JORNADAS ReSist

LISBOA RESILIENTE AOS SISMOS

Seismic Isolation: principles & benefits for new and existing buildings

Lisbon, October 28th 2022

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Among all natural hazards, earthquakes lead to the highest number fatalities and, after severe storms, cause the second highest annual economic losses. This is not only true worldwide, but also for the European continent.

From 2006 to 2015, Europe experienced 21 earthquake-related disasters that resulted in 1,049 fatalities, more than 18 billion Euros in economic losses and affected 284,000 people.

Source: International Federation of Red Cross and Red Crescent Societies (2016). World Disasters Report 2016. Resilience: saving lives today, investing for tomorrow, Eds. D. Sanderson & A. Sharma, Geneva, Switzerland ISBN: 978-92-9139-240-7. http://www.ifrc.org/Global/Documents/Secretariat/201610/WDR 2016-FINAL_web.pdf)

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DAMAGE TO BUILDINGS OCCURRED DURING RECENT SEISMIC EVENTS

http://www.reluis.it/>Emergenza Terremoto Abruzzo>report
http://www.reluis.it/ > Terremoto Emilia 2012 > rapporti tecnici

Bachmann H. "Seismic Conceptual Design of Buildings – Basic principles for engineers, architects, building owners, and authorities", Federal Office for the Environment FOEN

http://www.bafu.admin.ch/publikationen/publikation/00799/index.html?lang=en

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Factors influencing damage mechanisms in frame buildings

- Conceptual design
- Construction details
- Quality of materials

SOME EXAMPLES

Building close to
Via XX Settembre, L'Aquila

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"Soft-Storey" mechanism – ground floor
Hotel Duca degli Abruzzi, Via Giovanni XXIII (AQ)
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"Soft-Storey" mechanism – ground floor
Building in Pettino (AQ)
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“Soft-Storey” mechanism – ground floor

The 1971 San Fernando, California, earthquake (magnitude 6.7) severely damaged the recently built Olive View Hospital

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“Soft-Storey” mechanism – ground floor

San Salvatore Hospital after the L’Aquila 2009 earthquake

Column damage at the main entrance

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"Soft-Storey" mechanism – ground floor
Kocaeli (Izmit, Turkey)
1999 Earthquake
ARAS KARGO
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"Soft-Storey" mechanism – upper floor
Building in Pianola (AQ)
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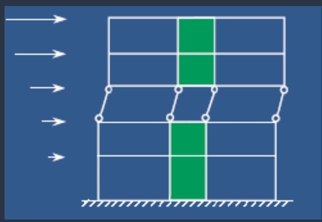
"Soft-Storey" mechanism – upper floor



Izmit, 1999

Kobe, 1995

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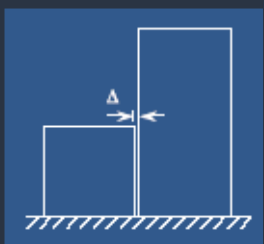
Pounding of adjacent structures or insufficient joints



School building in via Duca degli Abruzzi, L' Aquila

Messico, 1985

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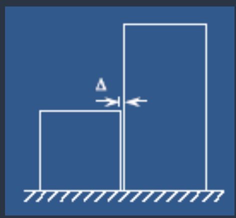
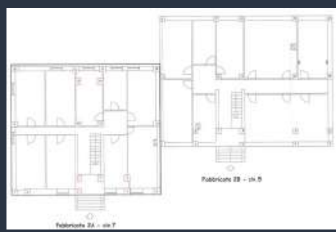
Pounding of adjacent structures or insufficient joints



L'Aquila, 2009



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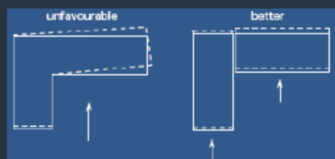
Asymmetric bracing and plan irregularity



Building in Pettino (AQ)

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Asymmetric bracing and plan irregularity

L'Aquila, 2009

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Lack of "capacity design" in the conceptual design phase

Buildings in L' Aquila

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During an earthquake
Cracks form in both concrete columns. In the poorly reinforced column at left, concrete chunks begin to fall. The well-reinforced column remains intact.
The brittle column begins to collapse as more chunks of concrete fall. Interlaced steel reinforcing bars hold the concrete in place in the strong column.
Source: UCLA ENGINEERING - Prof. J. Wallace
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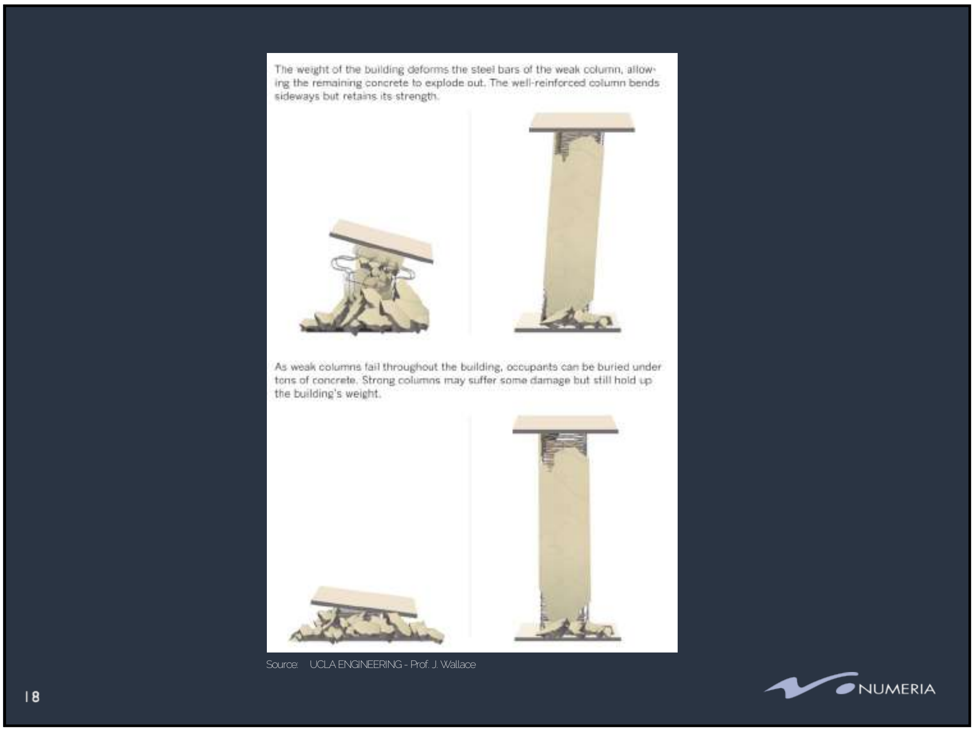
The weight of the building deforms the steel bars of the weak column, allowing the remaining concrete to explode out. The well-reinforced column bends sideways but retains its strength.
As weak columns fail throughout the building, occupants can be buried under tons of concrete. Strong columns may suffer some damage but still hold up the building's weight.
Source: UCLA ENGINEERING - Prof. J. Wallace
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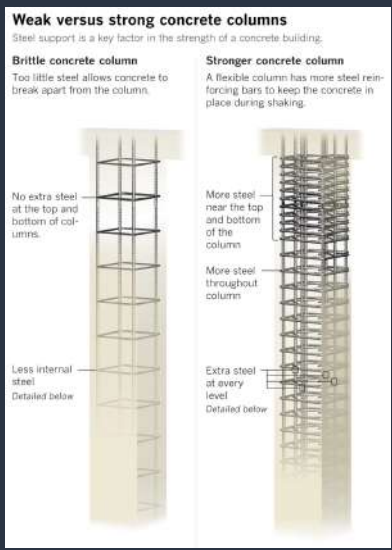

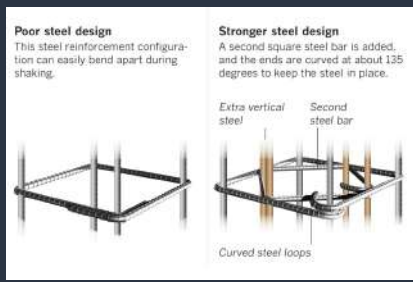

Source: UCLA ENGINEERING - Prof. J. Wallace

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In-plane and out-of-plane damage to infill walls

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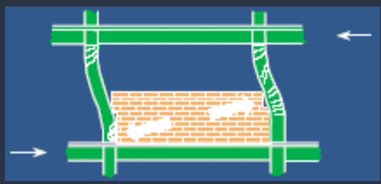
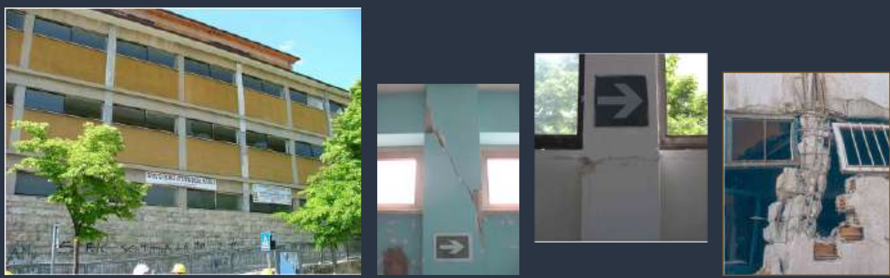
Partially infilled frames

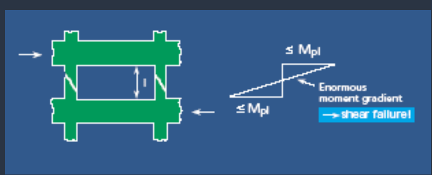


Friuli, 1976

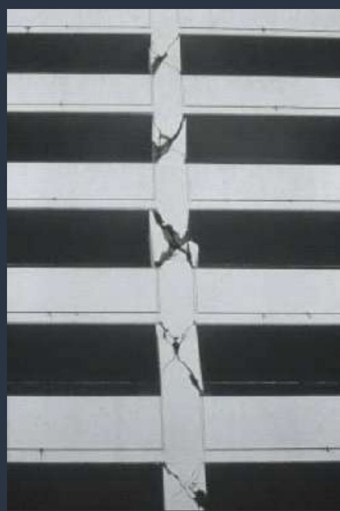


School building in via Duca degli Abruzzi, L' Aquila

Short columns effects



Stair in a building in L' Aquila



Northridge, 1994

Damage to structural joints and construction details

Buildings in and close by L' Aquila

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Construction details and quality of materials

Non-adequate reinforcement overlapping

Kocaeli (Izmit, Turkey)
1999 Earthquake

Shear failure of the column –insufficient stirrups

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Hospitals

Evacuated patients lie on their hospital beds shaded by a tree, in the aftermath of the 2017 earthquake, in Juchitan, Oaxaca state, Mexico

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Zagreb, Croatia – march 2020

New mothers were evacuated from a maternity ward following the earthquake

https://www.abc.net.au/news/2020-03-23/coronavirus-lockdown-zagreb-hampered-earthquake/12080066

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Zagreb, Croatia – march 2020

Responders salvaged infant incubators from the maternity ward

https://www.abc.net.au/news/2020-03-23/coronavirus-lockdown-zagreb-hampered-earthquake/12080066

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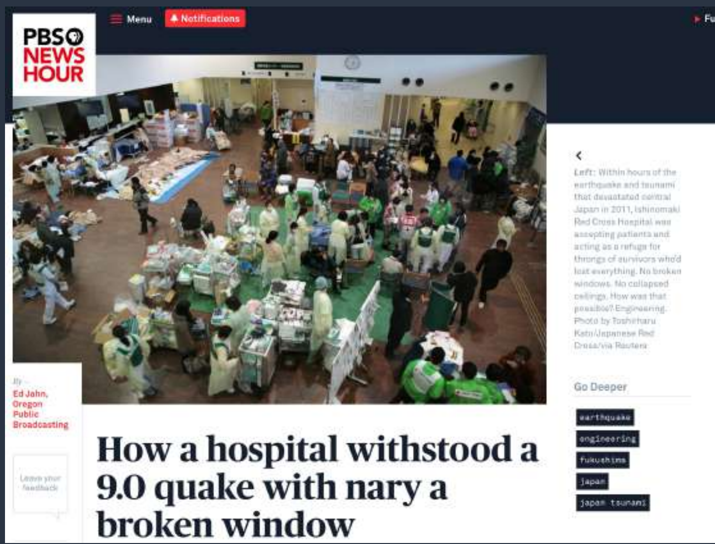
Ishinomaki, Japan – march 2011



Within an hour, the intact building was accepting patients and acting as a refuge for throngs of survivors who'd lost everything.

https://www.pbs.org/newshour/science/hospital-japan-withstood-9-0-earthquake-nary-broken-window

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Ishinomaki, Japan – march 2011

https://www.pbs.org/newshour/science/hospital-japan-withstood-9-0-earthquake-nary-broken-window

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DAMAGE TO NON-STRUCTURAL ELEMENTS

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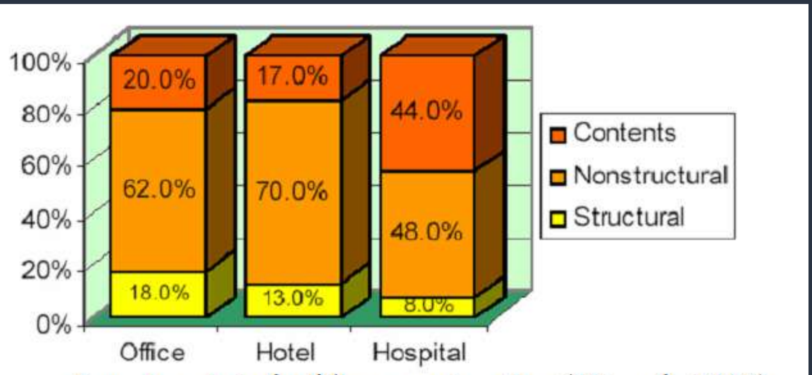

Investments in building construction (Miranda 2003)

Non-structural elements represent the major portion of the total investment in typical buildings.

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Damage to non-structural elements

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Damage to non-structural elements

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Damage to non-structural elements

Province building, L' Aquila

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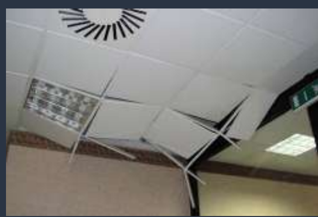
Damage to non-structural elements



Buildings in L' Aquila

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Damage to non-structural elements

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Damage to non-structural elements

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❑ PRIORITISE RISK REDUCTION

❑ REDUCE DISASTER RISK BY INNOVATIVE APPROACH WHICH IS SENSITIVE TO ECONOMICS, CULTURE AND USAGE

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SEISMIC DESIGN OF STRUCTURES

Philosophy of modern seismic design codes:

- ❑ Safeguard lives
- ❑ Limit structural damages
- ❑ Important civil structures remain operational

EC8 objectives:

- ❑ Structure withstand design seismic action (rare event) without local and global collapse
- ❑ Controlled (limited) damage of structure subjected to frequent, smaller intensity earthquake

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SEISMIC DESIGN OF STRUCTURES

Richter	Intensity	Return Interval	Hazard Level	Designated Performance
M<5	Minor	Often	No hazard for buildings	No architectural & structural damage
5<M<6	Moderate	Sometimes	Hazardous for rural buildings	Architectural damage but no structural damage
6<M<7	Strong	Rare	Hazardous for urban buildings	Structural damage but no collapse
M>7	Catastrophic	Very rare	Unrepaired damage of buildings	Severe damage but no collapse

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SEISMIC DESIGN OF STRUCTURES

Code Basis

Force ↘ Mass ↓ Acceleration ↙

$$F = M a$$

Reality Basis

Energy ↘ Mass ↓ Velocity ↙

$$E = \frac{1}{2} M v^2$$

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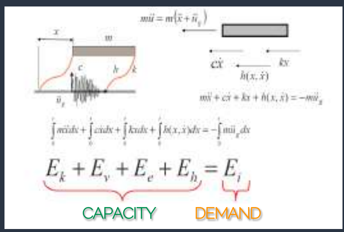
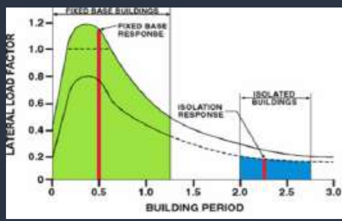
SEISMIC DESIGN OF STRUCTURES



Seismic protection can be obtained either by reducing the **demand** on the structure and/or increasing the **capacity**

$$E_i \leq E_e + E_k + \underbrace{E_h + E_v}_{E_d}$$

DEMAND ≤ CAPACITY



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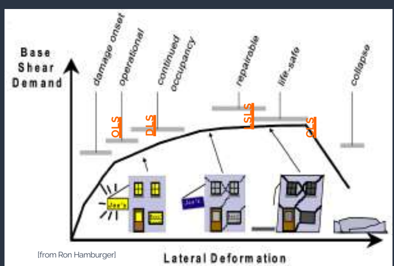
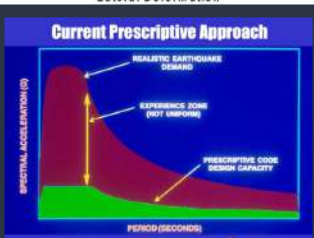
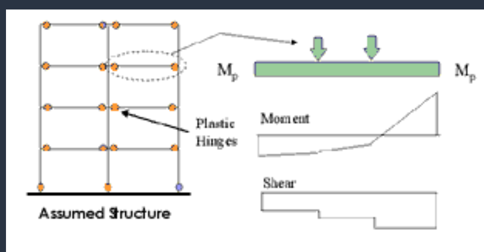
SEISMIC DESIGN OF STRUCTURES
CONVENTIONAL APPROACH





In well-designed conventional structures, the yielding action is designed to occur within the structural members at specifically selected locations ("plastic hinges zones"), e.g. mostly in the beams adjacent to beam-columns joints in moment-resisting framed structure.



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SEISMIC DESIGN OF STRUCTURES
CONVENTIONAL APPROACH

Yielding of structural members is an inherently damaging mechanism, even though appropriate selection of the hinge locations and carefully detailing can ensure structural integrity.

Conventional earthquake engineering design often results in structures, which, while they may be designed not to collapse, may be irreparably damaged beyond repair during strong ground shaking.

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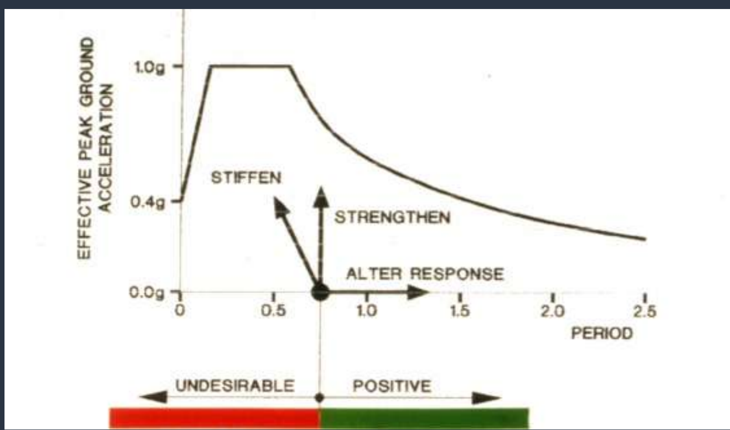
SEISMIC UPGRADE STRATEGIES



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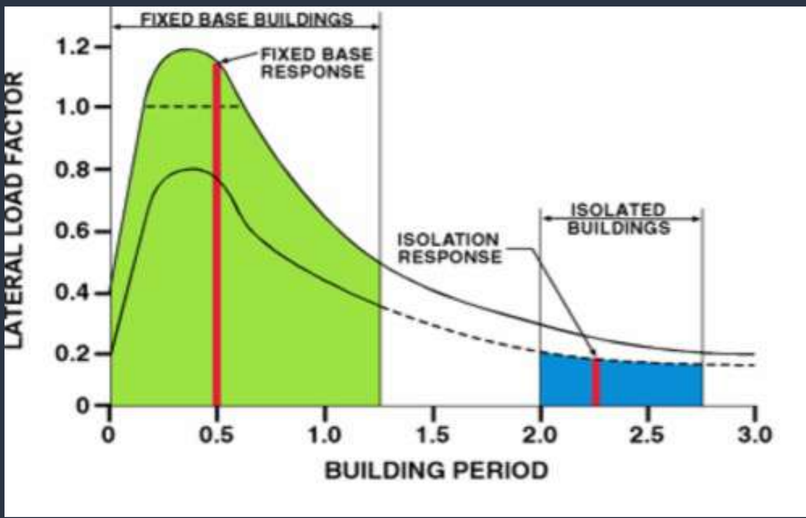
SEISMIC UPGRADE STRATEGIES



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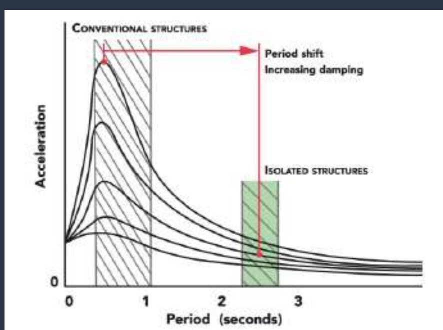
THE PRINCIPLES OF BASE ISOLATION

Isolation is achieved by mounting the structure on a system of supports giving a low stiffness in the horizontal direction.

Seismic isolation consists essentially of the installation of devices which decouple the structure, or its contents, from potentially damaging earthquake-induced ground, or support, motions



This decoupling is achieved by increasing the **flexibility** of the system, together with providing appropriate **damping**

It is important to realise that despite the need for some damping, **the isolators are not principally acting to absorb the energy of the earthquake**, but are providing an interface that reflects earthquake energy back into the ground so reducing its transmission into the structure.

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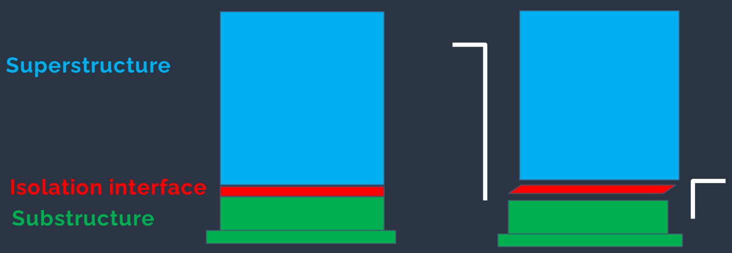
THE PRINCIPLES OF BASE ISOLATION



In seismic isolation part (or all) of the superstructure is separated from the lower part of the structure by an interface that is soft and flexible in the horizontal direction.

Generally, the interface is placed between the foundation or basement and the ground floor and so the term base isolation can be accurately applied.

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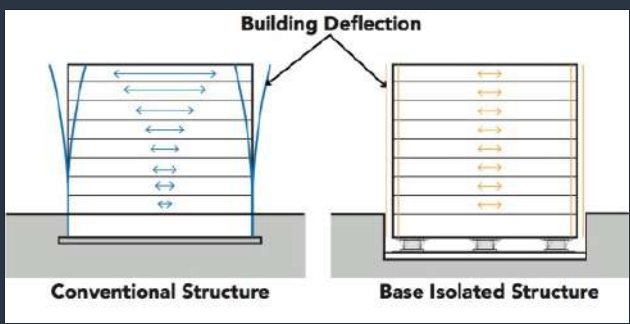
RESPONSE OF CONVENTIONAL AND BASE ISOLATED STRUCTURES TO EARTHQUAKES



The effect of the isolation system is that during an earthquake the structure moves virtually as a rigid body on the isolators. The deformation is concentrated at the isolation interface, but unlike the structure, the isolation system can accommodate large deformations without damage.

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RESPONSE OF CONVENTIONAL AND BASE ISOLATED STRUCTURES TO EARTHQUAKES

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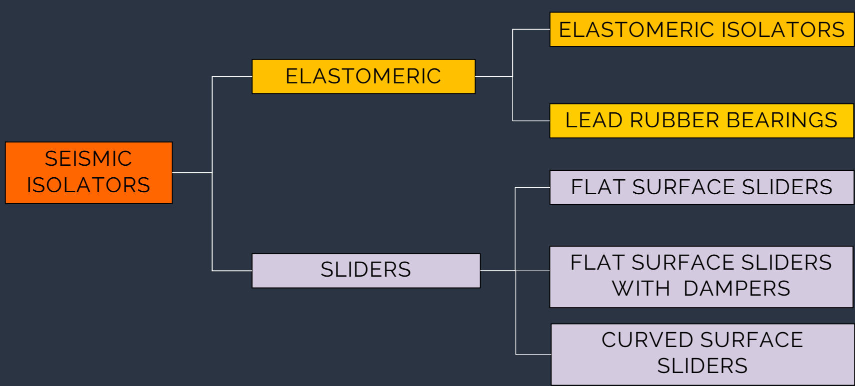
BASE ISOLATION DEVICES



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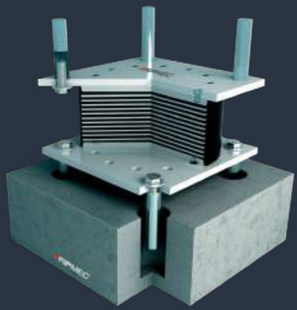
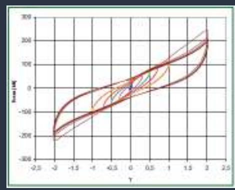
ELASTOMERIC ISOLATORS (HDRB)



HDRB: made of alternate layers of steel and hot-vulcanized rubber



Typical hysteretic curve of an elastomeric isolator obtained from dynamic tests with increasing shear strain amplitude (f=0.5 Hz).

Usually circular in shape but can be also produced in square or rectangular shape.

They are characterized by low horizontal stiffness, high vertical stiffness and suitable damping properties. These characteristics permit, respectively, to increase the fundamental period of vibration of the structure, to resist to vertical loads without appreciable settling, and to limit horizontal displacements in seismically isolated structures.

Equivalent viscous damping coefficient

ξ = 10 ÷ 15 %

(at a deformation of 100%)

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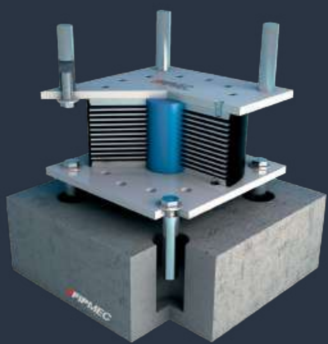
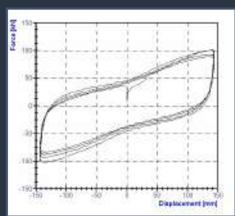
LEAD RUBBER BEARINGS (LRB)





Typical hysteretic curve of a Lead Rubber Bearing

Thanks to the high energy dissipation capacity, it is possible to reduce the horizontal displacement, in comparison with that of an isolation system with the same equivalent stiffness but lower energy dissipation capacity.

Equivalent viscous damping coefficient

up to 30 %

thanks to the yielding of the lead core

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FLAT SURFACE SLIDERS

Flat surface sliders are free multi-directional sliding bearings with low-friction sliding surfaces.

They are always used in combination with other seismic devices (isolators and/or dampers).

The dynamic friction coefficient is approximately 1%, as a consequence their contribution to horizontal forces is almost always negligible.

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FLAT SURFACE SLIDERS

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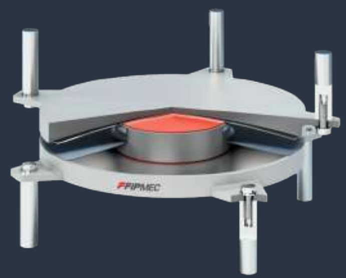
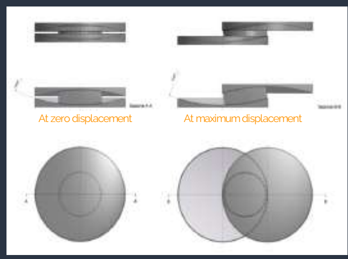
CURVED SURFACE SLIDERS





Double concave surface slider

Characterised by two primary concave sliding surfaces with the same radius of curvature; both surfaces accommodate horizontal displacement and rotation.

Each sliding surface is designed to accommodate only half of the horizontal displacement, so that the dimension in plan of the device are smaller than a similar curved surface slider.

Furthermore, the eccentricity of the vertical load is halved (with respect to a curved surface slider).

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DOUBLE CURVED SURFACE SLIDERS

1911 – Patent of a seismic isolator by Domenico Lodà ("bearing system for buildings aimed at avoiding the transmission of seismic movements")

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Shaking table tests on a scaled model of a seismically isolated building – pendulum isolator detail

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BASE ISOLATION CAN BE APPLIED TO EITHER NEW AND EXISTING STRUCTURES

The rationale for the use of seismic isolation varies for each project.

However, there are some basic incentives for the use of base isolation:

- **Achieve enhanced structural performance** (with reduced structural sections)
- **Need for continuous post earthquake operations**
- Protection of building content
- **Historic preservation**
- **Minor modification needed to make an aseismic design suitable for high seismicity areas**
- **Suitable for application to industrialized building systems**

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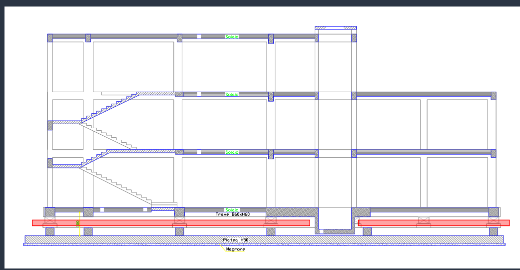
BASE ISOLATED NEW SCHOOL BUILDING



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SEISMIC RETROFIT OF R.C. BUILDING WITH BASE ISOLATION

If:

- the building has, at least, some capacity to resist horizontal loads;
- the materials characteristics are acceptable;
- the building can carry the design static loads;
- it is possible to insert the isolators

then

the adoption of the seismic isolation is simple, effective and convenient from the economical point of view because interventions will be limited to few structural elements and can be made with the building being **in use**

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RETROFITTED R.C. BUILDING

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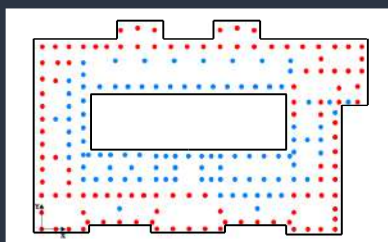
RETROFITTED MASONRY BUILDING SCHOOL



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SOME PECULIAR ASPECTS/DETAILS TO BE CONSIDERED IN BASE ISOLATION APPLICATIONS

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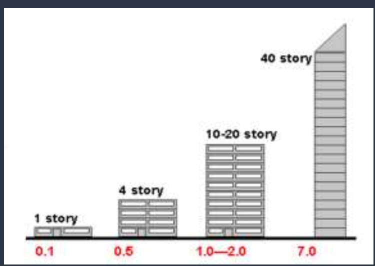
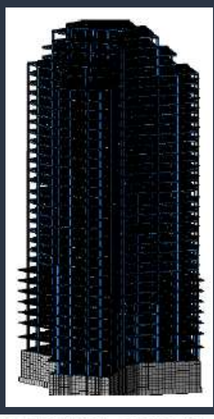
CAN THE BUILDING BE ISOLATED ?





EIGENVALUES, FREQUENCIES, PERIODS OF VIBRATIONS,

No.	EIGEN VALUES	FREQUENCIES rad/s	FREQUENCIES Hz	PERIODS s
1	0.695049	1.44	0.23	4.3649
2	0.690252	1.45	0.23	**4.3348**

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CAN THE BUILDING BE ISOLATED ?

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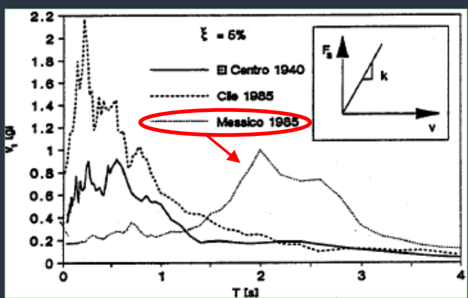
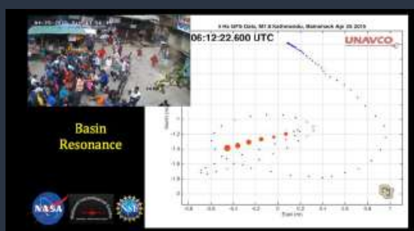
CAN THE BUILDING BE ISOLATED ?





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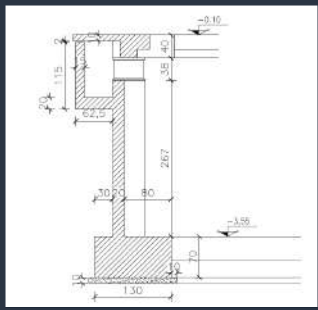
SEISMIC GAP



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SEISMIC GAP

70 NUMERIA

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STAIRS

71 | NUMERIA

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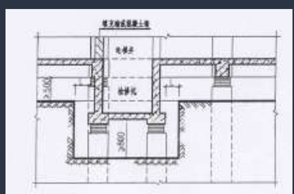
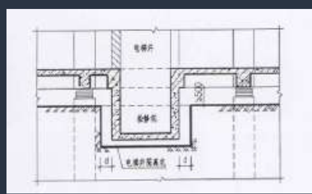
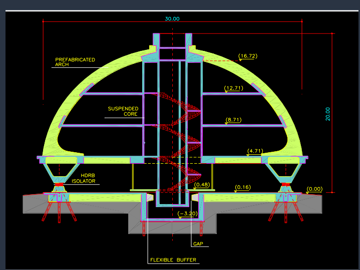
ELEVATORS







Courtesy of Prof. Parducci

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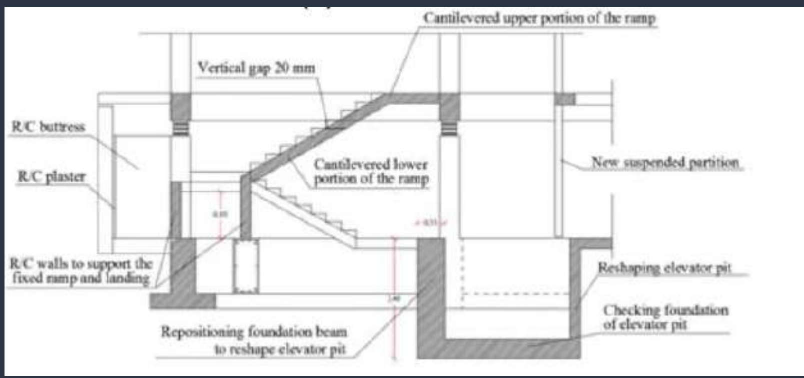
Solutions for retaining walls, stairs and elevator at basement level



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PIPELINES: FLEXIBLE CONNECTIONS

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Thank you

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JORNADAS ReSist

LISBOA RESILIENTE AOS SISMOS

Examples of existing buildings retrofitted with seismic isolation

Lisbon, October 28th 2022

Alberto Dusi

dusi@numeria-eng.it

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1

1

EXISTING R.C. BUILDINGS

- ✓ poor/inadequate structural details
- ✓ no control of damage mechanism (capacity design)
- ✓ no possibility to withstand unelastic deformation

Thanks to the adoption of seismic isolation, a structure with a capacity to resist horizontal forces even much lower than the capacity requested to a fixed base structure can resist strong earthquake remaining in the elastic domain.

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SEISMIC RETROFIT OF R.C. BUILDING WITH BASE ISOLATION

If:

- the building has, at least, some capacity to resist horizontal loads;
- the materials characteristics are acceptable;
- the building can carry the design static loads;
- it is possible to insert the isolators

then

the adoption of the seismic isolation is simple, effective and convenient from the economical point of view because interventions will be limited to few structural elements

3

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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

- Built in 1959 - A_{tot} = 7200 m^2
- Block A: 3 storeys above ground level
- Block B: 4 storeys above ground level
- Block C: 4 storeys above ground level + an underground level
- Block D: 4 storeys above ground level + an underground level
- Block E: 4 storeys above ground level + an underground level

4

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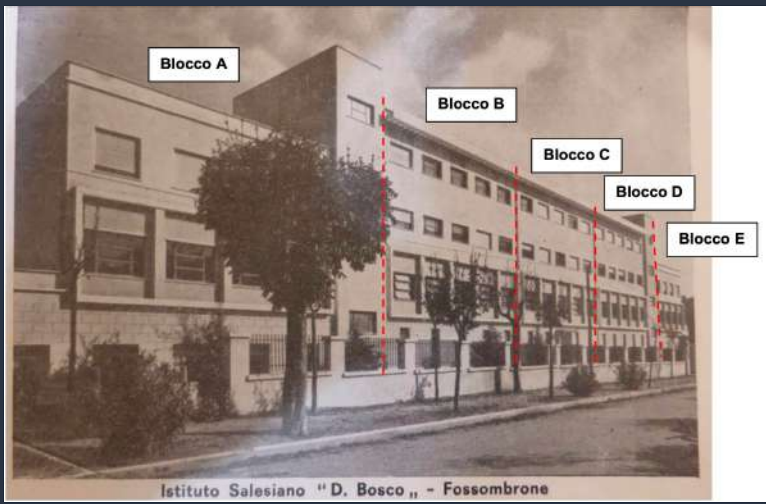
SEISMIC RETROFIT OF R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021



5 NUMERIA

5

SEISMIC RETROFIT OF R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

6 NUMERIA

6

SEISMIC RETROFIT OF R.C. SCHOOL BUILDING
WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

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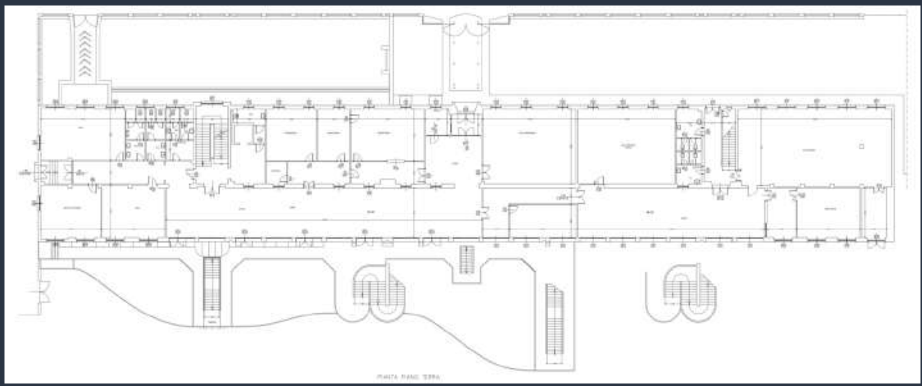
SEISMIC RETROFIT OF R.C. SCHOOL BUILDING
WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021



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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING WITH BASE ISOLATION

Vulnerability assessment results: seismic risk index ζ_E^*

Block A - ζ_E = 0,133

Block B - ζ_E = 0,167

Block C - ζ_E = 0,122

Block D - ζ_E = 0,151

Block E - ζ_E = 0,131

* Ratio between the maximum seismic action the building can resist and the maximum seismic action to be used in the design of a new structure

Istituto Donati, Fossombrone, 2021

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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

CONVENTIONAL RETROFIT

- Generalised strengthening (FRP) of beam, columns and joints
- Construction of new shear walls

Increase of seismic safety: ζ_E = 0,60

Cost: € 8.805.600, 00

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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

RETROFIT WITH BASE ISOLATION

- Limited strengthening intervention on short beams (stairs)
- Increase of the section of the part of the columns below the isolators

Increase of seismic safety: $\zeta_E = 0{,}80$

Cost: € 4.593.140, 14

11

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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

RETROFIT WITH BASE ISOLATION

Descrizione	Macrocategorie	Categorie	Subcategorie	Subcategorie
Riepilogo macrocategorie				
00_OPERE PROVVISIONALI	138.499,93			
01_DEMOLIZIONI	361.117,99			
02_OPERE STRUTTURALI	2.140.911,56			
02.1_CLS LAVORI INTERNI		645.454,00		
02.2_ISOLATORI		1.120.037,53		
02.3_SOLAI		254.309,74		
02.4_CLS LAVORI ESTERNI		121.110,29		
03_EDILI FINITURA	611.744,04			
04_IMPIANTI	106.060,48			
05_RIQUALIFICAZIONE ENERGETICA	1.234.806,14			
05.0_OPERE PROVVISIONALI		24.633,60		
05.1_DEMOLIZIONI		44.594,99		
05.2_COIBENTAZIONE TERMICA		392.492,15		
05.3_INFISSI		544.559,46		
05.4_CENTRALE TERMICA		148.968,08		
05.5_EDILI E IMPIANTI		79.557,86		
Importo lavori	**4.593.140,14**			

Istituto Donati, Fossombrone, 2021

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12

SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

CONVENTIONAL

ζ_E = 0,60

€ 8.805.600, 00

BASE ISOLATION

ζ_E = 0,80

€ 4.593.140, 14

The school can be used during the retrofit

Istituto Donati, Fossombrone, 2021

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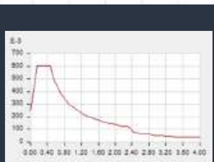
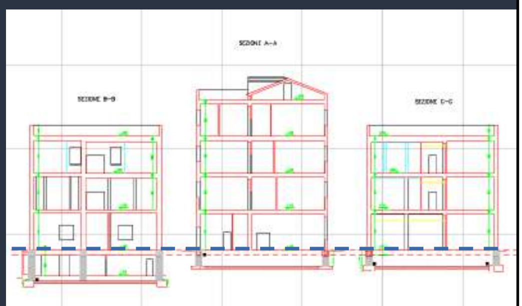
SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

RETROFIT WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021





BASE ISOLATION LEVEL

NUMERIA

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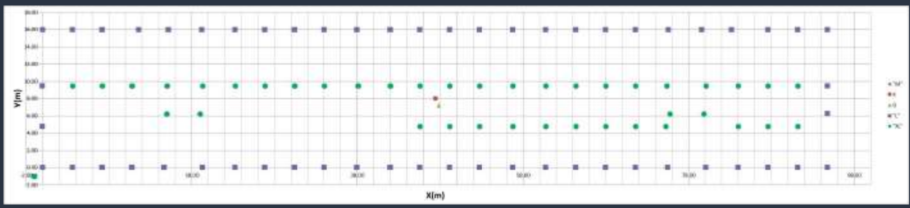
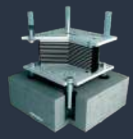
SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

RETROFIT WITH BASE ISOLATION



56 elastomeric isolators + 40 flat surfacesliders



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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING WITH BASE ISOLATION

Istituto Donati, Fossombrone, 2021

RETROFIT WITH BASE ISOLATION

Working sequence:

a. strengthening of the columns below the level of isolators location
b. cutting of the top portions of the columns at basement level
c. insertion of isolating devices
d. demolition and reconstruction of the first flight of the stairs., where present

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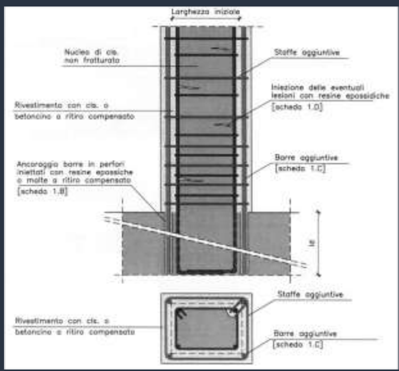
SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

RETROFIT WITH BASE ISOLATION



Reinforcement of the substructure's columns

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SEISMIC RETROFIT OF A R.C. SCHOOL BUILDING
WITH BASE ISOLATION

RETROFIT WITH BASE ISOLATION

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Residential Building, San Severino Marche, 2019

courtesy of FIPMEC

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Residential Building, San Severino Marche, 2019

- 14 SI + 14 VM

courtesy of FIPMEC

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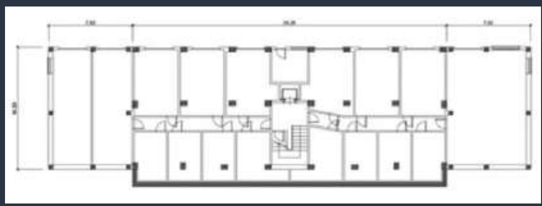
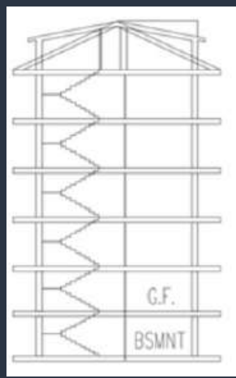
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

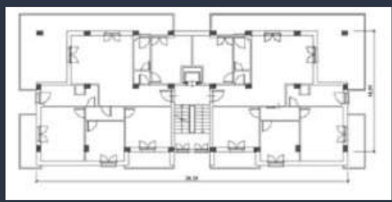
Building A



Basement plan



Transversal section



Intermediate floor plan

average cubic strength of concrete R_{cm} = 22.9 MPa

yield strength f_{yk} of steel = 435 MPa

NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

Vulnerability index* of the construction = 0,10

* Capacity/Demand (C/D) ratio between the capacity and demand accelerations

The damage scenario corresponding to the attainment of the limit state is associated with the **flexural failure** of beams, but a large number of beams and columns have C/D ratios lower than 0.6 for lack of both flexural and shear strength.

Moreover some factors of intrinsic **vulnerability** characterize the building: variation in height of the façade beams, misalignments of columns, cantilevered portions of the façades, presence of short beams near the staircase.

The building suffered damage in the seismic event, especially at the lower two levels, to both non-structural (claddings and internal partitions) and structural elements (cracking of r/c elements).

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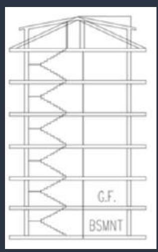
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

Why base isolation?

1. possibility to carry out interventions only at the basement level
2. almost no strengthening works on the elevation, in spite of the generalized low seismic-resistant capacity of the primary structural system.



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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

Working sequence:

a. strengthening of the columns below the level of isolators location
b. cutting of the top portions of the columns at basement level
c. insertion of isolating devices
d. cutting and strengthening of retaining wall at basement
e. demolition and reconstruction of the first flight of the stairs.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

For the substructure the strengthening of columns below the isolators was needed: a jacketing with r/c and steel profiles has been adopted.

25

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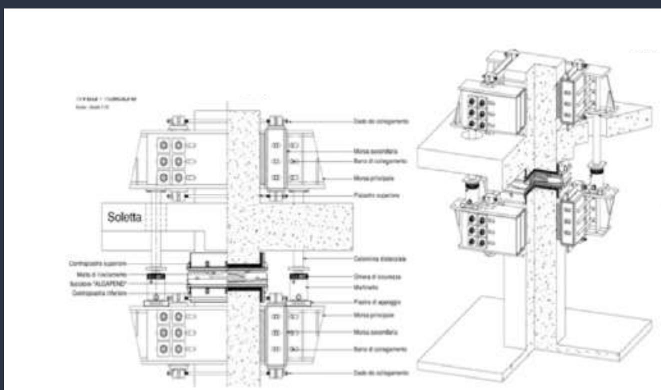
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A



The isolating system is made of curved surface sliders with a radius of curvature R=4000mm, nominal dynamic friction coefficient 3.0% and a displacement capacity ±200mm.

26

NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

27 NUMERIA

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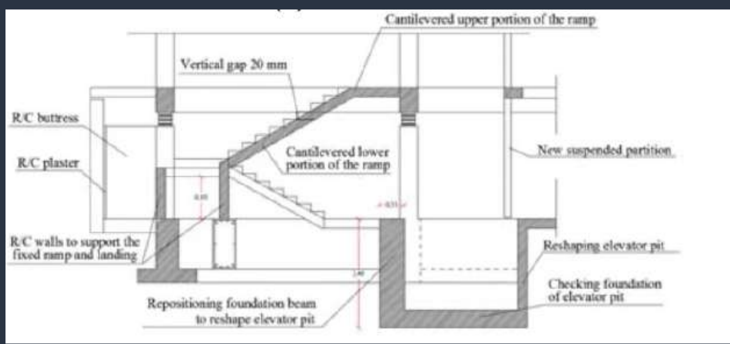
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A



Solutions for retaining walls, stairs and elevator at basement level

28 NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building A

- Strengthening of foundations: **not necessary**
- **No strengthening** of beams and columns of the building elevation
- No trouble related to the detail arrangements, since the detailing design rules for the ductility of seismic-resistant r/c structures are not prescribed for base-isolated constructions which perform in the elastic range.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH CONVENTIONAL RETROFIT

Building A – conventional retrofit

One of the most effective conventional technique for the seismic improvement of a r/c framed structure consists of infilling the frame net along vertical alignments to create **r/c walls** able to increase the lateral resistance and reduce the lateral and torsional deformability of the structure.

In the present case the solution is not feasible due to unavoidable interferences of the strengthening walls with the internal distribution of the apartments.

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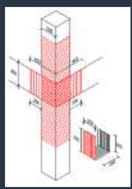
SEISMIC RETROFIT OF R.C. BUILDINGS WITH CONVENTIONAL RETROFIT

Building A – conventional retrofit

Due to these constraints the only practicable structural solutions for the seismic improvement should provide for the strengthening through r/c jacketing of the large number of inadequate beams and columns and the strengthening of the floors through the construction of a r/c thin slab to ensure a diaphragm behaviour. Local strengthening of some critical elements should be also provided (landing beams of stairs, beams with height equal to the floor thickness).



The conventional works would allow the seismically improved structure to achieve a capacitive acceleration $PGA_{C,LS}=0.211g$, that is a C/D ratio equal 0.70 which, being ≥0.60, is acceptable.

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31

SEISMIC RETROFIT OF R.C. BUILDINGS WITH CONVENTIONAL RETROFIT

Building A – conventional retrofit

- standard protection levels not reached
- high impact on the construction since almost all the non structural elements should be demolished
- very high cost with respect to the benefit achieved

NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS

Building A: cost comparison

Category of works	Traditional		Base-isolated		Diff.
Type A - Repair	€ 1.280.000	61.1 %	€ 199.000	14.7 %	-84.5%
Type B - Seismic enhancement	€ 582.000	27.8 %	€ 646.000	47.6 %	+11.0%
Retrofit due to Type B works	€ 78.000	3.7 %	€ 356.000	26.2 %	+356.4%
Hygienic-sanitary conformity	---	---	---	---	---
Conformity of plants	---	---	---	---	---
Energy saving conformity	€ 156.000	7.4 %	€ 156.000	11.5 %	=
Total	€ 2.096.000	100.00 %	€ 1.357.000	100.0 %	-34.1%

33 NUMERIA

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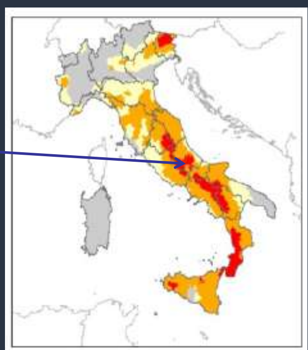
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B



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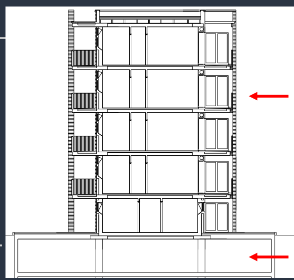
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

6089 t

Structure overall mass



4174 t

Mass of the superstructure

1915 t

Mass of the substructure

BASE SHEAR

CONVENTIONAL

30220 kN (x)
13310 kN (y)

BASE ISOLATED

6700 kN

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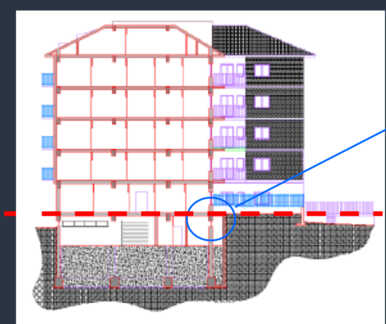
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B



BASE ISOLATION LEVEL

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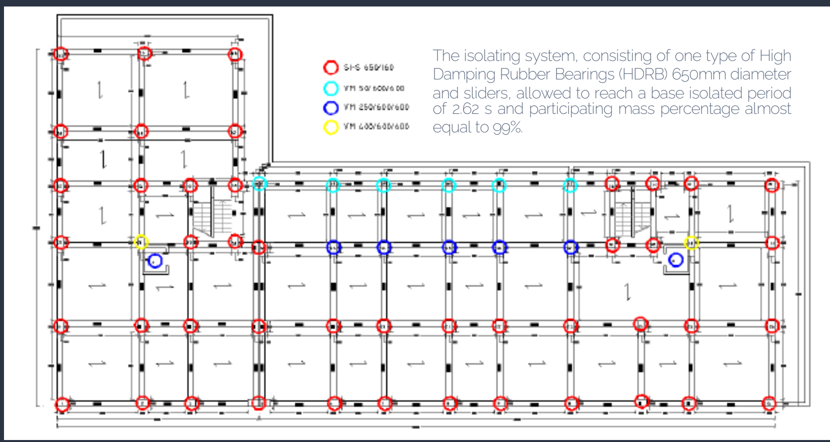
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B



The isolating system, consisting of one type of High Damping Rubber Bearings (HDRB) 650mm diameter and sliders, allowed to reach a base isolated period of 2.62 s and participating mass percentage almost equal to 99%.

Layout the base isolation system

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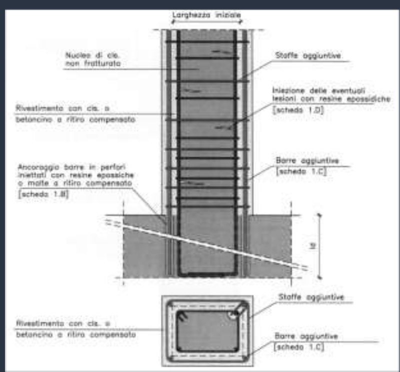
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B



Reinforcement of the substructure's columns

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

40 NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

41 NUMERIA

41

SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

42 NUMERIA

42

SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

43

NUMERIA

43

SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

44

NUMERIA

44

SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building B

NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS

Building B: cost comparison

CONVENTIONAL RETROFIT	BASE ISOLATION RETROFIT
Extensive interventions	Limited interventions
Building service disruption	Building remain operational
Performance level lower than the current codes demands (60%)	Performance level equal to the one required by the code (100%)
Damage expected for future earthquake	No damage for future earthquake
4.916.678,00 € total cost	3.029.118,00 € total cost
23 months working time	9 months working time

The base isolation approach allows to achieve an immediate saving of 37%, saving that, in the building lifetime, will be even greater.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C

average cubic strength of concrete R_{cm} = 12.5 MPa

yield strength f_{yk} of steel = 380 MPa

47 NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C

Vulnerability index* of the construction = 0,37

* Capacity/Demand (C/D) ratio between the capacity and demand accelerations

The collapse scenario associated to the shear failure of a column together with minor flexural damage of beams

Intrinsic vulnerability: variation in height of the beams and the presence of beam-column joints not fully confined involves values of risk indexes still lower than that estimated at the global level.

The building was severely damaged by the earthquake age, especially at the lower two or three levels. Almost all the claddings were damaged as well as many of the internal partitioning. A number of cracks were observed on the r/c elements of the basement story where the surface of the structural elements was not plastered.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C

Working sequence:

a. strengthening of the columns below and above the level of isolators location

b. controlled cutting of the top portions of the columns at basement level

c. insertion of isolating devices

d. cutting and strengthening of retaining wall at basement

NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C

The isolating system is made of curved surface sliders with a radius of curvature R=3100mm, nominal dynamic friction coefficient 2.5% and a displacement capacity ±200mm.

NUMERIA

50

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C

- Strengthening of foundations: **not necessary**
- **No strengthening** of beams and columns of the building elevation
- No trouble related to the detail arrangements, since the detailing design rules for the ductility of seismic-resistant r/c structures are not prescribed for base-isolated constructions which perform in the elastic range
- The P-delta effect caused by the isolators' displacements has been considered in the analyses

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C – conventional retrofit

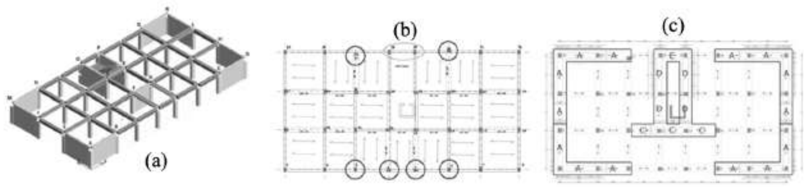

Figure 9 - Traditional retrofitting works: (a) walls insertion, (b) joints strengthening, (c) foundation widening

9

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Building C – conventional retrofit

- standard protection levels not reached
- high impact on the construction since almost all the non structural elements should be demolished
- very high cost with respect to the benefit achieved

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SEISMIC RETROFIT OF R.C. BUILDINGS

Building C – cost comparison

Category of works	Traditional		Base-isolated		Diff.
Type A - Repair	€ 891,892	39.40 %	€ 667,570	44.72 %	-25.2%
Type B - Seismic enhancement	€ 555,347	24.53 %	€ 185,487	12.43 %	-66.6%
Retrofit due to Type B works	€ 132,928	5.87 %	€ 3,786	0.25 %	-97.2%
Hygienic-sanitary conformity	€ 81,023	3.58 %	€ 57,072	3.82 %	-29.6%
Conformity of plants	€ 190,959	8.44 %	€ 18,270	1.22 %	-90.4%
Energy saving conformity	€ 251,118	11.09 %	€ 141,866	9.50 %	-43.5%
Overflow	€ 160,307	7.08 %	€ 418,756	28.05 %	+161.2%
Total	€ 2,263,575	100.00 %	€ 1,492,806	100.00 %	-34.1%

54 NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Remarks 1#2

- the cost comparison of the alternative seismic improvement strategies shows that **base-isolation allows for an immediate saving** (about 34%)
- since the earthquake-resistant capacity reached by conventional and base isolation strategies are significantly different, the **cost comparison should be extended to the building lifetime** considering the expected performances and consequences corresponding to the expected earthquakes. The base- isolated building will not suffer any damage, nor any consequence to the occupants, even under the maximum expected earthquake. On the contrary the traditionally retrofitted buildings will undergo serious consequences for an event having about 70% the intensity of the maximum expected earthquake. This event has about 25% probability to be overridden in the building residual life.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

Remarks 2#2

- some damage to non structural elements and minor damage to structural elements can also occur in the conventional retrofitted building for more frequent events of lower intensity.
- finally, for the maximum expected quake, that is with a probability of 10% in the life, the building will suffer a generalized damage with a cost of comparable to the sustained retrofitting cost.

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

the adoption of seismic isolation in retrofit is **simple**, **effective** and **convenient** from the economical point of view

BUT

57

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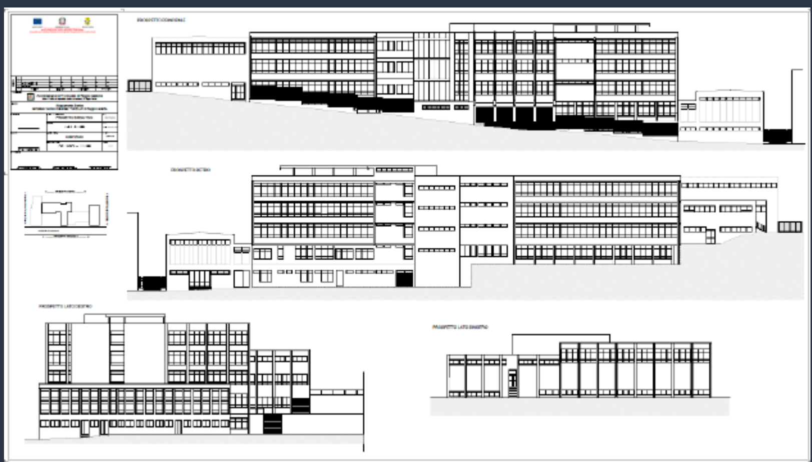
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

School building in Italy



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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

School building in Italy

INITIAL RETROFIT DESIGN

- ❑ BLOCKS **B** & **C**: **BASE ISOLATION**
- ❑ BLOCKS **A** & **D**: **CONVENTIONAL STRENGTHENING**

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NUMERIA

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SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

School building in Italy

RETROFIT DESIGN PROPOSED BY NUMERIA

- ❑ BLOCKS **B** & **C**: **BASE ISOLATION (FIP MEC-D devices)**
- ❑ BLOCKS **A** & **D**: **ENERGY DISSIPATION (FIP MEC BRAD devices)**

Minor strengthening intervention foreseen only on few superstructure structural elements (beams and columns).

↓

No need to reinforce the foundations

60

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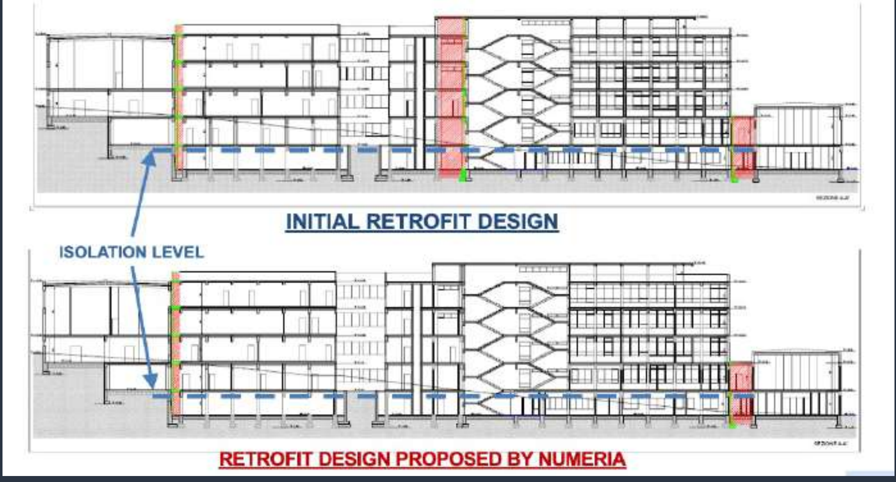
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

School building in Italy



61 | NUMERIA

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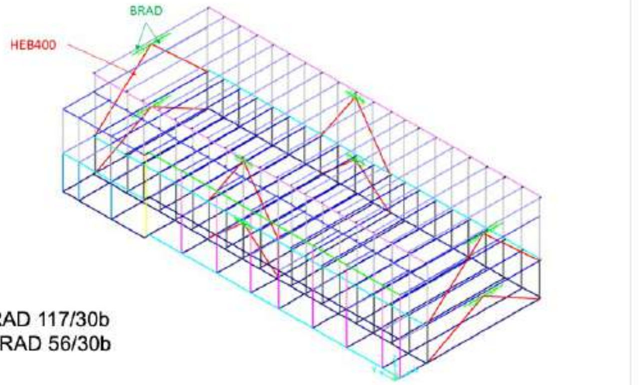
SEISMIC RETROFIT OF R.C. BUILDINGS WITH BASE ISOLATION

School building in Italy

RETROFIT DESIGN PROPOSED BY NUMERIA

- BLOCKS A & D: ENERGY DISSIPATION (BRAD devices)



BLOCK A
- N. 4 BRAD 117/30b
- N. 12 BRAD 56/30b

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SEISMIC RETROFIT OF MASONRY BUILDINGS WITH BASE ISOLATION

1. Make **foundation** accessible

2. Creation of **niches** for the isolators installation

3. **Reinforce** the foundation (e.g. by creating twin r.c. beams above and below the isolation devices)

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SEISMIC RETROFIT OF MASONRY BUILDINGS WITH BASE ISOLATION

4. Installation of the **isolators**

5. **Loading** the isolators (e.g. by means of flat jacks)

6. Realize the **separation** between substructure e superstructure (cut)

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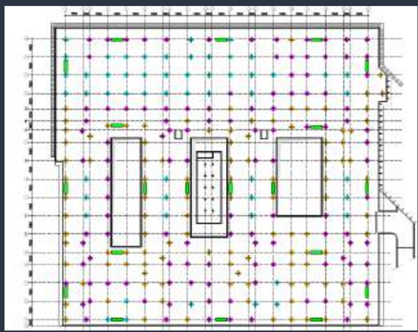
APPLICATION OF BASE ISOLATION TO HOSPITALS

Ancona hospital, Italy



20 Viscous Dampers
Fmax = 2200 kN
a=0.15
d= ± 250 mm

279 Pendulum isolators
N = 3500÷ 12500 kN
d= ± 250 mm
R=4000 mm

under construction in Central Italy,
seismically isolated
with very low friction pendulum isolators
+ non-linear fluid viscous dampers

courtesy of FIPMEC

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APPLICATION OF BASE ISOLATION TO HOSPITALS

Ancona hospital, Italy

courtesy of FIPMEC

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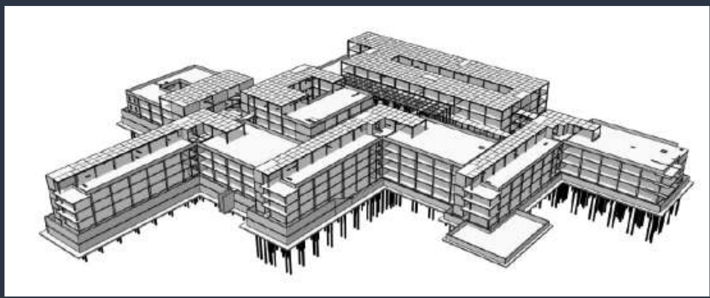
APPLICATION OF BASE ISOLATION TO HOSPITALS

Fermo hospital, Italy



under construction in Central Italy, seismically isolated with:

- 320 high damping rubber bearings
- 114 free sliding bearings
- 40 non-linear fluid viscous dampers

courtesy of FIPMEC

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APPLICATION OF BASE ISOLATION TO HOSPITALS

Fermo hospital, Italy

courtesy of FIPMEC

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APPLICATION OF BASE ISOLATION TO HOSPITALS

Fermo hospital, Italy

courtesy of FIPMEC

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APPLICATION OF BASE ISOLATION TO HOSPITALS

Fermo hospital, Italy

courtesy of FIPMEC

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APPLICATION OF BASE ISOLATION TO HOSPITALS

Fermo hospital, Italy

The cost of the seismic isolation system
is only 2% of the total construction cost of the hospital
(excluding all the equipment, which cost is very high).

Seismic isolation guarantee the hospital's functionality
even after a strong earthquake.

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Thank you

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Lisbon - 28 October 2022

Supplemental energy dissipation: principles and benefits for seismic retrofit of existing framed buildings

M.Gabriella Castellano, PhD

FIP MEC Academy

The energy approach to seismic engineering

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The energy approach to seismic engineering

Energy balance equation:

$$E_i = E_E + E_K + \underbrace{E_H + E_V}_{E_d}$$

E_i is the input energy, i.e. the work done by inertial force on the structure (=base shear) for the displacement of its application point

E_E is the elastic energy

E_K is the kinetic energy

E_d is the dissipated energy (hysteretic E_H or viscous E_V)

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The energy approach to seismic engineering

$$E_i \leq E_E + E_K + \underbrace{E_H + E_V}_{E_d}$$

request ≤ offer

Seismic protection can be realized by reducing the request or by increasing the offer

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The energy approach to seismic engineering

Seismic isolation = reduction of request

i.e. reduction of $E_i = \int_{v(0)}^{v(t)} m\ddot{v}_t \, dv_g$ (input energy)

Note: the input energy is not an intrinsic property of the earthquake, because it depends on structural response as well as on ground displacement

It depends essentially on the fundamental period as well as on the acceleration time hystory.

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The energy approach to seismic engineering

Capacity design = increase of offer

increase of E_d

In the conventional antiseismic design, the structure should be designed with sufficient ductility, i.e. should dissipate energy as much as possible.
Such dissipation is obtained
THROUGH DAMAGE
of the structural elements.

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The energy approach to seismic engineering

$$E_i \leq E_E + E_K + \underbrace{E_H + E_V}_{E_d}$$

Supplemental energy dissipation = increase of offer

i.e. increase of $\mathbf{E_d}$

through special devices called DAMPERS

or energy dissipation devices

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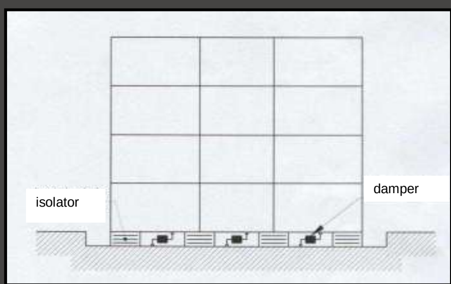
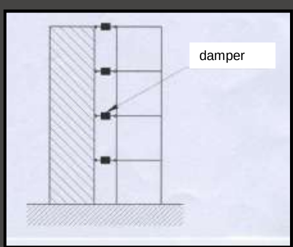
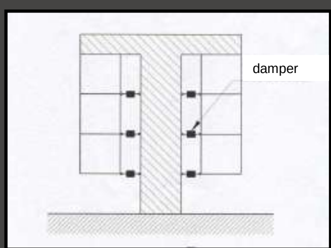
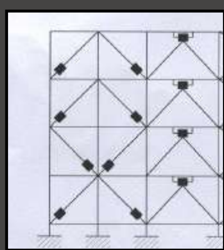
Energy dissipation in buildings

energy dissipation devices shall be installed where displacements are expected









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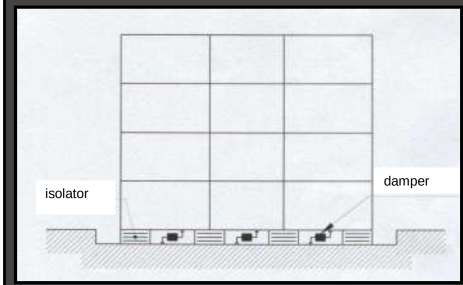
Energy dissipation in buildings

- Supplemental energy dissipation devices can be applied as components of a seismic isolation system, to increase the energy dissipation capacity.
- They can be combined with elastomeric isolators or with pendulum isolators



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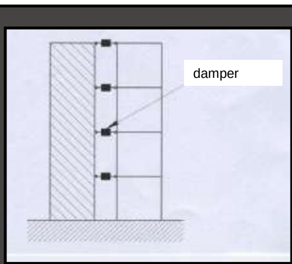
Energy dissipation in buildings

- energy dissipation devices can be installed between two structures with different stiffness, in order to exploit the relative displacement between them
- for example, between the existing framed structure to be retrofitted, and a new stiff structure acting as a «restraint»



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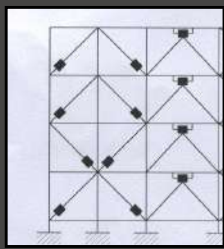
Energy dissipation in buildings

- in framed buildings, energy dissipation devices are usually inserted as part of braces (**dissipative braces**), thus exploiting the interstorey drift (relative displacement between stories)



- dissipative braces work both in tension and in compression, thus the brace shall be quite stiff

- the most common bracing shapes are the diagonal and the chevron

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Supplemental energy dissipation devices inserted in dissipative braces

Diagonal braces – viscous dampers

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Supplemental energy dissipation devices inserted in dissipative braces

Diagonal braces – BRAD®

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Supplemental energy dissipation devices inserted in dissipative braces

Chevron braces – viscous dampers

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Supplemental energy dissipation devices inserted in dissipative braces

Chevron braces – BRAD®

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Advantages of dissipative braces in seismic retrofit of existing framed buildings

- they allow to significantly improve the seismic behaviour of old framed structures built without any seismic design or with very old seismic design (without sufficient ductility)
- their energy dissipation substitutes, at least partially, the energy dissipation in the structural elements, thus reducing the damage in the existing elements
- the cost of intervention is often lower than with conventional retrofit approach

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Advantages of dissipative braces in new structures

- in new structures, dissipative braces can be used to completely avoid damage in the structural elements (i.e. keep structural elements in the elastic field)
- if used together with partitions that allow interstorey displacement, they can avoid nonstructural damages as well

Note: dissipative braces in new steel buildings are often considered as an evolution of eccentric braces

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Advantages of dissipative braces in comparison with seismic isolation

- the global displacement of the building is lower than with seismic isolation, thus:
  * there is not the need of a large gap around the building (or complex of buildings)
  * there is not the need of special joints for gas, water, etc.
- they are suitable in very flexible structures as well
- they are suitable also in areas with special seismicity (amplification at large periods) where seismic isolation is not suitable

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Drawbacks of dissipative braces in comparison with seismic isolation for seismic retrofit of existing structures

- the partitions and content protections is not so high as with seismic isolation (the displacement and accelerations are reduced in comparison with a conventionally retrofitted structure, but not so much as with seismic isolation)
- often it is not possible to reach complete retrofit without significant strengthening of many structural elements (foundations, nodes, etc.)

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Drawbacks of dissipative braces in comparison with seismic isolation for seismic retrofit of existing structures

- the works are not concentrated at one level, there is the need of distributing them along the height of the buildings
- not suitable for stiff structures (e.g. masonry buildings)

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The European Standard on Anti-seismic devices

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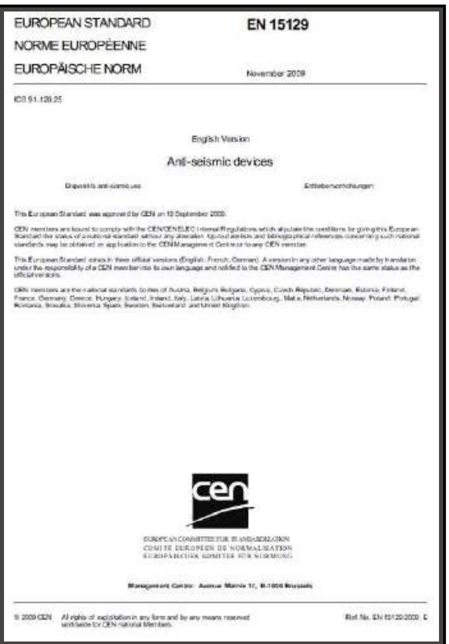
European standard EN 15129:2009 Anti-seismic devices

1 Scope

This European Standard covers the design of **devices that are provided in structures, with the aim of modifying their response to the seismic action**. It specifies functional requirements and general design rules for the seismic situation, material characteristics, manufacturing and testing requirements, as well as evaluation of conformity, installation and maintenance requirements. This European Standard covers the types of devices and combinations thereof as defined in 3.4.


EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 15129

November 2009

English Version

Anti-seismic devices

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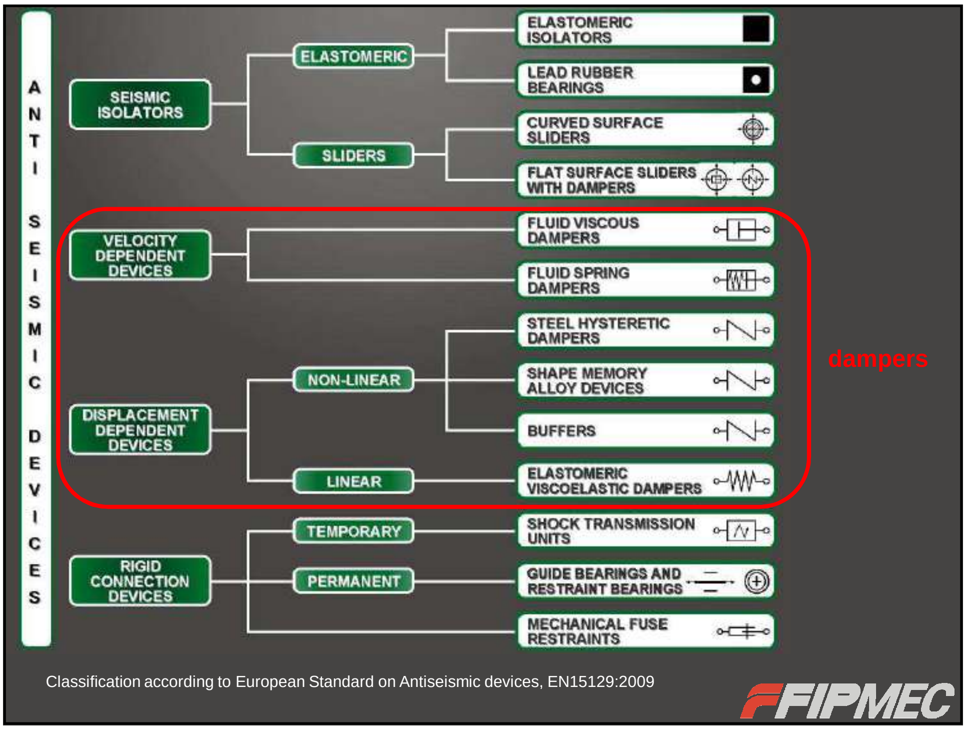

ANTI SEISMIC DEVICES
SEISMIC ISOLATORS
ELASTOMERIC
SLIDERS
ELASTOMERIC ISOLATORS
LEAD RUBBER BEARINGS
CURVED SURFACE SLIDERS
FLAT SURFACE SLIDERS WITH DAMPERS
VELOCITY DEPENDENT DEVICES
FLUID VISCOUS DAMPERS
FLUID SPRING DAMPERS
DISPLACEMENT DEPENDENT DEVICES
NON-LINEAR
LINEAR
STEEL HYSTERETIC DAMPERS
SHAPE MEMORY ALLOY DEVICES
BUFFERS
ELASTOMERIC VISCOELASTIC DAMPERS
dampers
RIGID CONNECTION DEVICES
TEMPORARY
PERMANENT
SHOCK TRANSMISSION UNITS
GUIDE BEARINGS AND RESTRAINT BEARINGS
MECHANICAL FUSE RESTRAINTS
Classification according to European Standard on Antiseismic devices, EN15129:2009
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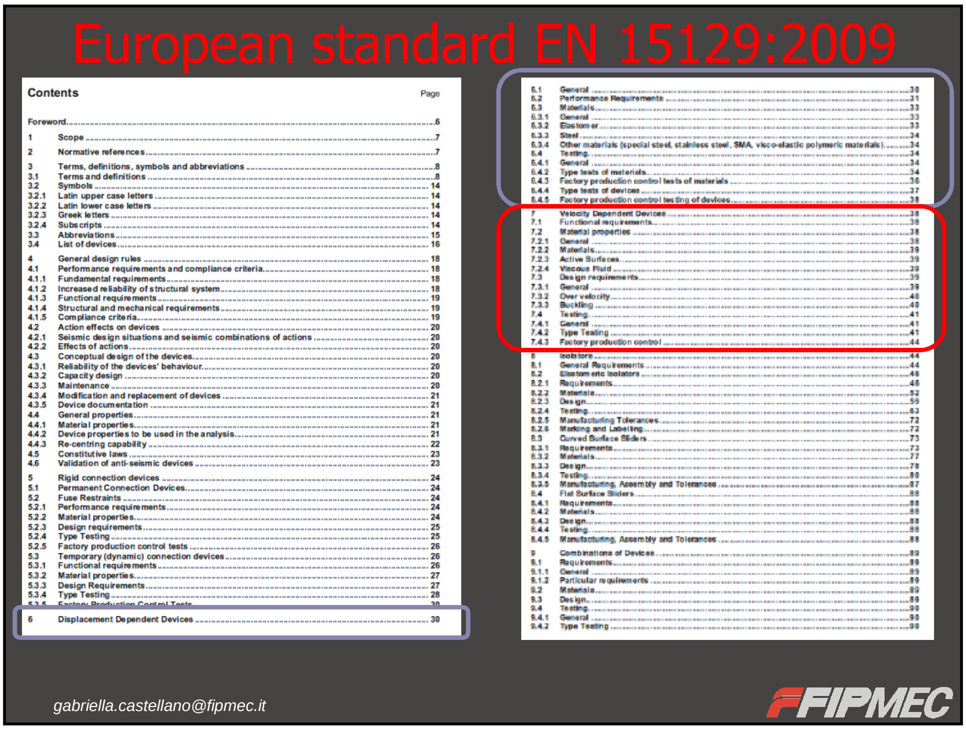

European standard EN 15129:2009
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6 Displacement Dependent Devices 30
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Steel hysteretic dampers for dissipative braces in framed buildings

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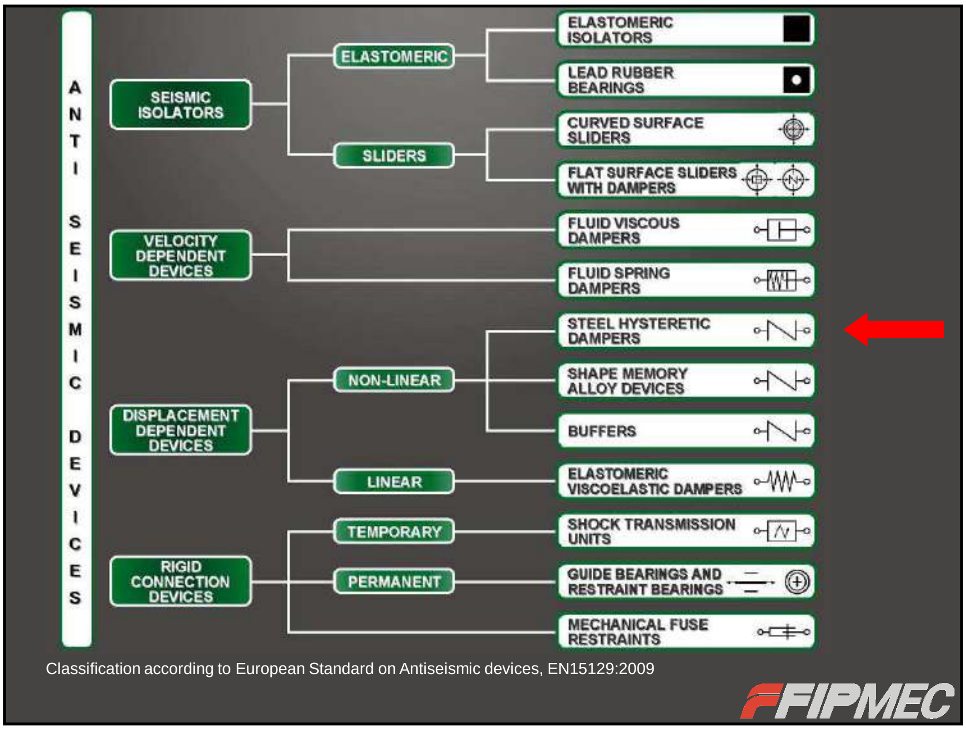
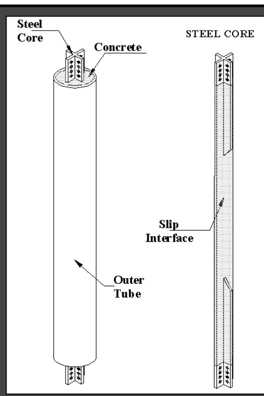


Classification according to European Standard on Antiseismic devices, EN15129:2009

Buckling-Restrained Axial Dampers (BRAD®)

- Italian version of BRB
- specific for use in dissipative braces in r.c. frames
- exploit yielding of steel core in tension and compression
- buckling is prevented by outer tube and concrete
- high dissipative efficiency
- very stable hysteretic behaviour
- good low-cycle fatigue life



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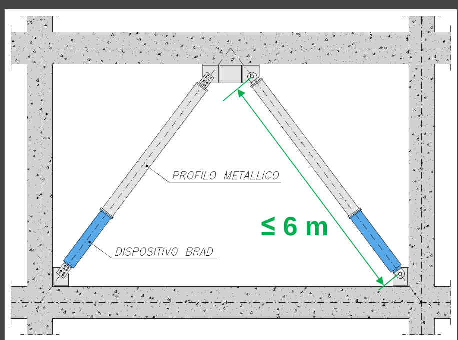
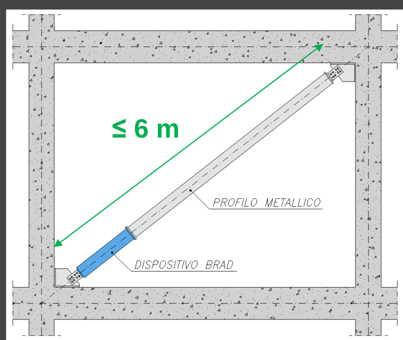
Buckling-Restrained Axial Dampers - BRAD®





- BRAD® are standard devices, specially designed for seismic retrofit of reinforced concrete framed buildings
- Displacement capacity ± 20 mm, maximum length of the brace 6 m

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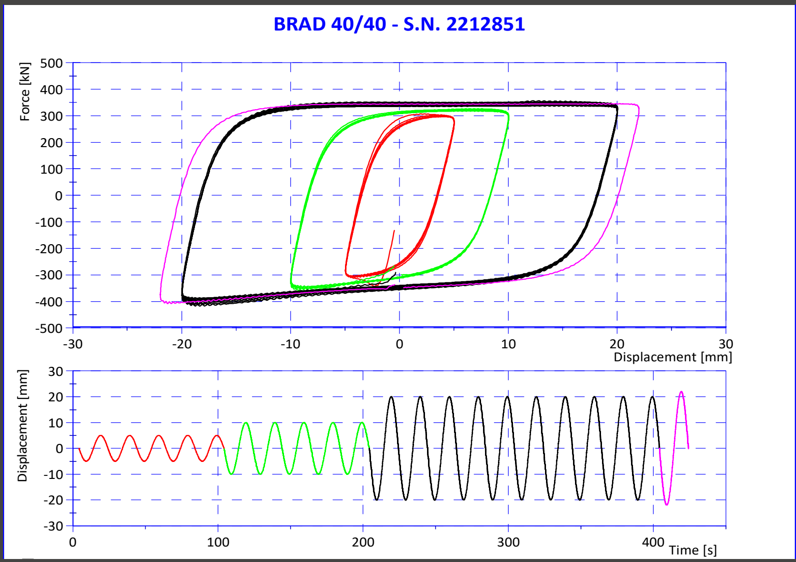
Buckling-Restrained Axial Dampers - BRAD®
typical experimental hysteretic cycles



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Buckling-Restrained Axial Dampers - BRAD®

- > 3600 BRAD® installed since 2004, mainly in seismic retrofit interventions, and mainly in schools
- some application in new buildings as well

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University of Ancona, Italy

- 1st application in Europe of BRB, 2004
- New precasted building
- Chevron braces
- 86 BRAD®
  in 43 span,
  23 at the ground floor
  and 20 at the 1st floor
- F_{max}=140 ÷ 190 kN
- d_{max}= ± 15 mm

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Fluid viscous dampers

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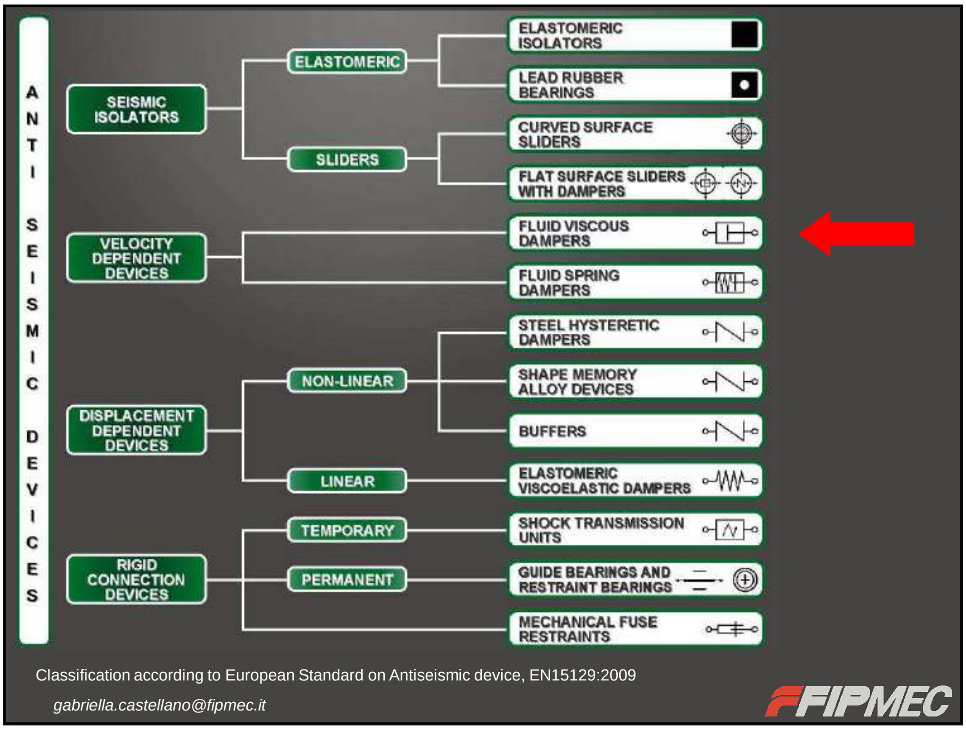
ANTISEISMIC DEVICES
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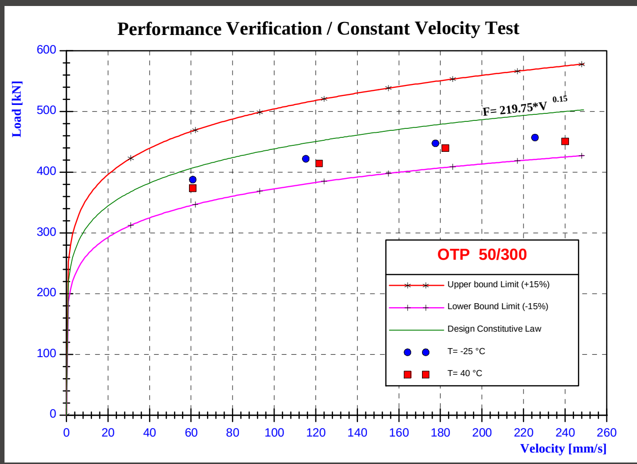
FLUID VISCOUS DAMPERS



$F = C\,v^{\alpha}$

$\alpha = 0.15$

where:

F = force

C = damping coefficient

v = velocity

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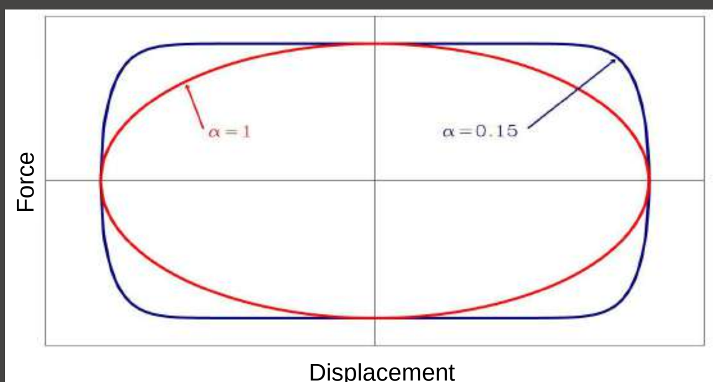
FLUID VISCOUS DAMPERS

Force vs displacement: comparison between linear and non-linear devices



Non-linear fluid viscous dampers with α=0.15 are the most suitable for seismic protection of structures.

Linear fluid viscous dampers (α=1) are used only for protection from wind effects (e.g. in skyscrapers)

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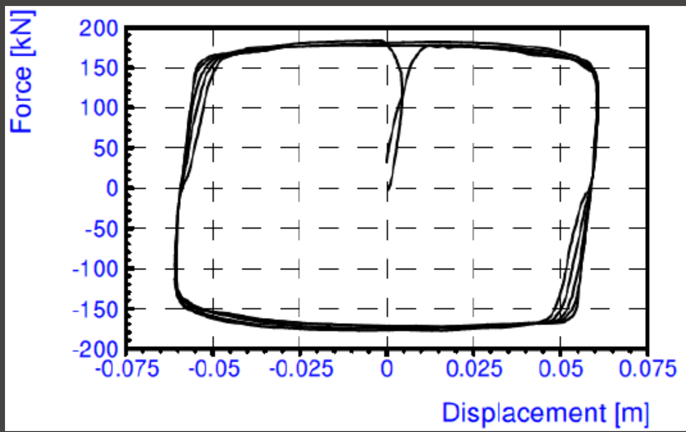
FLUID VISCOUS DAMPERS

Typical hysteretic cycles obtained in a damping efficiency test according to EN 15129:2009 carried out on a non linear fluid viscous damper with α=0.15



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Seismic retrofit of schools with supplemental dampers

In the last 20 years, in Italy the use of supplemental dampers to retrofit schools is continuously increasing.

Now more than 50 schools have been already retrofitted with dampers manufactured by FIP MEC, and many others have been designed and will be completed in next years, with the help of NextGenerationEU funds.

Initially, mostly steel hysteretic dampers (BRAD®) were used. Recently, the use of fluid viscous dampers is increasing.

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Few examples of schools retrofitted with supplemental dampers

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Perticari High School, Senigallia, Italy (seismic retrofit)

1st seismic retrofit application with BRAD® - 2005

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Perticari High School, Senigallia, Italy (seismic retrofit)

2005

- n° 23 BRAD® 14/30
- n° 22 BRAD® 21/30
- n° 8 BRAD® 41/30

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Primary school in Largo Madonna, Pescara, Italy – seismic retrofit

16 BRAD® (6 BRAD®11/40+6 BRAD®21/40+4 BRAD®34/40)

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Leopardi high school in Ancona, Italy (seismic retrofit)

built in 1960

seismic retrofit in 2014, with dissipative braces with BRAD® and local application of CFRP

37 BRAD®

(18 BRAD®14/40 +19 BRAD®48/40)

courtesy of F.Cappanera – ALL Ingegneria

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Scarpellini high school, Foligno, Italy

retrofit in 2018 with 18 BRAD® 82/40

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Capograssi School, Sulmona, Italy, seismic retrofit

seismic retrofit
in 2019-2020,
with dissipative towers

32 viscous dampers at the base of the towers, and 6 viscous dampers across joints

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Conclusions

- supplemental energy dissipation is a reliable and mature technology, supported by a lot of laboratory tests, as well as by the full satisfactory behavior under earthquake.
- energy dissipation devices are fruitfully applied in structural positions where relative displacement is expected under earthquake; a typical position is in braces in framed buildings, where the activating displacement is the interstorey drift
- supplemental energy dissipation can be used both in new and existing buildings
- in retrofit of existing buildings, supplemental energy dissipation is usually more effective than conventional interventions

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