REPAIR AND STRENGTHENING INTERVENTIONS ON VERTICAL AND HORIZONTAL ELEMENTS

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Contents

- Decisions on intervention.
- The Guidelines of ICOMOS / ISCARSAH Recommendations and the new Italian Guidelines:
  - Application of conservation principles in practice.
  - Prioritization and combination of conservation requirements for the evaluation of the impact of interventions and strengthening operations on the cultural value of monuments and historical constructions.
  - Maintenance and prevention. Emergency actions.
  - Control and assessment of restored or strengthened constructions.
- Discussion of examples of real cases of intervention on historical constructions:
  - The role of historical research, monitoring and structural analysis in the design and assessment of interventions: the consideration of cultural context.

Analysis and restoration of historic buildings (I)

Restoration was in the past reserved to monumental buildings. Restorers were few experienced professionals who took care for years and sometime for their professional life of the same monument or group of monuments.

After the second world war the historic centers in Italy were left to the poorest and to the immigrants lowering the level of **maintenance of historic building**.

On the other hand in high schools and universities, teaching of old traditional materials as **masonry** and wood was substituted by concrete, steel and new high-tech materials.

As frequently happened in the recent past, due to lack of knowledge and of appropriate analytical models, masonry was simply treated as a one material, as homogeneous as concrete, steel, or wood.

Analysis and restoration of historic buildings (II)

The assumption for masonry structures, especially, in seismic areas were that, they should **behave like a "box"** with stiff floors and stiff connections between the walls, no matter which was their geometry or material composition.

The strengthening project implied the use of the same **intervention techniques**: substitution of timber-floors and roofs with concrete ones, wall injection by grouts, use of concrete tie beams inserted in the existing walls.

Separation of leaves in a repaired stone masonry

Analysis and restoration of historic buildings (III)

Carefully considering what has be learned from the past and ongoing experiences, new concepts and tools are entering into codes and structural design practice:

- the differentiation of safety level for different classes of existing structures;
- assessment of mechanical properties of structures and materials with no real statistical evaluations (estimation based on limited data);
- global and local models to be used for structural analysis;
- the evaluation of safety based on pure equilibrium considerations;
- the use of qualitative evaluation of structural performances (observational approach: the existing structures as a model of itself);
- formalistic safety verifications: **improvement vs retrofitting**;
- the **limitation of interventions** at the minimum possible level, depending on the **level of knowledge** of the structure and on the use of appropriate **investigations/monitoring** techniques;
- the **removability** of the interventions and the **compatibility** of traditional/modern/innovative materials and construction techniques.

Standards for historical structures

Codes

- **ISO 13822** – bases for design of structures – assessment of existing structures (first edition 2001)
- **Italian code** for the design, assessment and seismic retrofitting of buildings – Chapter 11 (2003)
- **prEN 1998-3 Eurocode 8** – Design of structures for earthquake resistance Part 3 assessment and retrofitting of buildings

Guidelines

- **Iscarsah** Recommendations for the analysis, conservation, and structural restoration of architectural heritage
- **Italian guidelines** for the assessment and the reduction of seismic risk of cultural heritage

Decisions on intervention (I)

A **"to do list"** in case of strengthening intervention is **not viable**, since specific and effective intervention in one case can be ineffective or, even worst, detrimental to the seismic capacity of the structure in other cases.

In order to **respect the existing features** of the considered constructions special care has to be paid in order to limit in any case as much as possible variations not only of its external appearance, but also of its mechanical behavior.

Attention has to be focused on **limiting interventions to a strict minimum, avoiding unnecessary strengthening**, a goal that is clearly in agreement with the principles of sustainable development.

Tomaževič, ZRMK, Ljubljana, Slovenia

Decisions on intervention (II)

Efforts are needed to respond to "**conservative**" design criteria while intervening to ensure acceptable structural safety conditions of existing historic constructions.

This requires that it is necessary to analyze, theoretically and experimentally, the resisting properties of the considered construction, prior and after interventions are made, in order to **avoid over-designing approaches**.

Arche Scaligere, Verona, Italy Before and after intervention

The actual contribution of any **traditional/innovative material** and techniques, and of their possible combinations, can be adequately and scientifically exploited in order to ensure durability, compatibility and possibly removability of repair/strengthening interventions.

International Council on Monuments and Sites
Conseil International des Monuments et des Sites

Recommendations for the analysis, conservation and structural restoration of architectural heritage

Guidelines

1. *General criteria*
2. *Acquisition of data: Information and Investigation*
   - 2.2 *Historical and architectural investigations*
   - 2.3 *Investigation of the structure*
   - 2.4 *Field research and laboratory testing*
   - 2.5 *Monitoring*
3. *Structural behaviour*
   - 3.1 *General aspects*
   - 3.2 *The structural scheme and damage*
   - 3.3 *Material characteristics and decay processes*
   - 3.4 *Actions on the structure and the materials*
4. *Diagnosis and safety evaluation*
   - 4.1 *General aspects*
   - 4.2 *Identification of the causes (diagnosis)*
   - 4.3 *Safety evaluation*
     - *4.3.1 The problem of safety evaluation*
     - *4.3.2 Historical analysis*
     - *4.3.3 Qualitative analysis*
     - *4.3.4 The quantitative analytical approach*
     - *4.3.5 The experimental approach*
   - 4.4 *Judgement on safety*
5. *Decisions on interventions - The Explanatory Report*

Iscarsah Guidelines – Remedial measures and controls

Adequate **maintenance** can limit the need for subsequent intervention.

The basis for conservation and reinforcement must take into account both **safety evaluation** and understanding of **historical / cultural significance** of the structure.

Each intervention should, as far as possible, respect the **original concept and construction techniques**.

Where the application of current design codes would lead to excessive interventions that would involve the loss of historic fabric or historic character, it is necessary to provide adequate safety by alternative means.

Repair is always preferable to replacement.

Dismantling and reassembly should only be undertaken when required by the nature of the materials and structure and when conservation is more damaging.

Lack of maintenance: rural building in Milan in 1980 and 1998

Iscarsah Guidelines – Remedial measures and controls

The choice between "**traditional**" and "**innovative**" techniques should be determined on a case-by-case basis with preference to those that are **least invasive and most compatible** with heritage values, consistent with the need for safety and **durability**. When new products are used all possible negative side effects must be considered.

Interventions **should not be visible**, bur when that is impossible the aesthetic impact on the monument has to be carefully considered before taking any final decision.

Where possible, any measures adopted should be "**reversible**" to allow their removal and replacement with more suitable measures if new knowledge is acquired.

At times the difficulty of evaluating both the safety levels and the possible benefits of interventions may suggest an **incremental approach** ('design in process'), beginning with a minimum intervention, with the possible adoption of subsequent supplementary measures.

Any proposal for intervention must be accompanied by a **programme of monitoring** and control to be carried out, as far as possible, while the work is in progress.

Iscarsah Guidelines – § 5 – Decisions on interventions: the explanatory report

Decisions regarding any interventions should be **made by the team** and take into account both the safety of the structure and considerations of historic character.

The **explanatory report** is a commentary upon the more detailed specialist reports. It needs to be a **critical analysis** of the steps and of the decisions taken by the team.

The purpose is to explain those things that cannot be reduced to calculations, making clear the reliability of the data, the hypotheses used and the **choices made in the design**, showing the obtained improvement in the structural behaviour.

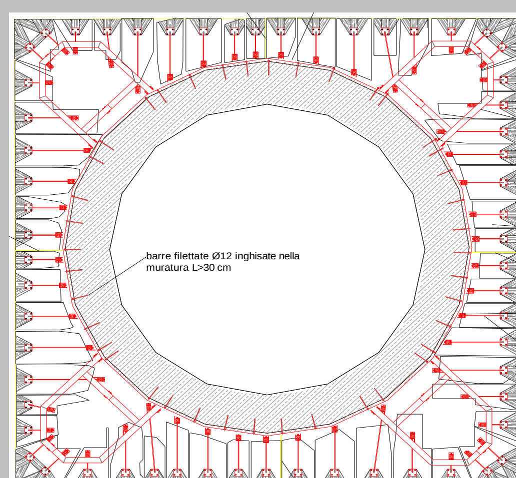
Many of the steps in the process will involve a number of **uncertainties**, which must be explained in the report. Uncertainties include:

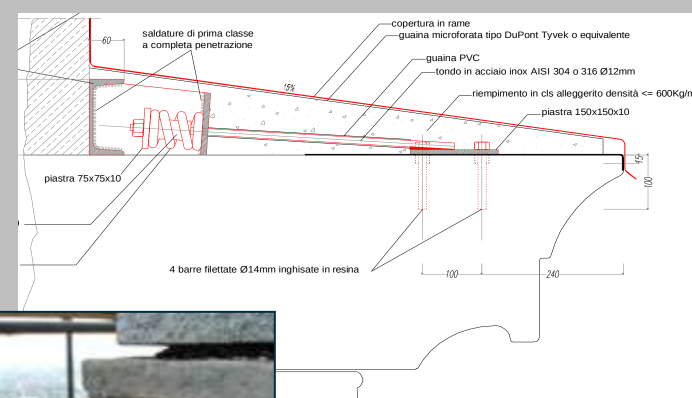
- The nature of the structural scheme;
- Knowledge of any weaknesses;
- The properties of the materials;
- The nature of the loading and other actions upon the structure.

Iscarsah Guidelines – Structural damage, material decay and remedial measures

When the causes of decay and damage have been established is it possible to plan the correct implementation of **techniques** and select the **appropriate materials for the conservation**. A first important factor in selecting appropriate intervention methods is the type of deformations that the structure has suffered, and in particular whether or not these deformations have stabilised.

A preservation plan may only be developed and applied after completion of a **systematic in-field and laboratory examination**.





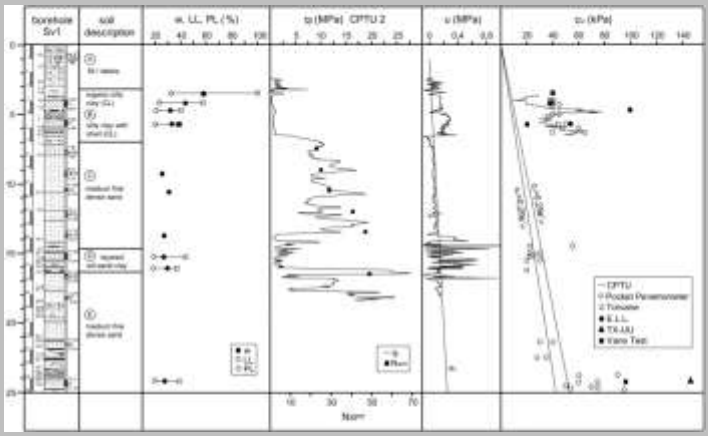
Iscarsah Guidelines – Soil settlements

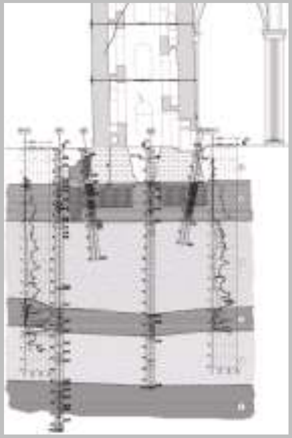
Often **soil settlements** have not stabilised and in such cases they are an important and often very complicated phenomena affecting structural behaviour. It is necessary to **determine the trend** of the phenomena and the consequences of increasing deformations on the structure. A **monitoring system** is usually necessary.

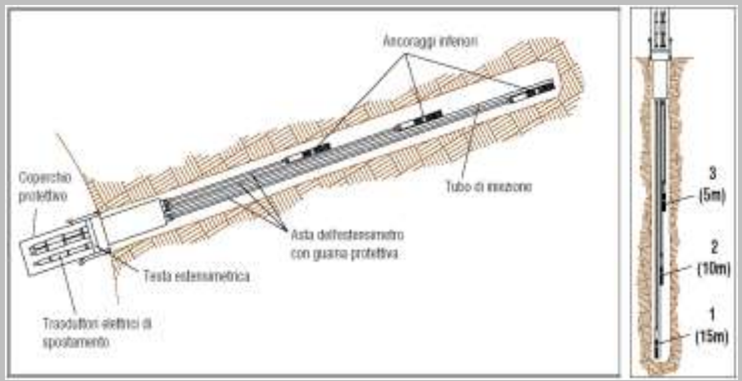
In general there are two possible course of action:

1 - to eliminate the cause by **reducing the effects upon the soil**, possibly by stabilising the water table, or to improve the stiffness of the foundations;

2 - to **increase the strength of the structure** to values sufficient to resist the induced stresses and to provide increased stiffness and continuity.







Iscarsah Guidelines – Masonry buildings

The term masonry refers to **stone, brick and earth based construction** (i.e. adobe, pisé de terre, cob, etc.). Masonry structures are made of materials that have **low tensile strength** and may show cracking or separation between elements.

The analysis of masonry requires the identification of the characteristics of the constituents of this composite material: type of stone or brick, and type of mortar.

Masonry structures rely upon the effect of the **floors or roofs to distribute lateral loads** and so ensure their overall stability: it is important to examine the disposition of such structures and their effective **connection** to the masonry.

The main causes of damage or collapse are **vertical loads**; **horizontal forces** are usually produced by the thrust of arches or vaults and may become dangerous if not balanced by other structural elements (heavy walls and abutments, tie bars…). In seismic areas horizontal forces may become produce extensive damage or collapse.

In-plane lateral loads can cause diagonal cracks or sliding. **Out-of-plane or eccentric loads** may cause separation of the leaves in a multi-leaf wall or rotation of an entire wall about its base (horizontal cracks at the base might be seen before overturning occurs).

Iscarsah Guidelines – Masonry buildings

Particularly attention has to be paid to **large walls** constructed of different kinds of material (cavity walls, rubble filled masonry walls and veneered brick walls with poor quality core): the **core material** may be less capable of carrying load and it can produce lateral thrusts on the faces. In this type of masonry the **external leaves** can separate from the core: it is necessary to determine if the facing and the core are acting together or separately.

Various strengthening interventions on walls are available:

- consolidating injection of the wall with **grout** (the appropriate fluid mortars based on lime, cement or resins depends on the characteristics of materials)
- **repointing** of the masonry,
- vertical longitudinal or transverse **reinforcement**,
- removal and **replacement** of decayed material,
- **dismantling** and rebuilding, either partially or completely.

Ties made of appropriate materials can be used to improve the load-bearing capacity and stability of the masonry.

Iscarsah Guidelines – Masonry buildings

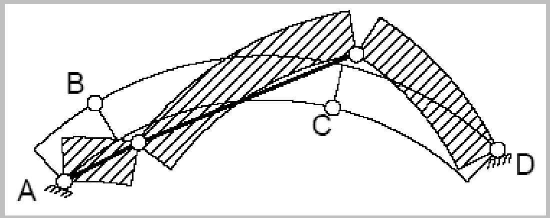
Typical of masonry structures are **arches and vaults**: they are compression structures relying on their curvature and the forces at the abutments, allowing the use of materials with low tensile strength.

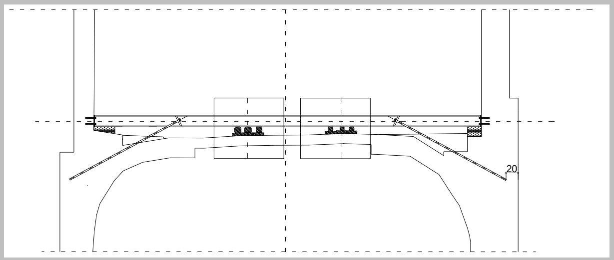
Structural distress may be associated with **poor execution** (poor bonding of units or low material quality), **inappropriate geometry** for the load distribution or **inadequate strength and stiffness of components** (chains or buttresses that resist the thrusts).

The relationship between load distribution and geometry of the structure needs to be carefully considered if loads (especially **heavy dead loads**) are removed or added.

The main **repair measures** include:

- addition of tie-rods (at the spring level in vaults, along parallel circles in domes);
- construction of buttresses;
- correction of the load distribution (in some cases by adding loads).



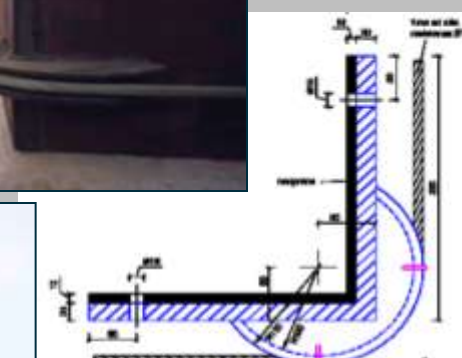


Repair and Strengthening Interventions

Prof. Claudio Modena

Iscarsah Guidelines – Masonry buildings

High-rise buildings such as **towers and minarets**, are often characterised by high compression stresses. In addition, these structures are further weakened by imperfect connections between the walls, by alterations such as the making or closing of openings. **Diaphragms, horizontal tie-bars and chains** can improve the ability to resist gravity as well as lateral loads.



Existing tie

New tie system

Iscarsah Guidelines – Timber

Wood has been used in load-bearing and **framed or trussed structures** and in **composite structures** of wood and masonry.

Preliminary operations should be identification of the **species**, which are differently susceptible to **biological attack**, and the evaluation of the strength of individual members which is related to the size and distribution of knots and other **growth characteristics**. Longitudinal cracks parallel to the fibres due to drying shrinkage are not dangerous when their dimensions are small.

Fungal and insect attack are the main sources of damage. In framed timber structures the main problems are related to local failure at the **joints**. Contact with masonry is often a source of moisture.

Chemical products can protect the wood against biological attack: where **reinforcing materials** or consolidants are introduced, compatibility must be verified.

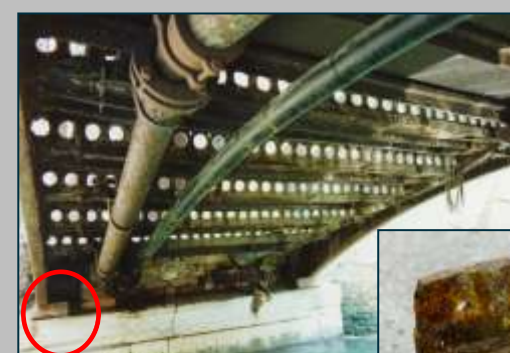
Iscarsah Guidelines – Iron and steel

Cast iron and steel are alloys and their susceptibility to **corrosion** depends upon their composition.

The most vulnerable aspects of iron and steel structures are often their **connections** where stresses are generally highest, especially at holes for fasteners.

Protection against corrosion of iron and steel requires first the elimination of rust from the surfaces (by sand-blasting, etc.) and then painting the surface with an appropriate product.

Malvasia Bridge, Venice, 1853 – cast iron

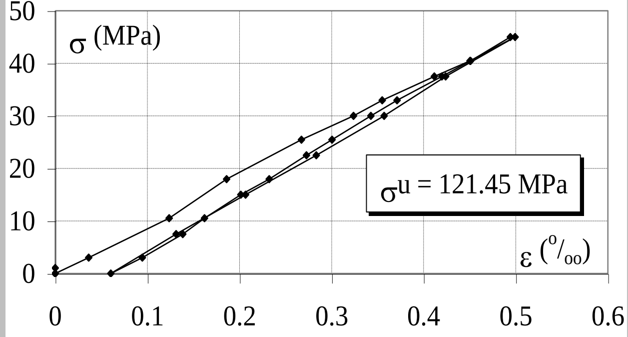


PROF. CLAUDIO MODENA

Repair of ferrous metal structures: research

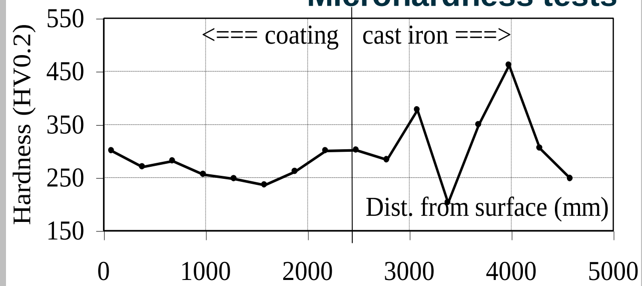
Welding

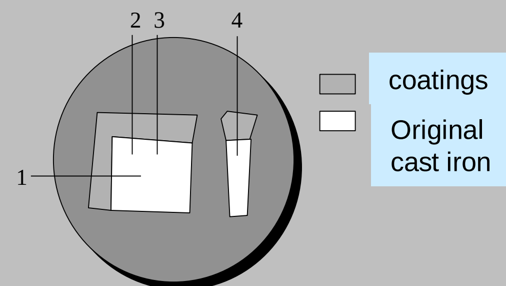
Tensile tests



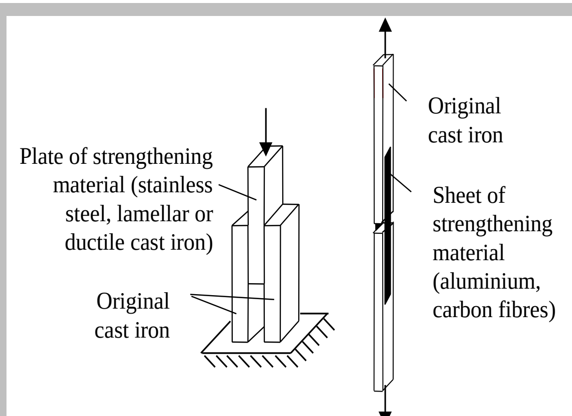
Flame spray coatings

Microhardness tests



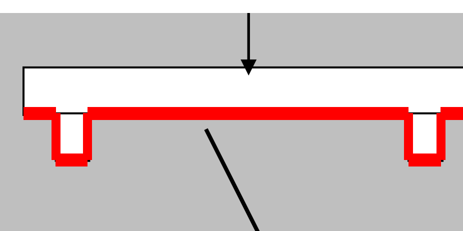


Structural coatings



- lamellar cast iron
- ductile cast iron
- aluminium alloy
- stainless steel
- carbon fibres

Bending tests before and after repair

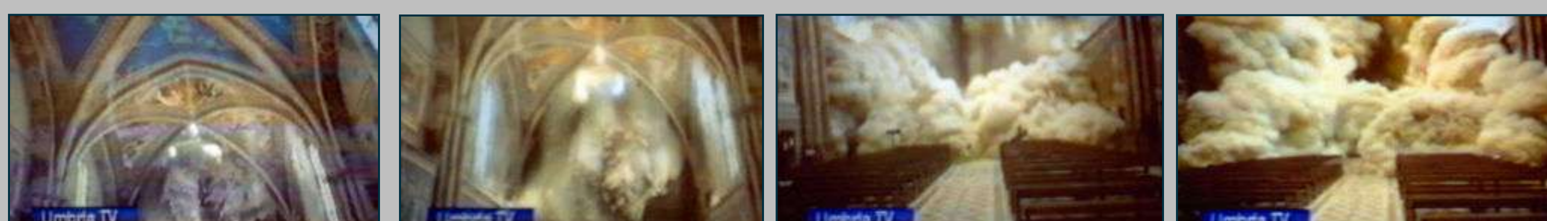


Strengthened area

Guidelines for the assessment and the reduction of seismic risk of cultural heritage

- CHAP. 1: OBJECT OF THE GUIDELINES
- CHAP. 2: SAFETY AND CONSERVATION REQUIREMENTS
- CHAP. 3: SEISMIC ACTION
- CHAP. 4: BUILDING KNOWLEDGE
- CHAP. 5: MODELS FOR SEISMIC SAFETY ASSESSMENT
- CHAP. 6: SEISMIC IMPROVEMENT AND INTERVENTION TECHNIQUES CRITERIA
- CHAP. 7: RESUME OF THE PROCESS

Guidelines Download (in Italian): http://www.bap.beniculturali.it/news/



Sequence of the collapse of the vault of the Assisi Basilica during the 1997 earthquake

General principles for existing buildings in Italian seismic code

Upgrading: necessary when
- adding storeys,
- changing use of the building with consequent increase of loads >20%,
- substantially changing the building shape
- substantially changing the building structural behaviour

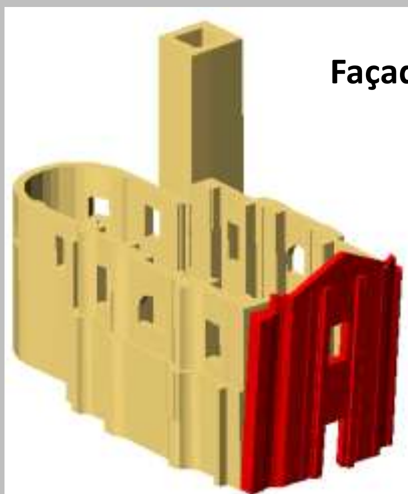
Improvement: possible when
- acting on single structural elements
- acting on monumental buildings

The obligatoriety of **safety evaluation for upgrading intervention** and the necessity of some kind of **evaluation for the improvements** is stated.

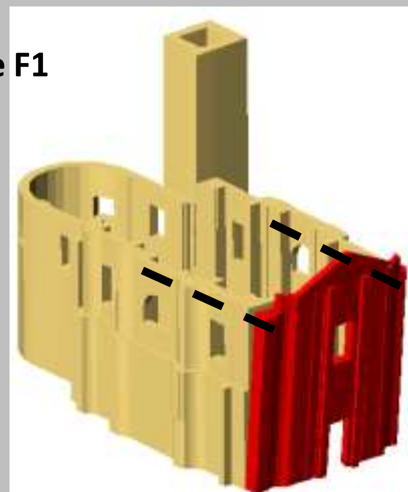
The **degree of uncertainty which affects the safety evaluations** of existing buildings and the design of the interventions is taken into account through the use of **confidence factors**: in fact the use of methods of analysis and assessment depends on the completeness and reliability of available information.

Example of seismic improvement: cultural heritage building

Façade F1

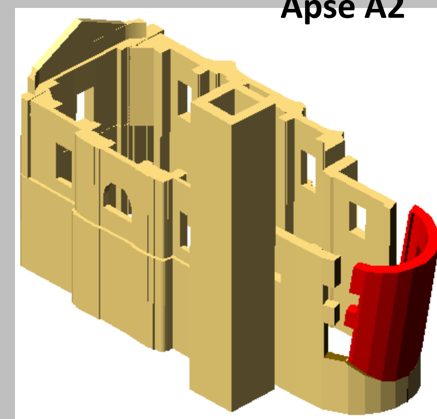


unstrengthened

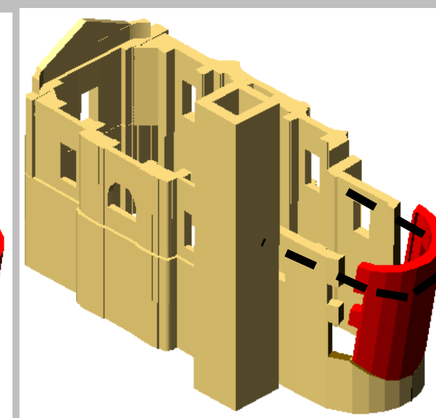


strengthened

Apse A2



unstrengthened



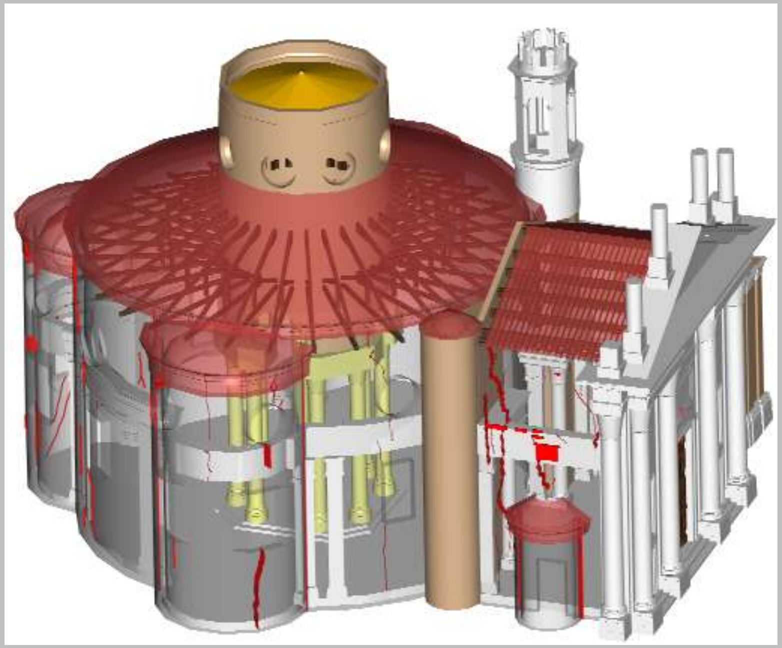
strengthened

Macroelement	Capacity (g) before the intervention	Capacity (g) after the intervention	Increase %	Seismic demand (g) defined by the code	Capacity / Demand (%) after the intervention
Façade F1	0,083	0,138	66%	0,273	51%
Façade F2	0,158	0,195	23%	0,280	70%
Upper façade F1	0,322	0,536	67%	0,375	143%
Apse A1	0,223	0,362	62%	0,289	125%
Apse A2	0,158	0,281	79%	0,277	101%

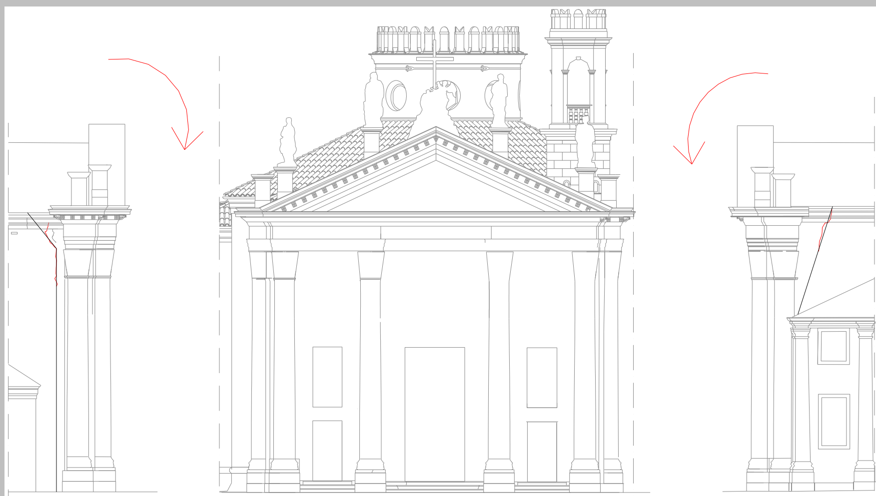
Example of seismic improvement: the church of S. Maria del Pianto

XVIII Century church by Frigimelica with central plan and some irregularities due to following resets done in the first half of the XX Century

Critical survey



Example of seismic improvement: the church of S. Maria del Pianto



From the analyses carried out, it was pointed out that the most vulnerable element is the **façade**, in case of **overturning with partial involvement of the lateral walls**.

This is also a possible mechanism, due to the presence of corresponding **crack pattern** close by the façade.

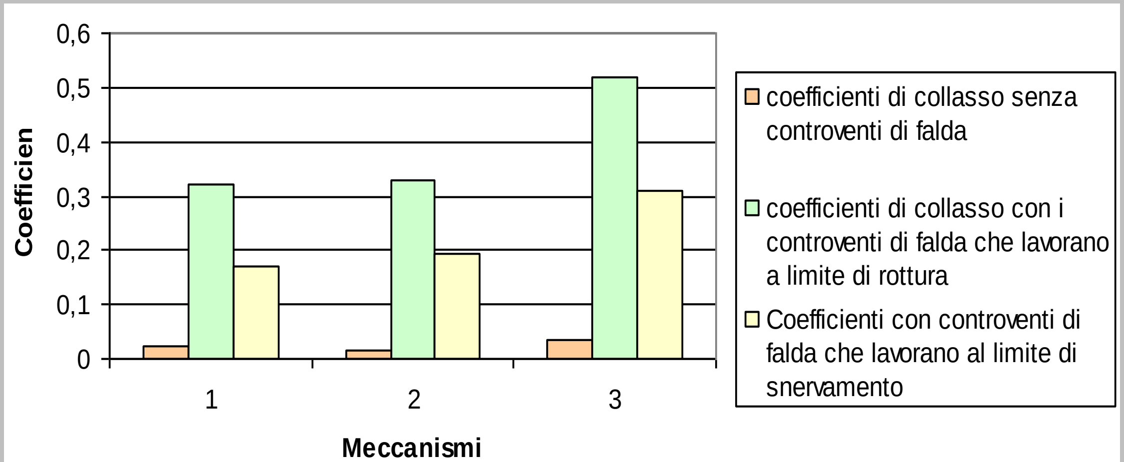
M_{st} = 52230 daN m

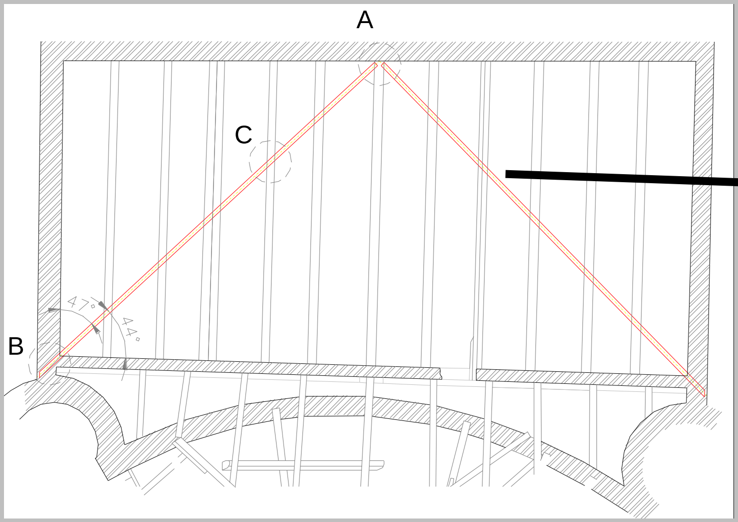
M_{inst} = 3984900 daN m

c = 0,0131

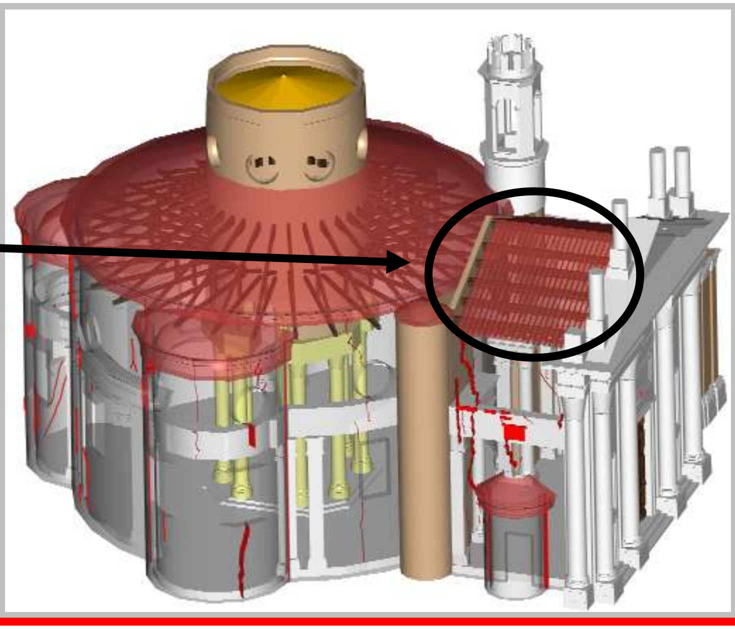
Example of seismic improvement: the church of S. Maria del Pianto

Collapse coefficients in the previous state (orange) and simulating **bracings** (green), installed between 2003 and 2004 on the roof above the façade. This has significantly **improved the seismic response of the façade**, as shown by the increase of the collapse coefficient for the overturning.





Roof bracing



Italian Guidelines – § 1 – Object of the Guidelines

Among the "**relevant buildings**" the guidelines consider those buildings that collapsing can determine significant damages to the historical and artistic heritage: in these cases the concept of "tight cost constraints" becomes much broader, as in the cost also the **loss of artistic and historic values** must be taken into account.

The document intend to define the process of **knowledge**, the methods for **seismic risk assessment**, the criteria for the design of **intervention**, according to the New Italian Seismic Code, but adapted to the needs of cultural heritage masonry buildings.

For those buildings it is not required an upgrading to current seismic protection level, but it is possible to proceed with **improvement** interventions.
In this case it is anyway required the assessment of the **safety level reached after the intervention**: this is useful in order to define the minimum intervention or the need for intervention. For strategic and relevant CHBs, **the reduction of seismic protection level related to the improvement cannot be always accepted**.

For the conservation of cultural heritage in seismic area, **different levels of assessment**, with different aims, are foreseen: for these types of evaluation, different analysis tools are made available.

Italian Guidelines – § 2 – Safety and conservation requirements

Procedure for the seismic safety assessment

- definition of the seismic action;
- definition of an aseismic protection level;
- obtain an appropriate knowledge of the building and define a correct confidence factor;
- definition of one or more mechanical models of the structure or of some parts of the structure (macro-elements) and use of one or more analysis methods;
- evaluation of safety indexes obtained considering the PGA corresponding to every limit state before and after a compatible intervention of improvement and (quantitative and qualitative) comparison of the reached protection level with the seismic risk and with the use of the building.
- **use of appropriate detail rules for the realisation of the interventions (compatibility, durability…).**

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

The seismic upgrading is not compulsory: what is required is a comparison between the current safety level and the safety level after the intervention, adopting a protection level (γ_I factor) that varies according to the relevance and the use of the building, and that is used to reduce or increase the reference seismic action.

The criteria for the intervention are the same already mentioned, but specific attention has to be paid to **conservation principles**. Besides, a clear understanding of the structural history of the building (type of action, causes of damage, etc.) should set its mark on the design.

Renaissance walls in Padova - Italy

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

Intervention should not only be aimed at reaching appropriate **safety level of construction**, but they should also guarantee:

Compability and durability

Integration or support to existing assessed behaviour

Correct typological behaviour of the building

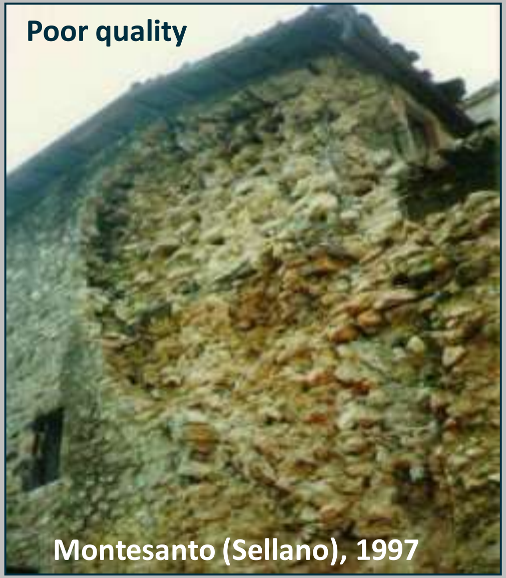
Use of non-invasive techniques

If possible, reversibility or removeability

Minimization of intervention

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

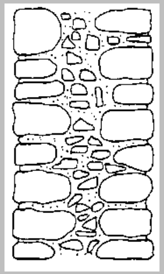
The damage obtained during the **Umbria-Marche earthquake** in 1997 on buildings retrofitted after the 1979 earthquake, together with experimental and theoretical studies carried out, pointed out problems related to **poor masonry quality** but also underlined the limits of some **badly executed strengthening intervention techniques** which became very popular and even compulsory according the previous seismic code: they in fact frequently showed scarce performances (injections, jacketing) or even worsened the local/global structural behaviour of existing masonry buildings (jacketing, replacement of flexible floors with stiff floors).



Poor quality

Montesanto (Sellano), 1997

Injections



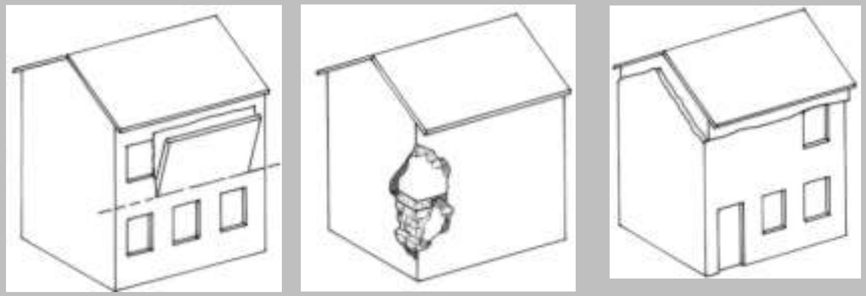
Building strengthened after the Bovec earthquake (Slovenia) in 1998, damaged again during the 12/07/2004 earthquake

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

The execution of interventions that locally change the stiffness of the structure has to be adequately evaluated. The **renovation of flexible floors into stiff floors** cause a different distribution of seismic actions that can be favourable/unfavourable and has to be taken into account into the modelling and analysis phases.

It was abandoned the idea that it is possible to confer to each structure a “box” behaviour, by means of indiscriminate “a priori” interventions, considering that, for example, **a stiff R.C. floor is not crucial for the safety of a masonry ordinary building**.

Some effects of the introduction of R.C. elements in masonry existing buildings

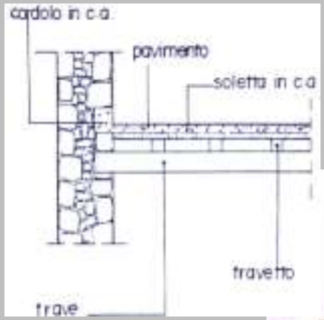


The orthogonal walls are not adequately connected each other and to the new R.C. slabs

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

The experience of the Umbria-Marche earthquake showed the effect of stiffening the horizontal diaphragm by **substituting original wooden floors with stiff reinforced concrete floors**: traditional techniques, aimed only at reducing excessive deformability of the floors, are now proposed.

Sliding of the roof floor: the masonry is not adequately strengthened

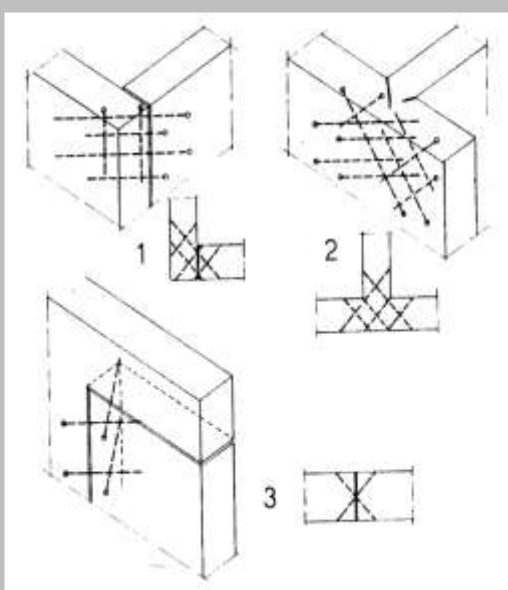


Expulsion of the façade: the tie-beam is supported only by the internal leaf of a multi-leafs masonry: load eccentricity and reduction of the resisting area

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

Reinforced injection:

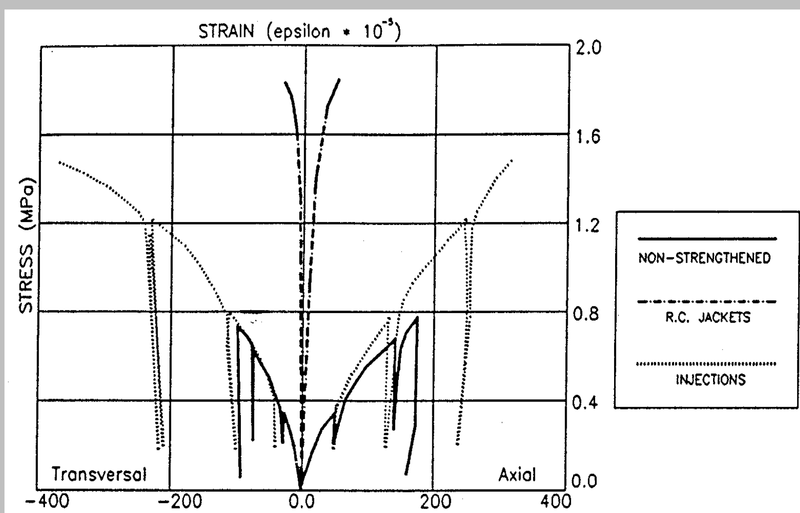
- highly invasive
- scarce performances
- adhesion problems

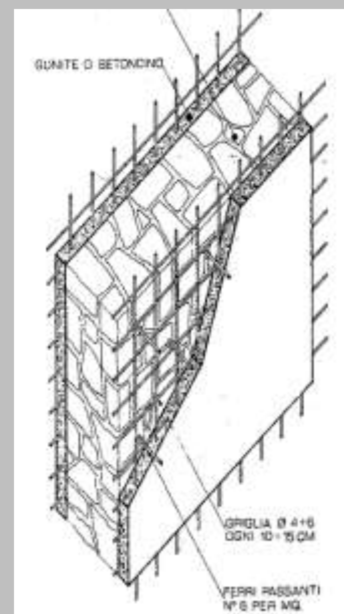


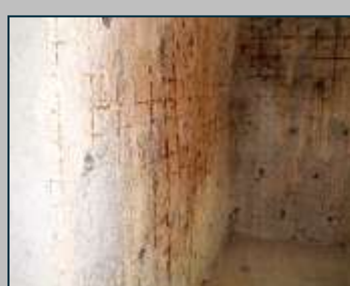
Montesanto (Sellano), 1997

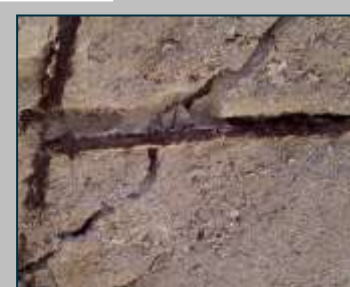
Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

Jacketing:
- scarce transversal connection
- scarce efficacy in the corners
- oxidation problems
- high stiffness









Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

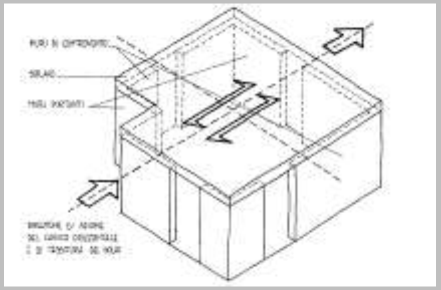
General requirements for interventions:

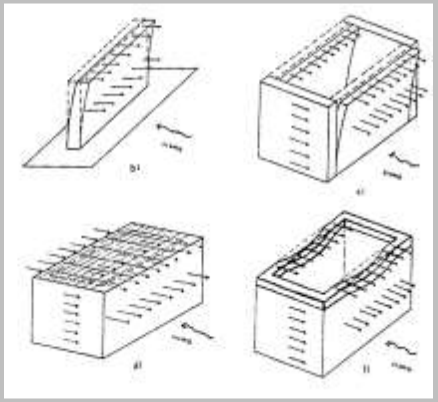
- **Respect of the functioning of the structure**, generally intervening in well defined areas and avoiding to vary in a significant manner the global stiffness distribution.
- Interventions to be performed only after the **evaluation of their effectiveness** and the impact on the historical construction.
- Interventions have to be **regular and uniform** on the structures. The execution of strengthening interventions on limited portion of the building has to be accurately evaluated (reduction or elimination of vulnerable elements and structural irregularity…) and justified by calculating the effect in terms of variation on the stiffness distribution.
- Particular attention has to be paid also to the **execution phase**, in order to ensure the actual effectiveness of the intervention, because the possible poor execution can cause deterioration of masonry characteristics or worsening of the global behaviour of the building, reducing the global ductility.

Italian Guidelines – § 6 – Seismic Improvement and Intervention Techniques Criteria

The guidelines analyse the following **types of interventions**, giving useful indications for the conception and the design of the intervention:

1. Interventions to improve the connections (walls – floors)
2. Interventions to improve the behaviour of arches and vaults
3. Interventions to reduce excessive floor deformability
4. Interventions on the roof structures
5. Interventions to strengthen the masonry walls
6. Interventions on pillars and columns
7. Interventions to improve connection of non-structural elements
8. Interventions on the foundation structures



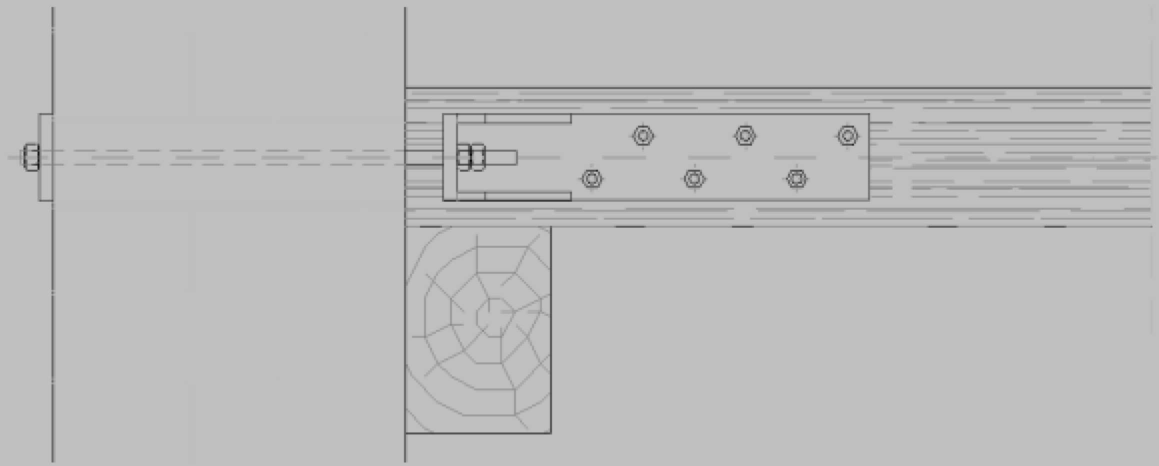


In the following slides some, **examples of improving and strengthening interventions** realised according with the indications of the guidelines are showed.

Interventions to improve the connections (walls – floors)

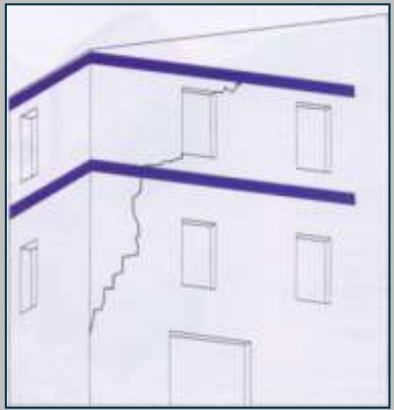
The goal is to allow the structure to manifest a **satisfactory global behaviour**, by improving the connections between masonry walls and between these and floors: this may be achieved via the **insertion of ties, confining rings and tie-beams**.

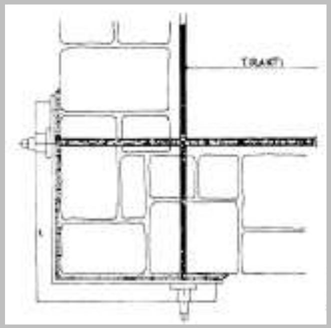
An effective connection between floors and walls is useful since it allows a **better load redistribution** between the different walls and exerts a restraining action towards the walls' overturning. Considering wooden floors, a satisfactory connection is provided by fasteners anchored on the external face of the wall

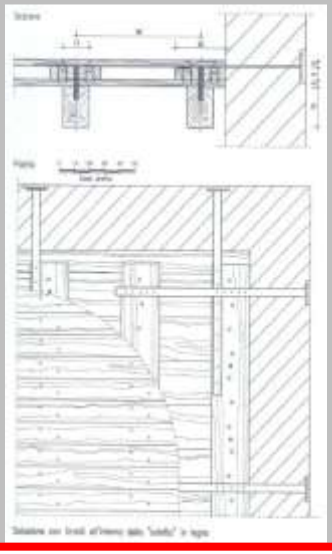


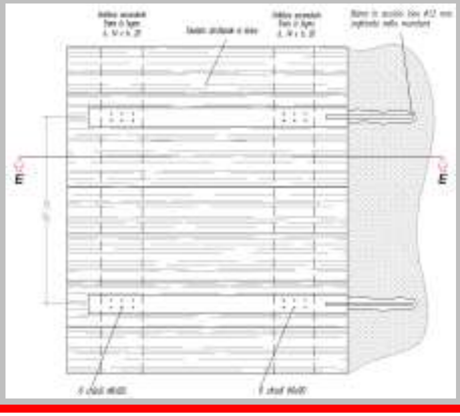
Interventions to improve the connections (walls – floors)

- Anchoring ties
- Reinforcing rings
- Floor/walls connections





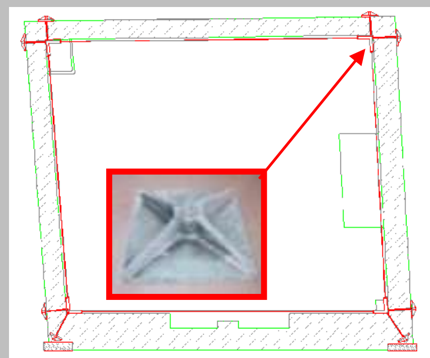


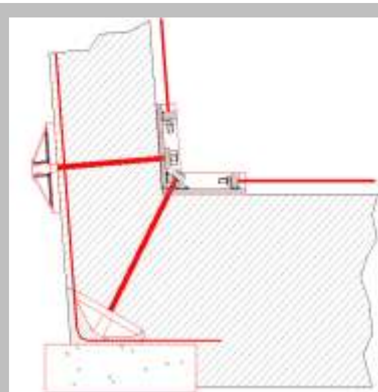


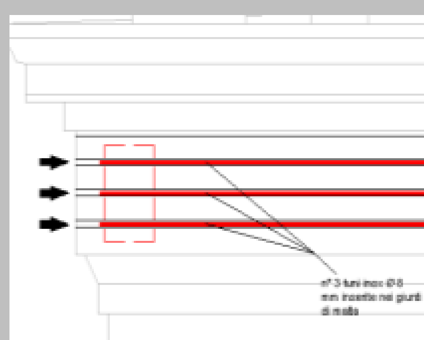
Residential buildings, Montesanto (Sellano)

Interventions to improve the connections (walls – floors)

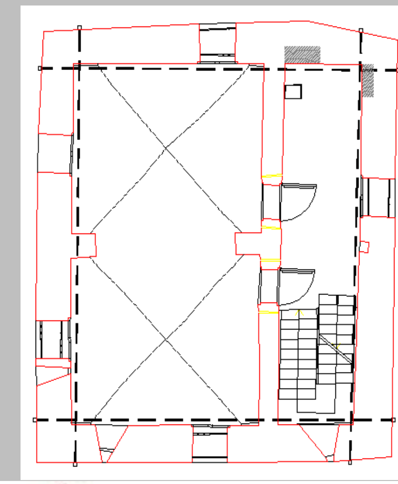
Orologio Tower,
Padova

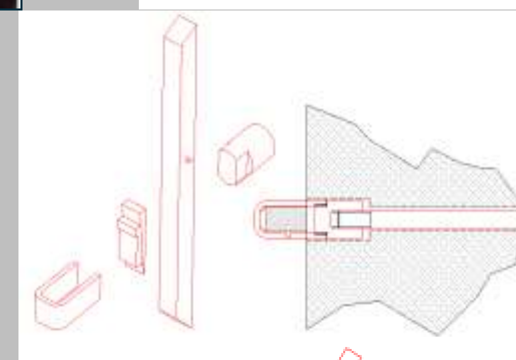


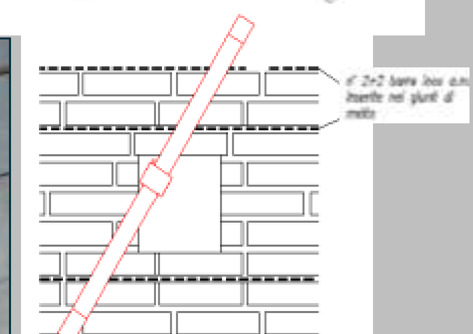




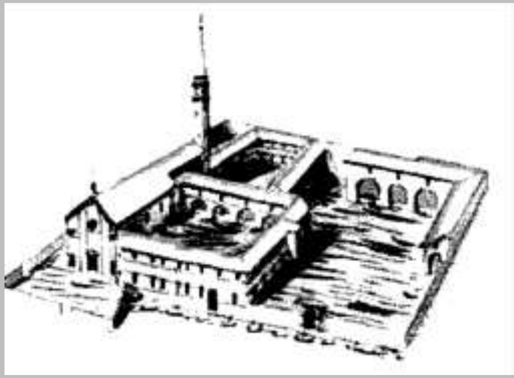
Vanga Tower, Trento



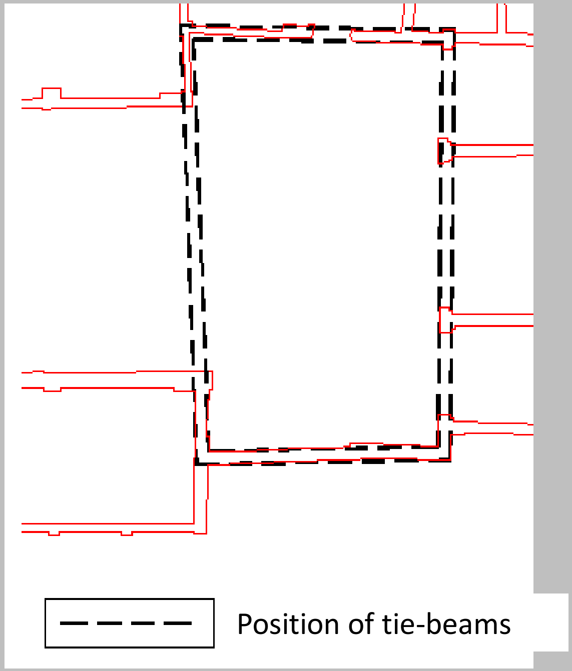


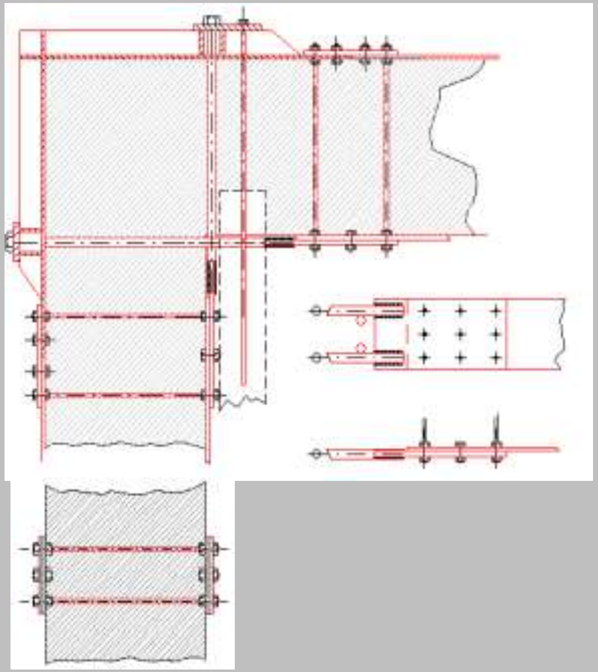


Interventions to improve the connections (walls – floors)



S. Stefano Church, Monselice

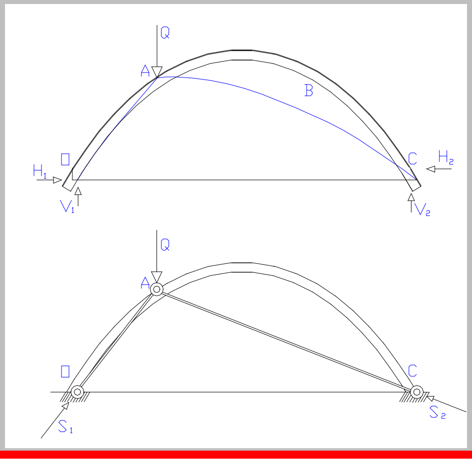


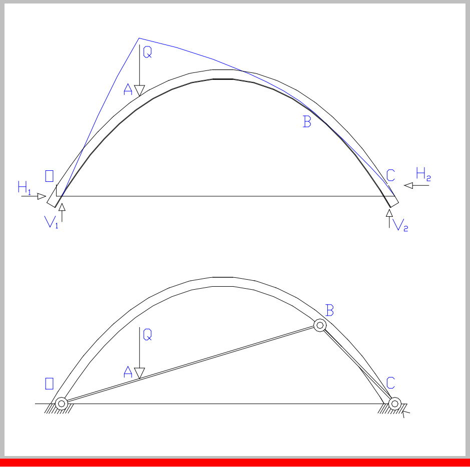


Interventions to improve the behaviour of arches and vaults

Application of FRP laminates to vaults: research



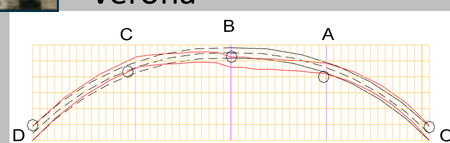


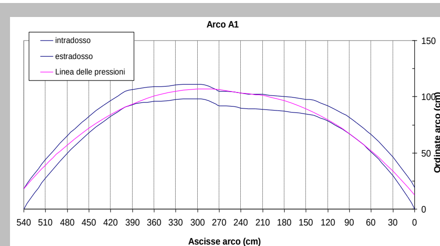
FRP strengthening of brick masonry vault specimens

Interventions to improve the behaviour of arches and vaults

Application of FRP laminates to vaults: examples

S. Fermo Church, Verona





Bruni Villa

Megliadino San Vitale (Padova)

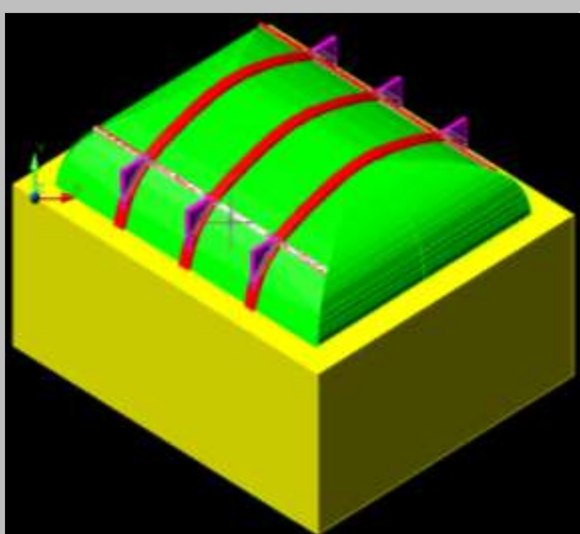
Sandro Gallo Bridge, Venezia

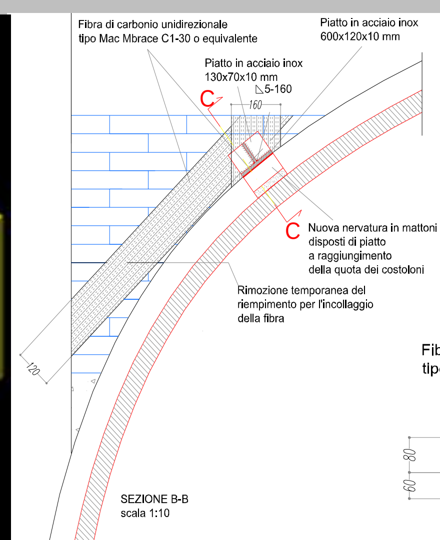
Interventions to improve the behaviour of arches and vaults

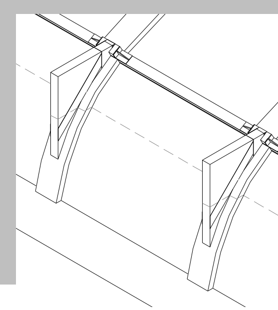
Application of extrados elements and FRP laminates to vaults: examples

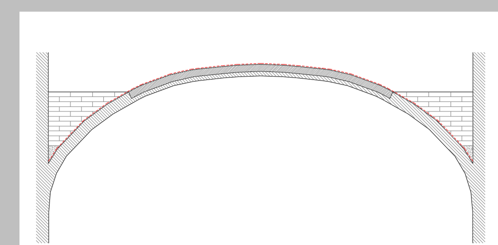
Ducale Palace, Urbino:

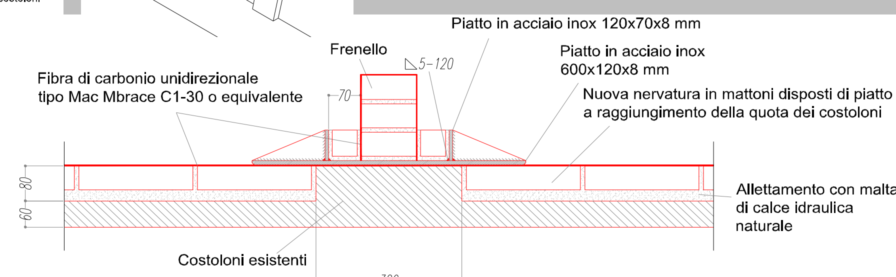
- Substitution of the thin “frenelli” (5 cm thick) with solid brick panels (16 cm thick).
- Application to the both sides of CFRP strips to make active the “frenelli” up to their ends.
- Realization of transverse ribs connected to the “frenelli” edges by thin solid brick panels and a CFRP strip on the top.







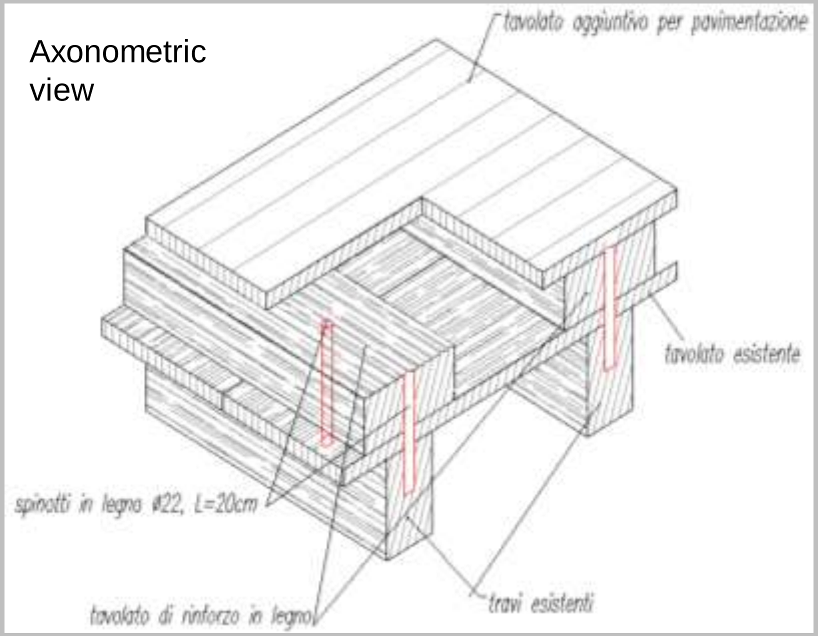




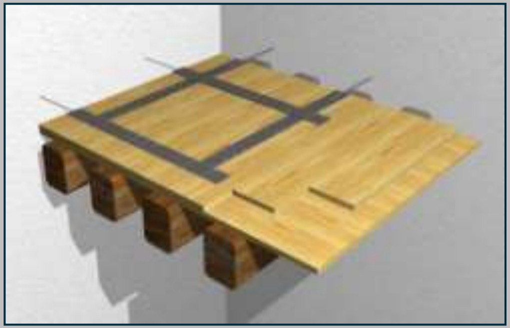
Interventions to reduce excessive floor deformability

Interventions aimed at the **in-plane stiffening of existing floors** must be carefully evaluated since the horizontal seismic action is transferred to the different masonry walls in function of the floor plane action, depending on its stiffness.

In plane and flexural floors stiffening with ‘dry’ techniques is obtained by providing, at the extrados of the existing floor, a further layer composed by **wooden planks**, with orthogonal direction respect the existing.



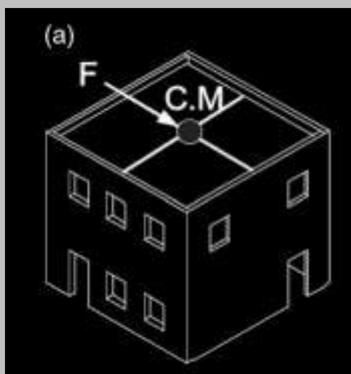
The use of **metallic belts or FRP strips**, disposed in a crossed pattern and fixed at the extrados of the wooden floor or the use of metallic tie-beams bracings, may improve the stiffening effect.



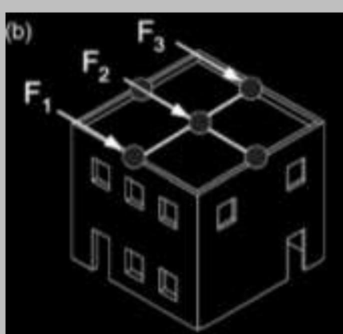
PROF. CLAUDIO MODENA

Interventions to reduce excessive floor deformability

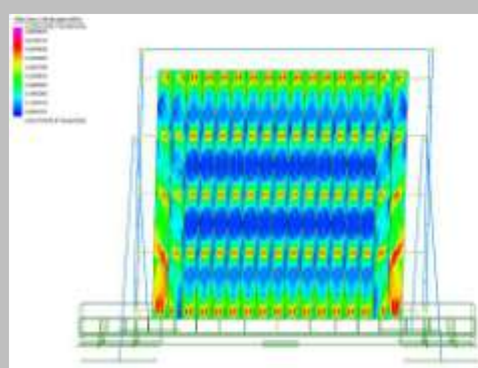
Development of new techniques for wooden floors: research testing and modeling

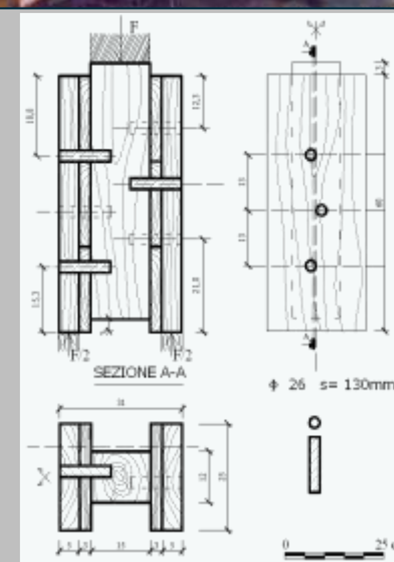


Stiff floor



Deformable floor





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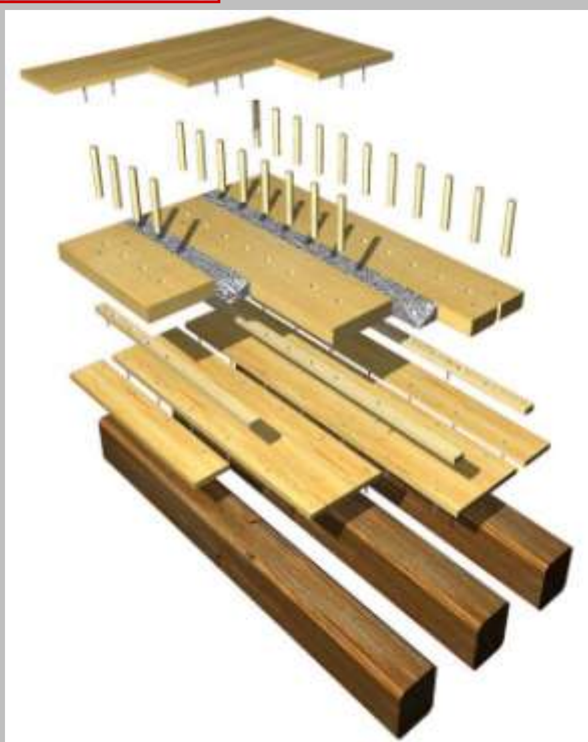
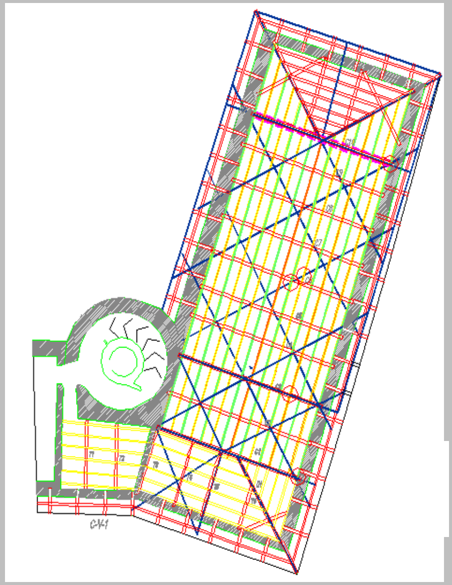
Interventions to reduce excessive floor deformability

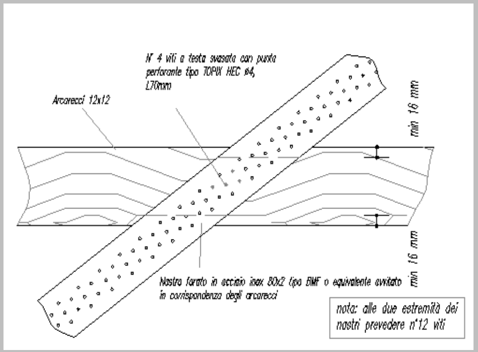
Ca’ Duodo, Padova, XV c.

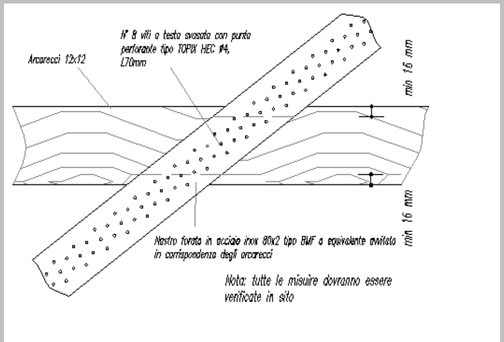


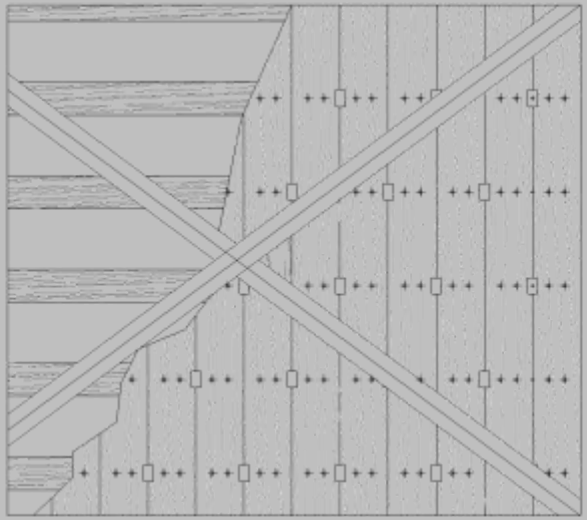
Interventions on the roof structures

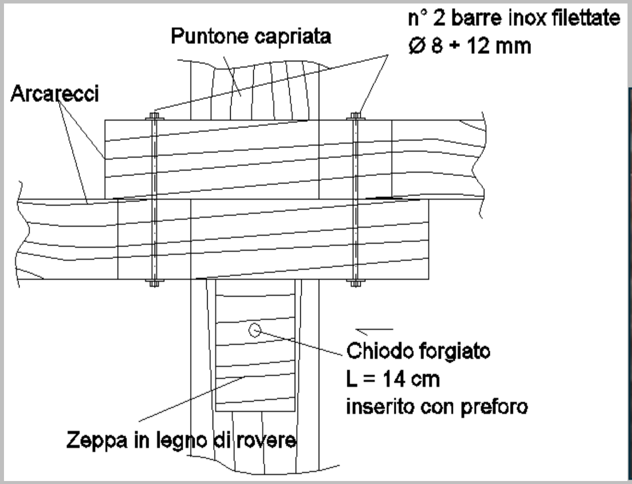
Ducale Palace, Urbino





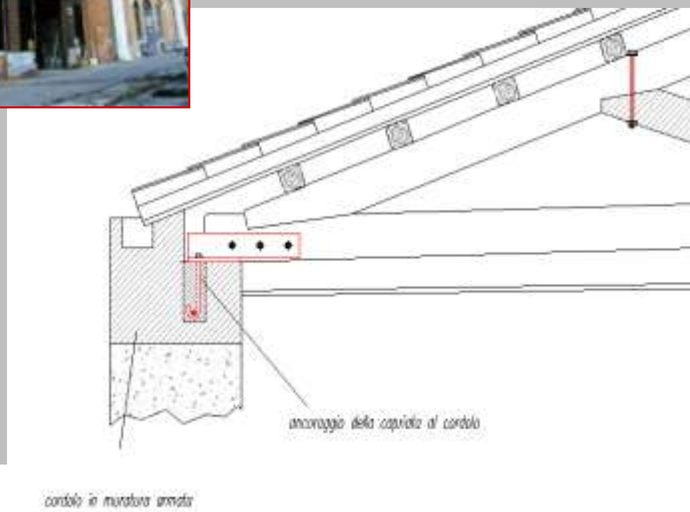


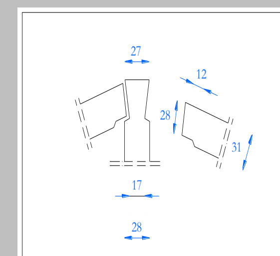


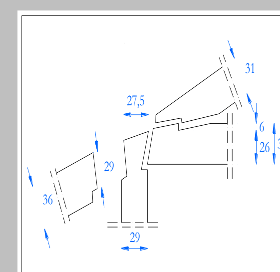


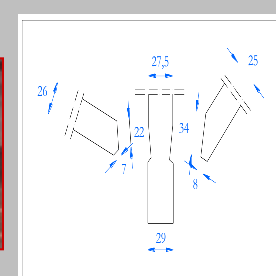
Interventions on the roof structures

Arsenale, Venice, XII c.









Interventions to strengthen the masonry walls

Interventions aimed at increasing the masonry strength may be used to **re-establish the original mechanical properties** lost because of material decay or to **upgrade the masonry performance**. Techniques used must employ materials with mechanical and chemical-physical properties similar to the original materials.

Interventions should be **uniformly distributed** (both strength and stiffness).

With opportune cautiousness, suggested techniques are the **"scuci-cuci"**, non cement-based mortar **grouting**, mortar **repointing**, insertion of "**diatoni**" (masonry units disposed in a orthogonal direction respect the wall's plane) or small **size tie beams** across the wall, with connective function between the wall's leaves.

Mortar repointing

Injections technique: example of suitable execution and of problems related to uncorrected execution (e.g. lack of uniformity)

Interventions to strengthen the masonry walls

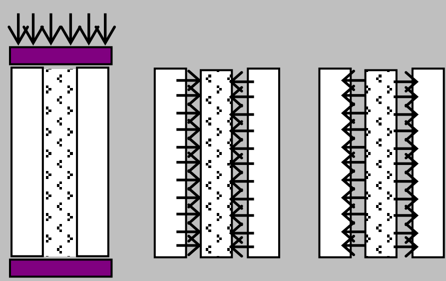
Grout injections research: grout selection through laboratory tests

Fluidity

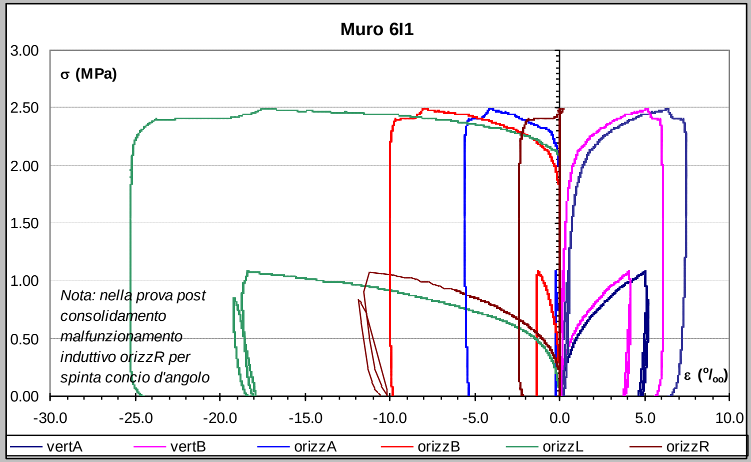
Stability

Injectability

Grout injections research: injection on multi-leaf stone walls and calibration of models



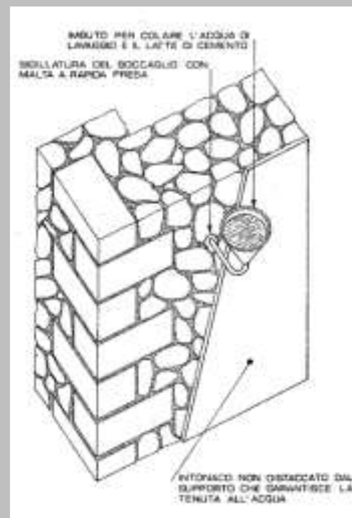
$$f_{wc,0} = (V_{ex}/V)\Theta_{ex} f_{ex,k} + (V_{inf}/V)\Theta_{inf} f_{inf,0}$$

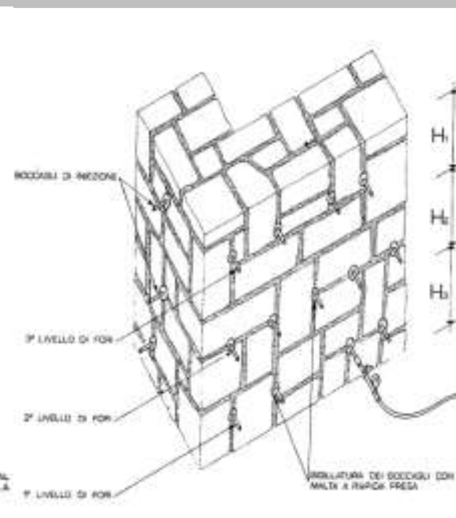


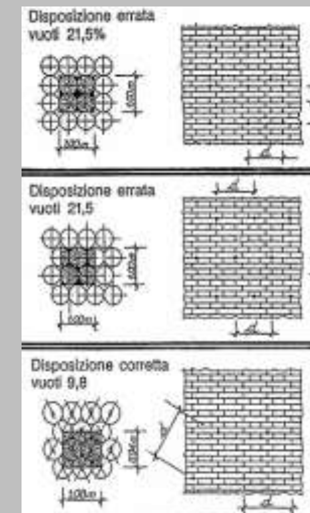
Interventions to strengthen the masonry walls

Town Walls, Cittadella:

- local rebuilding
- grout injection
- repointing





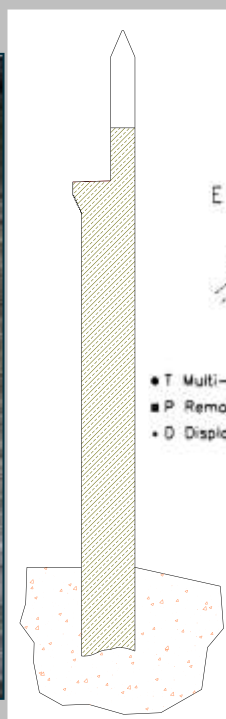


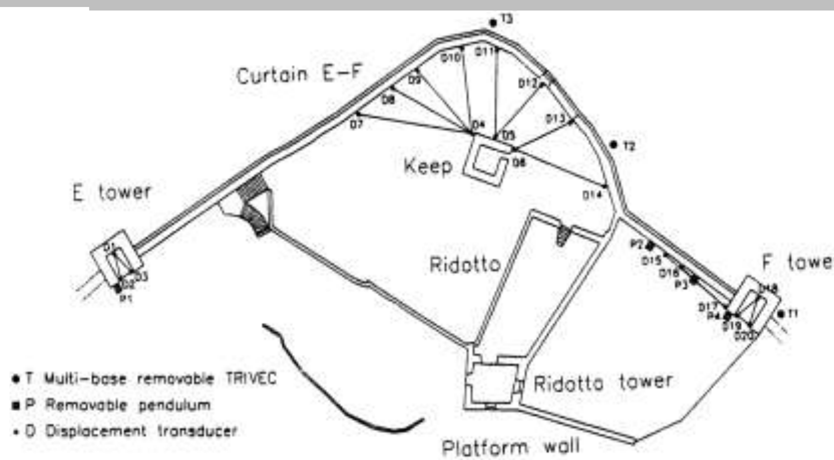
Interventions to strengthen the masonry walls

Grout injections: other applications

Castle of Este (Padova, XIV c.)
- local rebuilding
- metallic ties
- injections
- tie-beam at the top of the walls

S. Giustina Monastery Bell Tower (Padova, XIII-XVII c.):
- steel ties and frame
- local rebuilding
- injections
- reinforced repointing



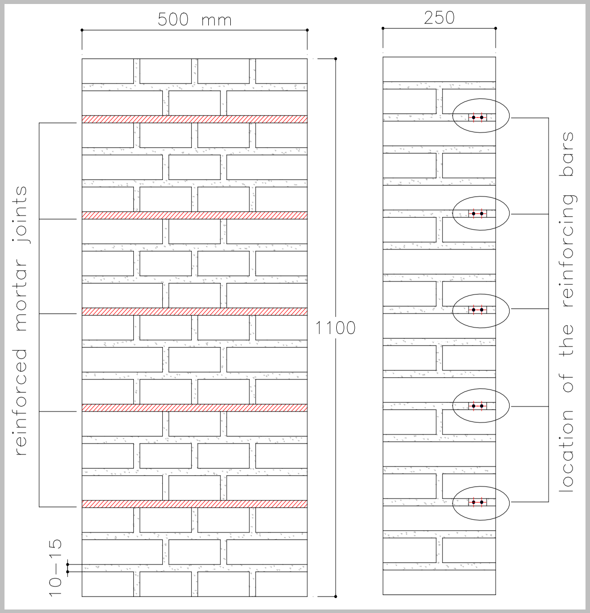


Plan of the area of intervention

S. Giustina Bell Tower

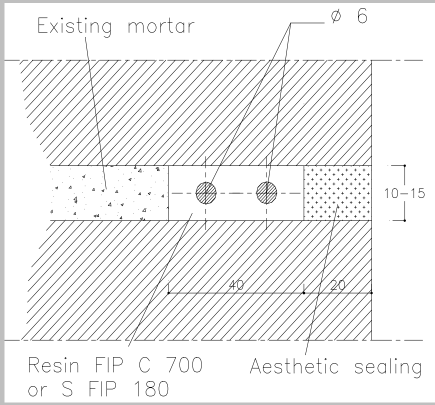
Interventions to strengthen the masonry walls

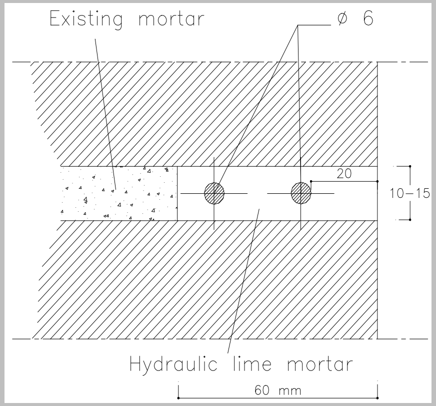
Reinforced repointing experimental researching and modeling: the use of steel bars

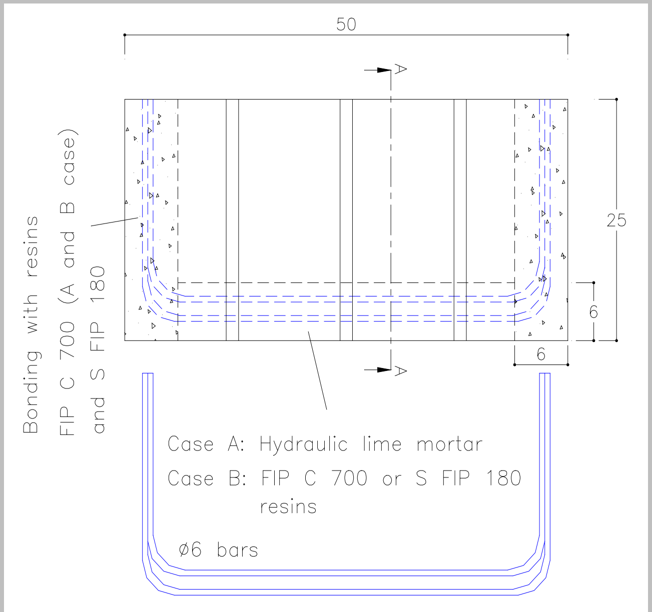


Monotonic compression tests:

- steel bars reinforcement (2∅6mm)
- repointing material:
  - hydraulic lime mortar
  - synthetic resins (2 types)
- one side strengthening



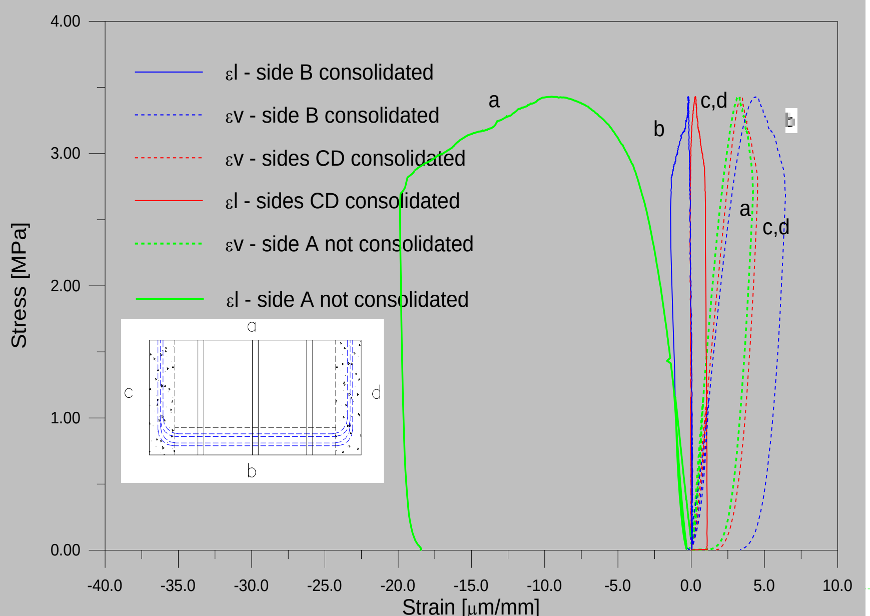




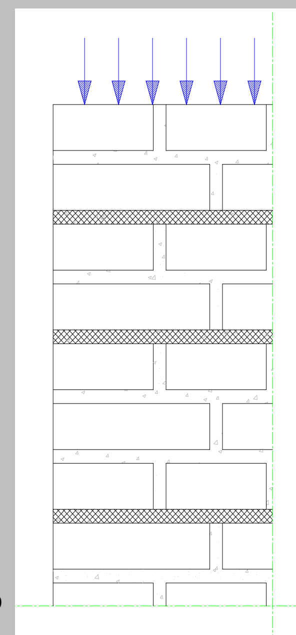
Interventions to strengthen the masonry walls

Reinforced repointing experimental researching and modeling: the use of steel bars

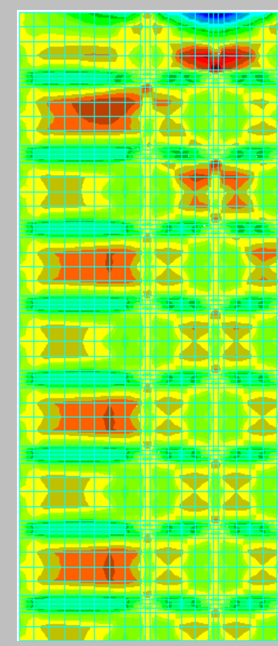
Experimental results:
comparison among the faces after repair



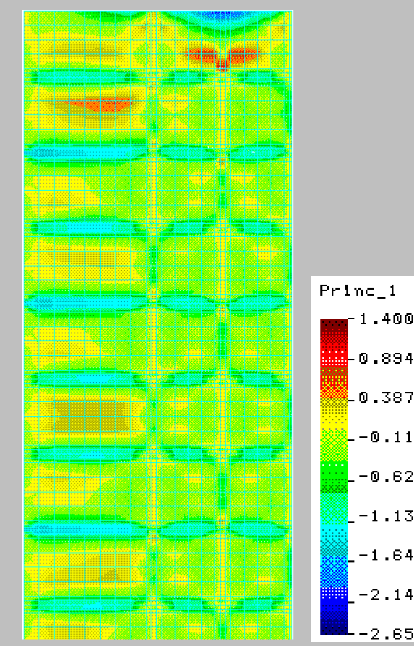
FE modeling scheme



Before repair



After repair



- **no improvement in the strength** of the wall
- **reduced dilation** of the repaired panels against the not consolidated ones
- reduced dilation of the consolidated faces of the repaired panels
- **reduced cracking pattern** on the repaired faces against the not repaired one
- **reduction of the tensile stresses** in the bricks (40%) and absorption by the bars

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Interventions to strengthen the masonry walls

Reinforced repointing experimental researching and modeling: the use of steel bars

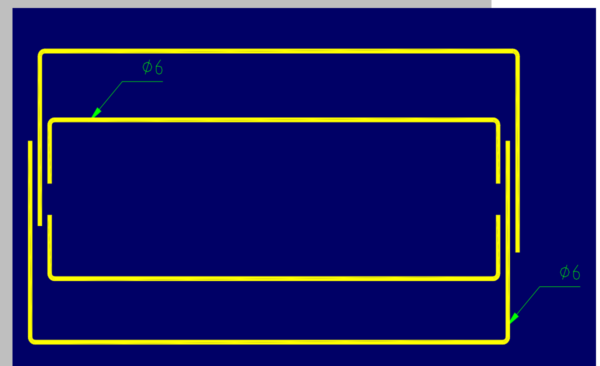
Creep tests:

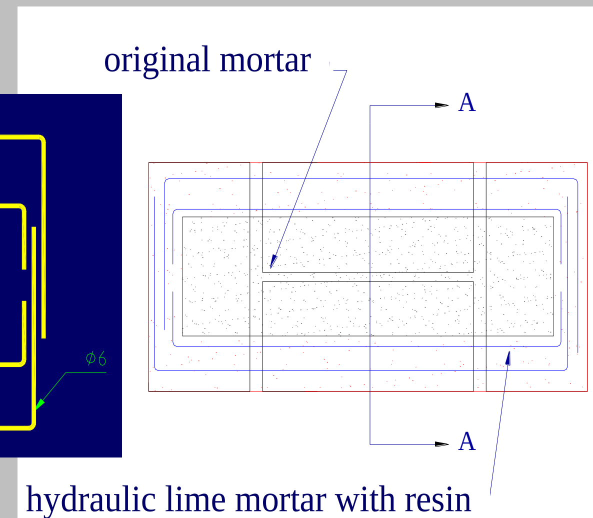
- Steel bars reinforcement (2∅6mm)
- Repointing mortars:

- polymeric hydraulic lime
- hydrated lime and pozzolana

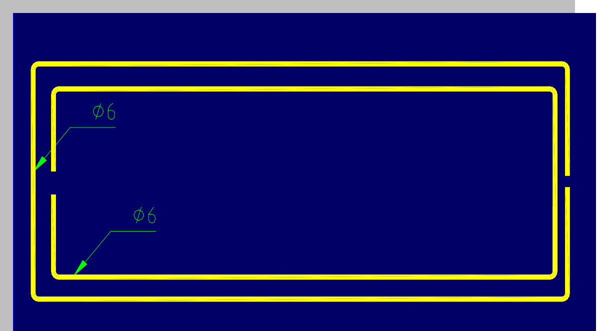
- Two sides strengthening with different configurations

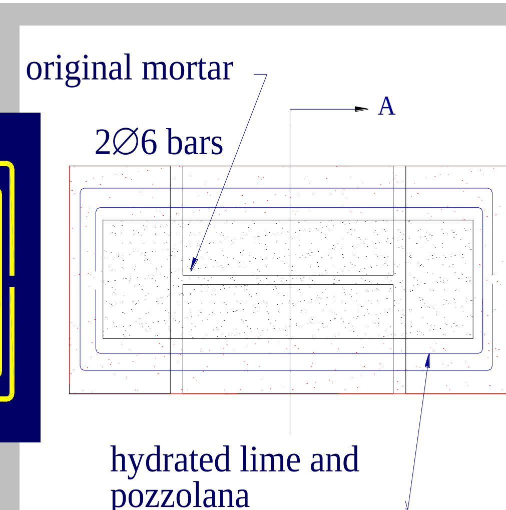
Strengthening case D





Strengthening case E

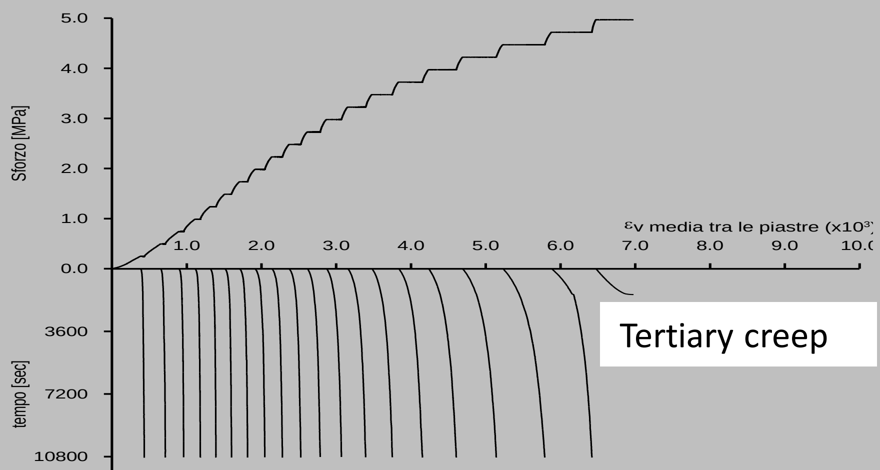


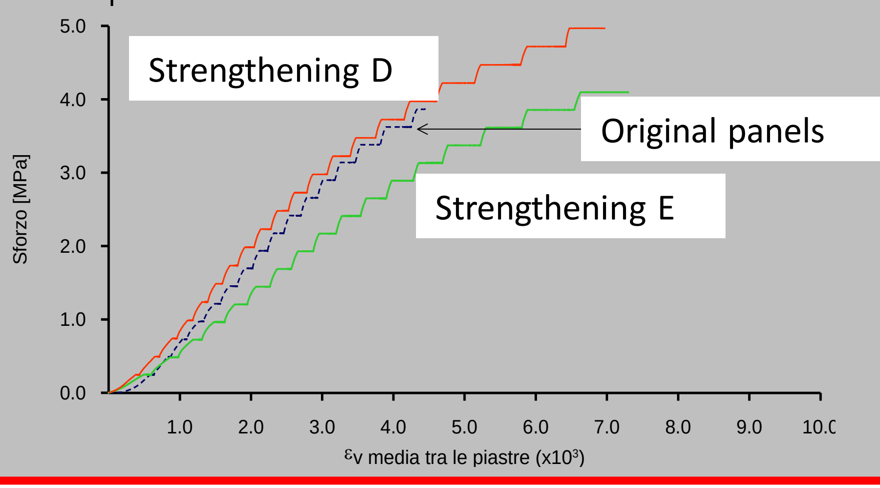


Interventions to strengthen the masonry walls

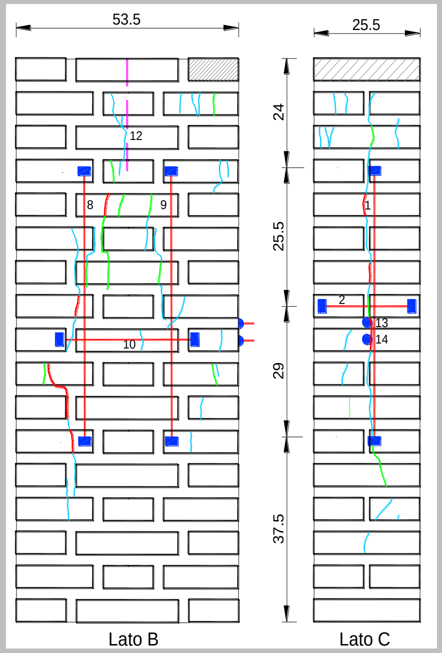
Reinforced repointing experimental researching and modeling: the use of steel bars

Experimental results:
constant single compression load steps (3^h)





Before

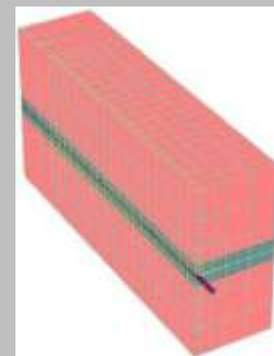


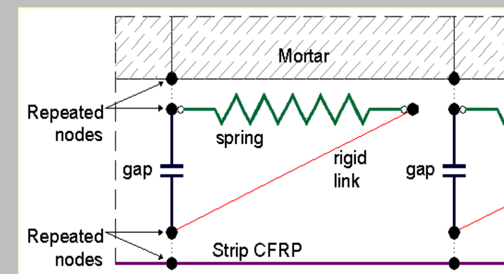
After

- Diffused cracking pattern
- Reduction of the dilatancy of the walls
- Tertiary creep condition in the strengthened panels achieved for deformations over 70% higher than the original ones

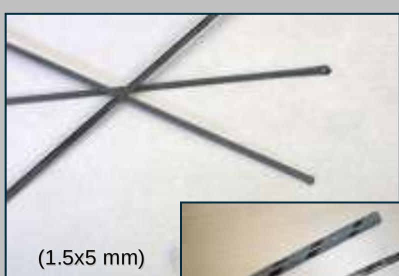
Interventions to strengthen the masonry walls

Reinforced repointing testing and modeling: the use of FRP bars and thin strips

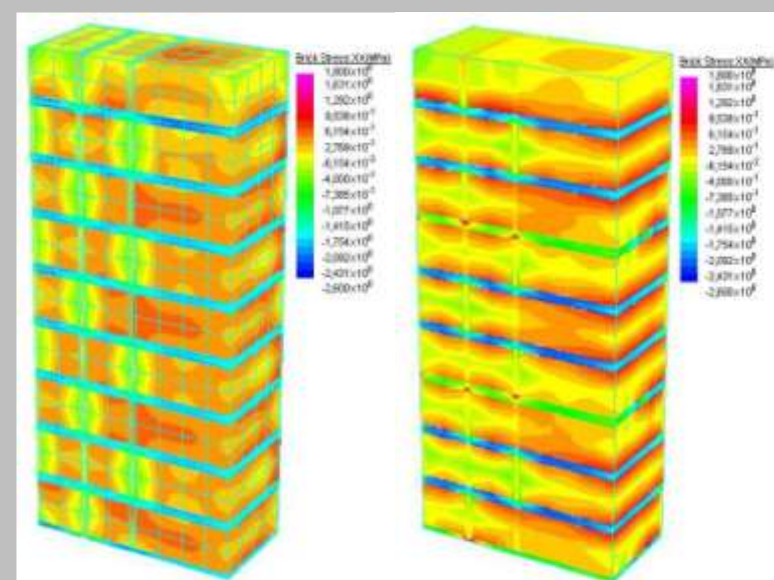




Using innovative materials while ensuring compatibility and removability



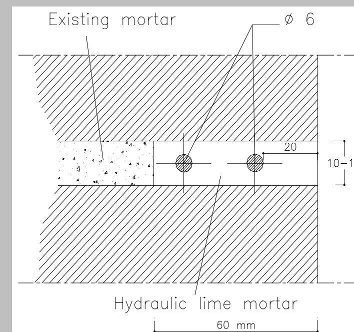
(1.5x5 mm)

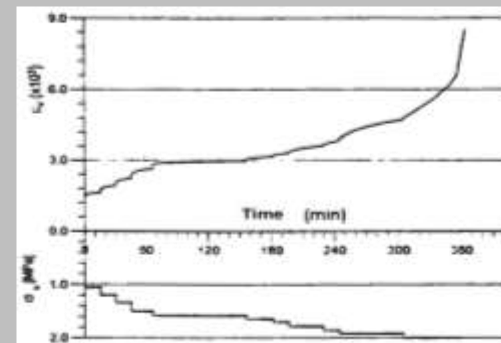


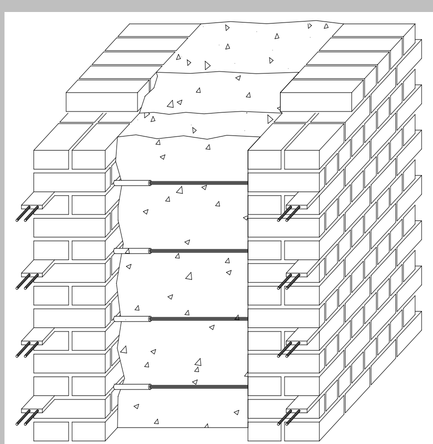
Interventions to strengthen the masonry walls

Reinforced repointing: application for the control of long term behavior

S. Sofia Church, Padova, XII c.







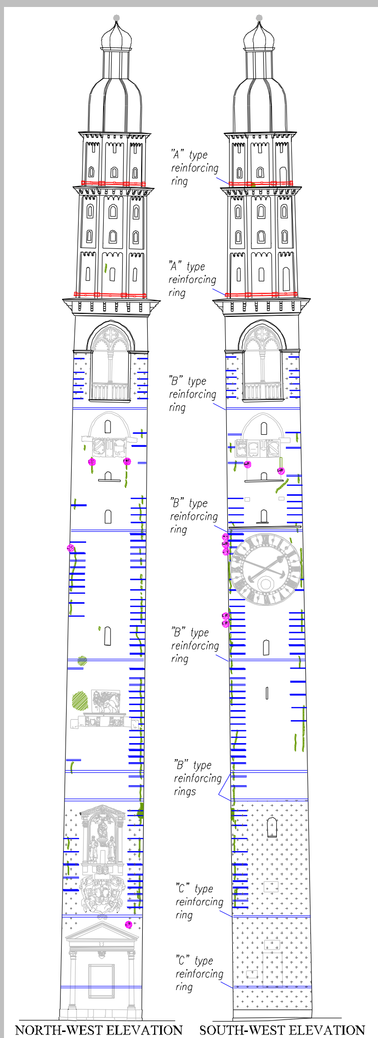
Interventions to strengthen the masonry walls

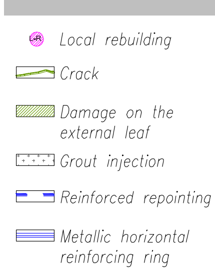
Reinforced repointing: application for the control of long term behavior

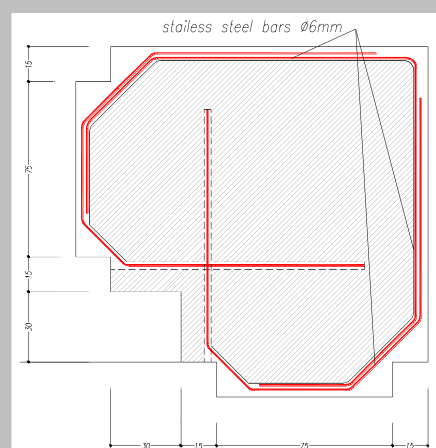
The Civic tower of Vicenza, XII-XV c.:
Slender structure with a base section of 6.2x6.5 m and a height of about 82 m, the Tower suffers a substantial out-of-plumb, and a damage characterized by localized **deep cracks**, **diffused micro-cracks** and **material deterioration**

The interventions:

- grout injections;
- pointing of mortar joints;
- reinforced repointing;
- metallic horizontal reinforcing rings and anchoring ties.





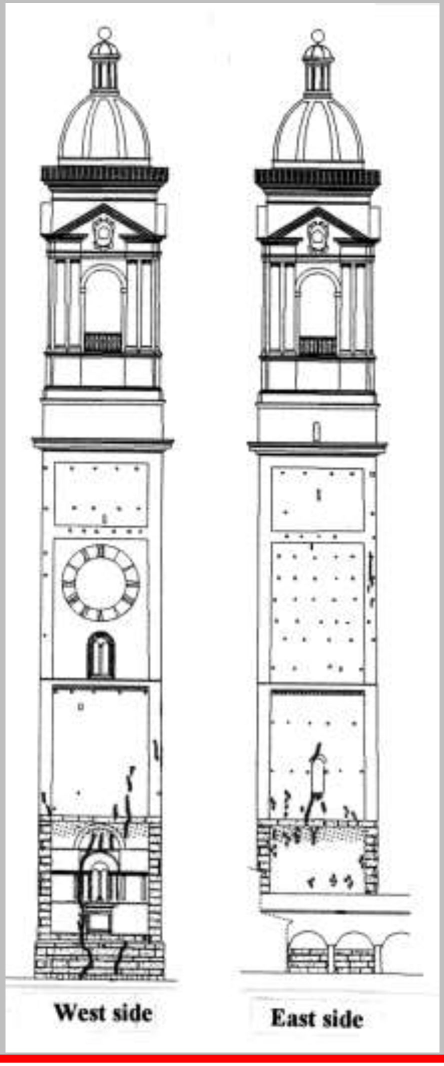


Interventions to strengthen the masonry walls

Reinforced repointing: application for the control of long term behavior

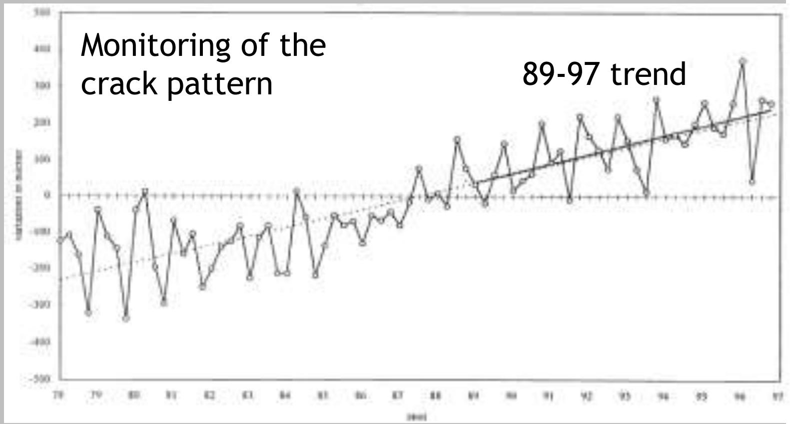
The bell tower of the Cathedral of Monza (XVI c.):

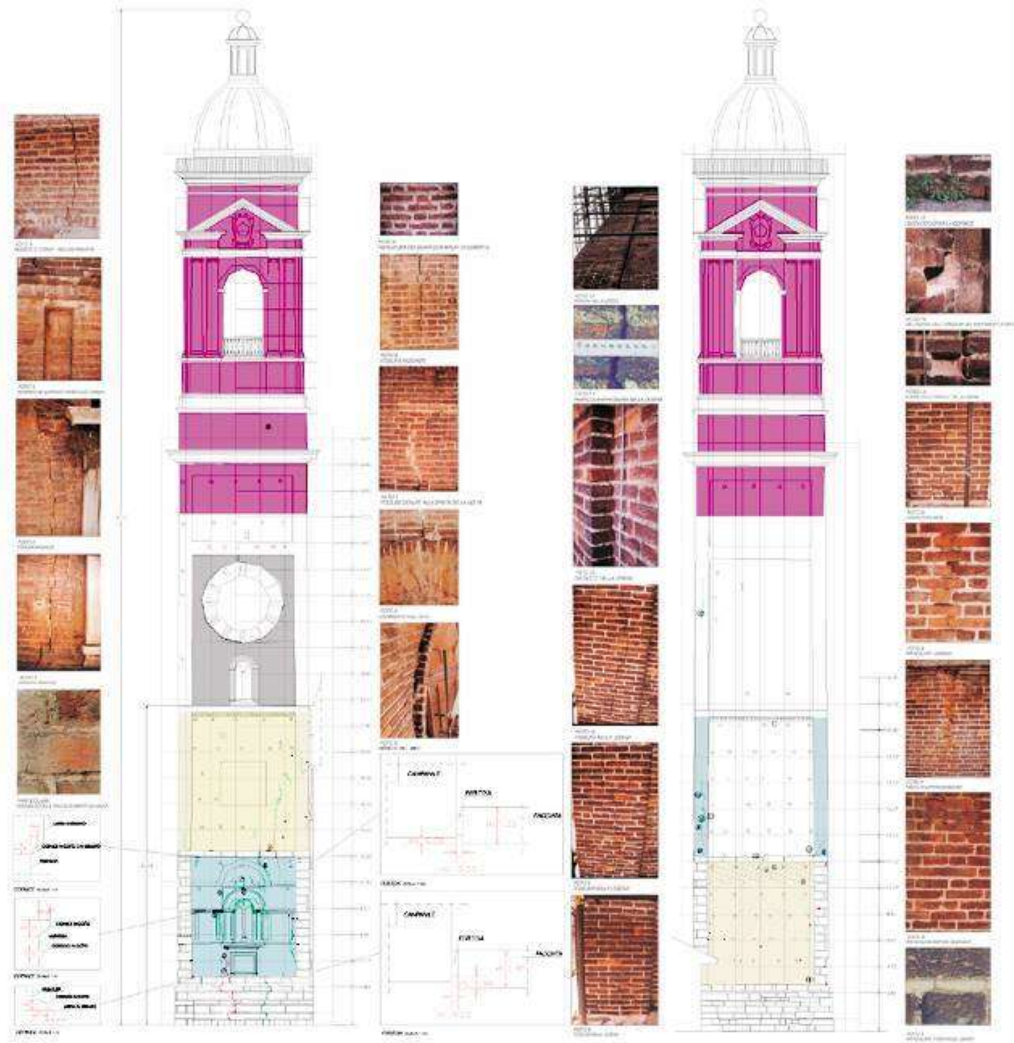
- 70 m tall
- **passing-through large vertical** cracks on some weak portions of the West and East sides (slowly but continuously opening since 1927)
- **wide cracks in the corners** of the tower up top 30m
- damaged zone at a height of 11 to 25 m with a multitude of **very thin and diffused vertical cracks**
- in the heaviest portions of the wall the current state of stress is close to the 70% of the masonry compression strength



Interventions to strengthen the masonry walls

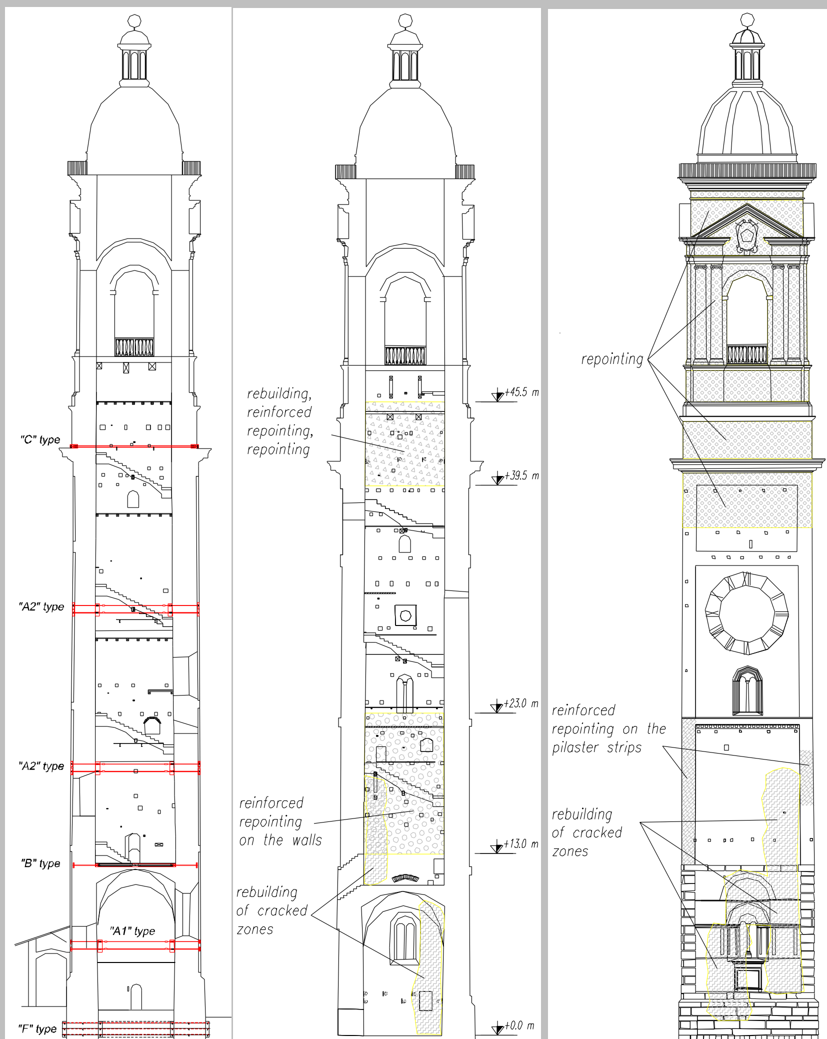
Reinforced repointing: application for the control of long term behavior

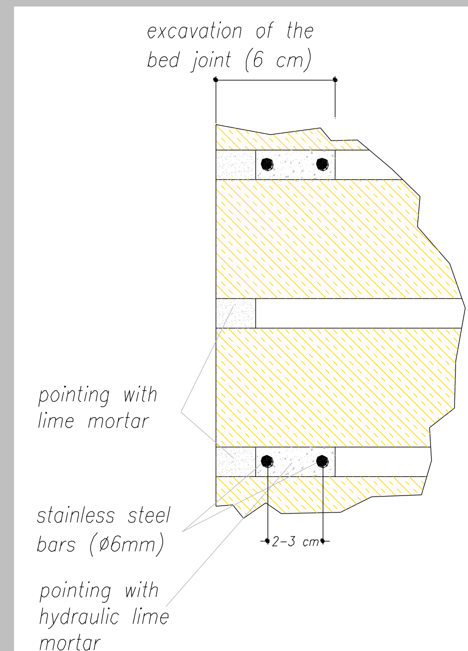


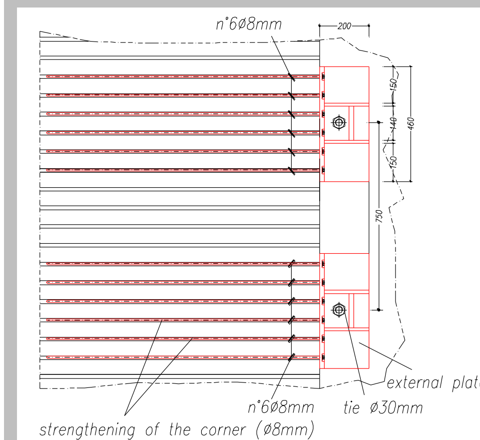


Decay pattern

Interventions to strengthen the masonry walls







Diffused **strengthening interventions design**:
- Injections
- "Scuci-Cuci"
- Bed joints reinforcement
- Placement of reinforcing metal rings reinforcing tie-rings at different levels
- Strengthening of the corners

Interventions to strengthen the masonry walls

Diffused **strengthening interventions execution**:
- Injections
- "Scuci-Cuci"
- Bed joints reinforcement
- Placement of reinforcing metal rings reinforcing tie-rings at different levels
- Strengthening of the corners

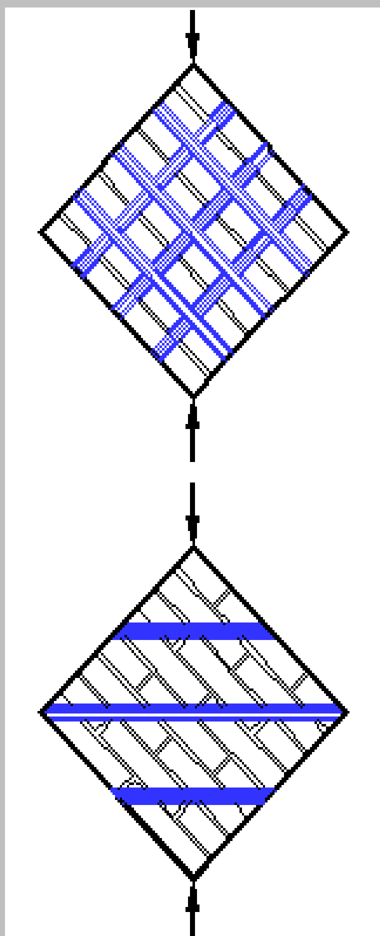






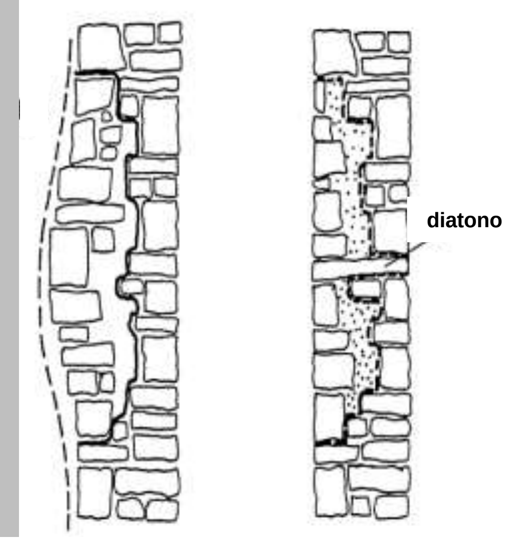
Interventions to strengthen the masonry walls

Application of FRP laminates to walls research: brick masonry wall specimens

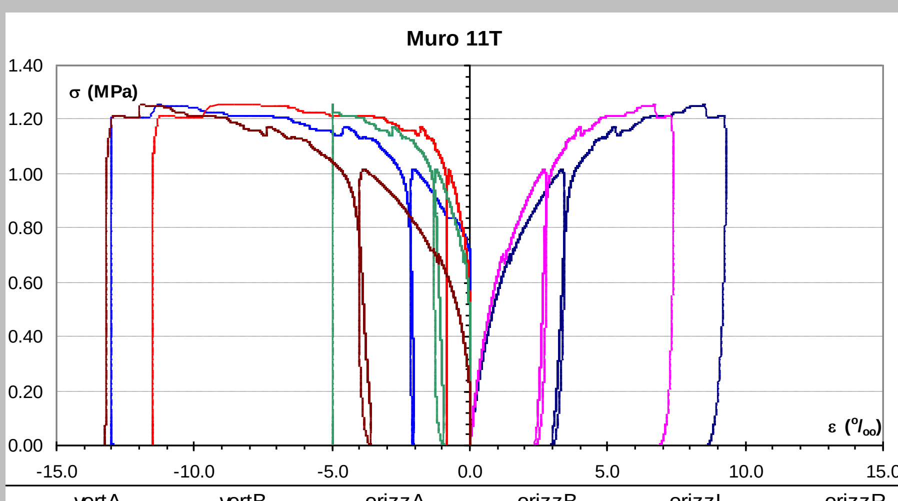


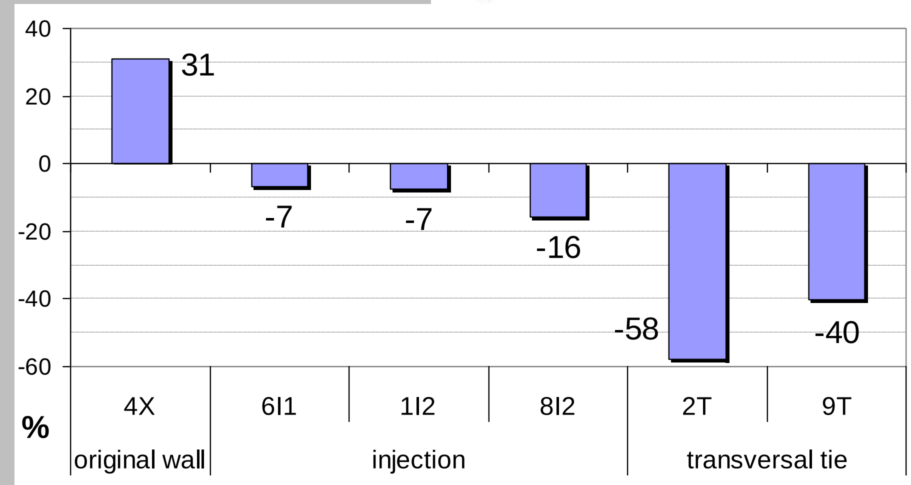
Interventions to strengthen the masonry walls

Application of transversal elements and ties to walls research: stone masonry wall



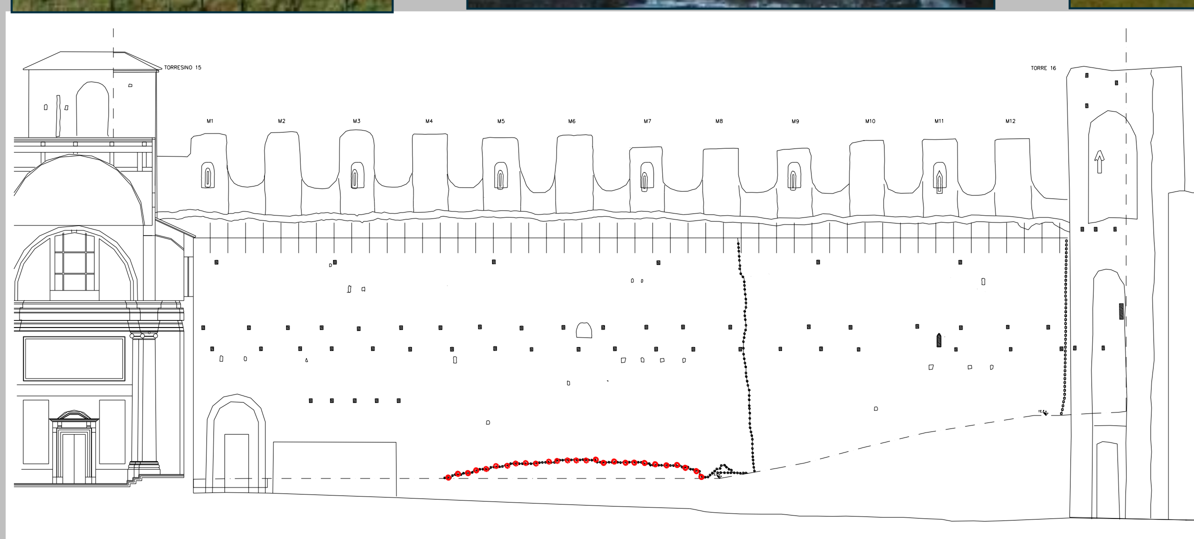
- Improvement in the strength of the wall
- Reduction of the dilatancy of the walls





Interventions on the foundation structures

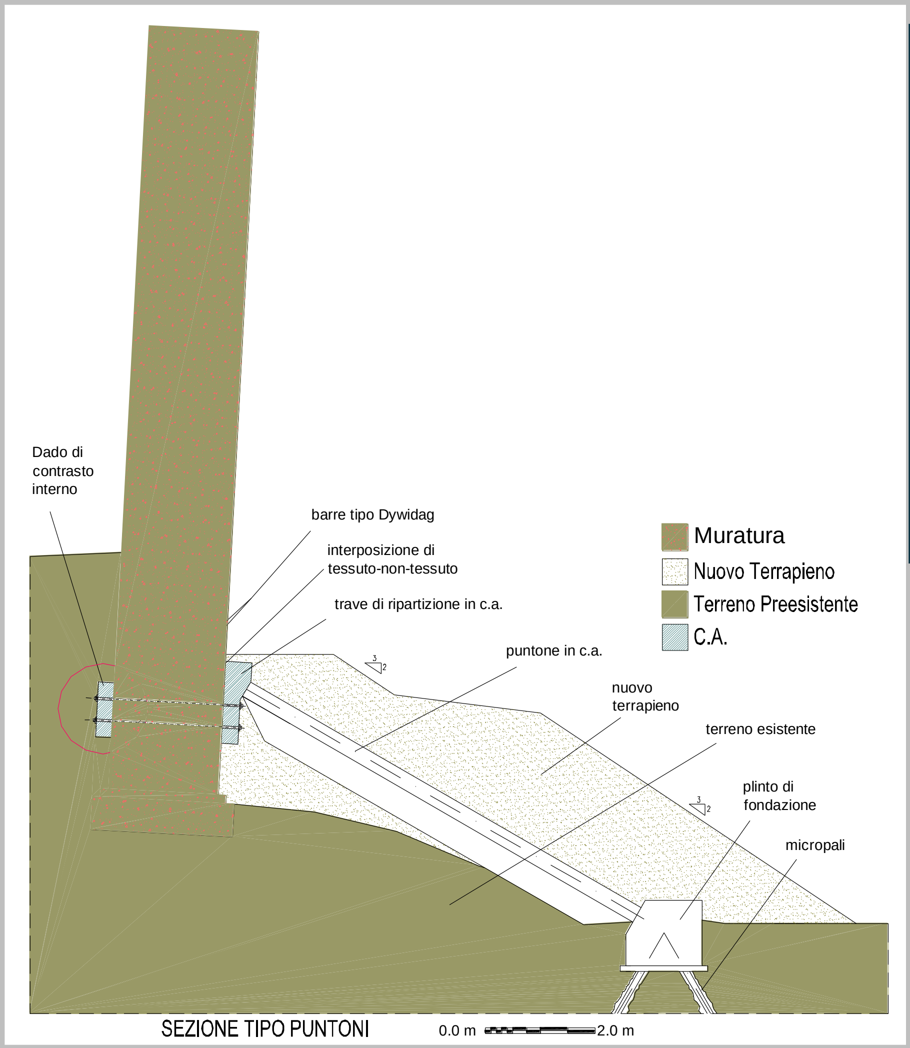


ARCO DI SCARICO

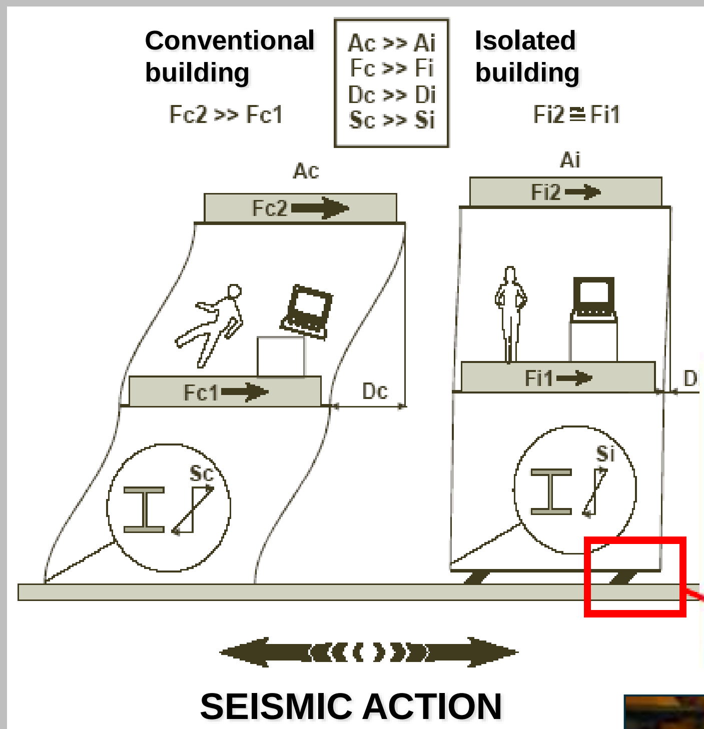
Town Walls, Cittadella

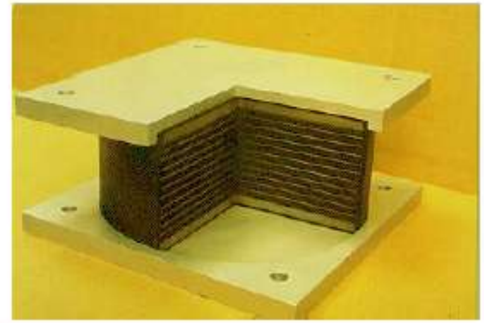
Interventions on the foundation structures



Town Walls, Cittadella

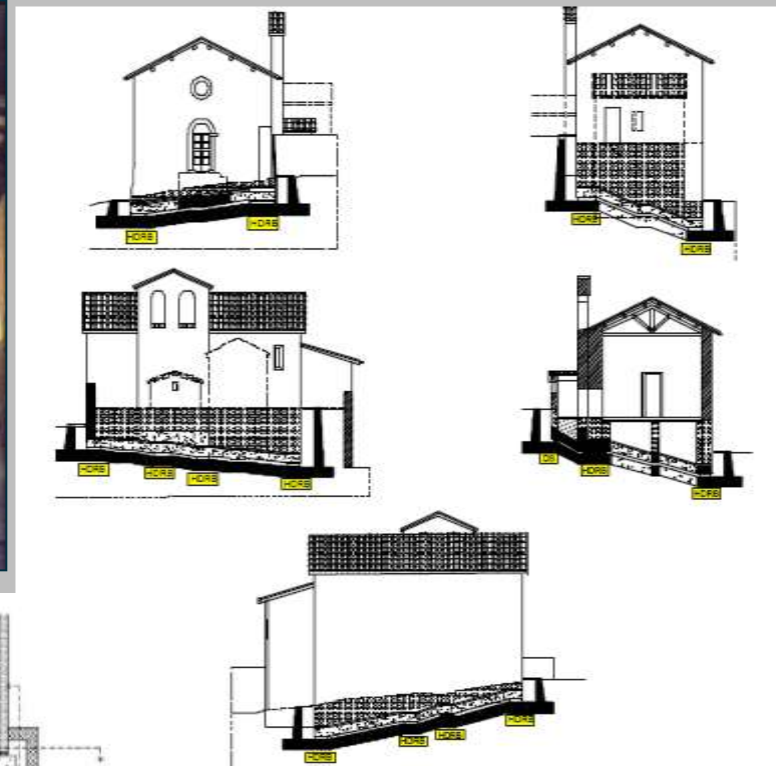
Introduction of seismic isolation and application to monuments

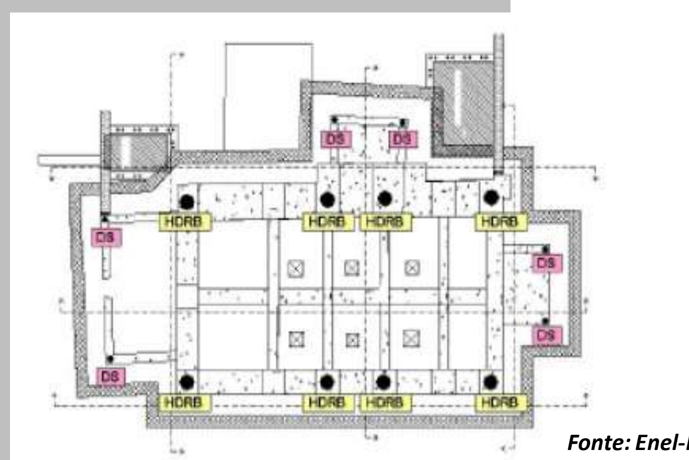




Seismic isolation of the Statue of Nettuno & Scilla in Messina (Sicily): particular of the support with **isolator and SMAD device**.

Introduction of seismic isolation and application to monuments





Fonte: Enel-Hydro, ENEA

Apagni Church, Perugia

THANK YOU!

SPEAKER: PROF. CLAUDIO MODENA

DEPARTMENT OF STRUCTURAL & TRANSPORTATIONS ENGINEERING
UNIVERSITY OF PADOVA, ITALY