State of the Art on New Technologies for Safeguarding Cultural Heritage:

A Short Report and Some Personal Points of View from Italy

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1. Introduction

When we deal with the protection and/or restoration of cultural heritage in a broad sense, the number of issues suitable for discussion is almost unlimited. This is due to the enormous variety of *items* which could be considered, from museum exhibits to complex structural systems. If we focus on most debated problems and most impressive financial efforts, we probably find out that environmental actions have been given particular attention during the last decades. For instance, biological processes and effects of humidity have been extensively studied with the aim of preventing the decay of materials such as stone or mortar or wood. Noteworthy research activities have also been carried out in order to prevent physical and chemical weathering, which represents a violent form of aggression due to pollutants and, in the case of coastal areas, to marine aerosol. Obviously, both the scientific community and the public opinion appear to be sensitive to this kind of problems, owing to the enormous loss, in terms of cultural heritage and money, which is due to the progressive deterioration of statues, building facades and paintings. Therefore, investigations on these subjects are highly motivated by the desire of preserving the beauty of artefacts and, consequently, by social reasons, since the appeal of historical monuments and their impact on the tourism industry is highly related to their state of conservation.

When we limit our attention to historical constructions and to their structural behaviour, we usually notice large interest (and conspicuous investments) for a few selected monuments, while possible problems concerned with *minor monuments* tend to be ignored. Although this attitude may be understood and, to some extent, justified, suitable maintenance programs should be considered for any historical building, since all monuments are subjected to classical problems, which range from progressive material deterioration to severe structural damage, from soil instability to seismic risk. As pointed out below, in the author’s opinion, particular emphasis should be given to prevention strategies, which tend to become more and more effective, more and more affordable. This is essentially due to a large number of research activities successfully carried out in the area of conservation and related structural issues. Thus, a significant progress has been made in several different fields, such as material science, test methods, monitoring techniques and numerical modelling. Consequently an important impulse to conservation procedures has been given during the last decades and innovative approaches have been introduced. Such approaches usually imply the combined contribution of professionals, scientists and authorities, who work in every field listed above. Indeed, the process of conservation has become a consequential sequence of operations, which usually start with inspections (supported by non destructive investigations) and historical analysis. Next, there is a diagnosis phase in order to determine major defects and possible causes. Finally, a safety evaluation should follow, which defines the purpose and the features of possible repairs.

In spite of the importance of each single phase, particular attention should be given to the role that may be played by monitoring methods. Indeed, in the writer’s opinion monitoring techniques usually give major contributions to the protection of cultural heritage and, in any case, represent a sound basis for any adequate prevention policy. Unfortunately, in spite of the large number of potential benefits which may be offered by monitoring techniques, they are hardly exploited. This fact is obviously related to the cost of experimental investigations, which is often accepted only in the presence of visible, severe damage and/or in the case of particular monuments, such as *St. Mark's Basilica* in Venice and the *Leaning Tower of Pisa*. It is worth noting that a policy of this kind (which, in principle, is aimed at a careful use of financial resources) may turn out to be the cause of severe accidents. In the worst cases such accidents imply loss of lives, monuments and money. Relatively recent outstanding examples are represented by the collapse of the *Civic Tower of Pavia* in 1989 and of the *Cathedral of Noto* in 1996 in Sicily.

The above remarks imply that an innovative approach to the conservation policy should be considered and encouraged, by exploiting techniques which are already available and may provide extensive, continuous monitoring of basic parameters at relatively low cost. As suggested in the paper, this is possible by using rather simple equipment and by employing reduced personnel, since protocols are available for the transmission of measured data to a limited number of remote control centres.

In view of the importance of this subject, the present report will start by considering monitoring techniques and related issues. Next, it will deal with different structural problems, avoiding remarks and comments on general ideas related to conservation (such as common arguments about the importance of synergetic cooperation, of historical background, of non-intrusive intervention and so on). Similarly, no reference will be made to numerical and/or experimental activities whose interest is mostly confined to single monuments. The report will rather focus on a selected number of subjects, which, according to the author, are characterised by innovative features and are applicable to a large class of monuments (not to specific cases). Therefore, the main purpose of the paper is the discussion of techniques and/or methodologies, which are susceptible of further developments and may be chosen for more extensive use in the framework of modern strategies aimed at the protection of cultural heritage as a whole. Again in the author's opinion, a wide range of applications at a reasonable cost is a crucial (often forgotten) issue for any official institution involved in conservation problems. Indeed, there is a rather common trend towards very expensive (and sometime useless) plans for the protection of a few monuments, while a large number of historical buildings is eventually ignored owing to lack of funds.

Thus, the following topics will be discussed in the next Sections:

- Remote monitoring
- Pseudo-dynamic tests
- Recent material models for numerical analysis
- Experimental tests on innovative reinforcement methods for brick masonry
- Shape memory devices

2. Remote monitoring

Appropriate plans aimed at the protection of historical monuments should always rely upon monitoring programs. Such programs involve different kinds of measurements, which obviously depend on the structural system to be investigated and on the available budget. Absolute displacements, relative displacements, tilting, crack opening, time-dependent accelerations in the presence of external excitation are the quantities which are usually measured in the case of historical buildings. These techniques are often combined with numerical methods in order to enhance mathematical models. Most applications of this kind are based on the use of dynamic measurements and of system identification, in order to make the computed response as close as possible to the measured data. Optimal estimates of the relevant parameters may be obtained by working in the frequency domain and/or in the time domain. Probably, the first approach is still more common. It requires vibration frequencies and modes as experimental data. These data can be successfully exploited in order to enhance numerical models. However, they are not very sensitive to local damages, since they tend to be representative of the overall structural properties. Thus, more accurate information, particularly for diagnostics purposes, may be derived by using identification methods which work in the time-domain. In this case, records concerned with displacements and/or velocities and/or accelerations represent the experimental information. In order to utilise measured quantities which are sensitive to damage processes, the measurement of relative displacements and/or curvatures appears to be a reasonable selection. In addition, in the case of relative displacements, optical fibres appear excellent devices for applications concerned with historical buildings.

To-day technology allows one to take any experimental measurement any time at relatively low cost. Indeed, remote data logging is possible and most measures can be taken without any need of personnel on the spot. Consequently, in spite of some initial cost due to the installation of the required equipment, remote monitoring should be considered a sort of final goal whenever a work-plan is developed for modern, efficient programs aimed at the safeguard of historical monuments. Indeed, by exploiting adequate tele-automatic data transfer protocols, official institutions may organise a limited number of control centres in charge of data acquisition. In the case of limited budgets, displacements only may be considered and obtained with minor financial effort. This way, the time-dependent behaviour of a large number of monuments could be investigated without permanent costs. Possible critical situations might be detected by personnel who are sitting down in control centres that are miles away from the actual monuments. By periodical checks of significant experimental data, critical values are easily detectable and proper actions may be taken when required (before the development of critical damages).

The above issue seems to be of paramount importance, since there are reasonable motivations to believe that some monuments (recently subjected to collapse or severe damage) might have been saved if periodic measurements had been considered. Here, we will mention three sample cases. The first one is concerned with the *Civic Tower of Pavia* collapsed in 1989 [1]. Mechanical tests carried out on large specimens (obtained by exploiting the debris), have clearly shown that persistent loads tend to decrease the ultimate strength. This concept may be explained by considering a specimen whose ultimate strength is σ_u if it is subjected to a monotonous increasing load that attains its peak values in a short time (few minutes or even few seconds). Indeed, it can be shown that the ultimate strength of the same specimen becomes $\alpha\sigma_u$ (with $\alpha<1$), if the load is kept constant for hours or days at one or more intermediate level(s) before failure. Test specimens made of modern brick masonry can also show this effect [2]. For instance, Fig. 1 refers to small size brick walls (200x200x30 mm) made up of miniaturised bricks (65x30x25 mm). After determining the ultimate stress due a monotonous increasing load, about half the failure stress (say σ_1) was imposed to each panel and was maintained constant for a time interval equal to τ (5 or 15 or 60 minutes). Next, each wall was unloaded and a new load cycle was imposed by attaining a higher stress level ($\sigma_2<\sigma_1$), which was held constant for the same time interval. Tests continued with loading/unloading cycles of this kind (with increasing peak loads) and the ultimate stresses shown in Fig. 1 were found. The plots clearly show that longer time intervals at constant load do enforce reduced strength.

Coming back to the collapse of the *Civic Tower of Pavia*, whose failure suddenly happened without any visible warning, it may be assumed that periodic monitoring of displacements could have provided some information about ongoing damage processes. Two additional significant cases are concerned with the *Basilica of St. Francis* at Assisi and the *Cathedral of Noto* in Sicily. Although their collapse was due to earthquakes, it appears to be likely that thorough periodic investigations might have shown progressive damage [3].

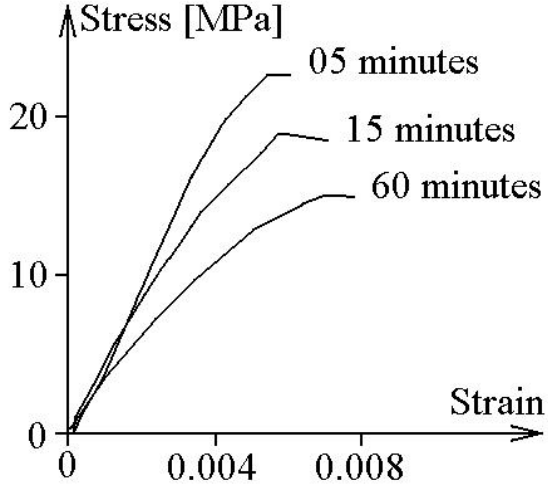


Fig. 1 – Effects due to persistent loads [2]

If we continue to focus on the broad field of remote monitoring, we should also mention recent advances in GPS technology. Indeed, GPS represents an useful tool also for the protection of cultural heritage. A practical case of high potential interest is concerned with the monitoring of historical sites subjected to landslide hazard. As shown in Fig. 2, which refers to a landslide occurred in 1970 in Japan [4], displacements may progress in such a way, that the present GPS technology seems to be a possible, valuable help to prevent dramatic events.

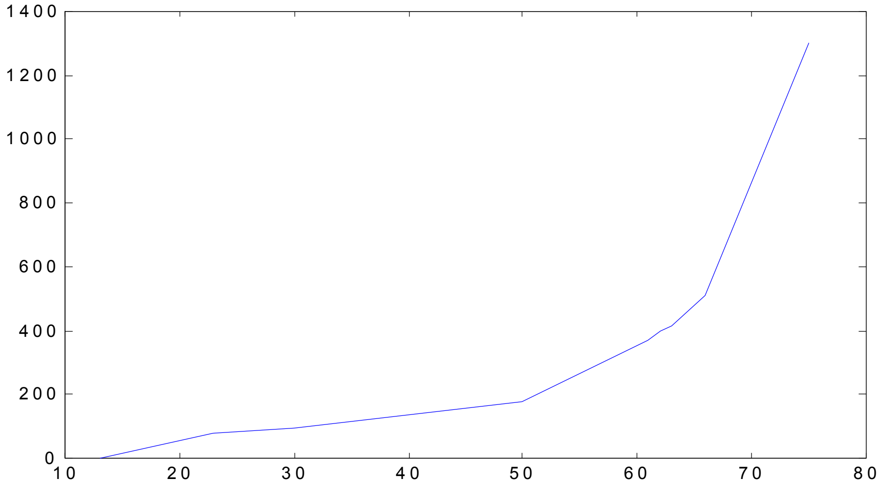


Fig. 2 – Displacements vs. time [4] measured during a landslide (units: mm & days)

Obviously, displacements as large as the ones reported in Fig. 2 are seldom encountered, but curves of this kind give an excellent feeling of the importance of monitoring. Indeed, the onset of constant strain rates (secondary creep) is a key moment in the slope life, since it actually denotes the beginning of a critical phase that is likely to end up with a landslide. Obviously, when secondary creep occurs, due actions should be taken. Although (to the author's knowledge) applications to areas of historical interest have not been introduced, yet, GPS monitoring may be considered as a valuable resource, as shown for similar applications [5]. Indeed, secondary creep may well be detected, since an accuracy up to ±10 mm (or even ±5 mm) in the long period is feasible, when measurements are taken at the same location and reference points are exploited in order to improve the accuracy of measurements.

Clearly, a monitoring network based on GPS technology would represent an effective tool for the simultaneous protection of different places subjected to landslide hazard. After a moderate initial investment, permanent low-cost monitoring could be ensured and adequate actions could be taken when the control unit acknowledges the development of critical conditions. The effectiveness and the relatively low cost of GPS is due to the capability of keeping any site under control at a remote distance, without requiring the presence of personnel in critical areas and without any time limitation (day and night, summer and winter).

3. Pseudo-dynamic tests

Non-destructive investigations (*e.g.*, based on sonic and/or electro-magnetic methods) and/or partially intrusive tests (*e.g.*, by using flat jacks and/or by taking samples to determine mechanical/physical properties), are often utilised in order to understand the conditions of a structural system and to derive adequate estimates for mechanical properties. There is, however, an alternative technique which may be considered to properly evaluate reinforcement methods. Indeed, significant data about the response of reinforced structural components may be obtained by means of *pseudo-dynamic tests*. This technique combines quasi-static tests and numerical simulations in such a way that dynamic load conditions are imposed by means of quasi-static loads. The basic idea is quite simple. The mathematical model of a structural system is considered and is subjected to a time-dependent input. The equation of motion can be written in the form

$$\mathbf{m}\,\mathbf{a} + \mathbf{c}\,\mathbf{v} + \mathbf{r}(\mathbf{u}) = \mathbf{f}(t)$$

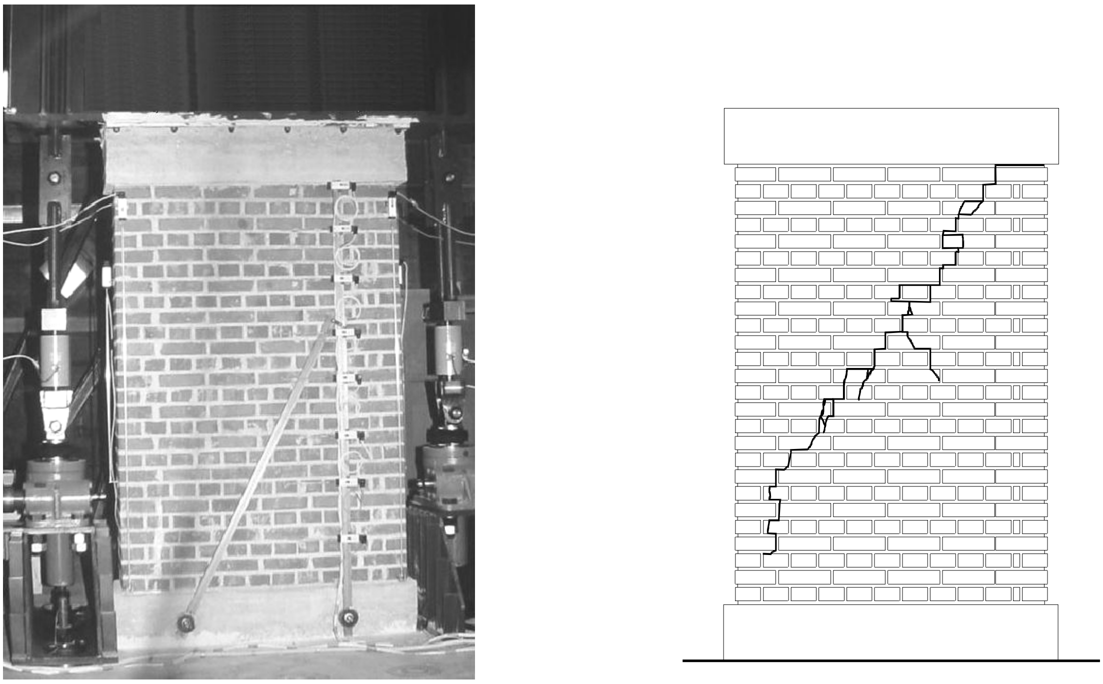
where $\mathbf{a}$, $\mathbf{v}$, $\mathbf{u}$ denote accelerations, velocities and displacements, while $\mathbf{m}$ and $\mathbf{c}$ are the usual mass matrix and damping matrix. The vector $\mathbf{f}(t)$ represents the time-dependent input loads, while $\mathbf{r}(\mathbf{u})$ gives the restoring forces and corresponds to the classical term $\mathbf{k}\,\mathbf{u}$ (with $\mathbf{k}$ = stiffness matrix) in the case of linear elastic response. As usual the numerical response can be determined by using any time-integration scheme. Although implicit algorithms may also be used, it is well known that an explicit algorithm allows one to determine the displacements at the end of each time step by exploiting the information available at the beginning of each interval. Next, the computed displacements can be imposed to a real system or to a convenient structural component by means of hydraulic and/or mechanical jacks. This way, the restoring forces, which obviously depend upon the actual, current stiffness of the structure are properly applied to the specimen under test. Similarly, stress fields and crack patterns developed in that specimen are the ones which actually correspond to a certain set of imposed displacements. In the meantime the forces $\mathbf{r}(\mathbf{u})$ can be experimentally found by means of load cells connected to the jacks. At this stage the knowledge of the term $\mathbf{r}(\mathbf{u})$ leads to the values of accelerations and velocities at the end of the current step. Thus, we complete the set of data needed to proceed with the subsequent time interval of the numerical analysis. This way, relatively simple and cheap experimental equipment for quasi-static load conditions may be used to understand the dynamic response of a structure.

This technique was originally developed in Japan [6] and, soon afterwards, in the United States [7]. Facilities for pseudo-dynamic tests were also set up in Europe. At present, the largest facility in our continent is located at Ispra, Italy, and belongs to the *Joint Research Centre* of the *European Commission* [8].

Pseudo-dynamic tests have been also used for masonry structures [9], even if it may be argued that applications to this kind of structures should be handled with care, since masonry is sensitive to the load rate. Consequently, the outcome of pseudo-dynamic tests may not reflect the actual behaviour of masonry to dynamic excitations (such as ground accelerations due to earthquakes), since an experimental record of a few seconds may take hours or even days to be processed.

In the case of historical buildings the method may be suitable, as pointed out above, for testing different reinforcement methods. Simple applications of this kind were considered at the *University of Trieste*, Italy, in the framework of a project supported by the *European Commission*

(EV5V-CT92-0106 - *Non-destructive testing and system identification to evaluate diagnostics methods and reinforcement techniques applied to historical monuments*). On that occasion mechanical jacks were utilised and brick masonry shear walls were subjected to pseudo-dynamic tests by considering the *El-Centro* record in order to impose an appropriate ground acceleration [10]. Here, we discuss some results concerned with one wall (Fig. 3*a*) subjected to a sequence of six tests. Eventually the wall under test was severely damaged (Fig. 3*b*). At first, one mass of 15,000 kg on the top edge was simulated. Pseudo-dynamic tests were carried out by imposing five sequences of ground accelerations based on the *El-Centro* record with peak value equal to 0.8 *g* (*g*=acceleration of gravity). Fig. 4 clearly shows the effects of damage after the first and the fifth test. During a subsequent test the same peak acceleration was maintained, but a mass equal to 22,500 kg was assumed. Fig. 5 refers to this test and gives the horizontal load as a function of the horizontal top displacement. A critical condition can easily be noted in view of the large displacement during the last load cycle.



(a) *(b)*

Fig. 3 – Masonry wall (a) and crack pattern (b)

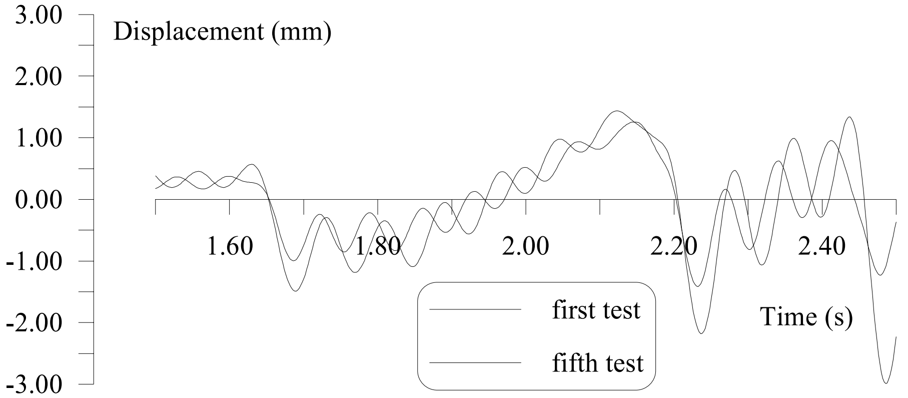


Fig. 4 – Horizontal displacement on top vs. time

Next, the wall was repaired by injecting a convenient material (*Epojet,* produced by *Mapei*, Milan, Italy) and the reinforced specimen was tested once more, showing an excellent behaviour.

The final goal of the experimental investigations carried out at the *University of Trieste* was to check a practical application of pseudo-dynamic testing to the important problem of retrofitting. Indeed, it was proved that pseudo-dynamic tests may be exploited as a standard procedure suitable for checking the performance of reinforcement techniques, since such performance can be verified at any laboratory for any selected input record. Clearly, the procedure appears to be of particular interest in the case of monuments subjected to seismic risk.

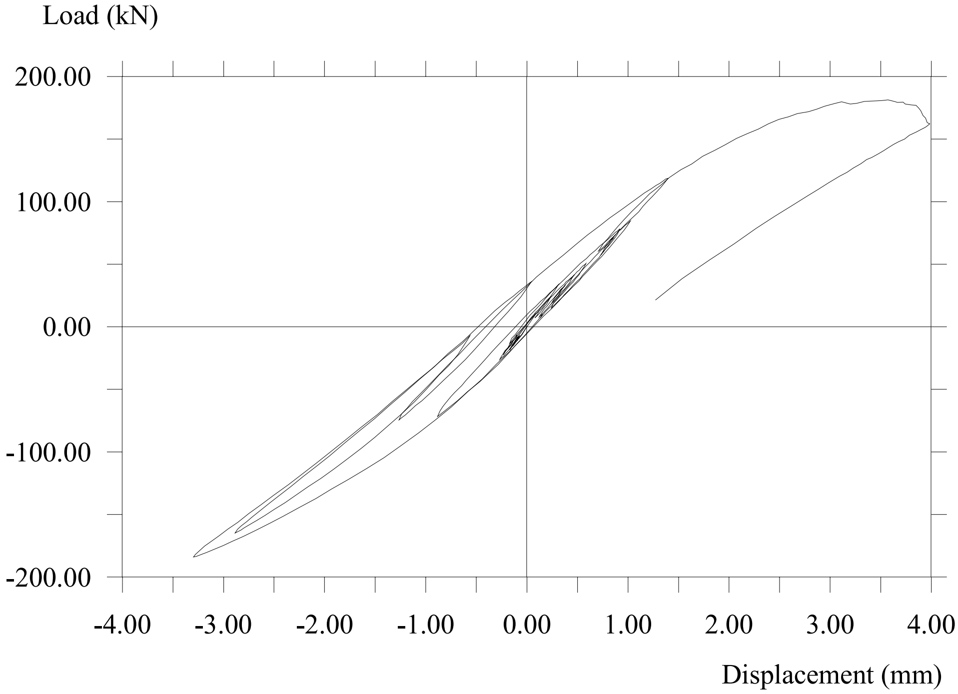


Fig. 5 – Horizontal force vs. horizontal displacement on top

4. Numerical models for brick masonry: recent developments

Numerical models for brick masonry have been developed for several decades. After initial applications of linear elastic [11] and no-tension models [12, 13], which are not adequate for dynamic actions, general models suitable for rock-like materials (such as Mohr-Coulomb's or Drucker-Prager's model) were introduced. Later, homogenisation techniques were developed, which essentially allow one to define the properties of a fictitious homogeneous material, which reflects the features of brick masonry [14, 15]. Approaches of this kind are usually subjected to some limitations, since the response of the fictitious material hardly matches the real response when the stiffness of the components is significantly different (as it happens in the case of mortar and bricks). More sophisticated models, centred on a proper description of inelastic phenomena along mortar beds and mortar joints, were also developed [16-19]. They tend to give excellent results, but their practical use is generally limited to the case of modern masonry, since the relevant parameters can hardly be found in the case of ancient brick-works. In addition, some models are based upon a very detailed mesh which accurately describes the geometry of bricks and mortar joints. As a consequence, the required discrete model of the structural system becomes exceedingly large for most practical cases.

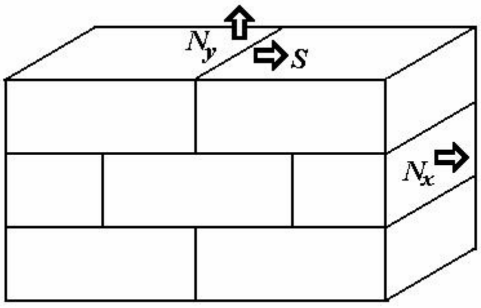


Fig. 6 - Typical brickwork

Some research activities, however, have also been centred on relatively simple models which still describe non-linear phenomena, but require a limited number of parameters. This way, they appear to be suitable also for those structural systems (such as historical buildings) for which material properties can not be easily determined.

Here, a recent material model specifically developed for masonry will be discussed. The main features of the model can be illustrated as follows [20].

Any masonry unit (*cf.* Fig. 6) is treated by assuming a macroscopically homogeneous material for which cracking phenomena may occur. More specifically, slips at mortar joints and/or brick fracture processes are described. Slips are governed by Mohr-Coulomb's condition by introducing a piecewise-linear yield surface in the space N_x-N_y-S. As clearly shown in Fig. 6, N_x, N_y and S represent normal and shear forces per unit length acting on masonry units. The projections of typical planes that contribute to the yield surface and govern the response of mortar beds (mostly due to forces N_y and S) can be seen in Fig. 7. Similar projections could be shown on the plane N_x-S for the yield planes that govern the response of vertical joints.

In the case of bricks, cracks occur when strains attain a critical value. Consequently, by using St. Venant's condition and by assuming plane stress states, we may add two further planes to the yield surface. Their projections on the plane N_x-N_y are shown in Fig. 8. The material model, however, may be simplified by limiting our attention to vertical or quasi-vertical cracks, as it often happens. Under this condition, one single plane (#8 in Fig. 8) must be considered.

At this stage it is assumed that inelastic strains may develop whenever the stress point reaches the yield surface. As we did before, cracks are not explicitly described, but are taken into account by means of inelastic strains. In addition, a *softening* law is introduced in order to simulate the decrease of strength. In other words, a convenient rule is established, that governs the translation of yield planes and enforces a lower strength whenever these planes get closer to the origin of the space N_x-N_y-S.

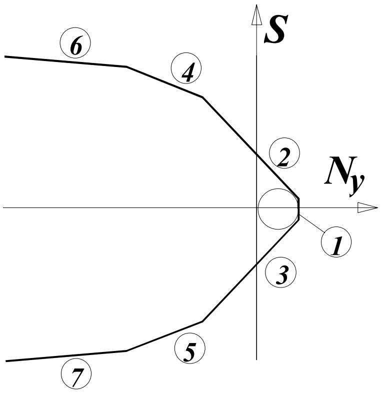


Fig. 7 – Yield planes 1-7

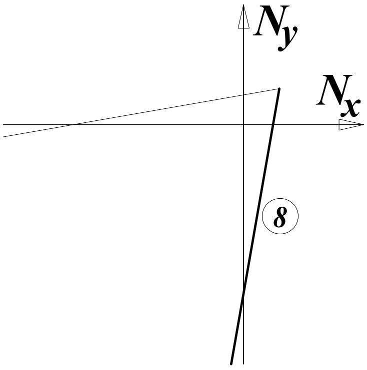


Fig. 8 – Yield plane 8

In our case we assume a simple piecewise-linear softening rule (*cf.* Fig. 9), where $\Delta\lambda$ denotes increments of inelastic strain vectors and *r* is referred to the distances of planes from the origin. As yield planes approach the origin, we obtain a generalisation of the softening stress-strain plot of Fig. 10.

The model was applied [21] to the dynamic analysis of the Church of the *Monastery of Caldarusani* (near Bucharest, Romania) in the framework of a project supported by the *European Commission* (ERBIC15-CT960208 - *Innovative techniques to increase resistance to earthquakes of cultural heritage buildings and to reduce the impact*). A three-dimensional finite element model and a typical displaced configuration are shown in Fig. 11.

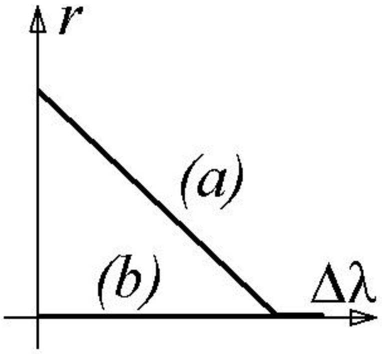


Fig. 9 – Softening rule

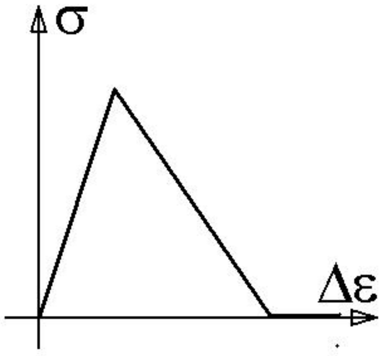


Fig. 10 – Softening stress-strain plot

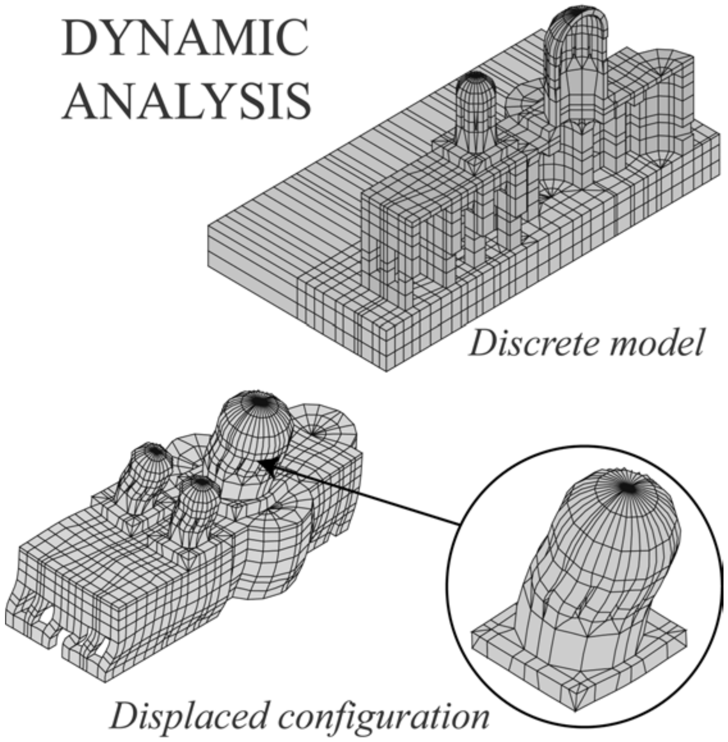


Fig. 11 – Non-linear finite element dynamic analysis of a historical building

5. Experimental tests on an innovative reinforcement method for brick masonry

A well known method suitable for reinforcing structural systems consists of sticking some material, such as glass fibre reinforced layers, on external surfaces. This idea has also been applied to masonry walls and publications on the subject can be found in the literature [22, 23]. In the case of brick masonry, however, the efficiency of this kind of retrofitting technique seems to be jeopardised by the stiffness of reinforced layers. Indeed, it is quite higher than the stiffness of masonry. Consequently, undesired side effects arise, as it usually happens when materials characterised by a significantly different stiffness are combined together.

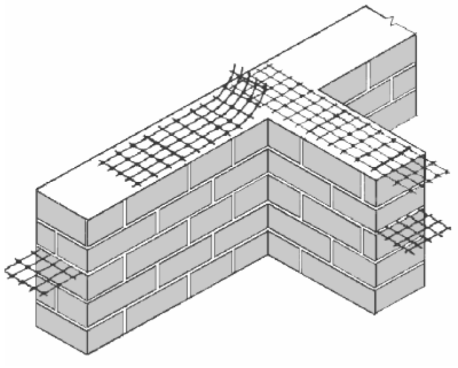


Fig. 12 – Polymer grids

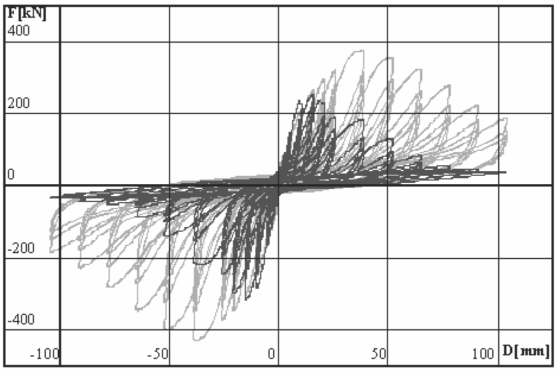


Fig. 13 – Load vs. displacement plot

Here, we will focus on a new technique, which is based on the use of polymer grids and has been tested at different laboratories. The original idea was developed at the *University of Bucharest*, Romania [24], and the material (commercially known as *Tensar*®) has been supplied by *Netlon Ltd*, Blackburn, UK. However, several experimental tests were recently carried out in Italy (at the *Joint Research Centre* of the *European Commission*, Ispra, and at the shaking table of *Enel.Hydro*, Seriate). Thus, the present Section will focus on some test results obtained at Ispra and Seriate.

The method was originally developed in order to reinforce soil. However, polymer grids can also be inserted in mortar joints and contribute to masonry overall strength by sustaining tensile stresses. They tend to improve the structural performance, since a ductile response is enforced. In the case of historical buildings the technique is applicable when collapsed walls are reconstructed or new masonry walls are built. Polymer grids are just laid down one on top of the other without mechanical joints (*cf.* Fig. 12). Similarly, grids may successfully improve the shear strength of walls by reinforcing external coatings. In this case, the approach is suitable for a large number of historical buildings and is only partially intrusive, since grids can be easily removed. Consequently, they would not represent permanent structural components and would not cause any major problem, if different (enhanced) reinforcement techniques could be selected in future times. Clearly, the most interesting applications would be related to maintenance works concerned with coated surfaces.

The methodology was checked by testing both plain and reinforced walls at the testing facility of the *Joint Research Centre* of the *European Commission*, at Ispra, Italy [25]. Here, some results will be briefly discusses, which are related to walls with openings. The walls were 4.6 m long and 2.6 m high. Cyclic shear loads were applied by imposing successive drifts whose amplitudes were 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 12.0, 2.5, 3.0, 3.5 and 4.0%. Therefore the maximum top displacement was 104 mm. The comparison between the responses of the unreinforced and reinforced wall is given in Fig. 13. The grey curve is concerned with the reinforced wall and points out a definitely improved behaviour when polymer grids are considered. Figs. 14 and 15 show the crack pattern for both walls (plain and reinforced) at the end of the loading processes.

Encouraging results were also obtained by reinforcing small scale buildings and by imposing dynamic loading conditions by means of shaking tables. Fig. 16 shows a reinforced specimen subjected to this kind of tests by *Enel.Hydro* (former *Ismes*), Seriate.

Fig. 14 - Plain wall

Fig. 15 - Reinforced wall

6. Shape memory devices

An important issue related to the protection of cultural heritage against seismic hazard is the development of materials suitable to dissipate energy. An example is represented by *shape memory alloys*, which are characterised by a super-elastic behaviour in view of phase changes [26, 27]. Typical alloys are made of nickel and titanium. Super-elasticity and, hence, energy dissipation takes place through phase changes from austenite to martensite and *viceversa*. As shown in Fig. 17 [28], stress-strain cycles are characterised by critical loading strains ε_l (after which stresses remain constant), by elastic limit strains ε_{el} (after which stiffness increases), by limit total strains ε_t and by small permanent strains ε_p. Eventually, at the end of a load cycle, some impressive energy dissipation may be observed.

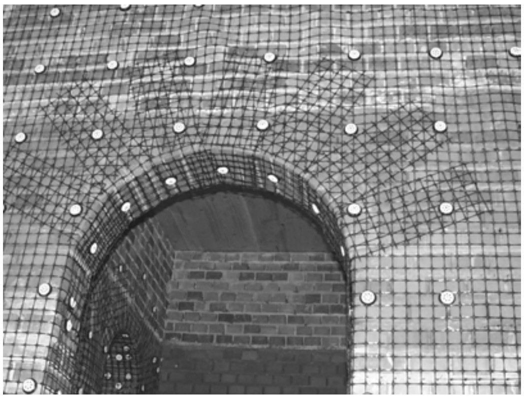


Fig. 16 – Reinforced test specimen

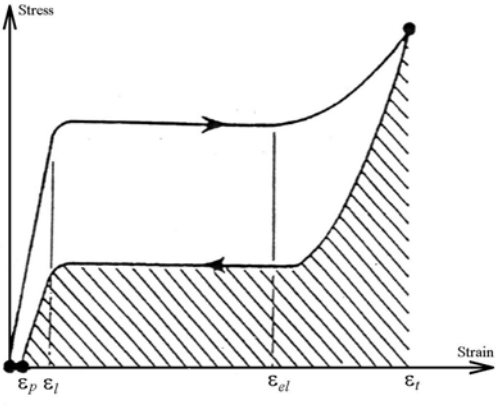


Fig. 17 – Superelastic cycle [28]

Consequently, shape memory alloy devices may be successfully exploited in the case of seismic events, as schematically explained by the schemes of Fig. 18 [28, 29], which refer to horizontal connections between two structural members. It can be noted that shape memory alloy devices are characterised by high stiffness at low stress levels, so that relative displacements between structural elements are not allowed (*cf.* Fig. 18, scheme 1). Next (scheme 2), they feature a reduced stiffness and relatively low forces are transferred to the structure. Finally (scheme 3), when high horizontal actions intervene, there is an increment of stiffness and large displacements are not allowed. Successful shaking table tests were carried out at the facilities of *ENEA-Casaccia*, Rome, Italy, in order to check floor-roof connections [28, 29]. The relevant mock-up is shown in Fig. 19 [28]. It was meant to investigate the behaviour of a vertical section connected to a stiffer system through horizontal joints.

An important application of shape memory alloy devices was concerned with the restoration works [29, 30] of the *Basilica of St. Francis*, Assisi, Italy, hit and severely damaged by a major earthquake in 1999.

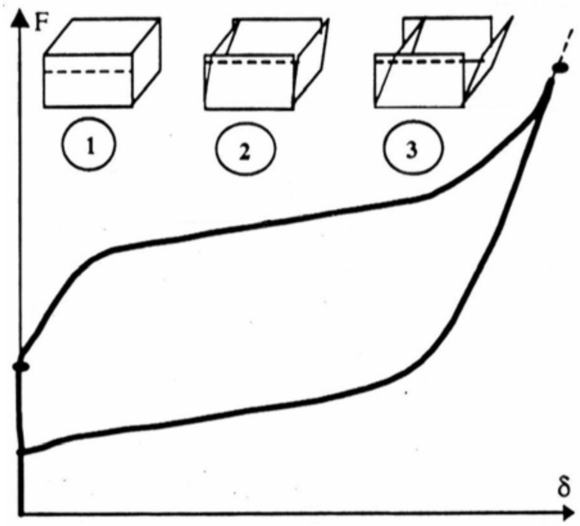


Fig. 18 – Use of shape memory alloys [28, 29]

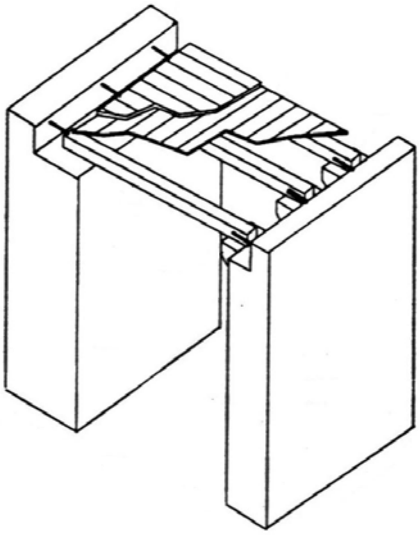


Fig. 19 – Test specimen [28]

7. Closing remarks

Monitoring, damage assessment, clear understanding of the structural behaviour and retrofitting represent four subsequent steps of any modern methodology aimed at the protection and conservation of cultural heritage. The monitoring phase should be considered with particular attention, since it may contribute to large savings, both in terms of money and of historical monuments. Therefore, in the author's opinion, at least some low-cost monitoring techniques should be considered for a large part of historical sites. It is also suggested that tele-monitoring methods be exploited, including GPS applications which may be very effective for areas subjected to landslide risk.

When experimental methods and visual inspections point out potential problems for a certain monument, it is necessary to assess the damage level and to define possible restoration strategies. To this aim, laboratory tests, numerical methods and innovative materials (such as the ones presented in the paper) should be considered. Obviously, retrofitting techniques should always be considered with care, since each restoration method can not be applied to any structure. It is also worth noting that any intervention should be reversible and as little intrusive as possible. Finally, the solutions selected on the basis of material sciences and structural engineering should always be supported by adequate historical analysis, since optimal restoration methods shall never alter the structural behaviour, but must enforce historical monuments to sustain loads according to their original design.

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