Keynote Papers

The Seismic Behaviour of Ancient Masonry Structures: Damage Scenarios and Role of FRP in Retrofit and Improvement

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Abstract

The Italian Emergency Management Agency proposed in the recent years special forms to record, describe, quantify and evaluate the effect of earthquakes on ancient historical buildings. The form contains a set of fundamental damage mechanisms. They are very useful to build-up a fast and synthetic image but we may need to understand more deeply the interactions and the cause-effect relationship among the observed damage scenarios, i.e. what mechanical engineers call the "fault tree".

It can be hard, given the specific amount of uncertainties, but the fault tree reconstruction can be seen as a set of observable symptoms of a reduced set of primary basic damage mechanisms that must be inhibited for the future by well-studied effective retrofit actions. The FRP technologies can help strongly to reach that goal, but they have specific application domains and are not an all-purpose resource. In the recent years FRP reinforcing devices proved being useful as sensors, but in Italy such applications are confined into the laboratory tests and are not in the common practice. Recent advances in seismic isolation technologies can make the seismic isolation a reasonable choice also for existing ancient buildings.

Keywords: Ancient Masonry, Seismic Damage Scenarios, Smart Damage Assessment, Retrofit and Protection, FRP, Technical Norms

CHARACTERS AND UNCERTAINTY CAUSES IN ITALIAN HISTORICAL CONSTRUCTIONS

The masonry constructions are largely the most important part of architectural heritage in Italy. “Masonry” is a general word that include a huge variety of wall textures, materials and types.

It is easy to realize that the main reason of the variety of materials in ancient original constructions is due to the geographical location and topography:

- Granites, crushed and roughly worked in mountain areas
- Rounded stones near mountain rivers
- Limestone and sandstone squared and well refined blocks in hilly regions
- Clay bricks in flat alluvial lowlands.
- Artificial conglomerate (pozzolana) in the Roman heritage.

The quality of the masonry constructions is also correlated with the original social function of the building or the social standing of the original private owner.

Important public buildings and reach people houses show compact texture, solid and durable construction, skilled design. Popular houses have poor structural components, irregular wall texture, infill walls with two external organized layers and randomly assorted waste material inside. Ancient masonry structures are also affected by life-long history of architectural modifications, interventions, manipulations that involve the properties of static and dynamic behaviour; e.g., new doors are opened, old openings are filled, new masonry insertions are often made using different material and texture, the structural continuity is interrupted. All that complex history is introducing uncertainty and making difficult to model and to evaluate the residual safety. To repair effectively a damaged building we shall remember that each historical building is a unique object and the extended observation of many cases in the past shall help to build-up specific culture and skill. The choice of retrofit techniques and technologies is not standard but shall be optimally adapted to the specific cases.

Nevertheless the damage mechanism configurations and the geometrical and mechanical properties of a structure are partially correlated and damage mechanisms can be predicted at list in a probabilistic sense. This is important to support decision making processes on the choice and design of the preventive protection measures where the earthquake is expected but still did not happen recently.

When the external actions are weak the structure can behave as a deformable elastic body, with non negligible damping. During a strong earthquake the ancient masonry structure develops cracks and failures that decompose the structural body into interacting but independent macro-components which survive if fundamental rigid body static and dynamic equilibrium conditions are respected. A deformable body dynamic analysis, linear or non-linear, makes sense only for vaults, domes and towers, not for massive components.

Two kinds of failure modes usually can occur to masonry walls: out-of-plane and in-plane. The latter requires an energy level much higher and happens only if the first one is inhibited. Poorly executed infill walls are highly vulnerable and subject to out of plane

failure under moderate quakes (see figure 1). The collapse mode of well executed, compact and well connected masonry walls is generally based on in-plane failure.

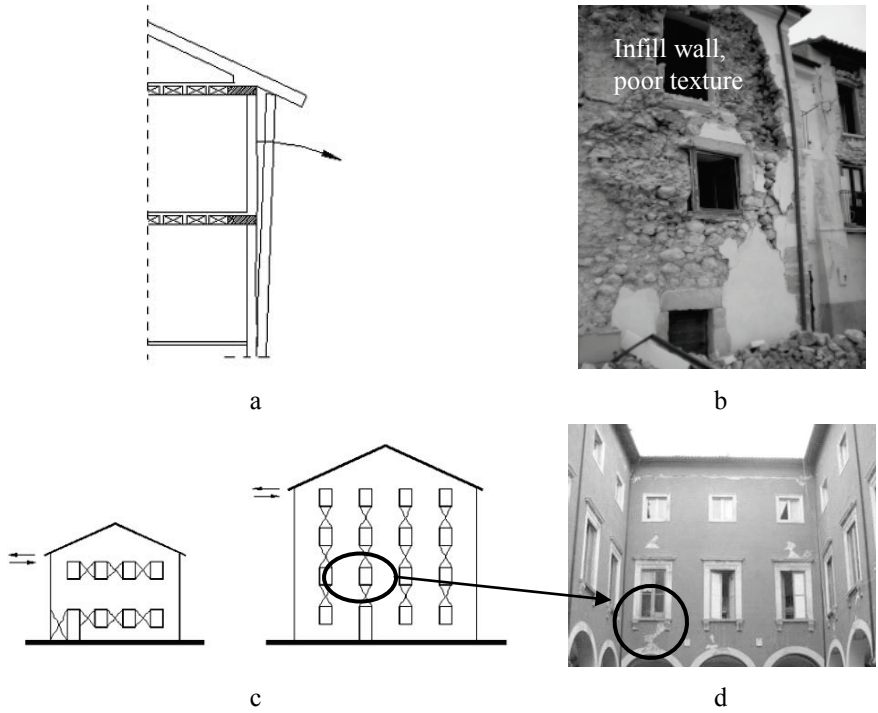


Figure 1: out-of-plane (a,b) and in-plane (c,d) failure

THE FAULT TREE

Examples of primary and induced damage mechanisms

It is not so easy to identify the fault tree by a simple visual observation. In most cases on site geometrical and topographical measures, non-destructive tests and numerical simulations are necessary, allowing to correlate the qualitative and quantitative description of damage scenarios to geometrical and mechanical properties of the structure, with particular attention to lack of verticality of walls, effectiveness in orthogonal walls connection, effectiveness of link between floors and walls, in-plane stiffness of walls. Roofs, arches and vaults can be pushing; they can cause damage depending on their size, shape and weight (figure 2) or they can suffer damage caused by the own dynamic response of the bearing walls (figure 3).

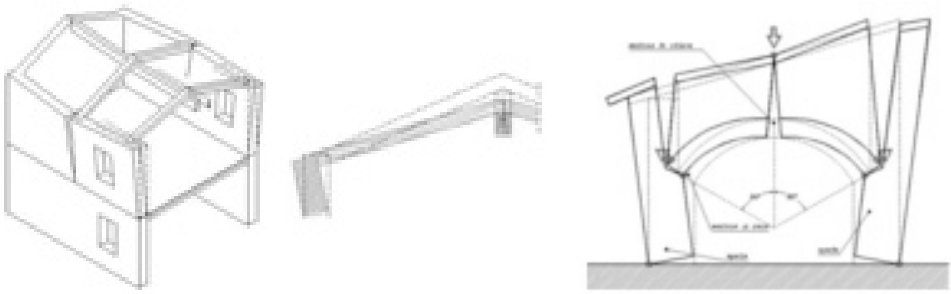


Figure 2: examples of pushing roof and arches

Figure 3: collapse of a floor due to wall motion

In the fault tree, which is a causal and hierarchical chain of damage effects, there are one or more main sources, or primary damage, and secondary or induced faults (figure 4)

The crushing at the column foot in figure 5 is caused by the overturning of the arcade. The latter can be a primary fault if the wall containing the arcade is rotating for its own dynamic behaviour, or can be secondary itself if the pressure of vaults or roof is the main cause of the wall rotation. The wall overturning shown in figure 6 is a primary fault, made easy by a lack of connection and continuity at the upper corner. The building is a library and a consistent mass of books was supported directly by the external wall generating on it consistent inertia.

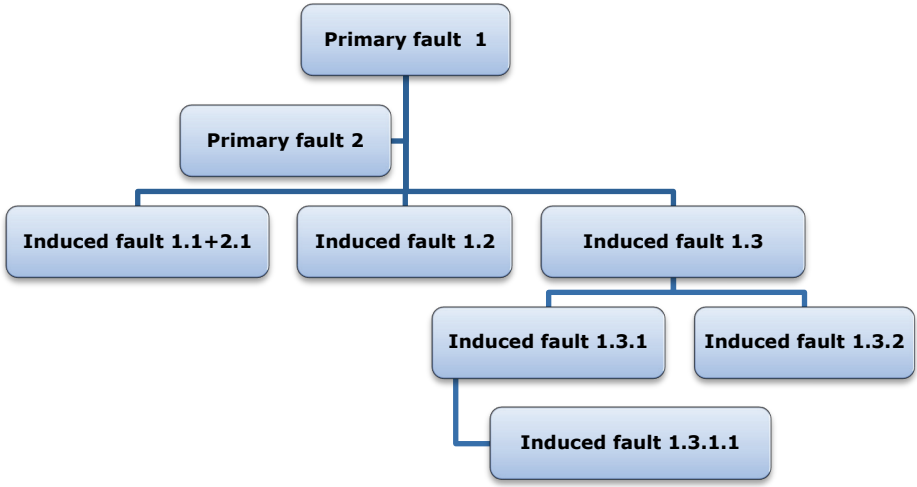


Figure 4: scheme of fault tree

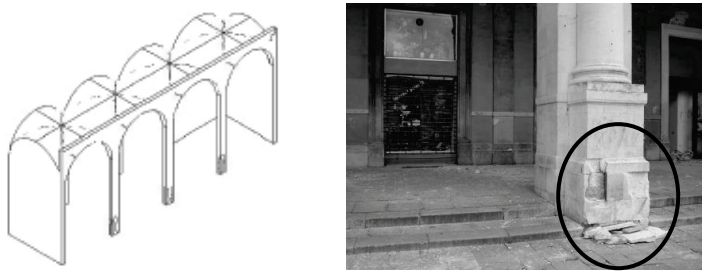


Figure 5: induced damage at the base of columns

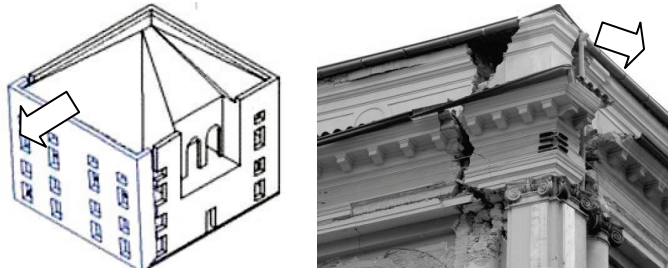


Figure 6: primary damage - overturning of the wall

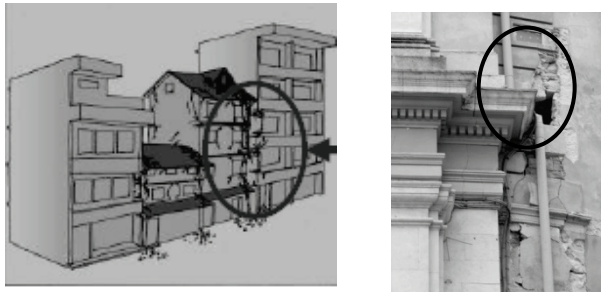


Figure 7: hammering, primary damage

Figure 7 shows the crushing effect of hammering, a primary cause that can induce heavy consequences. The local damage of figure 8 is due to insufficient restrain of horizontal structures or to the falling down of massive bodies from higher floors.

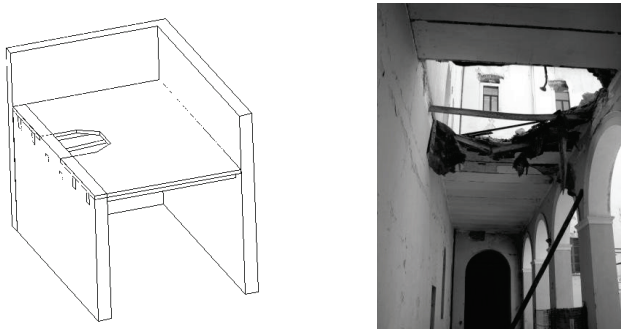


Figure 8: local collapse, induced damage

Damage, structural characters and expert systems

The induced damage effects are often local. One can look at them as symptoms of the principal fault that have generated them. [3]The observation of a set of local damage effects can make possible the reconstruction of the whole fault tree. An expert can achieve such reconstruction and link it with shape and properties of the structure, so to be able to use the knowledge of the structure to predict the most probable failure modes.

A well structured expert system could help also less experienced technicians to reach that goal. An automatic predictive expert system, based on probabilistic neural algorithms, was proposed years ago by one of the Authors [1].

Artificial neural networks are data processing systems possessing learning and generalisation capabilities. In a supervised neural network, training consists of presenting a set of examples and letting the network build up, on the basis of a well-defined algorithm, the interior structure it needs to perform its intended task. In mathematical terms this amounts to supplying a set of vector pairs, i.e. an input vector (X) and an

output vector (Y), and having the network associate all the X - Y pairs, with the least possible error, so as to build up a unique functional relationship Y = F(X), no matter how complex is the phenomenon to be interpreted. Having concluded the training stage, the network must be able to effectively predict the output vector Y most closely associated with the input vector X.

In classical neural networks, the answer is univocal, and vector Y is the one involving the greatest possibility of occurrence. Probabilistic networks, on the other hand, supply several answers Y_i, each of them associated with an estimate of the respective probability.

In the case being considered, the probabilistic network yields a Bayesian type classification.

The final goal is to exploit the fundamental learning and generalisation capabilities of neural networks to obtain a prediction of the damage mechanisms which may be triggered in the macro-elements of historical heritage buildings.

The application to the second one involves a transition from a visible damage estimate to an evaluation of the structural residual safety. To achieve a reliable estimate of the residual safety level, a numerical modelling is compelled, in order to enlarge the knowledge database originally built-up from the direct on-site observations. The construction of the probabilistic network is quite simple but the delicate and critical part of its utilisation is the way in which qualitative and quantitative data collected in the survey forms are translated into the vectors of conventional numerical codes. The information contained in in-situ measurement data sheets has been rearranged and elaborated in order to reduce any cause of uncertainty of attribution.

Bayesian classification

It is well known that Bayes stated his theorem based on binomial distributions and, later, its availability has been generalised to a wide set of statistical distributions in the discrete, as well as continuous, random variables domain. We can start by recalling the formulation of the Bayes' theorem for discrete distributions.

Given a space S, let us consider a partition consisting of mutually exclusive ($A_iA_j = 0,\ i \neq j$) and exhaustive($S = A_1 \cup A_2 \ldots \cup A_n$) events A_1, A_2,...., A_n and an arbitrary event B; since this event may occur together with A_1 or A_2,..., A_n, the probability of the occurrence of event B is given by:

$$P(B)=P(A_1)P(B|A_1)+P(A_2)P(B|A_2)+.....+P(A_n)P(B|A_n)=\sum_{j=1}^{n}P(B|A_j)P(A_j) \quad (1)$$

This formulation, known as "absolute probability theorem", retains its validity even in presence of an infinite number of events. A direct consequence of the conditional and absolute probability theorem is Bayes' theorem [4]:

$$P(A_i|B) = [P(B|A_i)P(A_i)] / \left[\sum_{j=1}^{n} P(B|A_j)P(A_j) \right] \quad (2)$$

Bayes' theorem is also known as theorem of the probability of causes, in that it makes it possible to determine the probability of events A_i having been the cause of the occurrence of event B. Bayes' theorem is used to convert an "a priori" probability estimate $P(A_i)$ into an "a posteriori" probability estimate $P(A_i|B)$ knowing the conditional probability $P(B|A_i)$: this theorem enables you to determine the conditional probability of event A_i given that event B has occurred.

In the damage prediction context, we want to classify a set of m-dimensional vectors $X = \{x_1, x_2, ..., x_m\}^T$ each one representing the typological characteristics of a building, into a discrete number of classes $\omega_1, \omega_2, \ldots, \omega_K$ representing the different damage mechanisms. In this case (discrete parameter) Bayes' theorem asserts that the probability mass function of ω_i for a given vector X is:

$$h(\omega_i|X) = [p(X|\omega_i)g(\omega_i)] / \left[\sum_{j=1}^{k} p(X|\omega_j)g(\omega_j) \right] \quad (3)$$

in which:

- $g(\omega_i)$ denotes the "a priori" probability density since it is determined prior to observing vector X in the current experiment (based upon previous understanding)
- $p(X|\omega_i)$ is the probability density function of X, conditional upon the class ω_i
- $h(\omega_i|X)$ is the "a posteriori" probability mass function of ω_i , given X, since it is determined posterior to observing the current set of data.

The equation (3) estimates the "a posteriori" probability density that vector X belongs to class ω_i. The key to using Bayes' theorem for classification problems is the ability to estimate $p(X|\omega_i)$. In this context we adopt "a priori" probability densities to be equally likely and have to estimate the different $p(X|\omega_i)$ by means of a probabilistic network based on training patterns.

The application of that expert system allowed a consistent prediction of failure mechanism type in macro-elements of ancient churches [2]

REPAIRING, STRENGTHENING, PROTECTING IN ADVANCE

The reference norms in Italy and EU [4]

Ever since the D.M. 24/01/1986 was adopted, the concept of "seismic improvement" was introduced in Italy. In the case of minor interventions that do not significantly alter the overall structural behaviour, it is not necessary to increase the seismic performances to the level required for new constructions and perform the safety checks required by standards prescriptions. In the D.M. 16/01/1996, this concept was then applied to the assessment of cultural heritage buildings, since it was considered

compatible with their preservation needs. These norms also listed some strengthening techniques to be adopted for improvement and upgrading interventions, which reflected the knowledge and state of art of the years when these were issued. From that moment onwards, the consequences of various earthquakes, listed in the introductions, led to a critical review of the technical content of these documents. The calibration of the safety level to the need of an existing structure is also proposed by international standards (ISO 13822, 2006), and can be based on the concepts of minimum total expected cost, comparison with other social risks, importance of the structure, possible failure consequences and socio-economical criteria, although its influence on the type of intervention to be adopted is not clearly defined in other norms.

These efforts, through the OPCM 3274 (2003) and OPCM 3431 (2005), have led to the documents currently in force: the NTC 2008 (D.M. 14/01/2008) and the Guidelines issued by the Ministry of Cultural Heritage in 2007. The innovative aspects of these guidelines emerge from the multidisciplinary approach that they propose. The outcomes of the process of assessment and reduction of seismic risk for cultural heritage buildings is thus a compromise between seismic protection requirements and respect of cultural and artistic values, according to the preservation criteria asserted in the various issued charters for the restoration of historic monuments (Athens Charter, 1931; Venice Charter, 1964) and recommendation for structural restoration of architectural heritage (ICOMOS/ISCARSAH, 2003).

The EN 1998-3 (2005), which introduced some of the concepts that have been further developed in the Italian norms, is currently lacking some reference values in order to make the methods applicable by the designers. In other fields, such as the definition of the seismic safety levels for existing structures and the methods of analysis and assessment, the Eurocode 8 is not updated with the latest findings and methods introduced in Italy. Even the established concept of "seismic improvement", which has a significant influence on the design of interventions, is not yet recalled by the EN 1998-3 (2005).

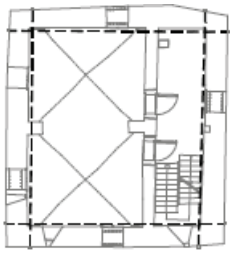
The Italian norms give some general principles to select and apply the interventions, which are valid regardless the specific technique being employed. One of these criteria is that interventions should be applied as much as possible regularly and uniformly on the building, so as to avoid uneven distributions of strength and stiffness. The surveys and damage observation indeed demonstrated that interventions carried out without paying the due attention to the above criteria were useless and even harmful.

The improvement of the building seismic performances may be achieved using traditional methodologies but also adopting innovative techniques and materials. The choice of the most appropriate approach depends on the results of the previous evaluation phases, thus the interventions listed in the Italian norms should not be considered as prescriptive and to be applied in any case, but should be targeted to the specific problem. Conservation of both materials and functionality of the structure is the main objective, therefore interventions should avoid significant alterations to the original structure and provide compatibility to the largest extent. It should be pointed out that these simple concepts have not been included in the Eurocode 8.

Italian norms propose classes of interventions that can solve specific problems such as improving the structural connections, reducing horizontal diaphragm deformability, increasing the masonry strength, reducing the vulnerability of vaults and arches, reinforcing pillars, etc. In this regard, the structure of EN 1998-3 is not coherent as it sometimes follows a rational path but some other times mixes or simplifies the approaches. As an example, in annex C of Eurocode 8 a sub-section is devoted to the repair of cracks. This is quite limited, if one thinks that being cracks the symptoms of more complex structural problems, say inadequate masonry strength under in-plane shear, or activation of kinematic mechanisms on vaults and arches, or presence of sustained dead-loads on pillars etc, the solution should be aimed at solving the basic problems. In this context, the interventions listed by the Italian norms, according to the current knowledge, cover all the main aspects of masonry building behaviour, but is not deemed to be exhaustive in terms of materials and techniques. The same norm, indeed, states that other materials and techniques, when proved to be viable for the solution of a specific problem, could be adopted by the designers. This is the proper role of performance oriented technical norms.

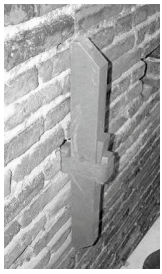
Interventions to improve connections

This goal may be achieved inserting ties (Figure 9), confining rings (Figure 10), and tie-beams at the top of the building, preferably in reinforced masonry or steel but also in r.c. though with restrictions (Figure 11). An effective connection between floors and walls is useful since it allows a better load redistribution and applies a restraining action towards the walls' overturning. In the case of wooden floors, a satisfactory connection is provided by fasteners anchored to the external face of the wall (Figure 12).



a

Tie positioning (plan view)



b

The external anchor

Figure 9: positioning of stainless steel ties, Vanga tower (Trento)

a

Insertion between mortar joints

b

View of the positioned cables, façade.

Figure 10: external confining stainless steel ties

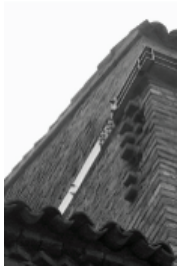


Figure 11: external steel tie

Figure 12: connecting wooden beams

Interventions to increase the masonry strength

The local rebuilding ("scuci-cuci") methodology aims to restore the wall continuity along cracking lines (substitution of damaged elements with new ones, reestablishment of the structural continuity) and to recover heavily damaged parts of masonry walls. The use of materials that are similar, in terms of shape, dimensions, stiffness and strength, to those employed in the original wall is preferable. Adequate connections should be provided to obtain monolithic behaviour.

Non cement-based mortar grouting increases the strength of multi-leaf masonry walls, and respects the requirement of compatibility, in terms of chemical-physical and mechanical properties between grout admixture and substrate wall.

It consists in the injection of mixture through a regular pattern of drilled holes for increasing the connection between masonry layers. Injections do not significantly change wall stiffness, differently from RC jackets, improving at the same time the strength and consistency of walls provided with voids and/or irregular morphology. The EN 1998-3 mentions the injection technique to strengthen multi-leaf walls (sub-section C.5.1.6) and to repair cracks (sub-section C.5.1.1), suggesting the use of cement-based materials or, in some cases, epoxy grouting, without taking into account the most recent research findings about chemical compatibility and effectiveness of low-strength grout injections.

The mortar bed-joint repointing is an other technique to improve deteriorated joints that consists in the replacement of degraded mortar. If steel bars are inserted within the joints to limit the opening of vertical cracks the method is known as structural repointing.

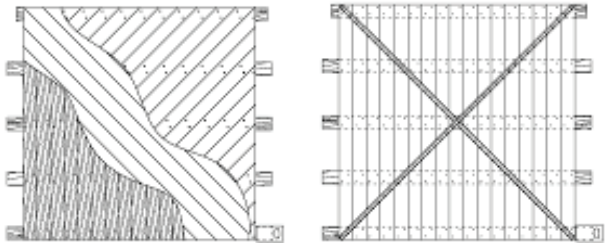
Laboratory tests and numerical models show that it is possible to use new materials as FRP laminates instead of steel, to ensure compatibility and removability as well as the control of creep deformations. This kind of intervention is described also by EN 1998-3 sub-section C.5.1.1.

Masonry strength can be also increased by means of the insertion of "diatoni" (masonry units disposed in a orthogonal direction with respect to the wall's plane), substituting damaged stones or introducing new elements to provide transversal connection between the external layers of wall (NTC 2008). Other methods are mentioned in the EN 1998-3, such as the use of RC jackets, the insertion of steel profiles

(sub-section C.5.1.7) or the application of polymeric grids jackets (sub-section C.5.1.8). A lack of critical evaluation about the proposed techniques is observed also in these cases: the suggested systems have to be carefully evaluated, since the suitability and the effectiveness should be demonstrated case by case. For instance, an incorrect application of RC jackets could easily worsen the structural behaviour because of the increased stiffness and mass of portions of the structure.

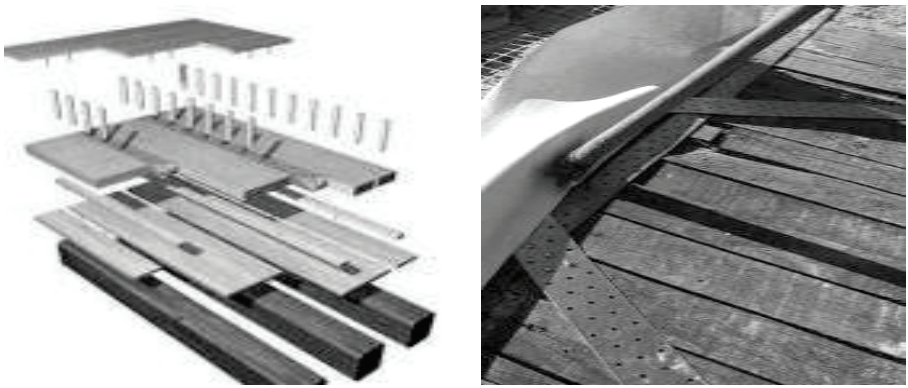
Interventions to reduce flexibility of floors and their consolidation

The role of diaphragms in the dynamic behaviour of masonry buildings consists in transferring seismic actions to the walls parallel to the earthquake direction. Sufficiently stiff diaphragms introduce higher structural redundancy increasing the global strength. An effective diaphragm-wall connection limits the overturning of the wall.



a b

Figure 13: strengthening intervention by: a) orthogonal double plank; b) orthogonal double plank with wooden, steel or FRP diagonals



a b

Figure 14: stiffening of an existing wooden floor: a) in- and out-of-plane with double orthogonal planks connected by wooden dowels; b) in-plane by steel plates

Interventions to reduce thrust of vaulted arches and their strengthening

Strengthening methods may be applied by using the traditional techniques of tie-rods to compensate the thrust induced on the bearing walls. In addition, to absorb thrust of vaulted arches, the possibility of realizing buttresses or reinforced transverse vertical diaphragms should be considered, whilst jacketing the extrados using concrete, reinforced or not, should be avoided. Composite materials, such as FRP or SGP/SRG could be a suitable option in some cases. In recent years, experimental researches focused on the behaviour of masonry vaults strengthened by new composite materials, as carbon or glass FRPs, placed at the intrados (inner surface) or at the extrados (outer surface) of the structure (Figure 15). The application of FRP layers at the intrados is more critical due to higher risk of debonding due to traction failure of the existing materials.

A multilayer system of adhesion based on epoxy adhesives and designed to provide a support as homogeneous as possible for the fibres has been adopted [5].

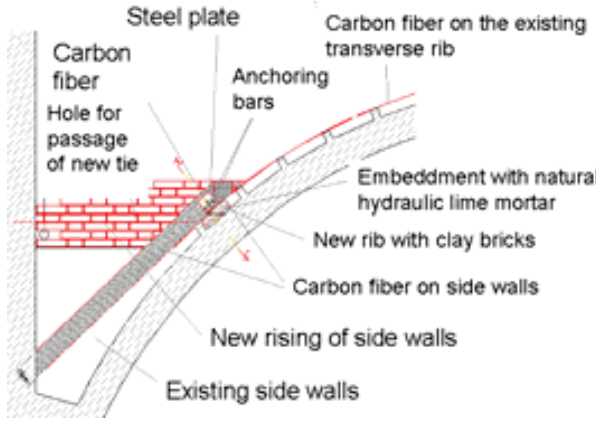


Figure 15: application of FRP on a vault extrados

FRP play an important role mainly in two kinds of application: shear strengthening of wall elements and confining of columns and piers. Of course problems can arise for aesthetical and architectural reasons if those elements are bricks or stones in open view, without any surface coating material.

Seismic isolation of historical buildings

The main reason that limits the applicability of the seismic isolation to the existing historical heritage in Italy is that a diffused sensitivity discourages any intervention modifying consistently the existing structure and structural behaviour.

Therefore many studies on that subject exist, but there is a very small number of real applications. Very recently an isolation new philosophy has been proposed and patented (Figure 16) [6].

The isolation is underground. Several adjacent horizontal pipes, built in segments, are cut horizontally and isolating devices are distributed inside the cuts. Strategies to reduce settlements during the construction process and vibration transfer are now object of study.

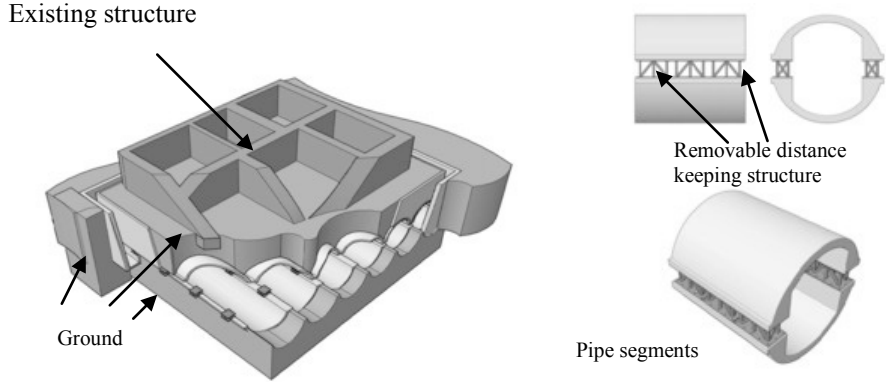


Figure 16: proposal of underground seismic isolation

REFERENCES

1. De Sstefano A., Aoki T., Ceravolo R., Genovese C., Sabia D. (2002). Seismic Vulnerability Assessment of Chemical Plant Structures through probabilistic neural networks. RELIABILITY ENGINEERING & SYSTEM SAFETY. vol. 77, pp. 263 ISSN: 0951-8320.
2. De Stefano A., SAabia D., Sabia L. (1999). Probabilistic Neural Networks for Seismic Damage Mechanisms Prediction. EARTHQUAKE ENGINEERING & STRUCTURAL DYNAMICS. vol. 28, pp. 807-821 ISSN: 0098-8847.
3. De Stefano A. (2009). SHM Actions on the holy shroud chapel in Torino.: Christian Boller, Fou-Kuo Chang, Yozo Fujino Editors, Encyclopedia of Structural Health Monitoring. vol. 4-Chapter 132, Chichester, Wiley&Sons, ISBN/ISSN: 978-0-470-05822-0
4. C. Modena, M.R. Valluzzi, F. da Porto, F. Casarin, E. Garbin, M. Munari, N. Mazzon, M. Panizza, M. Dalla Benetta (2009), Recent advances in the structural analysis and intervention criteria for historic stone masonry constructions subjected to seismic actions", ISCARSAH Symposium, Monstar, 12th July 2009, 13 pp (CD-ROM)
5. Valluzzi, M.R. (2009). Masonry strengthening with composites. Keynote lecture, Tecnología de la Rehabilitación y la Gestión del Patrimonio Construido - REHABEND'09, Bilbao (Spain), October 29-30.
6. De Stefano A., Clemente P., Barla G.;STRUTTURA DI ISOLAMENTO SISMICO PER EDIFICI ESISTENTI (2010)- Patent n. RM2010A000158