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Performance-based Seismic Design of Structures

Department of Structural Engineering

National University of Sciences and Technology (NUST)

Seismic Analysis & Design of Buildings using IBC-2021 (BCP-2021) & ASCE 7-16

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Seismic Hazard Assessment

Equivalent Lateral Force (ELF) Procedure (IBC-2021, BCP-2021, ASCE 7-16)

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Equivalent Lateral Force (ELF) Procedure (IBC-2021, BCP-2021, ASCE 7-16)

Step 1: Determination of the fundamental period of the structure.

T_a = Approximate lower bound period (based on measured response of buildings) in high seismic regions

$T = C_u T_a$ = Approximate upper bound period (based on best fit of measured response and is adjusted for local seismicity)

$T_{computed}$ = First mode time period (in the direction of consideration determined from computer analysis (e.g eigen value or Ritz analysis)

1) $T_a = C_t h_n^x$ (C_t, x are functions of structural system → Table 12.8-2)

h_n → structural height.

Alternatively, 2) $T_a = 0.1N$

N → No. of stories — For ≤12 stories, concrete or steel MRFs. Story height ≥10 ft

Determination of Approximate Time Period of the Building

3) $T_a = \frac{C_q}{\sqrt{C_w}} h_n$ For masonry or concrete Shear wall structures

$h_n \not> 120$ ft

$C_q = 0.0019$ ft
$= 0.00058$ m

$C_w = \frac{100}{A_B} \sum_{i=1}^{x} \frac{A_i}{\left[1 + 0.83\left(\frac{h_n}{D_i}\right)^2\right]}$

where
A_B = Area of base of structure
A_i = Web area of shear wall i
D_i = Length of shear wall i

x = No. of shear walls in building effective in the direction under consideration.

Table 12.8-2 Values of Approximate Period Parameters C_t and x

Structure Type	C_t	x
Moment-resisting frame systems in which the frames resist 100% of the required seismic force and are not enclosed or adjoined by components that are more rigid and will prevent the frames from deflecting where subjected to seismic forces:		
Steel moment-resisting frames	0.028 (0.0724)[a]	0.8
Concrete moment-resisting frames	0.016 (0.0466)[a]	0.9
Steel eccentrically braced frames in accordance with Table 12.2-1 lines B1 or D1	0.03 (0.0731)[a]	0.75
Steel buckling-restrained braced frames	0.03 (0.0731)[a]	0.75
All other structural systems	0.02 (0.0488)[a]	0.75

[a]Metric equivalents are shown in parentheses.

Determination of Approximate Time Period of the Building

* If $T_{computed}$ is not available → Use T_a
* If $T_{computed}$ is available, then:

  if $T_{computed} > C_u T_a$ → use $C_u T_a$

  if $T_{computed}$ is between T_a and $C_u T_a$ → Use $T_{computed}$

  if $T_{computed} < T_a$ → use T_a

Table 12.8-1 Coefficient for Upper Limit on Calculated Period

Design Spectral Response Acceleration Parameter at 1 s, S_{D1}	Coefficient C_u
≥0.4	1.4
0.3	1.4
0.2	1.5
0.15	1.6
≤0.1	1.7

Step 2: Determination of Seismic Weight.

Use section 12.7.2 in the modeling criteria → W

Step 3: Determination of base shear.

$$V = C_s W \quad (12.8\text{-}1)$$

W → Seismic weight

C_s → seismic response coefficient (or base shear coefficient)

Determination of Base Shear of the Building

$$C_s = \frac{S_{DS}}{(R/I_e)} \quad (12\cdot8-2)$$

Upper Limit on C_s: For $T \le T_L$, $C_s = \dfrac{S_{D1}}{T(R/I_e)}$ (12·8-3)

For $T > T_L$, $C_s = \dfrac{S_{D1}T_L}{T^2(R/I_e)}$ (12·8-4)

Lower Limits on C_s:

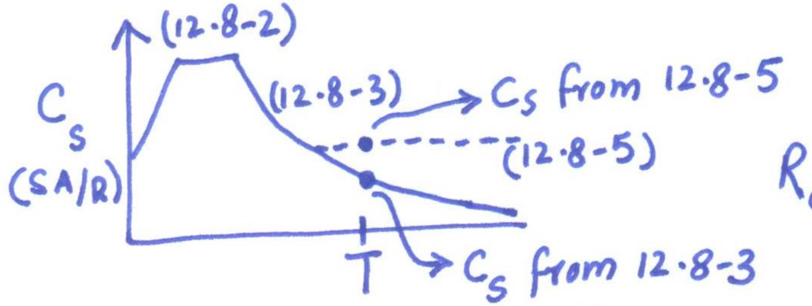
a) Larger of $\left[\begin{array}{l} C_s = 0.044\,S_{DS}I_e \\ C_s = 0.01 \end{array}\right]$ (12·8-5)

b) For $S_1 \ge 0.6g$, $C_s = \dfrac{0.5S_1}{(R/I_e)}$ (12·8-6)

T_L = long-period transition period.

For US → Figs 22-14 to 22-17.

Concept of Reffective :



[12·8-5 Controls]

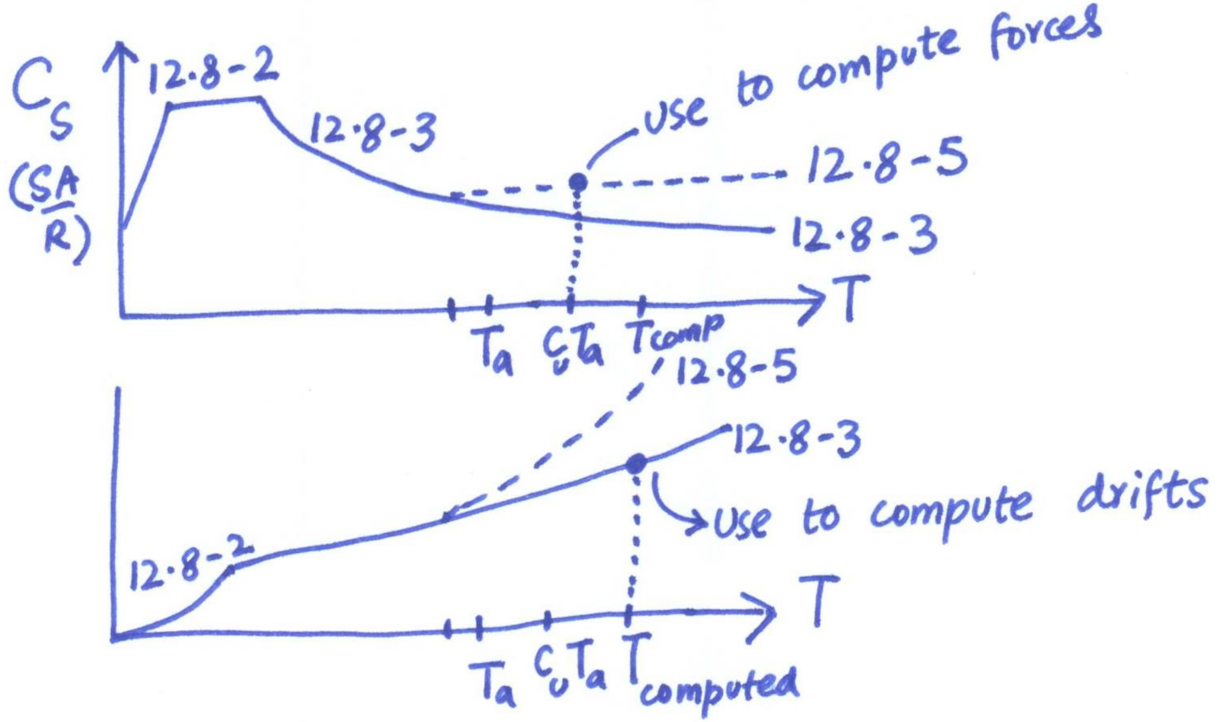
$$R_{effective} = \frac{C_{s(12\cdot8-3)}}{C_{s(12\cdot8-5)}} \cdot R$$

Use of Upper Limit on T for determining the Drifts

Issues related to T and Determination of drift:-

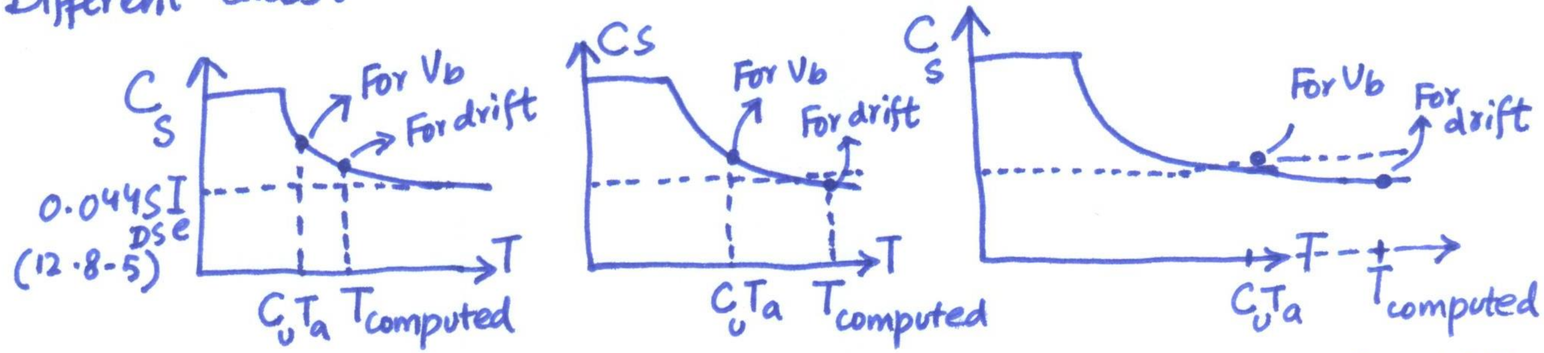
Section 12.8.6.1 → If 12.8-5 is controlling C_s → It may not be considered for computing drift.

Section 12.8.6.2 → For computing elastic drifts (δ_{xe}), the $T_{computed}$ can be used (without the upper limit ($C_u T_a$).

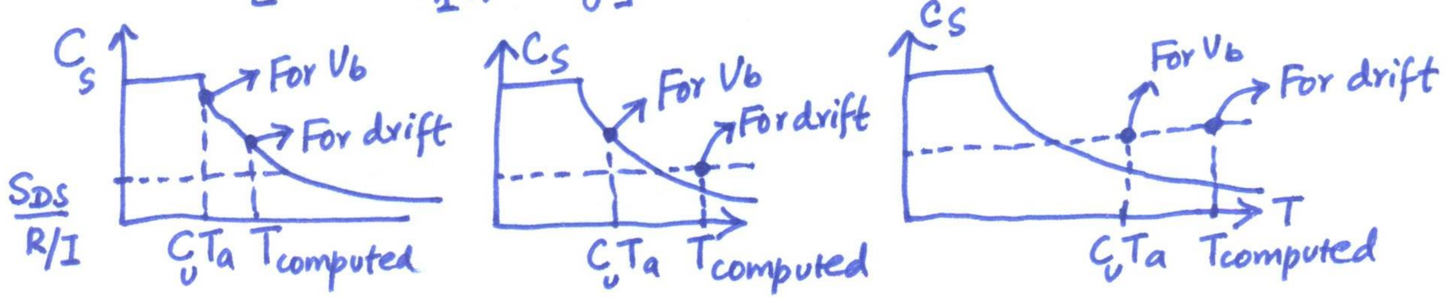


Different Cases for Using $C_u T_a$ vs. $T_{computed}$

Different Cases:



When 12.8-6 controls C_s, Use 12.8-6 For V_b as well as for drift.
[When $S_1 \geq 0.6g$]



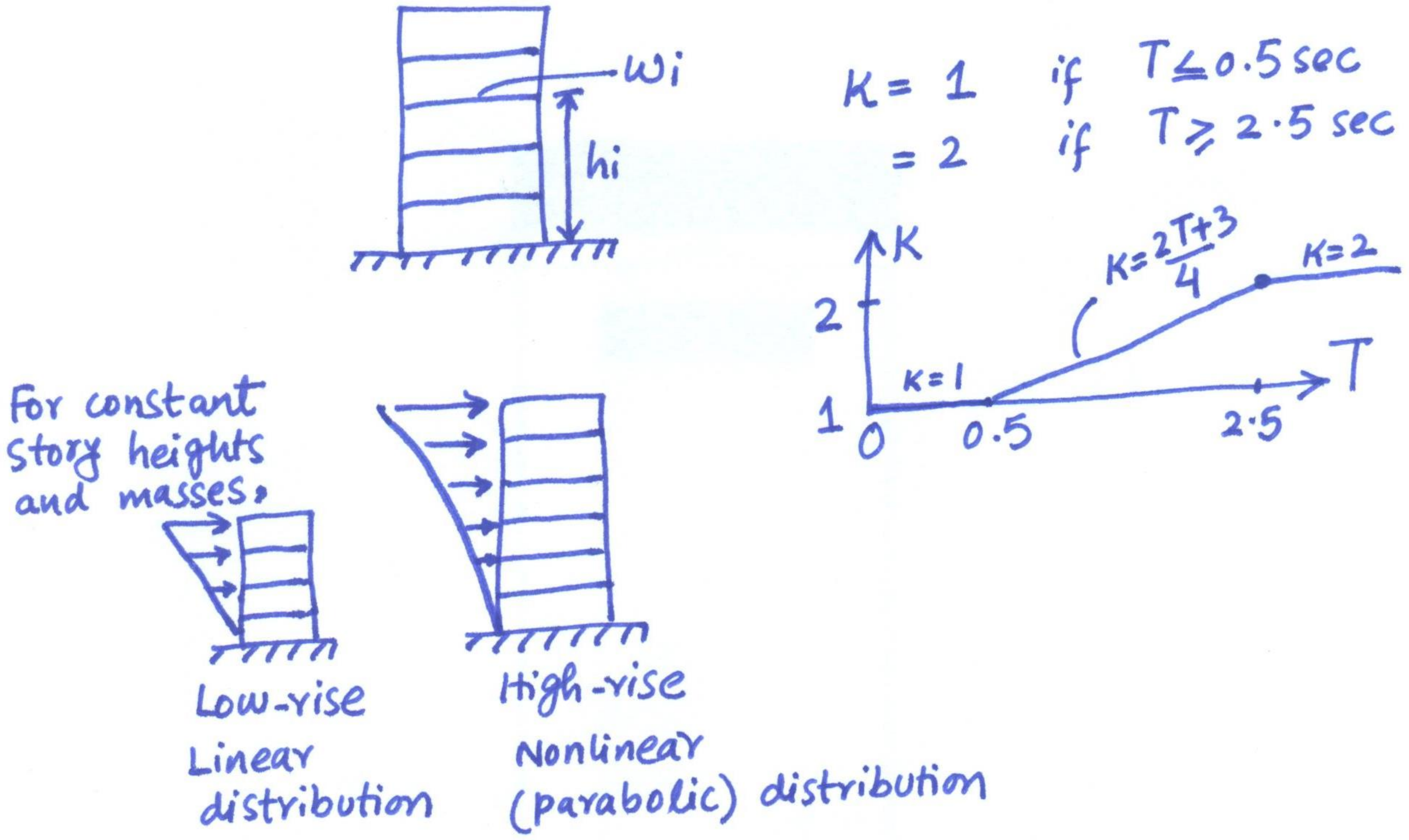
Step 4: Vertical Distribution of Seismic Forces.

$$F_x = C_{vx} V$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$

C_{vx} = Vertical distribution factor.

Vertical Distribution of Seismic Forces



Horizontal Distribution of Seismic Forces

Step 5: Horizontal Distribution of Forces.

$$V_x = \sum_{i=x}^{n} F_i$$

V_x — Seismic design story Shear in any story x.

F_i — portion of V at ith floor

V_x is distributed to various vertical elements in that story based on the relative lateral stiffness of vertical resisting elements and the diaphragm.

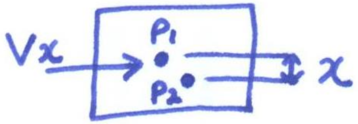
Step 6: Consideration of Inherent and Accidental Torsion.

For rigid diaphragms [Inherent Torsion] → The distribution of lateral forces at each level (step 5) shall consider the effect of inherent torsional moment (M_t) resulting from eccentricity between the center of mass and center of rigidity.

Inherent and Accidental Torsion

For flexible diaphragms → The distribution of forces to the vertical elements shall account for the position and distribution of the masses supported.
[Inherent Torsion]

Inherent torsion effects are automatically included in 3D structural analysis, and member forces associated with such effects need not be separated out from the analysis.



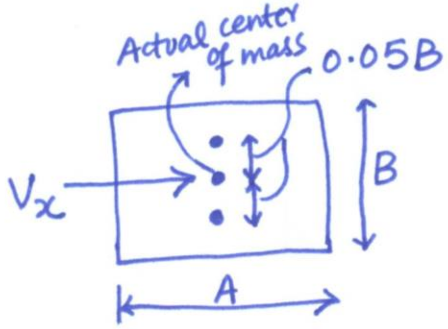
P_1 = Center of mass
P_2 = center of rigidity

$M_{t_x} = V_x \cdot x$ (clockwise)

Inherent and Accidental Torsion

For Rigid Diaphragms $\longrightarrow$ $M_t + M_{ta}$

[Inherent + Accidental Torsion]



$M_{tax} = V_x \cdot 0.05B$

Clockwise

$M_{tax} = V_x \cdot (-0.05B)$

Anticlockwise

Accidental torsional moments caused by assumed disp of the center of mass each way from its actual location by a distance equal to 5% of the dimension of structure perpendicular to the direction of applied forces.

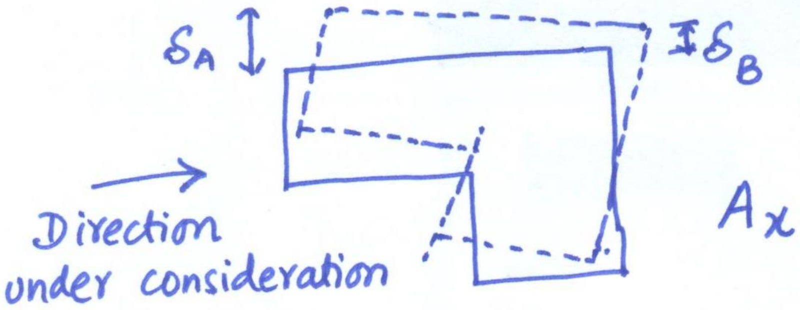
When the earthquake forces are applied concurrently in two orthogonal directions, the required 5% displacement of the center of mass need not be applied in both of the orthogonal directions at the same time, but shall be applied in the direction that produces the greater effect.

Inherent and Accidental Torsion

Amplification of Accidental Torsional Moment:

For case "C" $\rightarrow$ $M_{ta} \times A_x$

↳ Torsional amplification factor.



$\delta_{max} = Max\,(\delta_A , \delta_B)$ $\rightarrow$ computed without A_x

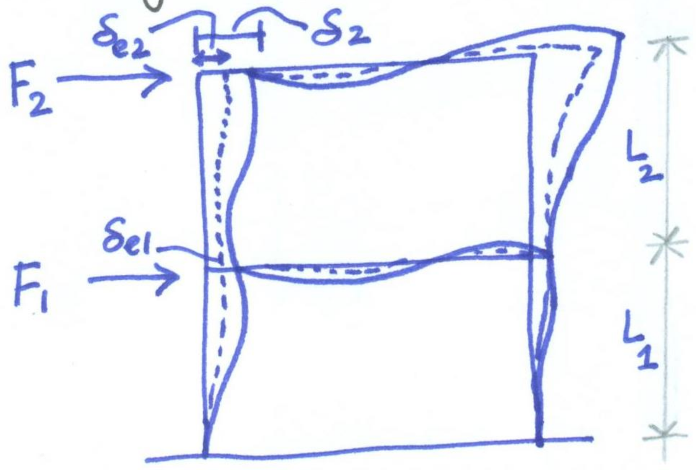
$$A_x = \left[\frac{\delta_{max}}{1.2\,\delta_{avg}}\right]^2$$

Where δ_{avg} = Average of the displacements at the extreme points of the structure at level x computed assuming $A_x = 1$

$$1 \le A_x \le 3$$

Story Drift Check

Step 7: Story Drift Determination.



..... Deflections due to Forces reduced with R

— Deflections determined by multiplying ..... with C_d/I_e. (Amplified displacements)

$F_1, F_2 \rightarrow$ Design forces (reduced with R)

$\delta_{e1}, \delta_{e2} \rightarrow$ Elastic Displacements caused by F_1, F_2.

$\delta_1, \delta_2 \rightarrow \dfrac{C_d \times \delta_{e1}}{I_e}$, $\dfrac{C_d\, \delta_{e2}}{I_e}$ (Amplified displacements)

$$\left.\begin{aligned} \Delta_2 &= \delta_2 - \delta_1 \\ \Delta_1 &= \delta_1 - 0 \end{aligned}\right] \text{Story drifts} \leq \Delta_a \left(\begin{smallmatrix}\text{Table}\\ 12.12\text{-}1\end{smallmatrix}\right)$$

$$\left.\frac{\Delta_2}{L_2}, \frac{\Delta_1}{L_1}\right] \begin{array}{l}\text{Story drift ratios}\\ \text{or Interstory drift ratios.}\end{array}$$

Story Drift Check

Step 8 : Checking story drift limit.

Allowable story drift $\Delta_a \rightarrow$ Table 12.12-1

↓ Type of Structure	Risk Category I or II	III	IV

$$\Delta < \Delta_a$$

For MRFs in SDC D through F, $\Delta < \frac{\Delta_a}{\rho}$

ρ → redundancy factor (Section 12.3.4.2)

Step 9 : Consideration of $P\Delta$ Effects.

a) Determine the stability coefficient for each story as follows.

$$\theta = \frac{P_x \Delta I_e}{V_x h_{sx} C_d}$$

P_x — Vertical design load at and above level x. (No load factor)

Δ — Drift from ELF (multiplied with Cd/I)

V_x — Seismic shear force acting b/w level x and $x-1$

h_{sx} — Story height below level x

Consideration of P-Delta Effects

b) Determine θ_{max} as follows.

$$\theta_{max} = \frac{0.5}{\beta C_d} \leq 0.25$$

ratio of shear demand to shear capacity for the story b/w level x and $x-1$ [conservatively → 1]

<u>Case 1</u>: If $\theta < 0.1$ → $P\Delta$ effects on all demands are not required to be considered.

<u>Case 2</u>: If $0.1 < \theta \leq \theta_{max}$, the incremental factor related to $P\Delta$ effects on displacements and member forces shall be determined by rational analysis.

Or

Multiply displacements and member forces by $\dfrac{1}{1-\theta}$.

Consideration of P-Delta Effects

<u>Case 3:</u> $\theta > \theta_{max}$, the structure is potentially unstable and shall be redesigned.

Note: When the $P\Delta$ effect is included in an automated analysis, the condition $\theta < \theta_{max}$ should still be satisfied, however the value of θ computed from $\frac{P_x \Delta I}{V_x h_{sx} C_d}$ is permitted to be divided by $(1+\theta)$ before checking this condition (only when the $P\Delta$ effect are automatically considered by the analysis program).

Note: The $P\Delta$ effects for modal RSA or modal RHA are checked using this ELF procedure.

Orthogonal Effects

Step 10: Check Orthogonal Loading Requirements.

a) SDC B → Design seismic forces are permitted to be applied independently in each of the two orthogonal directions.

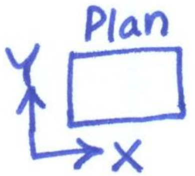
Neglect the orthogonal interaction effects.

Orthogonal Effects

b) SDC C → Requirement for "a" + the following.
If the structure possess horizontal irregularity Type 5 (Table 12.3-1), use one of the following options.

Type 5
↓
Non parallel System Irregularity
↓
When vertical lateral force-resisting elements are not parallel to the major orthogonal axes of the seismic force resisting system.

Option 1: Orthogonal Combination procedure:



100% EQX + 30% EQY
100% EQY + 30% EQX

Option 2: Simultaneous Application of orthogonal ground motion.

Note: Option 1 → ELF, RSA, LTHA
Option 2 → LTHA, NLTHA

c) SDC D through F → As a minimum, conform to the requirements for "a" and "b".

Load Cases of ELF Procedure

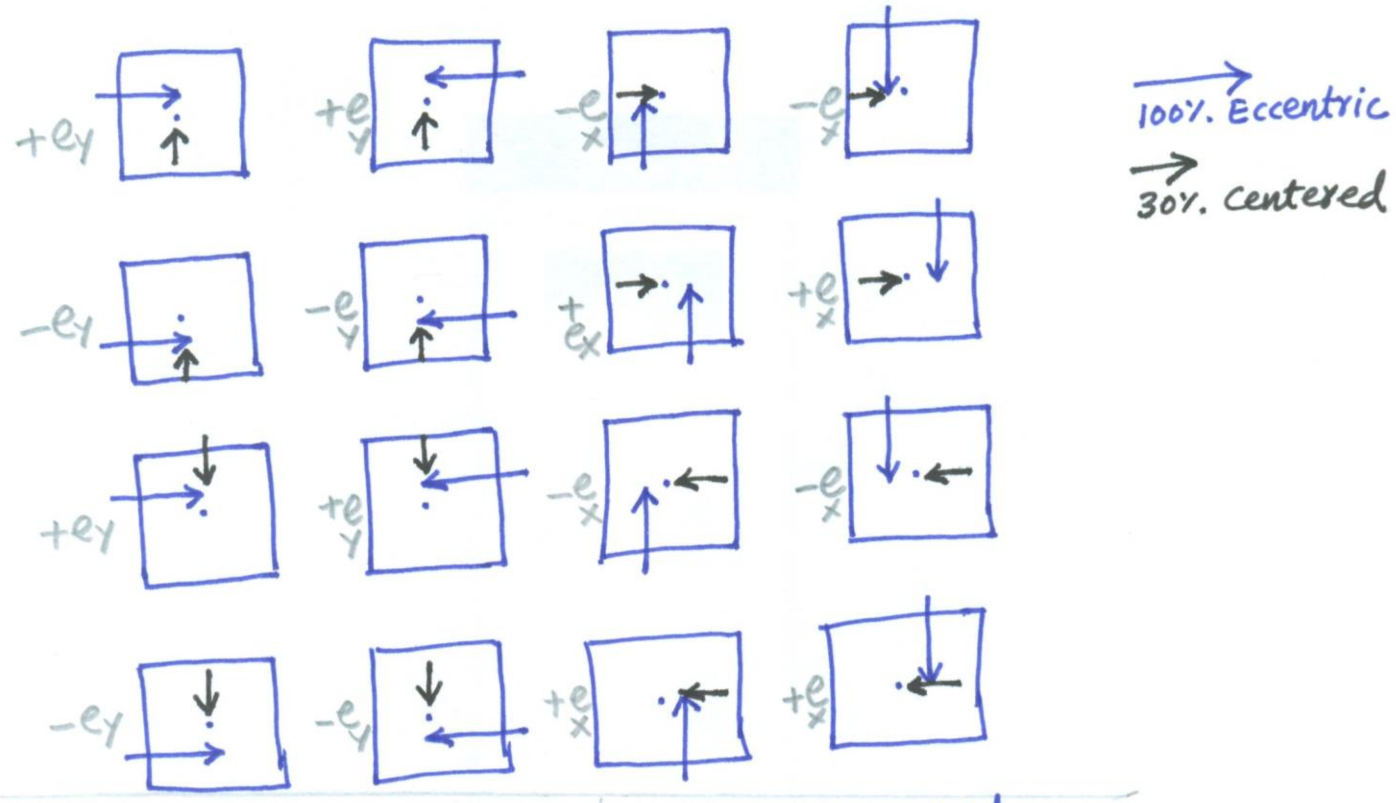
Step 11 : Basic Load Combinations used in ELF

16 combinations (including torsion) only for ELF.

Eccentricities		Signs of e_x, e_y		Direction of any force		Orthogonal Directions
e_x e_y	$\times$	$+$ $-$	$\times$	Push Pull	$\times$	X Y

$= 16$ possible cases for ELF.

Load Cases of ELF Procedure



Main direction	Rightward X	Leftward X	Upward Y	Downward Y
Orthogonal Forces	100% EQX+30% EQY		100% EQY+30% EQX	
Direction of Eccentricity	$\pm e_y$		$\pm e_x$	

Load Combinations for Design

Step 12: Load Combinations for Strength Design.

Ch 2 → ASCE 7-16

Basic Combinations

1) $1.4D$
2) $1.2D + 1.6L + 0.5[L_r \text{ or } S \text{ or } R]$
3) $1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$
4) $1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$
5) $0.9D + 1.0W$
6) $1.2D + E_v + E_h + L + 0.2S$
7) $0.9D - E_v + E_h$

In 6), $E = E_v + E_h$

E: Seismic Load effect

E_v: Vertical seismic effect applied in the downward direction. It shall be subject to reversal to the upward direction as in 7).

E_h: Effect of horizontal seismic forces

Load Combinations for Design

$E_h = \rho Q_E$ — Effect of horizontal seismic forces including orthogonal effects as applicable.

ρ — redundancy factor (section 12.3.4)

* ρ is assigned to the seismic force resisting system in each of two orthogonal directions of the structure.

Section 12.3.4.1 $\rightarrow$ Conditions where value of $\rho = 1$

Section 12.3.4.2 $\rightarrow$ ρ for SDC D through F

* ρ is applicable to ELF, Modal RSA and Modal RHA.

$$E_V = 0.2\, S_{DS}\, D$$

Exceptions:

1) When MCE_R vertical RS is constructed using Section 11.9 of ASCE 7-16,
   $E_V = 0.3\, S_{av}\, D$
   S_{av} — $\frac{2}{3}$ of MCE_R Vertical SA corresponding to vertical period.
2) $E_V = 0$ in both 6) and 7) for SDC B, or in 7) only if determining demands on soil-structure inteface of foundations.

Thank you for your attention