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AN ITALIAN ANTI-SEISMIC SYSTEM OF THE 18TH CENTURY DECAY, FAILURE MODES AND CONSERVATION PRINCIPLES

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Abstract

After the catastrophic earthquake that struck the Calabria region (Italy) in 1783, the Borbone government, among several measures, enacted an anti-seismic code. Such a law provided indications based on the most advanced criteria of the seismic engineering of the Age of Enlightenment, relative to resistant earthquake buildings execution, including masonry walls reinforced with timber frames. That structural organization has emphasized a proper response to seismic actions both orthogonal and parallel ones to the masonry panel. In September 2013, a full-scale replica of this type of wall, has been tested under quasi-static cyclic loads at the CNR IVALSA laboratory, recording limited damage. Furthermore, observations and indications about damage, in particular wall overturning, which buildings constructed according to the System suffered, drawn by means of a large collection of historical photos, is presented and discussed in the paper. The timber included in the compound structure is characterized by a moderate durability due to the potential high humidity generated at the wood-masonry interface, hence favourable conditions for biotic attacks. The contribution devotes its attention on the description of technological and theoretical criteria and principles on which a correct strengthening intervention on historical masonry framed wall has to be founded.

Keywords: *Borbone constructive system; Timber framing; Biotic decay; Seismic damage; Conservation principles.*

Introduction

On 5th of February 1783 a massive earthquake struck the Calabria region (Southern Italy) that disintegrated many villages and left many wrecked buildings. This earthquake caused such an extensive damage that brought the region close to the total collapse (Fig. 1).

In order to mitigate the catastrophic event consequences, Ferdinando the IVth of Borbone, king of *Regno di Napoli* to which the Calabria region belonged during the 18th century, intervened with a series of measures. Such provisions comprised a fund donation for people rescue and first interventions and the *Cassa Sacra* foundation with the task of confiscate and sell ecclesiastical assets and use the proceeds in the villages reconstruction. Furthermore, the Borbone king enacted a code aimed at regulating new earthquake-resistant constructions [1] and the strengthening of the damaged buildings.

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Fig. 1. A historical print representing the consequences of the 1783 earthquake:
Vue de la Ville de Regio dil Messinae et ces alentour detruite
par le terrible tremblement de Terre arrivée le Cinq Fevrier de l'année 1783
(Bibliothèque nationale de France, département Estampes et photographie).

The *Istruzioni per gli Ingegnieri commissionati nella Calabria Ulteriore,* the Borbone regulations deals with, based on the most advanced principles of seismic engineering of the 18th century, is the best practice in order to improve the performance of the building under earthquake loading. The most important article is represented by the recommendation to execute a wooden skeleton inner the masonry achieving a *box like* behaviour of the building under seismic actions.

Such constructive system has emphasized a proper response to the 1905 and 1908 earth tremors that hit the Calabria region again. In fact, the failures occurred to the buildings characterized by timber framings were limited to the partial overturning of the masonry leaf and few expulsions of stones from the top of the facade.

Moreover, the experimental research carried out in the CNR Ivalsa laboratories in Trento on Borbone system samples in full scale confirmed an appropriate behaviour under quasi static cyclic horizontal loads. Tests recorded discrete energy dissipation values, a negligible strength impairment and limited cracks and deformations related exclusively to the masonry infill [2].

However, the compound structure, i.e. timber, presents a certain vulnerability to biotic attacks. In particular, the masonry that embraced the entire wooden framing could represent a humidity source hence a favourable environmental factor for the development of insects and fungi colonies.

The Borbone constructive system represents an important chapter of the engineering history hence it needs measures of repairing and safeguarding compatible with the character of Monument and the chemical-physical features of these ancient materials.

The *Borbone* constructive system

In addition to indications regarding the viability dimensions of the new villages, building height and materials features, the anti-seismic code recommended to execute, inner the masonry, a *«... ossatura di grossi travi di Castagno o Quercia ... Questi si situeranno negli angoli ... legati con altri travi trasversali ... detta ossatura di legnami abbracciata di fabrica*[1]*, in maniera che ... non restino le mura men grossi di palmi due e mezzo ...*»[2] [1]. A structural organization aimed at forming a *box* with all the components that collaborate to counteract the earthquake-induced horizontal loads (Fig 2).

Fig. 2. An example of Borbone constructive system, masonry reinforced with an inner timber framing.

The *Istruzioni* were not accompanied by any explicative drawing; neither further details on dimensions, geometrical features and members and nodes arrangement were provided.

As a consequence, various and different structural configurations, however fully in compliance with the regulations, were built after the 1783 earthquake.

In fact, some examples of Borbone system are braced by Saint Andrew wooden crosses, others in which the stiffness to in plane action is provided mainly by means of the masonry infill, other *baraccati*[3] buildings exhibit a double timber framing suitably bonded trough transversal members. Among possible variations around the "*ossatura di grossi travi*", the location of the timber frames inside the masonry wall, realizing, in some cases, a fabric made out of more than one leaf [4].

[1] It seems, according to the legislator, that the wooden skeleton has a preponderant role compared to the masonry, the latter limiting itself to a simple covering of the timber structure, preserving it from biotic attacks, contrary to the real behaviour, at least in static field.

[2] «...skeleton of chestnut or oak big members. Those will be located in the corners ... will be linked to other transversal members ... the above-mentioned framework embraced by masonry, so that all even the smallest part not remain exposed to the environment and for such effect not will be the walls less thick of two and half *palmi.* »

[3] The term defined the Borbone system in the 19th century [3].

Such a load bearing system arrangement, generally, entails that the masonry plays a protagonist role under gravitational charges due to a higher elasticity module value and transversal section dimensions, if compared to the timber structure.

On the other hand, the wooden frame provides the bulk of the seismic capacity of the system through its traction resistance and flexibility that, at least for moderate values of the ground shaking, permits to the masonry subject to displacement to return back in its original position or close to it [5].

Furthermore the masonry represents a flexibility threshold limitation for the timber structure.

Typical decay and failures

Biotic decay

The wood biodegradation, due to the actions of various organisms, in particular fungi and insects, is influenced essentially by two factors: the natural durability of the wooden species[4] and the features of the environment in which the structure is immersed.

The temperature but above all the humidity degree represents conditions that facilitate xylophages agents attacks. An insect infestation may occur in an environment in which the timber moisture content is within the interval 7 - 15% [6], whilst the fungi presence is generally linked to accidental humidity sources (i.e. water infiltration) that generate a wooden moisture content higher than 20% [7].

Effects on the physical properties are discoloration (spalting), deterioration of the resistance properties, as a result of a process of biological agencies, mainly insects and fungi.

The latter are capable of enzymatically degrading complex cellulosic wooden materials into simple digestible products provoking, generally in limited areas, a significant loss of weight and strength of timber. Insects attack timber by opening tunnels that reduce the member resistant section, although the degradation usually interests only the peripheral part of the structural element for few centimetres deep.

The timber structure that composes the Borbone anti-seismic system, inner the masonry, can be characterized by a high value of moisture content. In fact, the lack of ventilation and the potential condensation formation at the wood-masonry interface[5] generate a favourable habitat to saprophyte organisms establishment. Another humidity factor may be represented by the mortar before drying and curing.

[4] First indications on the minor degradability of some wooden species are provided by Vitruvius in the Liber secundum, caput nonum: «... cupressso et pinu, quod eae habentes umoris abundantiam eaquamque ceterorum mistione, propter umores satietatem in operi bus solent esse pandea, sed in vetustatem sine vitiis conservantur, quod is liquor, quo inest penitusin corporibus earum, habet amarum saporem qui propter acritudinem non patitur penetrare cariem neque eas bestiolas quae sunt nocentes. Ideoque quae ex his generi bus opera constituuntur, permanent ad aetarnam diuturnitatem…» [8]
A behaviour differentiation relatively to the wooden species has been specified in EN 350-2 *Durability of wood and wood based products* in which, relying on experimental data, is indicated the durability of some wooden species towards insect and fungi.

[5] As little as Vitruvius intuited that the beam extremity in contact with the masonry presents a high vulnerability to biotic agents, recommending for the floor members that «... coaxationibus factis, si erit, filex, si non, palea sbsternatur, uti materies ab calcis vitiis defendatur…» [8] liber Septimus, 18, 2. Scamozzi resumed the suggestion of Vitruvius in his treatise in the 16th C.: «… non si deono murar la dentro con malte morbide; posciache la calce per sua natura le danneggia non poco, & anco ogni altra humidità, che elle sentono …» [9], p.341) (… must not set it in the wall with not cured mortar; in that the lime for its nature greatly degrades it, and even every other humidity that they suffer…). A micro-clime that generates in the masonry particularly favourable conditions to biotic establishment that became widespread knowledge among Eighteenth and Nineteenth century technicians. Giordano [10], and more recently Tampone [11], relying on principles already developed during the Renaissance, proposed solutions to the problem, avoiding the contact between masonry and timber by means of an interposition of an air layer.

In the case in which the frame is localized in the inner part of the wall, also the plaster, even though it is applied on a lathing that facilitates the adhesion, can transfer water to the timber members.

The Borbone constructive typology characterized by the wooden framing localized close to the median part of the wall and, in some cases, divided from the outside by a leaf of reduced dimensions, cannot ensure an adequate protection level toward meteoric waters. Moreover, if such leaf is constituted by bricks, devoid of the plaster, the natural porosity of the baked clay transports, due to the capillary action, water inside the masonry, representing a further humidity source for the timber elements.

A high inclination to establish fungi and insects of that kind of constructive organization witnessed by the bad state of conservation of the timber structures of *Palazzo Vescovile* in Mileto (Calabria region) [12]. Such construction, built at the end of 18th century according to the recommendations contained in the anti-seismic code for the *ricostruzione dei paesi diruti della Calabria* [1], highlights the scarce durability of timber embraced by masonry. That condition is aggravated by other threats in particular the state of abandon[6] and the partial lack of the roof.

Fig. 3. A decayed wooden post of a frame in which the damaged timber is reduced in powder.

A fungal phylogeny characterizes numerous structural elements with different intensity attacks. The decayed timber presents peculiar longitudinal and transversal fissures, typical of brown rot[7] with a minor wood mass and consistency in respect to sound material; moreover it is characterized by scarce cohesion and low resistance to transversal pressure. The inspection has recorded some cases in which the damaged timber is reduced in powder (Fig. 3). Based on a visual analysis the agent might be individuated in the *Serpula lacrimans*[8], Basidiomycota phyla, *Meruliaceae* family.

The degradation of the *Palazzo Vescovile* caused by insects is rarer. During the survey, it is recorded the presence of *Lyctus linearis,* belonging to *Coleoptera* order, Lictidi family,

[6] It is recorded the last collapse, the partial overturning of the west wall of the *Palazzo,* on 13rd March, 2016.

[7] Different from the white rot, it degrades the cellulose and hemicelluloses components without much effects on the lignin [13].

[8] The term derived by the wood decay that produced *lacrymans* (tears) when fungi growth is luxuriant with an excess of water.

characterized by surface tunnels parallel to the grain and round exit holes with dimension of about 1mm.

The case of a framed building in Seminara (Rc) is singular (Fig. 4). The consistency loose of the wooden member has generated on the brickwork 45° degree cracks tracing precisely the saint Andrew crosses[9], pointing out, by now, their ineffectiveness.

Fig. 4. Seminara (Rc). The consistency loose of the inner wooden member has generated on the brickwork 45° degree cracks tracing precisely the saint Andrew crosses.

The Borbone technicians were fully acquainted with the scarce durability of the timber structure belonging to the compound system, to which they tried to find remedy through several suggestions contained in the *Istruzioni*. In fact, the code recommends to isolate the wooden framing from the soil, potential humidity source, by means of …uno zoccolo di fabbrica …. dal piano della strada fino a 5 palmi …[10], provision anticipated by Vitruvius relatively to the *opus craticium*[11].

Furthermore, the Borbone regulations is rather peremptory about the wooden species to use for the elements constituting the wooden frames. The choice has to be represented solely by Chestnut or Oak, that in addition to guarantee proper mechanical performance, they ensure a certain durability to biotic attacks[12].

Earthquake damage

The evaluation of typical failures experienced by buildings characterized by Borbone structure was carried out by means the analysis of historical photos that describe *baraccati* buildings after the 1905 and 1908 destructive earthquakes that again hit the Calabria region.

[9] Unfortunately, only as a consequence of the cracks appear it is possible to deduce a wooden member failure. The conservator has to face with difficult to detect the state of conservation of timber elements without the removal of covering masonry and plaster. Non-destructive investigation methods, such as thermal imaging, are not really effective for that task.

[10] … a masonry base … from the street level to 5 palmi …,

[11] Vitruvius suggests to build underlaying the framing «…solum substruatur alte…» aimed at avoiding «…vetustate marcidi fiunt…» Liber II capo VIII [8].

[12] According to EN 350-2 *Durability of wood and wood based products*, the Chestnut (*Castanea sativa Mill.*), pedunculate Oak (*Quercus robur L.*) and Durmast Oak (*Quercus petrae Liebl.*) are *durable* if attacked by fungi and resistant to Hylotrupes.

Generally, it is recorded failures of modest degree and the cases of collapse, anyway of partial type, were sporadic.

The damages derived from dynamic action are ascribable to two fundamental typologies, little material expulsions at the building top and localised overturning and limited to the masonry external leaf [12].

The case presented in figure 5 describes a *baraccata* construction built in Reggio Calabria and damaged by the 1908 earth tremor.

Fig. 5. Reggio Calabria. A *baraccato* building damaged by the 1908 earthquake.

The failures are delimited to the facade cornice. The seismic action probably hit the building parallel to the front, deduction deriving from the analysis of the overturning motion of the contiguous construction. The occurred failures emphasize a possible low entity thrust originated from the king post truss constituting the roof structure. The upper part of the building reached the largest displacements and the earthquake loading had not been adequately counteracted by the roof wooden ring, hence it had not been totally effective[13].

Similar damage is showed by the photo that represents a building in Stefanaconi (Vv).

The architectural composition features are very similar to those of Reggio Calabria, witnessing a lack of particular peculiarities and aesthetic variations in the reconstruction of villages during the 18th century. The telluric event caused damage both in the wall parallel and perpendicular to the earthquake action. The extended overturned portion of masonry includes almost the entire cornice. It is worth highlighting material expulsions also in the area constituting the quoin, provoking the put in evidence of a timber post and denouncing the building corner weakness perhaps not properly executed.

The loss of equilibrium and the consequent overturning of a part of the wall was the most recurring failure during the earthquakes of the 20th century (Fig. 6).

Such a failure mode is mainly due to an improper execution of the masonry. In fact, the analyzed collapses emphasize a fabric constituted by small size and round stones and a probable scarce mortar quality. Moreover, the slender external leaf is not constrained to the remaining wall by means of transversal stones (*διάτονος*). A similar arrangement implicates a significant

[13] In addition to a roof structure with eliminated thrust, the Borbone system in the typical version is characterized by a timber ring at the top of the building [14].

overturning vulnerability, although limited to the external leaf, even under moderate accelerations.

Fig. 6. Messina. A *baraccato* building characterized by the overturning of the external masonry leaf after the 1908 earthquake.

However, it is worth noticing that the seismic perpendicular action did not provoked any damage to the wooden framing and, the partial overturning, at any rate toward the building exterior, did not cause the roof and floors collapse, guaranteeing the people life safety.

An experimental campaign including quasi static cyclic tests on samples of framed masonry in full scale (Fig. 7) has been carried out in 2013 in the CNR Ivalsa laboratories[14]. The tests, limited to horizontal parallel action to the wall, provided indications about the seismic performance of the Borbone constructive system. The numerical results deriving from the experimental investigations [2], synthesized in the table 1, and the qualitative analysis of the damage progression confirmed a proper behaviour of the Borbone masonry stressed by cyclic loads.

The tests highlighted a non-linear behaviour with a discrete amount of energy dissipated (a peak of 1579kNmm corresponding to a displacement of 80mm). The system, according to the definition contained in the European standard UNI-EN 12512:2006 (*Timber structures – Test methods – Cycling testing of joints made with mechanical fasteners*), showed a negligible degradation of the resistance, a strength impairment constant value of about 10% and a significant value of the ultimate displacement (about 80mm), reaching a ductility of about 8.

With regard the damage analysis, the timber joints and members didn't point out, during the entire test, any failures; hence they answered to the imposed stresses in elastic field. The masonry infill underwent few case of stones expulsion and cracks in the fragile bed-joints. Concerning the latter, it worth emphasizing that the presence of the timber frame prevented a further cracks growth. The major contribution to the energy dissipation was represented by the friction mainly generated by continuous structure disarrangement and resettling due to the reversed cycles. Moreover, detachments between the masonry infill and the timber frames were recorded.

[14] The tests are the result of a joint research between Università della Calabria (Ruggieri, N.; Zinno, R.) and CNR Ivalsa, National Council of Research (Ceccotti, A.; Polastri, A.) about the seismic behaviour of the Borbone masonry.

Fig. 7. The full scale sample of Borbone constructive system tested under quasi static cyclic loading

Table 1. Results of quasi-static cyclic tests on Borbone shear wall

	Lmax* (kN)	Dmax* (mm)	Lu# (kN)	Du# (mm)	Ly§ (kN)	Dy§ (mm)	α¥(kN/mm)	μ** Du/Dy)
Env. curve	103.6	59.2	100.7	79.1				
1st cycle	-101.6	-79.0	-101.6	-79.0				
Env. curve	93.9	79.3	93.9	79.3				
2nd cycle	-91.1	-79.2	-91.1	-79.2				
Env. curve	88.6	59.6	88.6	59.6	66.1	10.5	6.3	7.6
3rd cycle	-86.8	-79.7	-86.8	-79.7	60.5	9.11	6.6	8.6

*Load and displacement maximum; #Ultimate limit load and displacement; §Yielding load and displacement; ¥Initial stiffness (it is defined as the angle of the curve between 10% and 40% of the maximum load); ** Ductility

Conservation principles and criteria

An ancient construction, including its load bearing structure, represents an expressive form rich of aesthetical, historical, anthropological, scientific and technical significances. It is a no fortuitous or spontaneous product but it represents the result of the ideation and creativity of a designer and of the historical period to which the construction belongs.

A "document" characterized by a strong didactic value, essential means in order to develop a history hermeneutic, that needs actions aimed at integrally conserving both materials and structure that compose the Monument.

Furthermore, a physical and chemical compatibility of the repairs with the original materials is a mandatory requirement, keeping in account a condition of structural safety of the building.

Theoretical principles

The main aim is to conserve the Monument authenticity. In order to achieve such objective, interventions of minimal extent and the simplest strengthening techniques have to be preferred, minimising the sacrifice of original material [15, 16]. The protection and conservation works must repair the ancient pieces rather that replace them. Replacement of damaged parts should be limited exclusively to cases in which there are not adequate technical tools and means to conserve the authentic material.

The remedial works, including new members, must not be hidden, rejecting artificially age treatments or, generally speaking, aimed at camouflaging the intervention with the original material.

The interventions should be reversible and not prejudice or impede future preservation work should become necessary [15-17].

The design of repairs should conserve the entire load bearing assembly and scheme.

Hence adaptation to new serviceability requirements, generally involving higher loads and consequent structural variations, should be avoided.

The building use should preferably be the original one or in alternative with this compatible.

It is to be hoped that the repairing intervention recovers the residual load bearing capacity of the element to be conserved, adding strength to the original member, avoiding of humiliate the ancient structure, discharging it from any stresses deriving by gravitational or dynamic loads.

The strong didactic value contained in the historic fabric imposes to conserve the evidence, if it is feasible, of the structural failures, making clear the complementarity nexus between cause and the strengthening intervention.

In fact, the failures have a semiotic value fundamental to obtain information about the Monument features [18].

Technological criteria

The intervention should tend to remove the cause of the pathology rather to act on the effects.

Any repairs should be preceded by a detailed diagnosis of the condition and the causes of decay and structural failure [11; 15-17] and, generally, by a deep acquaintance of the ancient Monument.

Aimed at monitoring the repair works, measures that facilitate the inspection of strengthened members, joints or structural units and system, need to adopt.

The intervention has to be adjustable in order it can adapt to possible shape variations and natural movement due to the timber hygroscopic properties. The strengthening device should allow free wood dimensional changes generated by swelling /shrinkage produced by the fluctuations of temperature and humidity.

Regarding timber structure, additional pieces have to match the original in the moisture content and, generally, in the physical features. Metallic surfaces overlapping and covering the wooden ancient members have to be minimised, in that there is high probability of water condensation generation at the metal-timber interface, hence a favourable environment for biotic attacks. Generally speaking it is opportune to ensure an adequate ventilation degree to the wooden structure. In fact, a high moisture value due also to a condition of scarce natural ventilation represents a potential fungi and insects establishing.

Relatively to Monuments located in earthquake prone areas the anti-seismic properties of wooden elements is required to give consideration. The strengthening design has to follow the principle of the "capacity design". In other words, in designing structural system it is a mandatory criterion avoids premature brittle failure modes, "directing" ruptures and deformations to more dissipative and ductile members.

The intervention has to limit the masses addition.

The modifications in the stiffness distribution and degree and consequent inopportune change of the original stresses path have to be careful evaluated.

With regard timber structure, in order to follow the cited principles it is preferred to operate *in situ* without dismantling the carpentry or any of its parts [11, 17, 19].

Conclusion

The Borbone system represents the synthesis of the most advanced principles developed by the 18th century seismic engineering.

A compound structure that employs timber and masonry to their full potential mechanical properties, in order to improve the capacity of the building to withstand earthquake actions. In fact, the masonry takes advantage by an additional traction resource thank to the wooden structure presence, ensuring the walls cooperation, hence achieving a box like behaviour of the building, namely opposing to the earthquake a three-dimensional response of the construction.

A technology that represents a fundamental chapter in the history of the science of Europe, witness of a precise culture and historical period; so it must be conserved in its integrity including materials, the static scheme and the original structural configuration.

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