EARTHQUAKE ANALYSIS ACCORDING TO EC8

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Basic principles of conceptual design

In seismic regions the aspect of seismic hazard shall be taken into account in the early stages of the conceptual design of a building, thus enabling the achievement of a structural system which, within acceptable costs, satisfies the following fundamental requirements :

- No-collapse requirement.

The structure shall be designed and constructed to withstand the design seismic action without local or global collapse.

- Damage limitation requirement.

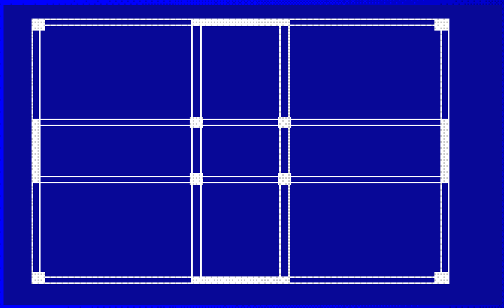
The structure shall be designed and constructed to withstand a seismic action having a larger probability of occurrence than the design seismic action, without the occurrence of damage and the associated limitations of use.

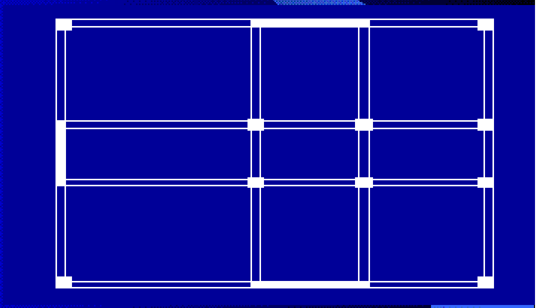
The fundamental requirements are deemed to be satisfied if the following principles govern the conceptual design:

- structural simplicity;
- uniformity, symmetry and redundancy;
- bi-directional resistance and stiffness;
- torsional resistance and stiffness;
- diaphragmatic behaviour at storey level;
- adequate foundation.

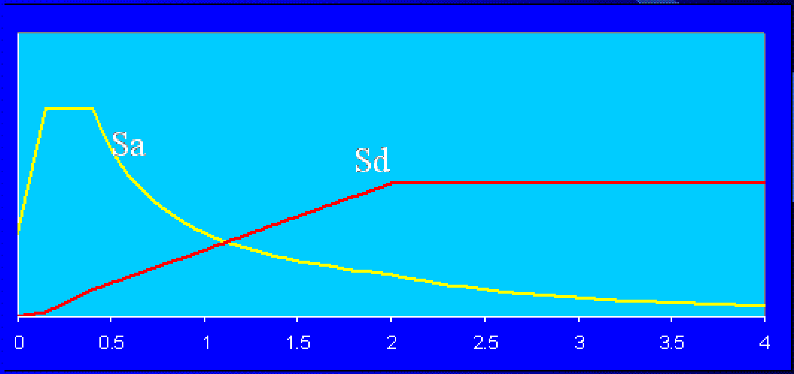
Bi-directional resistance and stiffness

Horizontal seismic motion is a bi-directional phenomenon and thus the building structure shall be able to resist horizontal actions in any direction. To satisfy **this**, the structural elements should be arranged in an orthogonal inplan structural pattern, ensuring similar resistance and stiffness characteristics in both main directions.



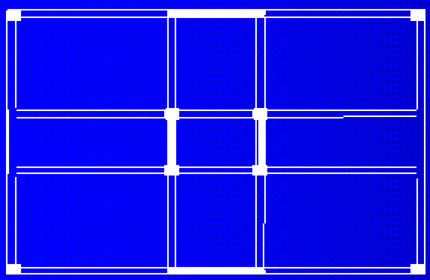


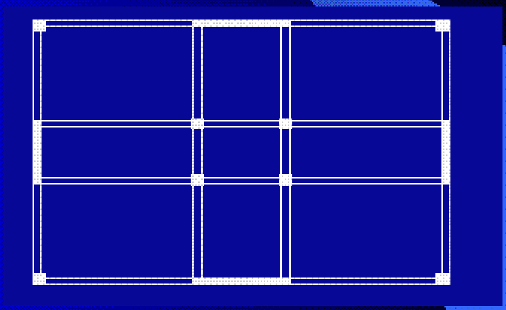
The choice of the stiffness characteristics of the structure, while attempting to minimise the effects of the seismic action should also limit the development of excessive displacements that might lead to either instabilities due to second order effects or excessive damages.



Torsional resistance and stiffness

Besides lateral resistance and stiffness, building structures should possess adequate torsional resistance and stiffness in order to limit the development of torsional motions which tend to stress the different structural elements in a non-uniform way . In this respect, arrangements in which the main elements resisting the seismic action are distributed close to the periphery of the building present clear advantages.





Criteria for structural regularity

For the purpose of seismic design, building structures are categorised into being regular or non-regular.

▪ the structural model, which can be either a simplified planar model or a spatial model ;

▪the method of analysis, which can be either a simplified response spectrum analysis (lateral force procedure) or a modal one;

▪The value of the behaviour factor *q*, which shall be decreased for buildings non-regular in elevation

Regularity		Allowed Simplification		Behaviour factor
Plan	Elevation	Model	Linear-elastic Analysis	(for linear analysis)
Yes	Yes	Planar	Lateral force[a]	Reference value
Yes	No	Planar	Modal	Decreased value
No	Yes	Spatial[b]	Lateral force[a]	Reference value
No	No	Spatial	Modal	Decreased value

Criteria for regularity in plan

For a building to be categorised as being regular in plan, it shall satisfy the following conditions :

➢The floor diaphragms behave as rigid in their own plane.

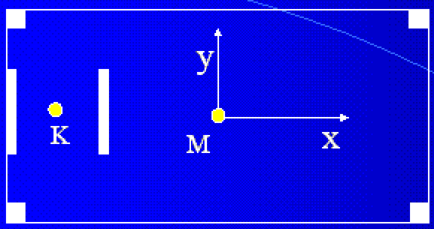
➢With respect to the lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.

➢The plan configuration shall be compact, i.e., each floor shall be delimited by a polygonal convex line

➢At each level and for each direction of analysis x and y, the structural eccentricity e_o and the **torsional radius r** shall be in accordance with the two conditions

$e_o \leq 0{,}30 \cdot r$ $\qquad$ $r \geq l_s$ (radius of gyration)

eo: eccentricity, $\qquad$ r =Kzz/Kyy



$$\begin{bmatrix} K_{xx} & 0 & 0 \\ 0 & K_{yy} & K_{yz} \\ 0 & K_{zy} & K_{zz} \end{bmatrix}$$

$r = K_{zz}/K_{yy}$

Single storey building

Multi-storey buildings: $K_i = \lambda K_o$ (1)

In general, this condition is not satisfied in dual systems.

In multi-storey buildings only approximate definitions of the centre of stiffness and of the torsional radius are possible.
The National Annex can include reference to documents that might provide definitions of the centre of stiffness and of the torsional radius in multi-storey buildings.

Criteria for regularity in elevation

For a building to be categorised as being regular in elevation, it shall satisfy the following conditions :

- All lateral load resisting systems, such as cores, structural walls, or frames, shall run without interruption from their foundations to the top of the building
- Both the lateral stiffness and the mass of the individual storeys shall remain constant or reduce gradually.

When setbacks are present, there are additional conditions that must be satisfied.

Accidental torsional effects

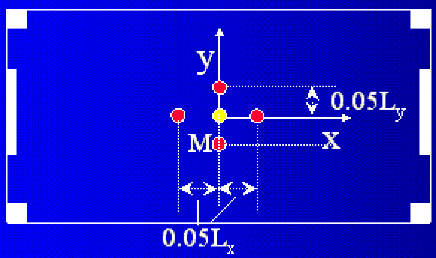
In order to account for uncertainties in the location of masses and in the spatial variation of the seismic motion, the calculated centre of mass at each floor *i* shall be considered as being displaced from its nominal location in each direction by an accidental eccentricity:

$e_{ai} = \pm 0,05 \cdot Li$ (1)

where

e_{ai} is the accidental eccentricity of storey mass *i* from its nominal location, applied in the same direction at all floors;

L_i is the floor-dimension perpendicular to the direction of the seismic action.



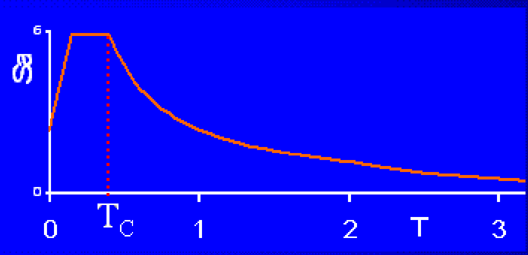
Methods of analysis

The seismic effects are determined on the basis of linear elastic behaviour of the structure. The reference method for determining the seismic effects shall be the modal response spectrum analysis using a linear elastic model and the design spectrum.

As an alternative to a linear method, a non-linear method may also be used. The choice of whether the nonlinear methods are applied to buildings in a particular country, will be defined in the National Annex of each country.

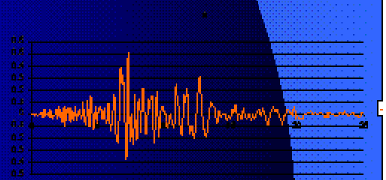
linear-methods

- lateral force method of analysis
- modal response spectrum analysis

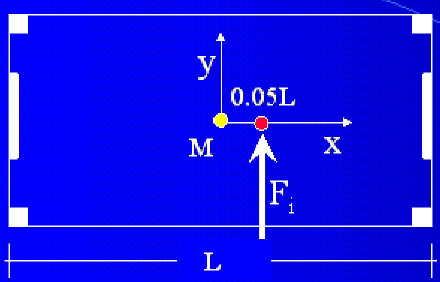


non-linear methods

- non-linear static (pushover) analysis
- non-linear time history (dynamic) analysis



lateral force method of analysis



Is applied to buildings whose response is not affected by higher modes.

a) Regular in elevation

b) $$T_1 \leq \begin{cases} 4Tc \\ 2.0s \end{cases}$$

Base shear

$F_b = \lambda . m . S_d(T_1)$, (1)

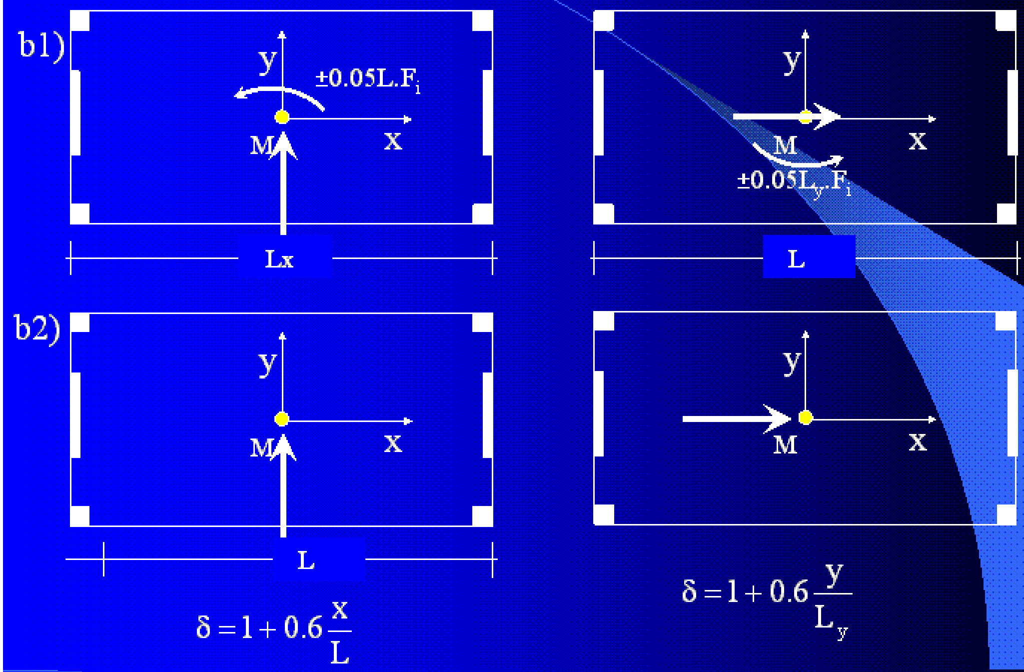
$$F_i = F_b \bullet \frac{z_i m_i}{\sum z_j m_j} \quad (2)$$

λ = 0,85 if $T_1 < 2\, T_C$ and the building has more than two storeys, or λ = 1,0 otherwise

Two planar models: one for each main direction

Torsional effects: $$\delta = 1 + 1.2 \frac{x}{L} \quad (3)$$

b) Spatial model



Combination of the effects of the seismic action components

1. SRSS: $E_{max} = (E_{Edx}^2 + E_{Edy}^2)^{1/2}$ (1)
2. Percentage rule

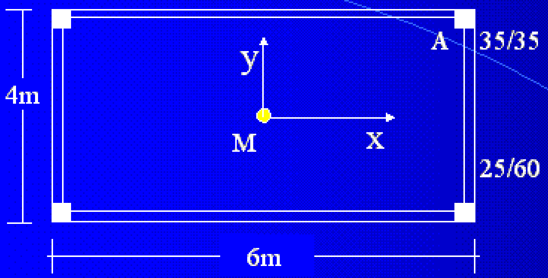
- E_{Edx} "+" $0.30E_{Edy}$
- $0.30E_{Edx}$ "+" E_{Edy} where

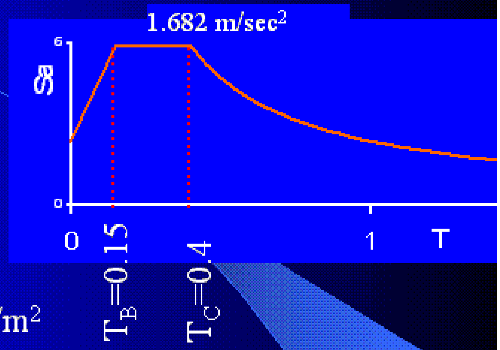
"+" implies "to be combined with";

E_{Edx} :represents the action effects due to seismic action along the horizontal axis x ;

E_{Edy} : represents the action effects due to seismic action along the orthogonal horizontal axis y

Application





$h_1=h_2=3.2$ m, $E=2.9*10^7$ kN/m^2

$m_1=m_2=24$ t(SI), $q=3.5$

Modelling

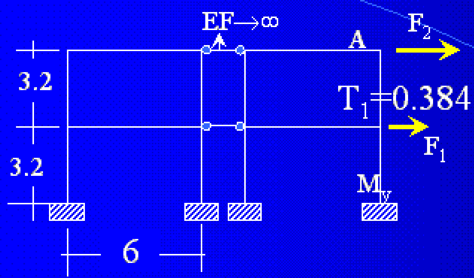
Floor diaphragms: rigid in their own planes

Masses: lumped at floor levels (centre of gravity)

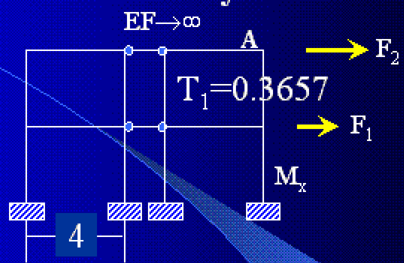
Stiffness: the effect of cracking is considered, hence flexural and shear stiffness equal to 0.5 of the uncracked stiffness.

a) Two planar models

Direction x



Direction y



<u>Base shear</u>

$F_b=\lambda.m.Sd(T1)=2*24*1.682$

$F_b=80.736$ kN

$F_1=26.912$, $F_2=53.824$ kN

$u_x=8.29*10^{-3}$ m

$M_y=36.58$ kNm

<u>Base shear</u>

$F_b=\lambda.m.Sd(T1)=2*24*1.682$

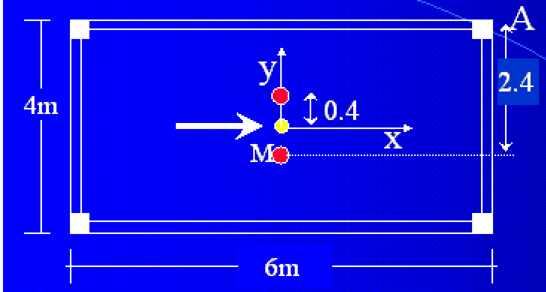
$F_b=80.736$ kN

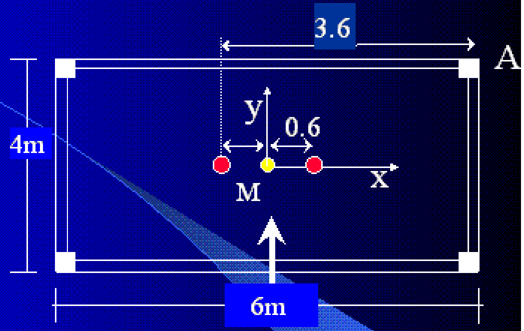
$F_1=26.912$, $F_2=53.824$ kN

$u_y=7.46*10^{-3}$ m

$M_x=35.43$ kNm

Torsional effects





$$\delta = 1 + 1.2 \bullet \frac{2.4}{4} = 1.72$$

$u_x^t = u_x . \delta = 8.29 * 10^{-3} * 1.72 = 14.26 * 10^{-3} m$

$M_y^t = 36.58 * 1.72 = 62.9$ kNm

$$\delta = 1 + 1.2 \bullet \frac{3.6}{6} = 1.72$$

$u_y^t = u_y . \delta = 7.46 * 10^{-3} * 1.72 =$
$= 12.83 * 10^{-3} m$

$M_x^t = 35.43 * 1.72 = 60.94$ kNm

Orthogonal effects (SRSS)

$$\max E = \sqrt{E,_x^2 + E,_y^2}$$

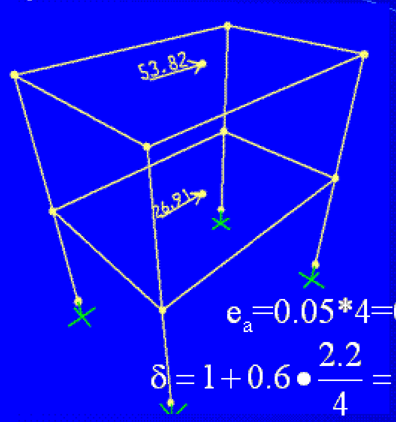
$$\max u_x = \sqrt{u_{x},_x^2 + u_{x},_y^2} = 10^{-3} \cdot \sqrt{14.26^2 + 0} = \pm 14.26 * 10^{-3} m$$

$$\max u_y = \sqrt{u_{y},_x^2 + u_{y},_y^2} = 10^{-3} \cdot \sqrt{0 + 12.83^2} = \pm 12.83 * 10^{-3} m$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{60.94^2 + 0} = \pm 60.94 kNm$$

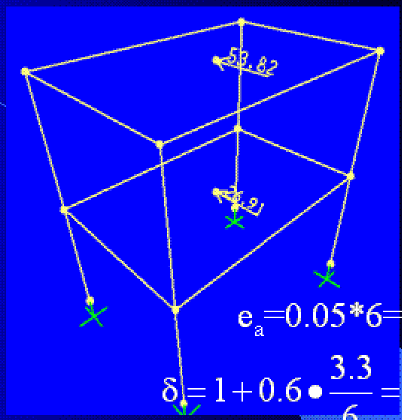
$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{0 + 62.9^2} = \pm 62.9 kNm$$

b_1) Spatial model



$e_a = 0.05*4 = 0.2$

$$\delta = 1 + 0.6 \bullet \frac{2.2}{4} = 1.33$$



$e_a = 0.05*6 = 0.3$

$$\delta = 1 + 0.6 \bullet \frac{3.3}{6} = 1.33$$

$u_x = 8.29*10^{-3}$ m
$M_y = 36.58$ kNm

$u_y = 7.46*10^{-3}$ m
$M_x = 35.43$ kNm

$u_x^t = 8.29*10^{-3}*1.33 = 11.02*10^{-3}$m

$M_y^t = 36.58*1.33 = 48.65$ kNm

$u_y^t = 7.46*10^{-3}*1.33 = 9.92*10^{-3}$m

$M_x^t = 35.43*1.33 = 47.12$ kNm

Orthogonal effects (SRSS)

$$\max E = \sqrt{E_{,x}^2 + E_{,y}^2}$$

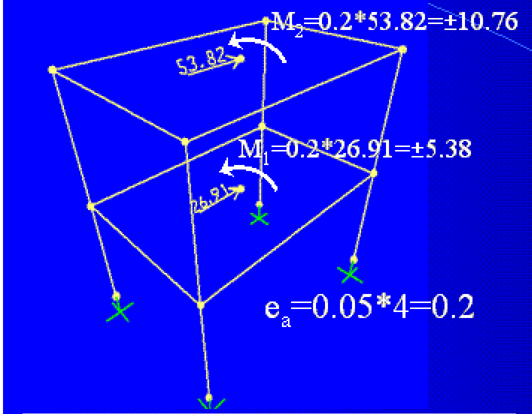
$$\max u_x = \sqrt{u_{x,x}^2 + u_{x,y}^2} = 10^{-3} \cdot \sqrt{11.02^2 + 0} = \pm 11.02*10^{-3}\text{m}$$

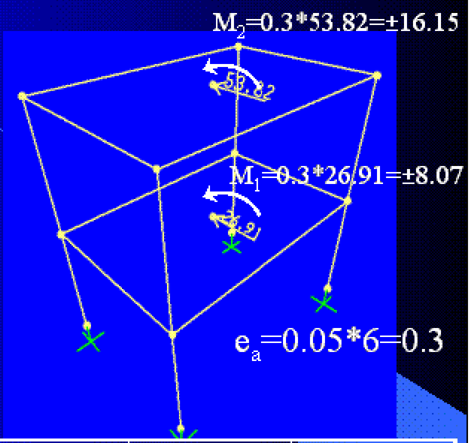
$$\max u_y = \sqrt{u_{y,x}^2 + u_{y,y}^2} = 10^{-3} \cdot \sqrt{0 + 9.92^2} = \pm 9.92*10^{-3}\text{m}$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{47.12^2 + 0} = \pm 47.12\text{kNm}$$

$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{0 + 48.65^2} = \pm 48.65\text{kNm}$$

b$_2$) Spatial model





	u_x	u_y
F_x+M	8.087e-3	**3.031e-4**
F_x-M	**8.419e-3**	-3.031e-4

	M_x	M_y
F_x+M	**1.48**	35.62
F_x-M	-1.48	**37.54**

	u_x	u_y
F_y+M	-3.032e-4	**7.92e-3**
F_y-M	**3.032e-4**	7.01e-3

	M_x	M_y
F_y+M	**37.64**	-1.44
F_y-M	33.21	**1.44**

Orthogonal effects (SRSS)

$$\max E = \sqrt{E_{,x}^2 + E_{,y}^2}$$

$$\max u_x = \sqrt{u_{x,x}^2 + u_{x,y}^2} = 10^{-3} \cdot \sqrt{8.419^2 + 0.3032^2} = \pm 8.42 * 10^{-3}\,\text{m}$$

$$\max u_y = \sqrt{u_{y,x}^2 + u_{y,y}^2} = 10^{-3} \cdot \sqrt{0.3031^2 + 7.919^2} = \pm 7.92 * 10^{-3}\,\text{m}$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{1.48^2 + 37.64^2} = \pm 37.67\,\text{kNm}$$

$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{37.54^2 + 1.44^2} = \pm 37.57\,\text{kNm}$$

Summarized results

Lateral force method

	u_x	u_y	M_x	M_y
Two planar	$14.26*10^{-3}$	$12.83*10^{-3}$	60.94	62.9
Spatial –δ	$11.02*10^{-3}$	$9.92*10^{-3}$	47.12	48.65
Spatial TM	$8.42*10^{-3}$	$7.92*10^{-3}$	37.67	37.57

Modal response spectrum analysis

This method applies to all buildings (regular and irregular)

Steps of the method

- **Determine the mass and stiffness matrices;**
- **Estimate the damping ratio;**
- **Determine the natural periods and modes of vibration;**

Excitation x

- **Compute the peak response due to each mode using the design spectrum;**
- **Determine an estimate for the peak value of any response quantity by combining the peak modal values (modal combination);**

Excitation y

- **Compute the peak response due to each mode using the design spectrum;**
- **Determine an estimate for the peak value of any response quantity by combining the peak modal values (modal combination);**

Simultaneous action of two orthogonal components

- **Combine the peak responses due to each component**

•How many modes to include?

✓the sum of the effective modal masses for the modes taken into account amounts to at least 90% of the total mass of the structure;

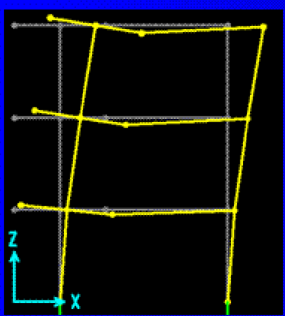
✓all modes with effective modal masses greater than 5% of the total mass are taken into account

$$M_i^* = \Gamma_i^2 \bullet M_i \quad (1) \qquad \Gamma_i = \frac{\phi_i^T \mathbf{M} \phi_i}{M_i} \quad (2) \qquad M_i = \phi_i^T \mathbf{M} \phi_i \quad (3)$$

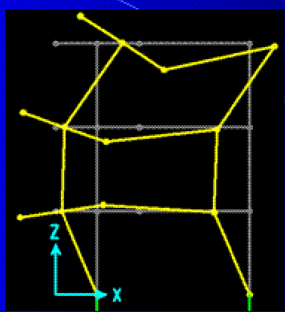
Effective modal mass — Modal contribution factor — Generalized mass

Combination of modal responses

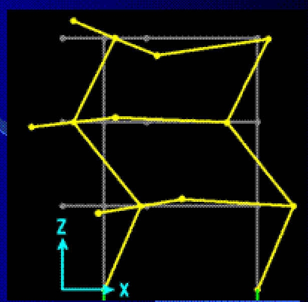
SRSS, CQC



R,1



R,2



R,3

SRSS: marxR= $\sqrt{\sum_n R_i^2}$ uncorrelated modes $T_j < 0.9T_i$ (1)

CQC: maxR= $\sqrt{R^T E R}$ R: the vector of modal responses

E: the correlation coefficient matrix

Torsional effects

By the same way as for the lateral force procedure

Combination of the effects of the components of the seismic action
(Directional combination or orthogonal effects)
Horizontal components of the seismic action

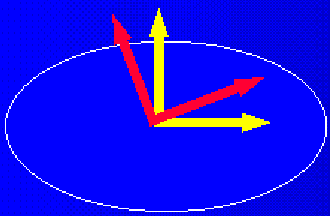
In general the horizontal components of the seismic action shall be taken as acting simultaneously.

The combination of the horizontal components of the seismic action may be accounted for as follows.

$maxE=(E,x^2+E,y^2)^{1/2}$ (SRSS)

$maxE=E,x+0.3E,y$ or $max\ E=0.3E,x+E,y$ (percentage rule)

Comments: (1) orientation of seismic action



The response does not depend on the orientation of seismic action if:

a) The spectra along the two axes are the same

b) The SRSS rule is used for the directional combination

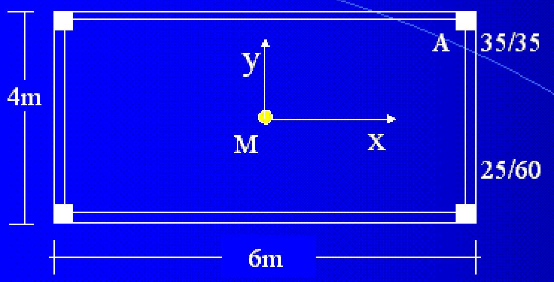
(2) The percentage rule has no theoretical basis and produces results that are not invariant with respect to the reference system

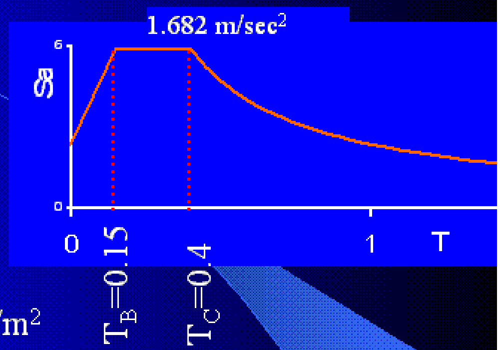
(3) The probable Maximum value of any response parameter is computed. These maxima do not have sign (+, -) and two maxima do not occur simultaneously.

(4) It is wrong to compute the maximum value of one response quantity from the maximum values of other response quantities, e.g the drift in one storey.

(5) The response spectrum method is an ***approximate method***

Application





$h_1=h_2=3.2$ m, $E=2.9*10^7$ kN/m²

$m_1=m_2=24$ t(SI), q=3.5

Modelling

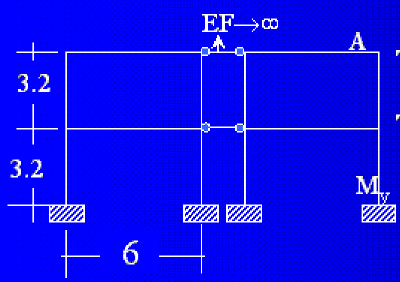
Floor diaphragms: rigid in their own planes

Masses: lumped at floor levels (centre of gravity)

Stiffness: the effect of cracking is considered, hence flexural and shear stiffness equal to 0.5 of the uncracked stiffness.

a) Two planar models

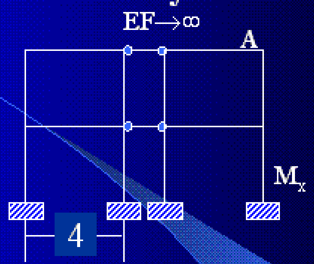
Direction x



$T_1=0.384$

$T_2=0.128$

Direction y



$T_1=0.366$

$T_2=0.126$

$u_x=\pm 7.51*10^{-3}$ m

$M_y=\pm 33.52$ kNm

Torsional effects

$$\delta = 1 + 1.2 \bullet \frac{2.4}{4} = 1.72$$

$u_x^t=u_x.\delta=7.51*10^{-3}*1.72=12.92*10^{-3}$m

$M_y^t=33.52*1.72=57.65$ kNm

$u_y=\pm 6.785*10^{-3}$ m

$M_x=\pm 32.7$ kNm

$$\delta = 1 + 1.2 \bullet \frac{3.6}{6} = 1.72$$

$u_y^t=6.78*10^{-3}*1.72=11.67*10^{-3}$m

$M_x^t=32.7*1.72=56.24$ kNm

Orthogonal effects (SRSS)

$$\max E = \sqrt{E_{,x}^2 + E_{,y}^2}$$

$$\max u_x = \sqrt{u_{x,x}^2 + u_{x,y}^2} = 10^{-3} \cdot \sqrt{12.92^2 + 0} = \pm 12.92 * 10^{-3}\,\mathrm{m}$$

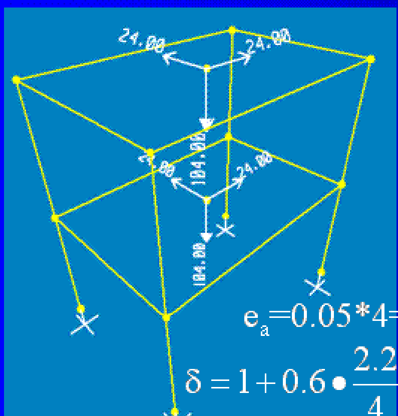
$$\max u_y = \sqrt{u_{y,x}^2 + u_{y,y}^2} = 10^{-3} \cdot \sqrt{0 + 11.67^2} = \pm 11.67 * 10^{-3}\,\mathrm{m}$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{56.24^2 + 0} = \pm 56.24\,\mathrm{kNm}$$

$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{0 + 57.65^2} = \pm 57.65\,\mathrm{kNm}$$

b_1) Spatial model

Excitation x



$e_a = 0.05*4 = 0.2$

$$\delta = 1 + 0.6 \bullet \frac{2.2}{4} = 1.33$$

$u_x = 7.51*10^{-3}$ m

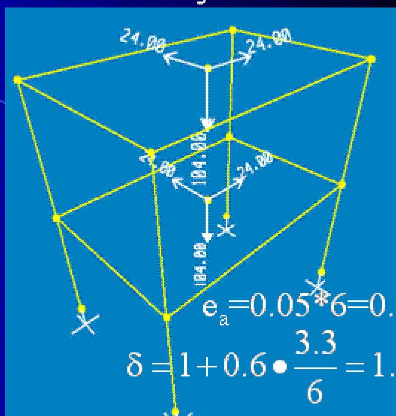
$M_y = 33.52$ kNm

Torsional effects

$u_x^t = u_x . \delta = 7.51*10^{-3}*1.33 = 9.99*10^{-3}$m

$M_y^t = 33.52*1.33 = 44.58$ kNm

excitation y



$e_a = 0.05*6 = 0.3$

$$\delta = 1 + 0.6 \bullet \frac{3.3}{6} = 1.33$$

$u_y = 6.785*10^{-3}$ m

$M_x = 32.7$ kNm

$u_y^t = 6.78*10^{-3}*1.33 = 9.02*10^{-3}$m

$M_x^t = 32.7*1.33 = 43.49$ kNm

Orthogonal effects (SRSS)

$$\max E = \sqrt{E,_x^2 + E,_y^2}$$

$$\max u_x = \sqrt{u_{x,x}^{\,2} + u_{x,y}^{\,2}} = 10^{-3} \cdot \sqrt{9.99^2 + 0} = \pm 9.99 * 10^{-3}\,\mathrm{m}$$

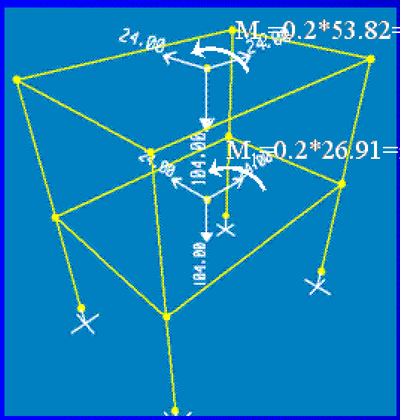
$$\max u_y = \sqrt{u_{y,x}^{\,2} + u_{y,y}^{\,2}} = 10^{-3} \cdot \sqrt{0 + 9.02^2} = \pm 9.02 * 10^{-3}\,\mathrm{m}$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{44.58^2 + 0} = \pm 44.58\,\mathrm{kNm}$$

$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{0 + 43.49^2} = \pm 43.49\,\mathrm{kNm}$$

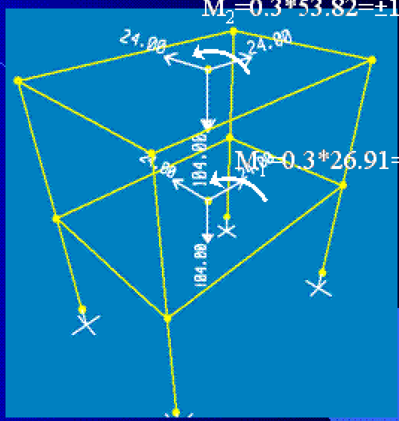
b_1) Spatial model

Excitation x



u_x	$\pm 7.712 * 10^{-3}$m
u_y	$\pm 3.031 * 10^{-4}$m
M_x	± 1.48
M_y	± 34.48

excitation y



u_x	$\pm 3.032 * 10^{-4}$m
u_y	$\pm 7.24 * 10^{-3}$m
M_x	± 34.91
M_y	± 1.44

Orthogonal effects (SRSS)

$$\max E = \sqrt{E_{,x}^{2} + E_{,y}^{2}}$$

$$\max u_x = \sqrt{u_{x,x}^{2} + u_{x,y}^{2}} = 10^{-3} \cdot \sqrt{7.712^2 + 0.3031^2} = \pm 7.718 * 10^{-3} m$$

$$\max u_y = \sqrt{u_{y,x}^{2} + u_{y,y}^{2}} = 10^{-3} \cdot \sqrt{0.3031^2 + 7.24^2} = \pm 7.246 * 10^{-3} m$$

$$\max M_x = \sqrt{M_{x,x}^2 + M_{x,y}^2} = \sqrt{1.48^2 + 34.91^2} = \pm 34.94 kNm$$

$$\max M_y = \sqrt{M_{y,x}^2 + M_{y,y}^2} = \sqrt{34.48^2 + 1.44^2} = \pm 34.51 kNm$$

Non-linear static (pushover) analysis

Pushover analysis is a non-linear static analysis carried out under conditions of constant gravity loads and monotonically increasing horizontal loads.

a) to verify or revise the overstrength ratio values $\alpha u/\alpha 1$;

b) to estimate the expected plastic mechanisms and the distribution of damage;

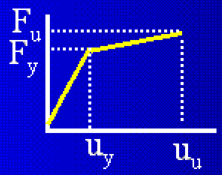
c) to assess the structural performance of existing or retrofitted buildings

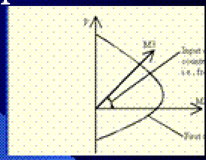
α_1 : is the value by which the horizontal seismic design action is multiplied in order to first reach the flexural resistance in any member in the structure, while all other design actions remain constant;

a_u:is the value by which the horizontal seismic design action is multiplied, in order to form plastic hinges in a number of sections sufficient for the development of overall structural instability, while all other design actions remain constant.

Modeling

The mathematical model used for elastic analysis shall be extended to include the strength of structural elements and their post-elastic behavior. As a minimum, a bilinear force–deformation relationship should be used at the element level.





Gravity loads shall be applied to appropriate elements of the mathematical model.

The seismic action shall be applied in both positive and negative directions and the maximum seismic effects as a result of this shall be used

Non regular buildings shall be analysed using a spatial model. Two independent analyses with lateral loads applied in one direction only may be performed.

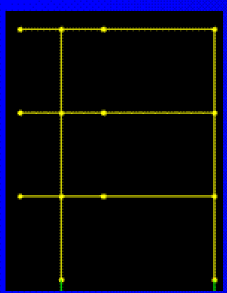
For regular buildings the analysis may be performed using two planar models, one for each main horizontal direction.

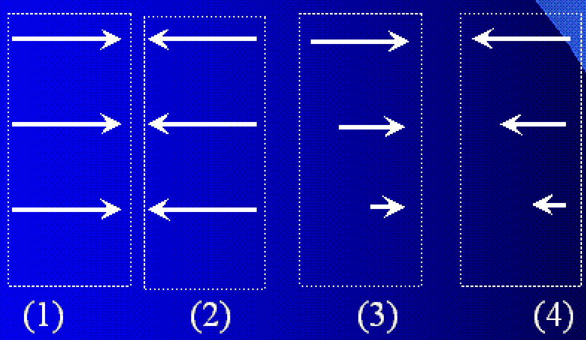
Lateral loads

(1) At least two vertical distributions of the lateral loads should be applied:

• a "uniform" pattern, based on lateral forces that are proportional to mass regardless of elevation (uniform response acceleration);

• a "modal" pattern, proportional to lateral forces consistent with the lateral force distribution in the direction under consideration determined in elastic analysis.



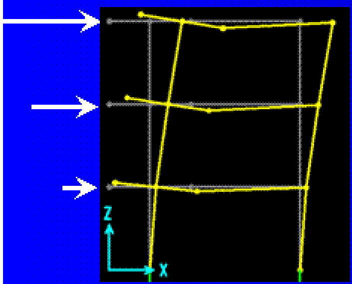


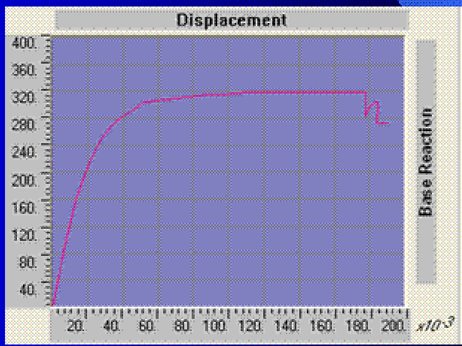
Four analyses for each direction ⟶ eight analyses totally

Capacity curve

The relation between base shear force and the control displacement (the "capacity curve") should be determined by pushover analysis for values of the control displacement ranging between zero and the value corresponding to 150% of the target displacement (which is computed on the basis of an Equivalent SDOF system)

The control displacement may be taken at the centre of mass of the roof of the building. The top of a penthouse should not be considered as the roof.

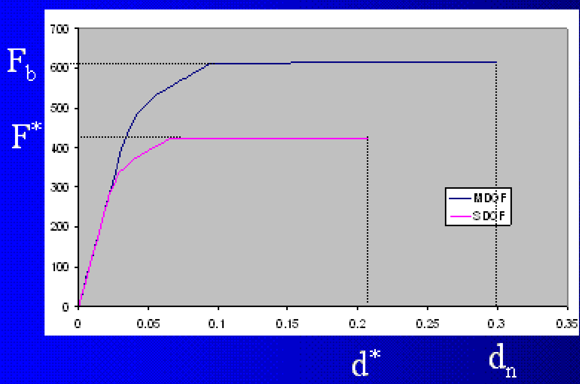




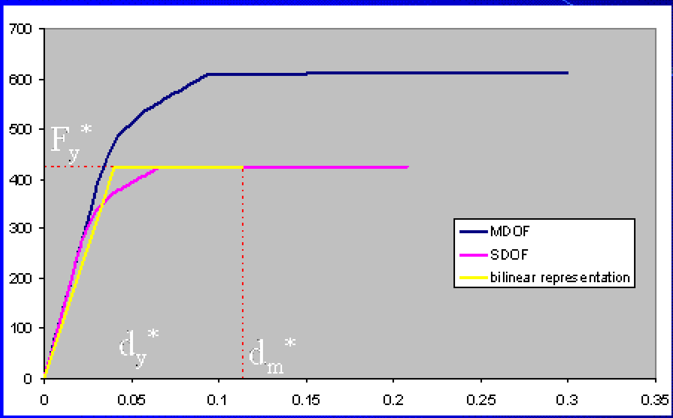
Transformation to an equivalent Single Degree of Freedom (SDOF) system

$$\Gamma = \frac{m^*}{\Sigma m_i \times \phi_i} \quad (2), \quad m^* = \Sigma\, m_i \times \phi_i \quad (3)$$

$$F^* = \frac{F_b}{\Gamma}, \quad d^* = \frac{d_n}{\Gamma} \quad (1)$$



Determination of the idealized elasto-perfectly plastic force – displacement relationship



$$d_y^* = 2\left(d_m - \frac{E_m^*}{F_y^*}\right)$$

E_m^* :is the actual deformation energy up to the formation of the plastic mechanism.

Determination of the period of the idealized equivalent SDOF system

$$T^* = 2\pi\sqrt{\frac{m^* d_y^*}{F_y^*}} \qquad (1)$$

Determination of the target displacement for the equivalent SDOF

$$d_{et}^* = S_e(T^*)\left[\frac{T^*}{2\pi}\right]^2 \qquad (2)$$

Determination of the target displacement d_t^*

a) $T^* < T_C$ (short period range)

If $F_y^* / m^* \geq S_e(T^*)$ $\longrightarrow d_t^* = d_{et}^*$

If $F_y^* / m^* < S_e(T^*)$ $\longrightarrow$ $d_t^* = \frac{d_{et}^*}{q_u}\left(1 + (q_u - 1)\frac{T_C}{T^*}\right) \geq d_{et}^*$ (3)

$$q_u = \frac{S_e(T^*) m^*}{F_y^*} \qquad (4)$$

b) $T^* \geq T_C$ (medium and long period range)

$d_t^* = d_{et}^*$

d_t^* need not exceed $3\, d_{et}^*$

Determination of the target displacement for the MDOF system

$d_t = \Gamma d_t^*$ (1)

The target displacement corresponds to the control node

Torsional effects

- For torsionally flexible structures, displacements at the stiff/strong side shall be increased, compared to those in the corresponding torsionally balanced structure.
- The amplification factor applied to the displacements of the stiff/strong side is based on the results of an elastic modal analysis of the spatial model.
- If two planar models are used for analysis the torsional effects are computed using the amplification factor δ

$$\delta = 1 + 1.2\frac{x}{L}$$

ORTHOGONAL EFFECTS

- When using non-linear static (pushover) analysis and applying a spatial model, the directional combination rules [SRSS and percentage (0.30)] are applied. The internal forces resulting from the combination should not exceed the corresponding capacities.
- For buildings satisfying the regularity criteria in plan and in which walls or independent bracing systems in the two main horizontal directions are the only primary seismic elements, the seismic action may be assumed to act separately and without combinations along the two main orthogonal horizontal axes of the structure.

Comments

The static pushover analysis has no rigorous theoretical foundation. It is based on the assumption that the **response** of the structure can be related to the response of an equivalent single degree-of-freedom (SDOF) system. This implies that the response is controlled by a single mode, and that the shape of this mode remains constant throughout the time history response. Clearly, both assumptions are incorrect.
In the pushover analysis it is assumed that the target displacement for the MDOF structure can be estimated as the displacement demand for the corresponding equivalent SDOF.
The simple conclusion is that much work needs to be done to make the static pushover analysis a general tool applicable to all structures.

There are important issues that need to be investigated.
Some of them are:

- Incorporation of torsional effects (due to mass, stiffness and strength irregularities).
- 3-D problems (orthogonality effects, direction of loading, semi-rigid diaphragms, etc.).
- The consideration of higher mode effects.

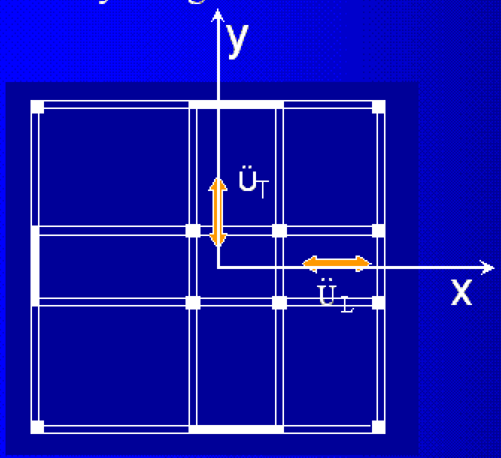
The pushover analysis is a useful, but not infallible, tool for assessing inelastic strength and deformation demands and for exposing design weaknesses.

In some cases it may provide a false feeling of security if its shortcomings and pitfalls are not recognized.

Pushover analysis procedure cannot be expected to provide satisfactory estimates of seismic demands for buildings deforming far into the inelastic range with significant degradation of the lateral capacity.

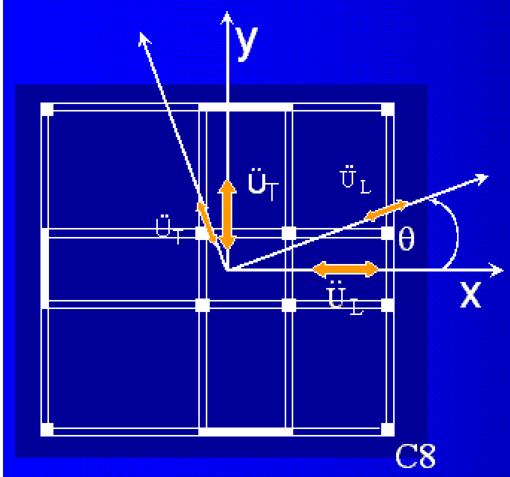
Non-linear time-history analysis

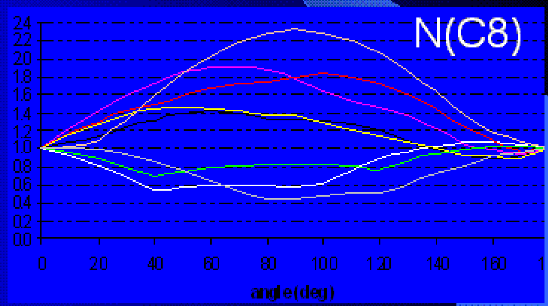
When a spatial model of the structure is used for analysis purposes, simultaneously acting accelerograms shall be taken as acting in both horizontal directions. The same accelerogram may not be used simultaneously along both horizontal directions.



The horizontal axes along which the accelerograms must be applied are not defined.

It has been proved that the seismic incident angle affects significantly the response.





The description of the seismic motion may be made by using artificial or recorded accelerograms.

The suite of artificial accelerograms should observe the following rules:

a) a minimum of 3 accelerograms should be used;

b) the mean of the zero period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the value of $ag.S$ for the site in question.

c) in the range of periods between 0,2$T1$ and 2$T1$, where $T1$ is the fundamental period of the structure in the direction where the accelerogram will be applied; no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be less than 90% of the corresponding value of the 5% damping elastic response spectrum.

The recorded accelerograms must be scaled using the above rules?

For buildings satisfying the regularity criteria in plan and in which walls or independent bracing systems in the two main horizontal directions are the only primary seismic elements the seismic action may be assumed to act separately and without directional combinations.

If the response is obtained from at least 7 nonlinear time-history analyses the average of the response quantities from all of these analyses should be used as the design value of the seismic action effect. Otherwise, the most unfavourable value of the response quantity among the analyses should be used.

Non linear Static Analysis	Non linear Dynamic Analysis
Detailed models needed	Detailed models needed
Stiffness and strength represented	Stiffness and strength represented
No mass representation required	Mass representation required
No damping representation required	Damping required
No additional operators required	Time integration operators required
No input motion required	Input motion required
Target displacement required	Target displacement is an output
Action distribution fixed	Actions vary in time
Faster than dynamic analysis	Slower than static analysis

Comments

Non-linear time-history analysis is the most rigorous procedure to compute the seismic response of the structures . It remains impractical for widespread use by the profession for the following reasons:

- large computational demands;
- the results are very sensitive to the time step of the ground motion;
- results for one excitation do not provide systematic trends;
- damping is a very serious parameter that affects significantly the results; (50% or more)

END