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Conservation of monuments in natural stone in earthquake zones: reversibility as an intervention strategy

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Abstract

The knowledge achieved by the various disciplines in the humanities and the technical sciences, today more than ever, can make it possible to correctly conserve our architectural heritage, even in zones which are subject to seismic activity. The act of conservation, is one of both repair and prevention.

Although our intervention will attempt to be accurate and sensitive, the priorities we define will lead to choices, which will irrimediably be followed by destruction of a part, hopefully a small one, of the historical-architectural information, and a part of that legacy of technical knowledge that is not visible to the naked eye, but is an integral part of any monument. This is why we feel that intervention should be the minimal required and reversible, in order to avoid creating obstacles for future intervention, which may be reinforced or repeated, whenever the need arises.

1. Introduction

Conservation is accomplished through restoration, or a material intervention that permits interpretation of the historical information contained in the monument itself. Works from the recent past may also be considered monuments, as long as they somehow document the values of the era they represent. The values of a work also involve the changes it has undergone during the course of history, including additions, adaptations, changes that have become an inseparable part of the monument. Saying this, we acknowledge the monument's right to change over time, assuming and passing on solutions that are not necessarily

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praiseworthy in aesthetic terms, but which contribute to make the monument something unique.

Although it may have been built in the best possible way, in its time, any structure must undergo an inevitable process of ageing, leading to the presence of the type of documentary evidence discussed above, and to that of a patina, which is also a part of its personality, and increases its value as historiographic material.

If we ignore these factors, we prevent future visitors from being able to recognize and grasp the individual character of the work. Often, in fact, restoration architects are tempted to re-establish volumetric or technical solutions we feel are original, based on free interpretations, but without any truly reliable documentation regarding the monument itself. In this manner, it is very easy to wind up transforming the artefact into a caricature, or a pale copy of itself. In either case, what has been accomplished is the destruction of an original and the creation of a forgery.

Moreover, if our intervention, apart from a lack of self-declaration, also makes use of improper or incompatible techniques and materials with respect to those of the original, we will irremediably damage the artefact, irreversibly destroying a part of its original substance. We should recall the fact that in historiographic terms (an architectural monument is a document), the only original available to us is that which has been physically documented, or what has survived of the object itself.

A monument is not just a beautiful object to be admired. But what is more important is the fact that a monument does not necessarily have to be beautiful in order to have documentary value. All to often we forget that apart from the archaeological, epigraphic, architectural and sculptural information contained in a monument, it also represents its own material and technical characteristics, below ground or above, visible or invisible. For example, inside a wall we can find different types of masonry or different types of structural parts, which may have been reinforced in the past (as in the doubling of an arch in the nave of a basilica or, in cases of three-layered ashlaring, in embedding a timber tie-belt in the mix-layer all around the outline, or in the filling in, with bricks, of parts of original stone walls that have collapsed). Such interventions were effected to ensure the survival of traditional elements, and usually involved a minimum, indispensable removal of original materials.

These stratifications of repairs from the past are precious indications, for those who wish to study the monument, regarding its material status over time; they provide information on materials and techniques, offering examples of well-intentioned mistakes and of successful intervention. But today these interventions are an integral part of the historical heritage we are trying to conserve.

2. Analysis of the vulnerability of monuments in natural stone in earthquake zones

To decide how to intervene in the restoration of a monument in a zone where there is risk of seismic activity, we must be able to evaluate the monument's

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vulnerability. This means estimating the probability that a certain category of damage may result from a seismic event.

To make a sufficiently accurate assessment, we need to know

- the likelihood of an earthquake at the site;
- the likelihood that the earthquake will produce the type of damage in question.

Historical sources and geological analysis are indispensable, but the information we can gather on the seismic history of the site cannot suffice to tell us, with precision, what type of earthquake may happen in the future, and when. Once we have outlined the seismic events of the past and their characteristics (date, epicentre, intensity) for a relatively long period of time, we can hypothesize that for a similar period of time in the future the seismic activity of the site will roughly resemble this profile.

Thus the expectation of seismic activity will be defined in terms of the probability analysis of the distribution of intensity. At this point we can describe the situation in terms of the frequency of tremors. For each expected possible intensity, based on the geological characteristics of the area that separates the site from a given seismogenic focal point, we must define the corresponding accelerogram, in order to analyze it in relation to the frequency of the edifice and that of the site; briefly: the site specific spectrum). But mere quantitative analysis of the data is not sufficient; qualitative analysis is necessary also. The greatest possible amount of data must be gathered on the damages caused by seismic activity in the past, the repairs subsequently made, including partial reconstructions or additions.

The study of the monument itself, through the dating of the masonry and the sequence of construction techniques, can round out the picture that has taken form through other types of study (archaeological findings, for example). Thus the research takes place in two types of archives: one made of paper, the other of stone. Statistical analysis of the damages caused by the earthquakes of the past is essential for the overall prediction of possible future damages. A new methodology for the classification of seismic damages developed by the Department of Stuctural and Geotechnical Engineering of the University of Genoa, in collaboration with the National Group for Defence from Earthquakes (8) should be mentioned. This research has been conducted for the protection of the monumental heritage in the Italian regions of Umbria and the Marches, where intense seismic activity has been underway since 26 September 1997. An initial result has been the numerical quantification of the damages undergone and the damages expected, through the definition of indices of damage and vulnerability for each single monument. The purpose of this work is to accelerate the estimates of the economic impact of the damages, in order to assign future interventions in keeping with the reference scenario of the cinematism. More than the percentage estimate of damage in relation to the intensity of the earthquake, what becomes important here is the prediction of the quality of the damage that may be caused.

The engineer with whom the architect works must be capable of formulating the following considerations: with respect to a given monument (with this specific type of stereometry, these specific structural elements, these foundations, these masonry techniques, these estimates of deterioration, etc.),

- a tremor of intensity X can provoke (f. ex.) the destruction of the spire;
- a tremor of intensity Y can cause the collapse of the cross elevations;

and so on.

In order to obtain data of this type one must identify the zones of possible concentration of stresses caused by the tremor. For an individual monument, this analysis should be made for each single portion of the structure. There is no reason to transform the structure into a single monolithic block if we can demonstrate that the individual parts are safe. For an analytical testing of the security of the masonry structures there is often a tendency to apply the same methodology of numerical analysis that has been developed for modern constructions, composed of elastic and continuous materials. But the ancient techniques of masonry, without structural homogeneity, cannot be compared to modern construction techniques.

3. Vulnerability factors: the earthquake, the land, the monument

Experience shows that analogous or even very similar cinematisms can take place in spite of a total lack of similarity between the earthquakes in question. For example, a monument may be impacted in a completely different way by two separate earthquakes, of equal magnitude from two different foci, whose characteristics of propagation differ due to the formation of the terrain separating the focus from the site being examined.

It is also true that two sites that are quite far apart, at different distances from a focus, can be damaged in completely different ways; the site nearest to the focus will not necessarily undergo the most severe damage. For example, the 1987 earthquake destroyed ten-storey modern buildings in Mexico City and left historic buildings scarcely damaged as their vibration mode did not coincide with that of the earthquake (5). For similar reasons, two earthquakes from two different seismogenic zones, because of the fact that their impact spreads in a different mode, will have different characteristics, and will therefore cause damages that differ in qualitative terms. The distance of the monument from the focus is not always a reliable indicator of the intensity of the effects of the earthquake. This means that we must be very cautious in our reliance on deterministic evaluations of the seismic prediction profile of a site and its monuments.

The vulnerability of monuments built in natural stone depends, essentially, on four elements: size, stereometry, type of masonry, present mechanical resistance levels. Masonry which has deteriorated (where the mortar has lost its adhesive force) can be loosened as a result of a tremor, leading to deformations and partial or total destruction.

Phenomena of collapse of the earth's crust (subsidence or liquification), with resulting damages for the masonry structure of edifices, must be taken into account along with the mechanisms of collapse of the masonry caused by horizontal accelerations. It is highly probable, in fact, that for certain types of terrain, the impact of strong tremors (seismic standards describe manifestations of collapse beginning with tremors at the 7th level on the MSK scale) can cause a breakdown both of the terrain and of the monument. Major subsequent adjustments in the terrain can make our intervention useless, if we focus only on the monument and not on the earth below in our evaluations.

Therefore we must also focus on the stratigraphy of the terrain, which provides us with data on the material composition of the land (and its mechanical characteristics), its degree of compactness and the level of the underground water bed. If the site has been effected by earthquakes in the past, we can evaluate the compacting of the terrain (which will clearly not be homogeneous) caused by the seismic vibrations.

The separation of masonry is a problem that was quite familiar to the artisans of ancient times, who developed a variety of systems for the repair of walls to arrest deterioration, recycling pieces of collapsed masonry, or walling up openings whose presence could be fatal in the dynamic reaction of the monument, or making more radical modifications to the original design of the structure. In the operations effected by craftsmen to improve the seismic performance of churches, we often find a return to, or adaptation of, typologies previously utilized as a result of earlier earthquakes. This type of intention can be seen in the reduction of the size of new constructions, in adjustments made to the stereometric design, and in other improvements in the area of masonry technique.

This type of history of a revision of methods on the part of artisans can be seen in Armenia and in other zones of seismic activity, like Italy, i.e. Umbria.

We should also be aware of the fact, however, that although these developments represent a case of true progress in the improvement of the seismic performance of monuments, we are also faced with real difficulties in documenting the conscious development of these choices.

4. Attenuation of the effects of tremors on monuments: repairs and reinforcements

In order to attenuate the effects of an earthquake or a tremor, two basic strategies can be used:

- increase in overall resistance (strength);
- increase in the ductility of the structures, without allowing them to reach the breaking point.

In cases in which our intervention strategy calls for substantial modifications to the structures, the problem becomes one of having a valid model that can permit effective analysis; in cases in which the original structure is to remain unchanged, this type of analysis is not necessarly required.

In a dynamic situation, as in the previous static situation, the masonry structures do not have homogeneous mechanical characteristics. The overall structure will contain areas in which the carbonation of the air-hardened lime is complete, and others in which this is not the case. This is due, in part, to the lack of sufficient humidity (a problem that doesn't arise with water-based mortar, whose hardening process lasts much longer) and to an insufficient reaction with carbon dioxide. Once again, this phenomenon depends upon a range of factors. The most important factors are:

a) the utilization of insufficiently clean sand in the mortar, not permitting the full carbonation between the binder and the aggregate;
b) the lack of prolonged mixing, in the open air, of the mortar and the aggregate;
c) excessively rapid construction, in the case of air-hardened lime, which hardens faster than water-based mortar, but nevertheless requires sufficient ventilation, which can only be guaranteed by a procedure of layering and hardening.

Historical buildings constructed according to consolidated rules of craftsmanship, therefore, have an intrinsic resistance capacity that is not inferior to that required of modern constructions. The ancient builders were more attentive than we are when it came to the quality of the overall project (not just the quality of the design and the structural choices, but also the quality of the materials and the craftsmanship involved in the building). This means that the restoration of a monument in keeping with its original state (assuming it was built properly from the outset) may be a way of guaranteeing its integrity for the future.

5. Why it is recommended that restorations, in seismic risk zones, be reversible in character.

The concept of reversibility in the field of architectural conservation of historical heritage has been borrowed from the discipline of art restoration, especially the field of restoration of paintings. In the field of architecture the concept has a multiple value, and therefore it is no simple matter to come up with a specific definition, because of the need to take all the various disciplines involved into account.

The concept of reversibility in our discipline refers, first of all, to the effective conservation of the original substance. To be reversible our intervention must be based on a profound knowledge of the artefact itself, in order to guarantee its survival, seeking to identify the limits and the advantages, using non-aggressive measures, which are never incompatible with the characteristics of the artefact, to avoid compromising the material tradition; in short, whatever is done should not prevent possible repair and restoration in the future.

To illustrate this concept, we would like to present three case studies in which a lack of comprehension of technical issues has led (or will very probably lead) to the irremediable loss of a part of the monuments in question.

6. Examples of intervention in the past

6.1 St. Francis of Assisi (1228-1236), Umbria region, Italy Interventions of 1453, 1957 and 1961

The complex is composed of two churches built one over the other, oriented toward the west (10). These are two apsidal halls with transepts. Both the naves have three spans, with ribbed groined vaults. The body of the nave has large buttresses with a circular plan, placed externally at the end of each span. The masonry work, particularly massive at the base, gradually tapers as it rises. It has a regular structure in natural stone.

The attic, added during the Renaissance (middle of the 15th century), is composed of a system of transversal intersecting arches in brick, following the modular pattern of the spans of the nave, the transept and the apse of the Basilica Superiore. The transversal arches are connected at their base by tie-beams (added later), with the exception of the large arches at the point of the intersection. The intervention in the 1400s was possibly made to reinforce the spans of the nave and the transept in case of an earthquake, to increase the shift resistance of the higher part of the nave that is not supported by the buttresses.

Using techniques and materials that are compatible with the rest of the construction, this intervention stands out for its reversible character, and for the fact that it adds significant architectural quality to the entire complex.

Subsequent reinforcements were made at the level of the attic and the foundations, in the 1950s. All of the eaves were fitted with large reinforced concrete girders. The wooden trusses were replaced with structures in reinforced concrete. The pitches of the roof were reconstructed in reinforced brickwork. This intervention not only destroyed the original carpentry, but also compromised the static integrity of the monument, excessively increasing the rigidity of the roofing in relation to the walls below, especially in the area of the intersecting vaults. In fact these vaults were the part of the church that collapsed (one at the transept and one above the span of the entrance) during the second tremor on 26 September 1997 (14), at 11:42 AM (ML = 5.8, corresponding to an intensity of 8th-9th degree MSK), following the first tremor, at 2:33 AM on the same day (ML =3D 5.5, I=3D VIII). The collapse ruined important parts of the original masonry structure, and destroyed large portions of the frescoes by Cimabue and Giotto. Although we cannot be completely certain that the collapse should be blamed exclusively on the added rigidity caused by the reinforcements, we would like to present the following reasoning.

A study made of the dynamic responses of the wooden carpentry of the roofing of several churches, conducted by the Institute of Bearing Structures, Faculty of Architecture, Karlsruhe University (7), allows us to observe that when the nave of the church is short, the tensions caused by the wind are absorbed by the rigid parts at the edges of the nave; if the nave is long, on the other hand, the horizontal tensions are absorbed by the pillars inside the nave and/or the external buttresses.

If the nave is rendered more rigid by the application of reinforced concrete girders, the stress is conducted to the sides, depriving the buttresses of their function. The problem lies in the fact that at Assisi the girders do not continue along the entire line of the eaves, but stop at the points of the facades of the nave and the transepts. If it is possible to draw a parallel with these studies, we can reason that during the earthquake last autumn, the stresses were conducted to the edges of the nave, due to the reinforcement of the roofing, but did not encounter transverse girders that could absorb the stress. Thus the tensions were transmitted to the vaults. Because the vaults were not built for this purpose (to withstand stress), they collapsed. Moreover, the use of Portland cement together with masonry structures originally built in lime mortar generates carbonation and sulphatation reactions. This process, which is just as serious in terms of damage as the mechanical collapse of the vaults, leads to the solubilization of part of the substance of the structure, and the deterioration of its mechanical qualities.

In 1961, during a new program of restoration, the foundations of the complex were "consolidated" with concrete (1,500 tons) applied to the substructures of the facade (10). The concrete brought, very probably, about a chemical reaction, due to humidity, with the original mortar of the foundation, leading to the formation of thaumasite and ettringite (1). Thaumasite is a sulphate, also a salt that is subject to crystallization. Ettringite is a colloid that is extremely expansible in contact with humidity. The pores of the blocks of stone of the masonry were first occupied by these substances, and then exploded due to the increase of volume caused, in the first case, by crystallization, and in the second case by the expansion of the colloid. The shearing or breakage of the blocks of Subasio stone (the calcareous stone typical of Assisi) which can be clearly seen at the bottom-level of the masonry, is most probably caused by the inertial forces set in motion by the expansion of the ettringite and/or the crystallization of the thaumasite.

In conclusion, while it is true that the extensive intervention with concrete did initially reinforce the foundations, it is also true that it erased any possible information on this essential part of the Basilica, while causing a slow but unstoppable process of breakage of the stones in the foundation of the Basilica Inferiore.

6.2. Funerary chapel of Yeghvart (1321). Intervention of 1972. Funerary chapel of Amaghu Noravank (1339). Interv. of 1998. Republic of Armenia.

Most seriously the improper use of reinforced concrete affected the restoration interventions of the funerary chapels of Yeghvart and Amaghu Noravank, both important monuments of Armenian funerary architecture in the 14th century.

At the basement level both monuments have an apsidal hall inserted in an external parallelepiped, which becomes cruciform at the upper level; the facades of the arms of the cross follow the profile of the elevations of the lower level; the edifices were topped by a lantern with twelve columns. Both lanterns were built with a cupola with a conical top. The lantern of Noravank had collapsed. Both lantern have been reconstructed.

The masonry of the buildings is constituded by a thick three-layered ashlaring, which is peculiar to Armenian architecture of the Middle Ages. The height of each course might vary, but all are unified in their middling layer by an external and an internal layer of tuff - (Yeghvart) or lime-cutstone (Noravank).

The renovation of the funerary chapel of Yeghvart, involved the reconstruction of the system of roofing and the lantern, in reinforced concrete, utilizing original stones and other newly cut blocks of stone, but only as a decorative facing material. The columns, after having been drilled through their axis for two-thirds of their length (one third from the base upward, one third from the capital downward), were reinforced with bracings.

The irreversible nature of the intervention is evident:

a) the stone elements become mere decorative facings, without any structural function, while disguising the nature of the intervention;
b) the masonry technique of the monument is utterly compromised

- preventing the absorbtion of vertical loads in each of the three layers of the masonry;
- utilizing a material (concrete) that is not compatible with the existing materials, because Portland cement does not adhere to lime mortar mixtures;
- reinforcing one entire element of the monument, the lantern, which is made much more rigid than the masonry below.

The renovation of the funerary chapel of Amaghu Noravank also features the concept of partial reinforcement of the lantern.

In contrast with Yeghvart, at Noravank the lantern had already collapsed, a long time ago. A photograph published in 1918 (12) documents its absence at the beginning of this century, showing the state of deterioration of the monument. The cinematisms of collapse seen here show that these damages are clearly the result of seismic activity. With respect to Yeghvart, at Noravank further reinforcements were effected, for the four tympana, by reinforcing the layer of internal masonry, once again using Portland cement as binder.

The improper character of the intervention is aggravated by the fact that it combines structures and materials with completely different mechanical characteristics, because natural stone masonry is an essentially rigid but plastic structure, while reinforced concrete has great elasticity. It has been repeatedly demonstrated, and the recent experiences in Marche and Umbria do this clearly, that the combination of these two structures not only is not advantageous, but is also problematic because each inhibits the performance of the other, reducing resistance to dynamic stress. Were another earthquake to strike, the lantern is not safe, and the original structure of the rest of the monument would be at risk, causing an irremediable loss.

7. Conclusion

The prevention of possible damage caused by seismic activity means, first of all, an evaluation of the vulnerability of the monument to be conserved, analysing, case by case, a range of variables: expectation of seismic activity, correlations between expected stress and size, stereometry and mechanical performance of the masonry structure of the monument in its present condition, and possible alterations of the substrata of the terrain itself, in keeping with the geological condition of the site.

While on the one hand our commitment to conserve, to the greatest possible extent, the values of a monument should not prevent us from intervening when parts of the structure are clearly unreliable or subject to damage, threatening the monument as a whole, on the other we should recall that before utilizing or inventing alternative technological solutions for the safeguarding of architectural

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heritage, it is worth re-examining the solutions of the near and distant past, solutions developed by engineers and craftsmen who had a profound knowledge of masonry structures, based on centuries of tradition and observation.

This consideration is the result of experience, in which the situations of "rejection" on the part of monuments as a result of the use of improper construction techniques, and incompatible materials, become an eloquent argument for a more careful approach.

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