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Review Article

Structural Uses of Stone and Timber in The European Historical Construction

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Abstract: This paper investigates the stone masonry with timber reinforcement through Europe. It is a remarkable practice, either historical or contemporary, consisting of combining different materials to build up a masonry. This technology shows a wide variety of typological, formal, and technological types of buildings across Europe as it is strongly influenced by the nature and availability of local materials, the cultural aspects of the various communities, and the soils geological nature. As a consequence, the same constructive typology is based on different premises and leads to many interesting results. In this paper, the various uses of such a mixed stone-timber masonry are shown in relation to the above-mentioned factors. It is important to stress that this traditional technology is also highly contemporary as it is highly exploited in many countries. Furthermore, novel regulations have been issued to regulate such a discipline. Finally, as a very common constructive technology, many historical buildings present such a mixed structural configuration, independently from the generating factors. In such a perspective, this study aims to describe the most common constructive features, as well as develop guidelines for preservation, whereas the typology is present, or design criteria for consolidation and structural improvement, whereas necessary.

Keywords: *stone; masonry; timber; constructive technology; construction material*

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0 Introduction

The use of structures made by mixing together different materials is not something new to the history of construction. Indeed, already in the ancient times, the primitive sheds were built by natural stone and wood, conveniently arranged and following empirical rules of statics depending on loads and stresses[1]. A well-established building practice is using materials with complementary features to improve the overall mechanical resistance and, as a consequence, the stability of the whole building. The most actual example is the well-known reinforced concrete where the concrete's high resistance in compression is integrated by the bending strength of steel.

Reinforced a stone masonry with some timber elements is an amazingly variegated practice belonging to the traditional/historical construction. However, many countries still exploit such a technology in a contemporary way. More particularly, in all the European countries such a mixed stone-timber masonry could be encountered and, considering the huge differences between the various regions of the continent, it shows many differences in usages' aim and technology. Indeed, technological, formal and typological types of buildings vary considerably across Europe as they are strongly influenced by many factors such as nature and availability of construction materials, geological conditions, as well as regional cultural and historical backgrounds.

A primary factor is the geology of the soils. Europe is a large continent crossed by many seismic faults that characterize its various regions from highly seismic to completely stable. Indeed, the active faults are about 1.100, for a total length of about 64.000 km. Seismicity tends to decrease when moving from the Mediterranean areas to the north side of the continent; thus, a huge variation is shown through the different countries [Figure 1], which in turn leads to various usages of the same mixed constructive technology. All the Mediterranean areas, where both stone and wood are easily available, use such a mixed technology to primary realize a structural seismic improvement, as a consequence of the geological features. In this case, the masonry is built by means of the insertion of a three-dimensional timber frame embedded in stone masonry to bind together the various parts and contribute to the overall seismic resistance. This system is very common in Italy (*Casa baraccata*), in Portugal (*Pombaline gaiola*), in the Greek and Anatolia areas (Turkish *hımış*), etc. Going toward the north of Europe, the overall seismicity tends to decrease - as in France, Germany, or United Kingdom - thus such a mixed technology begins to lose its function of seismic prevention to become a simple way to exploit the different mechanical performance of the two materials. Contemporary, a larger availability of wood, due to the vast extensions of forests that are not that present in the south of Europe, makes it easier to use more timber as a partial stone replacement. Beyond the minor costs of wood transformation in construction material if compared to stone. Furthermore, northern colder countries, as the Baltic or the Scandinavian ones, need some materials that, along with their structural performance, may contribute to the overall thermal insulation. Thus, the use of timber is greater to the detriment, or even exclusion, of stone.

1 The early examples of mixed stone-timber masonry usage

The first eminent usages of timber reinforcement in construction dated back to the Roman times with the *Opus craticium* [Figure 2]. Such a technology consisted in a timber framework, made of reeds or brushwood fastened tight by means of cordage, that acted as a sort of armor within the stone masonry and allowed to build bearing walls as well as light partitions[3,4]. At every attic level, a long horizontal sleeper-beam was located to better distribute the vertical loads and makes the usage of shorter vertical columns possible; horizontal and diagonal elements were used to stiffen the whole structure making it crushproof along with distributing the loads in a suboptimal way[5].

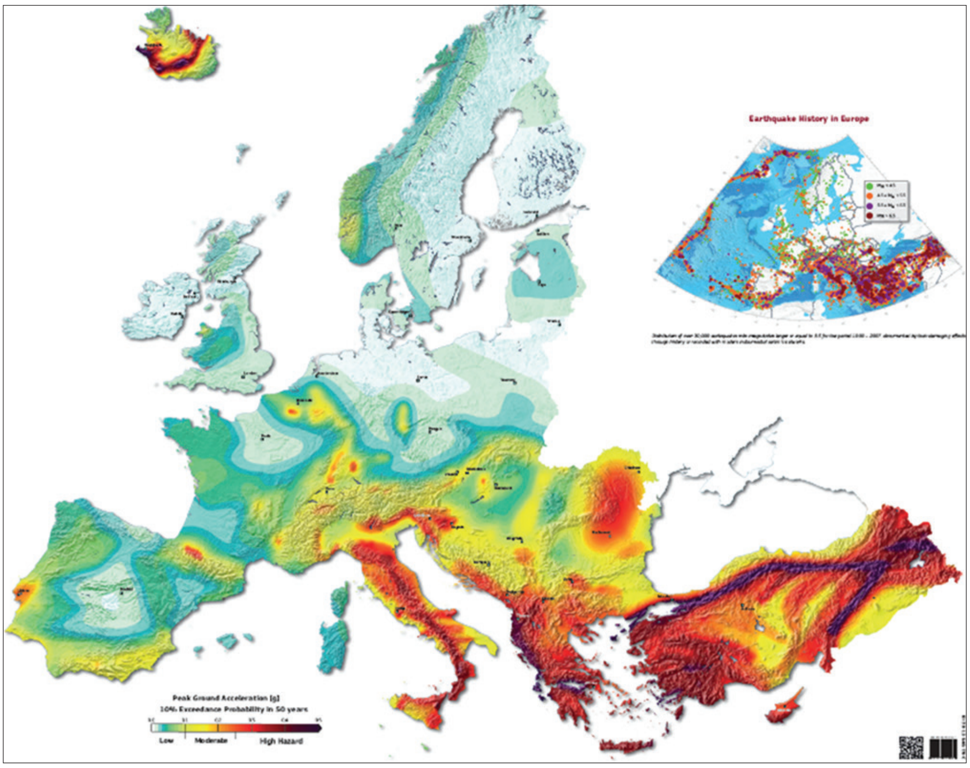

Figure 1. European seismic map. The most exposed countries are in the Mediterranean and the Balkan areas[2]

Figures 2. (a and b) Opus craticium: Particular of a wall (left), House of Frameworks in Herculaneum (right)

2 The mixed stone-timber masonry in the Mediterranean and Balkan area (half-timbering technology)

As already discussed, among the European areas the Mediterranean and the Balkan regions are the most active from a seismic point of view. An earthquake is a disastrous event not only because many persons may lose their lives but also because a large part of the built heritage usually undergoes deep damages, sometimes real collapses. Following such terrible events, unfortunately quite often during the centuries in these areas, buildings have been restored, reconfigured or completely rebuilt, depending on the damages. On the other hand, earthquakes immediately show the structural points of weakness or strength in a building. Thus, in a certain way, they represent an exceptional way, even if disastrous, to verify the constructive technologies used in a specific place in relation to the instances of expected structural performance.

During centuries, the Mediterranean region has developed various "anti-seismic" devices, conveniently chosen observing and analyzing the surviving or less damaged structures. In general speaking, the structures using timber frameworks usually survived to earthquakes, or suffered from less damages, thanks to the elastic behavior of wood, if compared to stone that is the most common historical construction material. As a consequence, the mixed stone-timber masonry, the half-timber technology, as a sort of compromise between tradition and immediate emergency, resulted the best way to reconstruct or rehabilitate any damaged building. Furthermore, wood made such operations faster and easier thanks to its versatility, easy availability, reduced costs, and fast manufacture. Very often, indeed, we can observe many timber devices (frameworks, chains, tie-beams, supports, shelves, etc.) used as masonry reinforcement in historical buildings as seismic prevention systems. Such a constructive system was usually realized by means of the insertion of a three-dimensional timber frame embedded in stone masonry to bind together its various parts and contribute to the overall structural and seismic resistance.

In the western Mediterranean area, the most significant examples of timber-frame constructions can be observed in southern Italy and in Portugal where most of the earthquakes occurred. More particularly, in the Bourbon Reign of the Two Sicilies the advanced studies on anti-seismic science gave birth to the typology of framed-reinforced house, the so-called *C. baraccata*[6]. The Bourbon government was also responsible for the first anti-seismic normative dealing with urban and building reconstruction. Beyond the overall urban asset and the infrastructural system equipped with large streets and squares designed to accommodate people in the case of a disaster, the collapsed structures must be rebuild using a masonry "(…) with an inner frame of large trusses (…) fasten by other transversal beams (…)"[7] [Figure 3]. Such a structural typology was designed by the military Spanish engineer La Vega who was in charge of the excavation of the Roman ruins of Herculaneum and Pompeii.

Important scientists/engineers of that time were Pirro Ligorio (1513-1583), Francesco La Vega (1737-1804), Giovanni Vivenzio (174?–1819). All of them, notice that wood could be bend without virtually breaking thanks to its high elasticity. Thus, it was ideal to resist to seismic waves. Furthermore, a part from the low cost and the fast construction, a building with a (partial) timber structure was more homogeneous and continuous as well as lighter and less dangerous in case of ruin.

In Portugal, the most famous anti-seismic device is the so-called *P. gaiola* [Figure 4]. It is a timber frame system used to reconstruct the city of Lisbon after the great earthquake of 1755, one of the most disruptive

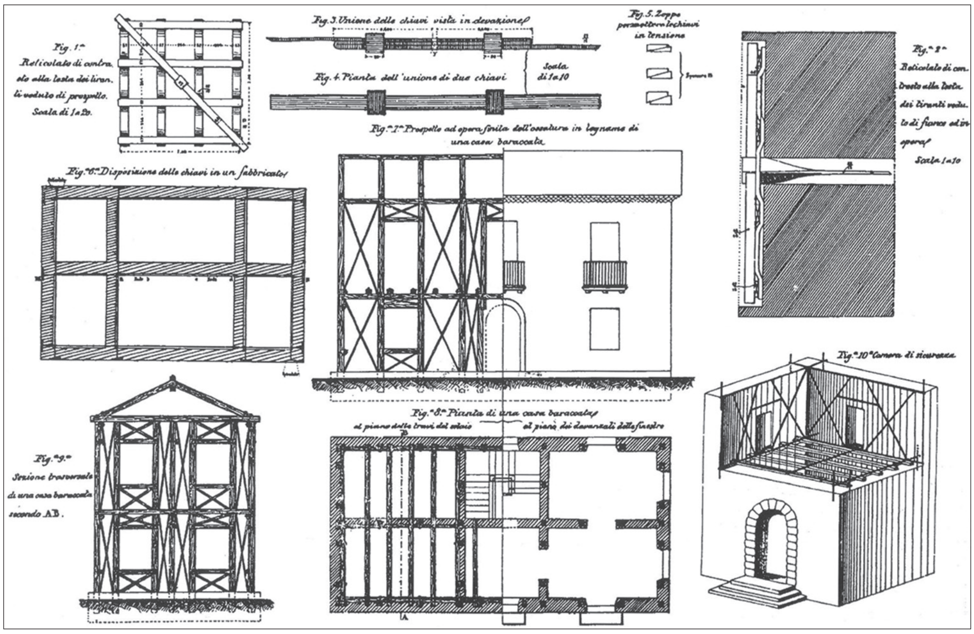

Figure 3. Studies of timber framework for seismic reinforcement[8]

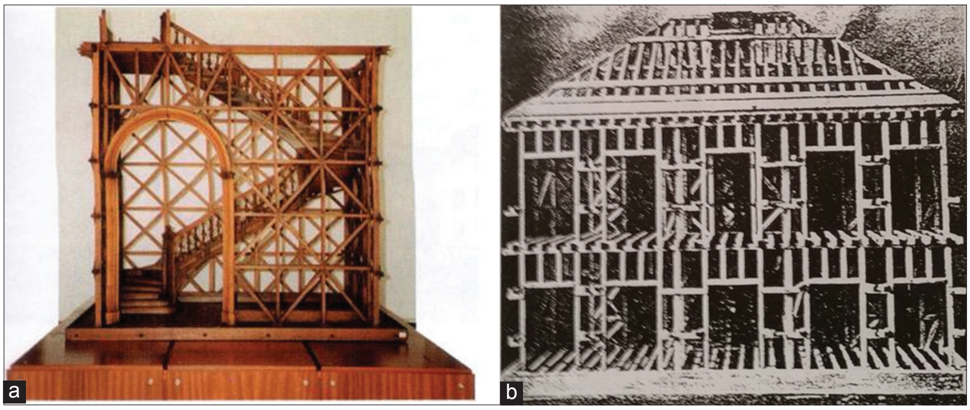

Figure 4. (a and b) Schemes of the *Gaiola* system: Reconstruction of a *Gaiola gaiola* (Instituto Superior Técnico de Lisboa) (left); structural scheme of a Pombaline building, using the *Gaiola* system (right)

natural events in European modern history[9]. Once again, it derived from the high technological level reached after the many past earthquakes[10,11]. The object of the pragmatic of the "Prime Minister," the 1st Marquis of Pombal, was the structural technology to be adopted in the reconstruction practice. Indeed, new buildings' masonry had to be reinforced by an inner wooden symmetrical cage, the *Gaiola*, aimed at distributing the seismic loads, and enforced by inter-terrace walls of about 50 cm in thickness and without any opening. In other words, such a framework provided strength to horizontal loading and higher capacity to dissipate seismic energy. It is notable that in the case of an earthquake, the timber framework might have supported the slabs and the roof, if the stone walls had ruined down, thanks to its structural independence from them. The timber framework elasticity granted to the cage an enormous ultimate resistance. Moreover, it was highly flexible thanks to a system of columns, beams, architraves, and rafters perfectly joined by means of dowels, tenons, and connections made of wood themselves and, finally, embedded into the walls through particular nuts[12,13].

In the eastern Mediterranean area, similar solutions are observed from the inner Anatolia to the Balkans and Greece, with slight differences, especially in terms of infill/cladding materials/types. The region of Turkey has experienced frequent seismic events that were easily overcome by the traditional vernacular hımış [Figure 5][5,14]. Typologically, the Turkish traditional architecture is characterized by a ground floor made of stone bearing walls that are often laced with horizontal runner beams, and the upper floors made of an infill construction: A timber framework and a masonry infill,

Figure 5. (a and b) Traditional buildings in the historical center of Antalya (Turkey)

the *hımış* precisely, that is sufficiently light to allow the typical bays and jetties overhanging the streets[15,16].

3 The mixed stone-timber masonry in the western and central Europe (timber-framing technology)

Going toward the north of Europe, the general seismicity tends to decrease even though some areas of great activity still remains [Figure 1]. In these countries - Switzerland [Figure 6] France [Figure 7], Germany [Figure 8], or United Kingdom [Figure 9] - the mixed stone-timber masonry constructive technology begins to lose its primary function of seismic reinforcement, or prevention, as we saw for the Mediterranean basin, to become a simple way to exploit the different mechanical performance of the two materials. More particularly, the most of the loads are absorbed by the timber structure itself. The so-called timber framing constructions (also known as "post-and-beam" or "box frame" constructions - *Fachwerk* in German) are characterized by a structure made of "heavy timbers:" Posts and beams indeed. The structural units' manufacture, underneath such a constructive technology, consists of manually cutting the tree trunks to obtain the desired elements. Then, by means of laborious woodworking, they are gradually assembled until building the entire structure. Such a construction is obviously affected by local traditions and customs, then many styles and variables may be observed. The first examples are dated back to the XIII century, and the methodology has been improved during the time to reach absolute perfection in creating the most extravagant structures, erected by a rich middle-class, that joined together structural instances with the need of excelling in extravagance. The timber-framing technology has been exploited till the end of the XIX century to be subsequently imported to the Americas during the early XX century where local materials were then adapted.

Architectural styles, configurations, and materials obviously varied among the various regions even though they influenced each other so much that it is possible to find some common factors in very far places. The usage of the timber-framed structures terminated during the age of Enlightenment for two main reasons. First, the new taste for neoclassic could not find in the extravagant forms of the medieval carpentry a reason to exist. Indeed, they were too much irregular, asymmetric, and antimodern. Second, the novel compositive rules of symmetry, uniformity, and sobriety, inspired to the classical age, introduced new constructive rules that foresaw the exploitation of stone rather than of wood, more subject to the risk of fire.

Usually, the whole building stands on a basement made of a "traditional" stone masonry that was then used to wedge many squat and short vertical column aimed of support the horizontal beams of the first floor. Subsequently, the main framework, made of horizontal and diagonal trusses, is erected to generate the flooring structure [Figure 10, left]. Sometimes, a planking level might show an autonomous beam to create some jettyings. Such a medieval technology showed many advantages as gaining more space in the building without obstructing the street and sheltering the lower walls from the aging actions of the weather. It also has a structural advantage as the protruding

Figure 6. (a and b) Zurich and Marthalen

Figure 7. (a and b) Troyes and Coupesarte Manor (Normandy)

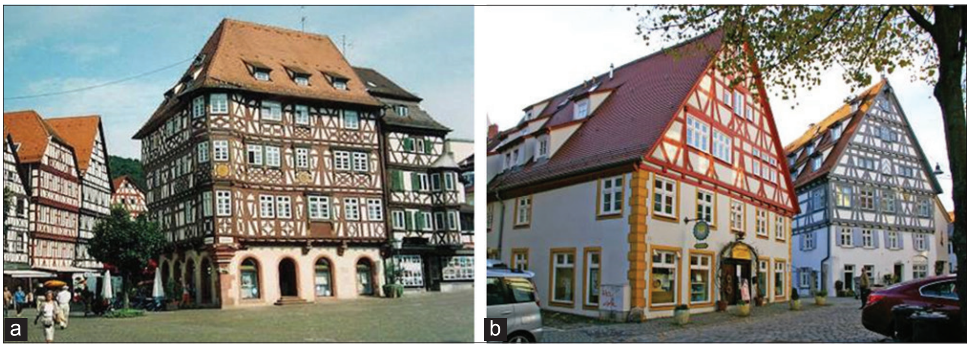

Figure 8. (a and b) Mosbach and Fischergasse

Figure 9. (a and b) Chester and Salisbury

walls counteract the forces in the joists and tie the stone walls together by means of short and robust timbers blocked by simplified joinery. Once the main structure has been assembled, the empty space between posts and beams was usually filled in with a net of thin branches, twigs, or even dried grass, mixed with small pieces of stone, usually pebbles, or bricks. Finally, the surfaces were coated by a layer of clay or natural lime mortar, generating the articulate façades that are visible from the streets[17]. In general speaking, the size of timbers, the façade composition, along with possible jettyings or other elements, acted as a status symbol[18]. Indeed, such elements were usually related to workmanship quality and ability of exploiting complicated timber framing carpentry [Figure 10, right].

Finally, it is possible to divide the timber framing buildings into three main typologies, based on temporary-stylistic parameters. The first buildings' typology, spread in the medieval times, showed a clear and organized structure with distanced columns, long diagonal beams, and short buttresses. Joint was usually made by means of chocking and wooden nails. Thanks to the increasing business activities and the novel markets, a greater financial availability lead to experimentations and more spectacular architectural configurations, less linked to statics and structure. Thus, the structure became more complex and packed with more intensive use of long beams, crosses, and joints made of pivots and dowels. At the same time, bow-windows and slim pinnacles and towers appeared. The structural complexity made the façades completely independent from it, by means of the possibility to use various structural elements to join the figurative/ornamental parts: Bent Saint Andrew's crosses, curved and oval struts, polygonal figures, etc. Finally, the last category, following more rational and late ideas, consists of a simpler configuration in terms of structure, with regular distances between the various columns or beams. However, the iconographic apparatus became extremely rich and completely disconnected from the structure letting the constructive fantasy flew.

4 The timber-framing technology in the north-eastern Europe

The north-eastern Europe is divided among many different small countries whose building practice present a huge variety of typologies and constructive technologies. However, it is possible to trace a common cultural root that is the strict relationship with nature and, more particularly, an absolute respect of the forests. Such a common background may be retraced in the ancient pagan religions that assigned a sort of holiness to woods and forests. Indeed, they represented real places of worship, of ritual sacrifices and the places where the divine presence used to reveal itself. As a consequence, such sacral places were preserved, and the buildings made of their wood assumed a sort of sacredness. As the Christianity spread out, all those believes were put aside, but a sort of mystery remained in a common feeling. As a consequence, the new buildings, in most of the cases of religious nature, were built in perfect harmony with the surrounding natural environment. Therefore, such a northern area saw a capillary diffusion of log buildings thanks to the large presence of forests, that in other words, meant of wood availability. Furthermore, wood often represented the only available construction material [Figure 11]. Wooden buildings were predominantly built using coniferous trees that were the most diffused, such as pines, spruce pines, and larches. Indeed, those trees are the most suitable as construction materials thanks to their few constitutive defects and intercellular gaps filled with resin. Accordingly, this timber is more resistant to decay, has more constant coloring and

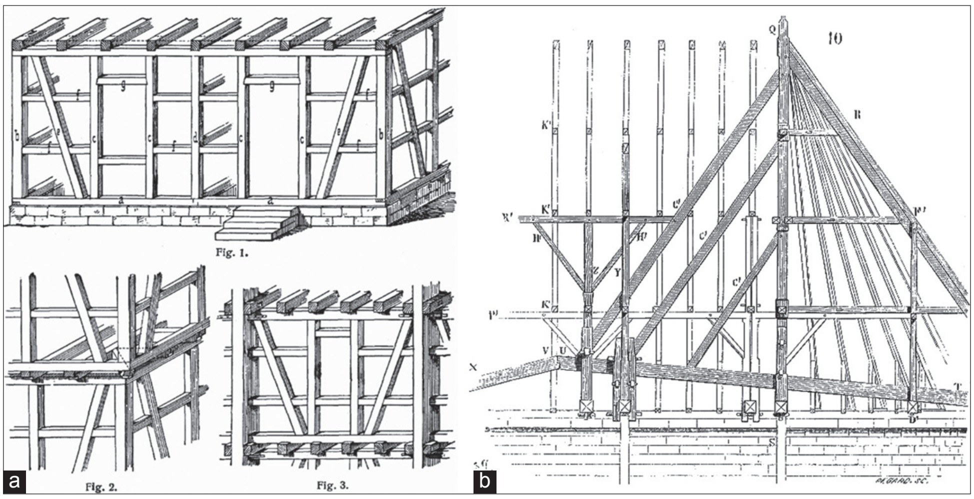

Figure 10. (a and b) Left: Image of timber framing from the *Lexikon der gesamten Technik*[17]. Right: Image of the carpentry used in Notre Dame in Paris[19]

texture, and is easier to cut and plane. Coniferous wood is quite light and flexible and shows a relatively short period of maturation. Furthermore, at those latitudes, such a species can grow to a height of about 30–40 m, with a 1 m in diameter trunk. Coniferous wood, especially the pine one, is used for all load-bearing structures (logs for foundation, structure of wooden vertical walls, beams and isolated supports, roofing systems, frame structure of bell towers, etc.). Pinewood is also used for technological finishing and external covering (internal and external coating of the wooden vertical walls, and the roof coating) and the manufacture of doors, windows, and external fences.

Thanks to such a large patrimony of natural wood, the north-eastern Europe shows a considerable number of log-buildings. Among the various typologies, the religious ones are the most interesting for both their historical value and the richness of constructive technologies applied as well as the decorative elements. Churches [Figures 12 and 13], and especially the Catholic ones, are characterized by a formal simplicity and clear functionality, with an interesting usage of timber structures that, at same time, assume the role of finishing, decoration, and even furniture[20,21]. Here, the use of stone is quite limited, often to the foundations only.

The majority of the oldest buildings have been erected without any foundation, but directly on the soil. Only in a few cases a sort of foundations, made by durmast or coniferous trunks rooted into the ground, can be observed at the corners or in the center of the building [Figure 14, left]. Along with the constructive technologies developments, foundations started to be built using isolated stone blocks or an embankment of small stones, bind with lime mortar and soil [Figure 14, center]. Subsequently, foundations began to be built as a real underground wall with proper ashlars layered with lime mortar [Figure 14, right). Usually, such a stones, either large or small, were extracted directly *in loco*, or as closer as possible to the construction site, to avoid the high expenses and difficulties of transportation among hills, mountains, and forests that is often the only usage reported for stone masonry in such an areas. The trunks, that were located directly in touch with the stone foundations, were subjected to a fast degradation, due to the ground humidity, and water capillarity. As a consequence, highly resistant wooden species were usually used such as the oak wood.

The most common structural systems used from the high middle age were the *Fachwerk* and the *Blockbau* technologies[21,22] [Figure 15]. The first one was characterized by a vertical disposition of the trunks within a frame structure. This system involved a limited number of timber elements. The *Blockbau* technology consisted of a horizontal disposition of the trunks that were then framed at the corners. Archaeological studies have demonstrated that the *Blockbau* technology is the oldest system, also considering the higher easiness of the process that did not require complex joints or nails. In general speaking, in the coldest areas the timber elements usually have larger sections and overall buildings dimensions basing on the characteristics of the used wood and the availability of long and thick trunks. The oldest vertical structural elements exploited timber sections of about 20 cm. The best results, in terms of both structural efficiency and architectural harmony, were reached when the trunks tended to have a constant section (parallelepiped section), without any significant enlargement or narrowing in the length. If such an ideal situation was not possible, then larger and smaller sections were arranged alternately.

Finally, the external walls were made of the same structural elements, in the oldest buildings. Later only, the external envelope was realized by means of wooden board to protect the structural components from the external element (rain, wind, humidity, etc.). At the same time, such a finishing assumed the function of

Figure 11. A state park in Lithuania, representing a typical natural environment of the north-eastern Europe

Figure 12. (a-c) Timber sacred buildings in Lithuania: Catholic church in Palūšė (1757) (left), Orthodox church in Lebeniškiai (1909) (center), Jewish synagogue in Kurkliai (XIX c.) (right)

Figure 13. Heddal Church (Norway) (top); Holmens Cemetery Chapel (Denmark), Nellim orthodox Church (Sweden) (center); Borgund Church (Norway) (bottom)

decorating the building disposing the boards in various directions and creating geometrical figures.

5 Conclusion

The stone-timber architecture with its many typologies, materials and constructive techniques represent a real cultural heritage that, with its several declinations and usages, characterizes the various European regions. We have reported how, from the southern-Mediterranean areas to the far northeast and west countries, timber structures, in various percentages, are exploited with different reasons and aims along with the stone masonry. Such a mixed practice belongs to the traditional and historical construction even though some countries, especially the one that is still rich in woods and forests, still exploit such technology in an

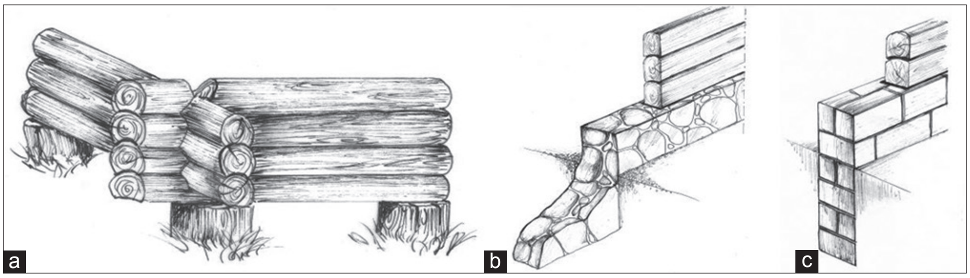

Figure 14. (a-c) Foundations typologies. Left: Isolated trunks rooted into the ground; center: Embankment of stones and lime mortar; right: Ashlars layered with lime mortar (drawings by L. Beržanskytė)

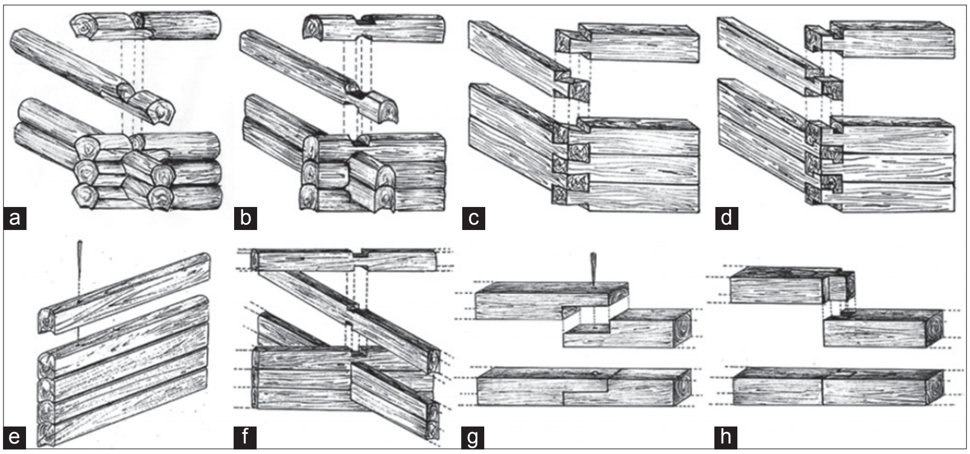

Figure 15. (a-d) *Blockbau* constructive system, (e) log connected to the lower one by wooden nails, (f) timber walls intersection, (g and h) log connections (drawings by L. Beržanskytė)

advanced contemporary way. Differences in usages' aim and technology mainly depend on technological, formal and typological types of buildings as well as intrinsic regional factors such as nature and availability of construction materials, geology, cultural, and historical aspects.

Unfortunately, such a mixed constructive technology, although it shows quite good durability, it is commonly less resistant than the stone or brick constructions. The reasons are quite intuitive. In general speaking, the causes of such a higher structural deficiency are due to the nature of wood, clearly more perishable than stone, either natural or artificial. Indeed, the natural aging of wood, along with the prolonged exposition to the external agents, some natural factors such as water and humidity, the ultraviolet exposition, and the insects' and fungi's attacks contribute in damaging such constructions. The problem increases with the larger usage of wood, going toward the north of Europe.

Sometimes, degradation and collapse are caused by wrong manufacture or a usage of bad, or not adequate, construction materials. Wood may show many intrinsic defects that must be avoided, especially in the most stressed or exposed parts. A wrong disposition, or a hurried and not precise elements' preparation, may also cause future damages and fast degradation. Again, the contact between stone and wood may lead to other deficiencies either structural or degrading due to the humidity by condensation. Finally, a wrong posthumous usage, erroneous works of maintenance or restoration, an atavist absence of regulations, or accidental catastrophic events such as fires or earthquakes, contributed to the loss of such constructions.

Preservation and maintenance of such a building are amazingly important not only to save some architectures that, in a certain way, belong to the past but also because they represent a real way of living and regional constructive practice. A cultural heritage that must be transmitted to the next generations. The sad awareness of how the serially industrial manufacture may - in the past as well as nowadays - slowly weakens, if not erases, the cultural richness of the artisanal production (associated to the transmission of its knowledge) requires an accurate consideration on the importance of the acknowledgement of the material and immaterial value of such a buildings and technologies. Furthermore, what still remains - either proper constructions as well as the practical ability to build and reproduce those technologies - must be considered a real source to be preserved and valorized. A deep knowledge of the historical and cultural contexts, along with the technical skills and the local materials capacities and possibilities, returns back an extremely variegated and interesting panorama within which a project of preservation, valorization, and reuse must begin.

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