INTERNATIONAL CONFERENCE ON SEISMIC DESIGN AND REHABILITATION OF BUILDINGS
Tbilisi – 29 & 30 May 2014

The EUROCODE 8

Applications to Buildings and Bridges

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Structural Eurocodes

EN1990 Eurocode 0: Basis of structural design
EN1991 Eurocode 1: Actions on structures
EN1992 Eurocode 2: Design of concrete structures
EN1993 Eurocode 3: Design of steel structures
EN1994 Eurocode 4: Design of composite steel and concrete structures
EN1995 Eurocode 5: Design of timber structures
EN1996 Eurocode 6: Design of masonry structures
EN1997 Eurocode 7: Geotechnical design
EN1998 Eurocode 8: Design of structures for earthquake resistance
EN1999 Eurocode 9: Design of aluminium structures

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Eurocode 8
Design of structures for earthquake resistance

EN1998-1: General rules, seismic actions and rules for buildings
EN1998-2: Bridges
EN1998-3: Assessment and retrofitting of buildings
EN1998-4: Silos, tanks and pipelines
EN1998-5: Foundations, retaining structures and geotechnical aspects
EN1998-6: Towers, masts and chimneys

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EN1998-1: General rules, seismic actions and rules for buildings

- General
- Performance requirements and compliance criteria
- Ground conditions and seismic action
- Design of buildings
- Specific rules for:
  - Concrete buildings
  - Steel buildings
  - Composite Steel-Concrete buildings
  - Timber buildings
  - Masonry buildings
- Base isolation

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-1

December 2004

ICS 91.120.25

Supersedes ENV 1998-1-1:1994, ENV 1998-1-2:1994, ENV 1998-1-3:1995

English version

Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

Eurocode 8: Calcul des structures pour leur résistance aux séismes - Partie 1: Règles générales, actions sismiques et règles pour les bâtiments

Eurocode 8: Auslegung von Bauwerken gegen Erdbeben - Teil 1: Grundlagen, Erdbebeneinwirkungen und Regeln für Hochbauten

This European Standard was approved by CEN on 23 April 2004.

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This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN member into its own language and notified to the Central Secretariat has the same status as the official versions.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
COMITÉ EUROPÉEN DE NORMALISATION
EUROPÄISCHES KOMITEE FÜR NORMUNG

Management Centre: rue de Stassart, 36 B-1050 Brussels

Ref. No. EN 1998-1:2004: E

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EUROCODE 8
Main objectives of seismic design

In the event of earthquakes:

- Human lives are protected

L'Áquila Earthquake - 2009

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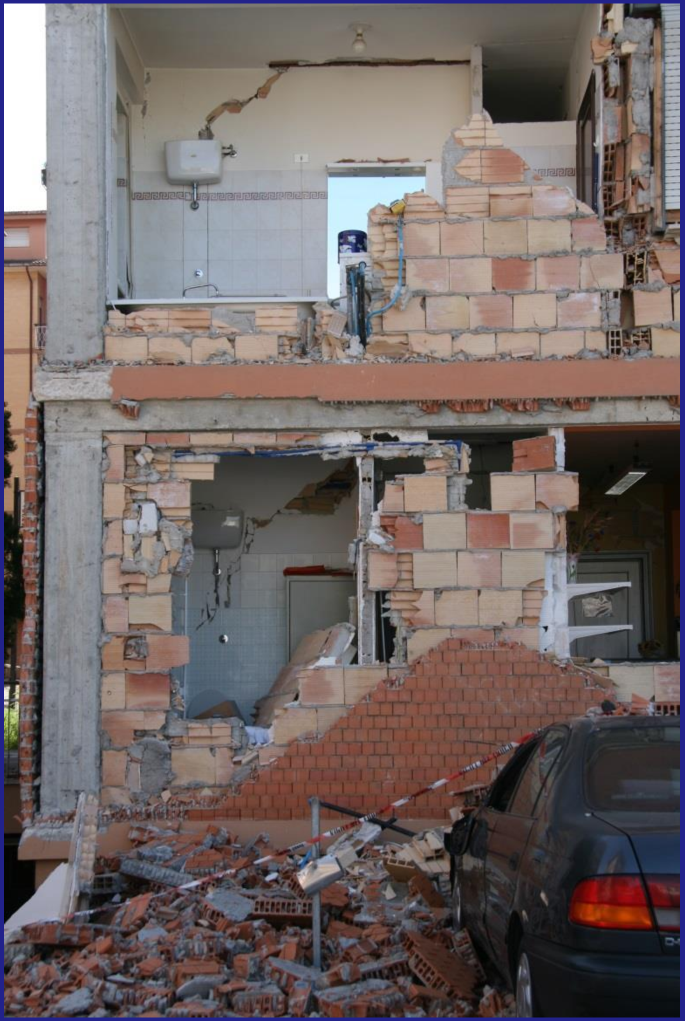
EUROCODE 8
Main objectives of seismic design

In the event of earthquakes:

- Human lives are protected
- Damage is limited



L'Áquila Earthquake - 2009

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EUROCODE 8
Main objectives of seismic design

In the event of earthquakes:

- Human lives are protected
- Damage is limited
- Important structures for civil protection remain operational

Bhaderwah Earthquake - 2013

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Requirement of “No-collapse”

- No local or global collapse may occur for the design seismic action

- Following the event, structural integrity and residual load bearing capacity shall be maintained

- The no-collapse requirement is associated with the Ultimate Limit State (ULS).

- Life must be protected under a rare event through the prevention of local or global collapse.

- Even if a structure is not economically recoverable after an event, it should allow safe evacuation and resist aftershocks.

- It is recommended that for ordinary structures, this requirement shall be applied to a reference seismic action with 10 % probability of exceedance in 50 years - 475 years Return Period.

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Requirement of "Damage limitation":

- No damage shall occur for more frequent seismic actions
- Limitations of use shall be avoided (specially costly ones)

- This damage limitation is associated with the Serviceability Limit State (SLS).
- Economic losses must be reduced for frequent earthquakes.
- Structures shall not have permanent deformations and their elements shall retain their original strength and stiffness with no need for repair.
- Non-structural damage shall be economically repairable.
- It is recommended that for ordinary structures, this requirement shall be applied to a reference seismic action with 10 % probability of exceedance in 10 years - 95 years Return Period.

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The reliability requirements depend on the consequences of failure

- Structures must be classified into importance classes
- One needs to assign a higher or lower return period to the design seismic action
- In practical terms, the reference seismic action must be multiplied by an importance factor γ_I

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Importance class	Buildings
I	Buildings of minor importance for public safety, e.g. agricultural buildings, etc.
II	Ordinary buildings, not belonging in the other categories.
III	Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions etc.
IV	Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc.

γ_I (II) =1.0; others to be defined in National Annexes

Recommended values: γ_I (I)=0.8; γ_I (III)=1.2; γ_I (IV)=1.4

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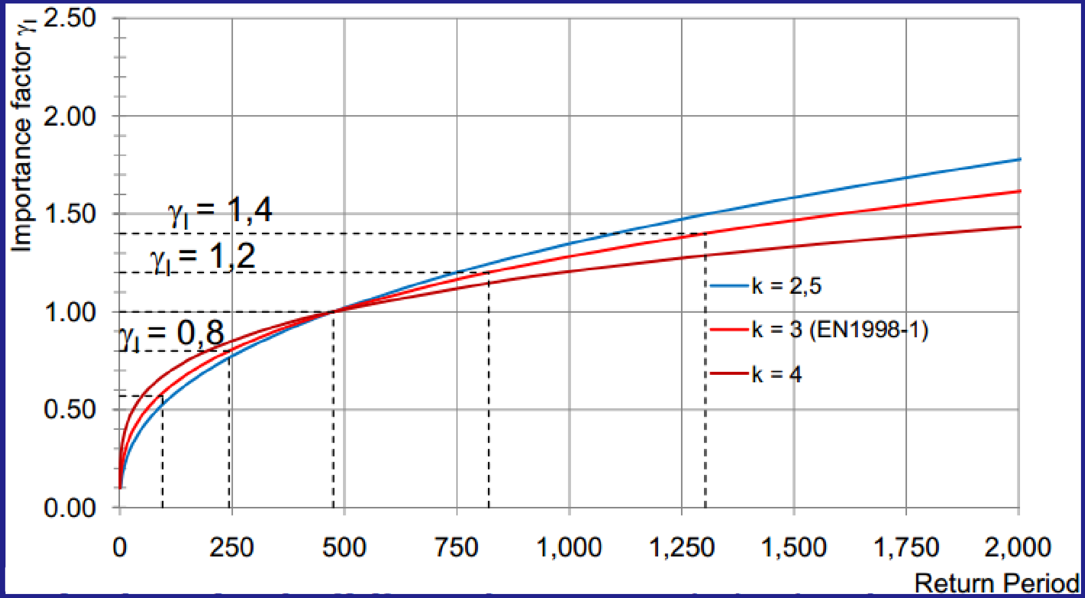
Importance factors can be related to the action return period

The value of the importance factor γ_I that multiplies the reference seismic action to achieve a similar probability of exceedance in T_L years as in the T_{LR} years for which the reference seismic action is defined, may be determined as:

$\gamma_I \approx (T_{LR}/T_L)^{-1/k}$, with $k \approx 3$ (depending on the site seismicity characteristics)

Reduction factor to account for the lower return period for damage limitation verification (recommended values) : ν = 0.5 (I and II) ; 0.4 (IIII and IV)



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Ultimate limit state (ULS)

The capacity to resist and dissipate energy are related to the exploitation of the non-linear response.

The balance between resistance and capacity for energy dissipation can be controlled by the values of the behaviour factor q, which is chosen by the designer, based on the ductility classes.

For structures classified as low-dissipative, no hysteretic energy dissipation may be considered and the behaviour factor, in general, may not be assumed as larger than 1.5, basically to account for overstrengths.

For dissipative structures, values of the behaviour factor larger than 1.5 can be assumed, considering the existence of hysteretic energy dissipation, which occurs mainly in specific dissipative or critical zones.

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Design verifications

Ultimate limit state (ULS)

- Resistance and Energy dissipation capacity
- Use of Ductility classes and Behaviour factor values (q)
- Sliding and overturning stability checking
- Resistance of foundation elements and soil
- Second order effects
- Non detrimental effect of non structural elements

Simplified checks for low seismicity cases (a_g< 0.08 g)

No application of EN 1998 for very low seismicity cases (a_g< 0.04 g)

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Design verifications

Damage limit state (DLS)

(DLS may often control the design)

- Deformation limits (Maximum interstorey drift due to the “frequent” earthquake):

  0,5 % for brittle non structural elements attached to the structure
  0,75 % for ductile non structural elements attached to the structure
  1,0 % for non structural elements not interfering with the structure

- Sufficient stiffness of the structure to guarantee the operationality of vital services and equipment (hospitals, relevant public services, etc.)

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Design verifications

- Take specific measures intended to reduce the response uncertainty and promote a good structural response, even under seismic actions more severe than the design seismic action.

- Implicitly equivalent to the satisfaction of a third performance requirement - Prevention of global collapse under a very rare event (1.500 to 2.000 years return period).

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Specific measures

- Use simple and regular forms (plan and elevation)
- Control the hierarchy of resistances and sequence of failure modes
- Avoid brittle failures
- Control the behaviour of critical regions (detailing)
- Use adequate structural model (account for soil deformability and non structural elements if appropriate)
- In zones of high seismicity, a formal Quality Plan for Design, Construction, Use and Maintenance is recommended

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Items to be defined at National level (NP EN1998-1)

- Seismic zones
- Design return period for the seismic action
- Shape of the response spectra and soil effects

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Seismic zonation

- Competence of National Authorities
- Used to define the Elastic response spectrum, with common shape for the ULS and DLS verifications
- Quantified by a_{gR} (reference peak ground acceleration on type A ground)
- Linked to the reference return period T_{NCR}
  modified by the Importance Factor γ_I
  to represent the design ground acceleration (on type A ground)

$$a_g = a_{gR} \cdot \gamma_I$$

- Used to define the Elastic response spectrum, with common shape for the ULS and DLS verifications
- Considers two orthogonal horizontal components (independent)
- Vertical spectrum shape different from the horizontal spectrum (common for all ground types)
- Possible need to use more than one spectral shape
  (to model different seismo-genetic mechanisms)

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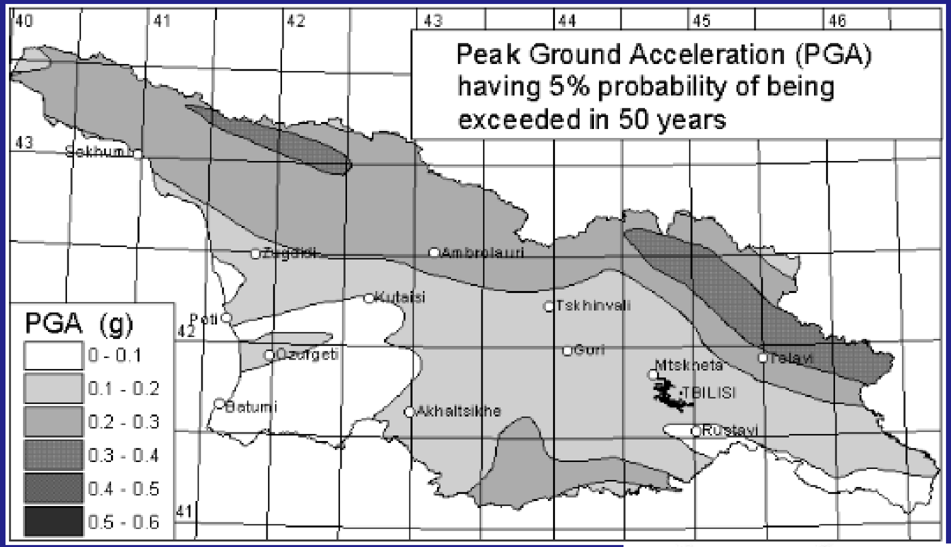
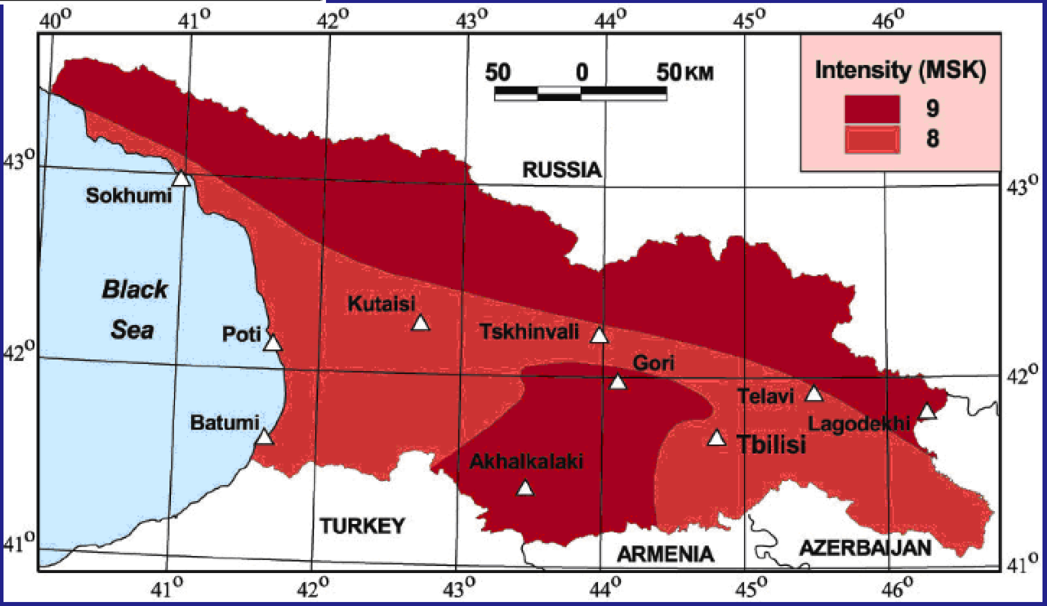
Georgia hazard map and seismic zonation - 1991



http://drm.cenn.org/Hazard_assessment_files/eng/Seismic_hazard_assessment_of_Georgia.pdf
T. Chelidze et al.



http://www.koeri.boun.edu.tr/depremmuh/eski/nato/project/pdf/progress1_983038.pdf

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Ground conditions

Five (+two) ground types (soil conditions):

A - Rock

B - Very dense sand or gravel or very stiff clay

C - Dense sand or gravel or stiff clay

D - Loose to medium cohesionless soil or soft to firm cohesive soil

E - Surface alluvium layer C or D, 5 to 20m thick, over a much stiffer material

2 special ground types S1 and S2 require special studies

Ground properties defined by
- shear wave velocities in the top 30 m
- indicative values for N_{SPT} and c_u

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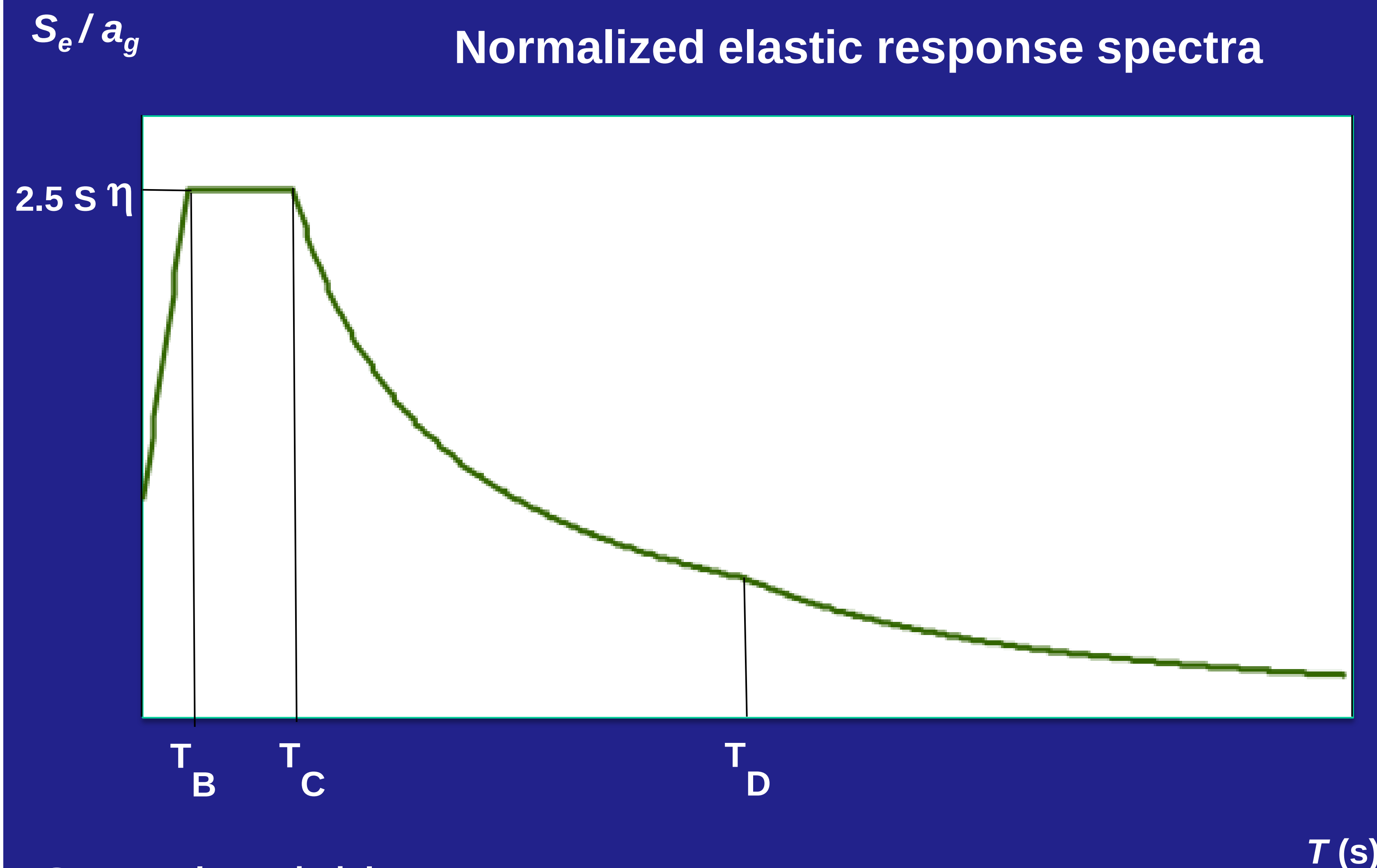
Normalized elastic response spectra



Control variables

S, T_B, T_C, T_D (Constant velocity, acceleration and displacement spectral zones)

η (≥ 0,55) damping correction for $\xi \neq 5$ %

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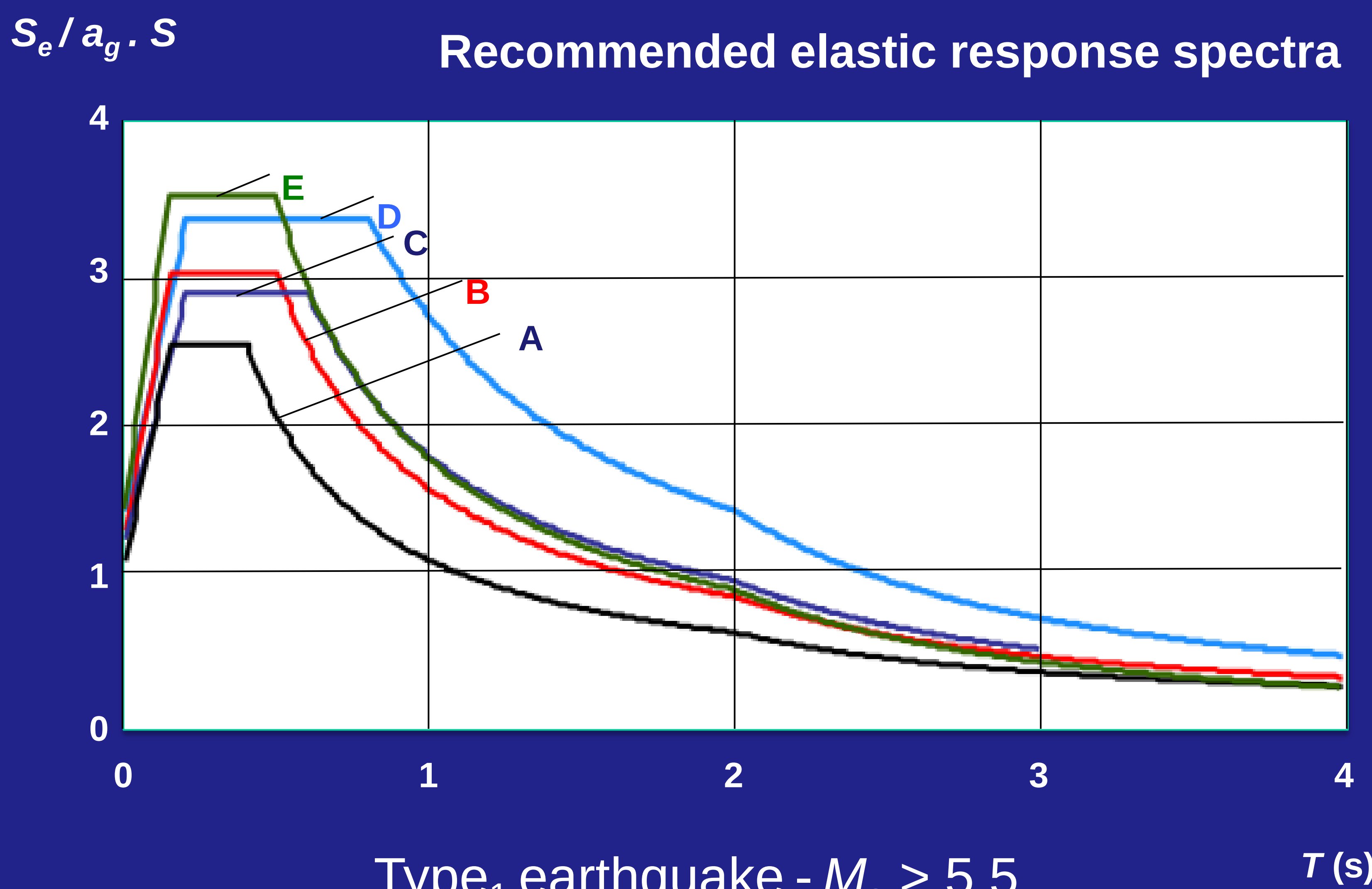
Recommended elastic response spectra



Type$_1$ earthquake - M_s > 5.5
High and moderate seismicity regions
Soil A, B, C, D and E

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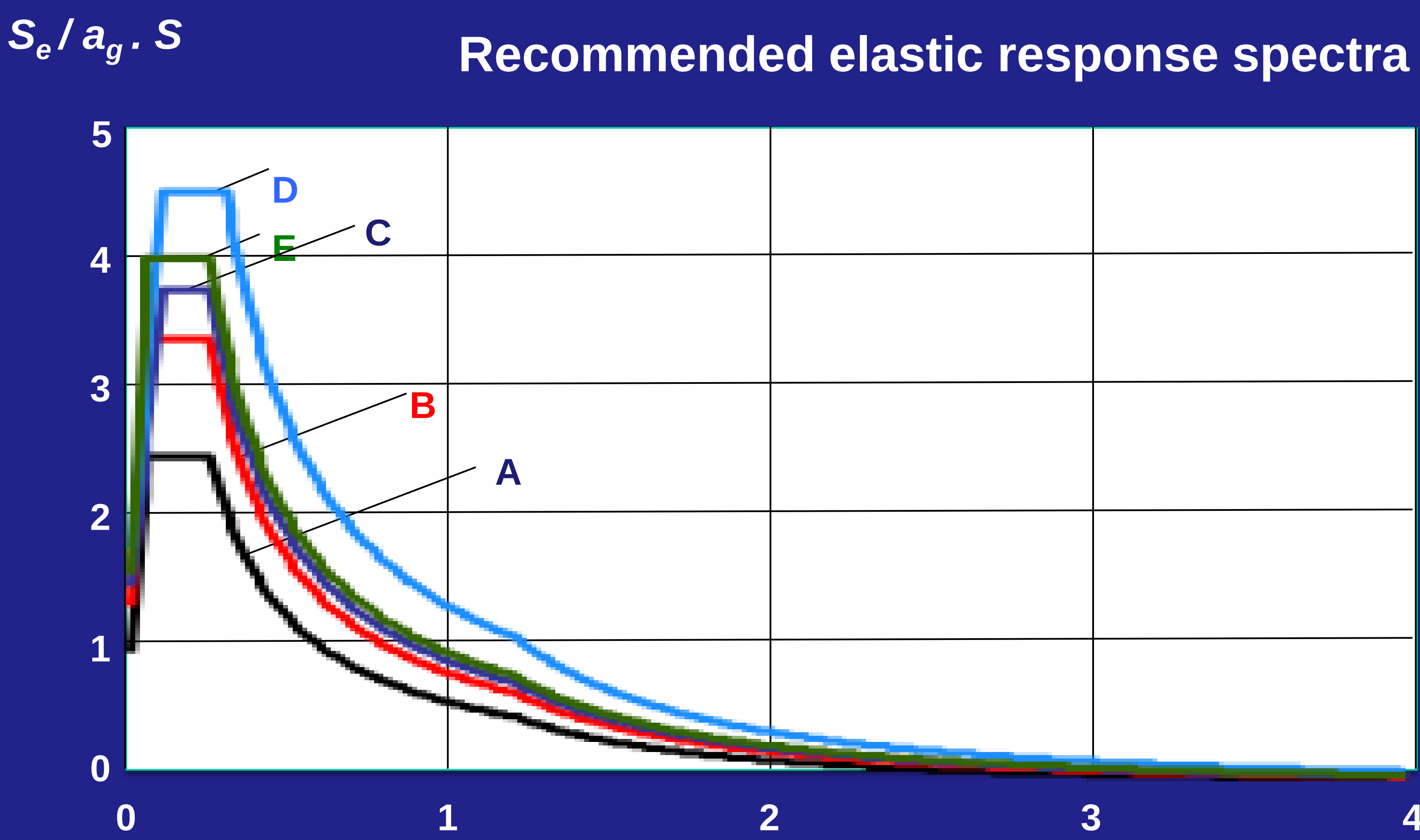
Recommended elastic response spectra



Type$_2$ earthquake – $M_s \leq 5.5$
Low seismicity regions – near field
Soil A, B, C, D and E

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Alternative way to account for the seismic action

Equivalent static lateral force

(not recommended except in simple and regular structures)

- Static lateral forces on storey or nodal masses proportional to the mass times its distance from the base (inverted triangular distribution in regular buildings).

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Alternative way to account for the seismic action

Time history representation

Mandatory for dynamic nonlinear analyses
Three simultaneously acting accelerograms

- **Artificial accelerograms**

  At least 3 sets of accelerograms
  Match the elastic response spectrum for 5% damping
  Duration compatible with Magnitude ($T_s \geq 10$ s)

- **Recorded or simulated accelerograms**

  Scaled to $a_g \cdot S$
  Match the elastic response spectrum for 5% damping

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Alternative way to account for the seismic action

Non-linear Static Analysis (Push-Over)

- Horizontal load pattern increased until the displacement at a reference point reaches the design seismic displacement of elastic response spectrum analysis (q = 1), for the selected combinations of seismic actions (x and y)

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Seismic Protection Systems

Devices that enhance the seismic behaviour of structures without the use of their deformation capacity.

Can act by changing the dynamic characteristics of the structure or increasing its capacity to dissipate energy.

Classification of Seismic Protection Systems:

- Passive Systems – do not require power supply
- Active Systems – need power to control the structural movement
- Semi-active Systems – need power to change the characteristics of the devices

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Passive Systems:

- Base Isolation
- Energy Dissipaters : Hysteretic
  Viscous
  Viscous-elastic
- SMA *"Shape memory alloys"*

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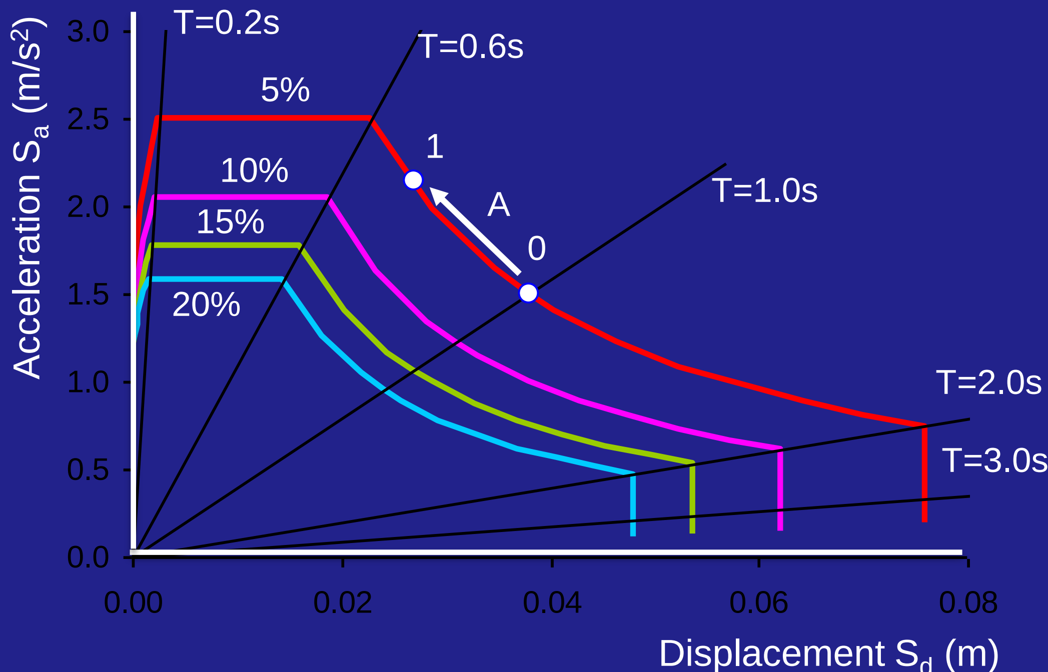
Strategies for Seismic Upgrade

A – Increase in Strength and Ductility



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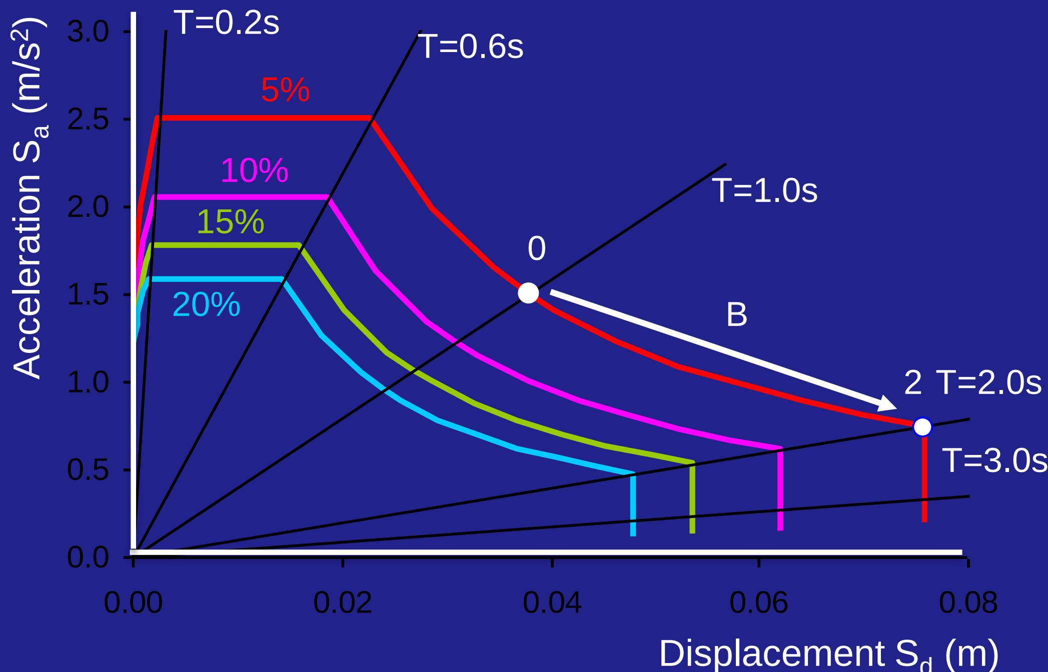
Strategies for Seismic Upgrade

B – Base Isolation



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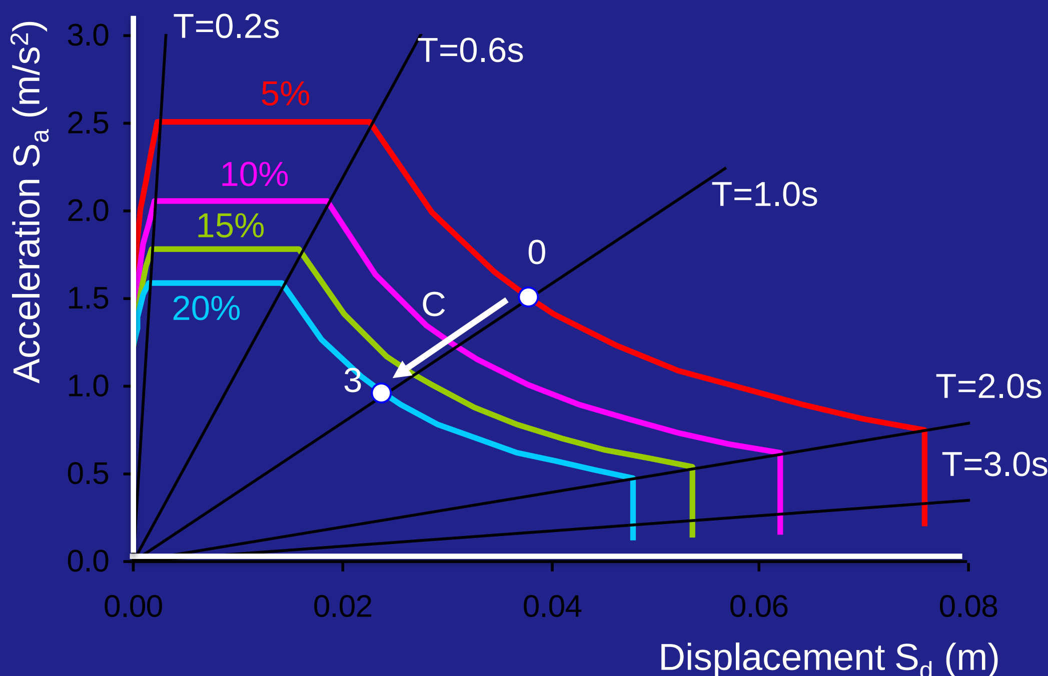
Strategies for Seismic Upgrade

C – Energy dissipation



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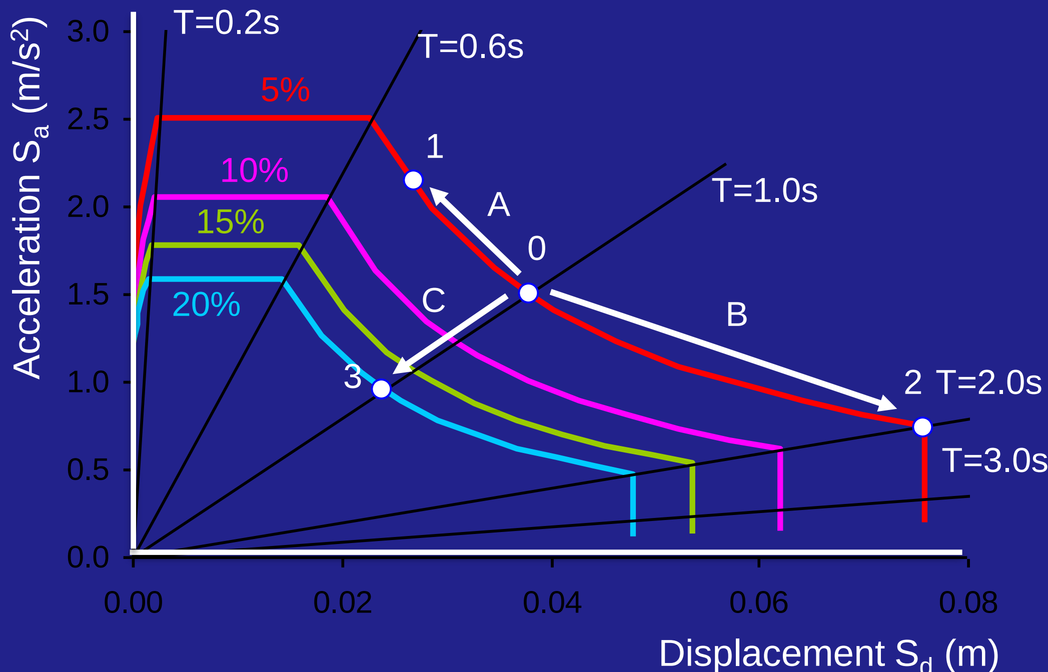
Strategies for Seismic Upgrade

A - Increase in Strength and Ductility

B - Base Isolation

C - Energy dissipation



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Seismic Protection Systems

Passive Systems	Active Systems	Semi – active Systems
Base Isolation	TMD active	TMD semi-active
Dissipaters	Active bracing	Systems with variable stiffness
"Tuned Mass Dampers"	Adaptive control	Systems with variable damping

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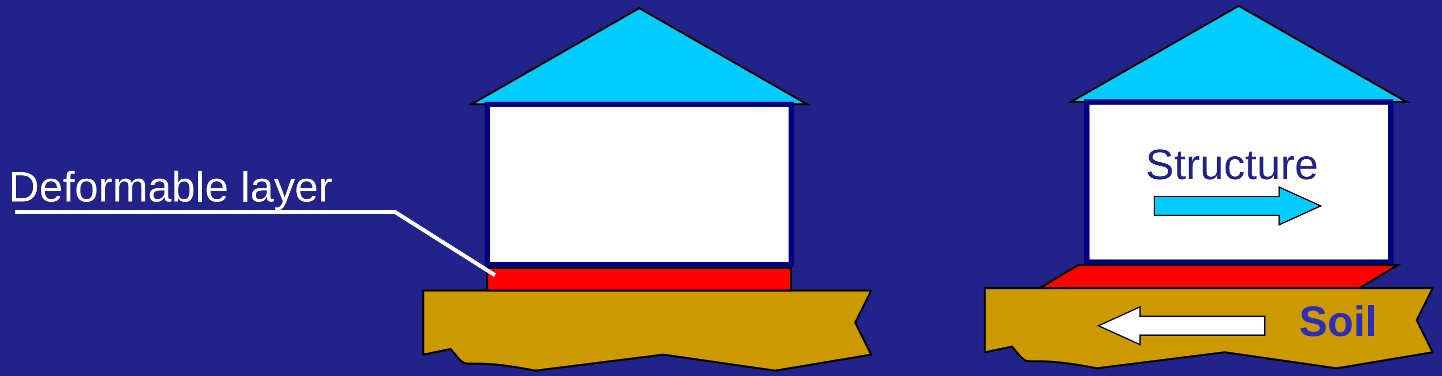
What is base isolation – The concept

In accordance with the concept of Base Isolation, the building (or structure) is "separated" from the components of the horizontal movement of the soil through the interposition of a layer with low horizontal stiffness between the structure and the foundation.



The immediate consequence of the interposition of a deformable layer is the reduction in the natural frequency of vibration.

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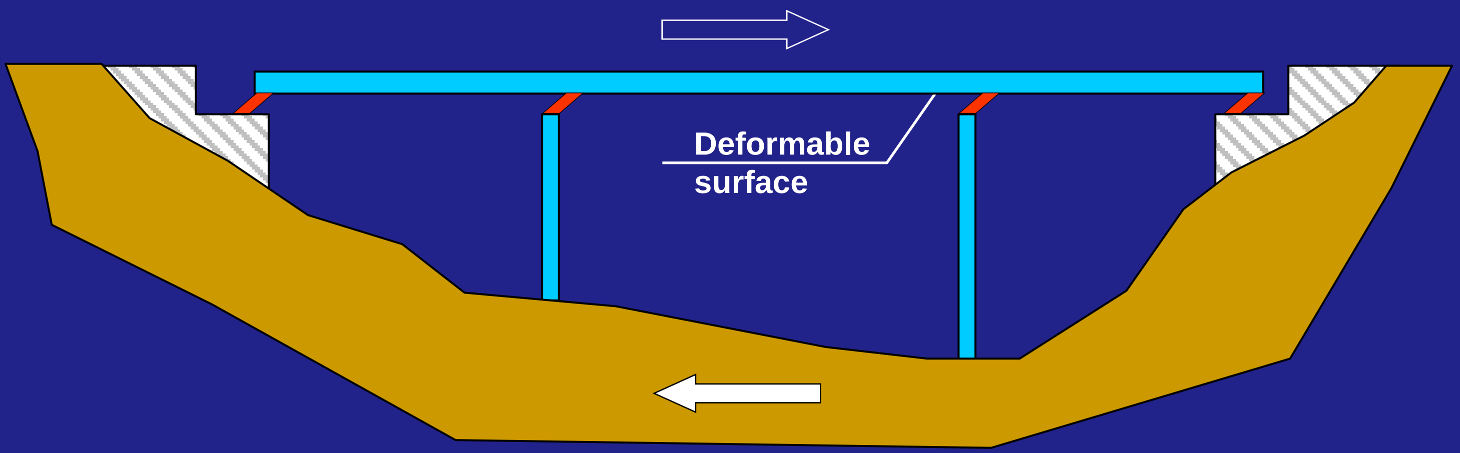
What is base isolation – The concept

In bridges, seismic isolation devices are installed under the deck, at the top of the columns or abutments



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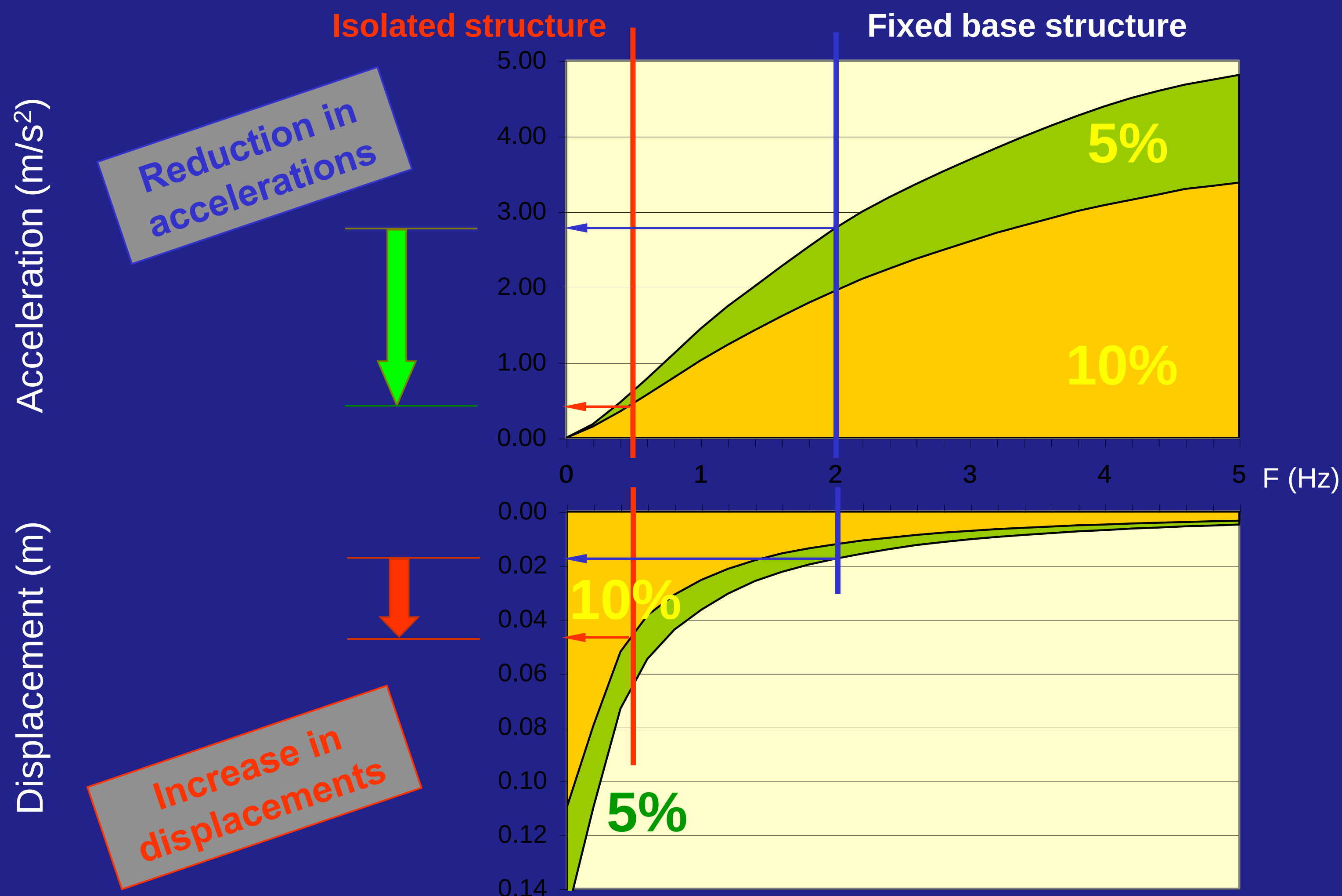
What is base isolation – Advantages and inconvenient



Response spectrum

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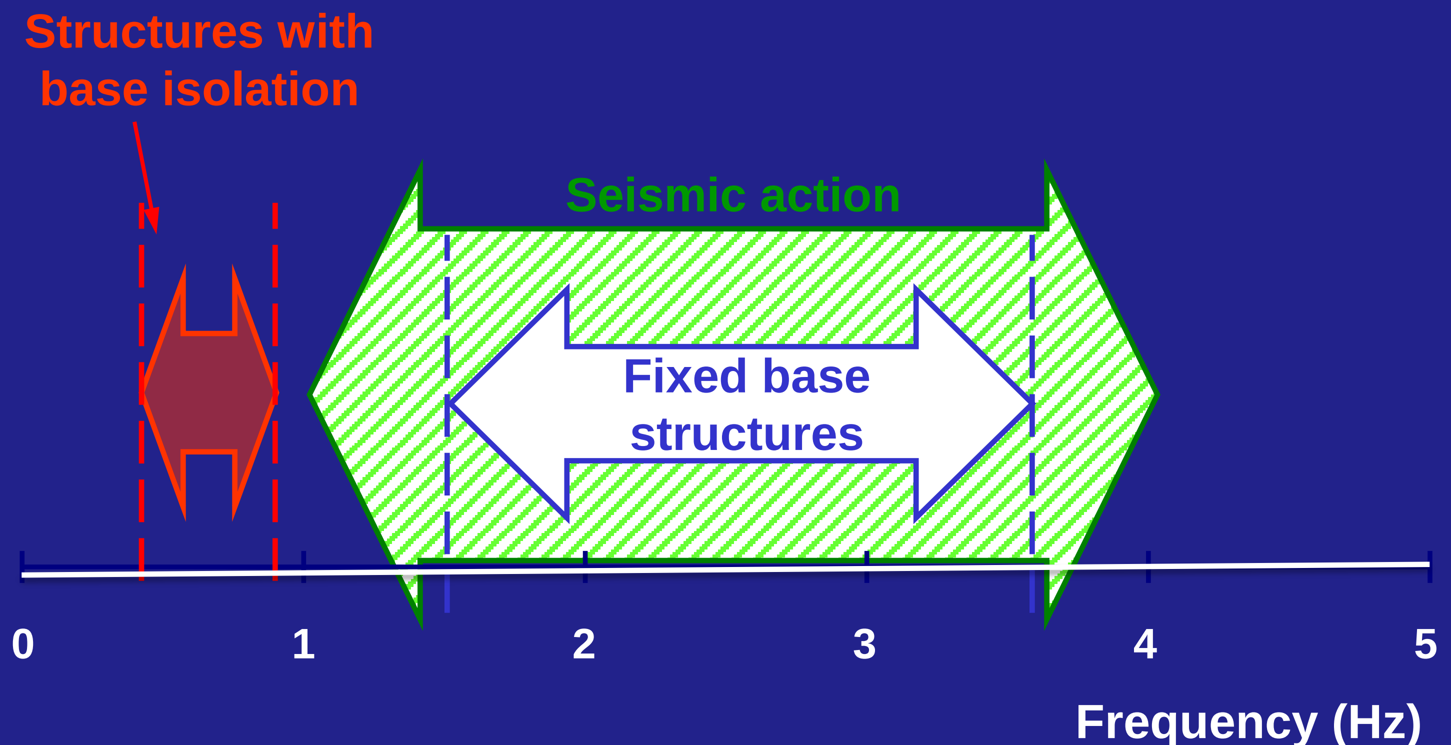
What is base isolation – Advantages and inconvenient

The natural frequency of isolated structures still has the advantage of being lower than the seismic action frequencies with higher energy content



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What is a base isolation system ?
– Essential characteristics

Characteristics that a base isolation system must present

- Support capacity
- Low horizontal stiffness
- Energy dissipation capacity ($\zeta > 5\%$)
- Recentering capacity

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Types of base isolation systems

The following main types of Base Isolation Systems are currently available:

- High Damping Rubber Bearings - HDRB
- Lead Rubber Bearings - LRB
- Friction Pendulum Systems - FPS
- Rubber Bearings in association with dissipaters

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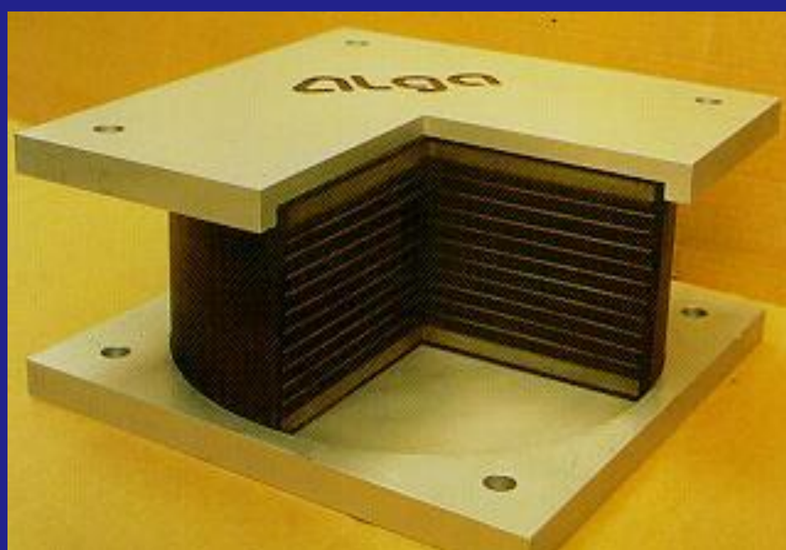
Types of Base Isolation Systems – HDRB

***H**igh **D**amping **R**ubber **B**earing* – HDRB

Through the use of appropriate additives the damping properties of the rubber mixture are optimized.

This way are achieved damping ratios between 10% and 20 %.



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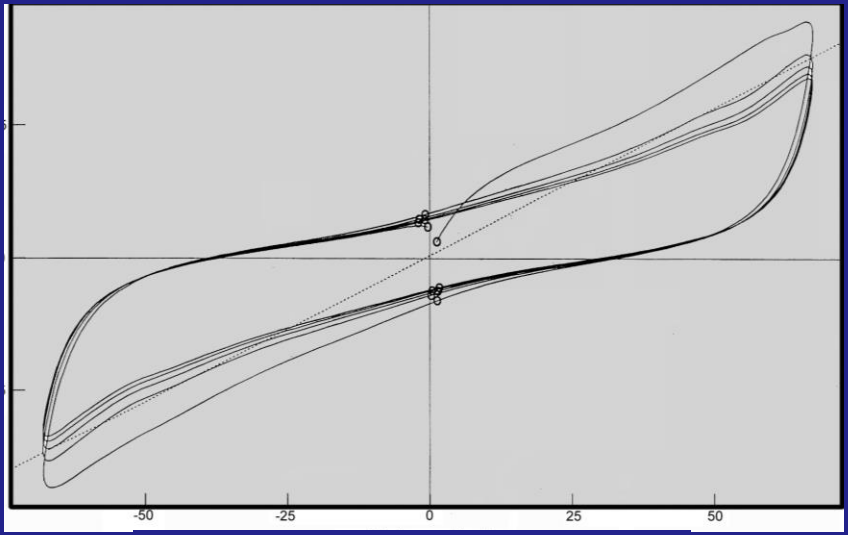
Types of Base Isolation Systems – HDRB

Properties of the HDRB

- Damping coefficients between 10% and 20%
- Shear modulus (G) between 0.4MPa and 1.4MPa
- The stiffness diminishes with increasing distortions
- For large distortions, the stiffness increases again

Horizontal Force



Deformation

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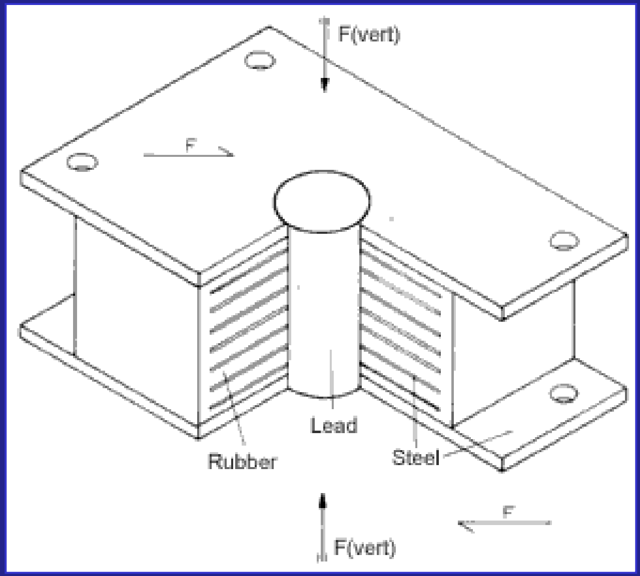
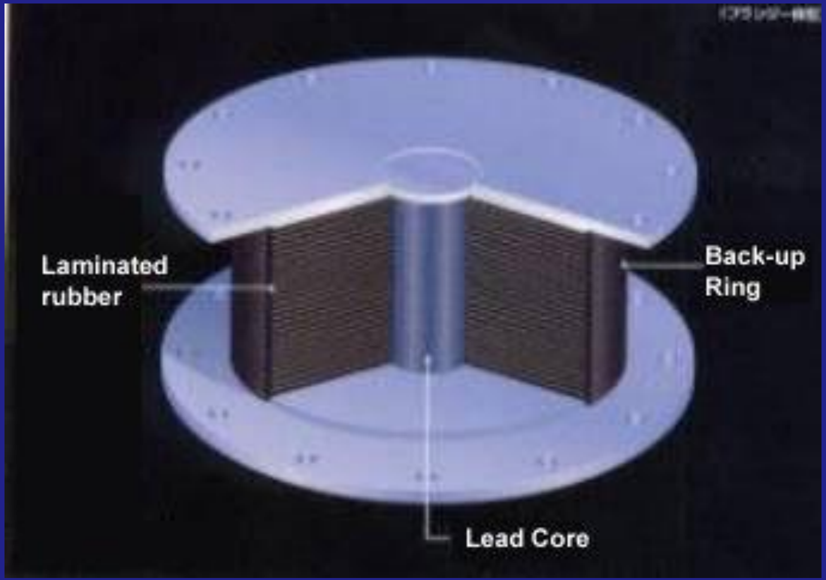
Types of Base Isolation Systems – LRB

Rubber blocks with Lead nucleus – LRB

(***L**ead **R**ubber **B**earing*)

Support Block of rubber to which is added a cylindrical lead core. The support block has a bi-linear behaviour achieving high damping values through the yielding of the lead core.





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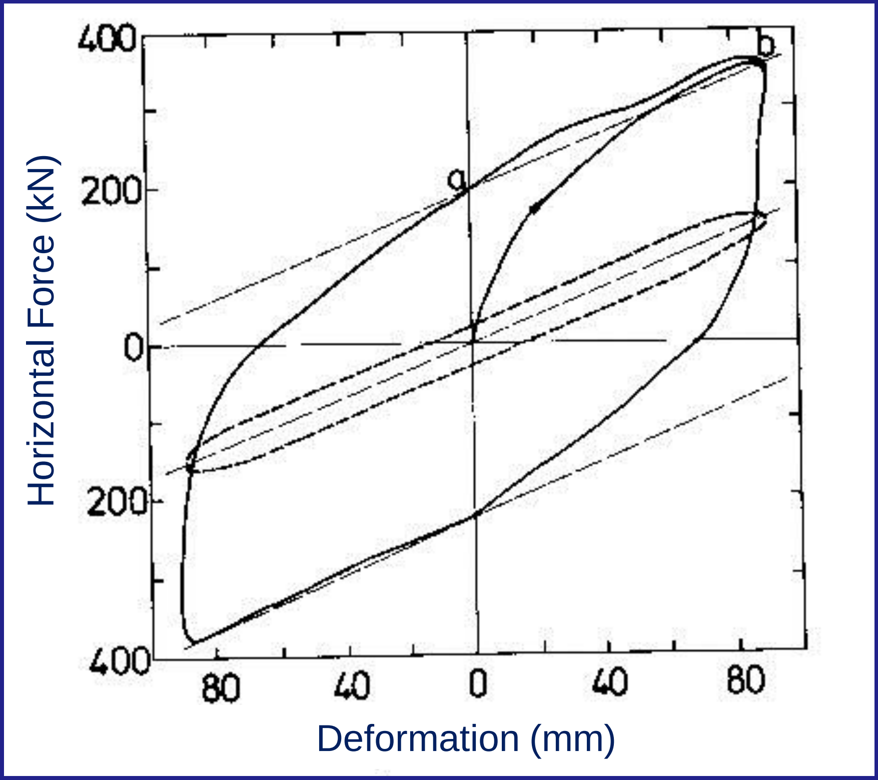
Types of Base Isolation Systems – LRB

Properties of the LRB

- The post-yielding stiffness is the stiffness of the rubber
- The lead yielding shear stress is approximately 10MPa
- The stiffness before yielding is approximately 10x the post yielding stiffness



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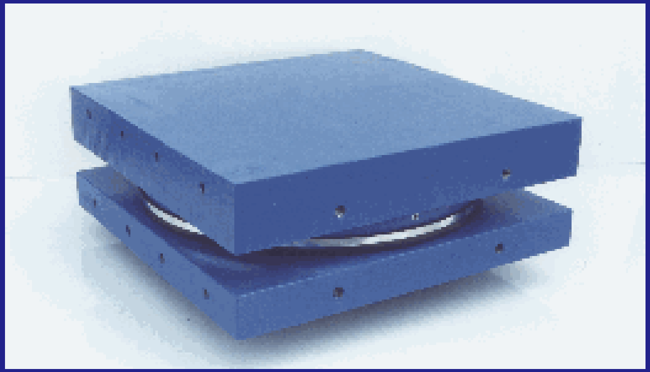
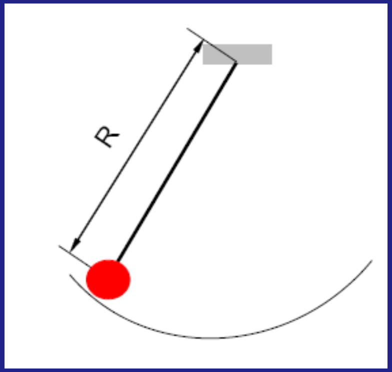
Types of Base Isolation Systems – SPS

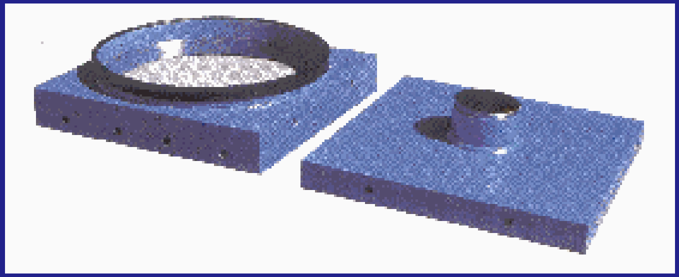
***S**liding **P**endulum **S**ystem – SPS*

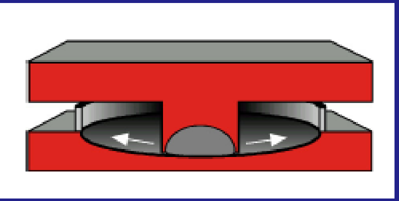
System composed of two overlapping steel elements. One of the elements has in its interior a concave surface. On this surface slides the other part containing a steel tip with an hinged end and coated with a low friction composite material





Pendulum movement





Movement of the FPS

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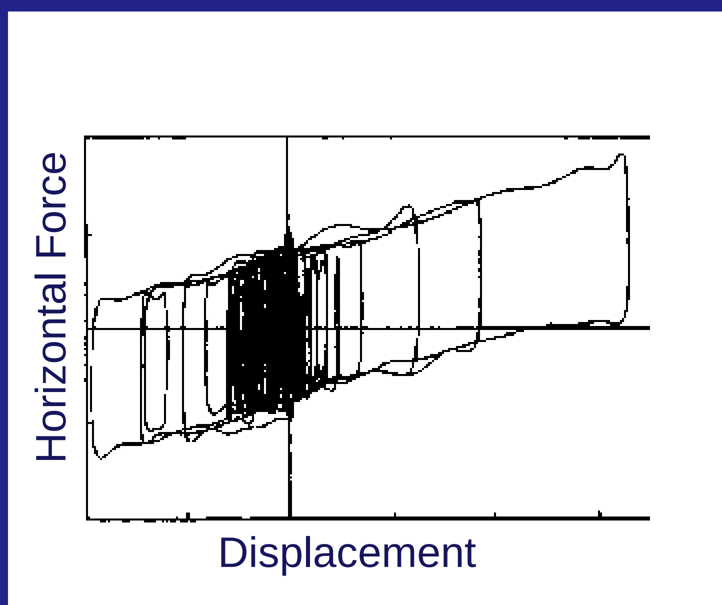
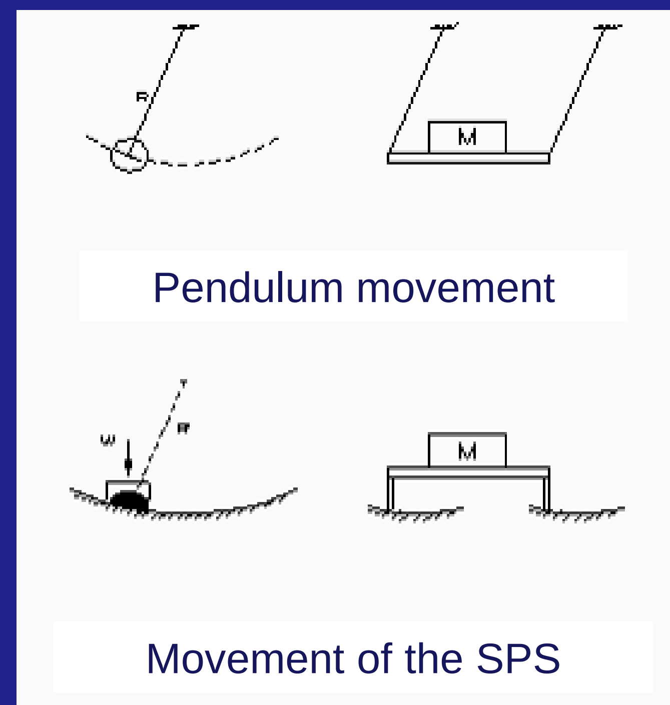
Types of Base Isolation Systems – SPS

SPS system

The dissipation of energy is achieved by friction. The recovery of the structure to the initial position is achieved through a mechanism inspired by the movement of the pendulum.





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Types of Base Isolation Systems – Dissipaters

Rubber bearings in association with dissipaters

This type of Isolation System is a combination of elements of low stiffness with horizontal energy dissipation systems. The low stiffness elements play the support role, without any requirement to the damping level. May be common supporting blocks or sliding systems.

The dissipaters have as single function to ensure the needed damping level. May be viscous or hysteretic dampers.

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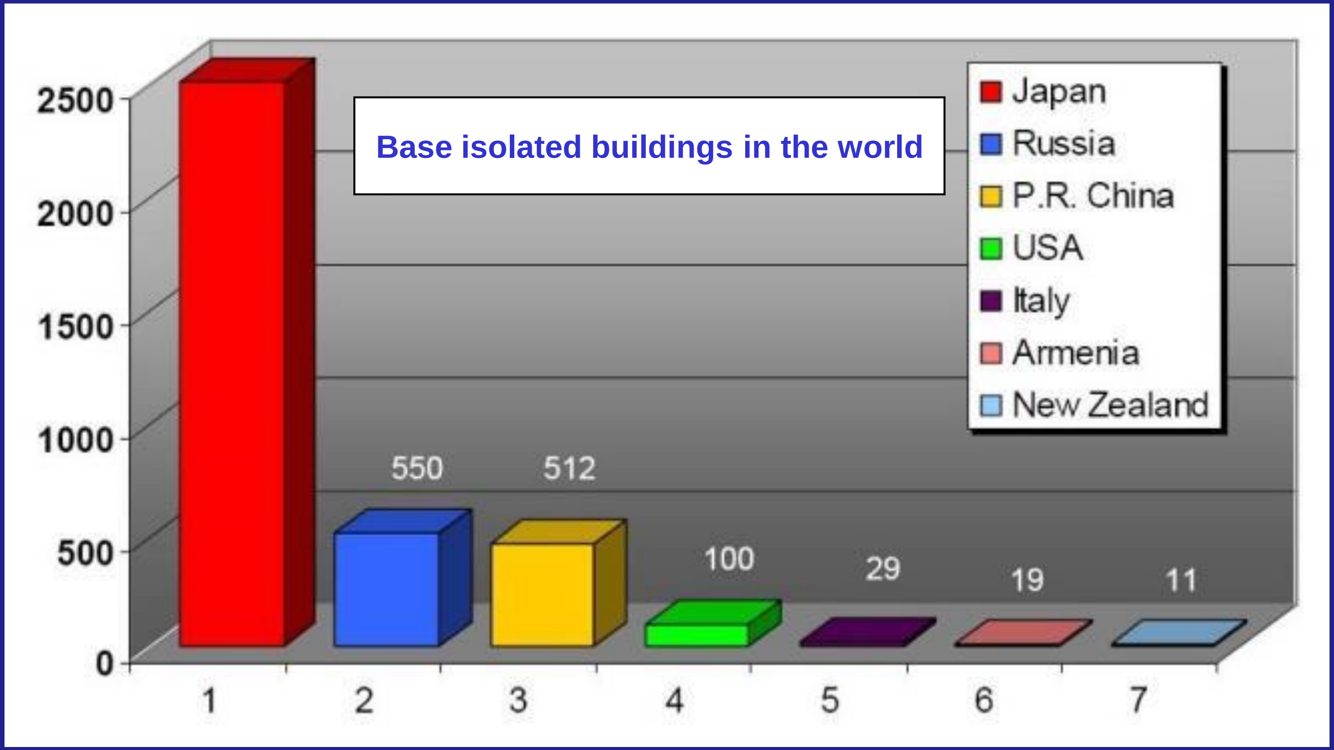
Applications in the world (2008)



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Source: GLIS

www.assisi-antiseismicsystems.org/Territorial/GLIS/Glisnews/glisnews.htm

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Application examples – Portugal

"Hospital and elderly residence", Lisbon

First base isolation building to be built in Portugal

A set of two separated buildings, with a total of 315 support blocks (HDRB).

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Base Isolated Hospital in Lisbon “Hospital da Luz”

The Hospital building has an almost square base, with plan dimensions of 110 x 110 m^2, and 6 stories height.

The Residence building is composed by a rectangular base, with plan dimensions of 55 x 110 m2, and 4 stories height.

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Base Isolated Hospital in Lisbon "Hospital da Luz"

The isolation system is composed by cylindrical High Damping Rubber Bearings produced by FIP Industriale.

The 315 isolators have diameters between 400 and 900 mm, and are made with two different rubber compounds.

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Base Isolated Hospital in Lisbon “Hospital da Luz”




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Detail – Construction phase

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Detail – Construction phase

1

2

3

4

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Detail – Construction phase

5

6

7

8

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Detail – Construction phase

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Codes and regulations

There are already regulations to apply base isolation to buildings and bridges

Europe:

Eurocode 8 – (Chapter 10)

Eurocode 8 – Part 2, Bridges (Chapter 7)

Italian Norm

United States:

Uniform Building Code (UBC) – International Conference of Building Officials

Guide Specifications for Seismic Isolation Design – AASHTO

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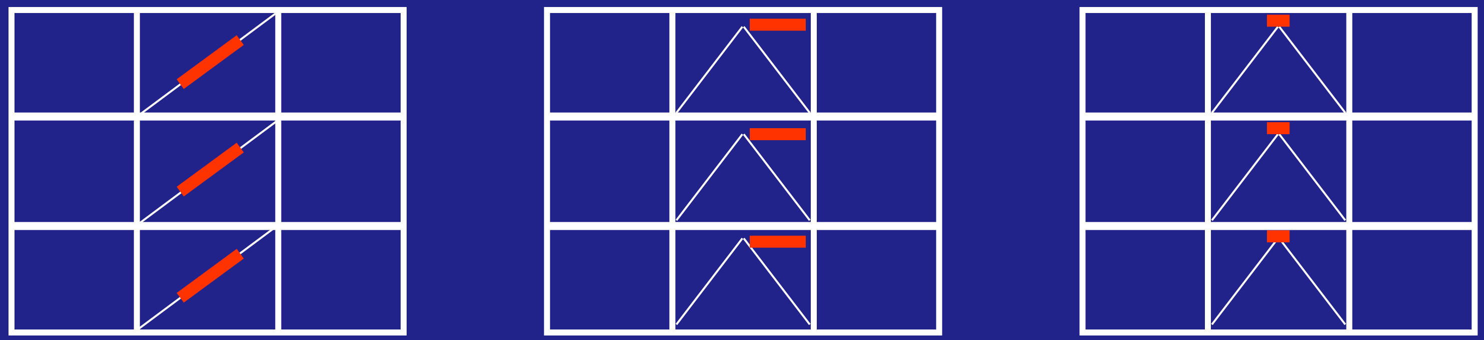
Energy dissipaters

The objective is to provide the structure with devices having energy-dissipating capacity.

This dissipation is associated with the deformation of the structure, so that the devices should be placed so as to be associated with its deformation. To optimize its performance, the dissipation systems must be placed in such a way as to maximize their deformation.



Examples of dissipaters location

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Viscous Dampers

These Dampers are similar to dampers from automobiles and motorbikes.

Its operation is the imposition of a movement, which forces the passage of a piston through a fluid (possibly oil).

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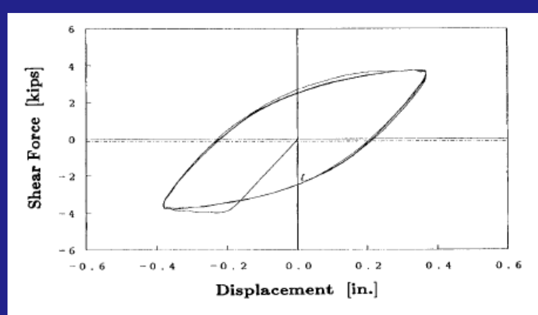
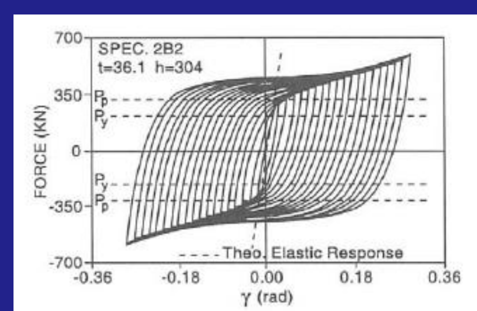
Hysteretic Dampers

These dampers take advantage of the post yielding behaviour of the metallic materials (hysteretic behaviour)





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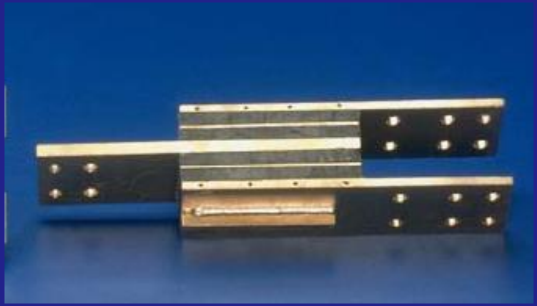
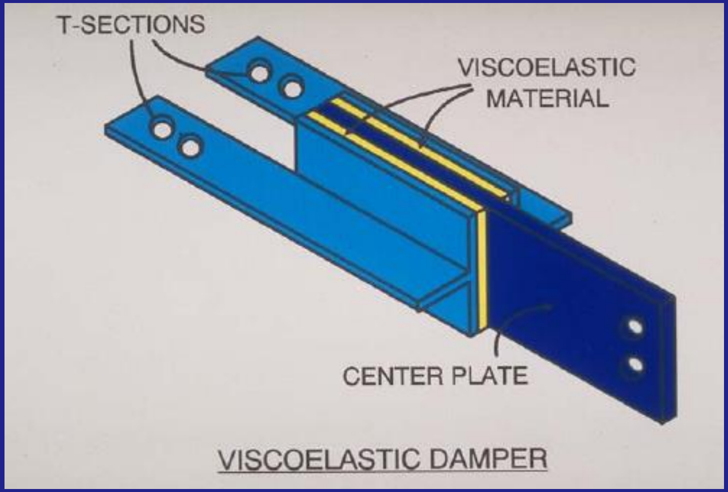
Viscous-elastic Dampers

The viscous-elastic dampers use polymers characterized by dissipating energy by means of displacement (elastic) and velocity.

They normally look like small rectangular plates deforming by shear.





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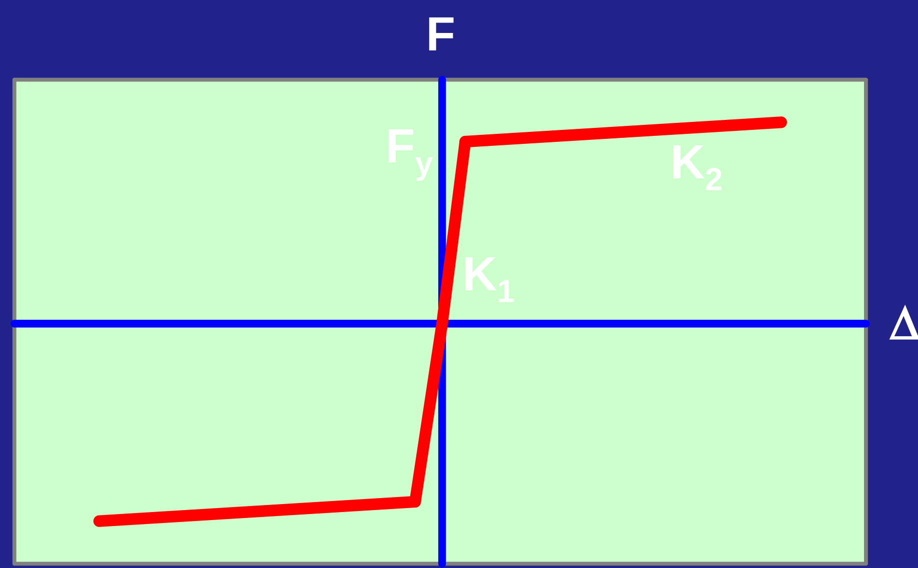
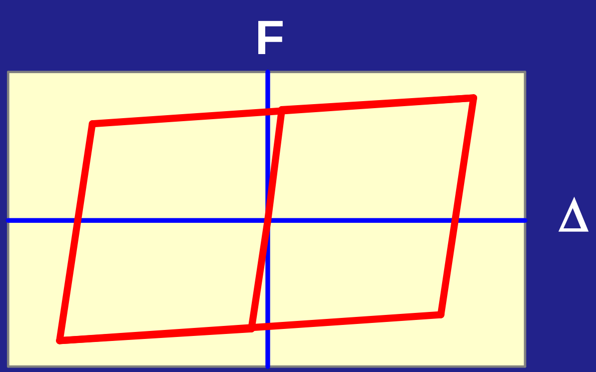
Hysteretic dampers

The hysteretic dampers take advantage of the capacity of plastic deformation of the metallic elements, usually of steel. In these systems, the strength depends on the deformation imposed on the damper, and the control parameters are the initial stiffness (K_1), the post-yielding stiffness (K_2) and the yielding force level (F_y).





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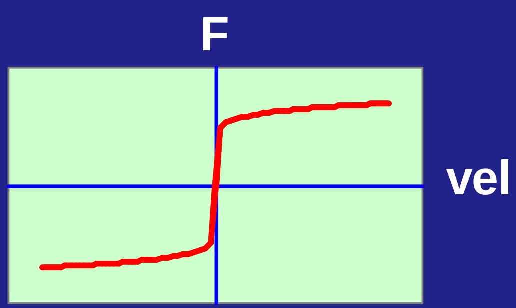
Viscous dampers

In systems with viscous energy dissipation, the force value depends on the relative velocity between its extremities. The type of force-velocity relationship that each type of damper features depends mainly on the characteristics of the used fluid, and can be determined by means of the following general expression:

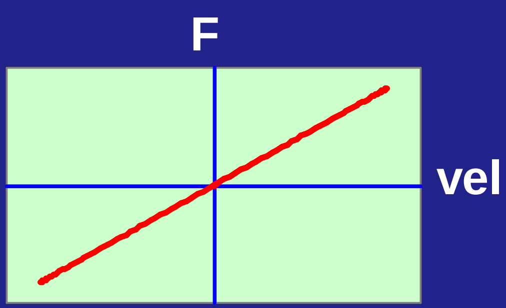
$$F = C\,|v|^{\alpha}\ \mathrm{signal}(v)$$

C, α – Damper parameters;

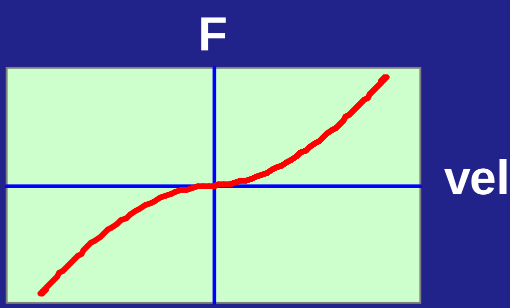
v - velocity



α = 0.10



α = 1.00



α = 1.80

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Hysteretic dampers

$\alpha = 0.10$

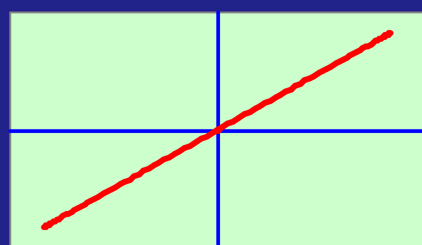
F

vel

- The force increases sharply for low velocity values;
- The force is limited to a maximum value;
- The device is “fixed” up to reaching a maximum force limit.

$\alpha = 1.00$

F

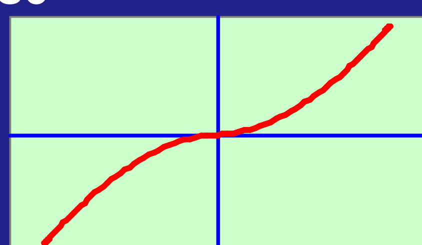


vel

- The force increases linearly with the velocity;
- Linear viscous damper;
- Direct application of the damping coefficient concept (z).

$\alpha = 1.80$

F



vel

- Forces almost null for low velocity values;
- The force increases faster than the velocity;
- Mobile support for low velocities.

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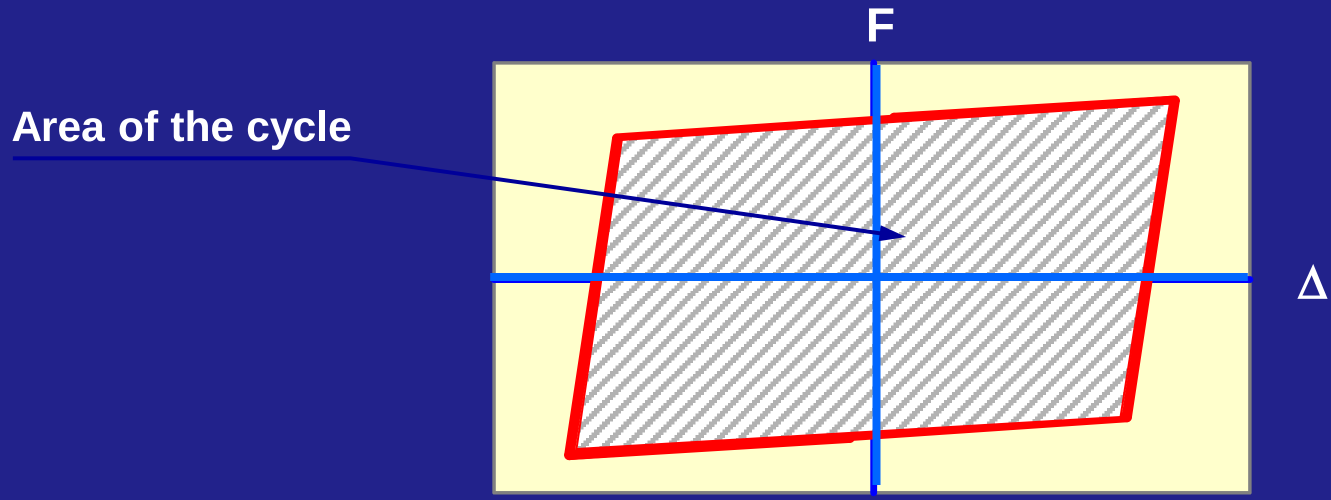
Damping

The damping that a particular damper introduces in the structure is measured by its ability to dissipate energy in each cycle. This dissipation can be by hysteresis (hysteretic dampers) or by viscous behaviour (viscous dampers)

The dissipated energy in each cycle can be assessed by calculating the area inside the cycle measured by the line that relates the force on the damper with its deformation.



Force – deformation relationship of the dissipater

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Damping

For a particular cycle it is possible to estimate the value of the equivalent damping coefficient from the following expression :

$$\zeta = \frac{\text{Area of the cycle}}{2\,\pi\, F_{max}\ d_{max}}$$

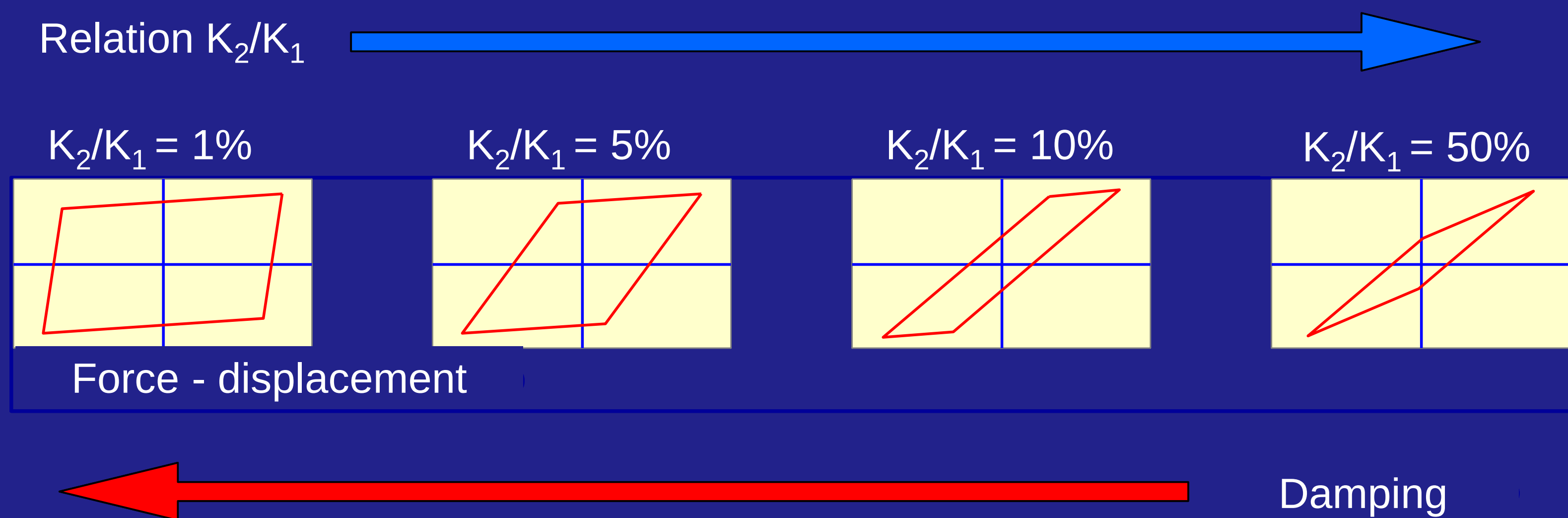
F_{max} – maximum force in the structure;

d_{max} – maximum deformation in the structure.

The energy-dissipating capacity of a damper will be all the better the more "rectangular" is the complete force-deformation cycle.

Damping

In the hysteretic dampers the form of the force-deformation cycle is much influenced by the relationship between the post yielding stiffness (k_2) and the initial stiffness. Another parameter that is also influential is the value of the yielding force. If the yielding force is too high the dissipater plasticizes few times, dissipating less energy.



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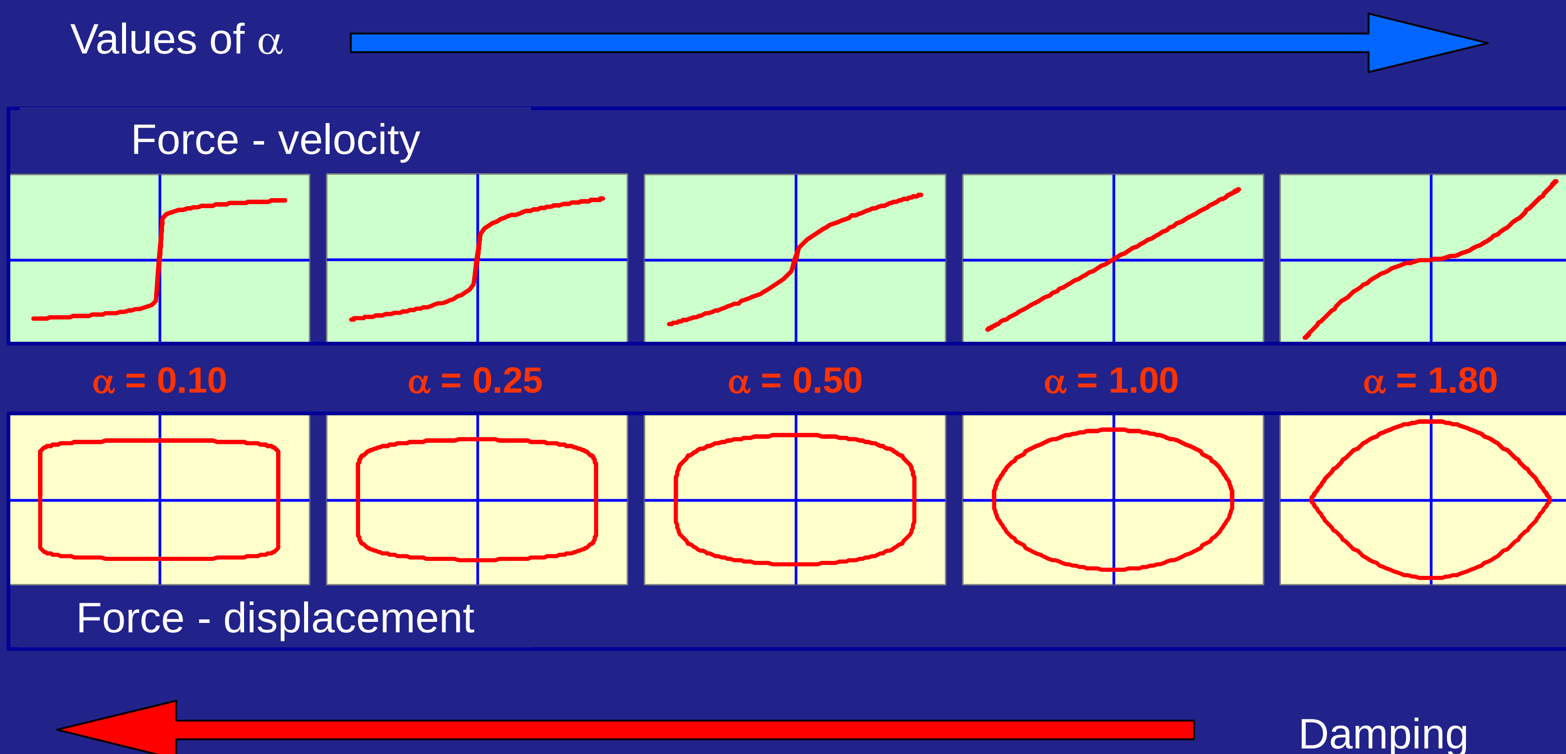
Damping

In the viscous dampers the shape of the force-displacement cycle depends on the parameter α.



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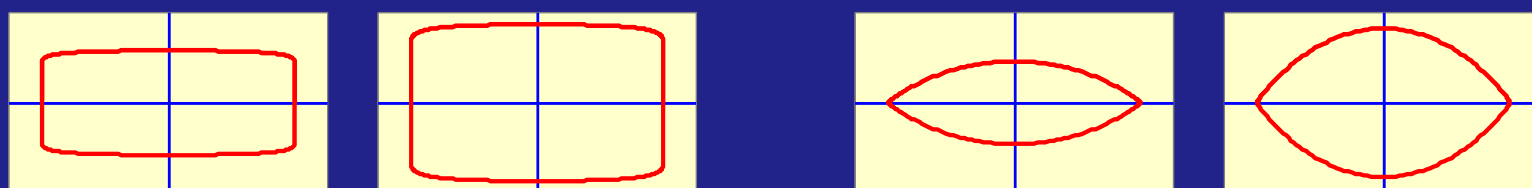
Damping

In viscous dampers, the parameter C does not alter the form of the cycle force-deformation, but increases the internal area of the cycle. The increase in the value of C leads to a greater ability to dissipation of energy but, on the other hand, increases the force on the dissipater.

α = 0.10 | α = 1.80



C = 2000 | C = 3000 | C = 28000 | C = 50000

C values

Damping

Force in the dissipater

C values

Damping

Force in the dissipater

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Methods of analysis

The majority of the energy dissipation systems has non-linear behaviour.

The hysteretic dampers have physical non-linear behaviour, with this property being explored to dissipate energy.

In the viscous dampers the non linearity derives from the behavioural relationship represented by a nonlinear equation:

$$F = C\,|v|^{\alpha}\ \text{signal}(v)$$

Only for α=1 the previous equation is linear, making the response analysis easier.

This way, the only possible way to correctly analyse the response of structures with such dampers is through the use of nonlinear dynamic analysis programs.

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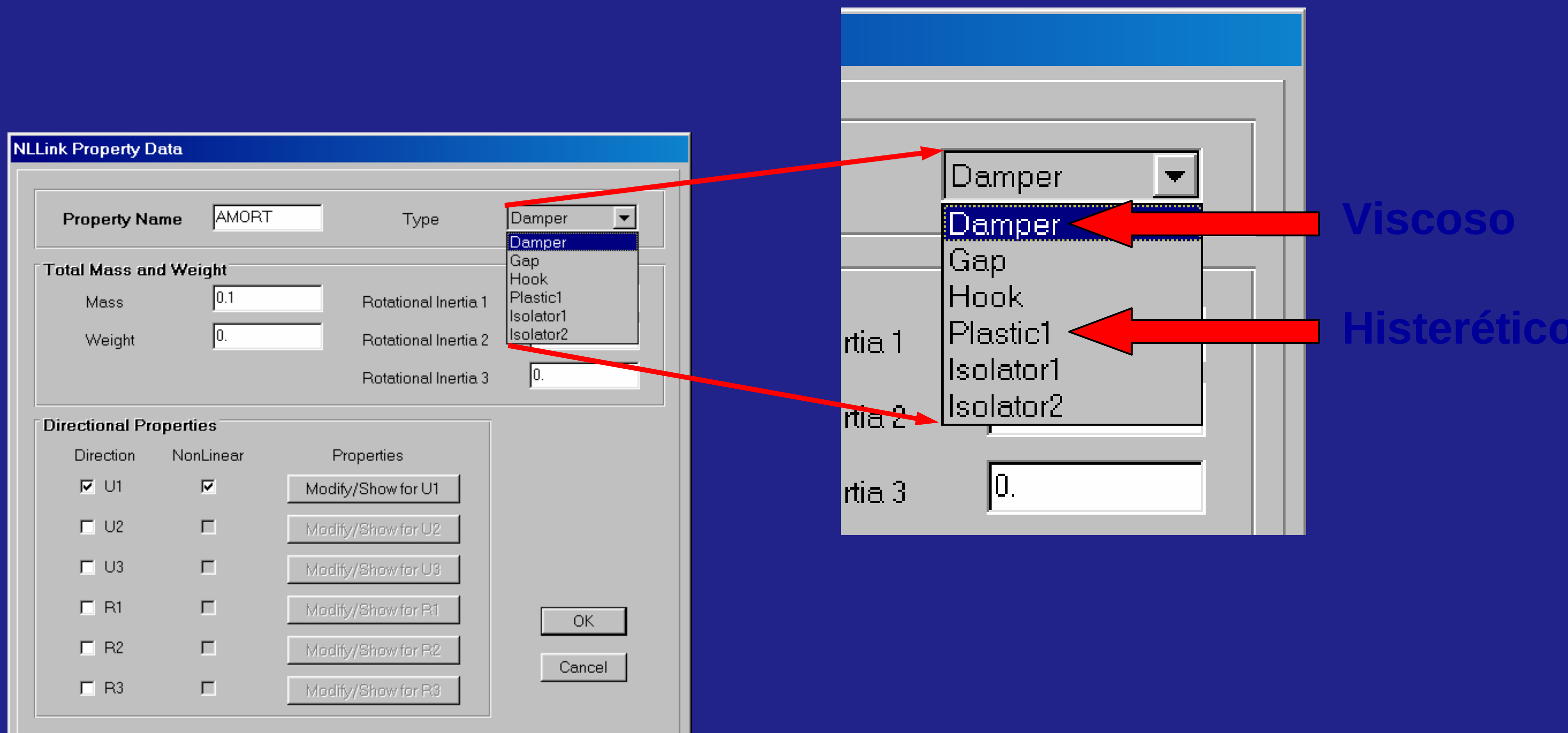
Methods of analysis

Available Programs have a set of elements that allow simulating the various types of dampers. In the case of SAP2000 these elements are designated by NLLink



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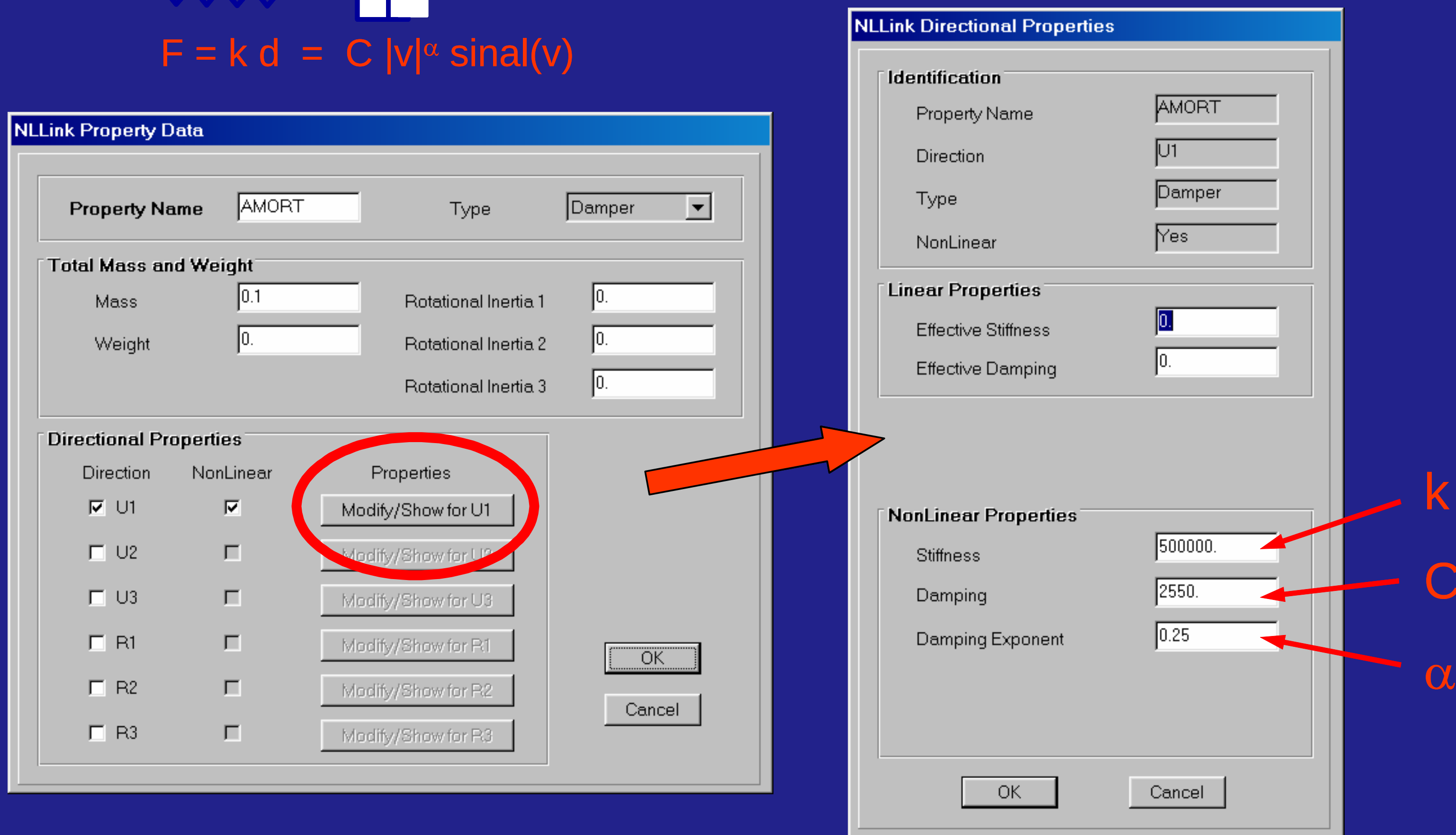
Methods of analysis

$F = k\,d \; = \; C\,|v|^{\alpha}\,\mathrm{sinal}(v)$



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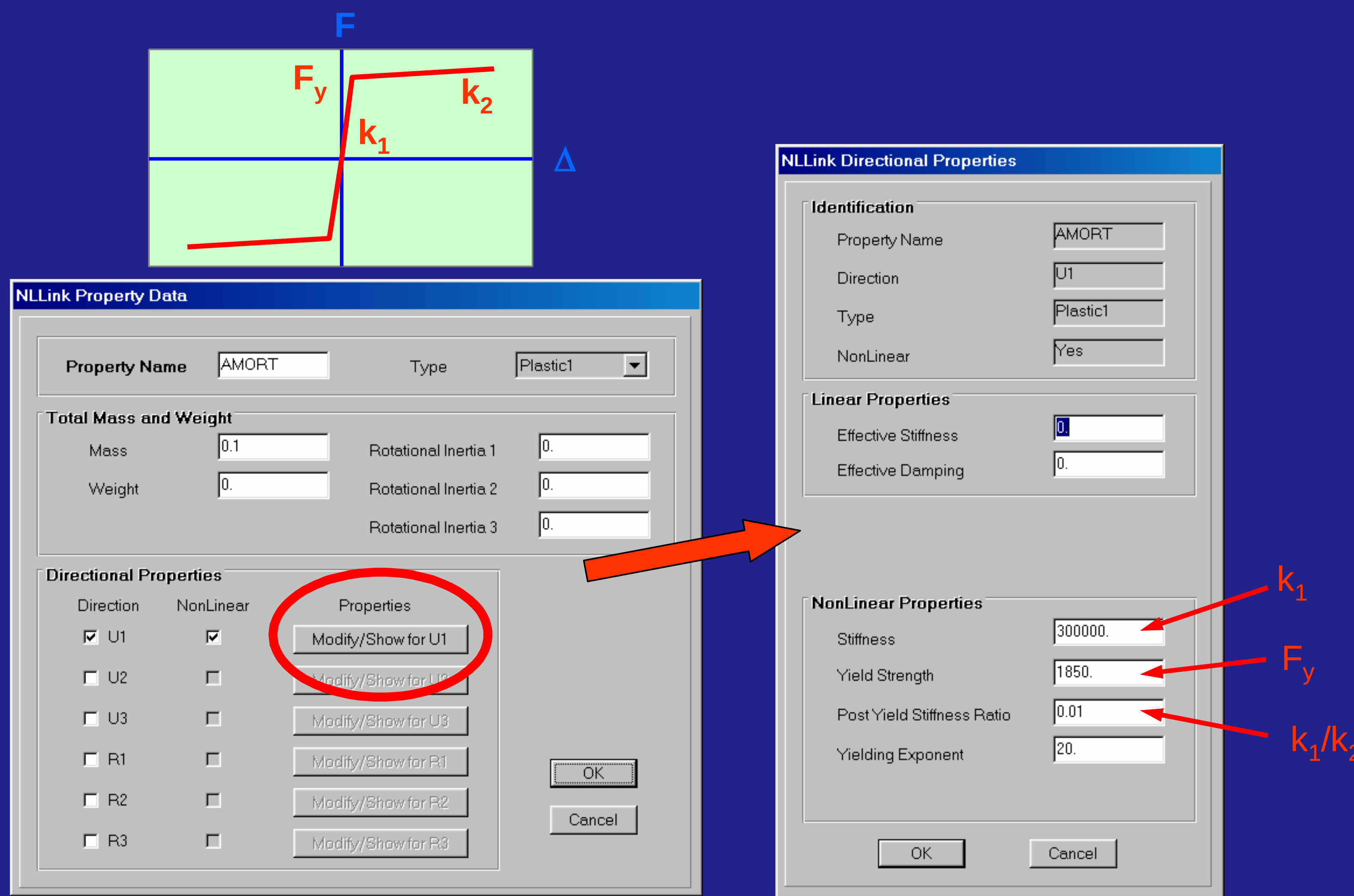
Methods of analysis



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Dampers Solutions

Hysteretic dampers PND & PNUD

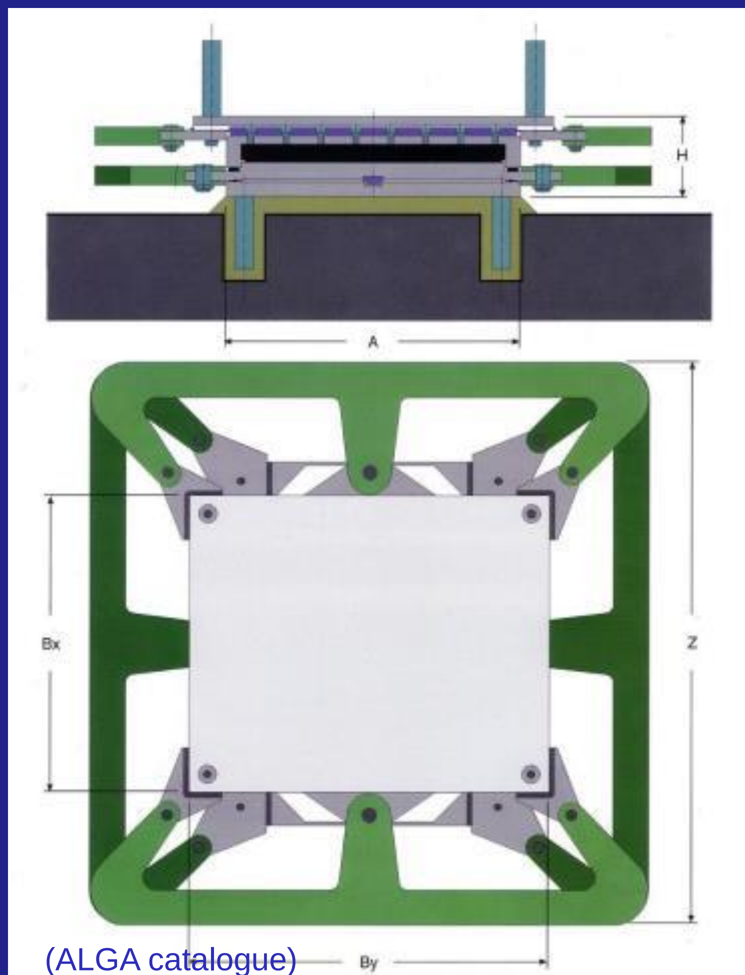
(ALGA catalogue)

Dampers Solutions

Algasism Dampers

PND

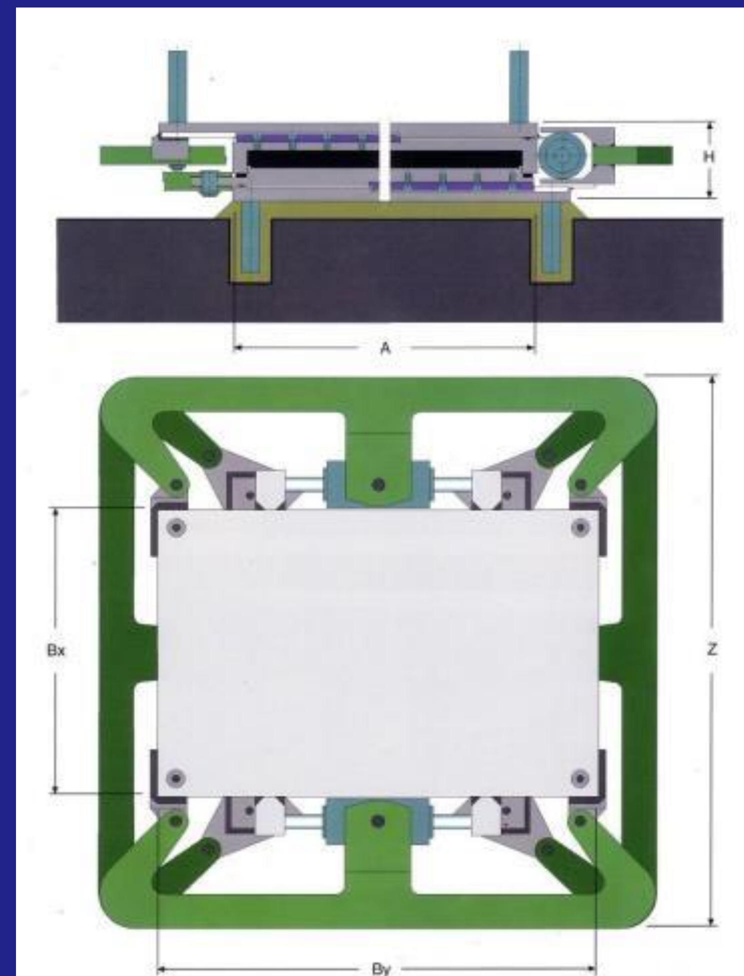
Steel hysteretic damper



(ALGA catalogue)

PNUD

Steel hysteretic damper
Free for slow movements



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Dampers Solutions

Algasism DECS

Electro inductive antiseismic device

(ALGA catalogue)

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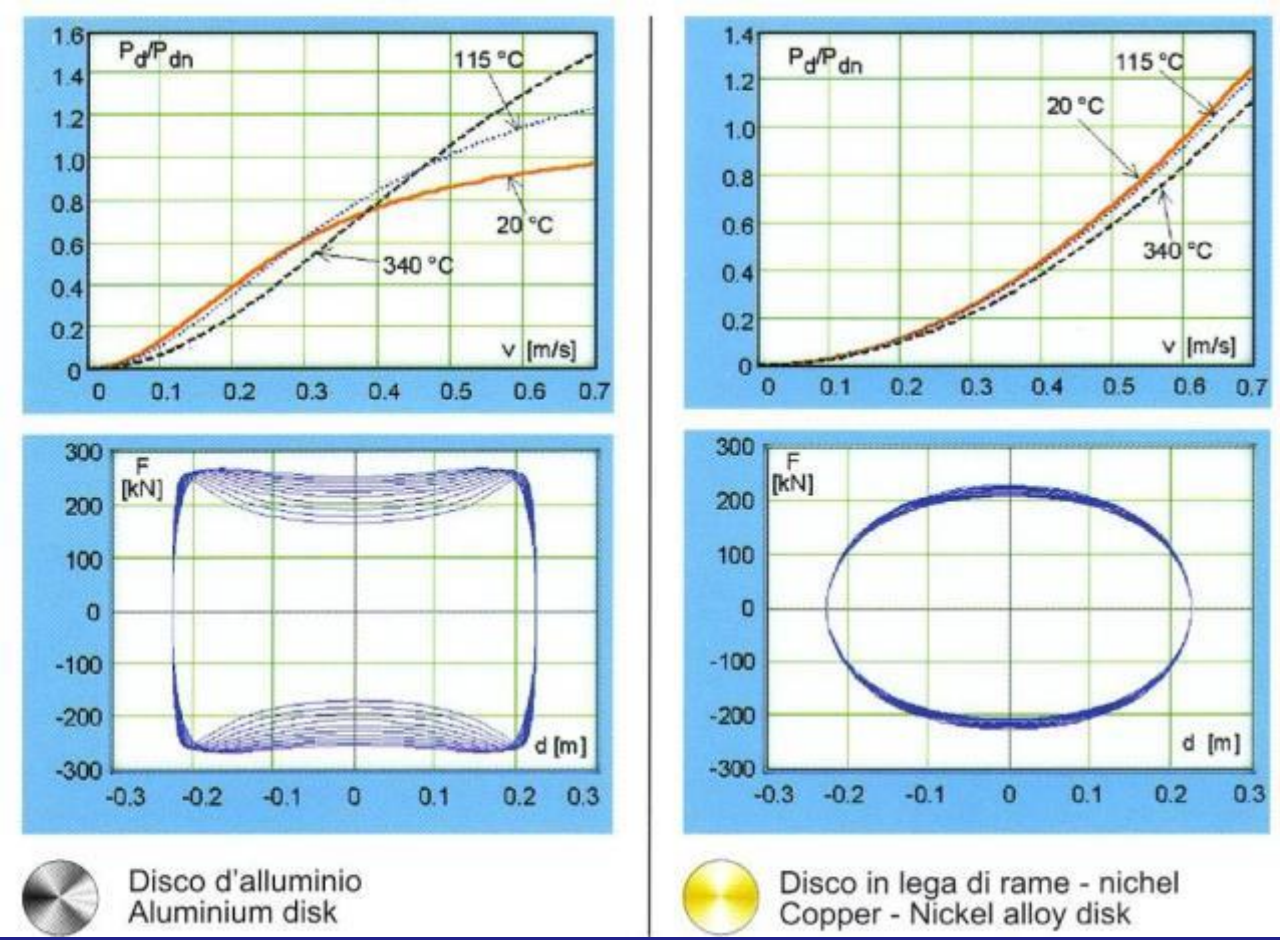
Dampers Solutions

Algasism DECS

Behaviour models



(ALGA catalogue)

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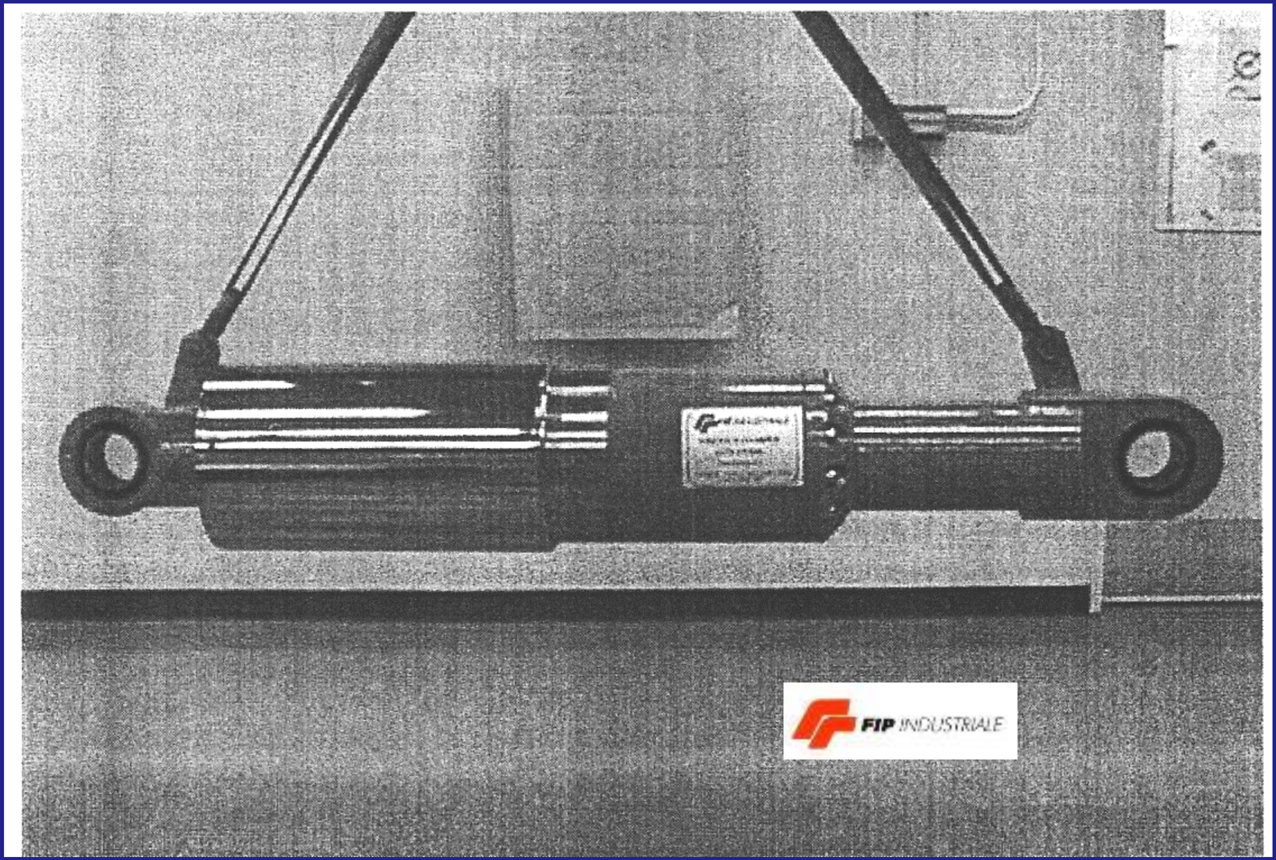
Dampers Solutions

Nonlinear Viscous Dissipater



(Infanti e Castellano, 2001)

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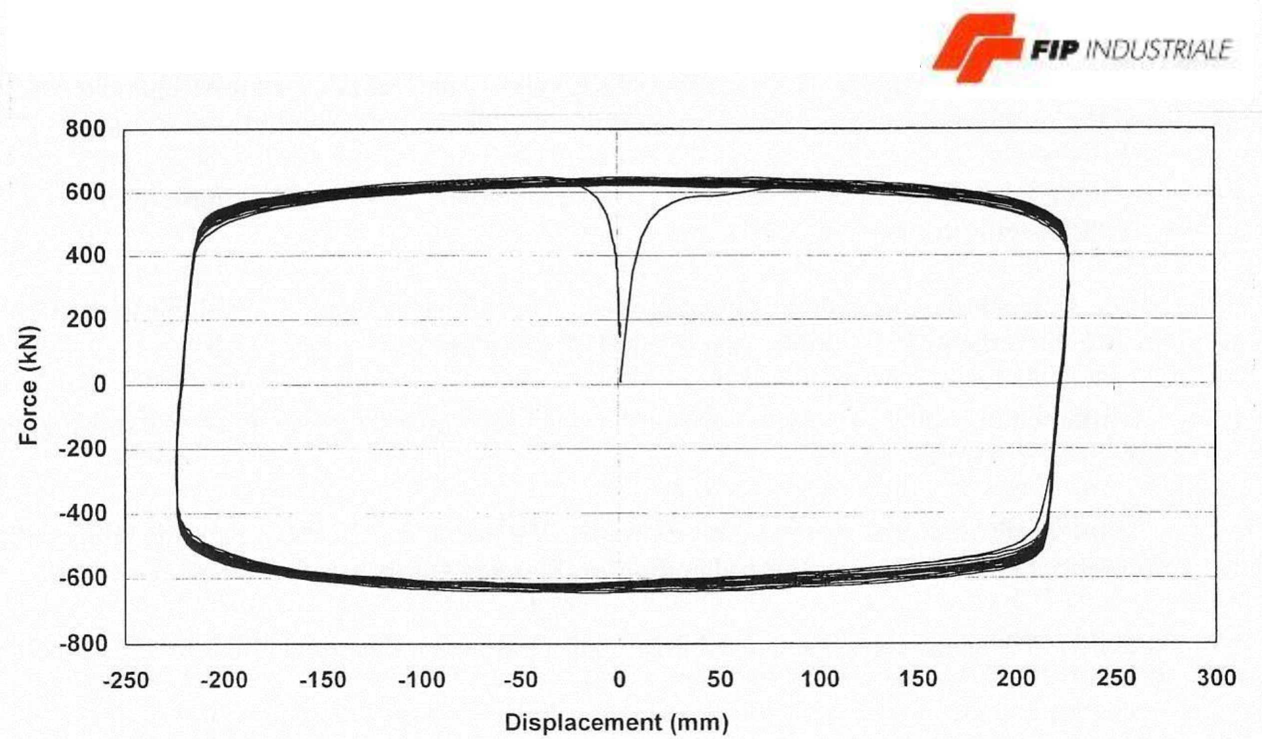
Nonlinear Viscous Damper



Typical behaviour model for viscous dissipaters (FIP)

(Infanti e Castellano, 2001)

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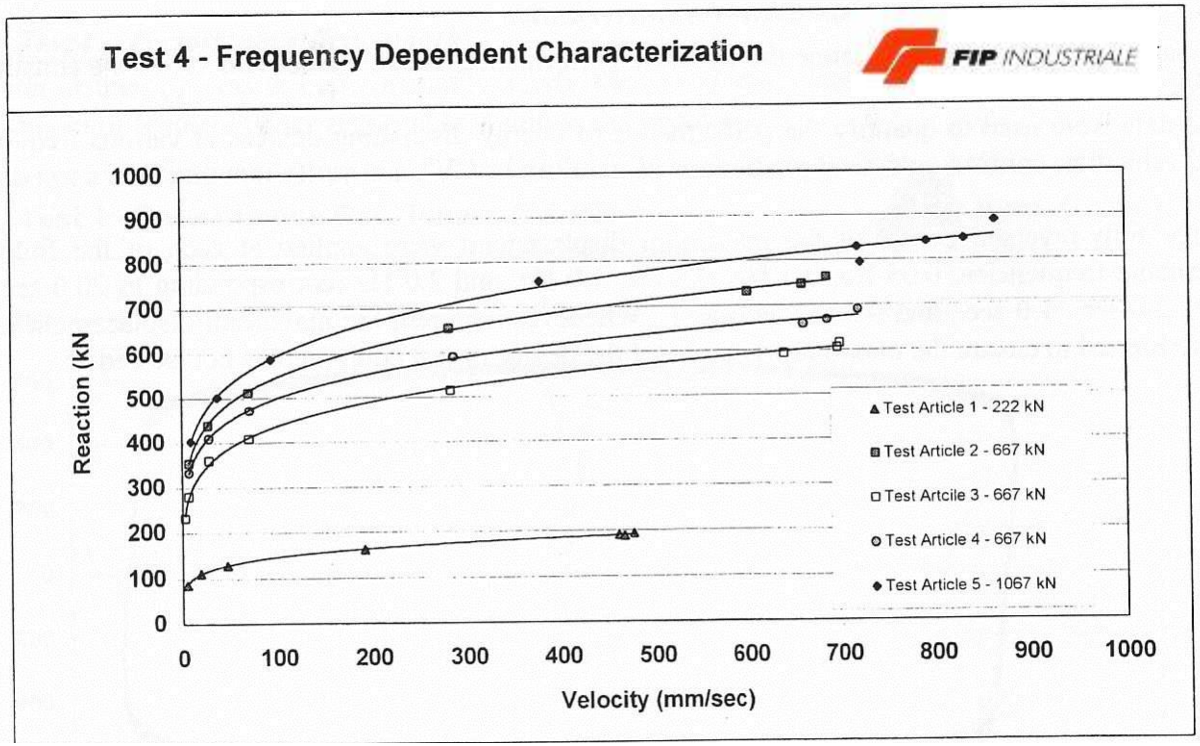
Nonlinear Viscous Damper



Force-Velocity relationship

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(Infanti & Castellano, 2001)

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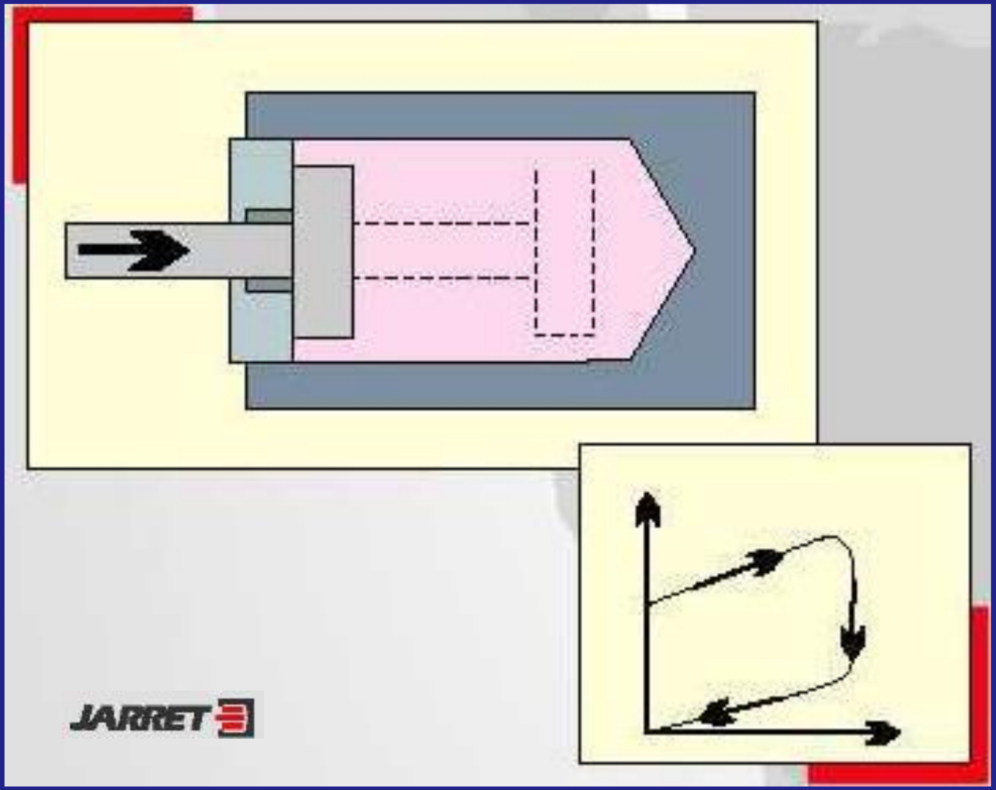
Dampers Solutions

Nonlinear Viscous Damper



$$F = F_0 + kx + Cv^{\alpha}$$

$$0.1 < \alpha < 0.4$$

(www.jarret.fr)

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Dampers and energy dissipation devices

Applications to bridges

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"Baixa do Rio Mondego - A1" Viaduct

Deck enlargement
Seismic Reinforcement (A2P)

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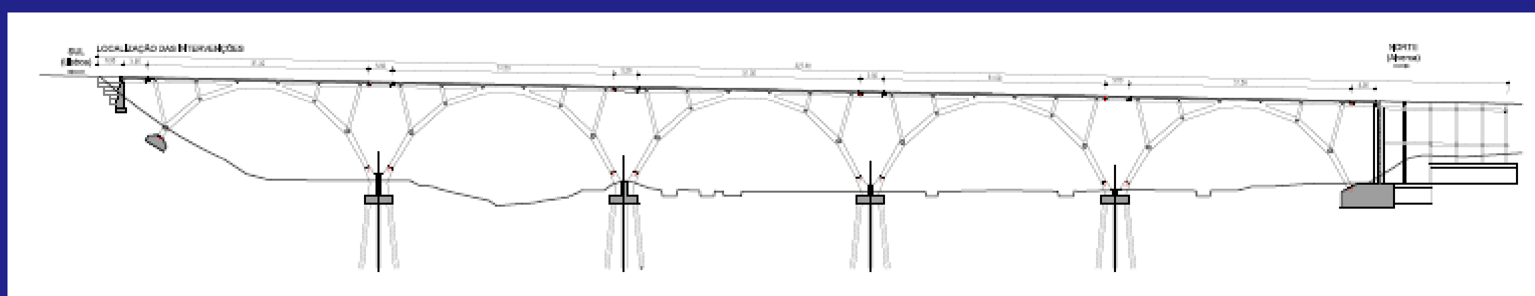
“Rio Trancão - A1” viaduct



Seismic Reinforcement (A2P)

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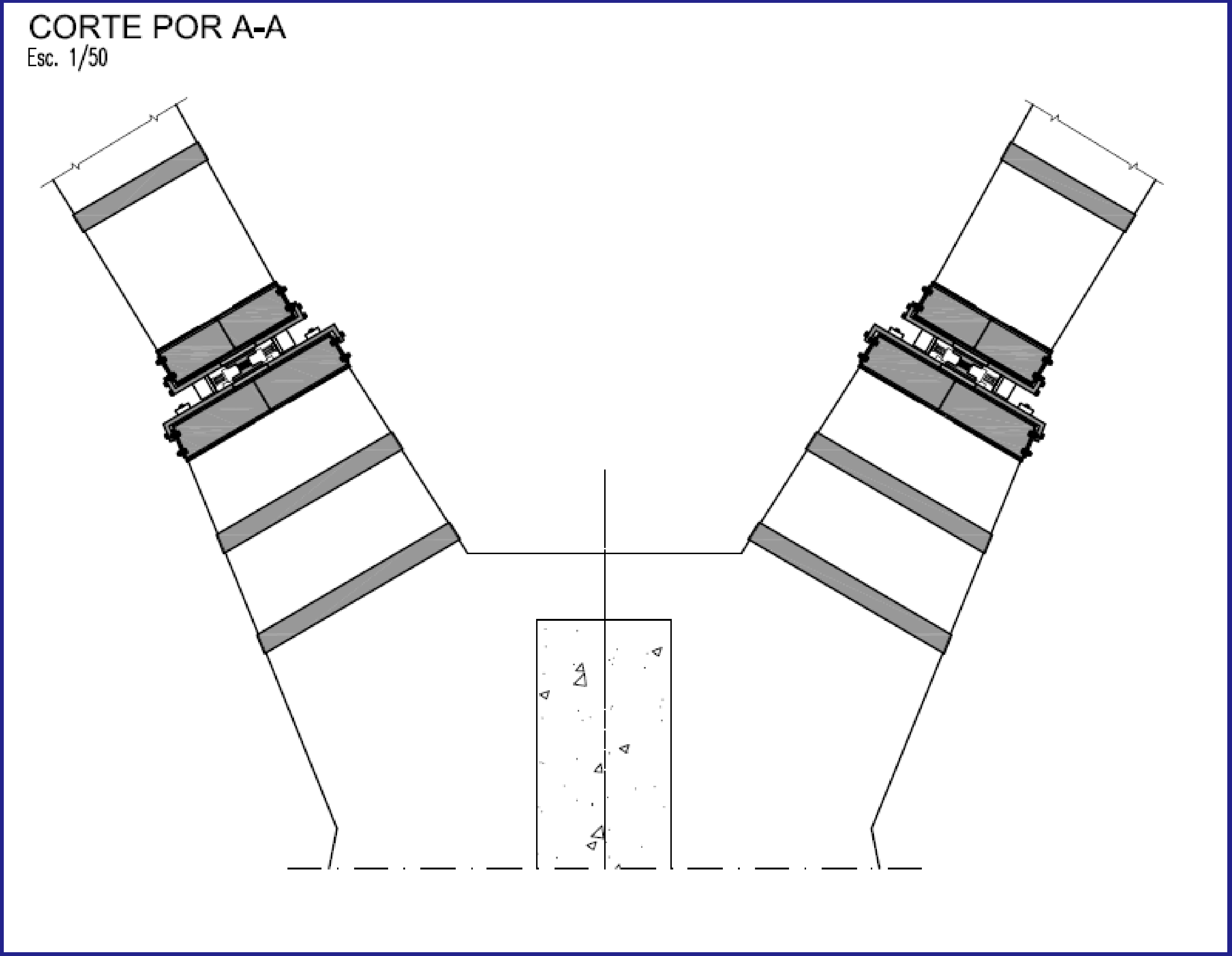
"Rio Trancão - A1" viaduct



Seismic Reinforcement (A2P)

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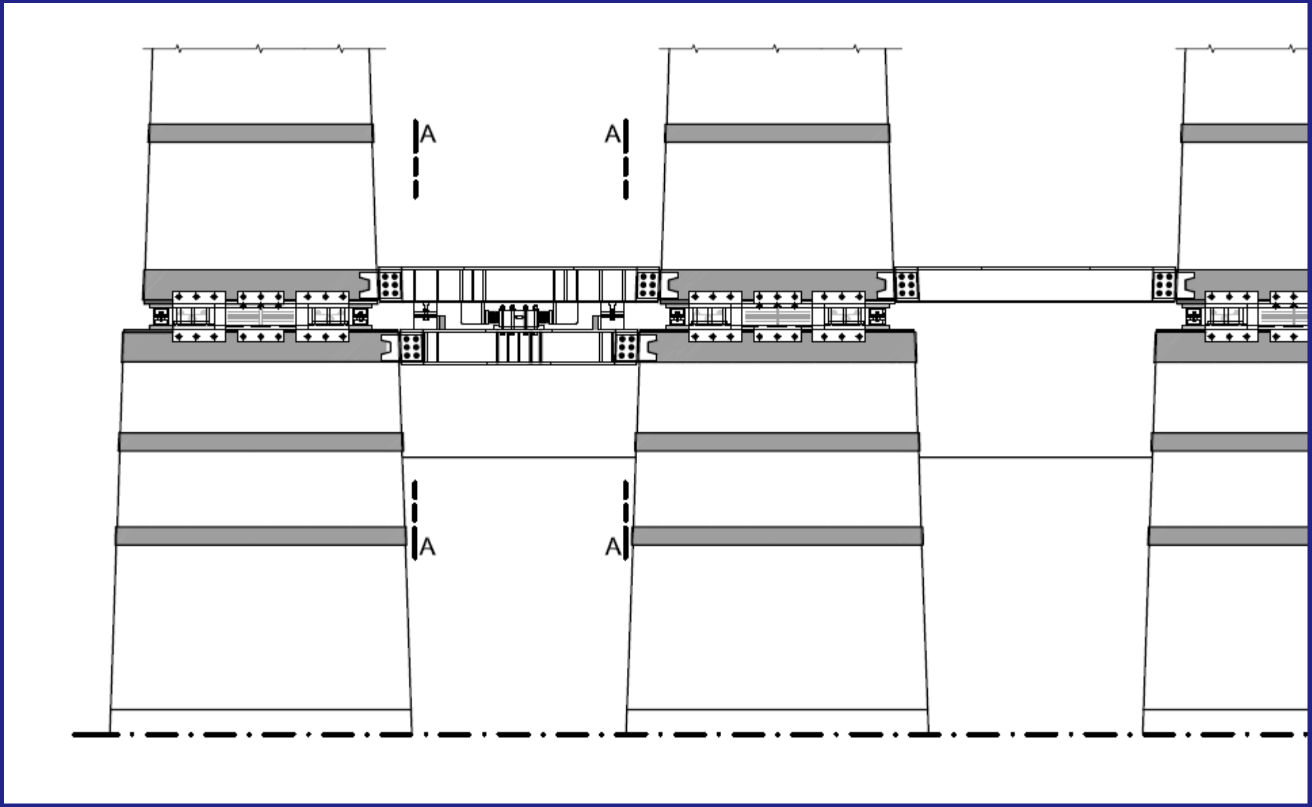
"Rio Trancão - A1" viaduct



Seismic Reinforcement (A2P)

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“Alhandra - A1” viaduct

Seismic Reinforcement (A2P)

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"Alhandra - A1" viaduct

Seismic Reinforcement (A2P)

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“Alhandra - A1” viaduct

Seismic Reinforcement (A2P)

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"Arcos Bridge – Sado River"

Seismic Reinforcement (A2P)

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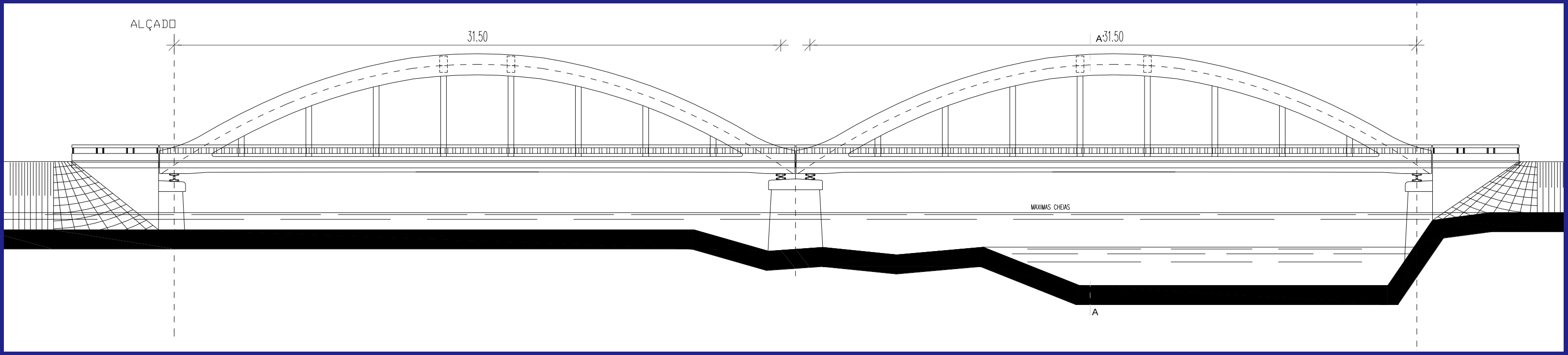
"Arcos Bridge – Sado River"



Seismic Reinforcement (A2P)

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Bridge applications of seismic protection systems

Vasco da Gama Bridge

Lisbon

Hysteretic dampers

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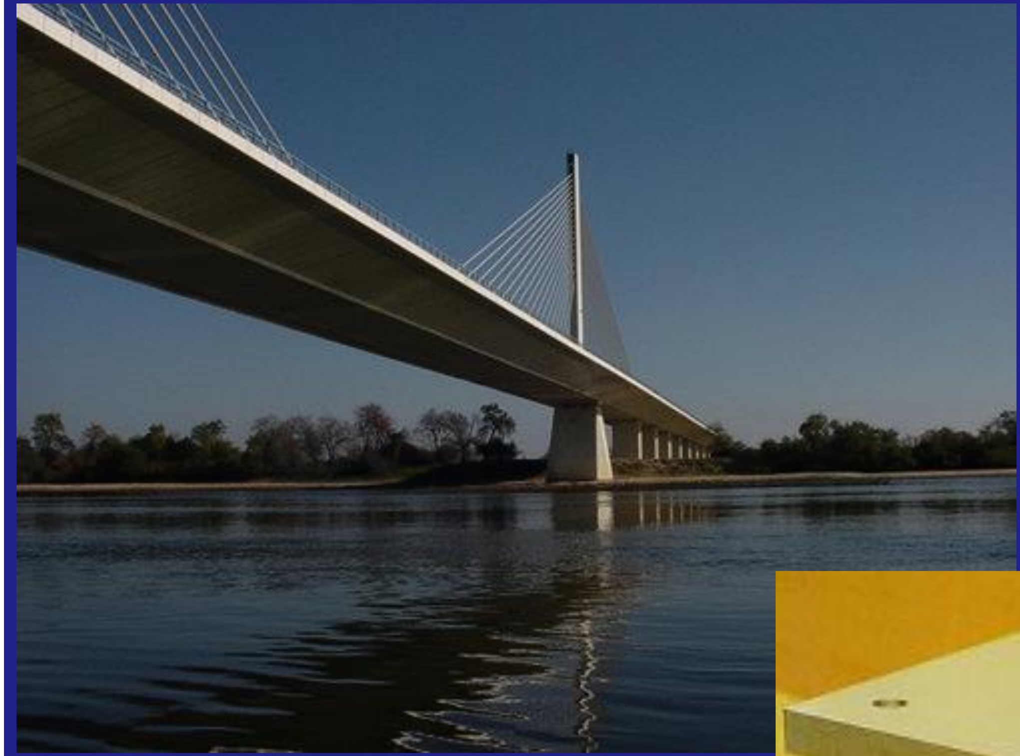
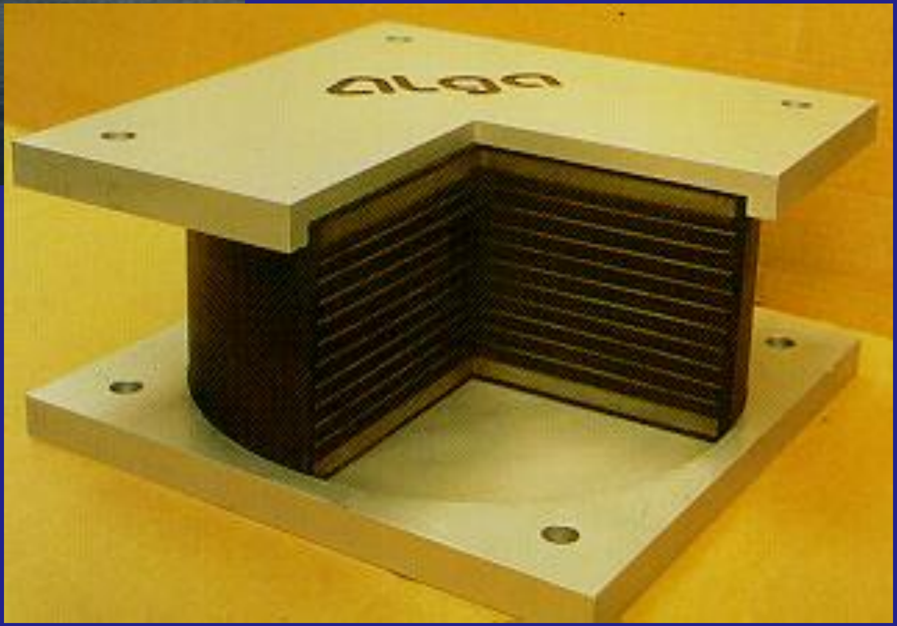
Bridge applications of seismic protection systems



Salgueiro Maia Bridge

Santarém



HDRB

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Bridge applications of seismic protection systems

Loureiro Viaduct

Viscous Damper

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Bridge applications of seismic protection systems

"Real" Viaduct

Shock absorbers

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Bridge applications of seismic protection systems

Viaduct over Ribeira da Laje and Rio Grande da Pipa

Viscous Damper

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Bridge applications of seismic protection systems

Vale da Lama Bridge – A22

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Bridge applications of seismic protection systems

Ribeira do Farelo Bridge

A22

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Bridge applications of seismic protection systems

Arade Bridge – A22

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The EUROCODE 8

Earthquakes are natural phenomena

Earthquake Disasters are not !

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