Base isolation

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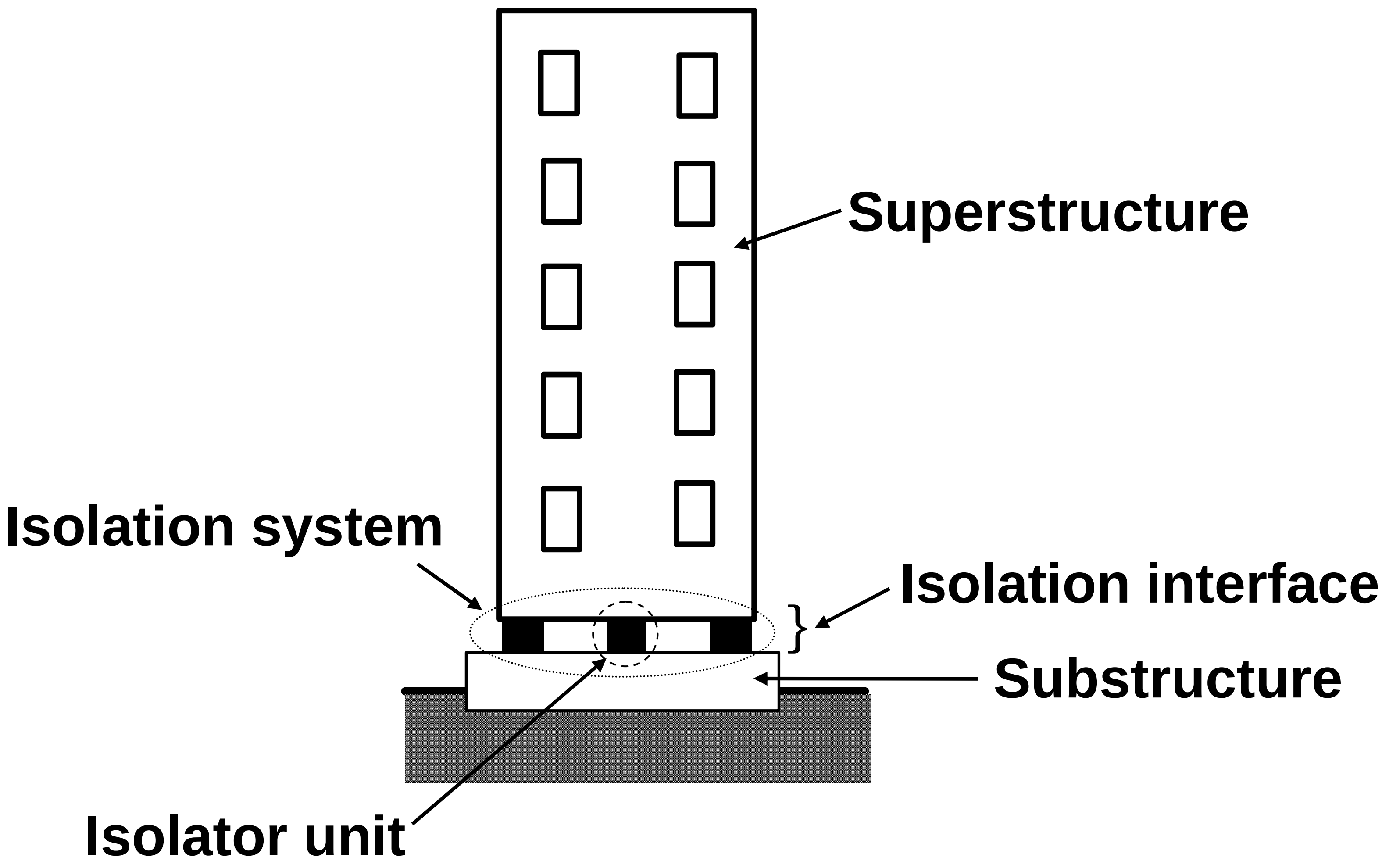
BASE ISOLATION: MAIN PRINCIPLES

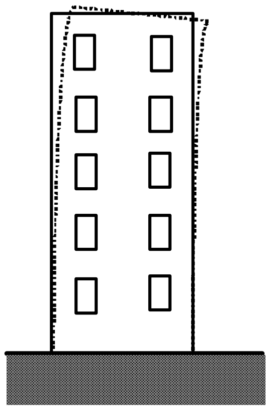
Main types of isolation systems used up to now are based on flexibility with respect to the horizontal forces acting on the structure, so as:

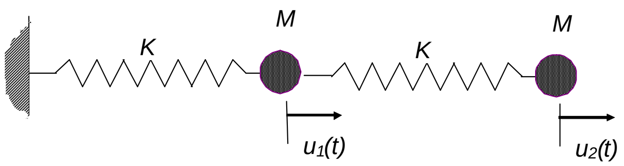
- **to increase the period of the fundamental mode to obtain a reduced spectral acceleration response,**
- **to force the fundamental modal shape to a pure translation, as much as possible,**
- **to make the higher modes response insignificant by concentrating the mass of the structure into the fundamental mode, thereby drastically decreasing the input energy.**

BASE ISOLATION: SOME DEFINITIONS



A BASIC EXAMPLE



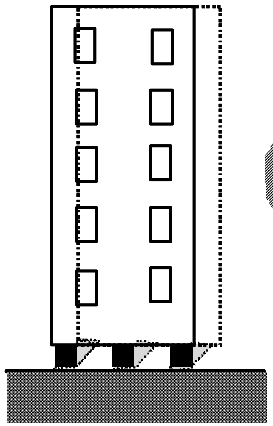


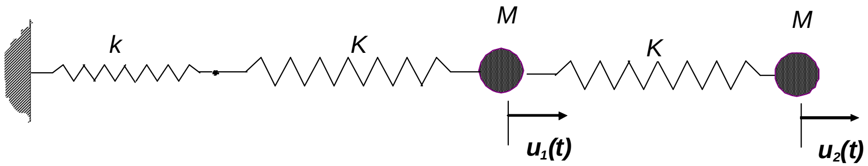
Modes:

$$X_1 = \begin{bmatrix} 1 \\ \frac{1+\sqrt{5}}{2} \approx 1,618 \end{bmatrix}; \quad X_2 = \begin{bmatrix} 1 \\ \frac{1-\sqrt{5}}{2} \approx -0,618 \end{bmatrix}$$

$$\omega_1^2 = \frac{K}{2M}\left(3-\sqrt{5}\right) \qquad \omega_2^2 = \frac{K}{2M}\left(3+\sqrt{5}\right)$$

The same, with base isolation





$$\frac{kK}{k+K} = \lambda k = (1-\lambda)K$$

$$2\alpha = 1 - \lambda << 1$$

Modes

$$X_1' = \left[\frac{1}{\alpha + \sqrt{1+\alpha^2}} \approx 1+\alpha\right] \qquad X_2' = \left[\frac{1}{\alpha - \sqrt{1+\alpha^2}} \approx -1+\alpha\right]$$

$$\omega_1'^2 = \frac{1}{2M}\left(2K + \lambda k - \sqrt{4K^2 + \lambda^2 k^2}\right) \qquad \omega_2'^2 = \frac{1}{2M}\left(2K + \lambda k + \sqrt{4K^2 + \lambda^2 k^2}\right)$$

$$\approx \alpha\left(1 - \frac{\alpha}{2}\right)\frac{K}{M} \qquad \approx \left[2 + \alpha\left(1 + \frac{\alpha}{2}\right)\right]\frac{K}{M}$$

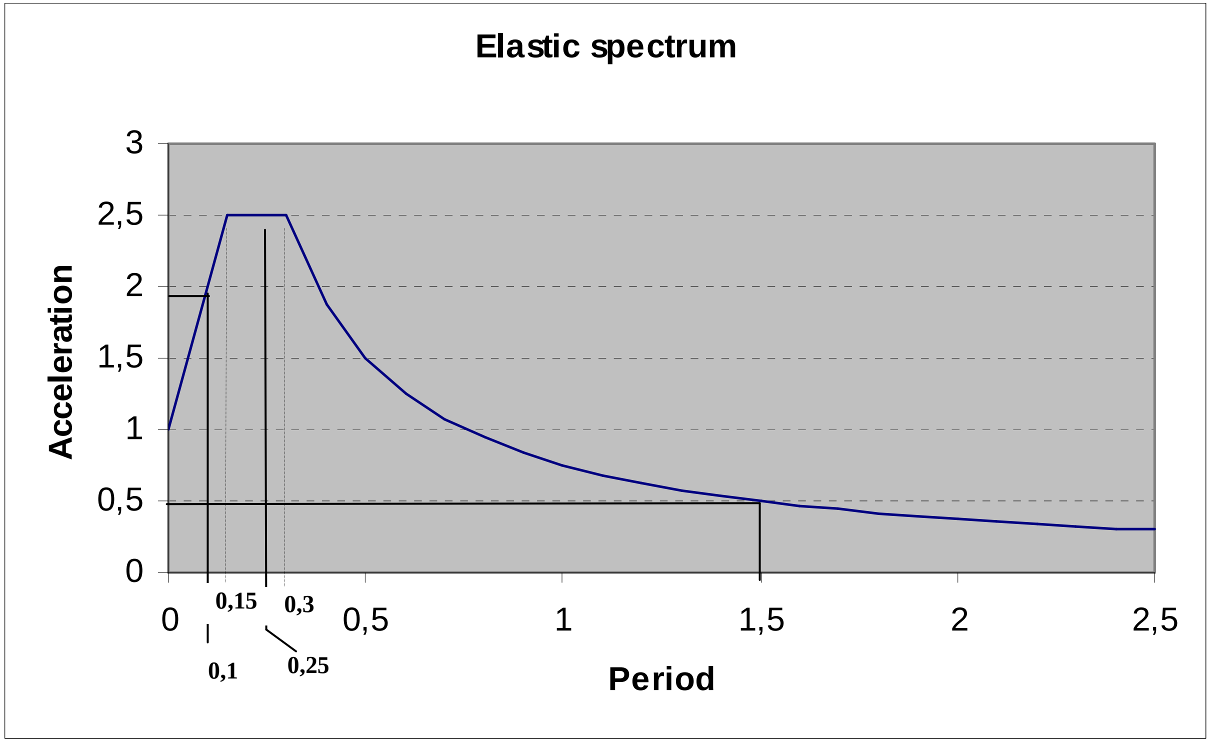
BASE ISOLATION: MAIN PRINCIPLES

Numerical application

K = 1 650 MN
M = 1 000 T
k = 35 MN

$\Rightarrow$

λ = 0,979
α = 0,01



Numerical application

Modal characteristics	Non isolated building		Isolated building	
	First mode	Second mode	First mode	Second mode
Period s	0,25	0,096	1,522	0,109
Mode	$X_1 = \begin{bmatrix} 1 \\ 1{,}618 \end{bmatrix}$	$X_2 = \begin{bmatrix} 1 \\ -0{,}618 \end{bmatrix}$	$X'_1 = \begin{bmatrix} 1 \\ X'^{2}_1 = 1{,}01 \end{bmatrix}$	$X'_2 = \begin{bmatrix} 1 \\ X'^{2}_2 = -0{,}99 \end{bmatrix}$
Spectral acceleration m/s^2	2,5	1,96	1,5	2,09
Percentage of mass %	$\rho_1 = 94{,}7$	$\rho_2 = 5{,}3$	$\rho'_1 \approx 100$	$\rho'_2 \approx 0$
Equivalent static forces kN	$\begin{pmatrix} 1\,810 \\ 2\,929 \end{pmatrix}$	$\begin{pmatrix} 541 \\ -334 \end{pmatrix}$	$\begin{pmatrix} 500 \\ 500 \end{pmatrix}$	$\approx \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
Displacement mm	$\begin{pmatrix} 2{,}87 \\ 4{,}64 \end{pmatrix}$	$\begin{pmatrix} 0{,}13 \\ -0{,}08 \end{pmatrix}$	$\begin{pmatrix} 29{,}2 \\ 29{,}2 \end{pmatrix}$	$\approx \begin{pmatrix} 0 \\ 0 \end{pmatrix}$
Force in first spring (base) kN	4 744		1 000	
Force in second spring (top) kN	2 948		500	

MAIN OBSERVATIONS

- The fundamental period is increased from 0,25 s to 1,52 s.
- The spectral acceleration of mode 1 is decreased from 2,5 m/s^2 to 0,5 m/s^2.
- The effects of the second mode (accelerations and displacements) are negligible.
- In a plane, the behaviour of the building is that of a quasi-rigid body in translation above the isolation system.
- In return of the decrease of response in terms of accelerations and forces, the displacements are widely increased.

GENERALISATION: Effectiveness of base isolation in the elastic domain

Two characteristic periods are defined:

- **The period T_a of the superstructure considered as rigid and lying on the isolating system:**

$$T_a = 2\pi\sqrt{\frac{2M}{k}}$$

- **A period T_f representative of the building without isolation, usually that of the first mode with a fixed base.**

In the above example, it can be taken as $2\pi\sqrt{M/K}$.

Parameter representative of the effectiveness of the isolation: $\beta = T_a / T_f$

$$\Rightarrow \frac{1}{\lambda} = \frac{2}{\beta^2} + 1; \ \alpha = \frac{1}{2+\beta^2}$$

BASE ISOLATION: MAIN PRINCIPLES

$$\left(\frac{T_a}{T_1'}\right)^2 = \frac{\beta^2}{2+\beta^2}\left(3+\beta^2-\sqrt{5+4\beta^2+\beta^4}\right)\xrightarrow[\beta\to\infty]{}1$$

$$\left(\frac{T_f}{T_2'}\right)^2 = \frac{1}{2+\beta^2}\left(3+\beta^2+\sqrt{5+4\beta^2+\beta^4}\right)\xrightarrow[\beta\to\infty]{}2$$

$$X_1'^{\,2} = \frac{1}{2+\beta^2}\left(1+\sqrt{5+4\beta^2+\beta^4}\right)\xrightarrow[\beta\to\infty]{}1$$

$$X_2'^{\,2} = \frac{1}{2+\beta^2}\left(1-\sqrt{5+4\beta^2+\beta^4}\right)\xrightarrow[\beta\to\infty]{}-1$$

$$\rho_1'\xrightarrow[\beta\to\infty]{}1\ ;\quad \rho_2'\xrightarrow[\beta\to\infty]{}0$$

Variation of response characteristics vs. β

β	$\frac{T_a}{T_1'}$	$\frac{T_f}{T_2'}$	$X_1'^2$	ρ_1'	$2\pi\frac{\delta_r}{S_v T_a}$
1	0,528	1,545	1,387	0,816	0,733
1,5	0,684	1,504	1,263	0,872	0,384
2	0,782	1,477	1,180	0,911	0,231
2,5	0,844	1,459	1,129	0,936	0,152
3	0,884	1,447	1,095	0,953	0,108
4	0,930	1,434	1,057	0,971	0,061
5	0,953	1,427	1,038	0,981	0,040
7	0,975	1,421	1,020	0,990	0,020
10	0,988	1,418	1,010	0,995	0,010
∞	1	1,414	1	1	0

CONCLUSIONS

when β is significantly greater than 1:

- **the period of the first mode is slightly greater than T_a;**
- **the first mode concentrates all the mass of the superstructure;**
- **the displacement is determined by the deformation of the isolation system;**
- **the superstructure remains quasi-rigid.**

MAIN PRINCIPLES OF DESIGN

- **the stiffness of the isolating system is chosen so that T_a is large (1 or 2s);**
- **the design favour a reduced acceleration response (add damping if necessary);**
- **usually, the first period is in the range of periods where the pseudo-velocity S_v is constant;**
- **displacement:**

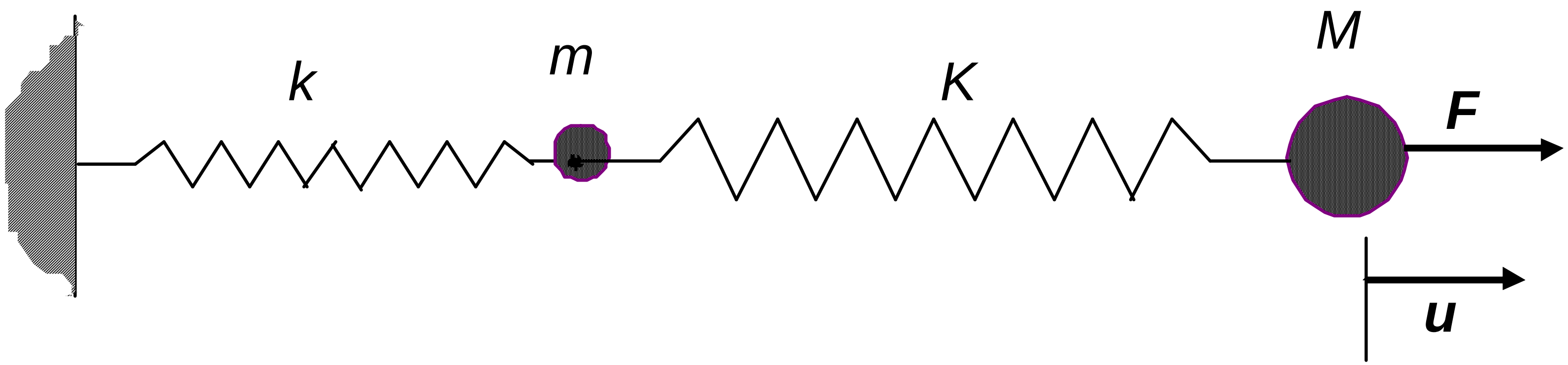
$$u_{\max} \approx \frac{1}{2\pi} S_v T_a$$

- **relative displacement between masses (first mode):**

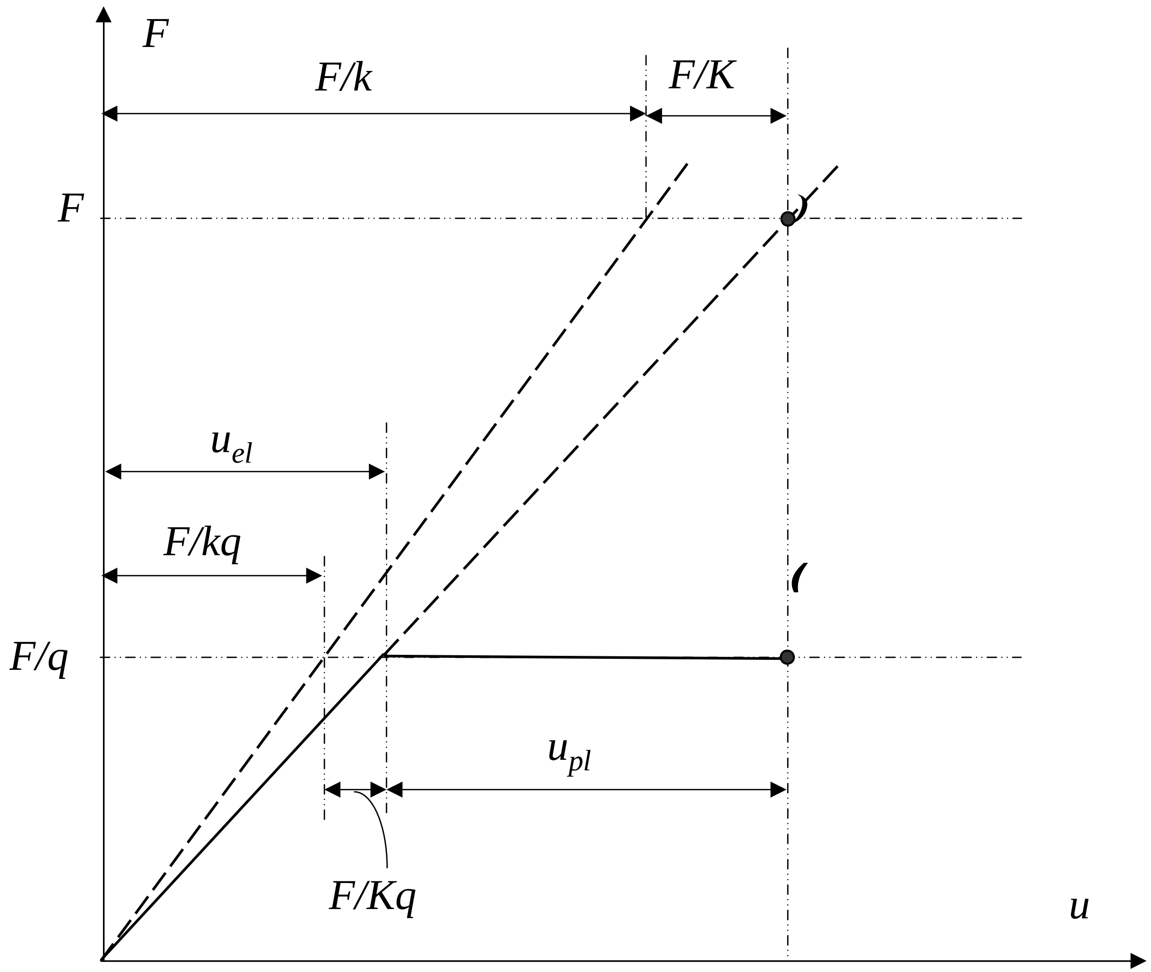
$$\delta_r \approx \frac{1}{2\pi} S_v T_1' \left(X_1'^2 - 1 \right)$$

BEHAVIOUR IN THE POST ELASTIC DOMAIN

Simple two masses model for post elastic assessment



Comparison of linear and non linear behaviours



Equality of displacements

$$\frac{F}{k}+\frac{F}{K}=\frac{F}{kq}+\frac{F}{Kq}+u_{pl}$$

⇒ Ductility demand in the superstructure

$$\mu=\frac{u_{pl}}{\frac{F}{Kq}}=\frac{\frac{F}{k}+\frac{F}{K}-\left(\frac{F}{kq}+\frac{F}{Kq}\right)}{\frac{F}{Kq}}=(q-1)\left[1+\left(\frac{T_a}{T_f}\right)^2\right]=(q-1)\left[1+\beta^2\right]$$

CONCLUSIONS

β	q	μ
3	3	20
5	3	52
10	3	202

- **the ductility demand is very high;**
- **a behaviour factor similar to that of the structure when it is not isolated can not be applied;**
- **a very limited behaviour factor is accepted in Eurocode 8 to account for margins.**

Main principles

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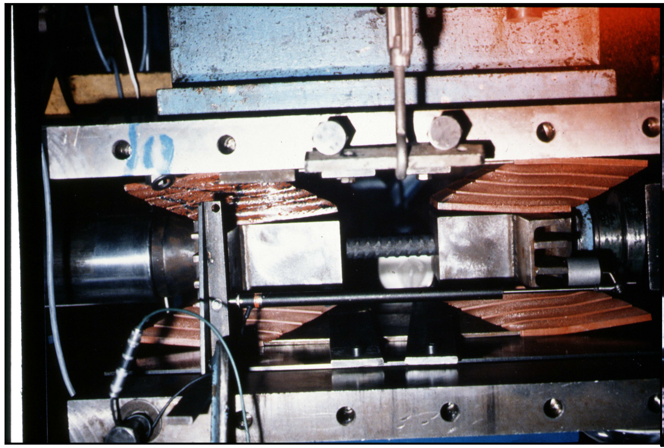
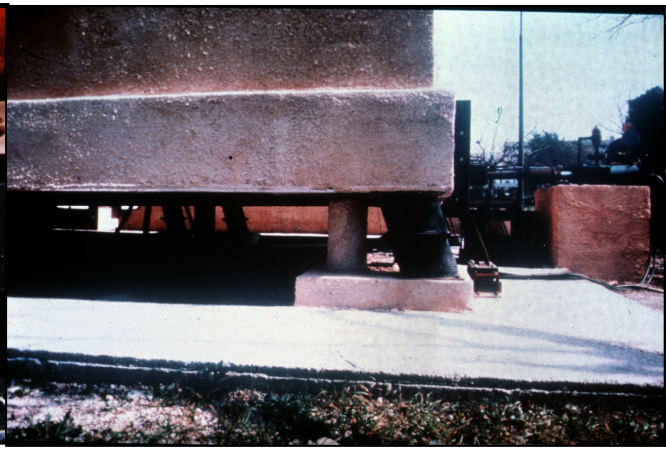
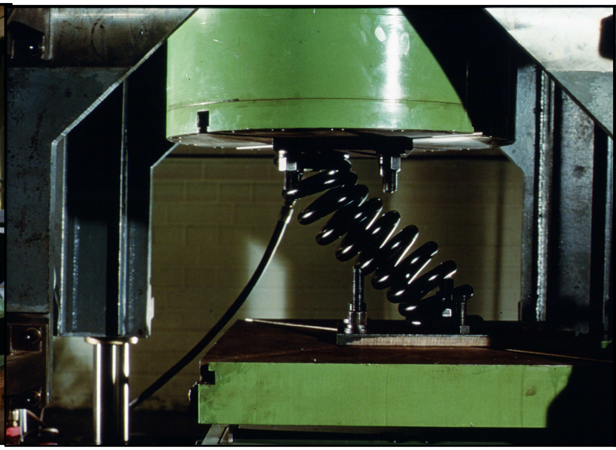
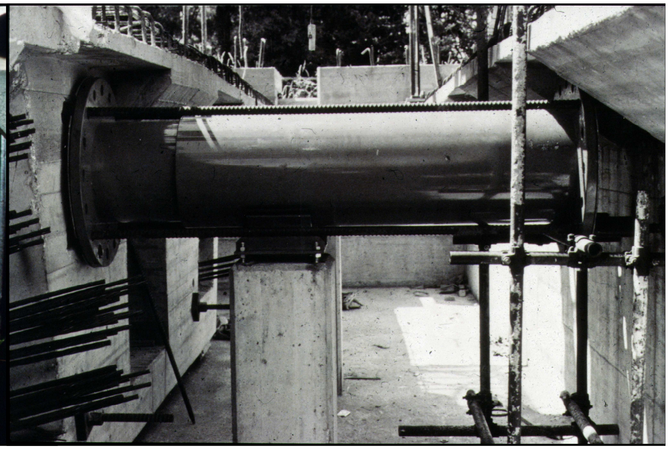
Types of isolation systems considered:

- laminated elastomeric bearings,
- elastic-plastic devices,
- viscous or friction dampers,
- pendulums,
- other devices the behaviour of which fulfils the objectives,
- other types of devices are covered in part 2.

THE ISOLATING DEVICES AND THEIR DESIGN

Reliability

- **increased reliability is required for the isolating devices, as the behaviour of the superstructure as a whole relies on the isolation system.**
- **a magnification factor γ_x on seismic displacements for the design of each unit.**
- **for buildings, the recommended value of γ_x is 1,2.**

Design of devices

- **Eurocode 8 deals with the design of the complete isolated building;**
- **the design of the devices (and their connection to the structure) is covered by the European norm EN 15129, which specifies:**
  - o functional requirements and general design rules for the seismic situation,
  - o material characteristics,
  - o manufacturing and testing requirements,
  - o evaluation of conformity,
  - o installation and maintenance requirements.

THE ISOLATING DEVICES AND THEIR DESIGN

Characteristics needed for seismic isolation:

- **ability to support gravity load of superstructure,**
- **ability to accommodate lateral displacements,**
- **ability to provide energy dissipation; this may be achieved in adding dampers,**
- **ability to contribute to the isolation system's recentering capability.**

THE ISOLATING DEVICES AND THEIR DESIGN

- **Devices should function according to the design requirements and tolerances throughout their projected service life, given the mechanical, physical, chemical, biological and environmental conditions expected.**

- **Devices should be constructed and installed in such a way that their routine inspection and replacement are possible during the service life of the construction.**

THE ISOLATING DEVICES AND THEIR DESIGN

Isolators and their connections to the structure are designed to the limit states defined in Eurocode 8:

- ✓ **to withstand the seismic action effects defined at ULS without local or global failure,**

- ✓ **to withstand the seismic action defined at Limit State of Limitation of Damage without the occurrence of damage and the associated limitations of use.**

THE ISOLATING DEVICES AND THEIR DESIGN

- **Capacity design is applied to the connections: an over-strength factor γ_{Rd} equal to 1,1 is applied to the actions transmitted by the device to the connections.**

- **Materials used in the design and construction of the devices and their connections to the structure must conform to European Standards.**

Material properties and device properties:

- ✓ **are assessed so as to represent their behaviour adequately under the conditions of strain and strain rate which can be attained during the design seismic situation;**
- ✓ **take into account the environmental (physical, biological, chemical and nuclear) conditions with which devices can be faced over their service life; in particular, the effects of temperature variation are taken into account;**
- ✓ **take into account the ageing phenomena that can occur during the service life of the device ;**
- ✓ **are represented by representative values.**

THE ISOLATING DEVICES AND THEIR DESIGN

Three sets of representative properties of the system of devices are defined:

- ✓ **Design (mean) properties (DP).**
- ✓ **Upper bound design properties (UBDP); they correspond to the maximum representative value in the conditions where upper values of properties are obtained.**
- ✓ **Lower bound design properties (LBDP); they correspond to the minimum representative value in the conditions where lower values of properties are obtained.**

Properties are obtained by considering the quasi permanent values of the variable actions, except for temperature for which the frequent value is taken into account.

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GENERAL ARRANGEMENT

Control of displacements relative to surrounding ground and constructions

- **Sufficient space between the superstructure and the surrounding ground and structures should be provided to allow free displacements of the superstructure.**

- **This space has also the function of allowing inspection, maintenance and replacement of the devices during the lifetime of the structure, as a possible inadmissible ageing of the devices may happen.**

Control of undesirable torsional movements

- **The effective stiffness centre and the centre of damping of the isolation system should be as close as possible to the projection of the centre of mass on the isolation interface.**

- **To minimise different behaviour of isolating devices, the compressive stress induced in them by the permanent actions should be as uniform as possible.**

- **Devices are fixed to the superstructure and the substructure (the case of sliding plates is excluded from this requirement).**

- **The isolation system is designed so that shocks and potential torsional movements are controlled by appropriate measures. To reach that aim, appropriate devices (e.g. dampers, shock-absorbers, etc.) may be provided.**

Control of differential seismic ground motions

- **Structural elements located above and below the isolation interface should be sufficiently rigid in both horizontal and vertical directions.**

- **A rigid diaphragm is provided above and under the isolating system, consisting of a reinforced concrete slab or a grid of tie-beams, designed taking into account all relevant local and global modes of buckling.**

- **The devices constituting the isolation system are fixed at both ends to the rigid diaphragms defined above**

GENERAL ARRANGEMENT

DESIGN CRITERIA

- **The fundamental requirements stated in other sections of Eurocode 8 part 1 for the type of structure considered should be complied with.**

- **The substructure is verified under the inertia forces directly applied to it and the forces and moments transmitted to it by the isolation system, the superstructure and the isolation system being in the linear elastic domain (**$q = 1$**)**

DESIGN CRITERIA

- **At ULS**
  - gas lines and other hazardous lifelines crossing the joints separating the superstructure from the surrounding ground or constructions are designed to accommodate safely the relative displacement between the isolated superstructure and the surrounding ground or constructions;
  - the structural elements of the substructure and the superstructure may be designed as non-dissipative;
  - it is acceptable to satisfy the resistance condition of the structural elements of the superstructure taking into account seismic action effects divided by a behaviour factor not greater than 1,5.
- **At DLS, all lifelines crossing the joints around the isolated structure should remain within the elastic range.**

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MODELLING OF THE ISOLATION SYSTEM

- **It should reflect the spatial distribution of the isolator units.**

- **It should represent adequately:**
  - **the translation in horizontal directions,**
  - **the overturning effects,**
  - **the rotation about the vertical axis.**

- **It should reflect adequately the properties of the different types of devices used.**

ANALYSIS

➢ **Values of physical and mechanical properties of the isolation system should be the most unfavourable ones to be attained during the lifetime of the structure**

- **accelerations and inertia forces are evaluated taking into account the maximum value of the stiffness and the minimum value of the damping and friction coefficients;**
- **displacements are evaluated taking into account the minimum value of stiffness and damping and friction coefficients.**

➢ **They shall reflect the influence of:**

- **rate of loading;**
- **magnitude of the simultaneous vertical load;**
- **magnitude of simultaneous horizontal load in the transverse direction;**
- **temperature;**
- **change of properties over projected service life.**

ANALYSIS

SEISMIC ACTION

- **3 components considered;**
- **elastic spectrum;**
- **site-specific spectra including near source effects considered for importance IV buildings when distance less than 15 km from the nearest potentially active fault with a magnitude $M_s \geq 6{,}5$.**

EQUIVALENT LINEAR ANALYSIS

- **Equivalent linear model = effective stiffness K_{eff} and effective damping ξ_{eff}.**
- **Conditions:**

- $K_{eff}(d_{db}) \geq 0{,}5\, K_{eff}(0{,}2 d_{dc})$;
- $\xi_{eff} \leq$ **30%; recommended at 15%;**
- **the force-displacement characteristics of the isolation system does not vary by more than 10% due to the rate of loading or due to the vertical loads;**
- **the increase of the restoring force in the isolation system for displacements between 0,5d_{dc} and d_{dc} is at least 2,5% of the total gravity load above the isolation system.**

TYPES OF ANALYSIS

- time-history analysis;
- full modal analysis;
- simplified modal analysis;
- simplified analysis.

CONDITIONS FOR SIMPLIFIED MODAL ANALYSIS

- **the superstructure and the substructure including foundations are rigid;**
- **the vertical stiffness of the isolation system is high compared to the horizontal one;**
- **regular distribution of the bracing system;**
- **condition** $\beta \geq 3$.

$\Rightarrow$ **three degrees of freedom: two horizontal translations and the torsional movement about the vertical axis (no rotation/horizontal).**

ANALYSIS

Detail of CONDITIONS

- **the distance from the site to the nearest potentially active fault with a magnitude $M_s \geq 6{,}5$ is greater than 15 km;**
- **the largest dimension of the superstructure in plan is not greater than 50 m;**
- **the substructure is sufficiently rigid to minimise the effects of differential displacements of the ground;**
- **all devices are located above elements of the substructure which support the vertical loads;**
- **the effective period** $T_{eff} = 2\pi\sqrt{\frac{M}{K_{eff}}}$ **satisfies the following condition:**

$$3T_{\mathrm{f}} \leq T_{\mathrm{eff}} \leq 3\ s$$

T_f **period of the first mode at fixed base;**

Detail of CONDITIONS

- **the lateral-load resisting system of the superstructure is regularly and symmetrically arranged along the two main axes of the structure in plan;**
- **the rocking rotation at the base of the substructure is negligible;**
- **the ratio between the vertical and the horizontal stiffness of the isolation system satisfies:**

$$\frac{K_{\mathrm{v}}}{K_{\mathrm{eff}}} \geq 150$$

- **the fundamental period in the vertical direction** $T_{\mathrm{V}} = 2\pi\sqrt{\frac{M}{K_{\mathrm{V}}}}$ **is not longer than 0,1 s.**

SIMPLIFIED ANALYSIS

- **A further simplification of the previous one, which applies to buildings where the natural eccentricity is limited: total eccentricity ≤ 0,075 L.**

- **Analysis in two planes, with amplification of the displacement applied to the devices:**

$$\delta_{xi} = 1 + \frac{e_{tot,y}}{r_y^2} y_i$$

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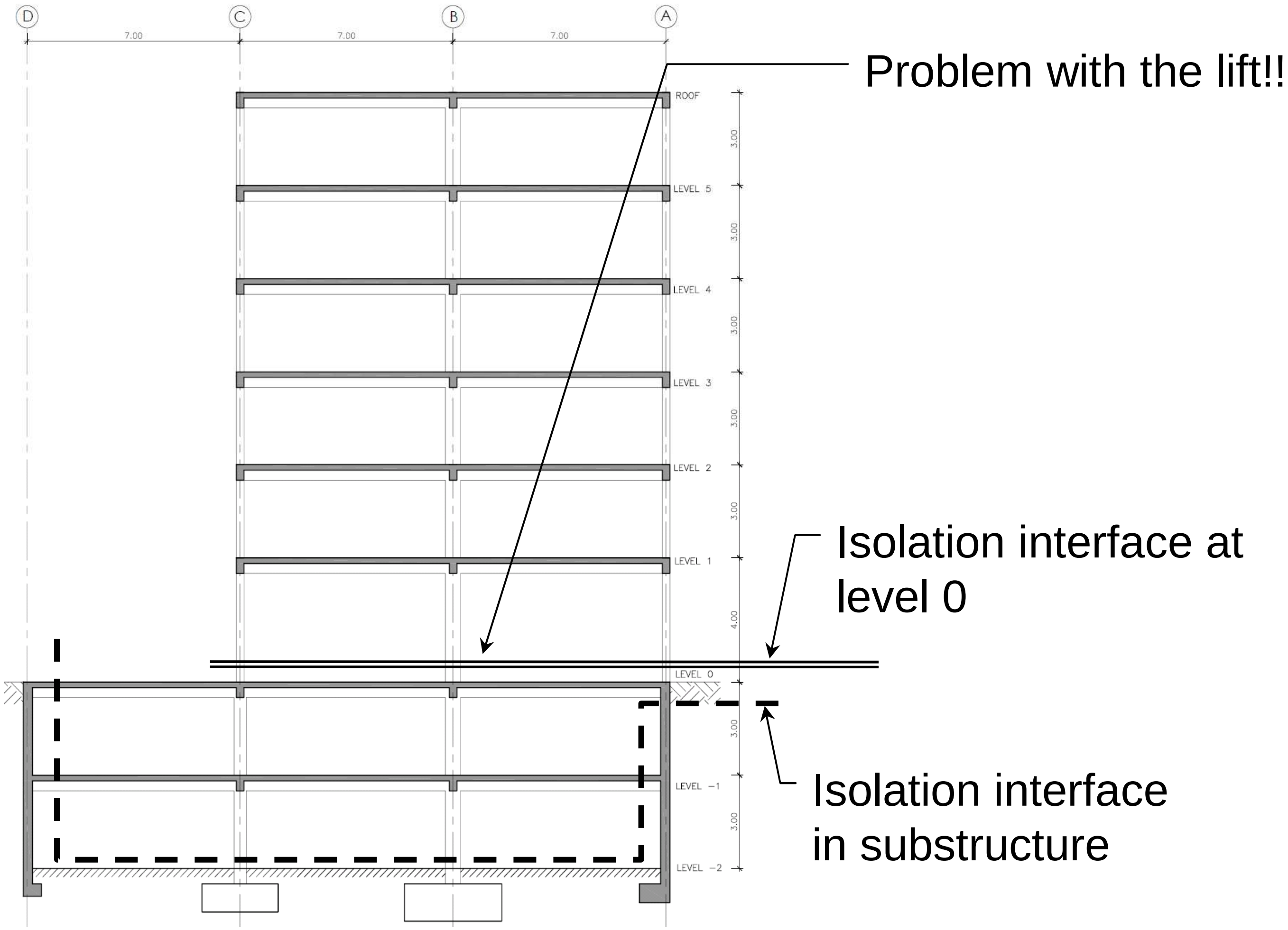
EXAMPLE


D
C
B
A
7.00
7.00
7.00
ROOF
LEVEL 5
LEVEL 4
LEVEL 3
LEVEL 2
LEVEL 1
LEVEL 0
LEVEL −1
LEVEL −2
3.00
4.00
Problem with the lift!!
Isolation interface at level 0
Isolation interface in substructure

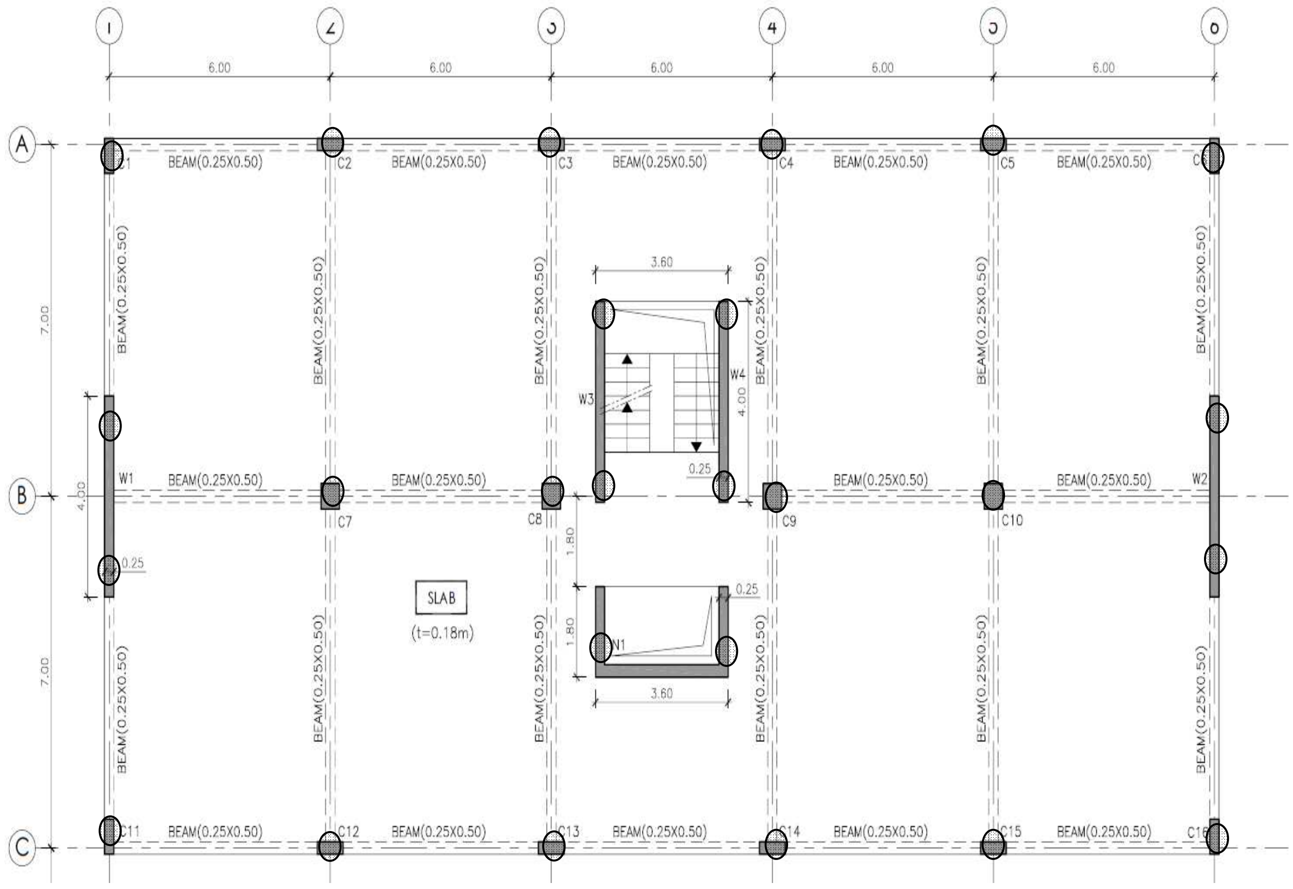
Base isolation at level 0

- T_f = 0,92 s and 0,68 s
- $\beta \geq 3 \quad \Rightarrow \quad T_a = 3$ s
- M = 2 362 T
- $K_{eff} = 2\ 362 \times (2\pi/3{,}0)2 = 10\ 361\ kN/m$
- ultimate strength $\approx 10\ MPa \Rightarrow$
  $A = 2{,}362 \times 9{,}81 \times 1{,}4 / 10 = 3{,}25$ m^2
- thickness of elastomer:
  $e = GA/K_{eff} = 1 \times 3{,}25 / 10{,}361 = 0{,}314$ m

EXAMPLE

40 layers of 8 mm = 32 cm

26 square pads 35 cm × 35 cm (Risk of buckling!!**)**



EXAMPLE

➢ Seismic response

$$T_D \leq T \leq 4s: \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\left[\frac{T_C T_D}{T^2}\right]$$

$$= 2{,}5 \times 1{,}2 \times \sqrt{\frac{10}{12}} \times 2{,}5\left[\frac{0{,}5 \times 2{,}0}{3{,}0^2}\right] = 0{,}761\, m/s^2$$

To be compared to the accelerations when fixed base (q = 1): 4,08 m/s^2 and 5,51 m/s^2.

- o Displacement: 0,761 / (2π/3,0)^2 = 0,174 m;
- o Distorsion: 17,4 / 32 = 0,55 to be multiplied by δ and γ_x ;
- o Shear force: 2 362 T × 0,761 m/s^2 = 1800 kN (id.).

Thank you for attention