3rd storey	CASE5 CASE6	7.5 15	87.63 85.56	-24.67 -26.45
Beams of 4th storey	CASE7 CASE8	7.5 15	84.67 83.4	-27.216 -28.30
Beams of 5th storey	CASE9 CASE10	7.5 15	82.79 75.908	-28.83 -34.74
Corner columns of all storey	CASE11 CASE12	36.11 50	112.249 112.78	-3.5 -3.05
Middle columns of all storey	CASE13 CASE14	30.61 50	115.39 75.25	-0.808 -35.313
Intermediate (central) columns of all storey	CASE15 CASE16	50 75	74.69 72.39	-14.03 -37.77

TABLE V. VARIATION OF ROOF DISPLACEMENT WITH BASE SHEAR FOR ALL CASES

Structural element	Cases	Percentage increase in reinforcement	Base shear (kN)	Roof displacement (mm)
Basic structure			815.265	116.331
Beams of 1st storey	CASE 1 CASE2	7.5 15	792.383 737.55	109.09 82.52
Beams of 2nd storey	CASE3 CASE4	7.5 15	795.26 756.14	94.04 90.8
Beams of 3rd storey	CASE5 CASE6	7.5 15	744.85 726.56	87.63 85.56
Beams of 4th storey	CASE7 CASE8	7.5 15	740.25 735.48	84.67 83.4
Beams of 5th storey	CASE9 CASE10	7.5 15	722.53 707.83	82.79 75.908
Corner columns of all storey	CASE11 CASE12	36.11 50	858.709 879.641	112.249 112.78
Middle columns of all storey	CASE13 CASE14	30.61 50	835.528 719.701	115.39 75.25
Intermediate (central) columns of all storey	CASE15 CASE16	50 75	797.66 702.14	74.69 72.39

TABLE VI. COMPARISION OF AREA OF REINFORCEMENT IN MM^2 IN BEAMS AND COLUMNS FOR ALL DESIGNS

Element	IS 456:2000	Performance Based Design	IS 1893:2002
Corner Columns	904	1240	1040
Mid-face Columns	1232	900	1040
Interior Columns	4926	5325	5260
Beams of 1st Storey	602 (top) 550(bottom)	940 (top) 550(bottom)	940 (top) 550(bottom)
Beams of 2nd Storey	600(top) 550(bottom)	940(top) 550(bottom)	940(top) 550(bottom)
Beams of 3rd Storey	600(top) 550(bottom)	940(top) 550(bottom)	940(top) 550(bottom)
Beams of 4th Storey	817(top) 632(bottom)	1022(top) 550(bottom)	1022(top) 550(bottom)
Beams of 5th Storey	720(top) 570(bottom)	1045(top) 550(bottom)	1045(top) 550(bottom)

VI. CONCLUSION

In this work, Performance based seismic design of a G+4 storey unsymmetrical building has been done by evaluating their performance using pushover analysis. Reinforcement of various elements of the structure i.e. the beams and the columns was increased in different combinations and their effect on the performance of the structure was studied. The design of reinforcement was done in STAAD.Pro and analysis was carried out using SAP2000 nonlinear software tool. The effect of shear wall on the performance of the structure is also studied in this work.

Based on the present study, the following conclusions can be drawn:

1. Performance increases on increasing reinforcement of columns only resulting into an appreciable decrease in the maximum roof displacement. Decrease in roof displacement is maximum interior column and for corner and mid-face columns it is comparable.
2. The increase in reinforcement of columns only results into a nominal increase in base shear. It is observed that changing reinforcement of 1ststorey affects base shear more than other storeys.
3. Performance of the building decreases when the sectional sizes of beams and columns are reduced while keeping same reinforcement.
4. Increasing reinforcement of beams and columns both result
in an appreciable decrease in roof displacement, for un-symmetrical building.
5. Provision of shear wall results in a huge decrease in base shear and roof displacement in unsymmetrical building.
6. The performance based seismic design obtained by above procedure satisfies the acceptance criteria for immediate occupancy and life safety limit states for various intensities of earthquakes.
7. Performance based seismic design obtained leads to small reduction in steel reinforcement when compared to code based seismic design (IS 1893:2002) obtained by STAAD.Pro.

As a closing remark, one can say that performance based seismic design gives a structure with better seismic load carrying capacity, thereby achieving the objective of **performance** as well as **Economy** and there is certainly room for further improvement in the aforementioned method.

VII.SCOPE OF FUTURE WORK

Within the limited scope of the present work, the broad conclusions drawn from this work have been reported. Further study can be undertaken in the following areas:

1. In the present study, the pushover analysis has been carried out for five storey buildings. This study can further be extended for tall buildings.
2. In the present study, the conceptual design i.e., the sizes of beams and columns are kept same. Work can be done to optimize the sizes of various frame elements using pushover analysis.
3. A comparative study can be done to see the effect of shear reinforcement on performance based seismic design.

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