Foreword: Safety and preservation of cultural heritage: to do or not to do?

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"A' flessiòn int'a' solètt'" (bending into a slab). These are the words of Antonello de Luca, Professor at the University of Naples Federico II, when in 2018, he was visiting an old Monastery in L'Aquila.

The monastery suffered from heavy damages due to the 2009 L'Aquila Earthquake. Because of this, reinforced concrete support hoods were under construction with the purpose of strengthening the ancient brick vaults.

It was a great surprise to discover that the original vaults, actually, did not share the bad state of disrepair and damage of the rest of the building. In fact, following the earthquake no damage could be observed upon the vaults.

The reinforced concrete slab had a thickness of about 20 cm and a weight of about 0.5 tons per square metre with an increase of the original weight of about three times. It is, then, apparent that the restoration works were substantially altering the original structural system and its response behaviour under horizontal loads. Particularly, the latter is shifting from a shape-resistant behaviour, which is defined by the geometry of the vaults to a strength-resistant behaviour that is here associated with the one of a reinforced concrete slab.

The idea of using reinforced concrete for strengthening monumental buildings and historical structures in Europe has ancient roots. This can be dated back to the early 20th century. Several examples exist. Among those, we can refer to:

1 the Abbey of San Clemente a Casauria, which, in 1919, following the 1915 Avezzano Earthquake was restored by Ignazio Carlo Gavini (Gavini, 1923)

2 other, the Basilica of San Gaudenzio in Novara, which in 1937 was strengthened by Arturo Danusso using reinforced concrete members inserted into the masonry pattern (Daverio, 1940).

At that time, the use of reinforced concrete was recognised to be a befitting solution which satisfied the three following lines of resolution (Calderini, 2008):

1 increased structural performance due to the metallic reinforcement and with respect to traditional materials

2 the possibility to cast the concrete in the desired shape – thus reproducing that of the existing element to be replaced

3 the differentiation of the new in the old due to materiality – thus using exposed concrete to prevent from the risk of transmitting historic forgery to posterity.

In the first half of the 20th century, the international standards for preservation of historic buildings were mainly related to the perception of monuments as works of art having aesthetic standards to be transmitted to future generation for experiencing culture. Opposite to this, their structural behaviour and integrity with respect to construction techniques was neglected or being very little valued. Preservation was, then, related to appearance – thus, to surface, shape, colour rather than structure and related construction techniques.

In 1931, the Athens Charter for Preservation of Monuments explicitly encouraged the use of innovative materials and technologies to reinforce ancient buildings – thus, approving the judicious use of all the resources of modern technology, and more especially of reinforced concrete (Giovannoni, 1931), provided they were concealed so as not to alter the image of the work of art.

In 1972, the Italian Carta del Restauro still allowed for modifications and works of addition with respect to the static while no changes in colour or material were permitted if visible on surfaces.

Today, we are aware that the preservation of a historic building is not limited to its appearance but also concerns the structure and its construction techniques as a whole. Preserving only its appearance, regardless of the structure behind this, would result in a loss of integrity of objects of knowledge. In spite of this, we still register incomprehensible structural interventions that are in contrast with preservation and remark the existence of this well-known dichotomy.

After the many recent seismic events that have stroked Italy (i.e., L'Aquila 2009, Emilia 2012, Amatrice 2016), Haiti (2010), Nepal (Gorkha, 2015) Mexico (Puebla, 2017) amongst other countries, a class of technicians have rediscovered a muscular approach to the retrofitting of historic buildings.

Safety and preservation are often conflicting objectives, which for the different cultural backgrounds, together with the different responsibilities at stake of the different actors, lead to divergent visions (Borri and De Maria, 2015).

Sometimes, safety becomes the bulwark to support an improper design solution. In the name of safety, historic roofs and floors are completely replaced with reinforced concrete slabs and perimeter beams, the plaster is removed to pack the masonry between two layers of steel mesh, reinforced concrete hoods are built above the extrados of vaults.

According to seismic engineering provisions, the aim of the designer is to ensure a box-like behaviour and get a better redistribution of earthquake loads among walls. However, this goal is achieved through the systematic loss of original construction techniques, removal of historic materials and alteration of finishes.

Paradoxically, the insertion of reinforced concrete prostheses does not always produce the expected seismic improvement.

The complex harmonisation between safety and preservation takes us back to 1993 when Antonino Giuffrè published the handbook *Sicurezza e Conservazione dei centri storici. Il caso Ortigia* (Giuffrè, 1993). At that time, as today, the debate was aimed at combining the preservation of historical centres with the seismic safety of buildings and people. There was, in fact, a rather unique situation in Ortigia. The masterplan designed by Giuseppe Pagnano, had been approved with specific prescriptions that are aiming at the preservation of vernacular architecture and construction techniques, even in the poorest houses. Despite the availability of funds and community's efforts into the preservation and recovery of Ortigia's ancient buildings, it was not easy to design the retrofitting: the designers working in compliance with the plan often saw their project rejected because it was in contrast with seismic regulations. In this institutional stalemate, the municipality asked Antonino Giuffrè to assess how to guarantee seismic safety without distorting the original material and construction characteristics of Ortigia's historic buildings. That was an opportunity to develop a different approach to the analysis of the seismic behaviour of historical masonry which for the first time was not based on global modelling and linear dynamic analysis but on the so-called collapse mechanisms. It was also an opportunity to open a new season of studies on the anti-seismic effectiveness of traditional technologies.

Today, despite great advances in the field, we find ourselves in similar conditions. This is mainly due to a more challenging context that is linking the many seismic events that have recently affected Italy to a need for quick and massive repairs of damaged buildings. We need to understand how to combine the safety of historic buildings with the preservation of our heritage.

Industry and research have been engaged in the design of structural solutions that are effectively sustainable, durable and reversible: the reinforced concrete curbs are replaced by rows of bricks with steel reinforced grout inserted in the mortar joints, the plasters are retrofitted with lime-based binders and reinforced with glass fibre reinforced polymer mesh. Vaults are helped to perform much larger non-linear displacement by means of thin bandages of inorganic matrix composites bonded to the extrados. Is this the right direction for retrofitting our heritage buildings?

Considering the responsibilities a designer is invested with, it is hard to blame someone saying that thanks to new technologies retrofitting works can increase the level of safety and this is not at odds with preservation principles. Then, why shall we avoid doing so?

This position would certainly lead to extensive and indiscriminate use of interventions, which in many cases will be unnecessary.

Opposite to this, there are those, who believe that if a structure already possesses an acceptable safety level, why further structural improvement measures shall be carried out at all?

Then, the choice of 'to do or not to do' falls into the category of safety assessment. There are those who believe that the seismic safety assessment is a superfluous and even dangerous exercise. This is because of it harbours possible interventions aimed at causing irreversible changes to the original structural design.

This position is difficult to share – even though this is motivated by too many examples where, in the name of the alleged safety request, excessive, useless and at times harmful interventions were performed on historical heritage buildings.

The designer has the possibility to make calculations and provide an assessment of the level of seismic protection, with the awareness that the estimation obtained from calculation, is affected by inherent uncertainties.

There are both, epistemic uncertainties related to the limited knowledge of the geometrical and mechanical properties and, especially, model uncertainties resorting from the inaccuracy of the model prediction.

The structural assessment is not a waste of time, provided that the designer does not confuse the automaticity of the calculation with the reliability of the result.

In the light of recent seismic events, we have experienced the dyscrasia between the result of structural analyses and the effects of earthquakes on historic buildings. Conventional calculation generally provides a largely conservative estimate of the real seismic capacity.

As far as structural modelling is concerned, too often the designer's attention is focused on the strength values that can be directly transposed into structural design codes, while neglecting construction characteristics, such as the quality of the masonry and the effectiveness of connection among walls. Invasive and expensive investigations are carried out, when the most important information remains the geometric and constructive survey. The uncritical application of the seismic requirements related to the mechanical properties of masonry has in many cases led to unnecessarily invasive interventions for the sole purpose of increasing the strength of the material in the structural model, to certify the seismic improvement achieved.

We must recognise the conventional character of the calculation models and return to the observation of the building, to identify the weakest points, the traumas suffered, the stratifications and deficiencies that have come to light. The damage caused by seismic events represents an experimental full-scale test of the actual seismic response.

Based on simple observation of seismic damages to historic buildings, we experience that earthquakes do not disintegrate houses but select the weakest structural parts and technological solutions. These are those that collapse through mechanisms that can be defined in advance (Giuffrè, 1993).

The lack of monolithicity is the main threat to the masonry. Due to the poor quality of masonry the wall disaggregate and fail by separation between the leaves (failure mode I) (de Felice, 2011). As recommended by the 19th century treaties, the builder must not skimp during the construction in arranging transverse stones capable of binding the wall in its thickness. In Syracuse, for example, the 18th century lists prescribe the use of parallelepiped stones arranged in such a way as to bind the two faces of a wall. In the Amatrice 2016 earthquake, the intrinsic weakness of many walls was further compromised by the ruinous effect of seismic aftershocks, so important in number and intensity, which affected the same buildings already weakened by previous events, in a dramatic progression of damage.

If walls are correctly built, either because the mortar is strong enough to ensure the bond between stones as in the case of Roman 'Caementa', or because the arrangement of the stones is made according to the rule of art (Rondelet, 1817; Donghi, 1906), the wall behaves monolithically. In this case, a different failure pattern (failure mode II) is expected to occur under seismic action, consisting of vertical cracks at the intersection between the walls.

While failure mode I is difficult to predict as a consequence of the difficulty in assessing the quality of masonry, failure mode II can be easily evaluated in the framework of the dynamics of rigid bodies. Once the expected mechanism is detected, the evaluation of the horizontal base acceleration that activates the out-of-plane motion is provided by a kinematic limit analysis approach.

The approach is not too different from the one used by the ancient builders, who were concerned with the stability of the construction rather than its strength, controlling its kinematics rather than assessing its internal stresses (Heyman, 1982). Design was based on geometry, regardless of statics. The two fundamental laws of statics, namely the equilibrium of the lever and the parallelogram of forces, which correspond respectively to the balance of rotations and translations, will only be provided in the late 16th century (Stevin, 1586) and at the beginning of the 17th (Galilei, 1638), and later used for architectural design (Benvenuto, 1991) to assess the stability of arches (La Hire, 1731; Bélidor, 1729) or the equilibrium of retaining walls (Coulomb, 1776), sometimes with questionable results (Huerta, 2006).

The analysis of out-of-plane collapse mechanisms become more complex face to the dynamic nature of seismic action. The relative simplicity to evaluate the acceleration that activates the motion is balanced by the corresponding difficulty in assessing the seismic action capable of producing the collapse.

The structures have a non-negligible displacement capacity from the activation of motion (i.e., from the detachment of the façade) to their overturning, which is difficult to assess. This explains how temples or obelisks have survived to great earthquakes without collapsing.

Earthquake engineering is traditionally based on the dynamics of elastic systems. Current seismic provisions refer to modal dynamic analysis as the structural design approach to be preferred. However, experimental evidence has shown that historical structures respond to the earthquake according to the dynamics of rigid bodies rather than elastic systems. Once the wall detaches and begins to rocking, its behaviour is no longer influenced by the rest of the complex. Its motion is hardly represented by the linear dynamics of the single degree of freedom system, since its period depends on the amplitude of motion, as in the inverted pendulum. However, the seismic action is commonly represented by an elastic response spectrum – despite the effort of proposing other kinds of spectra, such as the rocking spectrum (Housner, 1963) or the overturning spectrum (Makris and Konstantinidis, 2001; Mauro et al., 2015), there is still no seismic hazard assessment developed in a more appropriate framework for historical masonry structures.

Structural analysis based on the use of collapse mechanisms would also represent a valuable tool to guide the intervention, since the seismic strengthening can be designed simply to restrain the expected damage mechanism, without the need for generalised interventions to the whole complex. However, the complexity and variability of historical structures are such that there can be no single, reliable strategy for structural modelling and analysis. It is therefore necessary to take into account the assumptions and simplifications underlying the calculation, which affect the reliability of the results and the safety estimate. The designer should seek for the minimum intervention, by deepening, where necessary, the seismic safety assessment, checking through diversified tools and methodologies whether intervention is really necessary.

The approach illustrated in this note, ranging from observations of damages due to past seismic events to structural analysis methods, is one of the keys to understanding the behaviour of structures whose construction we have lost the habit. Structures need to be observed interpreted and appropriately modelled again.

Today, there is a community of scholars and researchers that deals with the analysis of historical masonry structures with the awareness that our heritage can be safely preserved and handed down to future generations. There is still much to be done, in terms of understanding and developing of sustainable and respectful solutions. Above all, it is essential to make a link between the different disciplines, to find a common alphabet in which scientific approach and technological innovation are guided and contaminated by humanistic thought.

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