The roots of the 18th century turning point in earthquake-resistant building

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and **Ana Paula Pires**

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The roots of the 18th century turning point in earthquake-resistant building

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ABSTRACT: The *gaiola pombalina* and the *casa baraccata* seem to be the turning point of a gradual improvement process that, in Italy, becomes clearly recognisable after the 1703 L'Aquila earthquake. The reconstruction following that event saw the introduction of a constructional system, based on wooden elements embedded in masonry works, quite distinct from the rigorous organization of the late 18th century systems but having seemingly comparable intents. Recent earthquakes in Italy have enabled the value of that early anti-seismic technique to be recognized. In this paper we describe this technique its comparison with the systems at the end of the century and attempt to trace them back to more ancient constructional techniques attested also in low seismicity areas In these areas they seem to refer to a general attempt to rationalize masonry building's procedures whose anti-seismic potential was gradually recognized during the Enlightenment, finally leading to the Portuguese and Bourbon systems.

1 INTRODUCTION

Codified in the 18th century for the reconstruction of the centres destroyed by the devastating earthquakes of Lisbon (1755) and southern Italy (1783), the *gaiola pombalina* and the *casa baraccata* represent the first formalization of expressly anti-seismic construction techniques. They were both based on the adoption of wooden elements interacting with masonry work aimed at strengthening the building's joints, thus showing quite a mature awareness of the inherent, as it were, seismic vulnerability of historical masonry constructions. The level of detail in terms of structural conception and technical expression (which is not surprising within the cultural context of the 18th century) suggests that their appearance cannot have been sudden but was a gradual evolutionary process in which construction traditions, already experimented with during the earthquakes, found their formal definition.

In the Italian context this process of intentional and systematic reflection (and action) becomes clearly recognizable during the reconstruction of the centres destroyed by the great earthquake of L'Aquila in 1703. Recent Italian earthquakes (L'Aquila, 2009 and central Italy, 2016), which affected the same areas struck by the 18th century's event, allowed a direct study of the main characteristics of that reconstruction technique which, even though far from the rigorous systematic approach adopted by the Bourbon and Portuguese Governments, aimed at the same purpose of ensuring the building behaved holistically and can, for this reason, be considered an explicitly anti-seismic technique.

The purpose of this paper is to consider the relationship between this rudimentary anti-seismic technique and the more mature expressions of the late 1700s, proposing some introductory reflections on the geographical spread of construction techniques comparable to those abovementioned. It will further consider the impact of these techniques on subsequent developments, and their use in low seismicity contexts, including of the period in which these techniques were practised.

2 FROM LATE TO EARLY 18TH CENTURY

2.1 *The Gaiola Pombalina and the Bourbon system*

The *gaiola pombalina* technique is based on the creation of an internal three-dimensional wooden structure which, systematically bonded to the external masonry walls, would exert a common action against earthquake loads. It could be argued that buildings using the *gaiola pombalina* system are based on the coexistence of different construction techniques: masonry reinforced with embedded timber braced frames for the ground floor and façade walls, and a wooden load-bearing braced frame for the internal structure of the above-ground levels. The internal timber frame – which is at the core of the construction process – is made of timber floors and vertical panels (the so-called *frontais*) connected to each other by classic woodwork joinery and iron ties. The *frontais* are made of a trussed frame of organized elements creating rigid shapes (diagonal and cross bracing) and

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Figure 1. L'Aquila, chiesa delle Anime Sante, three courses of wooden radiciamenti in the drum of the dome.

using different types of infill material. The latter is essentially independent of the timber structure which alone fulfils the entire building's structural function.

The Bourbon technique, adopted for reconstruction after the 1783 earthquake, is based on the prototype conceived by Giovanni Vivenzio, the physicist appointed by the Bourbon Government to study the earthquake's damage. Both contemporary theoretical studies and direct observation of the local buildings' responses to the earthquake formed the basis of the prototype's conception (Tobriner 1983). Timber braced frames were conceived to realize wall structures quite similar to the Portuguese *frontais* (in this respect, the latter's influence on the Bourbon model has still to be clarified); but otherwise, these vertical panels were used both for internal and external façade walls creating a uniform three-dimensional system which differs from the "specialized" Portuguese one. Moreover, the Italian prototype proposes, at least for "the great walls of public buildings" (Vivenzio 1783), the doubling of these panels, their mutual connection by means of wooden transverse elements and their placement on either side of a masonry wall made of squared stones bonded to each other with iron cramps.

It is not clear whether the timber frame's doubling was provided for ordinary buildings too. What is certain is that the scarcity of timber and the possibility of reusing rubble stones of the buildings damaged by the earthquake led the engineer Francesco La Vega (entrusted by the Bourbon Government with the reconstruction) to simplify Vivenzio's model through an increase of the masonry component and the settlement of a smaller quantity of wooden elements inside the wall's thickness. In La Vega's directions the timber frames are reduced to the vertical and horizontal elements while the diagonal ones are maintained for the internal partition walls only. Therefore, the *baraccato* system – as it became known from the 19th century – can be considered, partly in Vivenzio's first definition and definitely in the practical applications of the reconstruction, a pure masonry construction system within which wooden elements reinforce and connect the structural elements.

2.2 *The post 1703 L'Aquila technique*

The construction technique employed after the 1703 earthquake – which we want to compare with the late 1700's methods briefly described above – has been recognized thanks to the examination of buildings damaged by the earthquake which struck L'Aquila and the neighbouring areas in 2009 (Figure 1); confirmation and further observations on the areal extent of this technique have been deduced from the seismic sequence that occurred in central Italy between August 2016 and January 2017.

The *radiciamenti* are wooden logs embedded in masonry walls. Their role is to work in the building as real belts – to use a term referring to the similar, though more refined, Greek system known as *imantosis* (Figure 2). The features which distinguish the various practical applications of these devices (and which are usually strictly linked to the general construction quality of the building) refer both to the different level of finishing of the elements and their relationship with the masonry's assembly. In modest buildings it is possible to observe rough wooden elements whose mutual connection is entrusted to the sole timber, without the use of iron nails or ties (Figure 3); in more significant buildings the *radiciamenti* are made of dressed wood and are directly connected to the orthogonal wall by means of metal anchors

Figure 2. L'Aquila, chiesa di S. Giuseppe Artigiano, the metal anchors located in the corner walls connect the wooden 'radici- amenti'.

Figure 3. Villa S. Angelo (AQ), wooden *radiciamenti* placed in the thickness of corner walls.

(Figure 4). Their position is always dependent on that of doors and windows to ensure a continuous hooping system. It is not uncommon to find them associated with vaulted structures at the height of the haunch to counteract the horizontal thrusts.

The *impalettature* are elementary wooden devices that improve the support conditions of the roof structure. They provide an anchoring system that integrates the structural elements' interlocking aims of the technique.

With reference to the context of L'Aquila, trusses equipped with such devices working as constraints for the supporting walls are quite common (Figures 5–6). Similar devices were not seen in central Italy during analysis of the 2016 earthquake's damage. Their absence could be due to the recurring roof replacement practices undertaken in the wake of the Valnerina earthquake in 1979.

Although not the specific subject of the reflections here presented, it is worth noting that recent studies (Aloisio, Fragiacomo & D'Alò 2019) have highlighted further traits which might be included in this construction technique: timber frame walls made of vertical studs – both load-bearing and partition walls but mostly internal – were found and seem to

Figure 4. L'Aquila, chiesa di S. Flaviano, metal anchors of façade 'radiciamenti'.

Figure 5. L'Aquila, wooden anchors of the roof trusses.

suggest an even closer proximity to the mid-century codification.

2.3 *Comparisons*

The overall structural concepts – and geographical proximity – suggest how the anti-seismic technique of L'Aquila has a closer correlation to the Bourbon system. As a matter of fact, both techniques appear to be essentially masonry techniques in which, as opposed to the Portuguese system, wooden elements work jointly with the masonry walls, and not as independent structures. This underlines the importance of masonry work's quality for the system's efficacy. However, these wooden elements only work in the presence of horizontal forces (regardless of thrusts against vaulted structures or earthquake activity).

Figure 6. Detail of a wooden anchor connecting the roof trusses to the external wall.

What mainly sets the techniques apart is that the early 18th century technique provides for a simpler – in a sense, more elementary – configuration of the wooden material which is, to our knowledge, limited to the creation of horizontal elements. That appears to relate to these techniques' different aims: the first, essentially a reconstruction technique, appears to be suitable both for the construction *ab imis* of new buildings and, more frequently, for restoring earthquake-damaged buildings by reusing the remaining structures (usually the lower floors) and connecting them to the new completion. The second, the Bourbon system is, instead, a prototype for new buildings whose construction solutions do not need to be adapted to pre-existing configurations.

The difference between the two construction techniques seems to be coherent with an evolutionary interpretation where the Bourbon system represents a mature and normalized variation of the earlier L'Aquila system. Its most relevant outcome lies not so much in the connection between the different elements' efficacy as in the walls' in-plane strength. Recent earthquake activity has revealed the technique to be rightly tailored for that area's seismic severity, although a better or, more precisely, different quality of the Bourbon system is unquestionable. It is indeed true that the *radiciamenti* of L'Aquila technique can work as orthostats increasing the walls' shear capacity, but this improvement is not comparable to the one obtained by the trussed frames of the *baraccato* system.

The global seismic response of these systems is also affected by other factors: the quality of the masonry works (discussed later) and constructional organisation. The early 18th century system, theoretically less effective, would reveal itself more ductile than the turn-of-the century one.With reference to this second aspect, it is worth noting that the Bourbon system's strictly prescriptive nature and complexity made its effectiveness heavily dependent on the accuracy of the construction process: a rough execution could be the cause of an entire system's impairment – the more damaging, the greater differentiation from the prototype's specifications. In fact, buildings where the presence of wooden frames were not associated with their appropriate connection were observed (Tobriner

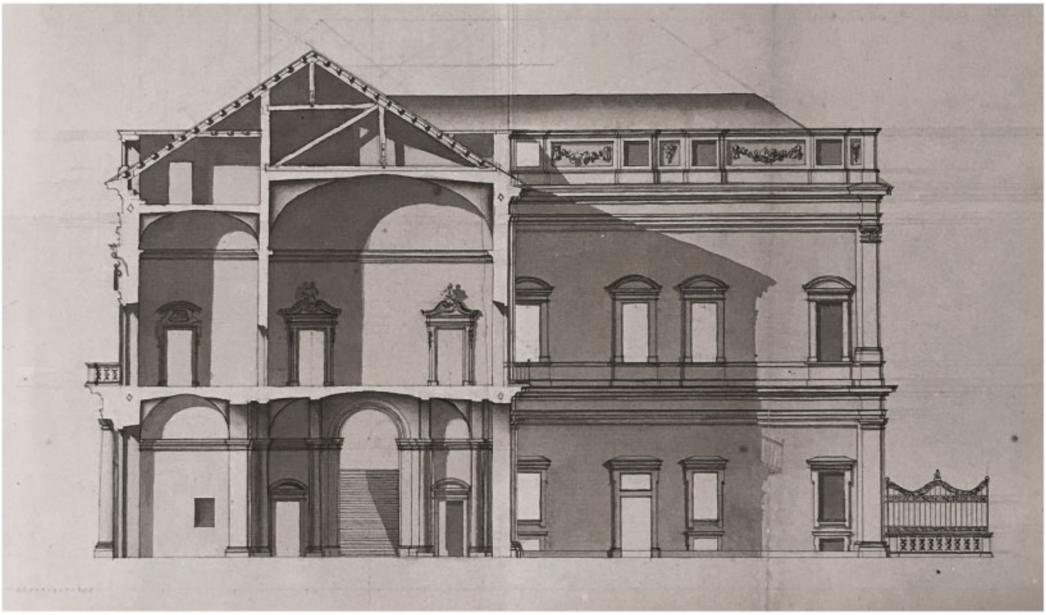

Figure 7. Transverse section of a palace (Palazzo Giriodi, Costigliole Saluzzo?) by B. Vittone's atelier (ca. 1740) showing a two-level order of *radiciamenti* (Musei Civici, Turin, coll. Vandone). Courtesy of E. Piccoli.

1983); Vivenzio himself had identified this kind of hidden danger warning that "the enormous complexities destroy the entire building's strength" (Vivenzio 1783).

L'Aquila technique, on the contrary, because of its uncoded character and its "essential" nature, appears to satisfy the performance aims in a more reliable way adapting the anti-seismic requirement to a consolidated local construction tradition: when some ineffectiveness of the technique has been surveyed, it was ascribable to subsequent transformations and not to some intrinsic fragilities of the system.

As regards the masonry work's quality which, together with that of the wooden elements, is essential for the anti-seismic efficacy of both systems, similar observations can be made with reference to different geographic areas, despite the differences in local construction techniques and the century which separates their development.

The introductory study carried out by Vivenzio in the wake of the 1783 earthquake had already noted the inadequacy of the typical building materials used until then: the *brest* or *bisari* (that is mud-and-straw bricks), rubble stones and poor-quality lime. The same criticalities had been later noted and confirmed – maybe with a more persuasive interpretation both based on the nature of the materials and their assembling – by the committee responsible for drawing up the standards in the wake of the 1908 earthquake which affected the same area (GGC 1909). Despite the suggestions provided by Vivenzio, some of which were integrated within the reconstruction regulation issued in 1784, and the cost savings which led Francesco La Vega to simplify the original prototype, those same materials belonging to the traditional construction technique were indiscriminately reintroduced during the reconstruction. These circumstances clearly undermined the buildings' seismic resistance ensured by the earlier use of timber frames and re-established the condition of fragility of the local construction technique which was, in fact, observed again in subsequent earthquakes (Tobriner 1983).

In a similar way, wooden bond elements (*radiciamenti* and *impalettature*) belonging to the early 18th century technique were defenceless against the 2009 and 2016 earthquakes when embedded in low quality masonry walls, which ruinously collapsed. But, at the same time, they turned out to be essential in raising the seismic capacity for those buildings where mastery of masonry construction had balanced the poor quality of local materials allowing the creation of state-of-the-art walls, which survived.

3 FROM HIGH TO LOW SEISMIC HAZARD AREAS

The 18th century construction technique which has been outlined in its essential traits could probably be considered an enhancement – promoted by a new "rational" awareness of the earthquake, not surprising in the favourable cultural climate of that period – of a technique already widely diffused, even in areas characterized by low seismic risk. In fact, construction systems conceived regardless of earthquake activity – but aimed at strictly connecting the entire building, not necessarily to counteract the vaulted structures' active thrusts – could have been recognized as anti-seismic devices once awareness of the earthquake's damage modes on historical buildings had been reached.

The practice of wooden elements to connect the entire building organism is attested in northern Italian regions, and specifically in the Lombard area, from the 16th and 17th centuries (Della Torre 1990).

Regarding this practice, it has been said that it exemplifies a gap between architectural theory and construction-site practice, the former being attested on an ideal of masonry buildings able to stand by themselves, without the "*stringhe*" (laces) condemned by Vignola, while the current technique has employed different materials' ligatures continuously since the Middle Ages. However, the issue is not so simple, and examples can be found (Villani 2009) in which the need for connections stronger than those based on simple masonry bonding is not only exploited by expert masons but also recognized by architects involved in practical as well as theoretical activity (Figure 7).

Whatever the case, this very ambiguity is significant. It shows the existence of an evolutionary process in which building traditions selected by trial-and-error in ordinary conditions were recognized, from a certain point onwards, as equally effective to resist earthquake activity.

Such a process seems to be echoed in the lexicon's evolution. The oldest terms used to define wooden reinforcing devices – "*chiave*" (key) or "*ligato*" (binder) – refer to single elements with basically a local nature. They are systematically replaced, in Venetian and Lombard sources of the 18th and late 18th century respectively (Concina 1988), with the far more expressive "*telaro*" (frame). From as early as the 17th century, the new term has a wider meaning and precisely indicates a skeletal wooden structure working together with the masonry organism and somewhat affecting its "global" structural behaviour.

In the same period the term is recorded in Piedmont. In the citadel of Alessandria, a huge construction site of the second half of the 18th century in the Kingdom of Sardinia, a *telaro* "to be formed both lengthwise and across with large red oak logs" (Piccoli et al. 2018) is embedded in the perimeter walls of the barracks and its technical features shows surprising similarities with the aforementioned Lombard cases.

Just think of how wooden elements are joined to each other by means of nailed metal strips (*grappe incavigliate*) for *radiciamenti* longer than the available wooden logs; or timber is replaced with metal bars (*lamoni*) in relation to the chimneys (Figure 8).

But what sets this Piedmont example apart from the Lombard cases cited in Della Torre (1990) are not so much the construction aspects as the general purpose of the system as a whole. Such a system indeed no

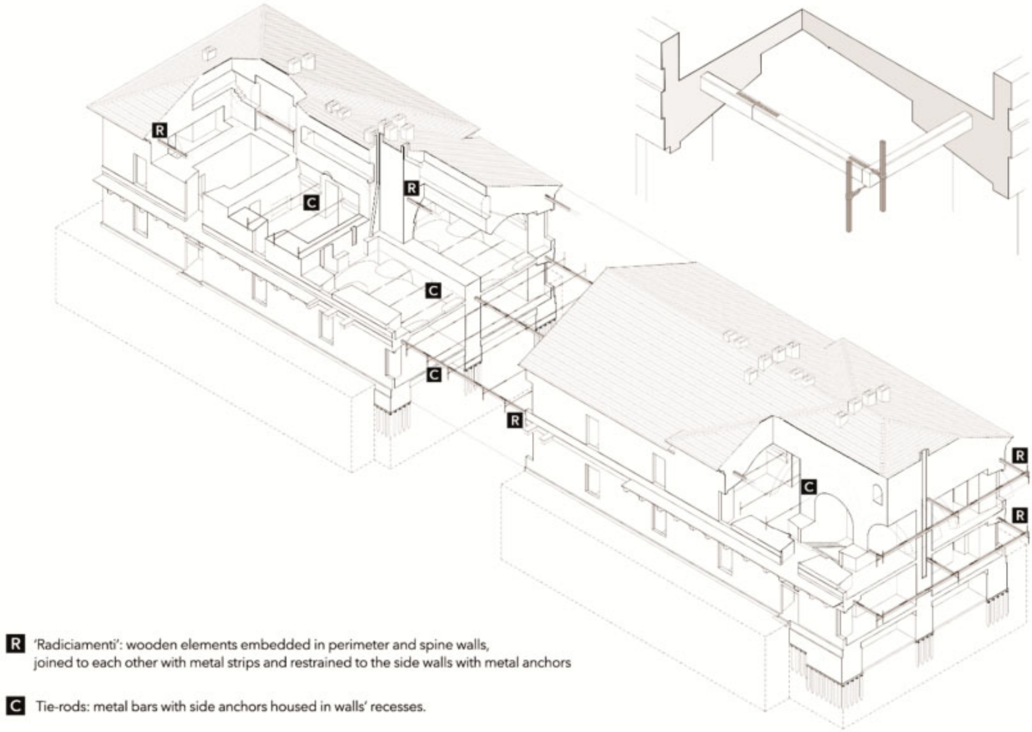

Figure 8. Citadel of Alessandria, the wooden *radiciamenti* and metal tie-rods as an overall connection system for San Tommaso barracks (1749-59). (Rossi 2019).

longer serves to counteract the thrust of the vaulted structures (for which a dense system of metal tie-rods had been designed) and represents, instead, the answer to a new problem, which is similar to the one we are discussing in this paper.

The Alessandria barracks had been designed to be "bomb-proof", a structure that needed to be impenetrable to cannonballs and stable against the actions induced by their impact. The first is obtained by increasing the thickness of the walls, the second by ensuring that all elements act as a whole, introducing more efficient constraints than those deriving from simple bonding (the *radiciamenti*, indeed).

The "bomb-proof" requirement invokes dynamic actions, which were explicitly taken into account by military engineers in an extraordinary mathematical discussion that took place late century (Piccoli & Tocci 2019). Just as dynamic was the result of the earthquake, whose effects in the early 18th century were evidently clear for those who rebuilt damaged areas in central Italy, even if they could not yet attempt any theoretical reflection (which started soon afterwards – Barbisan & Laner 1983). Similarly, the vibrations induced by carriages, which Rondelet had thought of, at the end of the same century, led to the introduction of nothing but metal *radiciamenti* (or *telari*) in order to increase the stability of buildings.

But at the dawn of the 19th century, in the high-risk seismic area of southern Italy, the *radiciamenti* technique had already turned into that extraordinary anti-seismic system that is the "*casa baraccata*". Outside of this exceptional context, and especially in low seismicity areas, the technique maintains its original configuration, only within a formulation by now mature and perfectly recognizable in its anti-seismic intent. It is in Piedmont that we can still find some interesting examples. In the early 1800s the technique of "*racinnements*" is used – together with a refined tie-rods' arrangement strictly cooperating with vaults and roof trusses – as a connection system for the Waldensian temple in Luserna San Giovanni, at the foot of the Cottian Alps (Ravera 2019). Just two years after the temple's completion, the same technique, using a smart metal transposition of the original tying wooden system, was proposed by the French architect Philippe Ghigliani to repair the damage caused by the earthquake which affected the valley of Pellice in April 1808.

This was not an isolated case, as evidenced by the widespread presence of metal *radiciamenti* in Turin buildings (Figures 9-10-11).

Already known in the 1700s – as we have seen with the Savoy military construction yards – at least for huge public buildings (where it is clearly recognizable due to the local habit of exposed brick facings) the presence of the *radiciamenti* seems to have no presence in residential constructions that constitute the backbone of the 19th century town expansion.

Figure 9. Turin, anchors of façade's metal *radiciamenti* emerging from recesses housed in the transverse wall.

Figure 10. Montalenghe (TO), metal anchor recessed in the masonry toothing revealing the presence of a metal tie-rod in the half-width of the back transverse wall.

The presence of the INA-casa specifications defined as *radiciamenti*, the reinforced concrete ring beams resting on load-bearing masonry walls and supporting the joist slabs with hollow tiles, in the 1900s provides evidence of the prevalence of a construction practice that, tackling the root of masonry building issues (which can be summarized in the inherent weakness of connections), had become the most effective response to earthquake activity, (Barelli 2020). Despite the material (timber, iron or reinforced concrete), it is evident that the function was (correctly) believed to be the same.

4 CONCLUSIONS

The evolutionary process outlined in this report – which from a set of uncodified construction practices (recognised in territorial contexts which differ in building technique and earthquake intensity and frequency) would lead to an expressly anti-seismic normative system – certainly deserve to be investigated in detail.

Figure 11. Turin, the closeness to the façade edge of the metal anchor reveals that the corresponding tie-rod is embedded in the orthogonal wall.

This process should, first, try to define more precisely the geographic scope and time frame within which it is possible to find the first (even if embryonic) appearance of what, with time, was to become an anti-seismic technique. For this purpose, the large existing literature (Langenbach 2007; Touliatos 2016) could be examined to highlight similar cases across different territorial contexts which reveal the connection between construction practices and awareness of the destructive potential of earthquakes.

The scepticism expressed more than 30 years ago by Emanuela Guidoboni is probably still justified today regarding the possibility of finding traces in "the great earthquakes of 1117, 1169, 1222, 1348 […] for considerations or dispositions dealing with measures against earthquakes' effects [or] subsequent devices incorporated into the practice of building techniques, which could be interpreted somehow as preventive measures for future damage" (Arrighetti 2015).

Nevertheless, the recent strong Italian earthquakes (L'Aquila 2009, Emilia 2012, central Italy 2016) unveiled a technique that indisputably contains "preventive measures for future damage" about which nothing of its real spread and anti-seismic efficacy was known until then. They further demonstrate how the same traces are just waiting to be systematically documented for seismic events immediately following those discussed which we linked with the great earthquakes of the early 1700s. In this respect post-earthquake restoration works could continue providing precious documentary evidence – as referred to here – supported by systematic interpretation of the data obtained.

At the same time, it seems inevitable that the approach adopted in this work, based on the gathering of information from single buildings, construction sites and experiences in accordance with the typical method of construction history, will continue at the expense of large syntheses of anthological collections.

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