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Assessment and improvement of structural safety under seismic actions of existing constructions: Historic Buildings and R.C. Structures

SEMINAR

R.C. STRUCTURES:

INTERVENTION TECHNIQUES

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Beer Sheva, Shamoom College

Summary

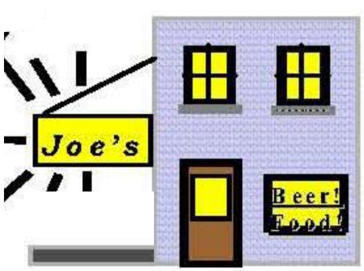
- 1. INTRODUCTION
- 2. RETROFIT INTERVENTION FOR IMPROVEMENT OF LOCAL STRENGHT/DUCTILITY
- 3. RETROFIT INTERVENTION FOR IMPROVEMENT OF GLOBAL CAPACITY
- 4. PASSIVE PROTECTION OF STRUCTURES: BASE ISOLATION AND ENERGY DISSIPATION DEVICES

Introduction

DESIGN OF THE SEISMIC RETROFITTING (+STATIC REPAIR+REFURBISHMENT)

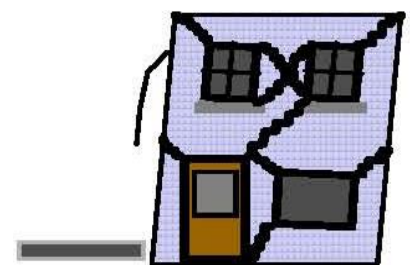
UNDAMAGED BUILDING

- **Structural Retrofit** (compulsory)
- **Functional Adaptation** (optional/compulsory)



DAMAGED BUILDING

- **Structural Repair** (compulsory)
- **Structural Retrofit** (optional/compulsory)
- **Functional Adaptation** (optional/compulsory)



Design philophy depends on:

1. The technical context : e.g. new seismic code requirements…)
2. Economic context: e.g. there is public financing post-earthquake reconstruction, or there are rules to finance energy saving and the client want to combine refurbishment with seismic retrofit to reduce costs (that can be direct or indirect, the latter can be particularly high for industrial activities….)

Introduction

DESIGN OF THE SEISMIC RETROFITTING (+STATIC REPAIR+REFURBISHMENT)

1 Typological /structural characteristics

- Typology (frame, wall, dual structure…)
- Static scheme (degree of hyperstaticity, boundary condition)
- Materials properties
-Regularity/irregularity of the structure in plan and elevation

2 State of maintenance of the structure

-Degradation process (carbonation, corrosion..)
-Intrinsic weakness point (joints..)
-Damages related to previous seismic events

3 History of the building

-Evolution of construction phases
-Structural additions

4 Seismic Performance Level

- Level of enhacement and performance required (structure shall be operational after the event? Plants shall be functioning?)

5 Durability

-Nominal Life
- Material compatibility

6 Functional requirements

- How new structures will be used (new RC core used for emergency stairs..) ?

7 Sustainability

-Aesthetics
-Environmental aspects

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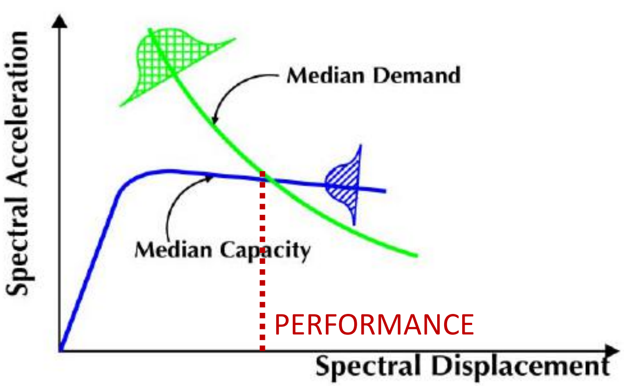
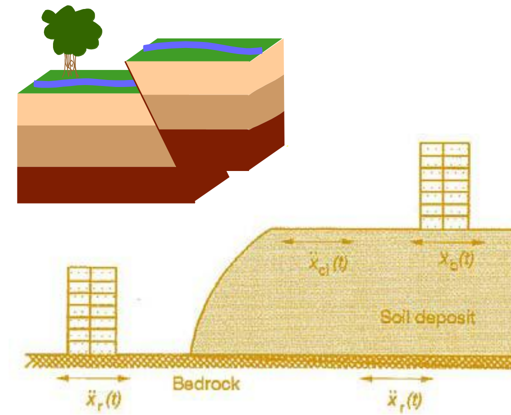
SEISMIC PERFORMANCE

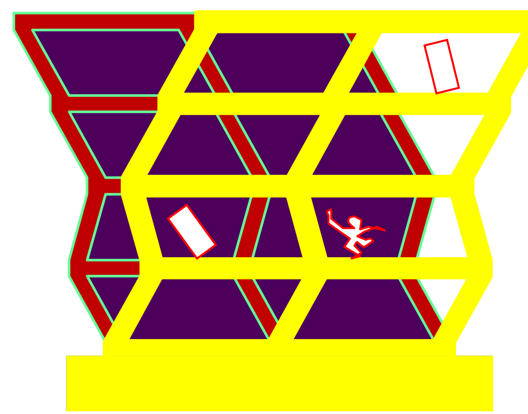


- **DEMAND:** is governed by the site hazard , soil local characteristics, and by intrinisc dynamic properties of the structure (T, ξ)



- **CAPACITY:**

  is related to the structural strength/resistance in terms of force and displacement of the single members and overall system.



SEISMIC RETROFITTING OBJECTIVE

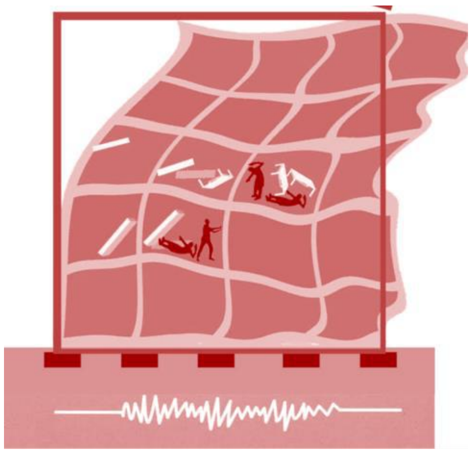
$$\text{Safety Factor} = \frac{\text{Capacity}}{\text{Demand}} \geq 1$$

where the "Demand" is influenced by the ground motion, and the "Capacity" is given by the resistance.
The design inequality must be satisfied not only in terms of strength, but also in terms of displacements.

IMPROVE SEISMIC PERFORMANCE REQUIRES

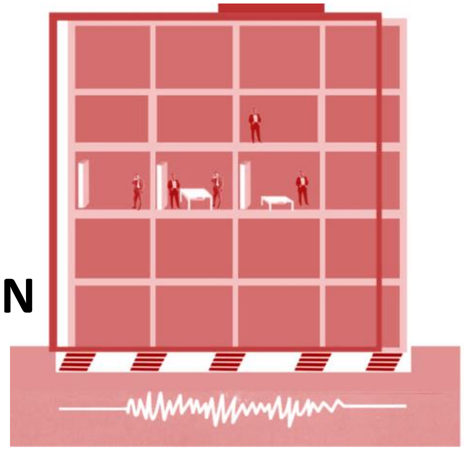
INCREASE THE CAPACITY

REDUCE THE DEMAND



CAPACITY DESIGN

SEISMIC ISOLATION



INCREASE THE CAPACITY

C_s= Capacity curve for strengthened structure

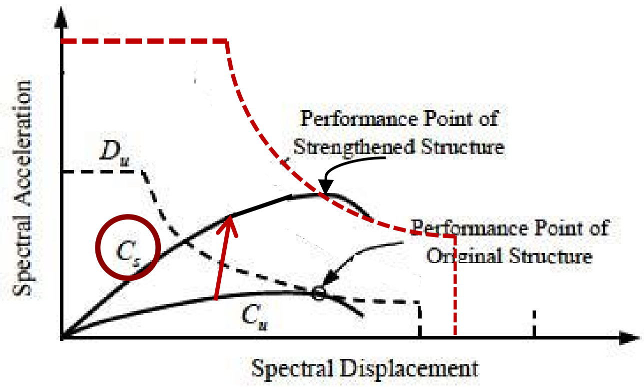
C_u= Capacity curve for unstrengthened structure

D_s= Demand curve for strengthened structure

D_u= Demand curve for unstrengthened structure

1.

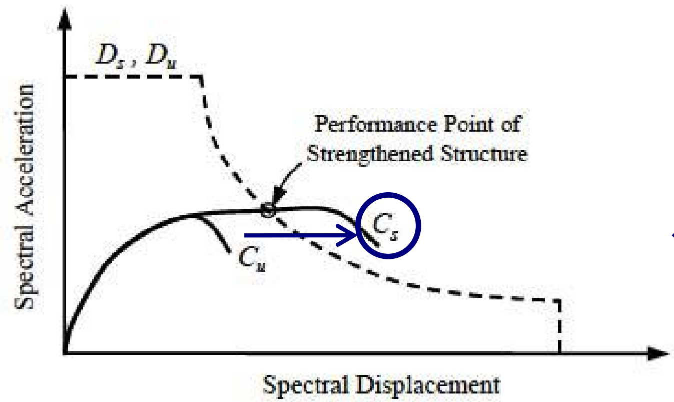
Conventional strengthening applications generally lead to an increase in both the stiffness and strength



(a) Effect of structural strengthening

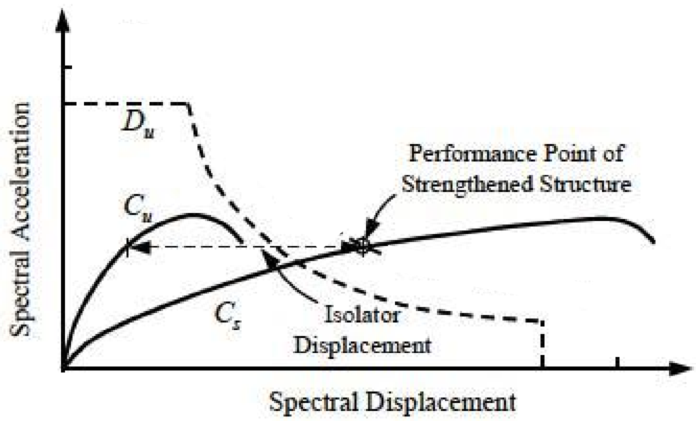
2.

Insufficient deformation capacity is usually caused by inadequate detailing. Increasing the overall displacement capacity is an effective seismic Retrofitting.

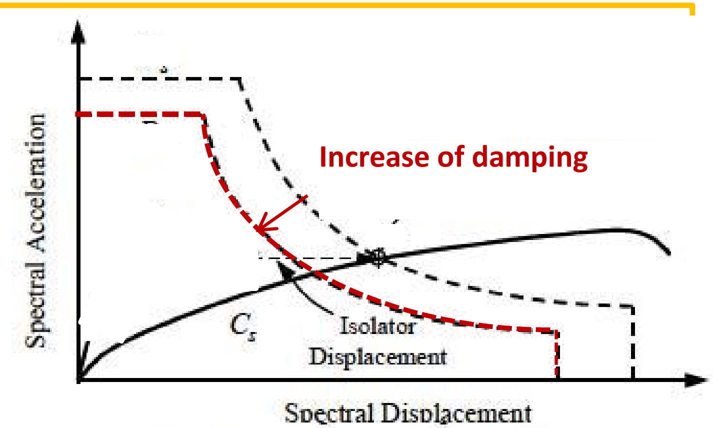


(b) Effect of deformation enhancement

REDUCE THE DEMAND



(c) Effect of base isolation



(d) Effect of enhanced energy dissipation

C_s = Capacity curve for strengthened structure

C_u = Capacity curve for unstrengthened structure

D_s = Demand curve for strengthened structure

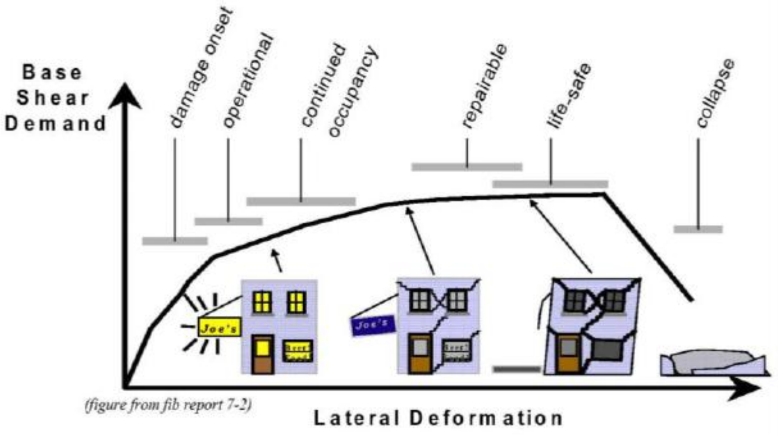
D_u = Demand curve for unstrengthened structure

3. Base isolation significantly increases the effective fundamental period and deformation capacity of the structure.

   Additional advantage of using energy dissipation devices is that the seismic demand on the structure is also reduced due to increase in the effective damping of the structure.

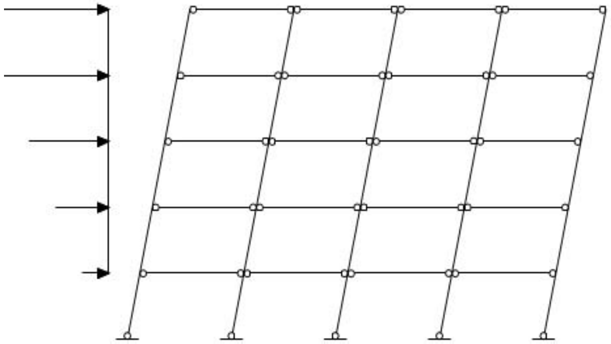
BUILDINGS SEISMICALLY DESIGNED

- Conventional **Fixed-Base Structures cannot be conveniently designed to remain elastic** in large seismic events (especially in regions of high seismicity)
- Common practice is to design them so that they **experience damage in a controlled manner** and have large inelastic displacements potential



(figure from fib report 7-2)

- 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.



Global mechanism

BUILDINGS DESIGNED ONLY FOR GRAVITY LOADS/ SEISMICALLY DESIGNED WITH UNSATISFACTORY BEHAVIOUR

Global collapse, soft story
(at ground floor or intermediate floor…)

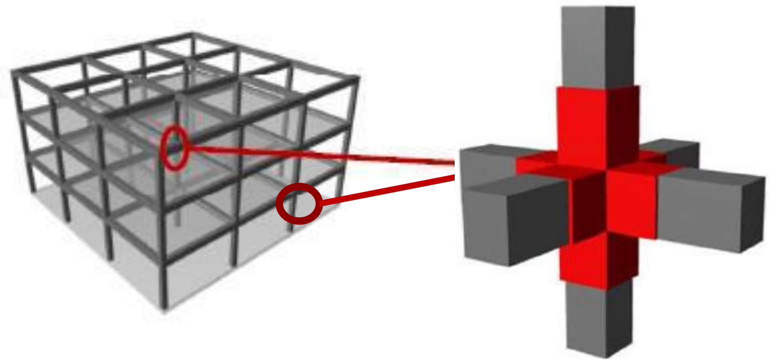
Local mechanism

BUILDINGS DESIGNED ONLY FOR GRAVITY LOADS/ SEISMICALLY DESIGNED WITH UNSATISFACTORY BEHAVIOUR

Joint /Element Failures
(shear failure, lack of ductility..)

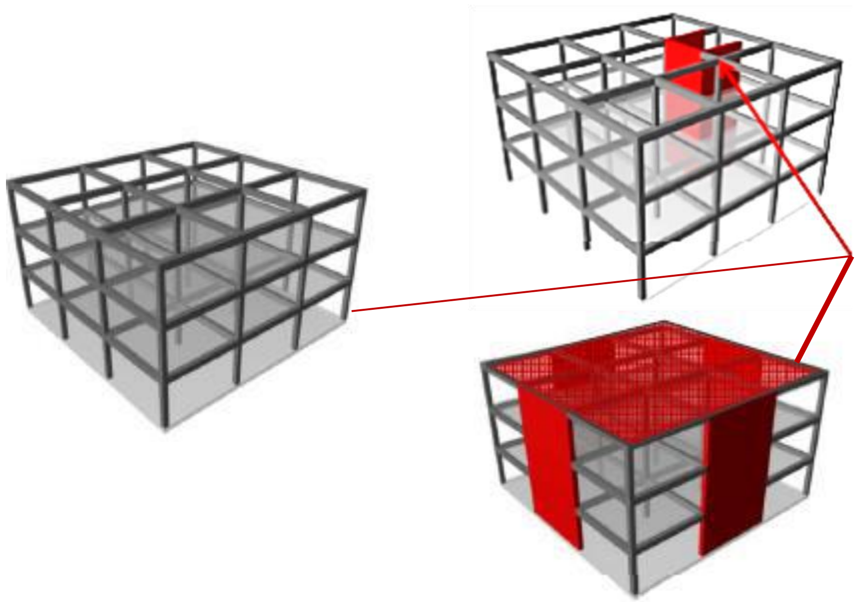
Increment of capacity

LOCAL INTERVENTION



Repair+strengthening of single joints/elements (even all nodes, columns, etc..).

GLOBAL INTERVENTION



Creation of a new resisting systems, acting in parallel (dual system - for partial transfer of inertial horozontal forces) or completely substituting the existing one.

TRADITIONAL & INNOVATIVE TECHNIQUES

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- 2. RETROFIT INTERVENTION FOR IMPROVEMENT OF LOCAL STRENGHT/DUCTILITY

Repair intervention

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INJECTION OF CRACKS FOR DAMAGED BUILDINGS

- Crack injection is a versatile and economical method of repairing reinforced concrete (RC) structures. The effectiveness of the repair process depends on the ability of the adhesive material (usually epoxies) to penetrate, under appropriate pressure, into the fine cracks of the damaged concrete.
- This repair method can be used in minor (<0.1mm), medium (<3mm) size cracks, and large crack widths (up to 5–6 mm). In case of larger cracks, up to 20mm wide, cement grout, as opposed to epoxy compounds, is the appropriate material for injection,
- Injection is deemed complete for a portion of the crack when epoxy is expelled from the next higher nozzle. Once the repair epoxy has set, the nozzles are bent and tied firmly. They can be cut flush and sealed with an epoxy patching compound prior to rendering of the affected member.

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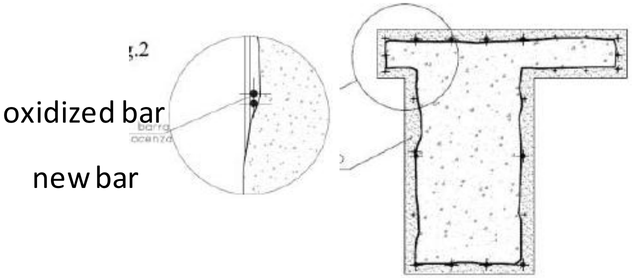
Repair intervention

TREATMENT OF DEGRADED MATERIALS

- The concrete cover is generally **hydrodemolished** in seriously damaged parts, lighter treatment by **blast sanding** can be used for the well preserved concrete. These operations can be done <u>mechanically</u> for large surfaces (like slabs), <u>manually</u> for elements of small dimensions.

- The **entire surface** area is then **dressed by pressurised sanding**, until clean degreased surfaces were obtained.
- All the **exposed rebars** are **sanded down to white metal**, blown with *pressurised air jets* and **treated with an anti-corrosive agent**.



- **New plastering is applied to the cover** using thixotropic shrinkage-compensated cement mortar, fiber-reinforced with polymers.
- **Final protective coating** is applied

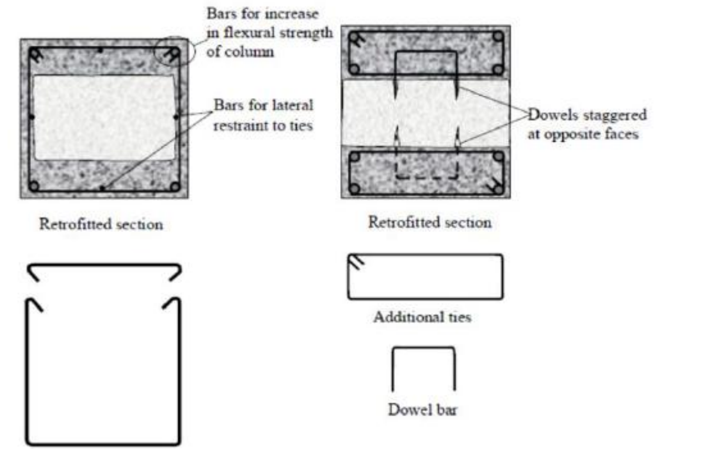
Local intervention

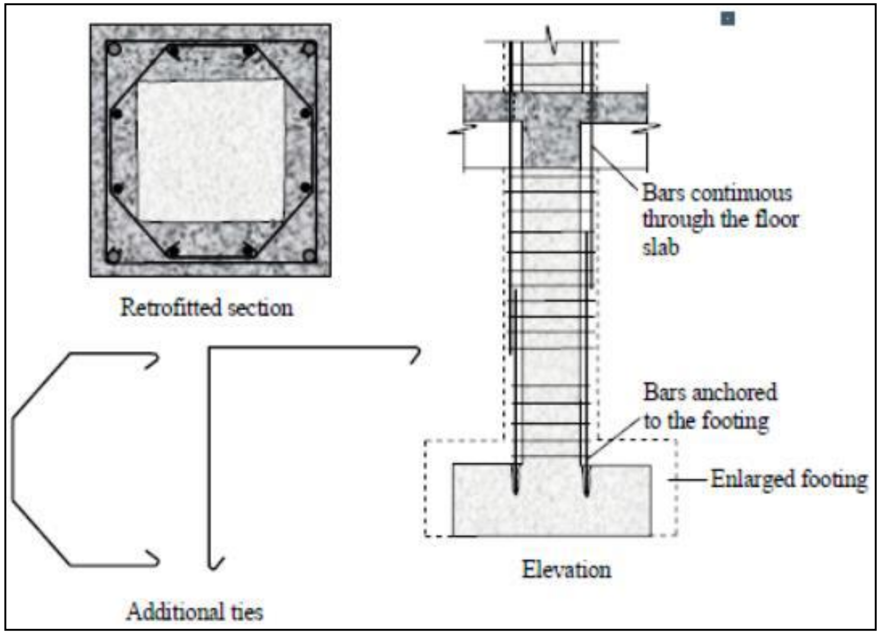
Local retrofit strategies pertain to retrofitting of columns, beams, joints, slabs, walls and foundations.

Retrofit strategy	Merits	Demerits	Comments
Concrete jacketing	• Increases flexural and shear strengths and ductility of the member • Easy to analyse • Compatible with original substrate	• Size of member increases • Anchoring of bars for flexural strength; involves drilling of holes in the existing concrete • Needs preparation of the surface of existing member	• Low cost • High disruption • Experience of traditional RC construction is adequate
Steel jacketing of columns	• Increases shear strength and ductility • Minimal increase in size	• Cannot be used for increasing the flexural strength • Needs protection against corrosion and fire	• Can be used as a temporary measure after an earthquake • Cost can be high • Low disruption • Needs skilled labour
Bonding steel plates to beams	• Increases either flexural or shear strengths • Minimal increase in size	• Use of bolts involves drilling in the existing concrete • Needs protection against corrosion and fire	• More suitable for strengthening against gravity loads • Cost can be high • Low disruption • Needs skilled labour
Fibre Reinforced Polymer wrapping	• Increases ductility • May increase flexural or shear strengths • Minimal increase in size • Rapid installation	• Needs protection against fire	• Cost can be high • Low disruption • Needs skilled labour

CONCRETE JACKETING

- Involves addition of a layer of concrete, longitudinal bars and closely spaced ties.
- The jacket increases both flexural and shear strength, if the thickness of the jacket is small there is non appreciable increase in stiffness.
- The placement of ties at the beam-clumn joints is difficult, if not impossibile
- There is an increase of the coulmn size
- Drilling holes in the existing concrete can cause damages if the concrete is of poor quality (this is particularly true for already damage structures with cracks etc…)





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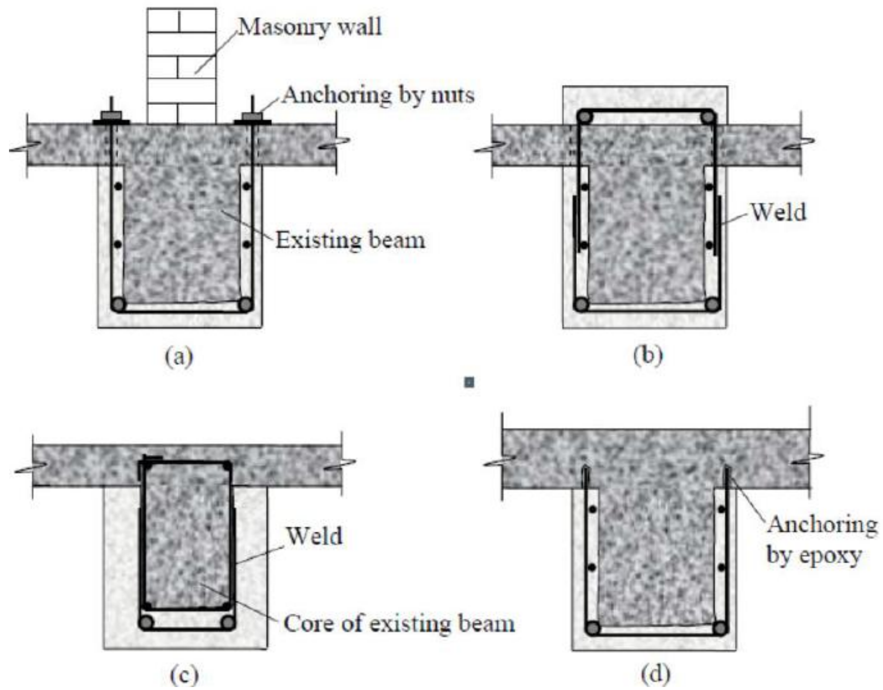
CONCRETE JACKETING

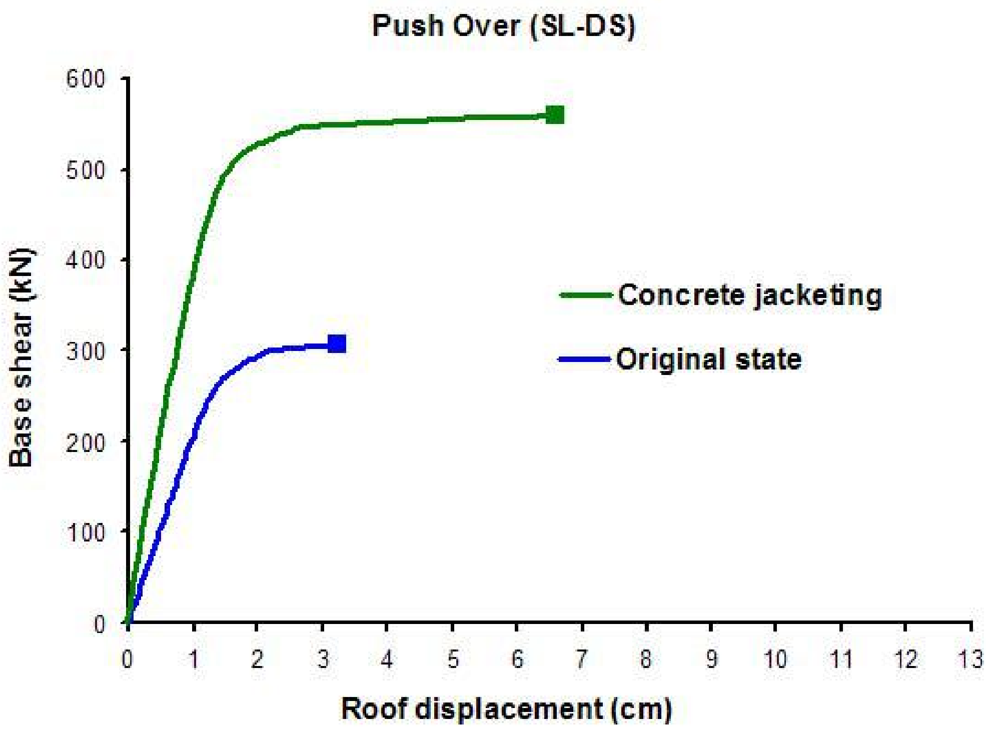
- Anti-shrinkage fiber-reinforced concrete (or mortar) should be used
- The new bars can be welded to the existing ones using Z or U shaped bent bars
- The analysis of the retrofitted system assumes that there is perfect bond between the old and new concrete



Example of beam jacketing

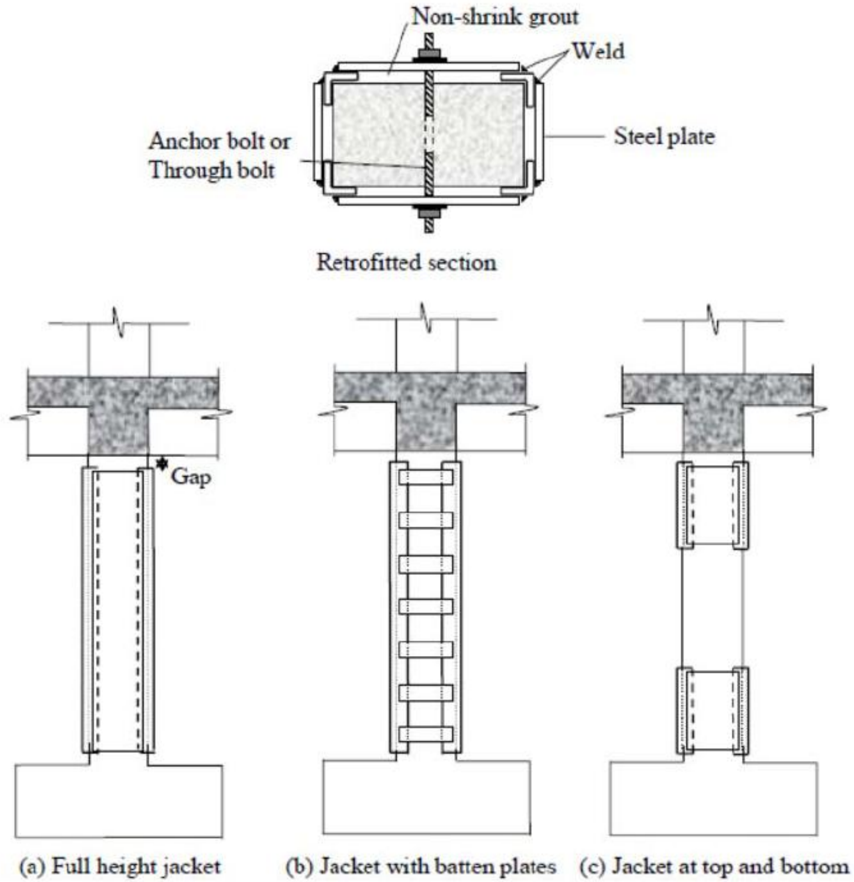
Local intervention

CONCRETE JACKETING



STEEL JACKETING

- Refers to an encasing of the column with steel plates and filling the gap with non shrink grout
- The jacket is effective to remedy inadequate shear strength and provide passive confinement to the column (plates cannot be anchored and made continuous, thus are not used for enhancement of flexural strength).
- It is also used to stregthen the region of faulty splicing of longitudinal bars
- As a temporary measure can be placed before an engineered scheme is implemented.



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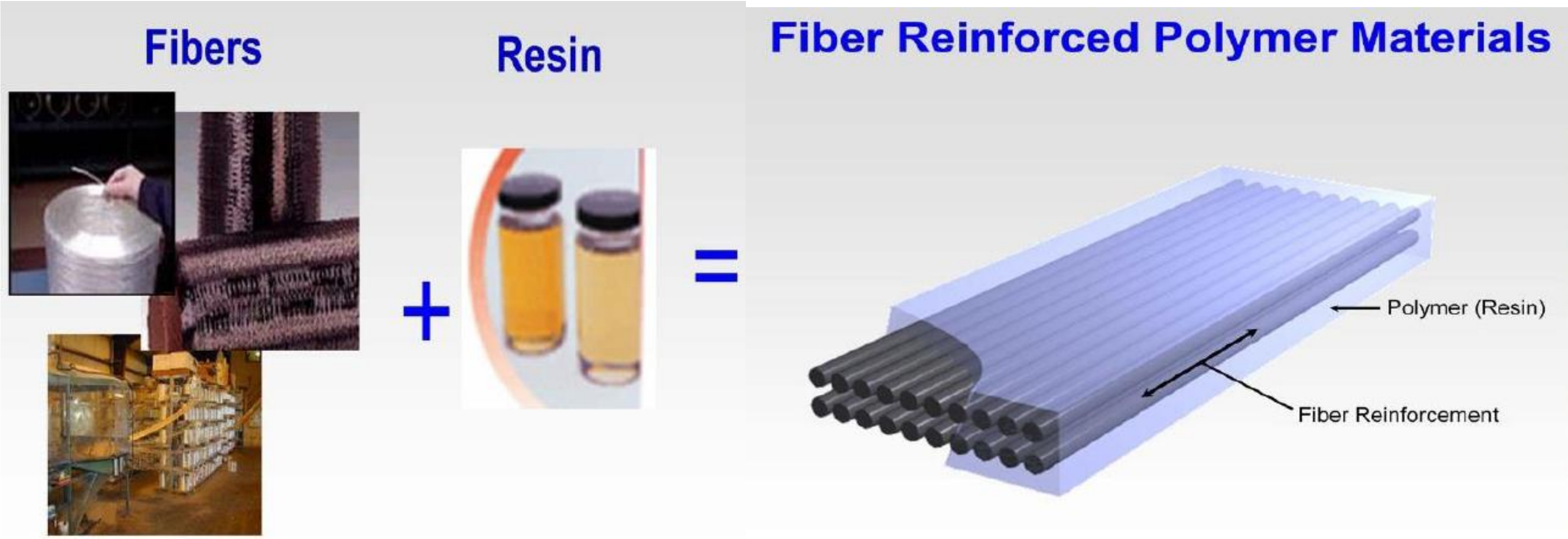
FRP (Fiber Reinforced Polymer)

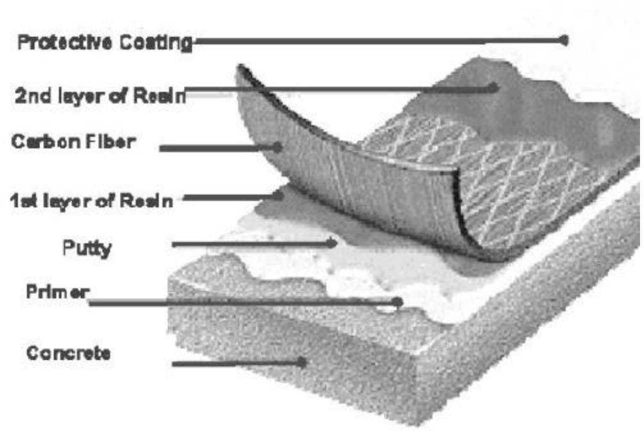
- Fiber reinforced polymer (or FRP) materials are created by combining high strength, thread-like fibers with a polymer or resin material. The result is a rigid material that is high strength yet light weight.
- The fibers in the material give the material all of its strength and stiffness characteristics while the polymer holds the fibers in alignment.
- The fibers are available in the form of sheets (or fabrics), pre-formed shapes and bars

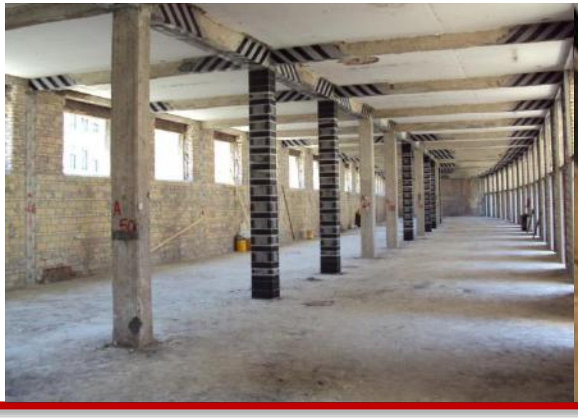


Local intervention

The fibre reinforced polymer (FRP) composites are useful for repair, rehabilitation and retrofit of structures for the following reasons.

- The FRP sheets are light and flexible, which facilitates installation. It does not need drilling of concrete or masonry. There is less disruption during strengthening.
- The curing time is less. This leads to reduced down time to the users of a building.
- The sheets are thin and hence there is marginal increase in the size of a retrofitted member.
- The sheets have high strength-to-weight ratio and superior creep properties.
- The material is chemically inert and has resistance against electro-chemical corrosion.
- There is good fatigue strength, which is suitable for fluctuating loads.





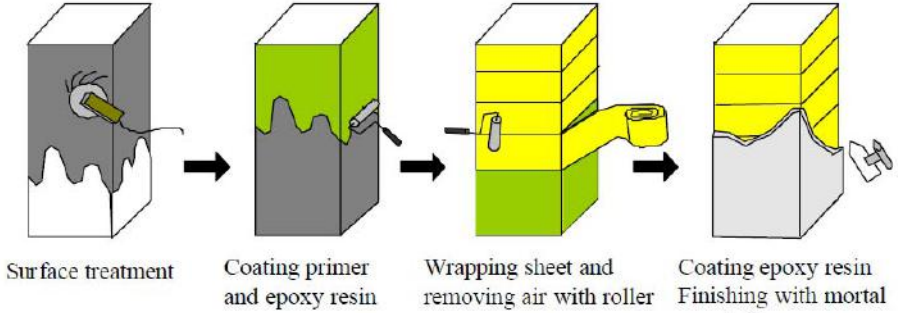
FRP (Fiber Reinforced Polymer)

Pros

- Highest strength,
- Highest stiffness,
- Most durable fibers.
- Highly resistant to most environmental conditions.
- Low creep
- High fatigue endurance.

Cons

- fabricate this composite material is very expensive compared to traditional concrete and steel materials.
- Required Chemicals (epoxy, resin, etc)



the cost of the material is balanced by much lower installation costs.

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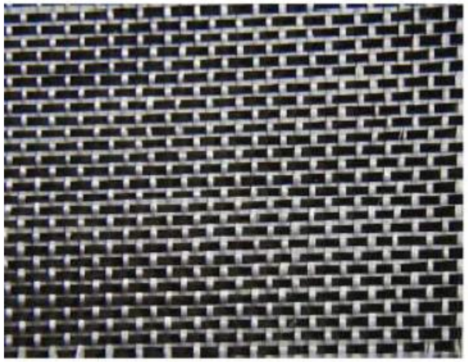
Local intervention

FRP (Fiber Reinforced Polymer)

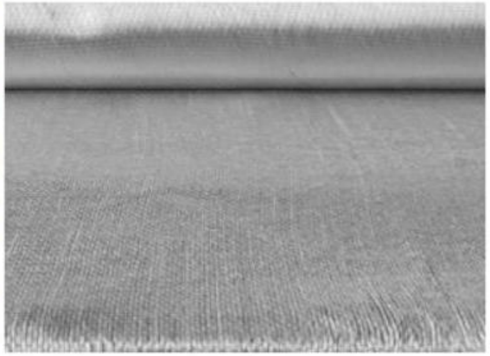
- Fibers can be of glass, carbon or aramid. Glass fibers have lower stiffness and cost as compared to carbon fibers. Fibers in sheet or fabric can be oriented uni-directional or in two directions.
- Final composites are elastic up to failure and do not exhibit plasticity.
- They are very sensitive to transverse actions (i.e. corner or discontinuity effects) and unable to transfer local shear (i.e. interfacial failure).

TYPICAL VALUES OF THE PROPERITIES OF GLASS FIBRE

Density	0.9 kg/m^3
Tensile strength	1700 N/mm^2
Tensile modulus of elasticity	75,000 N/mm^2



(a) Carbon fibres



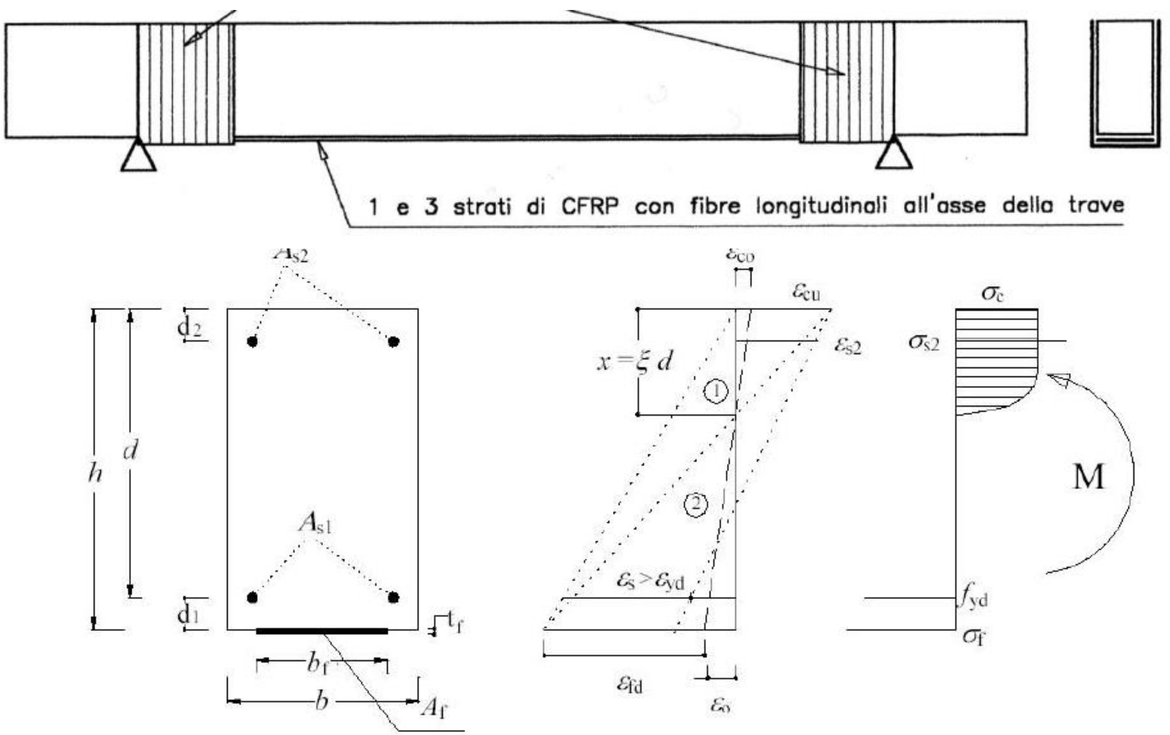
(b) Glass fibres

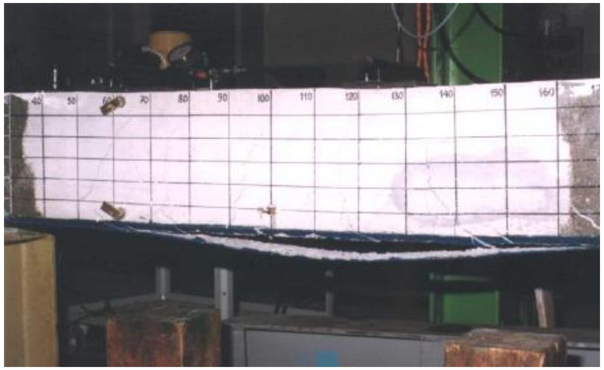
Wabo®MBrace CF 160
High Strength Unidirectional Carbon Fiber Fabric

Physical Properties:	
Fiber Material:	High Strength Carbon
Areal Weight:	0.124 lb/ft^2 [600 g/m^2]
Fabric Width:	24 in [610 mm]
Nominal Thickness, t_f (1)	0.013 in/ply [0.33 mm/ply]
Functional Properties:	
CTE:	-0.21·10^{-6}/°F (-0.38·10^{-6}/°C)
0° Tensile Properties (2,3):	
Ultimate Tensile Strength, f^*_{fu}	550 ksi [3800 MPa]
Tensile Modulus, E_f	33000 ksi [227 GPa]
Ultimate Tensile Strength per Unit Width, $f^*_{fu}\,t_f$	7.14 kips/in/ply [1.25 kN/mm/ply]
Tensile Modulus per Unit Width, $E_f t_f$	430 kips/in/ply [76 kN/mm/ply]
Ultimate Rupture Strain, ε^*_{fu}	1.67 %
90° Tensile Properties (2,4):	
Ultimate Tensile Strength:	0
Tensile Modulus:	0
Ultimate Rupture Strain:	n/a

NOTES:
(1) The nominal fabric thickness is based on the total area of fibers (only) in a unit width. From experience, the actual cured thickness of a single ply laminate (fibers plus saturating resins) is larger.
(2) The tensile properties given are those to be used for design. These values are derived by testing cured laminates (per ASTM D3039) and dividing the resulting strength and modulus per unit width by the nominal fabric thickness.
(3) The 0° direction denotes the direction along the length of the fabric.
(4) The 90° direction denotes the direction along the width of the fabric.

- FLEXURAL STRENGTHENING





Zone (1): fiber rupture

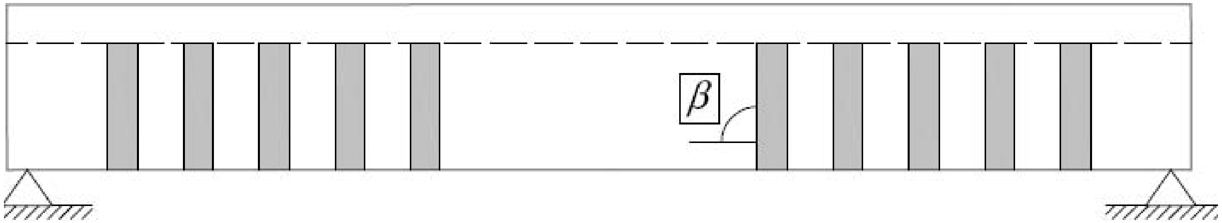
Zone (2): concrete collapse

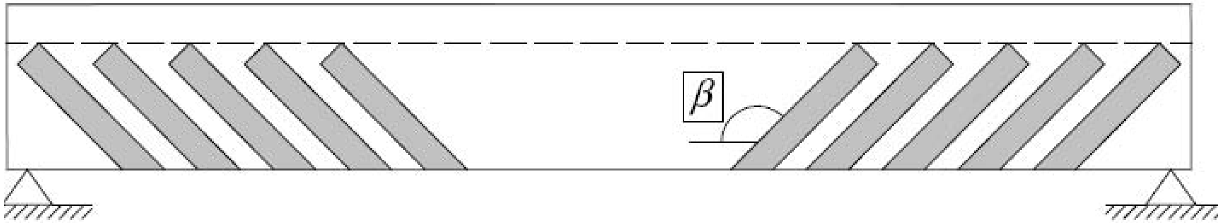
$$0 = \psi \cdot b \cdot x \cdot f_{cd} + A_{s2} \cdot \sigma_{s2} - A_{s1} \cdot f_{yd} - A_f \cdot \sigma_f$$

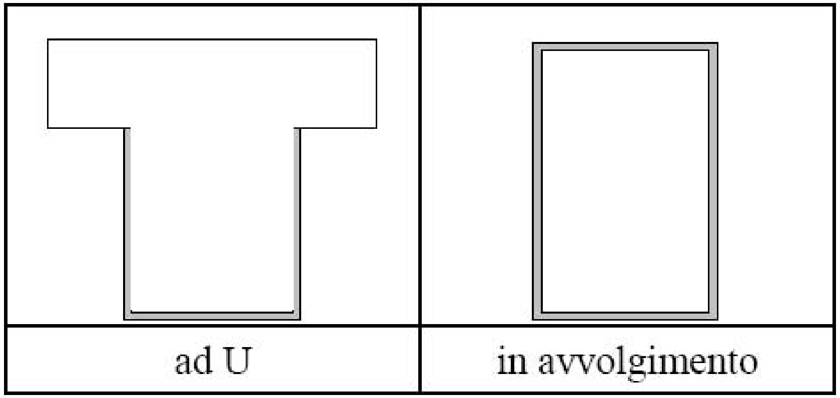
$$M_{Rd} = \frac{1}{\gamma_{Rd}} \cdot \left[\psi \cdot b \cdot x \cdot f_{cd} \cdot (d - \lambda \cdot x) + A_{s2} \cdot \sigma_{s2} \cdot (d - d_2) + A_f \cdot \sigma_f \cdot d_1 \right]$$

FRP (Fiber Reinforced Polymer)

- For shear reinforcement the application can be done with a continuous wrapping or discontinuous .
- It is suggested to apply trasnverse connections of fibers to the to enhance debonding.

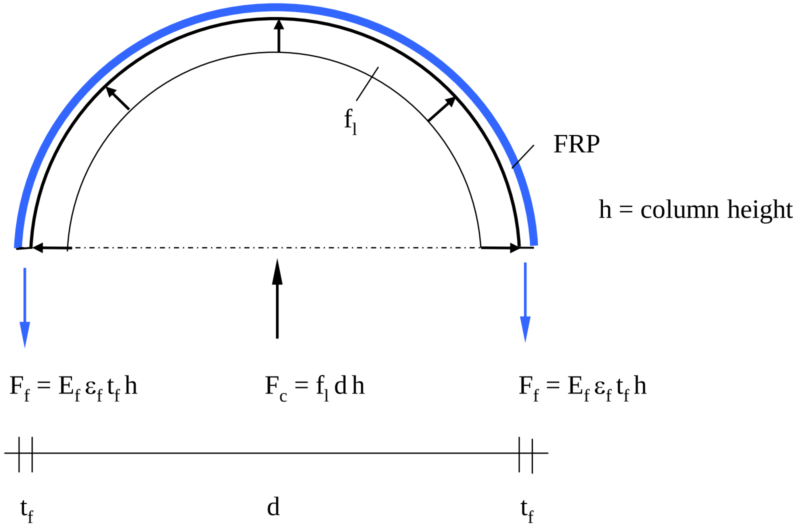






FRP (Fiber Reinforced Polymer)

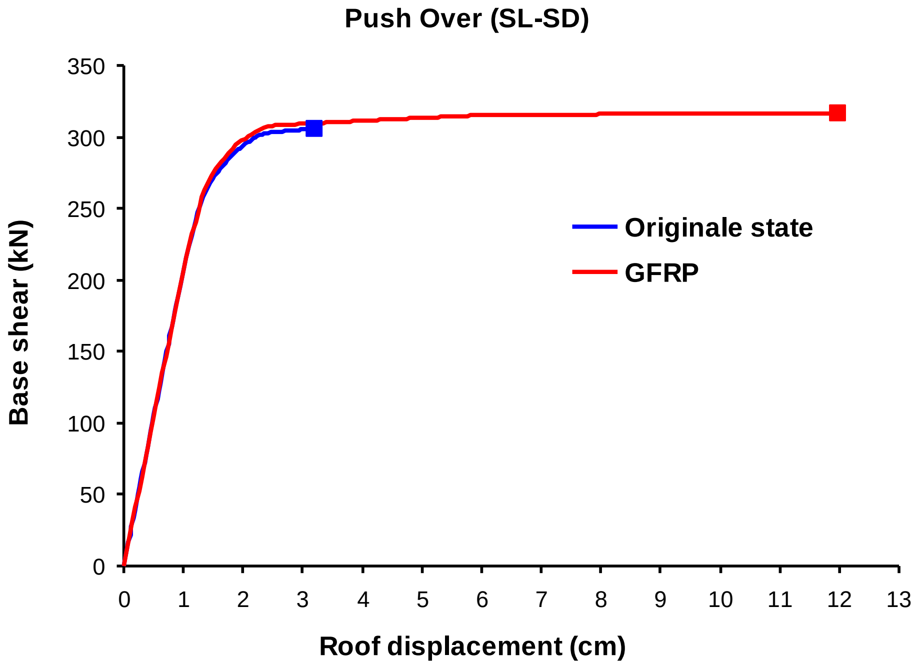
- Application for confinement



Local intervention

FRP (Fiber Reinforced Polymer)

Choosing the type of fibers, their orientation, their thickness and the number of plies, results in a great flexibility in selecting the appropriate retrofit scheme that allows to target the strength hierarchy at both local (i.e. upgrade of single elements) and global (i.e. achievement of a desired global mechanism) levels.



Local intervention

FRCM (Fiber Reinforced Cementitious Matrix

- FRCM (Fiber Reinforced Cementitious Matrix) derived from the coupling of a carbon fiber or glass mesh with an inorganic cement matrix.
- When adhered to concrete or masonry structural members, they form an FRCM system that acts as supplemental, externally bonded reinforcement.

- RCM has been the technology that has recently supplanted the traditional plasters reinforced with metallic mesh. Indeed FRCM systems have been shown to have numerous technical and applicative advantages in their favor such as the handling and the on-site workability on yard or the ray permeability

They are used for reinforced plasters, restoration of shrinkage cracks through (by applying them on two sides) and non-through (applying on only one side), or for the perimeter connection of claddings and internal partitions to pillars and beams emerging and not.

Local intervention

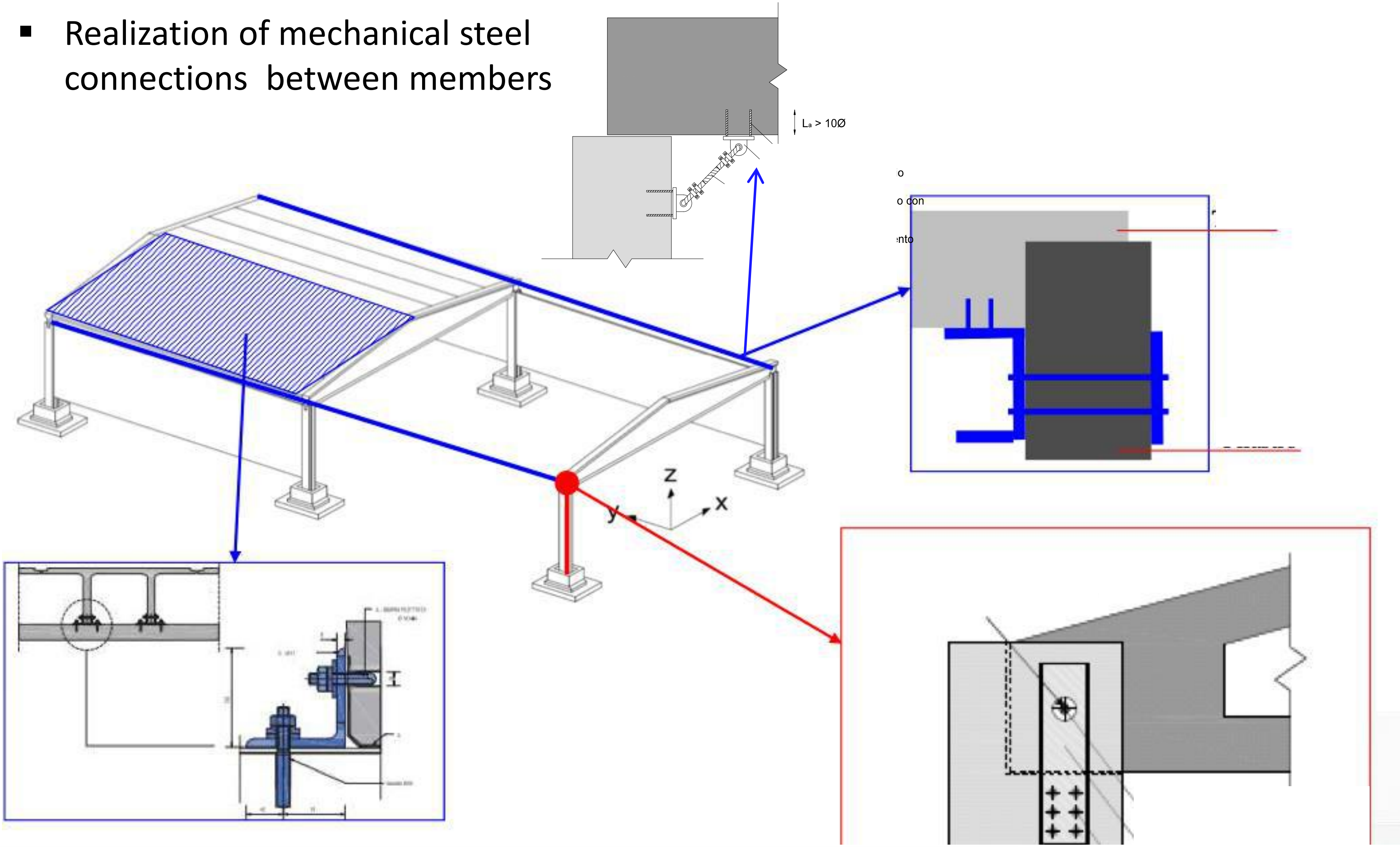
REALIZATIONS OF NEW CONNECTIONS

Lack of effective connections in pre-fabricated buildings:

- secondary-main beams;
- Beams-columns
- Column-foundations
- Column and perimetral infills

Local intervention

- Realization of mechanical steel connections between members

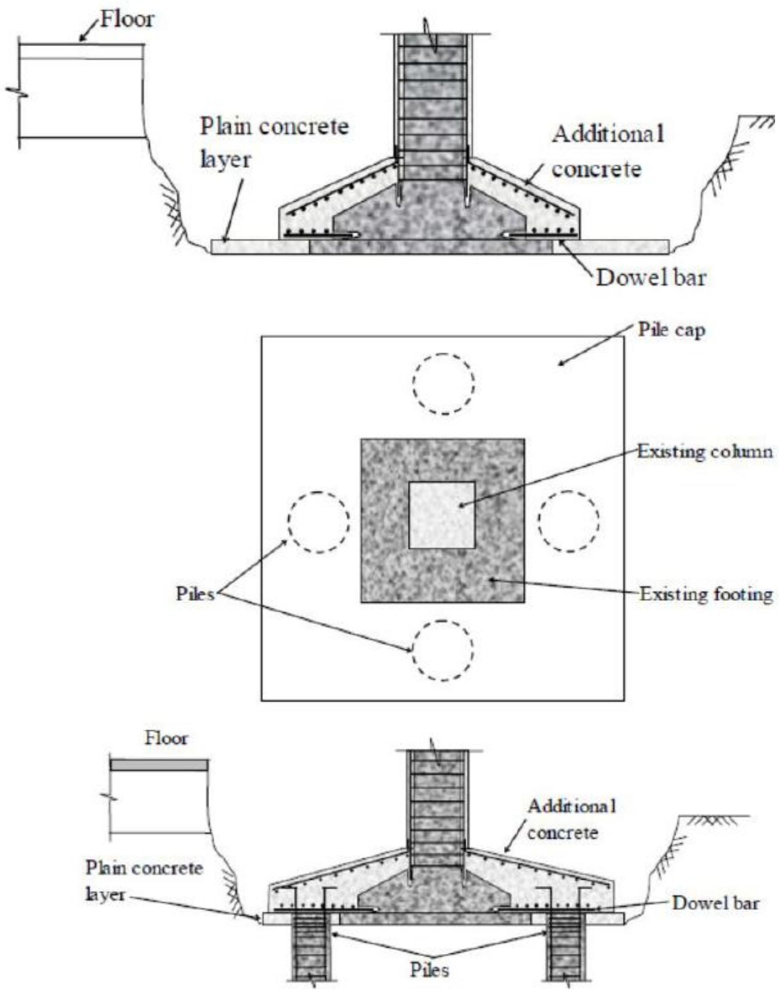


RETROFIT OF FOUNDATIONS

- In many buildings designed only for gravity loads, foundation pad are unsufficient for overturning moment and slipping effects due to horizonthal forces.

- Often there are no connection between isolated plinths, as required for asesimic structures to prevent from differential settlements

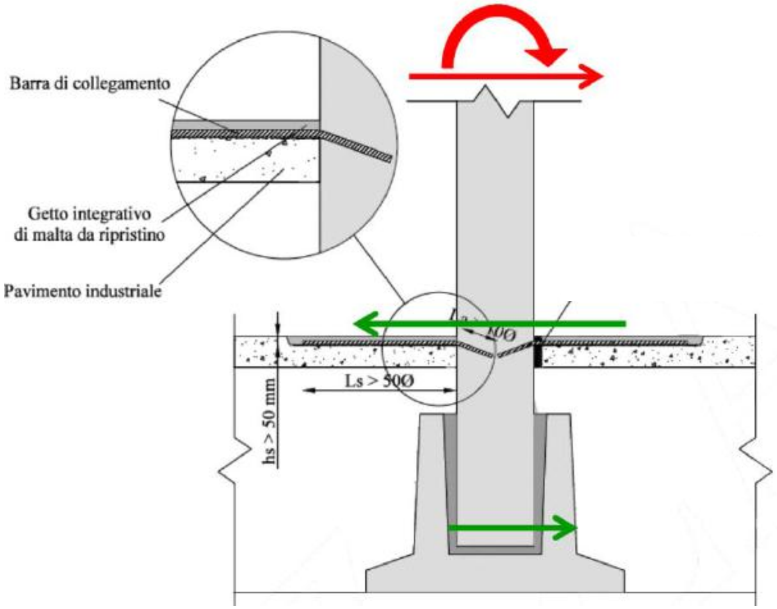
- Retrofit can require the enlargement of swallow existing foundation , or realization of piles to sustain overturining moments.



Local interventions

- Retrofit of foundation can be very expensive

- Effective connections of the coulmn with existing (reinforced)ground slab to transfer shear forces can be realized in some cases to avoid further heavier interventions



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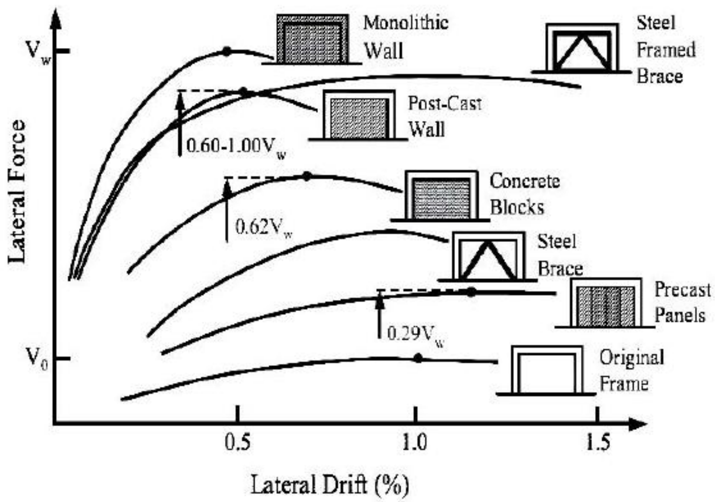
- 3. IMPROVEMENT OF GLOBAL CAPACITY

Global interventions



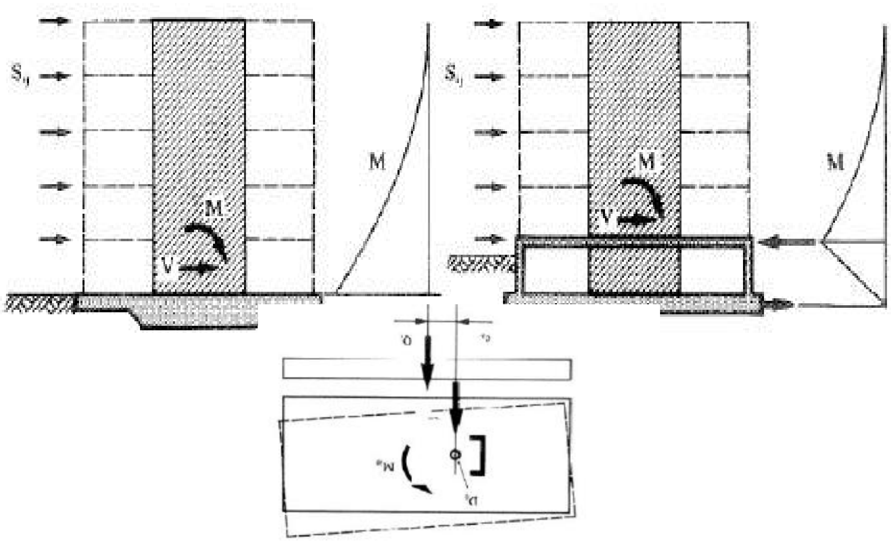
Retrofit strategy	Merits	Demerits	Comments
Addition of infill walls	• Increases lateral stiffness of a storey • Can support vertical load if adjacent column fails	• May have premature failure due to crushing of corners or dislodging • Does not increase ductility • Increases weight	• Low cost • Low disruption • Easy to implement
Addition of shear walls, wing walls and buttress walls	• Increases lateral strength and stiffness of the building substantially • May increase ductility	• May increase design base shear • Increase in lateral resistance is concentrated near the walls • Needs adequate foundation	• Needs integration of the walls to the building • High disruption based on location, involves drilling of holes in the existing members
Addition of braces	• Increases lateral strength and stiffness of a storey substantially • Increases ductility	• Connection of braces to an existing frame can be difficult	• Passive energy dissipation devices can be incorporated to increase damping / stiffness or both
Addition of frames	• Increases lateral strength and stiffness of the building • May increase ductility	• Needs adequate foundation	• Needs integration of the frames to the building

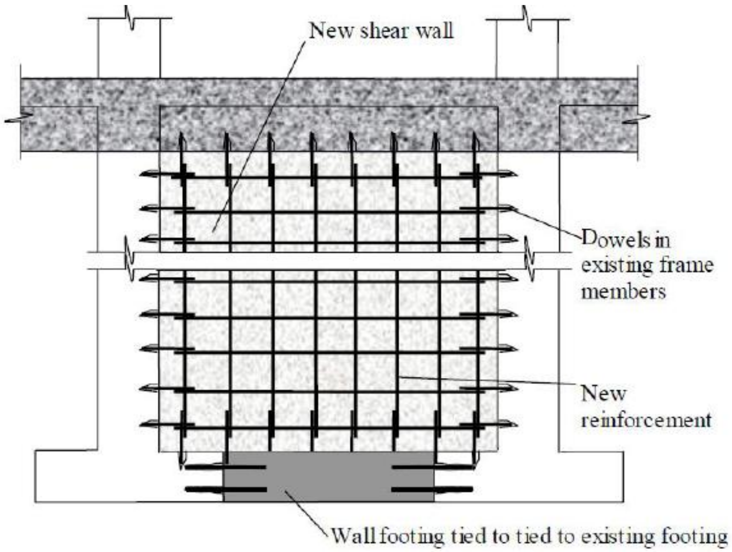
Local interventions

ADDITION OF SHEAR WALLS

Shear walls, wing walls or buttress wall are added to increase lateral strength and stiffness of a building, and to reduce eccentricity between of the Centre of Mass and Center of Stiffness .

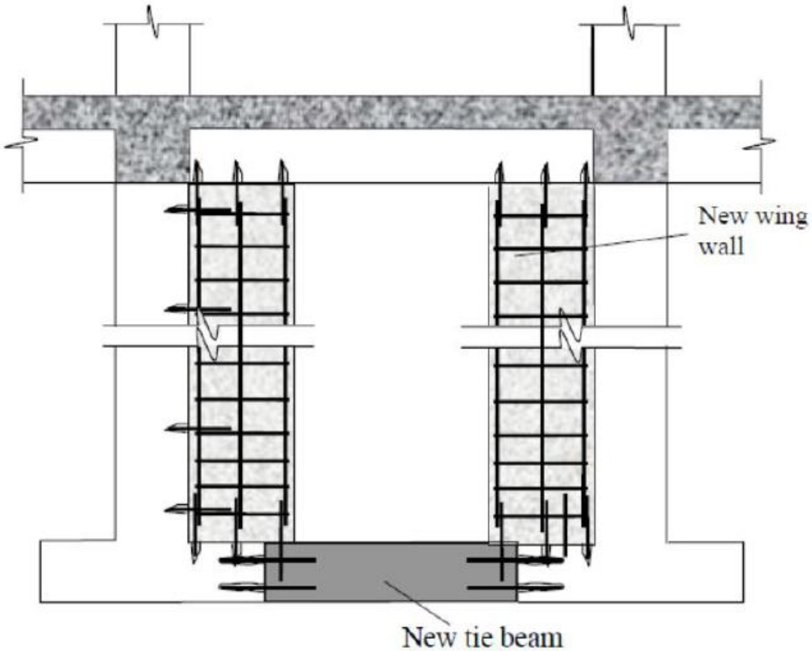
- Frequently used for retrofitting of non ductile reinforced concrete frame buildings.
- The added elements can be either cast-in-place or precast concrete elements.



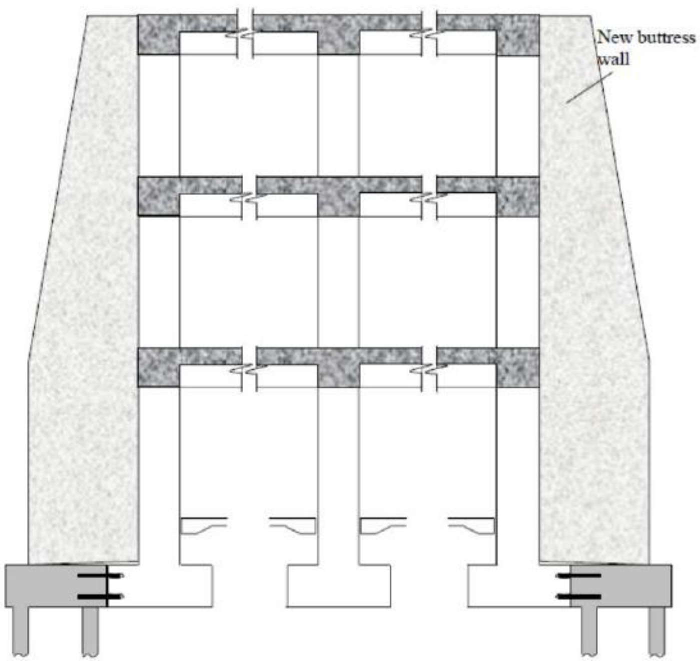


Global interventions

Addition of wing walls



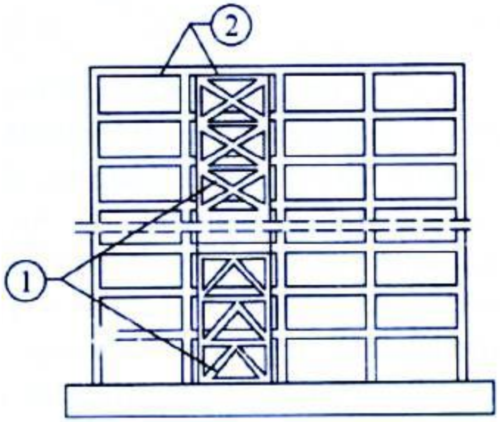
Addition of buttress walls

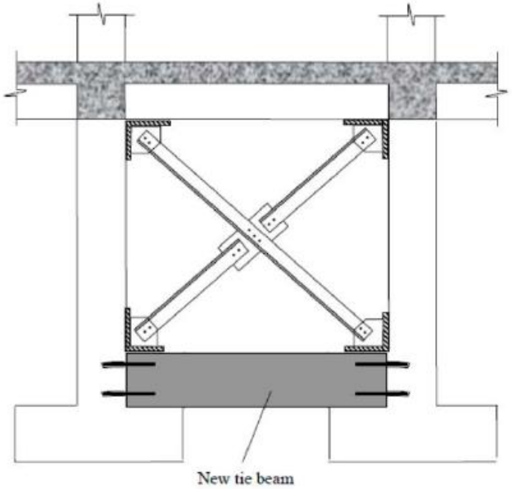


- Not preferred in the interior of the structure to avoid interior mouldings.
- New elements preferably be placed at the exterior of the building.
- If ony one or two walls are introduced, the increase in lateral resistance is concentrated in the new elements (the new foundation should be adequate to resist the overturning moment without rocking or uplift. The stabilizing momet is only due to the self -weight.

ADDITION OF BRACING

- A steel bracing system can be inserted in a RC frame to provide lateral stiffness, strength, ductility, or any combination of these.
- The braces can be better effective for relatively flexible frames (without infills)
- For an open ground storey, the braces can be placed in appropriate bays while maintaining the appropriate use.
- The connection between the braces and the existing frame is of great importance: one possibility is to installa an independent steel frame within the designated RC frame. Else, the braces can be connected directly to the RC frame

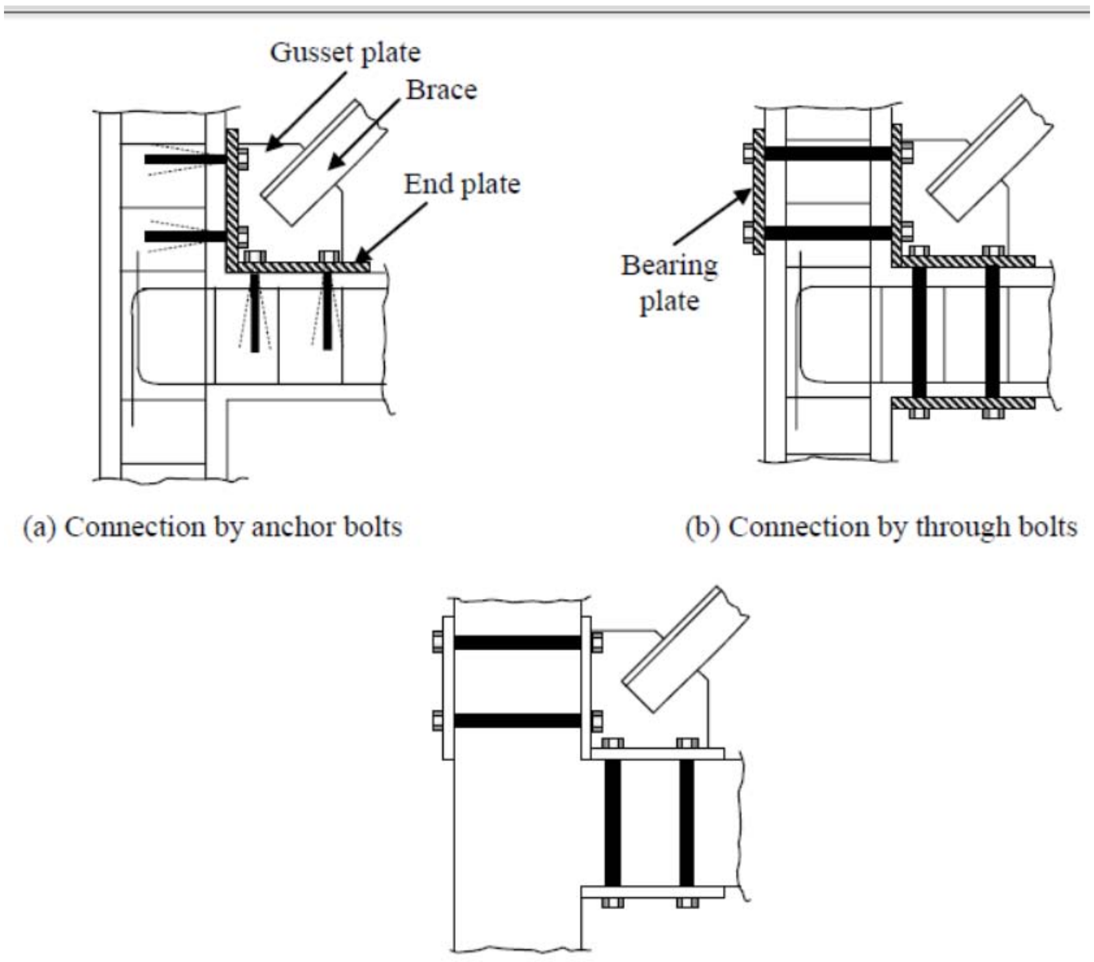




Local interventions

ADDITION OF BRACING

- When the braces are connected to the RC frame at the beam-coulmn joints, the forces resisted by the braces are transferred to the joints in the form of axial forces, both in compression and tension. While the addition of compressive forces may be tolerated, the resulting of tensile forces are of concern
- There are different possibile type of connections: a) the force in brace is transferred to the frame through the gusset plate, end plate and anchor inserts; b) end plate is connected using through bolts; end plate and bearing plate project beyond the width o the beam and column.



(a) Connection by anchor bolts

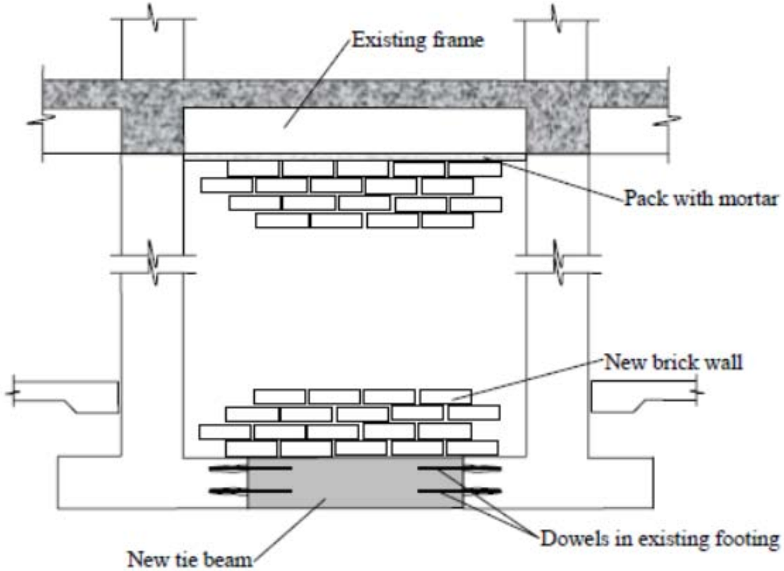
(b) Connection by through bolts

(c) Connection by bolts placed outside the members

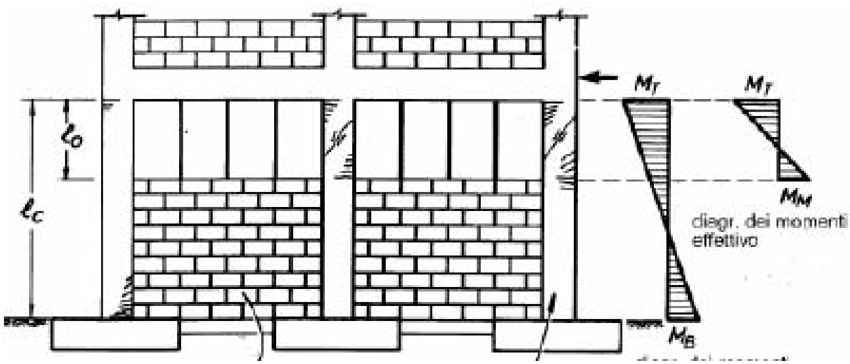
ADDITION/STRENGHTENING OF INFILL WALLS

- The lateral stiffness of a story increases with infill walls
- Addition of infill walls in the ground storey is a viable option to retrofit buildings with open ground storeys. Due to the «strut action» of the infilled walls, the flexural and shear forces and the ductility demand on the ground story columns are substantially reduced.

Addition of a masonry infill wall



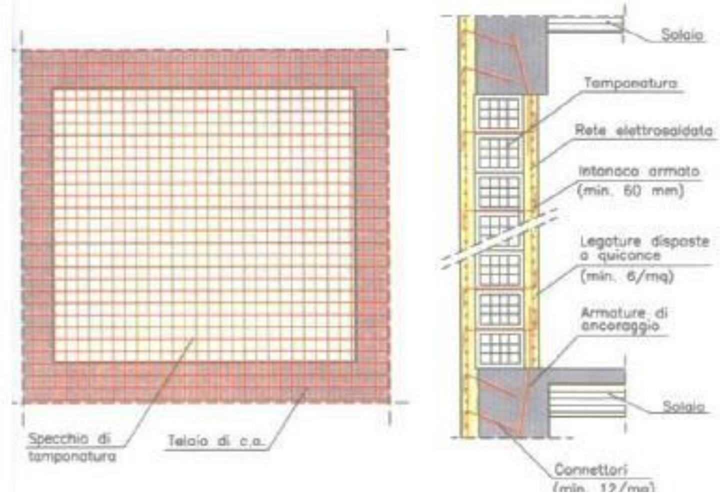
Infill walls of partial heigh can be extended to reduce the vulnerability of short and stiff columns

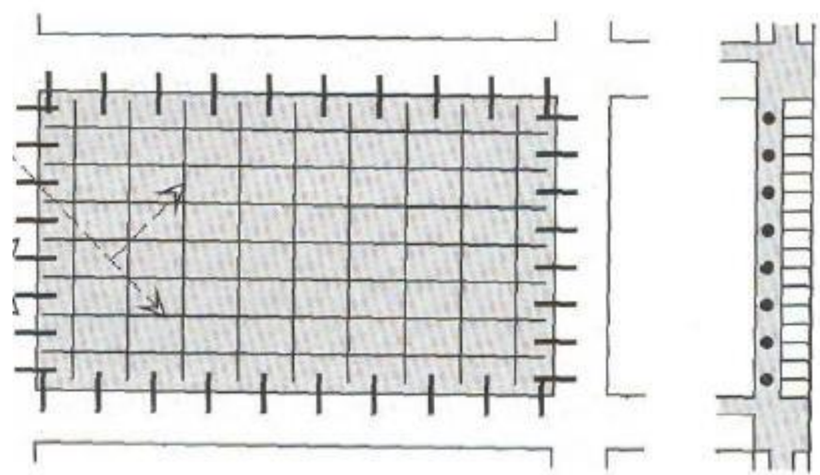


Local interventions

ADDITION/STRENGHTENING OF INFILL WALLS

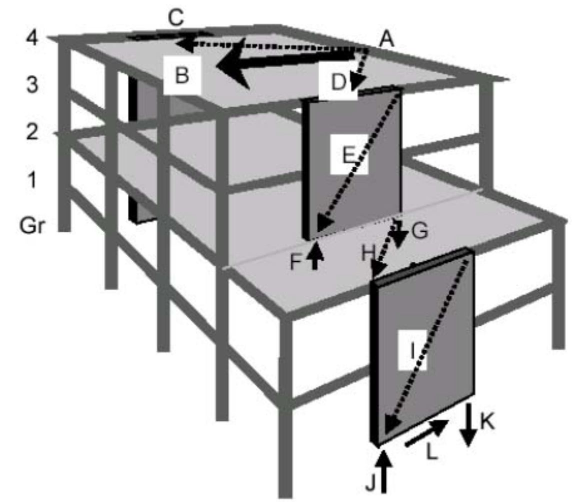
Jacketing of existing masonry infill walls can be also adopted both as local intervention (to reduce vulnearbility related to out-of-plane rotation of the element), and global strenghtening





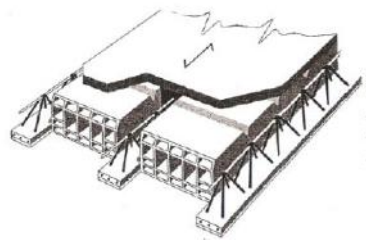
FURTHER ISSUES

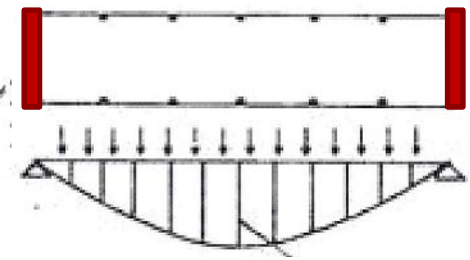
- **<u>Continuous load path</u>** of horizontal forces down to the foundations.
- **<u>Structural regularity</u>** in mass, stiffness and resistance distribution to achieve
  - reduction of global *torsional effects*
  - reduction of local concentrations demands in terms of *resistance* or *capacity*
  - reduction of *soft storey collapse* probability
- **<u>Redundancy</u>** of structural elements, which permits bending moment redistribution behaviour to postpone structural collapse
- **<u>Limited masses and adequate stiffness</u>** to achieve low displacements and
  - reduction of second order effects
  - reduction of non-structural elements damage

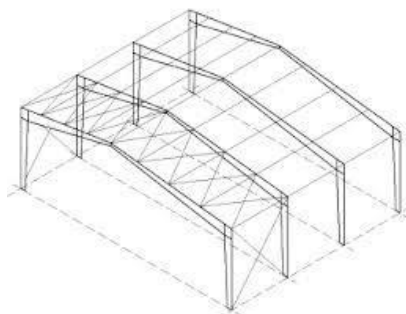


FURTHER ISSUES

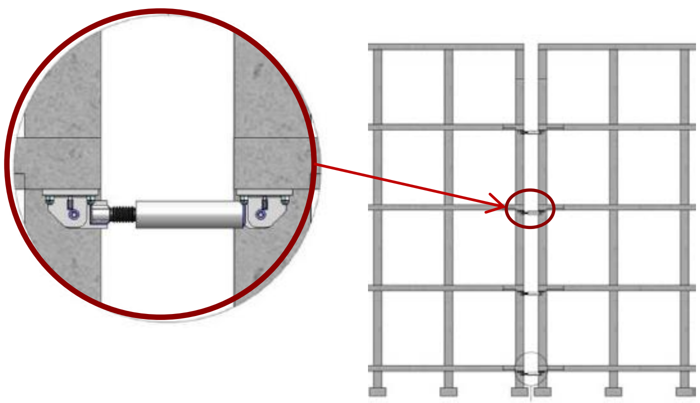
- **Rigid diaphgram** : the distribution of horizontal forces by the horizontal diaphragm to the various lateral load resisting elements depends on the rigidity of the horizontal diaphragm.
  A flexible roof or intermediate plan can be stabilized as rigid diaphgram adding a system of steel bracing or a collaborating RC slab (min. 4-5 cm thick), or using FRP strips applied at the extrados







- **Elimination of joints** . Shock-transmitter can be In this way the forces produced by earthquake can be transferred to those points, suitably dimensioned, stated by the designer, but in order to freely allow the slow movements.



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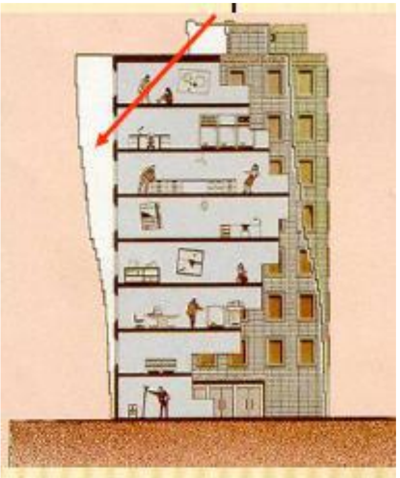
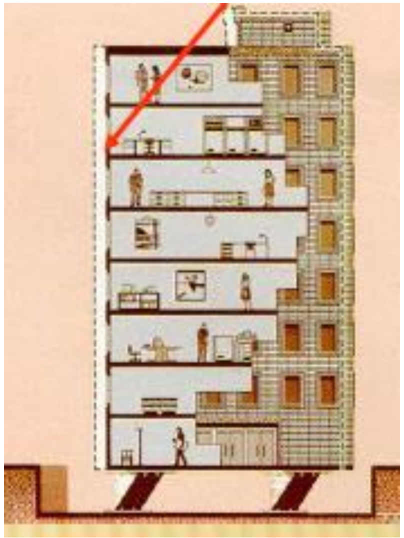
- 4. BASE ISOLATION AND
  ENERGY DISSIPATION DEVICES

Seismic isolation is applicable to existing structures:

- when higher performance levels are required, which calls for the building to be operational immediately after an earthquake: e.g. in hospitals police stations, fire stations, when a structure has a critical Civil Defence role for emergency, etc.. The required low levels of structural and non-structural damage may be achieved by using an isolation system that limits structural deformations and ductility demands to low values;
- when a structure is inherently non-ductile and has only moderate strength, seismic isolation may provide a required level of earthquake resistance which cannot be provided practically by other seismic techniques;



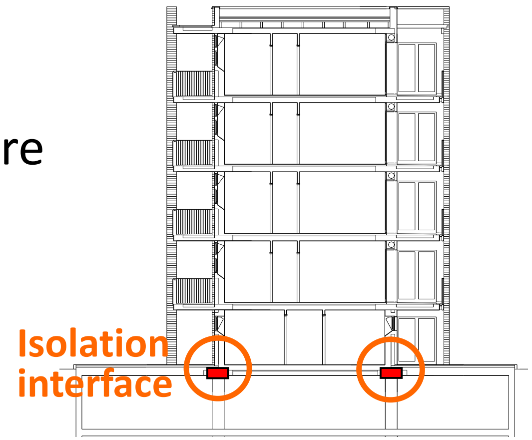


Introduction to Base Isolation

Benefits

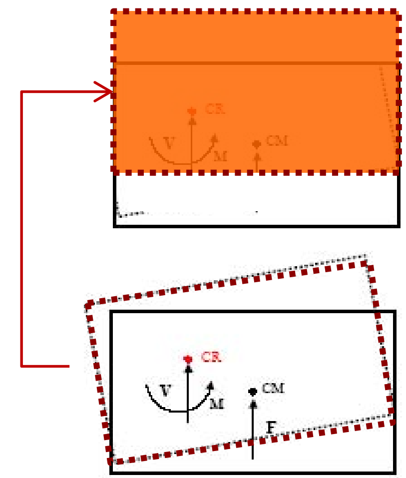
The seismic performance of based isolated structures is improved (reduced/eliminated) by:

- Reduction of seismic acceleration on the superstructure
- Almost elastic seismic response of the structure
- Reduction of interstory drift/residual displacements
- Recentering of eccentricity (eventual)



Short term benefits:

1. Possible reduction of resisting member cross-sections
2. Saving in geometrically irregular structures



Long term benefits:

1. Higher global structural safety
2. Reduction of repair/recover costs
3. Continuous operativity

ENERGY BALANCE:

$$E_i \leq E_e + E_k + E_h + E_v$$

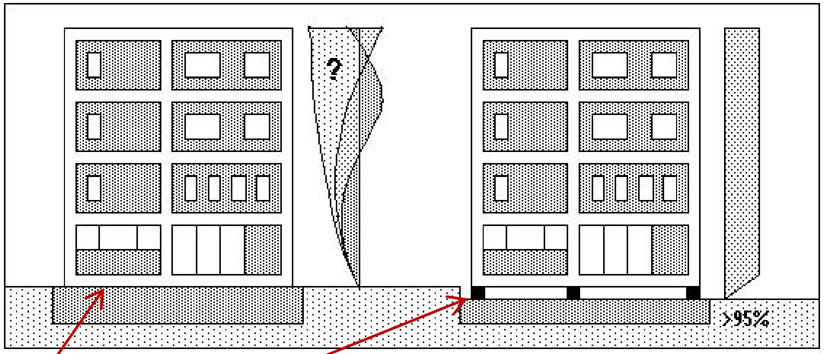
E_i =input energy

E_e =elastic deformation energy

E_h =hysteretic energy

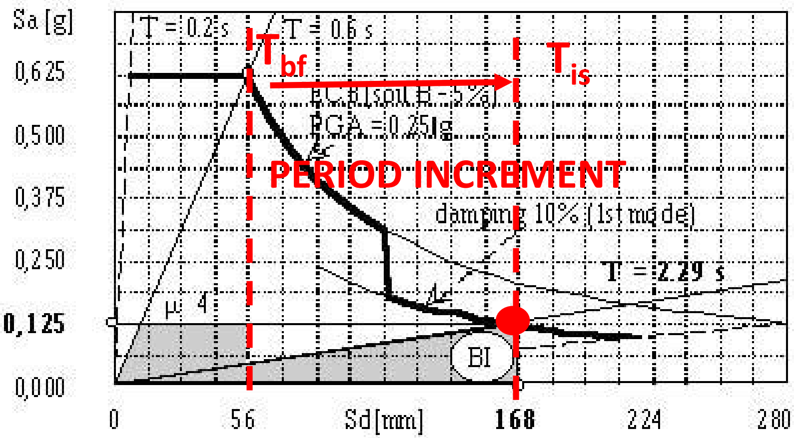
E_k =kinetic energy

E_k =viscous energy



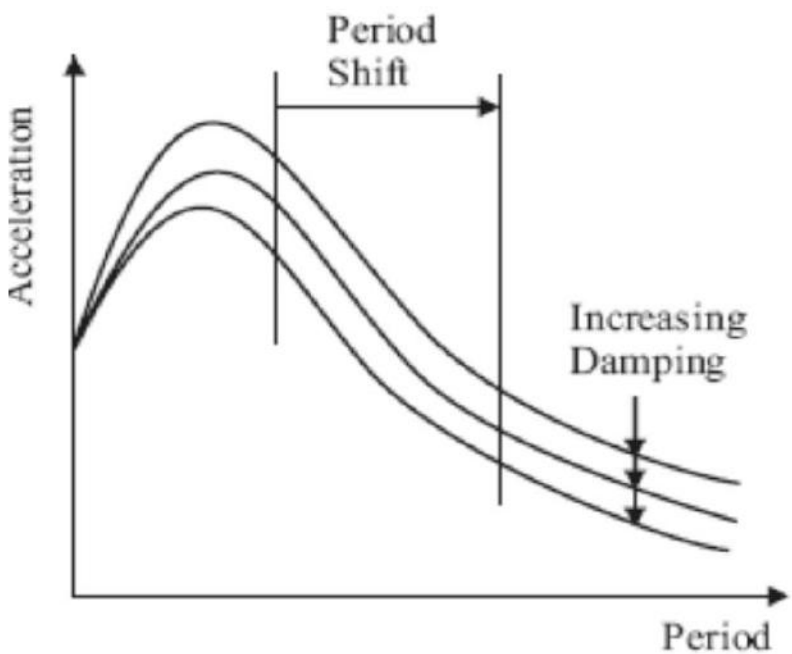
The structural behaviour is modified trough:

- REDUCTION OF INPUT ENERGY
  period lengthening ($T_{is} \geq 3T_{bf}$)
- INCREMENT OF DAMPING
  using of additional dissipation devices

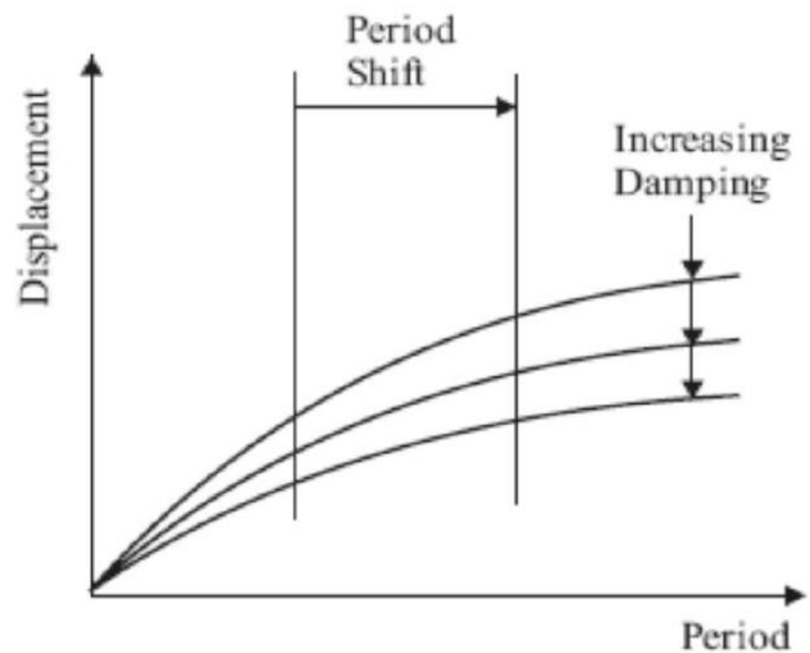


Aspects of seismic isolation strategy

Effect of period lengthening and damping increase on the **acceleration** seismic spectrum



Effect of period lengthening and damping increase on the **displacement** seismic spectrum



Isolation devices

ISOLATION SYSTEM

- ISOLATORS
- AUXILIARY DEVICES

Comprises:

- High horizontal / lateral flexibility
- Vertical load capacity to support gravity loads
- Stability at high shear strain
- Uplift restrainer and tensile capacity
- Energy dissipation
- Restoring force for self-centering capability
- Adequate rigidity for non-seismic loads (e.g. wind and breaking) while accommodating thermal, creep and other shortening effects

All isolation systems have generally nonlinear properties; a simplified linear approach can be used for pre-dimensioning. System property modification for aging, temperature, wear and tear, contamination, etc. must be taken into serious consideration

CONTROL SYSTEMS FOR THE PROTECTION OF STRUCTURES

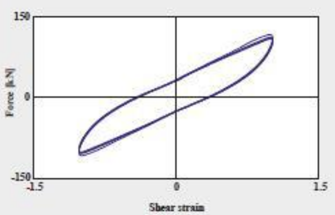
- PASSIVE CONTROL
  - BASE ISOLATION
    - ELASTOMERIC ISOLATORS
    - SLIDING DEVICES
    - LEAD RUBBER ELASTOMERIC ISOLATORS
    - SLIDING DEVICES + ELASTO-PLASTIC ELEMENTS
  - HYBRID SYSTEMS
  - ENERGY DISSIPATION
    - VISCOUS DAMPERS
    - STEEL HYSTERETIC DEVICES
    - VISCOELASTIC DEVICES
    - SMA DEVICES
- SEMI-ACTIVE & ACTIVE CONTROL
  - VARIABLE STIFFNESS DEVICES
  - VARIABLE DAMPING DEVICES
  - ACTIVE BRACINGS

Isolation/Dissipation devices

ISOLATORS

ELASTOMERIC ISOLATORS

Elastomeric isolators (EIs) are made up of rubber layers alternating with steel laminates joined together through vulcanization.Their behaviour can be modelled as linear, by means of effective stiffness and equivalent viscous damping.
Usually they are manufactured with High Damping Rubber compound, i.e. with equivalent viscous damping 10÷15% at 100% shear strain (HDRB).

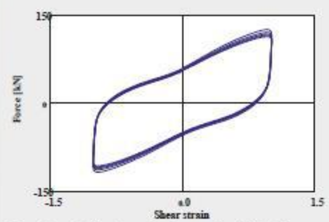


Experimental hysteresis loops of an EI at frequency 0.5 Hz, shear strain ± 100%.

Setting up for testing of two 1150 mm diameter EIs at FIP laboratory.

LEAD RUBBER BEARINGS

Lead Rubber Bearings (LRBs) are elastomeric isolators with a cylindrical lead plug inserted in their centre, with the aim to increase the damping by hysteretic shear deformations of the lead.
The equivalent viscous damping can be up to 30%. Their constitutive behaviour, typically bilinear, can be modelled as linear or non-linear, according to the used code.

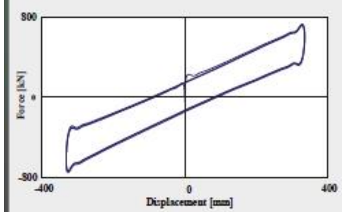


Experimental hysteresis loops of a LRB at frequency 0.5 Hz, shear strain ± 100 %.

LRB under shaking table testing at the National Technical University of Athens, Greece.

CURVED SURFACE SLIDERS

The Curved Surface Sliders (CSSs) or Friction Isolation Pendula (FIP®) use gravity as the restoring force. Energy dissipation is provided by friction in the main sliding surface. The parameters of the bilinear constitutive law depend on the radius of curvature and friction coefficient. For very large displacements CSSs may be substituted by Double Concave Curved Surface Sliders (DCCSSs).

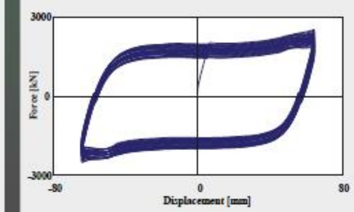


Experimental hysteresis loops of a CSS (Friction Isolation Pendulum - FIP®).

A DCCSS under testing at the Eucentre Laboratory, Pavia, Italy.

FLAT SURFACE SLIDERS WITH DAMPERS

These isolators combine in a single device a slider and dampers, that typically are steel hysteretic and/or fluid viscous dampers.
Thus, the resulting behaviour is characterised by a very high energy dissipation capacity. The slider can be free-sliding or guided, as required.
The isolator can also combine STUs or mechanical fuse restraints.



Experimental hysteresis loops of a flat surface slider with steel hysteretic dampers.

A flat surface slider with steel hysteretic dampers for the Crescenza Viaduct, Italy.

Ref. www.fip-group.it

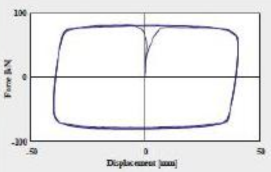
Isolation/Dissipation devices

DAMPERS

VELOCITY-DEPENDENT DEVICES

FLUID VISCOUS DAMPERS

Fluid Viscous Dampers (FVDs) are cylinder/piston devices that exploit the reaction force of silicon fluid forced to flow through an orifice and/or valve system.
The typical force-velocity law of FIP's FVDs is non-linear, i.e. $F=Cv^{\alpha}$, where $\alpha=0.15$, F is the force, C is the damping constant and v is the velocity.
Different values of the exponent α can be provided on request.

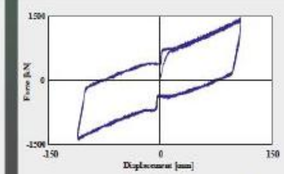


Experimental hysteresis loops of a FVD under sinusoidal input.

FVDs for the Rion-Antirion Bridge (Greece) under testing at FIP laboratory.

FLUID SPRING DAMPERS

The reaction force F of Fluid Spring Dampers (FSDs) depend on both imposed velocity v and displacement x according to the law $F=F0+Kx+Cv^{\alpha}$, where F0 is the pre-load force, K is the stiffness, C is the damping constant and $\alpha=0.15$.
The pre-load force can be useful to avoid displacements under service horizontal loads (e.g. braking forces in a bridge).



Experimental hysteresis loops of a FSD without pre-load force.

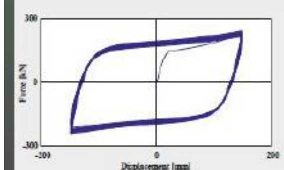
A FSD for the Badia Nuova Viaduct on the A1 Highway, Italy.

DISPLACEMENT –DEPENDENT DEVICES

Non-linear

STEEL HYSTERETIC DAMPERS

Steel Hysteretic Dampers (SHDs) use as a source of energy dissipation the hysteretic yielding of steel elements of various shapes, developed to guarantee many stable hysteresis loops.
The most used elements are the crescent moon and the tapered pin (single or double). SHDs can be combined with STUs, when necessary to handle significant thermal movements.

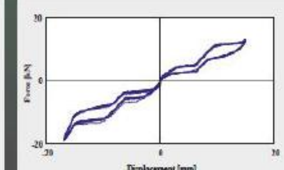


Experimental hysteresis loops of a SHD with crescent moon elements.

A steel hysteretic damper comprising double tapered pin elements and STUs (Jamuna Bridge, Bangladesh)

SHAPE MEMORY ALLOY DEVICES

Shape Memory Alloy Devices (SMADs) are axial restraint devices exploiting the superelastic properties of shape memory alloys in the austenitic state.
Their force-displacement curve exhibiting one or more "plateaux" enables SMADs to limit the maximum load transmitted to the structure to which they are connected. They have a strong recentring capability.

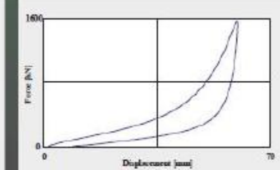


Experimental force vs displacement curve of a SMAD.

Shaking table tests on masonry walls connected with SMADs

BUFFERS

Buffers are double-acting axial devices comprising a certain number of elastomeric discs, each of them vulcanized to two steel plates.
A particular arrangement of steel rods allows the discs to always be compressed, regardless of the direction of the movement.
Buffers are used in bridges at abutments and/or between adjacent decks where expansion joints are located.



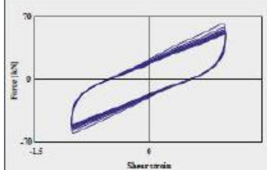
Experimental force vs displacement curve of a buffer.

Buffers for viaducts on the TAG Motorway, Turkey.

Linear

ELASTOMERIC VISCOEASTIC DAMPERS

Elastomeric Viscoelastic Dampers (EVEDs) are made of one or several layers of elastomer which are strained in shear, connecting the relatively moving parts of a structure. Usually they are installed in bracings in framed buildings.
The elastomer compound used is high damping, with equivalent viscous damping 15÷20% at 100% shear strain.



Experimental hysteresis loops of an EVED at frequency 0.5 Hz, shear strain = 100 %.

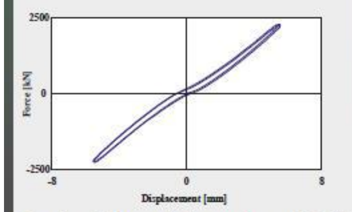
Shaking table tests on a reinforced concrete frame with EVED along chevron bracings

Ref. www.fip-group.it

RIGID-CONNECTION DEVICES

SHOCK TRANSMISSION UNITS

Shock Transmission Units (STUs) provide a very stiff dynamic connection, whilst their reaction to low velocity applied displacements, e.g. due to thermal changes, is negligible. STUs find valid application whenever the structure is requested to change its behaviour in the event of earthquakes or other dynamic actions. Sometimes STUs are also referred to as lock-up devices.

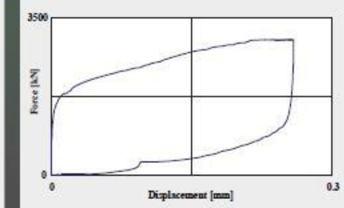


Experimental force vs displacement curve of a STU.

Setting up for testing at FIP laboratory of a STU for the Storebælt Bridge, Denmark.

GUIDE BEARINGS AND RESTRAINT BEARINGS

Guide bearings and restraint bearings are devices which provide steady restraint in one or two horizontal directions, respectively, accommodate rotations and vertical displacements, i.e. do not transmit bending moments and vertical loads. Guide bearings are also referred to as Moveable Connection Devices, and restrained bearings as Fixed Connection Devices.

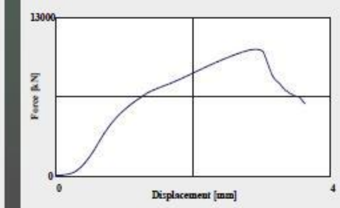


Experimental force vs displacement curve of a guide bearing.

A guide bearing for the Panagia Grevena Section Bridges, Greece.

MECHANICAL FUSE RESTRAINTS

Mechanical Fuse Restraints (MFRs) below a pre-established force threshold prevent relative movement between connected parts, whilst they permit movements after the aforesaid threshold has been exceeded, provoking the breakaway of sacrificial components.
Movements can be in one or any direction; i.e. a MFR can be designed to become a guide bearing after breakaway.



Experimental force vs displacement curve of a MFR.

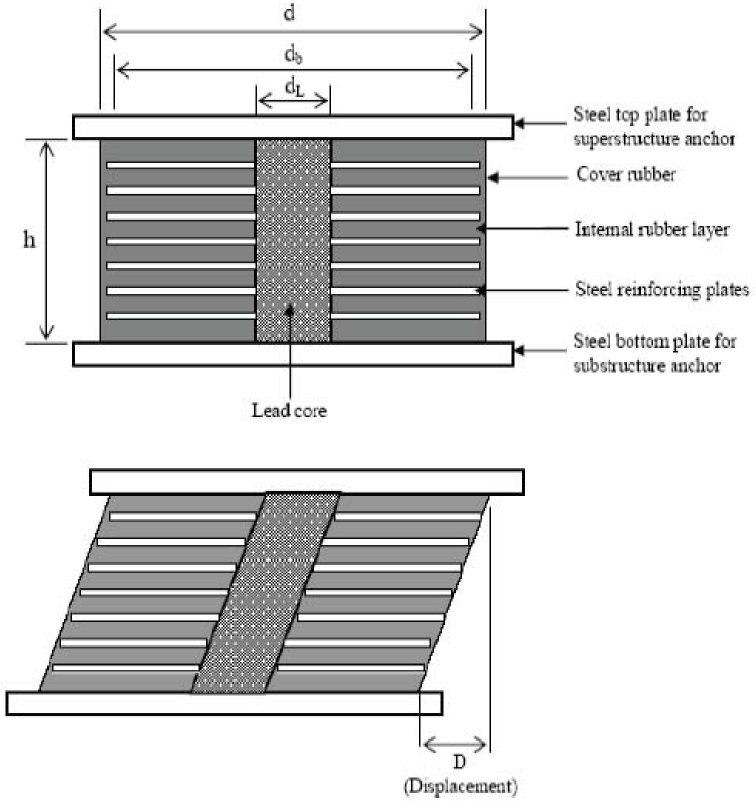
A MFR for the Viaduct 1.1, Caracas-Tuy Medio Railway, Venezuela (guided after failure).

Typologies of isolators

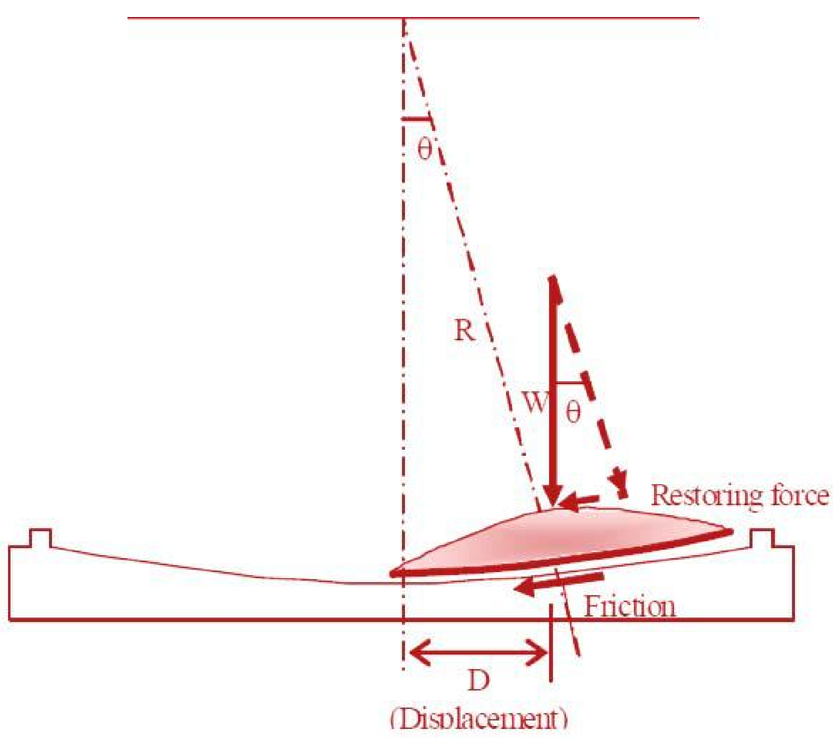
Isolators typically used for retrofit intervention:

- Elastomeric bearings with or without lead cores
- Curved sliders which used gravity as restoring force

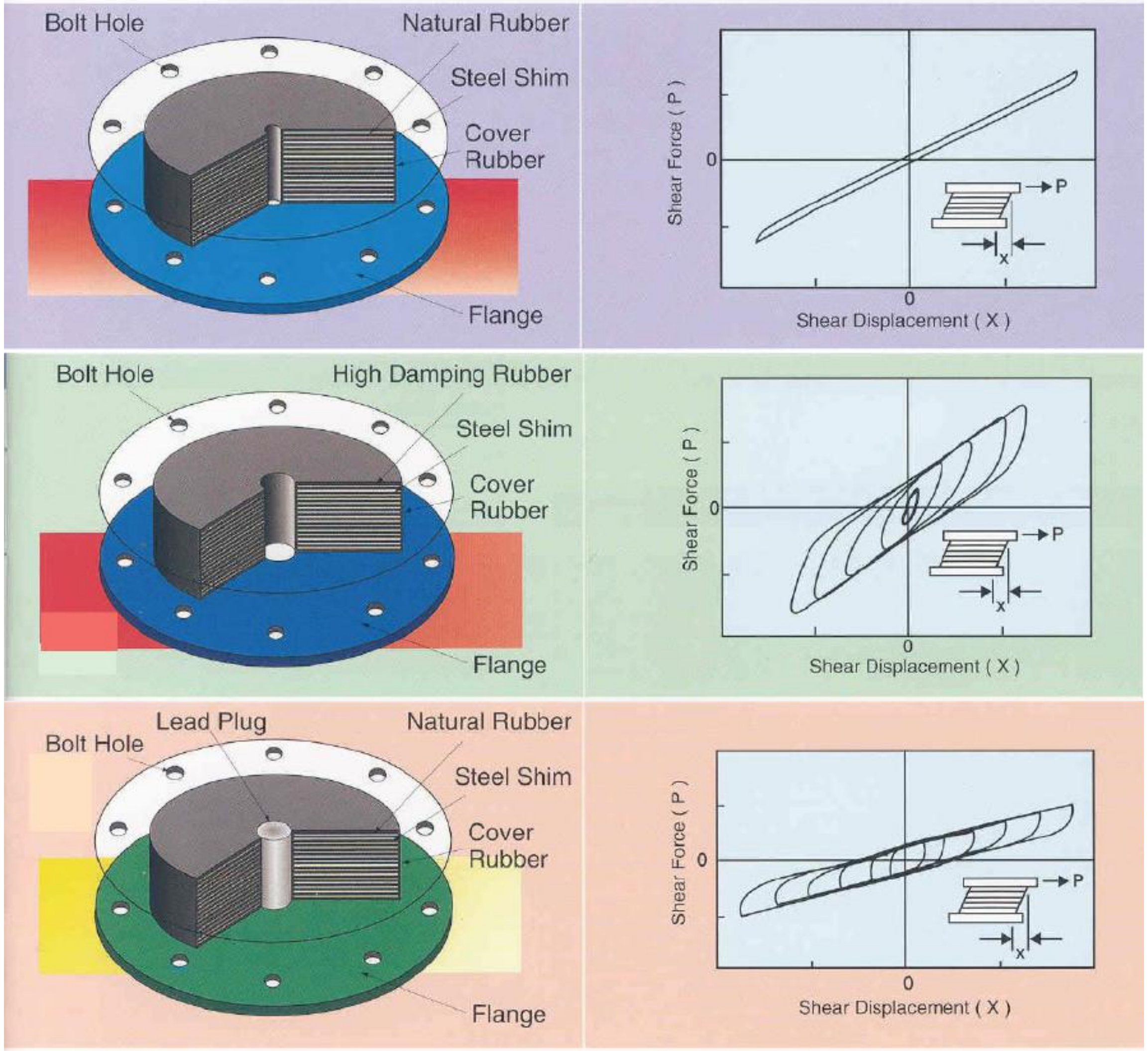
Rubber Bearing (or Lead Rubber Bearing)



Friction Pendulum System (FPS)



Laminated rubber bearings:



NRB: natural rubber bearing

Disadvantage: relatively low damping provided by the rubber

HDRB: high damping rubber bearing

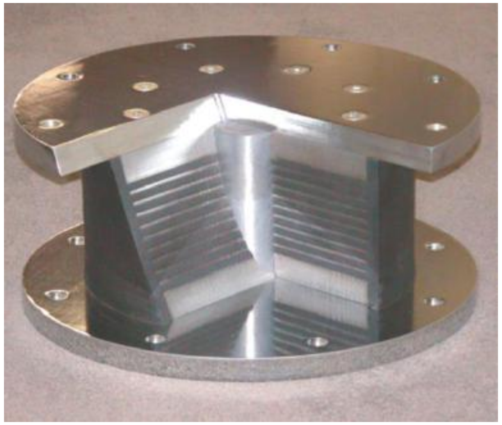
More susceptible to heat related property changes during cyclic loading and to aging effects

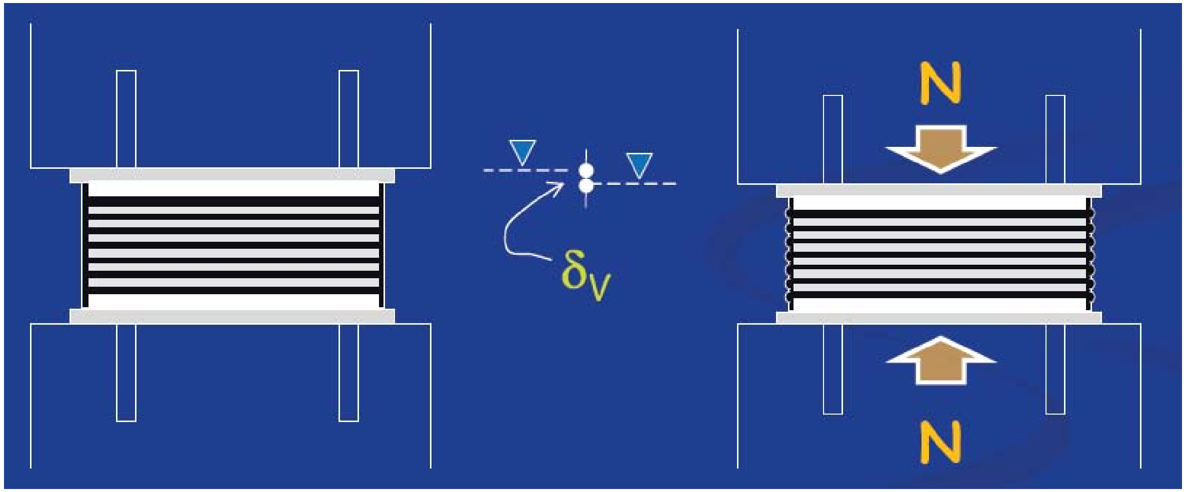
LRB: lead rubber bearing

lead plug designed to yield under lateral deformation and to dissipate supplemental energy

Elastomeric bearing:

Steel laminates increase significantly the vertical stiffness of the device





Typologies of isolators

HDRB: High Damping Rubber Bearing

- Behavior: max shear deformation 150-200%
- Equivalent viscous damping: 10÷15%
- Shear modulus: G=0.4-0.7 MPa
- Nominal limit axial stress σ_v=10-15 MPa

Advantages:

- High-moderate damping
- High lateral stiffness for small shear deformations
  - This allows to reduce the vibration amplitude for moderate shear forces (e.g. wind action)
- Low lateral stiffness for large shear deformations
  - This allows to reduce the seismic vibrations on the superstructure

Disadvantages:

- Stiffness and damping depend on deformations
- More susceptible to heat related property changes during cyclic loading and to aging effects

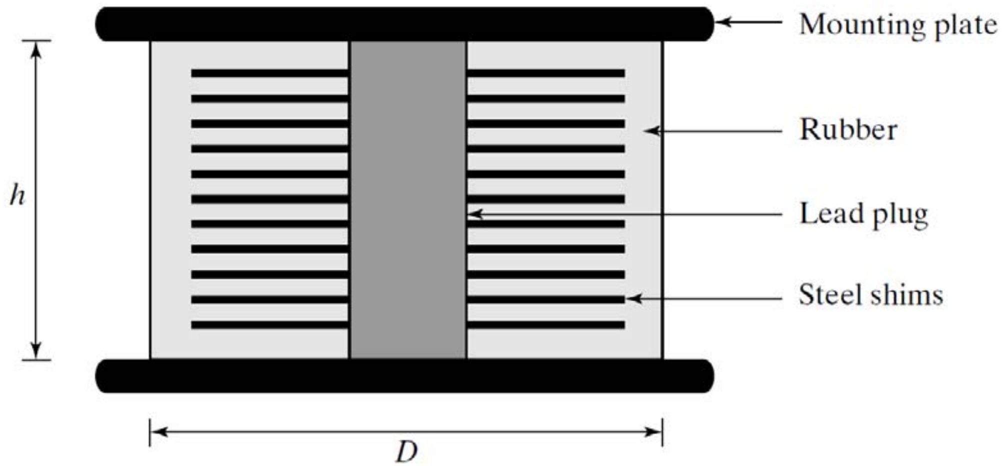
Typologies of isolators

LRB: Lead Rubber Bearing

- Behavior: strongly non-linear with max shear deformation 125÷200%
- Equivalent viscous damping: 30%

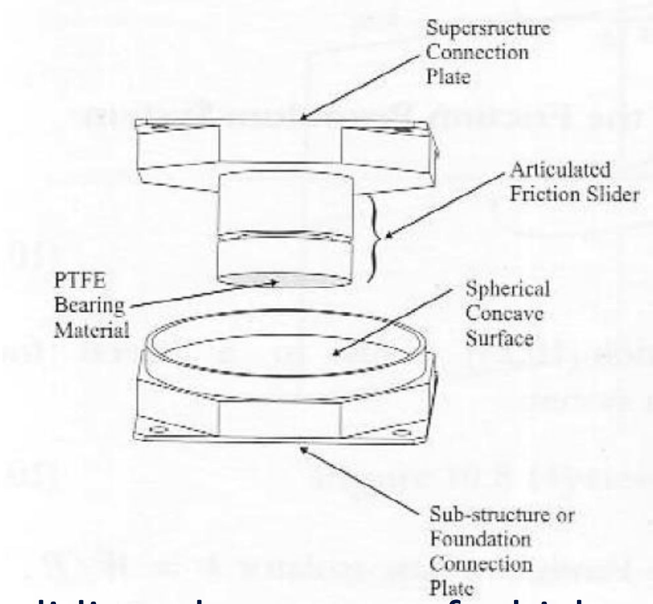
Advantages:

- Natural rubber is used with wide range od stiffness and damping
- Lateral stiffness and effective damping are less variable than HDRB
- Lead plug is designed to yield under lateral deformation and to dissipate supplemental energy



Friction Pendulum System:

Curved surface sliders use gravity as a recentering force; the operating principle is the same as the pendulum.
Energy dissipation is ensured by the friction of the main sliding surface. The parameters for the bilinear constitutive bond depend on the bending radius and friction coefficient.



It consists of two sliding plates, one of which with a spherical concave lining surface, connected by a lentil-shaped articulated slider

Typologies of isolators

The device behaviour is characterized by :

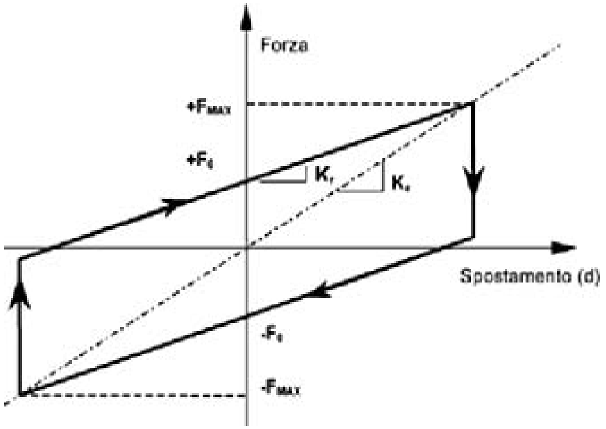
- the radius of curvature (device geometry)
- the friction (material)

Tipically the behaviour is non linear (bi-linear). For pre-dimensioning a linearized approach can be used, with equivalent stifffness K_e and equivalent damping ξ_e.

$$K_e = N_{sd}\left(\frac{1}{R}+\frac{\mu}{d}\right)$$

$$\xi_e = \frac{2}{\pi}\left(\frac{1}{(d/\mu R)+1}\right)$$

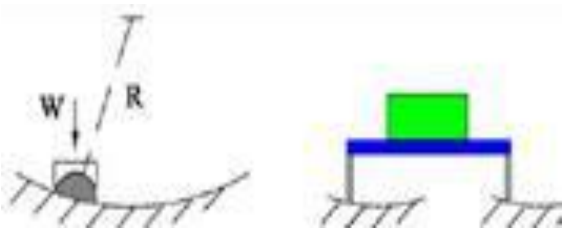
The procedure is iterative, since K_e and ξ_e depend on design diaplcement.



$$T_e = 2\pi\sqrt{\frac{1}{g\left(\frac{1}{R}+\frac{\mu}{d}\right)}}$$

NOTE: The equivalent period T_e does not depend on the mass

Behaviour similar to simple pendulum

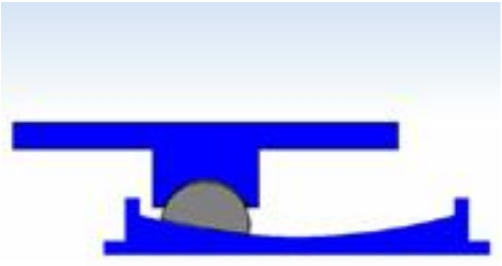


$$T = 2\pi\sqrt{\frac{M}{K_r}} = 2\pi\sqrt{\frac{M}{N_{sd}/R}} = 2\pi\sqrt{\frac{R}{g}}$$

Typologies of isolators

FPS: Friction Pendulum System

- Behavior: rigid with hardening and recentering capacities
- Friction coefficient: variable 2÷10%

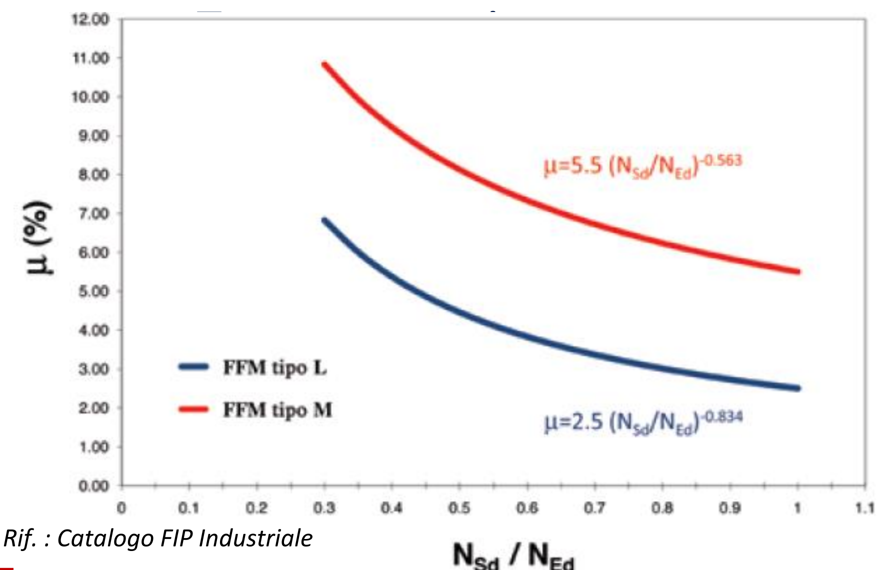


Advantages:

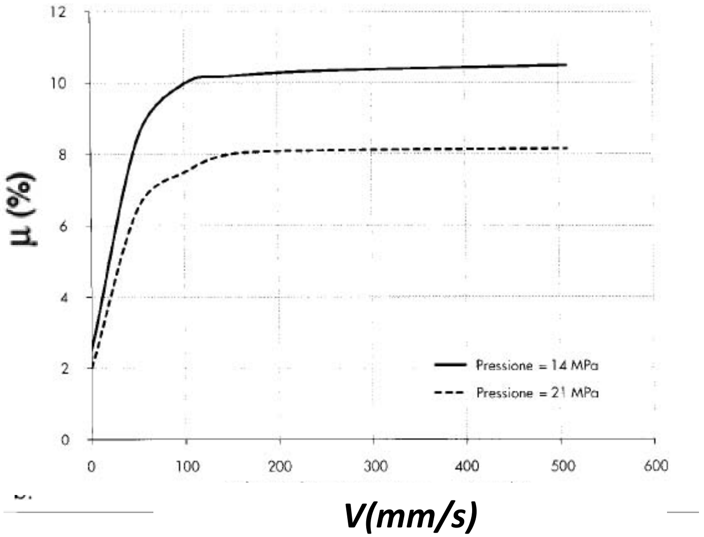
- Moderate-high damping

Disadvantages:

- Friction properties depends on pressure
- Properties function of velocity



Rif. : Catalogo FIP Industriale



Rif. : Costantinou et al., 1987

Design/Retrofit of a base-isolation system

1. Load calculation - dead, seismic (from the analysis)
2. Selection of the type of isolator/location
3. Set force/displacement limits
   Set isolation period
   Set isolators' damping
4. Design of the isolators
5. Analyze the building with isolators
6. Performance check
7. Repeat and refine
   (new axial loads/displacement form the analysis)

SIMPLIFIED LINEAR APPROACH (Pre-dimensioning)

Equivalent SDOF system for base-isolated structure:

$$T_{is} = 2\pi\sqrt{\frac{M}{K}} \xrightarrow{\text{Set period}} K_{is} = M\frac{4\pi^2}{T^2}$$

Calculate stiffness

$$S_{De}(T) = S_e(T)\left(\frac{T}{2\pi}\right)^2$$

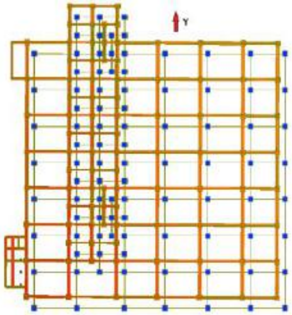
Check displacement

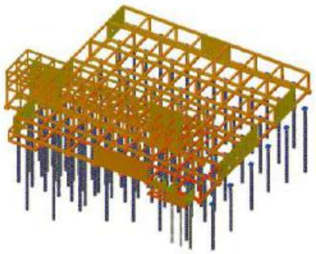
check device properties

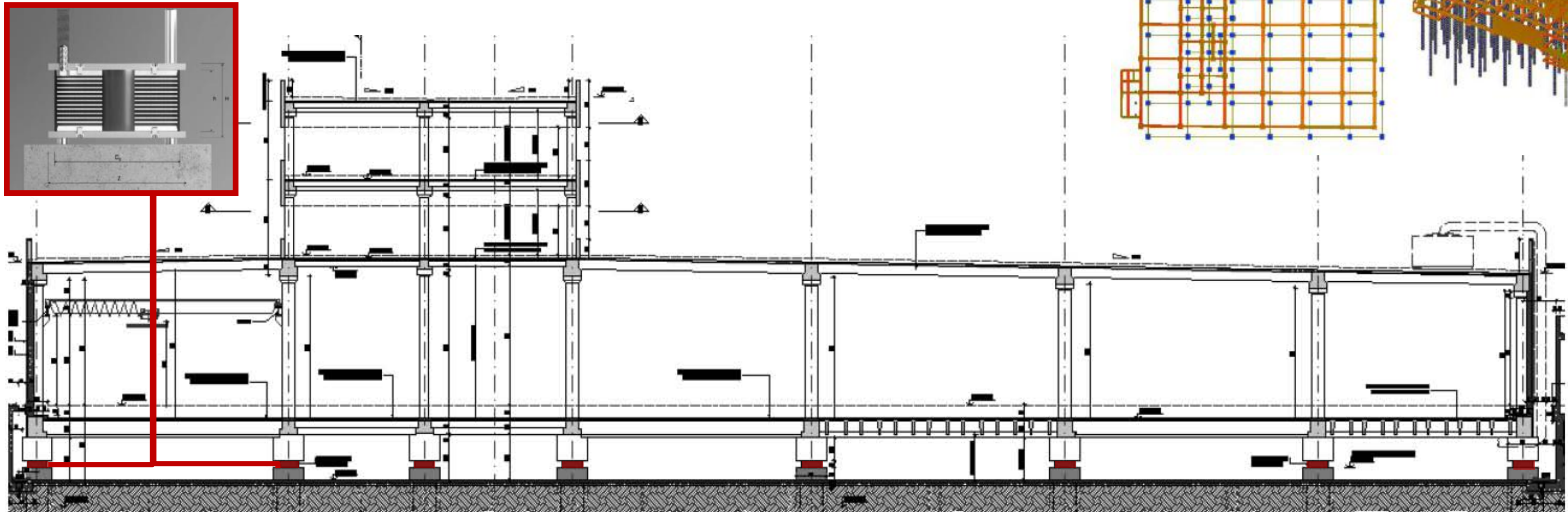
Single device (e.g. rubber bearing):

$$K_{d,j} = \frac{K_{is}}{n},$$

$$h_g = \frac{GA}{k_{d,j}} \qquad \tan\gamma = \frac{S_{De}(T)}{h_g} \leq \tan\gamma_{,LIM}$$







Conclusions

- The selection of a particular retrofitting technique depends on:
  - The intensity of seismic action expected (**DEMAND**);
  - The structural resistance in terms of forces and displacement **CAPACITY**;
  - The required performance level, related to the functional characteristics and the importance of the structure.
- The main challenge is to **achieve a desired performance level at a minimum cost** (*direct & indirect costs* related to building use interruption), and **with the minimum intervention.** Ideally, each structure must be evaluated in detail to determine the optimum retrofit strategy compatible with its characteristic.
- Considering the cost of retrofit, it is imperative to have seismic evaluations of a building both for the existing and retrofitted conditions to justify the selected strategies.
- When a member is added to the existing building, the load transfer and the compatibility of deformation shall be carefully evaluated, and ensured by proper detailing. Additional demand on the foundations has to be accounted for.
- Passive protection with sesimic isolation can be adopted when higher performances are required , e.g. for buildings that shall remain operational after the earthquake.

Thanks for your kind attention!

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Department of Civil, Environmental and Architectural Engineering

ועדת ההיגוי הבין-משרדית להיערכות לרעידות אדמה
National Steering Committee for Earthquake Preparedness