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Seismic Vulnerability of Tall Steel Structures Using by Nonlinear Static Analysis

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1 ABSTRACT
This paper is inclusive concepts about performance based design in evaluation of vulnerability and retrofit of steel structures relevant to Iran’s retrofit Instructions “Code-360” and analyse the structure and presents the several solutions in suitable performance levels for specific and definite hazard levels of the earthquake.
In this project a 18 Storey steel building is evaluated completely by nonlinear statics (Pushover) analysis with numerical software and then , several diagrams and programs are prepared for increase the efficiency and accuracy in calculations for many important parameters such as trace the response spectrums , reduced response spectrums (calculate SRa & SRv base on ATC40) ، capacity spectrums and bi-linear representation of capacity spectrums in ADRS formats and calculate the plastic hinges for different structural elements and performance point with use Microsoft Excel program base on Iran's retrofit and seismic instructions.
Keywords: Capacity Spectrum Method (CSM), Response Spectra, Viscose Damping, Seismic Vulnerability, Pushover Curve

2 INTRODUCTION
The researchers have done consideration based on studies on the effects of recent earthquakes such as Northridge Earthquake in America in 1994 and the earthquake in Kobe, Japan in 1995 and other cases, they observed that the structures have been designed with common regulations , have shown good performance in terms of residents health and security, but the damages and injures on the structures, especially structures with the high importance in type of performance have been high remarkably.
In the retrofiting existing regulations has been provided useful tools that are expected to ensure the necessary criteria to maintain security for the building's residents during an earthquake by applying these tools.

3 EVALUATION AND RETROFITING CONCEPTS
1.1 Retrofiting Structures
The survey and inspection of condition (failure rate or plastic and permanent deformation) structural members in the necessary displacement for earthquake energy depreciation, (or linear forces with this displacement) with a defined failure rate (performance) in structural members are significant aims.

1.2 Various levels of building performance
1.2.1 Immediate occupancy Level: (IO)
This level Refers to the performance level that is expected due to earthquake, resistance and stiffness of structural components,not to find a significant change and continuous use of it may be done.

1.2.2 Life safety Level: (LS)
This level Refers to the performance level that is forecasted due to earthquake, destruction to be created in the structural elements, but the failure rate isn't a proportion that leads to life damage.

1.2.3 Collapse prevention Level: (CP)

the performance level that due to earthquake is forecasted, the destruction is created in the structural elements extensively, but buildings do not collapse, and minimize loss of life.

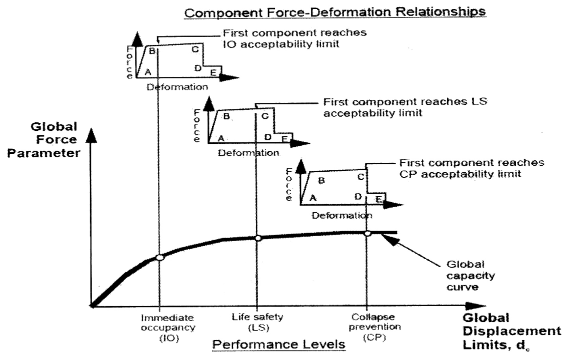

Figure 1: Performance level

A performance level indicates maximum structural failure, so that if the destruction increases from this limit, structures performance level will change.

1.3 Retrofiting objectives and risk levels

Risk Level 1: This level of risk based on 10% event probability in 50 years is determined, that it is equivalent with return period of 475 years. this level of risk in iran's 2800 standard regulations, has been called "Earthquake Plan" (DBE).

Risk Level 2: This level of risk is determined based on 2% event probability in 50 years, equivalent with return period of 2475 years,. Risk level 2 is called as the " maximum probable earthquake"(MPE).

Selected risk level (an earthquake with each event probability – in 50 years) : This level of risk is suitable for specific cases with special considerations,

Basis retrofiting: is as follows life satety for an earthquake with risk level 1 or Plan earthquake in iran's 2800 Regulations.

Desirable retrofiting: in this retrofiting are expected in addition to protection life safety in risk level 1, is ensured collapse threshold for earthquake with hazard level 2 or the maximum probable earthquake.

1.4 Failure mechanism control

The structural behavior of elements based on failure mechanism is controlled in two ways:

1.4.1 controlled by deformation and

1.4.2 controlled by forces.

4 PUSHOVER ANALYSIS

In nonlinear static analysis, the forces or lateral displacement have been applyed in structural models and to be increased in successive steps gradually. and the model is corrected in every step so that reduction of stiffness due to elements or loss of strength be formed in plastic hinges. and on the modified model is done a linear analysis in every step. Increase the load is continued to limit so that other elements be yeilded.

4.1 Nonlinear method (stiffness method)

In limit of elasticity, the elements stiffness will be according to linear method. But in limit of non-elasticity, can be used from the diagram such as under shape, in this diagram, strain stiffness effect have been noticed by considering the slope equivalent with three percent of slope of elastic part.

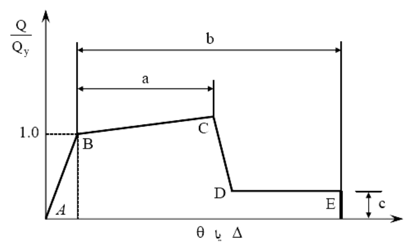

Figure 2: Generalized displacement-force diagram for steel elements

4.2 Capacity Curve

Capacity curve indicate relationship between applied lateral force to structures, against the lateral displacement of the point of structure (roof for example). In order to obtain that, is used nonlinear static analysis.

4.3 lateral load criteria

Distribution of lateral load on structure, must create critical states of displacement and axial forces in elements. Therefore according to FEMA regulation and iran's retrofiting prescription must be applyed two types of distribution lateral load on structure:

4.3.1 Distribution of type 1

4.3.1.1 Distribution of lateral load by linear static method

4.3.1.2 Distribution according to the first mode shape in desired direction:

4.3.1.3 Proportional distribution of lateral forces resulting from linear Dynamic Analysis

For this purpose, multipcity of vibration modes should be selected so that at least 90% of structural mass to participate in the analysis.

4.3.2 Distribution of type 2

4-3-2-1-uniform distribution

In this case, the lateral load is calculated proportionate to the weight of every story, if weight of all stories should be the same, distribution will be rectangular in the whole structure.

4.3.2.2 Variable distribution

In this case, lateral load distribution based on nonlinear behavior state of construction model in each step are increased, and will be changed by using a reliable method.

4.4 Transformation of capacity curve to capacity spectrum

capacity curve is drawn in the form of base shear versus roof displacement by analyzing the nonlinear softwares. According to ATC-40 regulations, this capacity curve can be transformed to ADRS curves coordinate.

For each point with (Δ_{roof}, V) Coordinates on the capacity curve and with using the following relations can to obtained the corresponding point (S_a and S_d) on spectrum capacity.

$$PF_m = \left\{ \frac{\sum_{i=1}^{N} (W_i \phi_{im}) / g}{\sum_{i=1}^{N} (W_i \phi_{im}^2) / g} \right\} \tag{1}$$

$$\alpha_m = \frac{\left[\sum_{i=1}^{N} (W_i \phi_{im}) / g \right]^2}{\left[\sum_{i=1}^{N} W_i / g \right] \left[\sum_{i=1}^{N} (W_i \phi_{im}^2) / g \right]} \tag{2}$$

$$Sd_i = \frac{\Delta_{roof}}{PF_1 \times \phi_{roof\,1}} \tag{3}$$

$$Sa_i = \frac{V_i / W}{\alpha_1} \tag{4}$$

4.5 Transformation of demand spectrum to ADRS format (Acceleration Displacement Response Spectrum)

Standard response spectrum curves are drawn in the form of spectral acceleration (S_a) versus period of structures (T),but the ADRS curves are drawn in the form of S_a against S_d.

In under shapes have been shown the same spectrum in two different format:

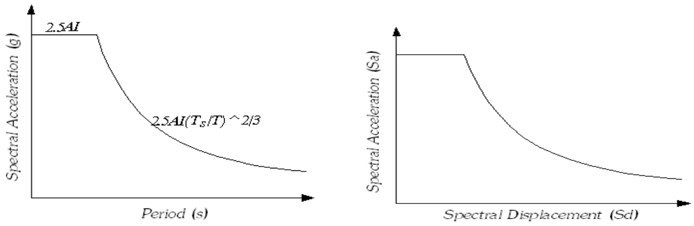

Figure 3: Transformation of demand spectrum to ADRS format

For two points with specifications (T, S_a) on the standard spectrum, spectral displacement (S_d) and spectral acceleration (S_a) the corresponding point on the ADRS spectrum is as follows:

$$Sa = 2.5 \times A \times I \times \begin{cases} 1 & T < T_S \\ \left(\frac{T_S}{T}\right)^{2/3} & T \geq T_S \end{cases} \quad , \qquad Sd = \left[\frac{T}{2\pi}\right]^2 Sa.g \tag{5}$$

5 ESTIMATION OF EQUAL VISCOSE DAMPING IN EACH POINT OF CAPACTY SPECTRUM

Structural damping into the non-linear area is defined in the form of combination of viscose damping (intrinsic damping) and hysteresis damping.

hysteresis damping is proportionate to area of force-displacement curve. This damping can be expressed as equivalent viscose damping (βeq).

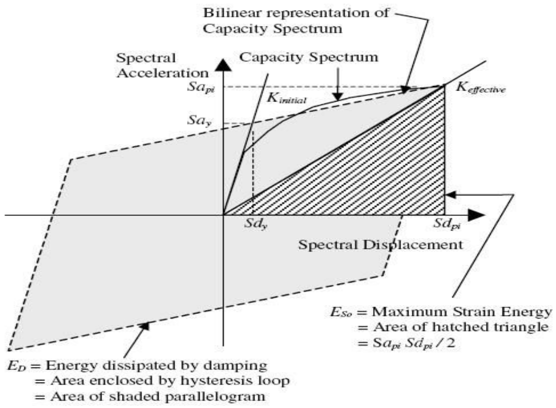

Figure 4: Definition of absorbed energy and maximum strain energy

$$\beta_{eq} = \beta_0 + 0.05 \quad , \quad \beta_0 = \frac{1}{4\pi} \cdot \frac{E_D}{Es_0} \tag{6}$$

hysteresis curve of a non-elastic system in ideal state can be considered as a parallelogram shape.

E_D: dissipated energy by plastic deformation in one cycle of motion

E_{S0}: Maximum strain energy in the same cycle of motion equal to hachured area

$$E_D = 4\left(a_y d_{pi} - d_y a_{pi}\right) \quad Es_0 = a_{pi} d_{pi} / 2 \tag{7}$$

$$\beta_0 = \frac{0.637\left(a_y d_{pi} - d_y a_{pi}\right)}{a_{pi} d_{pi}} \tag{8}$$

$$\beta_{eq} = \beta_0 + 5 = \frac{63.7\left(a_y d_{pi} - d_y a_{pi}\right)}{a_{pi} d_{pi}} + 5 \tag{9}$$

5.1 Effective viscose damping

In fact, due to phenomenon of buckling, fatigue and loss of strength and etc, hysteresis loops is incomplete, and their internal areas decrease in successive cycles.

So in order that damping factor can to simulate the incomplete hysteresis loops must be used of the concept of effective viscose damping with use of K correction factor.

$$\beta_{eff} = K\beta_0 + 5 = \frac{63.7K\left(a_y d_{pi} - d_y a_{pi}\right)}{a_{pi} d_{pi}} + 5 \tag{10}$$

5.1.1 K coefficient

K: Corrective coefficient according to under table, by means of that, the equivalent viscose damping resulting from ideal hysteresis curve is transformed to equal viscose damping, corresponding with the actual hysteresis curve of building.

5.2 Reduction of demand spectrum with 5% damping

For reduction of response spectrum with 5% damping is used of resonance coefficients with magnification factors of NewMark's and Hall's plan spectrum.
resonance coefficients of invariable acceleration and fixed spectral velocity of plan earthquake is determined respectively according to following relations by means of effective viscose damping(β_{eff}):

$$\alpha_A\left(\beta_{eff}\right) = 3.21 - 0.63Ln(\beta_{eff}) \tag{11}$$

$$\alpha_V\left(\beta_{eff}\right) = 2.31 - 0.41Ln(\beta_{eff}) \tag{12}$$

Plan spectrum in Iran's 2800 standard correspond to 5% viscose damping of structure.Thus for reducing this spectrum is divided respectively on $\alpha_A(5)$ and $\alpha_V(5)$. And elastic plan spectrum with zero damping is produced. Then the same areas are multiplied respectively in $\beta_{eff}(\alpha_A)$ and β_{eff} (α_V). And are achieved the reduced plan spectrum corresponding to effective damping (β_{eff}).
These proportions in ATC-40 regulation are expressed respectively with SR_A and SR_V coefficients (spectral decrease coefficients), as following:

$$SR_A = \frac{3.21 - 0.681Ln(\beta_{eff})}{2.12} \geq (SR_A)_{\min} \tag{13}$$

$$SR_V = \frac{2.31 - 0.41Ln(\beta_{eff})}{1.65} \geq (SR_V)_{\min} \tag{14}$$

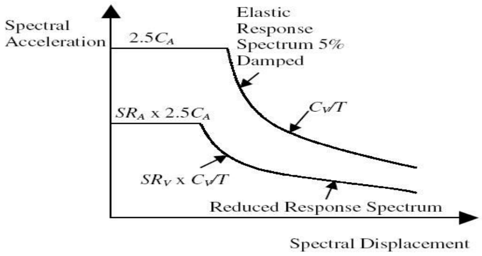

Figure 5: Comparison of reduced and primary demand spectrum

6 METHODS OF DETERMINATION THE PERFORMANCE POINT AND TARGET DISPLACEMENT BASED ON ATC–40 REGULATION

Position of performance point on the capacity spectrum depends on the reduction of elastic demand spectrum with 5% damping. Also the amount of reduced elastic demand spectrum with 5% damping depends on the effective viscose damping corresponding to performance point.
Therefore,to determine the performance point on capacity spectrum exists related two-unknown.
1- Performance point position
2- Effective viscose damping corresponding to performance point

6.1 Step by step method to determine the performance point with capacity spectrum method

1- Preparation of elastic response spectrum with 5% damping, for this purpose, can be used of smoothed response spectrum or special spectrum.
2- Transformation of capacity curve into the capacity spectrum with using previous relationships, and drawing this spectrum on the same page consisting of the drawn response spectrum in the ADRS format.
3- Selection of a point as a assumptive behavior point for first step of operations by try and error

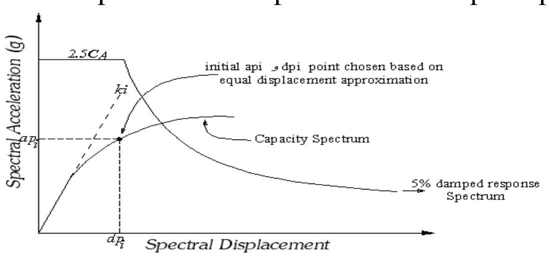

Figure 6: Capacity spectrum method after three steps

4– Organizing bilinear curve of the capacity spectrum by using the point of choiced behavior in previous step, and considering to equality areas of under curves, a_y and d_y are obtained in end of this step.

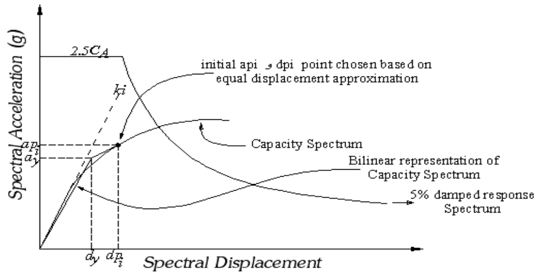

Figure 7: Capacity spectrum method after four steps

5- calculation of spectral reduction coefficients by using the previous relationships and drawing reduced demand spectrum on the same page.

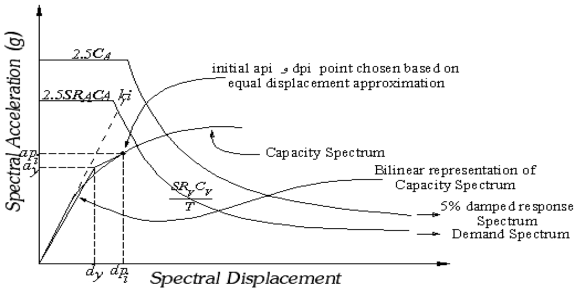

Figure 8: Capacity spectrum method after five steps

6- Control of intersection point of demand spectrum and capacity spectrum,if the intersection point conforms to initial selected point with 5% error, the analysis is finished. according to following shape, otherwise, another point is selected and steps of 4, 5 and 6 are repeated.

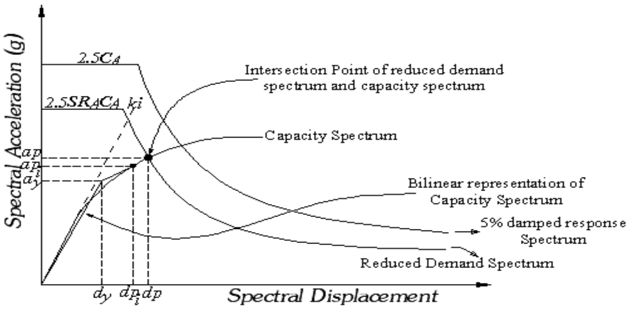

Figure 9: Capacity spectrum method after six steps

7- determination of final point in the range of acceptable error as characteristic point of structural behavior. dp is obtained from this analysis and that is maximum of displacement as desired structure will be tolerated during the applied earthquake.

7 INTRODUCING THE BUILDING

In this project, a 18 floor steel building, with residential user, has been applied nonlinear analysis and has been designed. specifications of geometrical plan and sections of the building is available.

For transfering gravitational load from floor to beams has been used from block-joist system and distributing it as a (checkered) grid system. This buiding has been located in Tehran.

Structural lateral bearing system is special bending frame combined with convergent braces (CBF) in two sides (with type of ∧)

Building behavior factor, R by considering special steel bending frame dual system combined with convergent braces have been considered nine based on Iran's earthquake regulations (Standard No.2800).

Figure 10: View of building

8 CALCULATING THE ELEMENT PLASTIC HINGE PROPERTIES

8.1 calculating beam plastic hinge properties

In the beams, the rotation in yield limit (θ_y), based on the written relations in chapter five in 360 prescription of Iran's retrofiting regulation, are equal to:

$$\theta_y = \frac{ZF_{ye} L_b}{6EI_b} \qquad (15)$$

and also the bending plastic capacity of beams are equal to:

$$Q_{CE} = M_{CE} = ZF_{ye} \qquad (16)$$

8.2 Calculating column plastic hinge properties

In the columns, has been calculated the rotation in yield limit (θ_y), based on the written existing relations in chapter five in Code 360 of Iran's retrofiting regulation and also has been calculated the bending plastic capacity of columns

8.3 Calculating brace plastic hinge properties

9 CALCULATION OF TARGET DISPLACEMENT QUANTITIES

Calculation of target displacement in 18 story model including special bending frame combined with convergent braces (CBF) by coefficients method in Code: 360 of Iran's retrofiting Codes:

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{Te^2}{4\pi^2} g \qquad (17)$$

Table 1:Calculation of target displacement

risk levels	C_0	C_1	C_2	C_3	S_a	T_e	δ_t
risk level 1	1.5	1	1.2	1	0.385	1.71	0.503
risk level 2	1.5	1	1.2	1	0.66	1.71	0.863

10 CONCLUSIONS

10.1 *Seismic evaluation and control of acceptance criteria of bending frames*

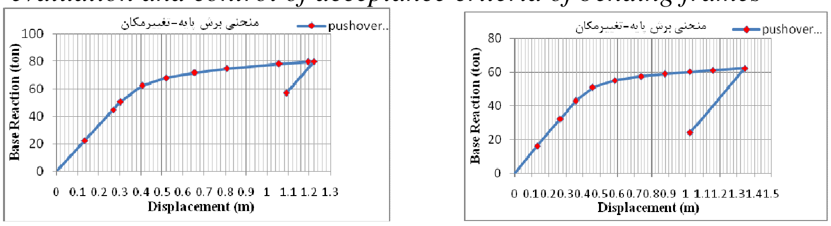

Figure 11: Displacement-base shear curves in loading of type 1 , 2

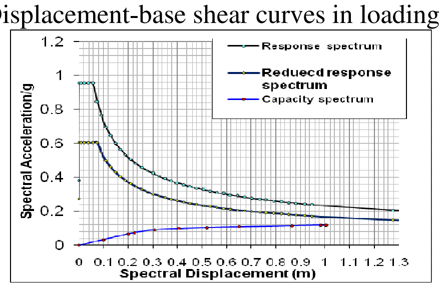

Figure 12: Capacity spectrum and reduced demand spectrum of bending frames for loading of type 2

10.2 Seismic evaluation and control of acceptance criteria of bending frames combined with convergent braces

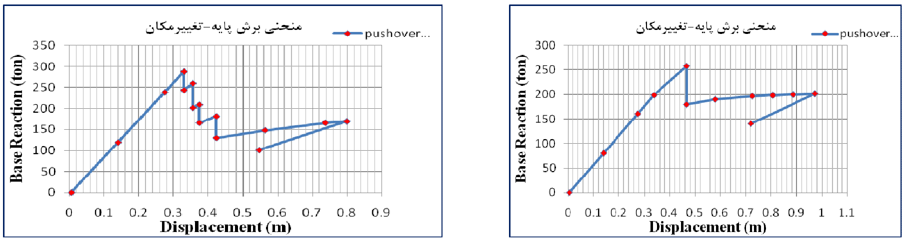

Figure 13: Displacement-base shear curves in loading of type 1 , 2

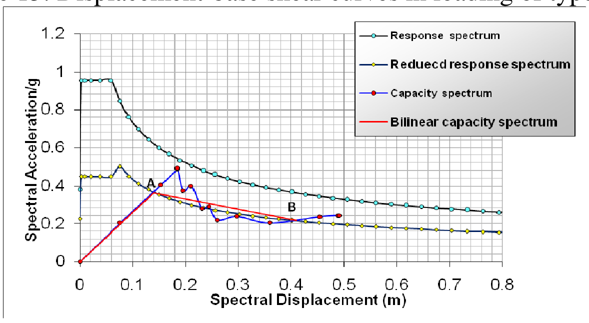

Figure 14: Capacity spectrum and reduced demand spectrum for loading of type 2
(point B is performance point)

10.3 Evaluation of acceptance criteria in columns with controlled by forces behavior

In sec1 and sec2 of columns, P/P_{CL} proportion has been greaten than 0.5, so in combination of stresses, equations are as follows:

$$\frac{P_{UF}}{kP_{CL}}+\frac{C_{mx}M_{UFX}}{k\left[1-\frac{P_{UF}}{kP_{ex}}\right]M_{CLX}}+\frac{C_{my}M_{UFy}}{k\left[1-\frac{P_{UF}}{kP_{ey}}\right]M_{CLy}}\leq 1.0 \tag{18}$$

$$\frac{P_{UF}}{k.A.F_{ye}}+0.85\left[\frac{M_{UFX}}{k.M_{PCLX}}+\frac{M_{UFy}}{k.M_{PCLy}}\right]\leq 1.0 \tag{19}$$

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