Design approaches of interventions for the safety and conservation of historic buildings

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ABSTRACT: Unconventional design approaches of repair/strengthening interventions on historic masonry buildings are more and more required and actually becoming popular among engineers and architects. This implies all the aspects of the design, and first of all theoretical/experimental ways and tools for evaluating the structural behaviour until failure of existing structures prior and after interventions are made. Primary scope of a conservative “attitude” in this field is in fact to avoid over-designing of interventions, which of course requires to limit as much as possible underestimations of the actual resisting capabilities of the existing structure. Important are, then, the proper use of materials and of their application techniques. What makes very critical this point is the fact that “new/innovative” materials are more and more proposed and actually used in structural restoration works. Appropriate preliminary investigations are in such cases necessary in order to avoid unexpected further problems.

1 INTRODUCTION

The conservation of architectural heritage is a very complex cultural operation, which was, and still is object of debates that greatly influenced – among many other aspects of the activity of the involved art historians, architects and engineers – the way how the crucial issue of “structural safety” is dealt with.

The problem is very well known. Modern structural safety concepts – based on the calculation of “accepted probabilities” that something considered “wrong”, first of all the failure, happens to the “load bearing components” – works very well for new constructions. The properties of the used materials and structural components can be precisely modeled in this case, thus allowing “precise” (even if substantially conventional) evaluations of the distance between a state of the structure that is considered “safe” and the state of the same structure can experience in any moment of its expected life. Materials and construction techniques are then selected with no substantial restrictions during the design process in order to make such distance complying with precise code prescriptions. In the case of existing historic structures, on the contrary, reliable and feasible structural models are difficultly available and in any case data on their mechanical properties are very scarce, generally insufficient to feed the models; on the other hand, substantial restrictions are imposed by conservation criteria to the possibilities of intervening to “increase” the safety.

Absolutely relevant outcomes of the debates raised by this situation were new structural design concepts and tools which are more and more entering into the codes and then into the design practice (M.B.C.A. 1986 & 1996, M.LL.PP. 1996, ISCARSAH-ICOMOS 2001). It is enough to mention: the differentiation of the accepted safety level for different classes of existing structures; the use of qualitative evaluation of structural performances (observational approach); the evaluation of safety based on pure equilibrium considerations; the limitation of interventions at the minimum possible level, depending on the level of knowledge of the structure and then on the use of appropriate investigations/monitoring techniques; the compatibility of (traditional/modern/innovative) materials and construction techniques; the removability of the interventions. This situation is also stimulating the search for “new solutions”, i.e. new materials, new techniques, new investigation tools, etc. which can offer new possibility of better satisfying the new design concepts.

The design process is thus continuously evolving and becoming more and more complex and sophisticated. At this stage of the technical and scientific knowledge it must be necessarily based on a “case by case” approach. The continuous learning from practical applications is then essential in order to have
the above concepts more and more clear and "stabilized", and then implemented into as much as possible generalized and controllable procedures.

With this aim some design experiences carried out in Italy are presented and commented.

2 LIMITING THE INTERVENTIONS BY USING INVESTIGATIONS AND MONITORING

An example where the strong influence on the design choices is very clear of having appropriate preliminary investigations and long term monitoring available is the timber roof of the "Palazzo della Ragione" in Padua (Figs. 1 and 2). The construction properties of the structure are really impressive: it covers a unique, skewed room, approximately 28 m wide and 80 m long, and is formed by slender ribs (the section is approximately $36 \times 40\,\text{cm}^2$, but obtained by joining curved boards 12 cm thick, whose length varies from less than one meter to three meters), which 3 cm thick boards are simply nailed to. Preliminary design hypotheses assumed that only a complete dismounting could have permitted a "safe" repairing of heavily deteriorated zones of the ribs (Figs. 3 and 4) of such a "delicate audacious" structure, being conscious however that this solution could have caused unacceptable losses of the existing material and components and, in general, of its original character.

Figure 1. External view of the roof of the "Palazzo della Ragione" in Padua.

Figure 2. Internal view of the roof.

Figure 3. Detail of the deterioration of the ribs detected in the joints.

Figure 4. Deterioration of the internal part of the ribs.
A cautious and really conservative approach should have permitted to limit the repairing works to the pure substitution of the deteriorated parts of the timber ribs avoiding any previous dismantling but also extremely expensive and heavy (and dangerous for the remaining parts of the building) temporary supports.

This obviously implies the possibility of relying, during the works, on the capability of the structure to offer enough strength and stiffness, with minor "temporary aids", to resist with acceptable stresses and deformations, to the self weight and, even more crucial, to the most critical action which could cause severe damages to such a light structure, i.e. wind.

Major efforts were for such reasons primarily dedicated to a clear understanding of both static and dynamic effects of wind on the roof structure, taking into account its precise geometry and position inside the town (for static effects) and for its real wind/structure interaction (for dynamic effects).

Two different types of investigation were used for the analysis of static and dynamic effects of wind.

In situ measurements of wind pressure (Figs. 5 and 6) on selected points were in fact compared with wind tunnel tests (Fig. 7) on a reduced scale model of the building and of significant surrounding part of the historical center of the town, to determine static effects.

Dynamic characterization via in situ measurements of forced vibrations (obtained by a harmonic exciter applied to a rib) demonstrated that the fundamental period of vibration is far from giving dynamic interaction with wind (Figs. 8 and 9) (Modena et al. 1999).
In conclusion, the results of the investigations, combined with appropriate structural analyses (which were calibrated with the test results, as in Fig. 10), allowed to design the intervention being much more confident on the “robustness” of the structure, provided is full 3D behaviour, and the essential contribution given to the stability by the “shell” formed by the nailed boards, would be in any phase maintained.

The design of the local repairing was made possible by taking simple temporary measures allowing for maintaining the stable 3D behaviour and inhibiting local buckling in any phase of the works. The first condition was assured by simply limiting the removal (when needed) of the boards forming the shell very locally, in order to permit local repairing, and the second through simple lateral support, as shown in (Figs. 11 to 14).

A supplementary measure was taken to avoid sliding at the supports during the works. To this scope a temporary tie was added as indicated in (Fig. 15). The force needed to ensure stability was theoretically calculated, and then monitored during the works (Fig. 15), together with relevant parameters of the overall behaviour of the timber and masonry structures (Fig. 16).
3 USING INNOVATIVE MATERIALS WHILE ENSURING COMPATIBILITY AND REMOVABILITY

Among innovative materials highly durable stainless steel and even more FRPs (Fiber Reinforced Polymers) have high potentiality for possible application on historic structures, due to several well-known advantages (for FRP especially corrosion immunity, low weight, etc.). In particular, the use of the more durable CFRP (Carbon FRP) bars combined with traditional mortars properly selected, can be proposed for the bed joint reinforcement of masonry structures (Modena & Valluzzi 2003) (Fig. 17).

In any case, what characterize the use of such sophisticated and high performance materials is the fact that the employ of traditional mortars, properly selected, to make them work together with the existing materials, is highly preferred. This is not only due to conservation considerations, but also to the search for reducing as much as possible high stress concentrations which could occur using high strength/high stiffness modern bonding materials like resins, high strength mortars etc., or, in other words, to ensure better “compatibility” from the mechanical point of view.

Specific applications of steel bars embedded superficially in the bed joints of massive structures (towers, curtain walls, large pillars), proved on experimental laboratory bases, demonstrated their high efficiency in counteracting typical masonry creep damage (Binda et al. 1999b & 2001) (Fig. 18).

More advantages can be achieved by the use of thin CFRP strips (1.5 x 5 mm in section size), assuring low obtrusiveness of the intervention and a better adaptability to the possible joints unevenness (Valluzzi et al. 2003b) (Figs. 17 and 19).
Current applications are by now made by stainless steel (one or two small diameter reinforcing bars) connected to the inner core of the masonry by transversal short pins, as some aspects connected to innovative materials, especially concerning durability, compatibility and removability, still need to deeper experimental investigations. Both excavated joints and drilled holes for pins insertion are successively sealed by mortar and grout, respectively.

Applicability of such innovative materials is anyway very promising, thus many research groups are involved in clarifying specific problems.

The bed joint reinforcement is often used in combination with other techniques, aimed in solving specific structural problems (injection and limited rebuilding, to re-establish homogeneity, uniformity of strength and continuity of masonry walls; tie-rods confinement, etc.).

Some recent examples of application of the above mentioned technique to towers in hazardous safety
conditions are the Cathedral of Monza and the Civic Tower of Vicenza (Italy).

The bell tower of the Cathedral of Monza (XVI century) was suffering passing-through large vertical potentially dangerous cracks on some particularly weak portions of the West and East sides (Modena et al. 2001). They were slowly but continuously opening since 1927; moreover, wide cracks in the corners of the tower up to 30 m and a damaged zone at a height of 11 to 25 m with a multitude of very thin and diffused vertical cracks were detected (Fig. 20).

Design of intervention was mainly aimed in providing an overall confining action of masonry walls, limiting the dilation of the material. They consisted of: (i) metallic horizontal reinforcing rings applied on several sections along the height of the Tower, to improve the connection between the contiguous walls; (ii) the application of the reinforced repointing technique diffused on various portions of the walls, to counteract the creep damage, and concentrated on some pilaster strips to strengthen the corners; (iii) local interventions of injection, rebuilding, and pointing of the mortar joints, to restore the zones having high material deterioration (Fig. 21).

The intervention design was strictly based on the results of the investigations carried out on site and in laboratory both on materials and structure (also static and dynamic tests were useful to calibrate FE mathematical models). They allow to identify the bed reinforcement as a technique which, respecting as much as possible the original structure, provides an improvement capable to save the preservation concepts (Fig. 22).

The Civic Tower of Vicenza (XII century) is a slender structure with a base section of 6.2 x 6.5 m and a height of about 82 m. During centuries, it was subjected to several repairs and changes, due to several causes (earthquake, bombing, etc.). The Tower suffers a substantial out-of-plumb, and a damage characterized by localized deep cracks, diffused micro-cracks and material deterioration. Many of the main deep large cracks were located near the corners and complete or partial detachment of the external leaf and of local buckling of the masonry was found also in some areas of the façades (Valuzzi et al. 2003a) (Fig. 23).

The interventions (Fig. 23) consisted of: (i) grout injection at the base of the tower and on the belfry pillars, (ii) local rebuilding, (iii) pointing of mortar joints, to restore the areas characterized by high material deterioration; (iv) reinforced repointing applied on various portions of the walls and on the pillars, to counteract the creep damage and to strengthen the corners (Fig. 24); (v) metallic horizontal reinforcing rings and anchoring ties placed at different levels along the height of the tower to confine the masonry and improve the connection between contiguous walls.

Figure 22. Insertion of a small diameter bar in an excavated joint of the West side of the Cathedral of Monza (Modena et al. 2001).

Figure 23. Civic Tower of Vicenza (Italy): scheme of the intervention measures on the damaged sides.
Figure 24. Reinforced repointing applied on the belfry pillars of the Civic Tower of Vicenza.

4 APPLYING EQUILIBRIUM ANALYSES FOR VULNERABILITY ASSESSMENTS AND STRUCTURAL IMPROVEMENT IN SEISMIC AREA

A complete limit analysis approach of existing masonry buildings, especially in seismic areas, is proving to be the most efficient way for making reliable safety evaluations without underestimating their actual resisting capabilities, thus avoiding over-designing repair/strengthening interventions.

Such method, based on single or combined kinematics models involving the equilibrium of structural macro-elements (Giuffré 1993), is particularly addressed to existing masonry buildings in historic centres. They, in fact, often do not satisfy the general conditions which allow the application of common equivalent static procedures, based on the “box” behaviour of the structure (which requires the presence of well-connected walls and floors and a proper horizontal stiffness of the floors) and on the elastic-plastic behaviour of the masonry. Common buildings in historic areas are often realized according to typologies (multi-material masonry, multi-leaf walls) and constructive details (poor connection between intersecting walls, between walls and floors and even among the layers in the thickness), which can evidence fundamental deficiencies for the stability and the safety under seismic actions.

The ultimate capacity of the building depends on the stability of its macro-elements, that is of portions of the structure bounded by the potential damage pattern (cracks, borders of poor connections, etc.) which can behave as a whole, following a kinematics mechanism. Macro-elements are defined by single or combined structural components (walls, floors and roof), considering their mutual bond and restraints (e.g. the presence of ties or ring beams), the constructive deficiencies and the characteristics of the constitutive materials. Once the critical structural configuration is defined, the subsequent step is the identification of the most probable collapse mechanism/s characterizing the macro-element.

Several studies based on the in-situ observations after seismic events allowed to systematize abacuses of
the typical damages occurring in constructive typologies (buildings, churches), which led to the consequent systematization of the mechanical models able to describe their specific behaviour by kinematics models, both for in-plane and out-of-plane mechanisms (Giuffrè & Carocci 1999, Binda et al. 1999a, Penazzi et al. 2001).

Those models, calibrated on the real damaged sites, are usefully applied for analyses of vulnerability for centres under seismic hazard, in order to examine the current condition and to prevent their future damage. Moreover, the simulation of possible interventions can be performed, both in damaged and undamaged conditions, evaluating their impact with the pre-existing situation (Avorio et al. 2002, Valluzzi et al. 2004).

5 CONCLUSIONS

Some case studies have been presented and commented where efforts have been made to respond to “conservative” design criteria while intervening to ensure acceptable structural safety conditions of existing historic constructions.

As it is first of all expected in order to respect the existing features of the considered constructions, attention has been focused on avoiding unnecessary interventions and special care has been paid in order to limit in any case as much as possible variations not only of its external appearance, but also of its mechanical behavior.

This requires that special efforts are made to accurately analyze, theoretically and experimentally, the actual resisting properties of the considered constructions, prior and after interventions are made, in order to avoid over-designing approaches. Moreover, the actual contribution of any traditional/innovative material and technique, and of their possible combinations, can be adequately and scientifically exploited in order to ensure durability, compatibility and possibly removability of repair/strengthening interventions.

REFERENCES


