

TIMBER+, COMPOSITE TIMBER CONSTRUCTIONS

(Constructions composites en bois. Récolte et analyse d'exemples de constructions vernaculaires en bois associé à d'autres matériaux minéraux./Composite timber construction. Collection and analysis of vernacular timber construction mix with mineral materials)

First of all, I would like to express my deep and sincere gratitude to the research supervisor of the Enoncé, Prof. Yves Weinand (ibois) who gave me the opportunity and freedom to carry out this project on “Composite Timber Construction”, providing me with invaluable support throughout the research, it was a great privilege and honor to work and study under his guidance. I am also extremely grateful to Prof. Corentin Fivet (SXL) who introduced me to the most contemporary thoughts on Circular Economy. I would also thank Prof. Katrin Beyer (EESD) for his/her availability as Maître EPFL.

I would also like to express my special thanks to Guber Natur Steine through the person of Mr. Kluser Michael who, despite his busy schedule provided me with valuable data and took the time to show me their facilities. In addition, I have to thank Krystian Grzybek of Küngholzbau for sharing with me the incredible work they are doing, I truly see this company as one of the few examples of new circular and intelligent approach to timber construction today.

A special thanks goes to the department of “Rischio Sismico, Normativa Antisismica e Prevenione sismica” of the Umbria region in Italy. More specifically, I would like to thank the engineer De Maria Alessandro for being an invaluable reference point in seismic construction and the engineer Barluzzi Marco without whom this book would never have existed.

I am very grateful to a number of people who have been crucial in bringing this work to completion. Some, however, deserve special mention: first among all Gregorio Sicurezza, who still represents for me one of the sharpest and most genuine thinkers in Architecture, and last but not least Philip Tidwell and Pekka Heikkinen (Aalto University) for introducing me to a different way of thinking design through wood construction.

ACKNOWLEDGEMENTS

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Timber+ is meant to features themes that should interest students, design professionals, engineers and all those people who have an interest in construction. Therefore, I introduced axonometric drawings and infographics that are intended to make this publication accessible also to a wider public, other than experts in the field .

This work will present to the reader a different type of timber construction, for sure less known and studied then the most traditional Nordic European timber systems. The time we live in calls for a sincere reassessment of even the *greenest* of all materials: wood.

I wish that my generation of designers can become untouched by ecological slogans and will start to go beyond even the most convincing green marketing. The entire research has been build and nourished by this kind of *esprit*, for which I cannot find more suitable words than those recently written by Klaus Zwerger to describe it: *“Many architects are already investing a great deal of brainpower and design time in developing construction methods that facilitate a clean separation of the various construction materials used after the expiry of the building. Students write diploma theses on this subject. The awareness that wooden components glued with plastics do not simply return residue-free into natural cycle when they are left to decay has led to a reflection on alternative, residue-free wood composites. This begs the question: Are products developers allowed to be content with the fact that distributors of their new products are using high-budget marketing to hide and lie or even necessary here? Despite our fascination for new developments, should we not investigate the consequences of our actions as intensively as we pursue goals to optimize nature according to our ideas? Business-focused entrepreneurs make no room for such ifs and buts. So, the first responsibility remains with the developers. It must also be taken into consideration in the development process. Because let’s face it: no one – end especially not those working with wood – wants to be accused of being short-sighted”* (Klaus Zwerger, 2019)¹

1 Markus Hudert and Sven Pfeiffer (Eds.), *Rethinking Wood* (Birkhäuser, n.d.).

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This work, entitled *Timber+* presents a preliminary research on composite timber constructions. Differently from typical full dry timber constructions, these constructions are always realized with two materials: timber plus something else (clay, daub, brick or stone masonry, wet or dry infills, straw, adobe or rubble).

The *Atlas* is meant to understand and classify these constructions according to their durable qualities, maintenance features, resilience through catastrophic events and, finally, for their qualities of absorbing and integrating discarded mineral-based materials. Once we have familiarized ourselves with composite timber constructions, one thing becomes clear: timber frames could play a much more important role in contemporary construction than we might expect. In those constructions, the timber frame is like an appendix which provides the system with the overall set of technological and structural qualities. Masonry (in the large sense as agglomerated infill/mass) is the suffix: it complements the construction by tuning some of its technological qualities.

Although numerous combinations are possible due to large numbers of masonries (suffix), the timber *bases* can be roughly grouped in three families, following their structural behavior and organization:

A: MONO TIMBER FRAMES

This is the most canonic *nogged* construction: infills and timber frames are embedded in the same wall thickness. Although the timber frame is the basic structure, masonry contributes in many ways to the overhaul behavior and properties of the system. Nevertheless, its main function is to sustain compressive stress.

B: DUAL TIMBER FRAMES

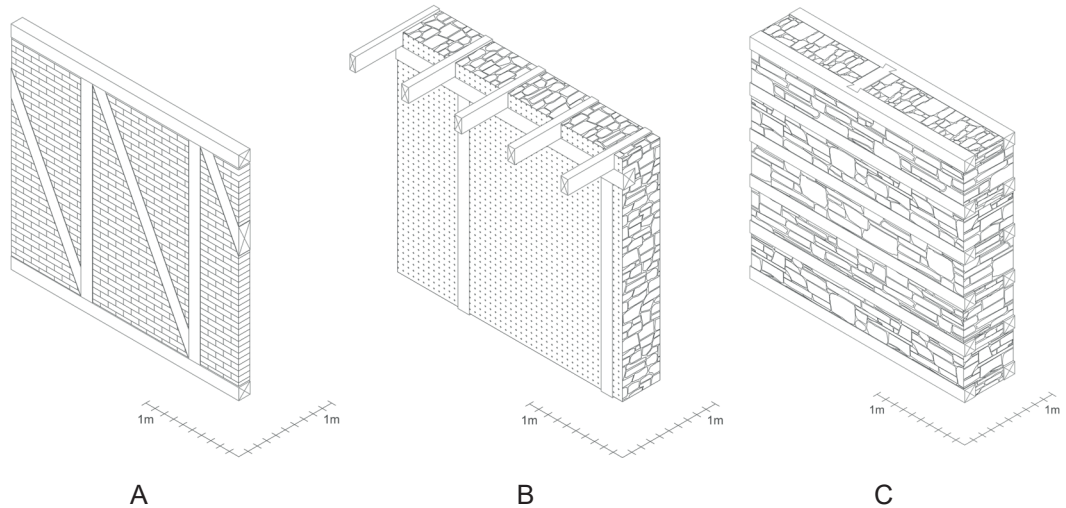
In this case the timber frame is juxtaposed to the masonry, but they are kept separate. They mainly work alternately: once the masonry fails or need to be partially replaced, the timber frame bears all the static or dynamic charges until the main masonry is not repaired.

C: TIMBER LACE FRAMES

It is the most particular category, but it can still be considered as a timber frame since it partitions masonries into containments. The timber frame is horizontally laid on top of each masonry containment. Most important is that no vertical elements are attached to the load-bearing wall, this allows a uniform

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settling of the building over time. The load-bearing walls are made by layer of dry-stack masonry interrupted by continuous timber belts.



Each family has its own peculiarities that will be explored through each example of the *Atlas*, but they all share a common feature: structural redundancy. There are different logistic, constructive and structural reasons behind their shared hyper static qualities, but in most cases, this translates into building components which are easily reparable, demountable or removable. Next introductory chapters address first, the motivations behind the apparently unusual connection that these types of construction have with anti-seismic building logics, their repertory and cataloging criteria; second, the reason why these buildings have disappeared at least in the western world.

The central part of the work is composed by the collection of different buildings regrouped in the previously mentioned categories: mono timber frame, dual timber frame and timber lace frame. I hope that this work may serve as an introductory research in the field of composite timber constructions. The aim is to showcase a series of buildings that benefited from the wide range of advantages and solutions that such types of systems could also offer to the contemporary construction. Each example is illustrated by an axonometric drawing which display the whole system in scale.

The third and last section is devoted to the analysis of how composite timber constructions could be re-introduced in today's building and material sourcing logics, a series of considerations on possible updates given the actual environmental crisis. The preliminary chapter is focused on one of the three families of composite timber construction, the dry-stacked timber lace system. The content of this section discusses why this family of constructions would be more eligible for an update than the other two. The next two chapters presents today's necessary considerations, possible developments, and materials life-assessments of the two main elements of the system: wood and mineral masonry.

Finally, the conclusions evoke and address the next steps to continue a research on *Composite Timber Constructions*: it addresses some thoughts on possible degree of prefabrication and assembly, it considers eventual modifications to the system and it evokes next steps of analytical research for a better comprehension of *Composite Timber Constructions*.

1.2 COMPOSITE TIMBER CONSTRUCTION AT THE AGE OF WOOD PRODUCTS

Although some examples are slowly reappearing into contemporary architectural production², most composite timber structures belong to the past. And yet, they embodied sustainable models that could potentially have a second life today. In fact, the true contemporary added value of composite timber structures as we stated before, is to absorb other materials and merging their properties into one coherent durable and repairable building. Yet, this last years we have witnessed the raise of *wood products* such as recomposed timber components, highly engineered and fabricated from either stripes, veneers, chips or planks and joint in the most various shapes and dimensions thanks to the use of adhesives.

Their radical opposition, in the form of *mass timber* systems, to the global establishment of mineral-based systems (*new* because CLT was introduced for the first time in Austria and Germany only in the early 90s) has recently characterized the global construction market. Besides, timber industry could also have the potential to mediate and absorb mineral materials rather than completely oppose itself to them, as an autoreferential building system. This is the logic of product replacement still heavily influenced by a linear economy in which the old product we replace, once substituted, it is no longer our

² “Architekturbüro Patrick Thurston – Aktuell – BärenWald,” accessed November 2, 2019, https://www.thurston.ch/zoo/baer/baer_home.html.

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concern. And yet, this ideal solution is hardly the more practical one. In the next transitional economic we will (and still we are) indeed facing conflicts of interest and frictions in an attempt to put into practice all those strategic construction issues that we are now theoretically redefining as *sustainable*. Despite the recent growing popularity and new possibilities of engineered timber constructions, timber industry still struggles to conquer a larger audience with the exception of leading industries in Austria or in the south of Germany because of some of its disadvantages: fire prevention, sound insulation, thermal inertia and ultimately, a lack of proper forests management. Contemporary adaptation of mixed timber and dry-mineral systems could offer today a unique chance to embrace a good transitory model of construction which could absorb the embodied energy of mineral wastes, not only stone wastes issue of extraction, but also everyday-life demolition rubble, or those produced by calamities like earthquakes or destructive event like conflicts. It could eventually give the opportunity to progressively reconvert the heavy mineral industry assets towards more sustainable recycling facilities, making it possible to reinvent and propose a wide range of new mixed building components (e.g. *ballasted timber slabs* or *prefabricated dry timber laced masonry* are just glimpses of ideas).

In recent years we have been constantly exposed to the term of *Sustainability* without referencing a clear and unique definition. According to the *Brundtland report* presented at the UN, this term has been used with multiple meanings and definitions, sometimes improper, hermetic or not pertinent. Far from a common set of agreements, theoretical queries on the future role of constructing technologies are still up to date among designers and engineers: the most recurrent is whether to encourage *low-tech* practices in construction in opposition to new *hi-tech* building systems. This dichotomy is in part related to the fact that: “people working with digital tools barely speak to people working in sustainability. In architectural teaching, students working with digital and parametric tools rarely truly exchange with people in the sustainability field. They’re not the same species [...]” “consequently the real question “*isn’t about low-tech or high-tech- that’s too simple. The real question is knowing what to use according to the context (A. Picon)*³”.

Our context has been for a long time mainly built in mineral-based materials. This is the context in which we should adapt our ideas of timber construction

³ Marilyne Andersen, Emmanuel Rey et al., *Thinking Visions for Architectural Design*, Park books (Zurich, 2018).

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to show its true contemporary pertinence. But in order to be relevant for the actual ecological crisis we need to approach timber construction in a *non-canonical*⁴ way. This means to start considering timber construction again not only as an unique, hermetic, autoreferential and isolated constructing system, but also as the only sustainable building material which too has the potential to absorb other mineral materials into one coherent building, by making their execution easier, reducing their consume of water, resources, embodied energy, and at the same time embodying their qualities that wood alone has never been able to outmatch.

⁴ “From the Greek Canon, Any Straight Rod, Bar, Rule, or Standard for Excellence, Uncanonical Signifies the Opposite,” n.d.

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San Pellegrino (IT) village after the earthquake of 2016.

“ [...] all the best examples we have of efficient resource use in architecture are from the past. What would be innovative in architecture today would be rediscovering some of these past virtues and incorporating them in the way we work today” (Lionel Devliger, Rotor)⁵

The research started by looking at earthquake-proved vernacular construction. The reason is simple: if there are building cultures around the world that had to learn to deal and cope with enormous and recurrent amounts of construction waste, those cultures can be found in seismic-areas. This assumption is not as linear as it could seem at first. However, building cultures do respond (to a certain extent) to natural phenomena: among these, earthquakes are the only ones which force inhabitants to consider building recycling and rubble disposal not as accessory features but as basic survival needs. Hence, among all the vernacular building stock, earthquake-proved buildings are those where it is most probable to find robust, circular and sustainable strategies. Furthermore, as we will discover and explain later, these constructions are often associated with wood, even in areas where this resource is scarce.

On 24 August 2016 Central Italy was hit by an earthquake measuring 6.0 on the magnitude scale. In less than twenty seconds, entire villages and towns were torn down into rubble. Less than one year later, on 18 January the same area was hit by a second series of seismic events with a peak magnitude of 6.5. This time all the villages surrounding the major town of *Norcia* suffered, for most part, irreparable damages.

Earthquakes are the only contemporary situation, at least in the western world, where population has to face from one day to the next not only an important number of human losses, but also the problem of dealing with tremendous amount of waste, debris and rubble. Hence, buildings in seismic areas have been constantly exposed to the necessity of coping with building waste and frequent repairs.

In 2017, while visiting the destroyed villages in the regions of *Umbria*, *Abruzzo* and *Marche* I was surprised by the fact that there was no consistent building culture in place to counter act earthquake's consequences, no trace of a vernacular or at least traditional technique developed in order to adapt to this hazardous event. Furthermore, despite the abundant forests, there was no

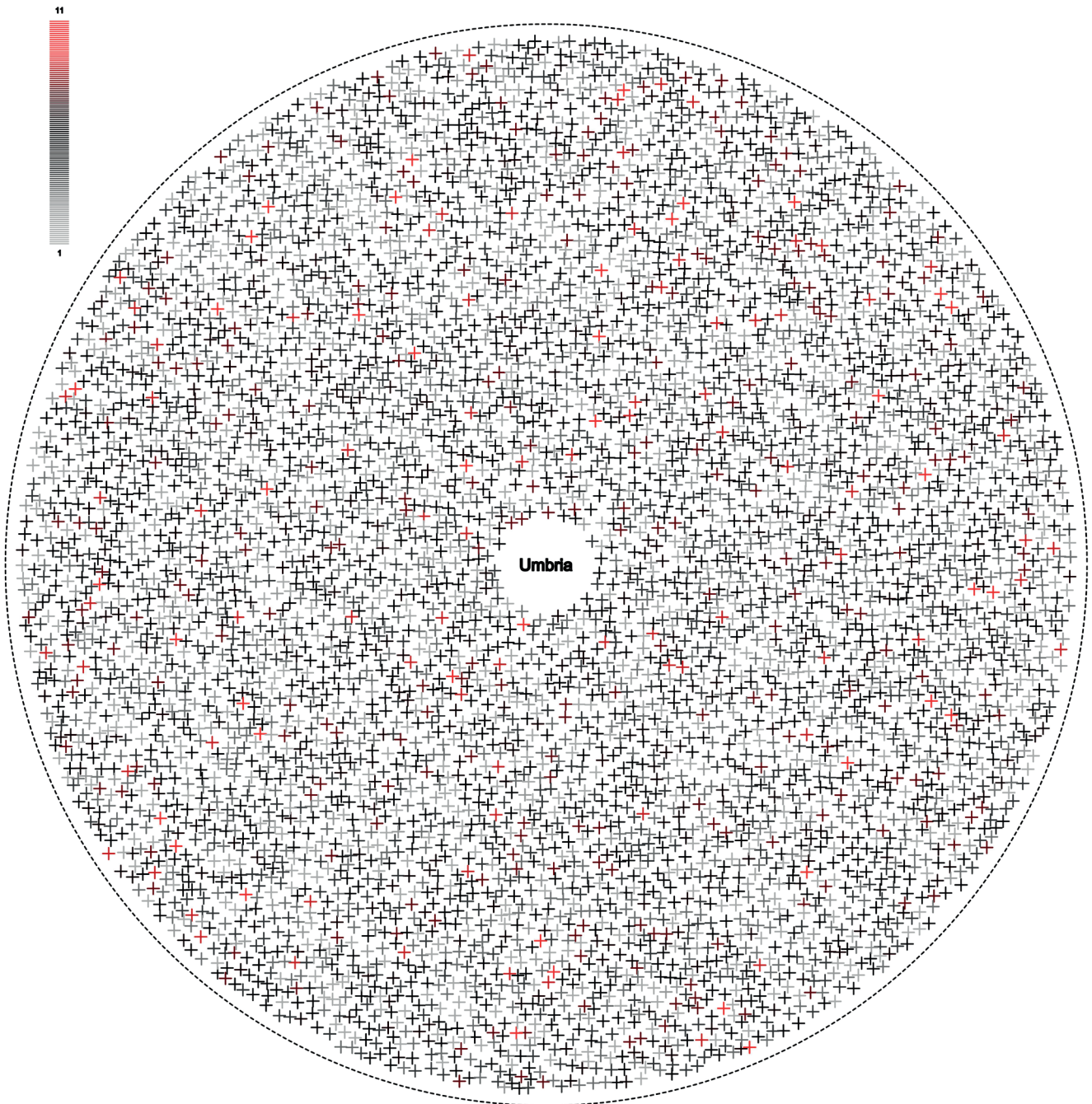
⁵ *Marilyne Andersen, Emmanuel Rey et al., Thinking Visions for Architectural Design, Park books (Zurich, 2018).*

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trace of vernacular timber constructions. The introduction of timber elements in typical masonry techniques is a common practice especially in high seismic areas due to timber ductile behavior, especially under dynamic charges. How come?

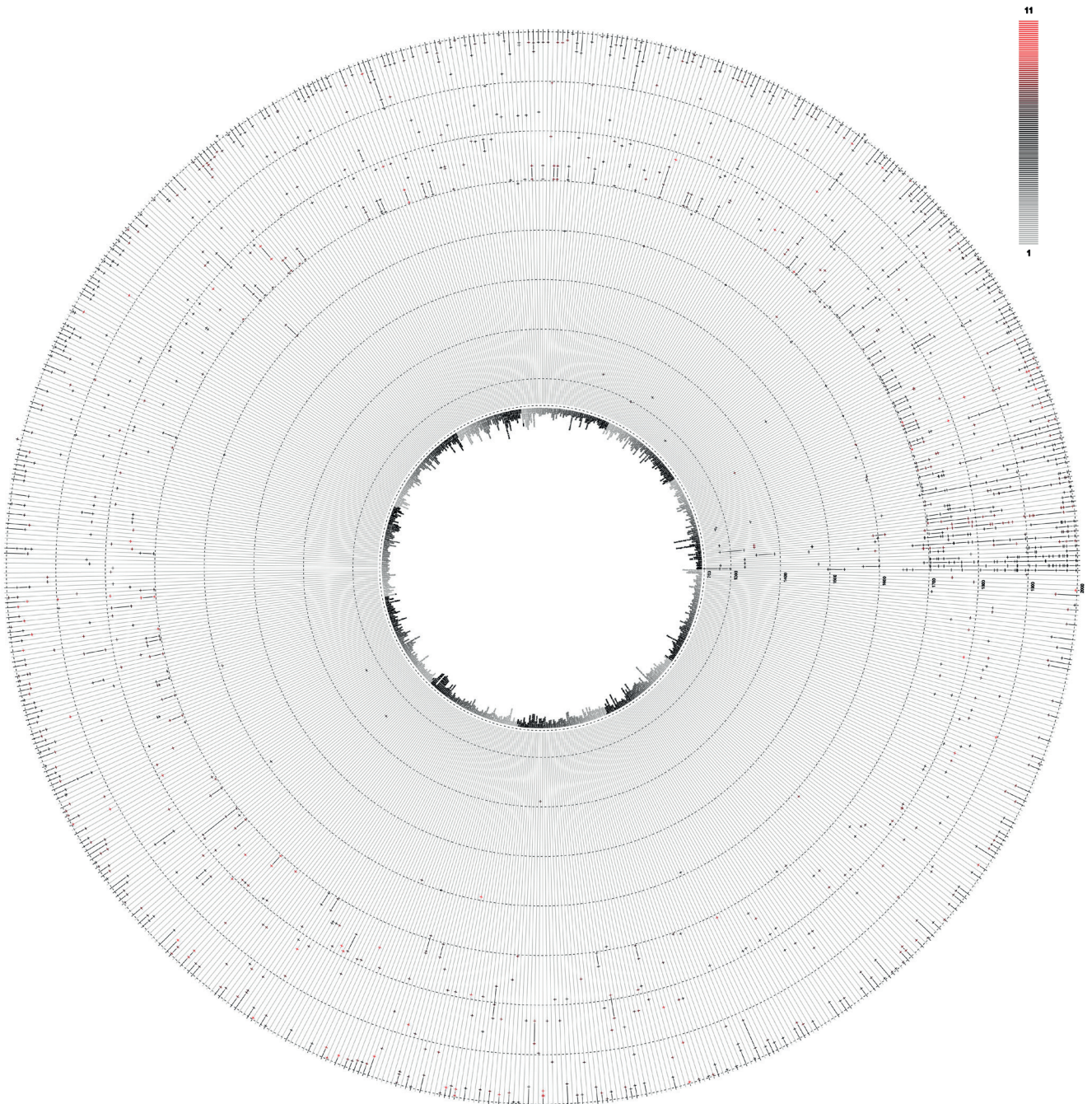
There are multiple theories on how anti-seismic building cultures can originate. *Ferrigni* asserts that adaptative and regenerative building cultures are developed whenever destructive earthquakes occur with a frequency of at least 70 years. The time span corresponds to an entire generation, and if it is short enough, building techniques can be tested and improved, resulting eventually worthy of maintenance. On the other hand, if the time span it is too long people lose memory of earthquake-related building techniques and just go back to normal construction practices. This theory was applied to Umbria hit by the above-mentioned earthquakes. I considered all the earthquakes which hit this region from the date 1246 until 2014 (database: INGV). Each earthquake is marked with a "+" and every visualization shows a different aspect of the same situation: all the *non-heavily-destructive* earthquakes were removed (intensity < 6 on the Richter scale), and finally for each village was traced a timeline by highlighting the time spans shorter than 70 years in order to see in which town or area it was most likely to find vernacular anti-seismic constructions.

The results were in a way deceptive. It is true that, as shown by the graph, towns with shorter seismic recurrences (less than 70 years) present a discrete quantity of historical records and even famous paintings illustrating towns destroyed by earthquakes. But no trace of practical adaptation in tectonic terms. The theory turned out to be more reliable on a psychological impact of earthquakes on the population, than their resilience in building techniques. This is of course a simplification, multiple factors influencing building cultures are put aside for the moment.

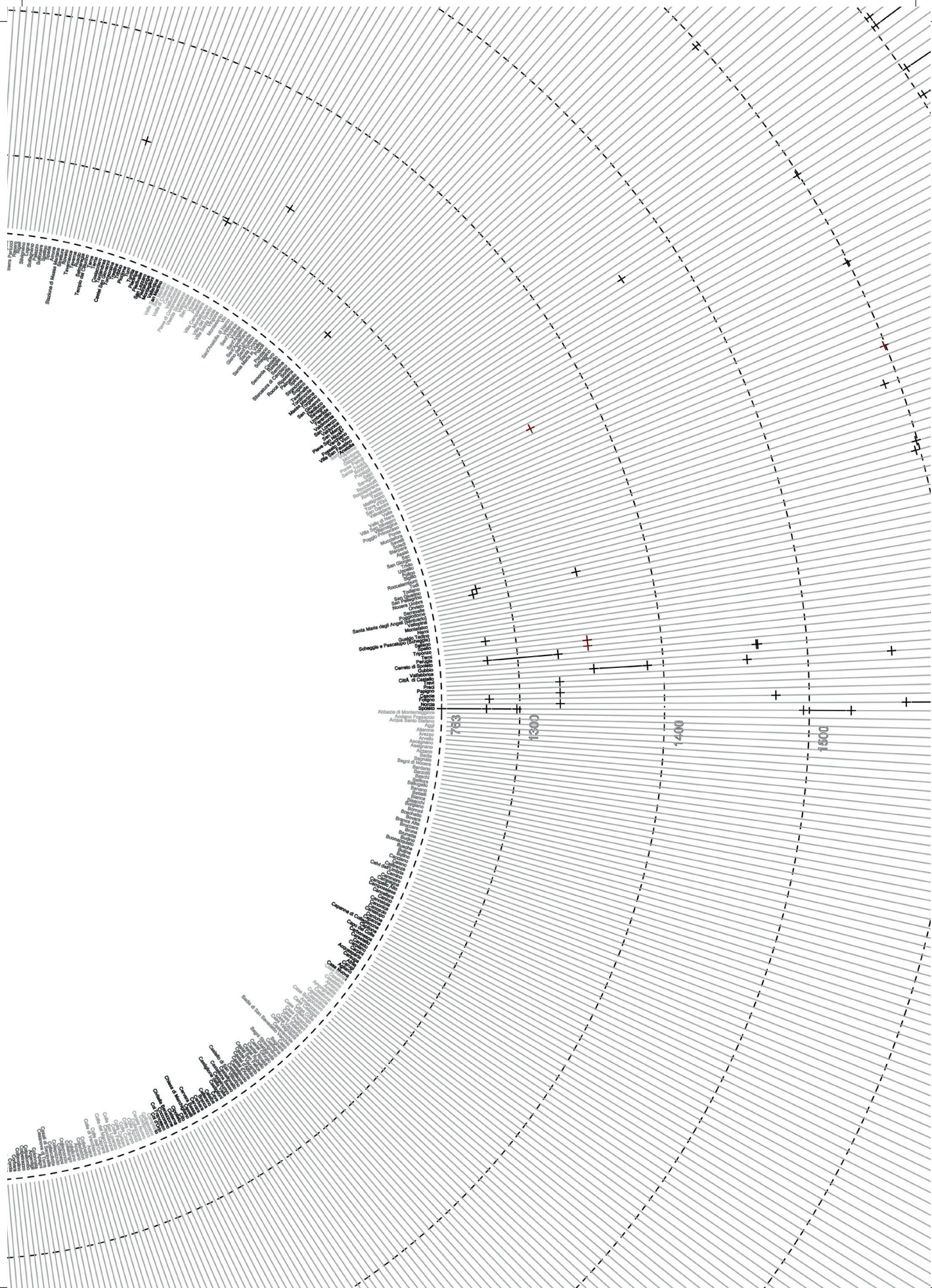


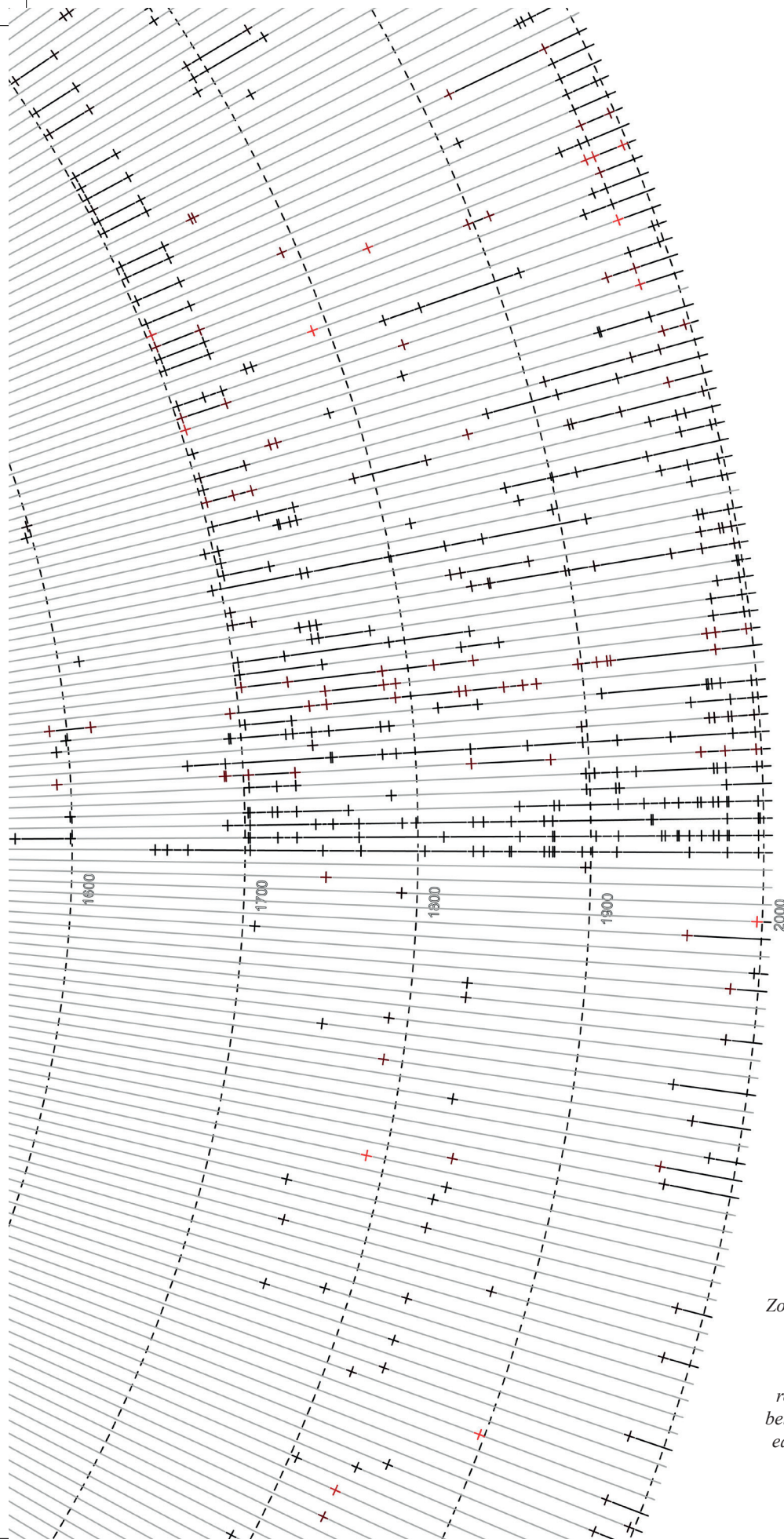
Earthquakes from 1246 to 2014 in Umbria
 Database: Locati M., Camassi R., Rovida A., Ercolani E., Bernardini F., Castelli V., Caracciolo
 C.H., Tertulliani A., Rossi A., Azzaro R., D'Amico S., Conte S., Rocchetti E. (2016). Database
 Macrosismico Italiano (DBMI15). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.6092/INGV.IT-DBMI15>

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Earthquakes from 1246 to 2014 in Umbrian villages: timespan between earthquakes for each village
Database: Locati M., Camassi R., Rovida A., Ercolani E., Bernardini F., Castelli V., Caracciolo C.H., Tertulliani A., Rossi A., Azzaro R., D'Amico S., Conte S., Rocchetti E. (2016). Database Macrosismico Italiano (DBMI15). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.6092/INGV.IT-DBMI15>





Zoom on the previous visualisation,
each line represents a timeline
for each village of the region.
"+" represents earthquakes, the
redder, the stronger. When the line
between crosses is red it means that
earthquakes occurred in a timespan
smaller than 70 years.

Nevertheless, in order to put those first results in a comparative perspective, I decided to include in the analysis the entire Italian territory. What follows is once again a visualization of all earthquakes occurred from 1246 to 2014, but this time on the entire surface of Italy.

Later, all the “+” (each plus corresponds to an earthquake) have been divided and grouped by region. In this visualization the area of each rectangle is proportionally direct to the number of earthquakes occurred in each region. As mentioned before, the colors refer to the intensity of the earthquake: the redder the symbol, the stronger the correspondent seism.

The scheme highlights one important thing: among all the regions, there is one area that stands out for the frequency of strong earthquakes (the redder one, see next page): *Calabria*.

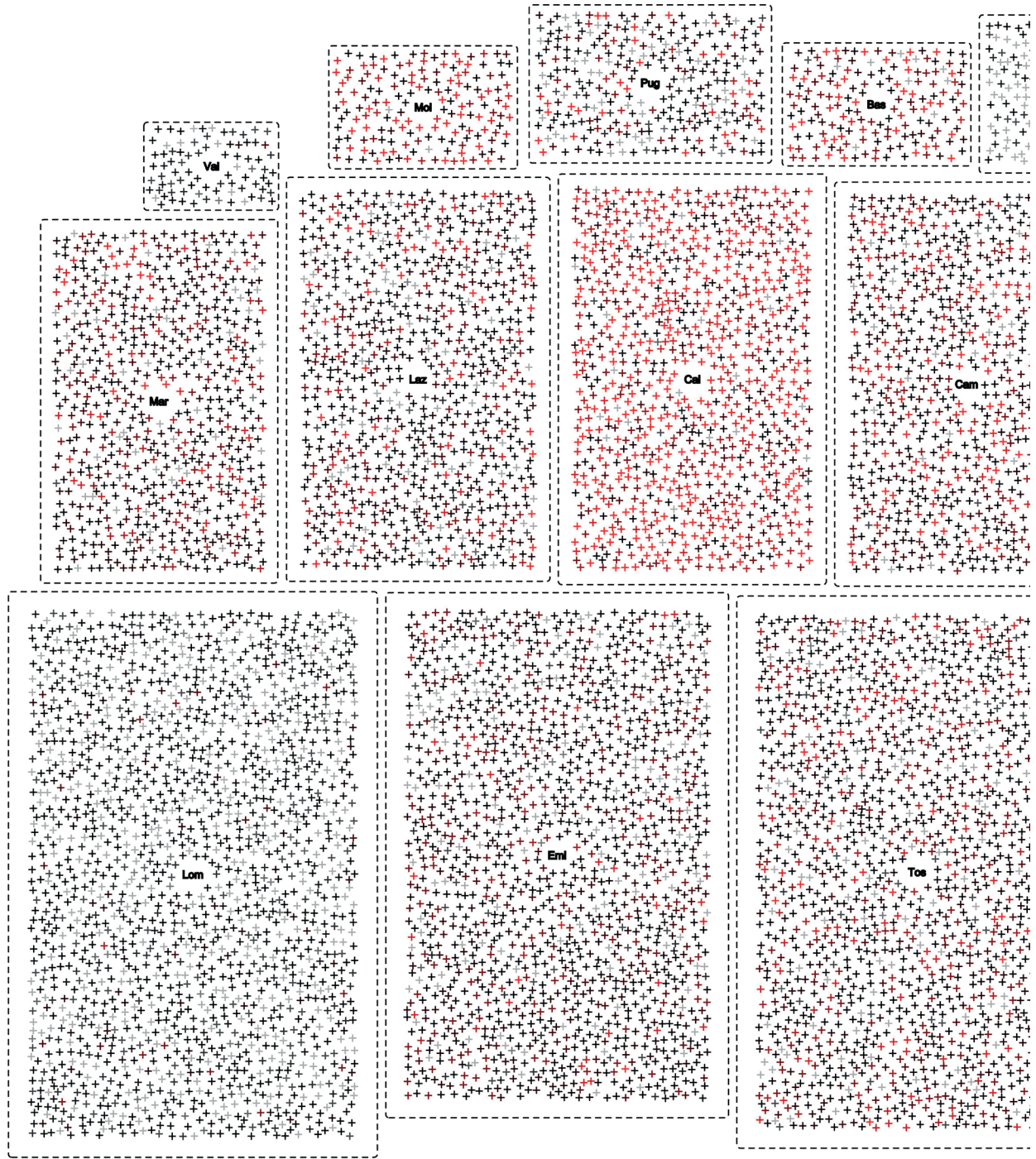
In reason of this disclosure I started to search for traditional anti-seismic timber construction in Calabria. The tradition of *Calabrian* region in terms of earthquake-proved construction was incredibly rich, and more specifically it presents a wide range of both vernacular and engineered typologies. All of them present a distinctive and common feature: the integration in masonry of an efficient and punctual use of timber elements (for further information concerning the *Calabrian timber constructions*, please see the chapter about *The Borbone* and the *Casa Baraccata* systems). The *Calabrian* half-timber constructions brilliantly integrated few mechanisms of protection against earthquakes but also excellent strategies in repairing and quickly re-absorbing rubble, waste and debris back into the building again. Today this very definition could easily be added to the many of *circular economy*.

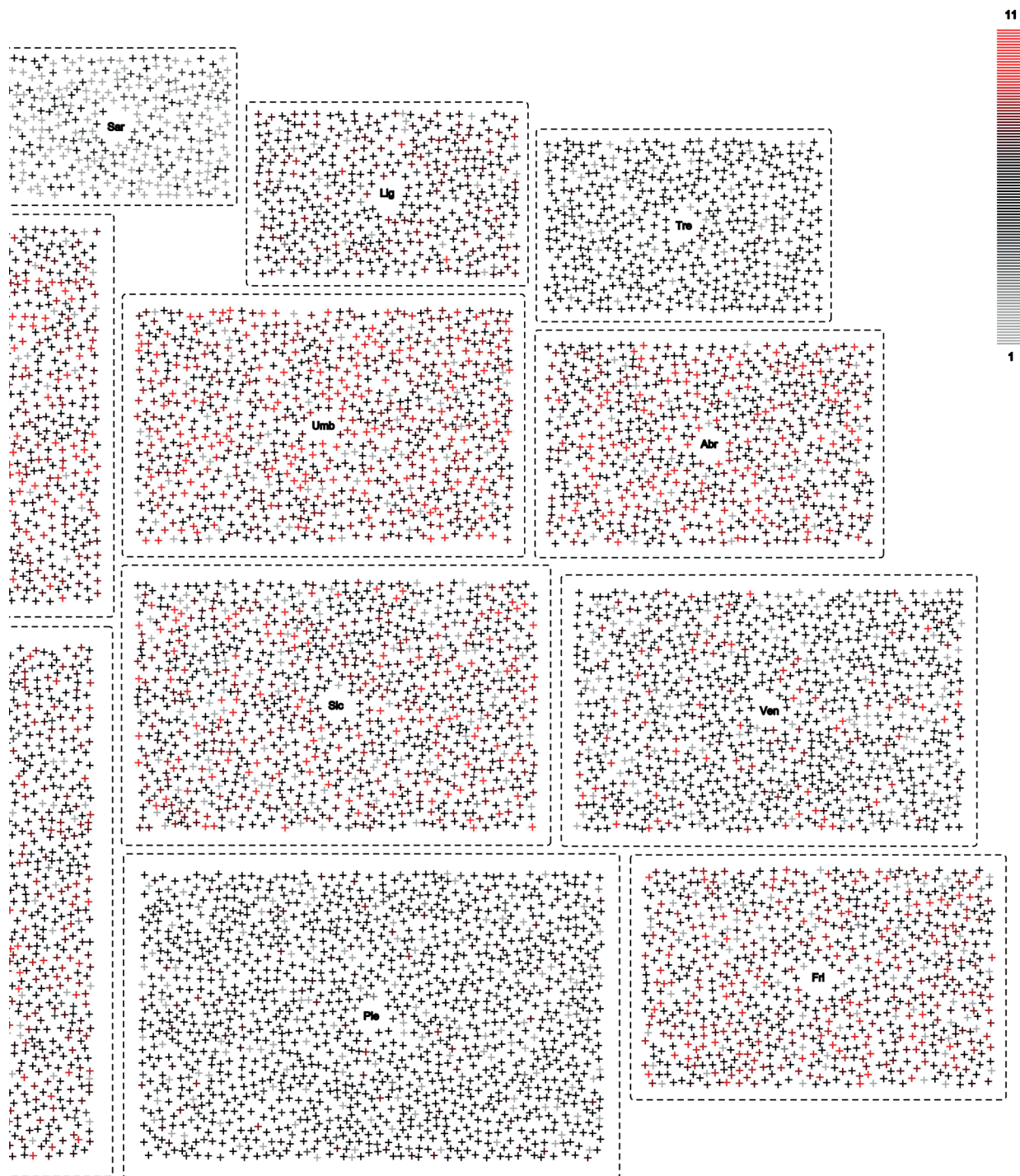
Therefore, I started looking for other similar *composite timber constructions*: in other words, all those constructions that integrate timber elements with the most various type of masonries. From there the research field went wide open by recording all different types of construction methods from all around the world and from different *époques*, present days included. Even though most of them are situated in seismic areas, there are other examples which share similar properties without having been developed in hazardous areas, such as military or remotely located buildings. Every study case has been recorded, analyzed, categorized following the three above-mentioned categories and included in the central section of the Diploma, the *Atlas*.

I hope that the reader will realize, by going through some of the examples, that

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all those buildings, for many different reasons, share a set of values of which we are in critical need today: easily repairable and down-cycling components, low (or any) use of cement or water, and for some of them, extremely proficient in thermal and building comfort domains. In addition, the reader will realize how deep is the understanding of wood as building material in such constructions: wooden elements are constantly being exposed to moisture, due to the contact with masonry layers or infills. For this reason local builders have developed incredibly refined but simple way to enhance its durability and maintenance against moisture decay and fungi attacks.





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Earthquakes from 1246 to 2014 in Italy by department: quakes / surface
 Database: Locati M., Camassi R., Rovida A., Ercolani E., Bernardini F., Castelli V., Caracciolo C.H., Tertulliani A., Rossi A., Azzaro R., D'Amico S., Conte S., Rocchetti E. (2016). Database Macrosismico Italiano (DBMI15). Istituto Nazionale di Geofisica e Vulcanologia (INGV). <https://doi.org/10.6092/INGV.IT-DBMI15>

Throughout the affirmation of modern concepts of engineering and construction during all the 19th and 20th century, and finally with the last industrialization, timber construction has been progressively turned from what has been for long considered like a life-standing process, into a product. This modern approach reflects in a way our present-day tendency of invoking efficiency in design, especially structural design. But how to define *constructive efficiency*? Timesaving, designing with less mass as possible, concentrating top-quality components only for load-bearing elements, hence limiting the quality of the rest of the building to the bone: a *tailored* approach to design. Just like a bulb, we know that our building has a limited lifespan and we bare this in mind during the design phase. The very true value of our design is not probably longevity but repeatability. Because we know that after 50-60 years a building will be “discarded” and a new one will just take its place.

The evolution of western composite timber frame construction and its fall is attributable to the advent of industrialization. All type of composite timber construction has of course its proper evolutions, but they all tend to share the same de-evolutionary dynamics. Let's consider the most familiar of all these constructing systems: the most classical Half-timber construction: *Colombage* or *Pan-de-bois* in France, *Fachwerk* in Germany, *Riegelbau* in Switzerland, *Intelaglio* in Italy...

From the 12th until the 16th century the *Long Bois* (literarily *Long Wood*, it was in many ways the ancestor of *balloon-frame*) represented the most common timber construction in Europe (the whole *Quartier Latin* in Paris was built entirely following this technique). It was characterized by long span elements, both columns and beams, interlocked to form the skeleton of the building. It was mainly present in rural areas with good quality, straight and tall species of trees. It is no coincidence that the highest expression of this technique can be found in Norway or Sweden. Starting from the 13th, 14th century good-quality timber started to become extremely rare due to the heavy deforestation taking place all over Europe, and concomitantly with the progressive expansion of urban areas, the *Long Bois* construction faded out from European landscapes. *Long Bois* became then utterly impractical due to the manipulation of long span elements in dense building environments. *Long Bois* was far too wide and not fire and moisture proof for buildings in the town centers. The emergence of structured urban or sub-urban societies allowed the creation of strong and

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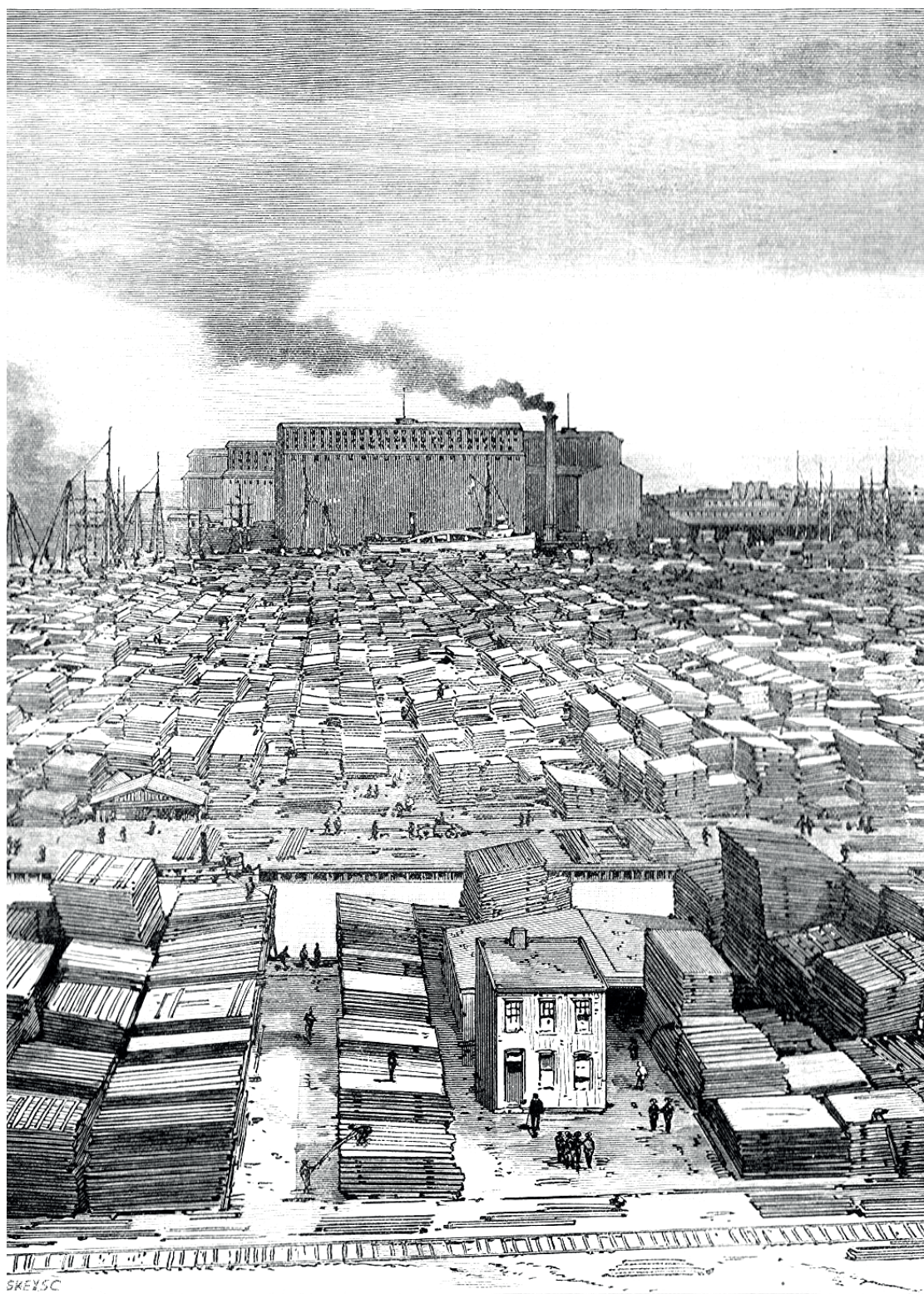
rich companies of carpenters, which were eventually able to compensate the low-quality and scarce quantity of wood at disposal with a far more complex manufacture and joinery of the shorter timber elements available. This *état d'esprit* is the same to the one behind the logic of contemporary glued wood products, CLT (Cross Laminated Timber) in particular: joinery and high-level of manufacture can offset minor quality source materials.

Those were the technological premises for modern *Colombage* (from Latin *columna*, column), *Fachwerk*, and *Riegelbau*.

Traditional *Fachwerk* construction was characterized by an hyper-static timber frame composed by extra diagonals in order to make up, as we said, for the low quality of available wood, especially under compression. This is the reason why these very same houses required a constant maintenance: replacing elements or infill was easier exactly because of their structural redundancy, the same feature for which the structure was in a constant need of repair. This entropic loop was the price to pay for its longevity.

The same system, especially the English variation, which had fewer diagonal bracings due to the good quality of hard-wood species employed, arrived at last to America with the first settlers. There, the massive industrialization of timber components production would take place for the very first time: gravures of the Chicago sawmill district are quite emblematic of this new conception of timber construction, in 1870 more than 200 were discharging lumbers in Chicago twice a day. It is within the American industrialized context that we assist to the shift from the Old World *evolutionary* platform-frame model (*evolutionary* because with *Fachwerk* the number of storeys was constantly adapted to the inhabitant's necessities) to the *balloon-frame* system, settlers went back to the over-mentioned Long Bois technique: wood stock shortage didn't represent a problem anymore due to the vast forests of North America (mainly populated by *Douglas Firs* and pines, hence tall and straight softwood species), this kind of construction was much more finite in its design, a true *building-product* to deploy, use and discard in favor of new opportunities in better lands. This is the same practice responsible for the disappearance of *nogs* (masonry infills in all half-timber construction) and complex timber joinery: too time consuming and long-standing for an instable nomadic way of life. Funny enough the modernization of timber construction was intimately linked to the colonization of future USA: nomadic, fast, efficient and situated in a

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THE LUMBER DISTRICT OF CHICAGO—VIEW FROM THE WEST



WEST SIDE WATERWORKS.—DRAWN BY CHARLES GRAHAM.—[SEE PAGE 666.]

Charles Graham, "The Lumber District of Chicago"—View from the West Side Waterworks", from *Harper's Weekly*(New York: Harper's Magazine Co., 1883), p. 663

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limitless-resource environment in reason of the abundance of the New World. Modern capitalism in timber construction was born and today timber mass housing construction still anchored, to a certain extent, to this work frame. It would not take long before the mass-produced insulation will replace the *nogs* (infills) of all half-timber typologies.

Yet in some remote areas, composite timber constructions withstand the first industrialization.

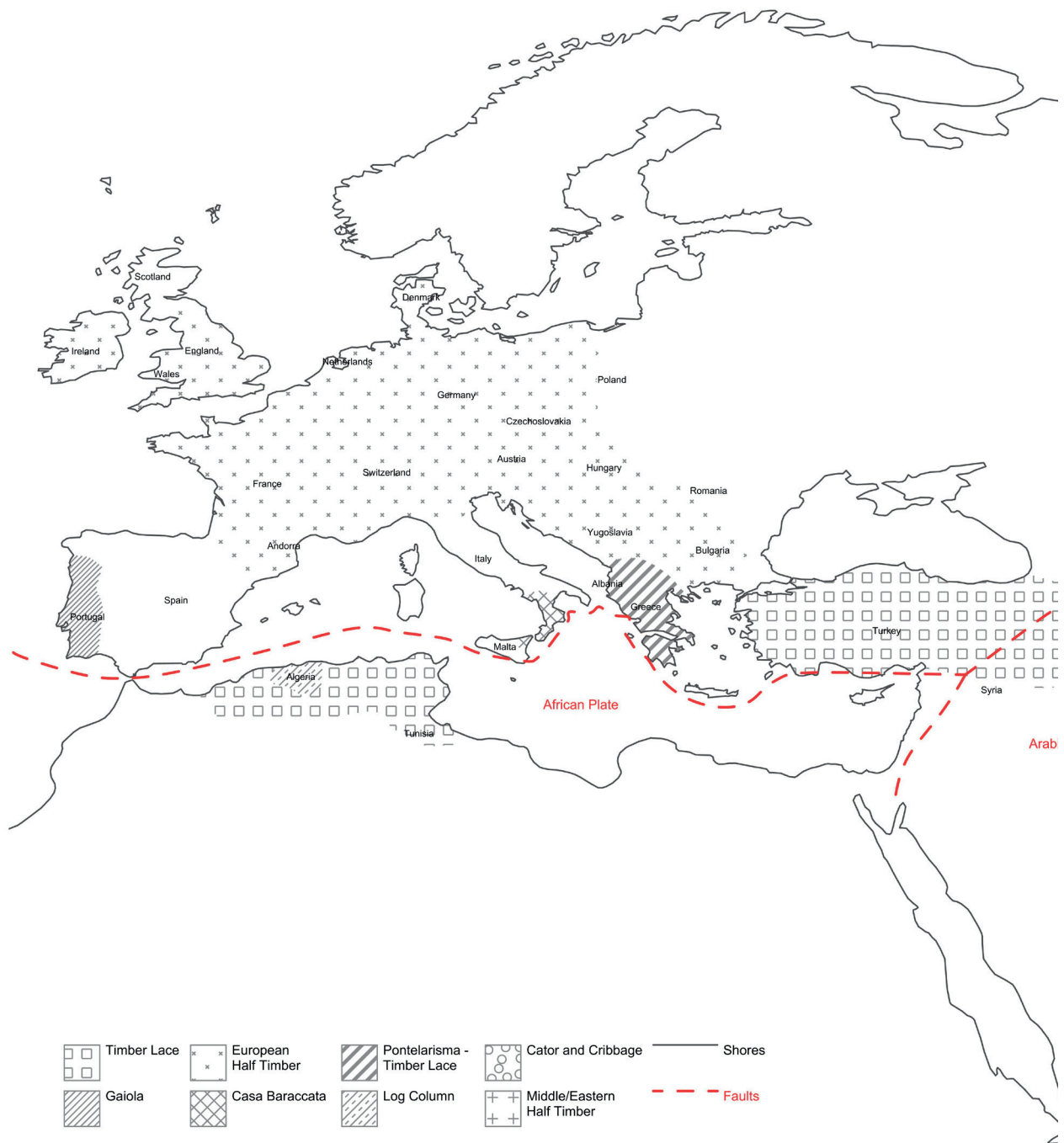
As we know the 20th century was marked by the hegemony of concrete. During the first half of the century number of composite timber constructions were partially replaced by concrete infills or destroyed in favor of post-and-beam structures. But unlike more urbanized and industrialized cities, remote, marginal and mountainous regions have been maintaining and conserving most of the original composite timber techniques, as a result of their isolated positions. This is accountable to the expensive costs of acquiring good quality sand and clay to make good quality concrete. Dispendious use of water for the concrete or lime mix could have also discouraged the adoption of modern concrete post-and-beam constructions, with the consequent survival of traditional composite timber buildings, at least in hotter climate areas (e.g. Ionic islands) or in very inaccessible locations (e.g. Anatolian regions).

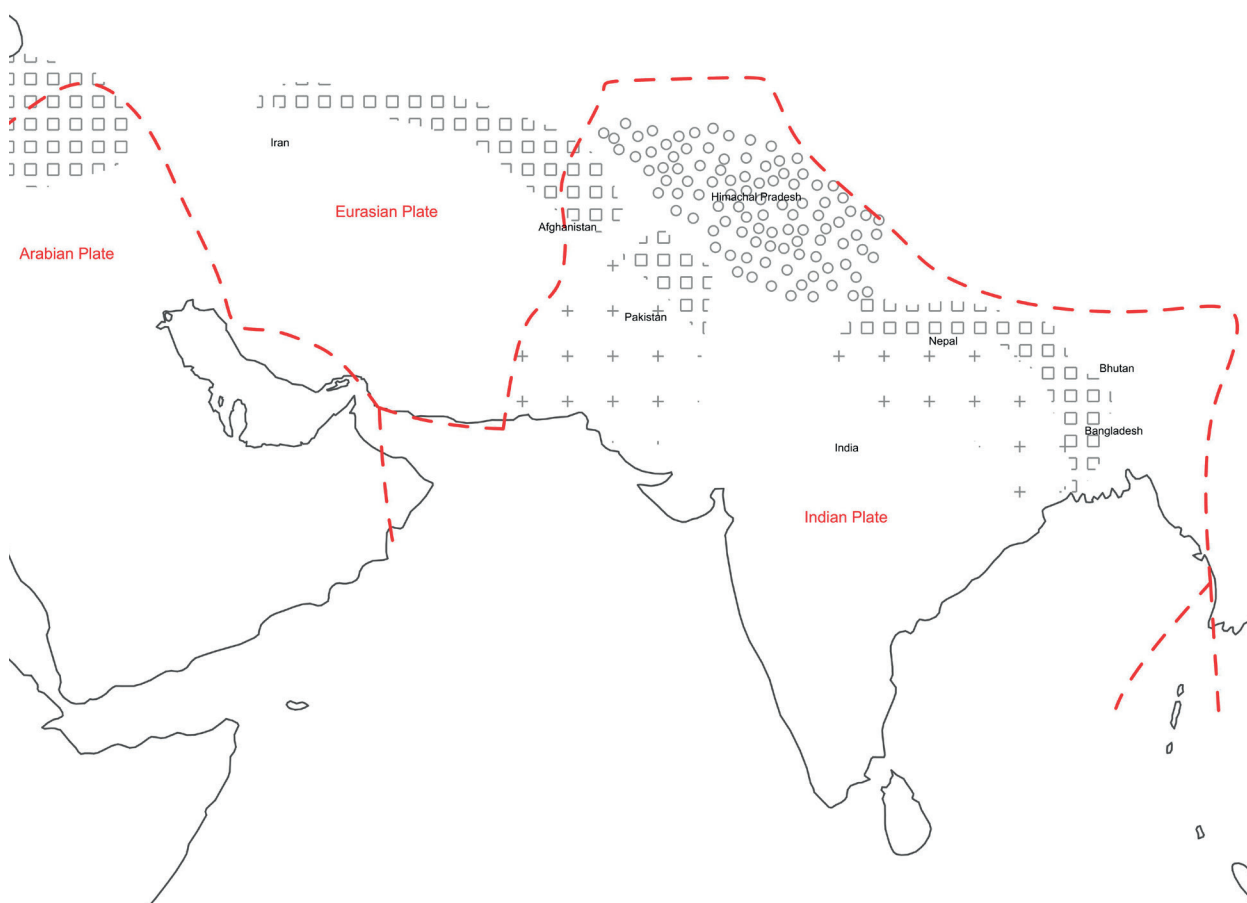
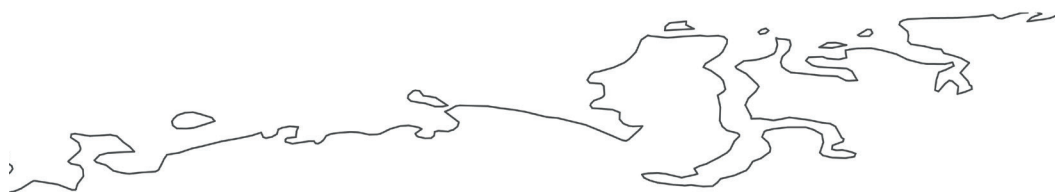
The regenerative qualities of such half-timber systems, which requires low resources but high labor for construction and proper maintenance no longer represent reliable values in 20th century construction, at least in the western side of the world.

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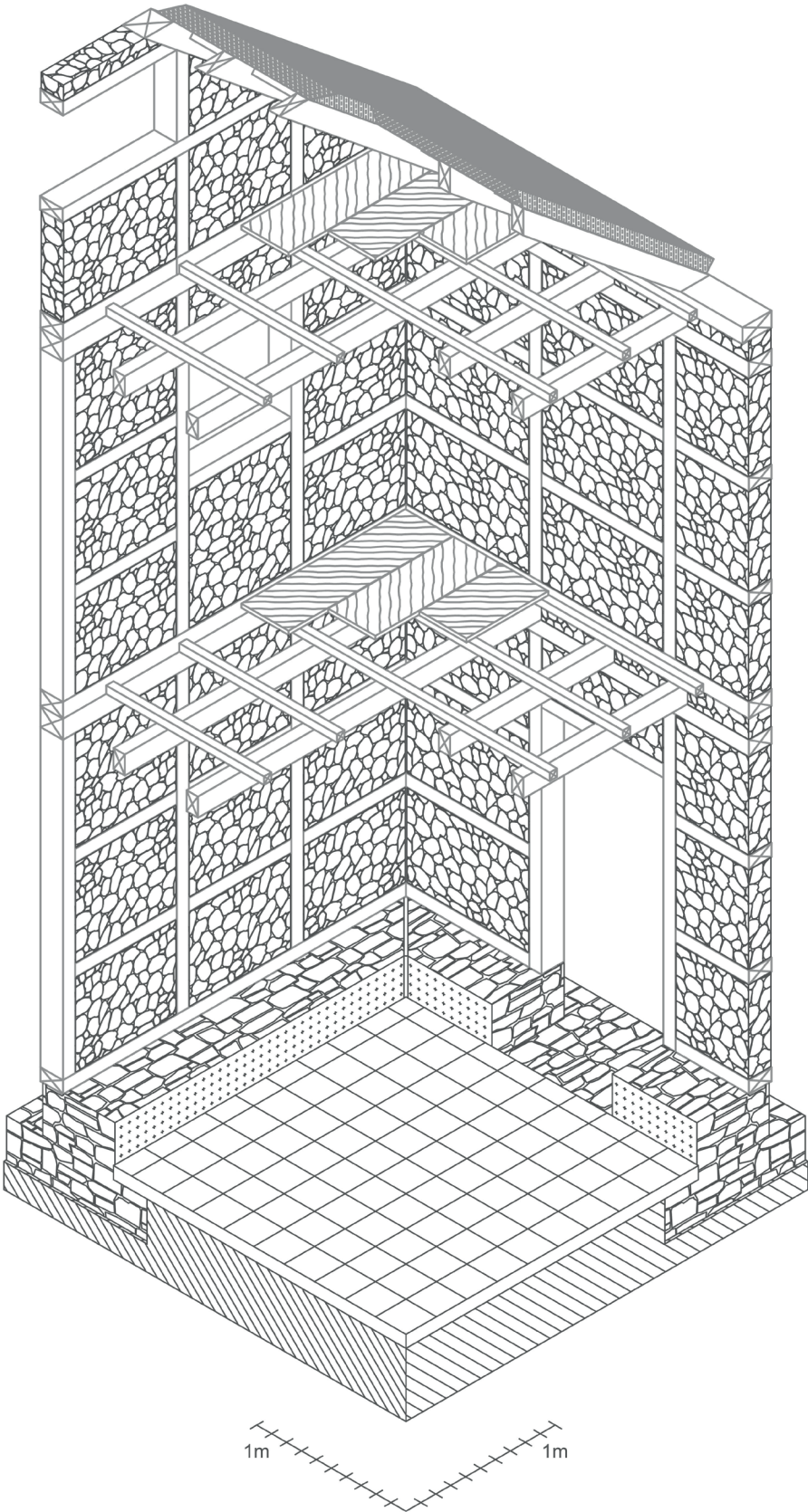




2 ATLAS

*Map showing typologies of composite timber constructions (*Latin American not included): most of them, especially timber lace systems developed in correspondence of faults (red lines), hence in high seismic and remote areas.*

TIMBER+



2.1 MONO STRUCTURE

2.1.1 OPUS CRATICUM

In his second book of *De Architectura*, Vitruvius describes a half-timber system called *opus craticum*. This construction goes also under the name of wattle and daub, in which the wooden frame, the *wattle*, is daubed with the most heterogeneous and weak-bonded masonry. Very often the infills were realized with irregular boulders, uncut rocks, mineral wastes and the all mass was bonded with weak and poor-quality mortar. This type of *nob* (infill) was defined by Ancient Romans as *opus incertum*.

Opus craticum has been included in the *Atlas* since it represents one of the oldest timber frame systems described and documented in an official document.

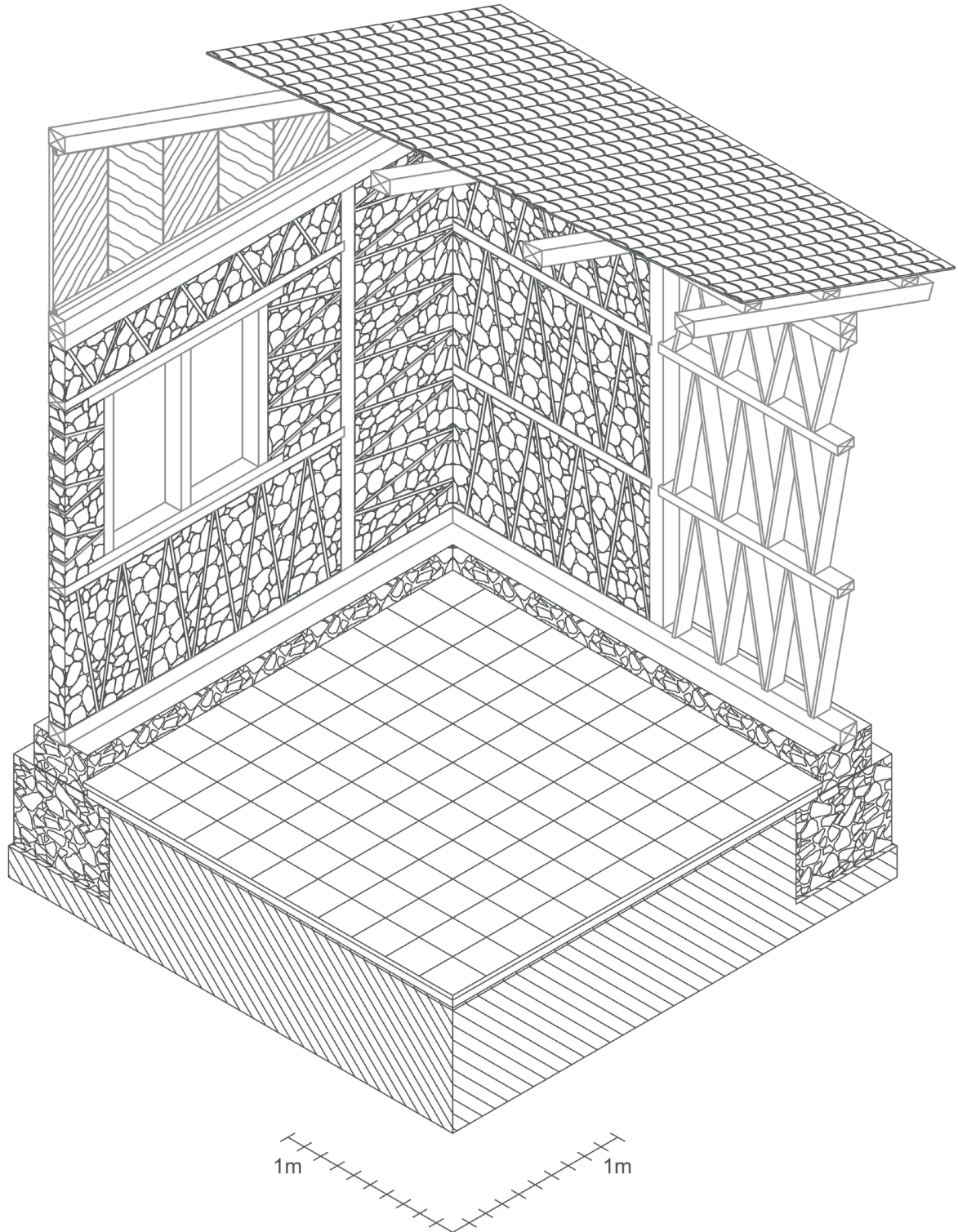
It is possible to find examples of the described construction in Pompeii, Italy. Romans had already guessed the good reliable properties of this constructing system, but as Vitruvius reports, this technique was employed for small walls, and it presented the problem of maintenance due to the shrinkage of the timber grid in contact with the moist wall made out of adobe. Dwellings had from two to three storeys, and it was possible to add one floor at any moment thanks to the platform frame system. Only the infills were plastered, leaving the timber elements exposed to weathering. Infills were not larger than 90 cm per side and the timber frame grid was interlocked by cross lap joints most of the time. The vertical elements running from floor to floor were called *Arrectaria*, whereas the horizontal small timber joists were known as *Transversaria*. Even though the quads often

lack of bracing, they were later adopted in larger urban buildings for the construction of cheap multi-storey buildings called *insulae*. Despite quick and resistant construction, *opus craticum* had always been considered as an economic solution and of less value than a full clay brick or stone masonry building.

This construction survived until Medieval times where it went under the name of *Graticcio*: still have some existing examples in the town of Spoleto (Umbria), Cortona (Tuscany) and few examples located up north in the Piemonte region, more specifically in Ozzano Monferrato, Biella, Arquata Scrivia, Monza, and Susa.

2.1.1 OPUS CRATICUM

TIMBER+



2.1 MONO STRUCTURE

2.1.2 DHAJI DEWARI

DESCRIPTION OF THE SYSTEM

Dhajji Dewari can be defined as a timber frame platform system with masonry infills or *timber nogged* (infill) construction (similar to the European *Fachwerk*, *half-timber* or *Colombage* systems).

It has masonry infills and presents often diagonal bracings. The name comes from the Persian “*patchwork quilt wall*”.⁶

This type of construction is still in use in most regions of Pakistan and Kashmir. It can be typically found in mountain or sub-urban regions, and it is still in use for buildings from 1 to 4 floors tall. In rural areas width ratios are in the order of 2:1 or 3:1, contrary to towns where the plan is frequently square shaped.

NOB FRAMING

There is a variation of *dhajji dewari* nogging which presents quite a different approach from any other versions of the same system. This version does not count diagonal bracing, instead smaller pieces of timber are randomly placed in order to form a nest. Each hole is later infilled with mud mortar and the most heterogeneous types of rubbles or mineral masses that can be found. Finally, as it happens in all the other nogs, the masonry is coated with a layer of mud plaster. The robust timber frame (with an average post cross-section of 10/10 cm) helps to considerably reduce the wall thickness, thus the amount of materials and finally the overhaul mass of the building (key-feature in such seismic regions).

The strategy adopted for the choice of the infill composition seems counter intuitive: instead of using sand-cement mortar, to enhance the resistance of the wall, local population preferred mud mortar.

Despite the loose structure of the mud infills, it covers two important tasks: in static condition they take part at the overhaul compression response which could eventually overburns the timber frame, and secondly, in the event of an earthquake, rubble masonry cracks in-plane almost immediately due the weak mud mortar composition, allowing to dissipate energy through friction thanks to the hysteric shakings between stones, the mud-layer, and the timber frame. Wooden elements play a central role at this stage because they can withstand a remarkable amount of shocks thanks to its ductile behavior.

SUITABLE TIMBER SPECIES AND PRESERVATION

The main wood species employed in the construction of the *Dhajji Dewari* is a type of *Cedar* called *Deodar*, an autochthone specie of Himalaya. A similar Cedar is often used in North America as well for exterior shingles and cladding (similarly to Larch). It is appreciated to build wardrobe thanks to its repellent oils against moths or insects. For its rot resistance and good strength *Deodar* heartwood is employed in the main frame structure, whereas bracings and partitioning elements are made from softwood of the same log.

⁶ Randolph Langenbach, *Don't Tear It down! Preserving the Earthquake Resistant Vernacular Architecture of Kashmir* (UNESCO, 2009).

⁷ “World Housing Encyclopedia -WHE,” accessed October 16, 2019, <http://db.world-housing.net/building/146/>.

2.1.2 DHAJI DEWARI

Most of the windows result to be deteriorated due to the use of the *Deodar* sapwood for this part of the building. In fact, the sapwood is the most tender and rich of nutrients section of the tree, thus the most likely to be attacked by moistures and insects, it is also the part of the log absorbing less (protective) painting. On the other hand, elements build with *Deodar* heartwood present no sign of decay. This is because heartwood durability can outlast sapwoods by 10 to 20 times ⁷.

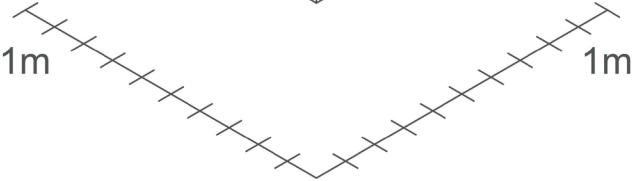
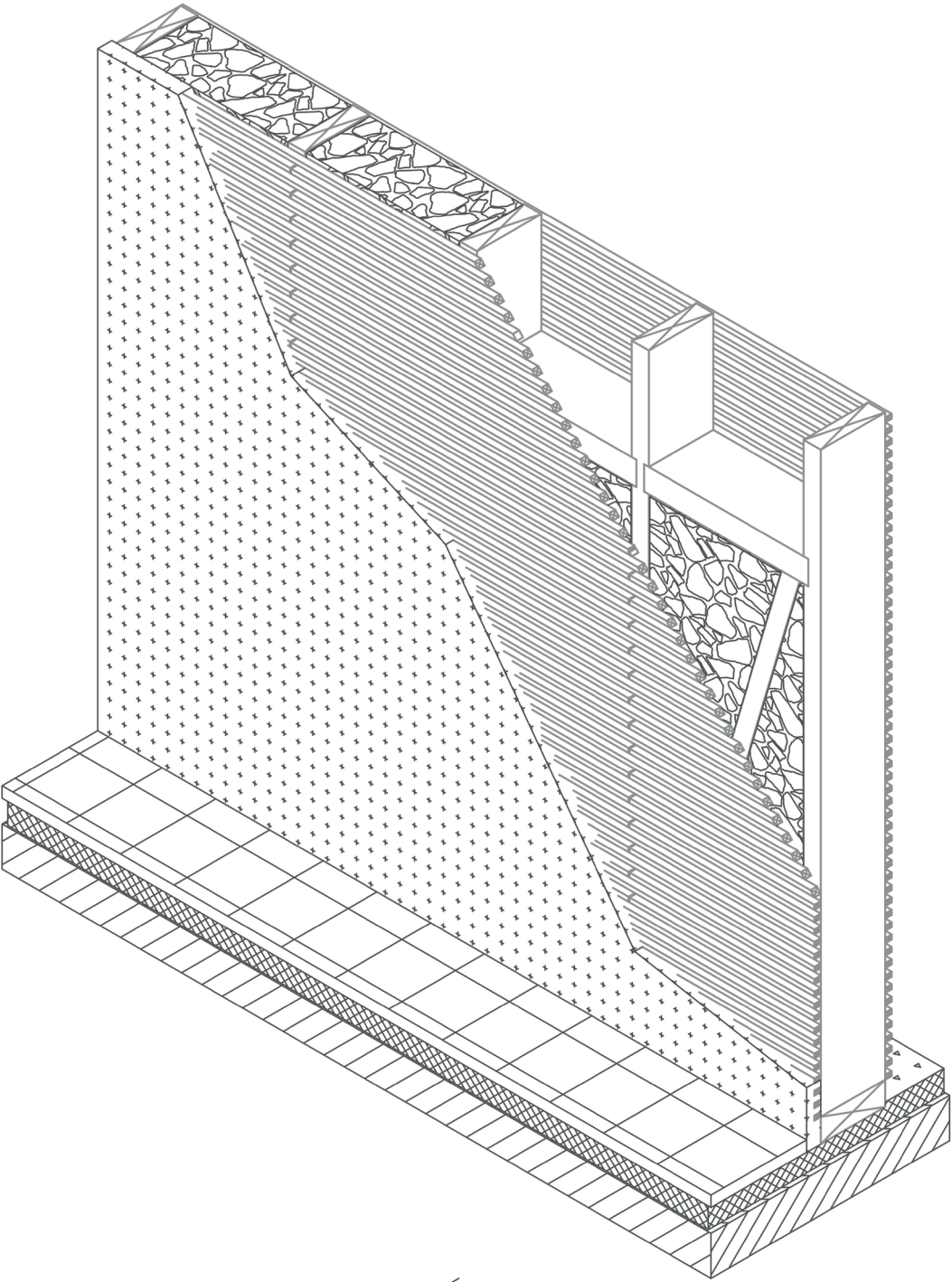
TIMBER+





2.1.2 DHAJI DEWARI

*This infill technique makes good use of recycled wooden window or door frames
(All rights reserved to Kubilâý Hiçyılmaz, report on “World Housing Encyclopedia -WHE,”
accessed October 16, 2019, <http://db.world-housing.net/building/146/>.)*



2.1 MONO STRUCTURE

2.1.3 QUINCHA

Quincha, *Bahreque*, *Bajareque*, *Fajina*, *Embarrado* or *Tequezal* are different names which all indicate a similar constructing technique employed in Southern America: it is characterized by the use of vegetal frames (made of timber but also ropes and split canes), adobe and dry masonry. Also known as *wattle and cob* techniques, most of them are the result of resilient pre-Colombian adaptations to the high seismic activity of the continent (South America lies between the North American, Caribbean and South American plates), and the influence of European timber frame constructions brought on the continent by *Conquistadores* around the 16th century.

Dependently on climate conditions, the northern arid areas have developed dry masonries with little or no use of water, whereas the southern ones made an extensive use of timber but also minor vegetal products as binders. It is worthy to quote the indigenous stacked system made of rope bags filled with boulders (called *Shicra*), employed for the construction of *Caral* pyramids in Peru and dated by 2600 b.C., a sort of antecedent of the gabion wall.

Nevertheless, most of *Quincha* techniques fall into the category of *mono timber frames*, hence the frame infills do not cover a load-bearing function, on the other hand they enhance thermal inertia of the timber wall and, in case of an earthquake, helps to dissipate part of the seismic energy through friction.

The infills are composed of adobe mixture,

less frequently by loose rubble, encaged inside two traced canes or lattice wall leaves. The entire wall is completely plastered, so timber elements are rarely left exposed.

Before the 18th century, especially in Lima it was possible to find heavy *Quincha* constructions made of adobe and boulders infills and more than one storey high. Unfortunately, after the 1687 and 1746 destructive earthquakes, the *Spanish Royal Ordinance* prohibited all earth construction exceeding one storey. This is the reason why it is only possible to find *Quincha* examples in remote areas across all South America.

Although the *Quincha* system presents its limits in a contemporary urban environment (among all, limitations in height and demanding maintenance), it still remains a good example of how timber frames can absorb all kind of mineral (and vegetal) construction waste without losing any structural integrity, on the contrary, by gaining from them extra qualities such as thermal inertia and sound proving.

2.1.3 QUINCHA



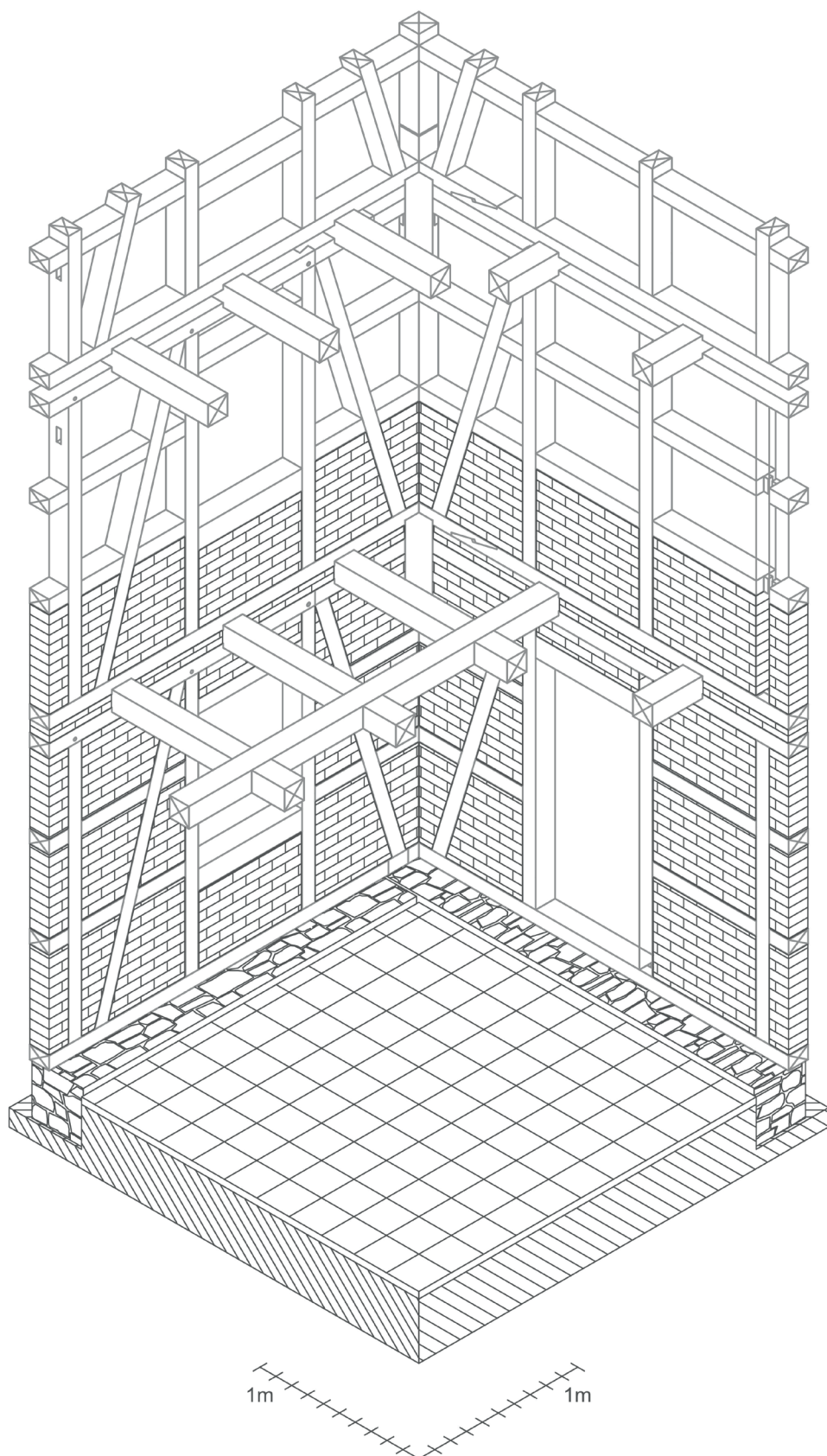
Wattle and daub wall (similar to Quincha, it's called "Taquezal" in Granada, Nicaragua (photo credits to Luis Fernando Guerrero Baca, 2008)



2.1.3 QUINCHA

Stonewall bagged in ropes (called "Shicra"), 2000 b.C., Pyramids of Caral, Peru (photo credits to Julio Vargas, 2010, L.F. Guerrero Baca, J. Vargas Neumann, "Local Seismic Culture in Latin America" Universidad Autónoma Metropolitana & Pontificia Universidad Católica del Perú, n.d.)

TIMBER+



2.1 MONO STRUCTURE

2.1.4 FACHWERK

URBAN AND RURAL TIMBER CONSTRUCTIONS

Half-timber buildings are characterized by a timber frame structure composed of short (often) hardwood interlocked elements thanks to several variations of lap-joints secured by hardwood dowels and pegs. The nobs (*Hourdage* in French) can be filled with a vast range of daub materials. This building system can go different names from one region to another: *Colombage* in French (from *Columna* in Latin or *pan-de-bois* if more than of storey), *Fachwerk* in German (*Fach* designates a filar polygon), *Rigelbau* in Swiss-German (from *Rigel* for *straight* due to the limited use of diagonals thanks to abundance of good quality softwood in some Helvetic cantons), *Intelaiatura* in Italian (which means literally *wireframe*), *Half-timber* in English.

Half-timber is born and it was associated to urban or semi-urban build environment. It is indeed important to state it from the beginning because its structural and technological evolution would be deeply influenced by the same constraints that designers encounter today in designing city buildings: limited room for in-situ operations, prefabrication necessity, hence limitation of component's dimensions.

Half-timber origins are probably retraceable to Balkan regions. We know, for example, that it was introduced even in southern Italy by Romanian immigrants after the fall of the Western Roman Empire (see *Opus Craticum* chapter on this subject).

From the 12th until the 16th century the *Long Bois* (literarily *Long Wood*, it was in many ways the ancestor of *balloon-frame*) represented the most common timber construction in Europe (the whole *Quartier Latin* in Paris was build following this technique). It was characterized by long span elements, both columns and beams, interlocked to form the skeleton of the building, and it was mainly widespread in rural areas with good quality, straight and tall species of trees. It is no coincidence that the highest expression of this technique can be found in Norway or Sweden. Starting from the 13th, 14th century good-quality timber started to become extremely rare due to the heavy deforestation taking place all around Europe, and concomitantly with the progressive expansion of urban areas, the *Long Bois* construction fades out from European landscapes. *Long Bois* became then utterly impractical due to the manipulation of long span elements in dense building environments. Furthermore, *Long Bois* provided far too wide and not fire and moisture proof buildings in town centers. The emergence of structured urban or sub-urban societies allowed the creation of strong and healthy companies of carpenters, which were eventually able to compensate the low-quality and scarce quantity of wood at their disposal with a far more complex manufacture and joinery, resulting in shorter but highly prefabricated timber elements. Bracing diagonals by instance, had the role of relieving transversal beams from compression stress. As said before, half-timber structures were for the most part realized out of average (if

2.1.4 FACHWERK

not bad) quality timber, hence presenting even weaker properties when charges are applied perpendicularly to their grain.

This *état d'esprit* is assimilable to the one behind the logic of contemporary glued wood products: joinery and high-level of manufacture can offset minor quality materials. These were the technological premises for modern *Colombage*, *Fachwerk*, and *Riegelbau*.

JOINERY

Short-span elements and high complexity of joinery are two of the most typical features of half-timber constructions. It would be impossible to envisage this type of construction without lap joints, tenon mortise, dowels and pegs. In fact, unlike *Long Bois* construction, where good joinery was mainly reserved to tightly fasten the long span elements together, in half-timber construction each joint is almost equally responsible for the overhaul stability of the structure. This is because, as all composite timber constructions, its structure can be defined as hyper-static. This is the reason why also these very same buildings required a constant maintenance: replacing elements or infills was easier exactly because of their structural redundancy, the same feature for which the structure was in constant need of repair. This entropic loop was the price to pay for their longevity.

By using short structural elements, the number of components increased significantly, as well as the work on site. From the previous

massive, rural constructions we shifted to a more elaborate and pre-fabricated type of construction. Pieces labelling and inventory started to become progressively more important. Roman numbers were often carved out on each piece to instruct builders on where to install each piece⁸.

The infills were either reinforced by a small wireframe made of interlocked sticks and then plastered in mud or plaster (*Torchis* in French), or (e.g. Southern Germany) filled with stick encapsulated in a coating envelope made of straw, mud and, whenever possible, lime. In more modern times, bricks will start to slowly replace mud and rubble infills, especially in towns.

Tendency of applying plaster also to the previously visible timber structure became quite popular. This practice harmed the wooden structures by incapacitating its chance to dry and became wide-spread due to the big fires of London (1666) first and then of Turku (1827), also because people started to consider this kind of timber construction as an expression of provinciality and precariousness compared to brick, concrete or even steel construction, which in 19th century were able to communicate progress and wealth, much more than the old half-timber construction.

This chapter does not aim to cover all consideration on tectonic or style aspects necessary to give to the lector a full understanding of all the incredibly wide range of different half-timber construction. But rather

⁸ Weiss, Walter; *Fachwerk : Bautraditionen in Mitteleuropa* (Stuttgart: Fraunhofer IRB Verlag, 2019).

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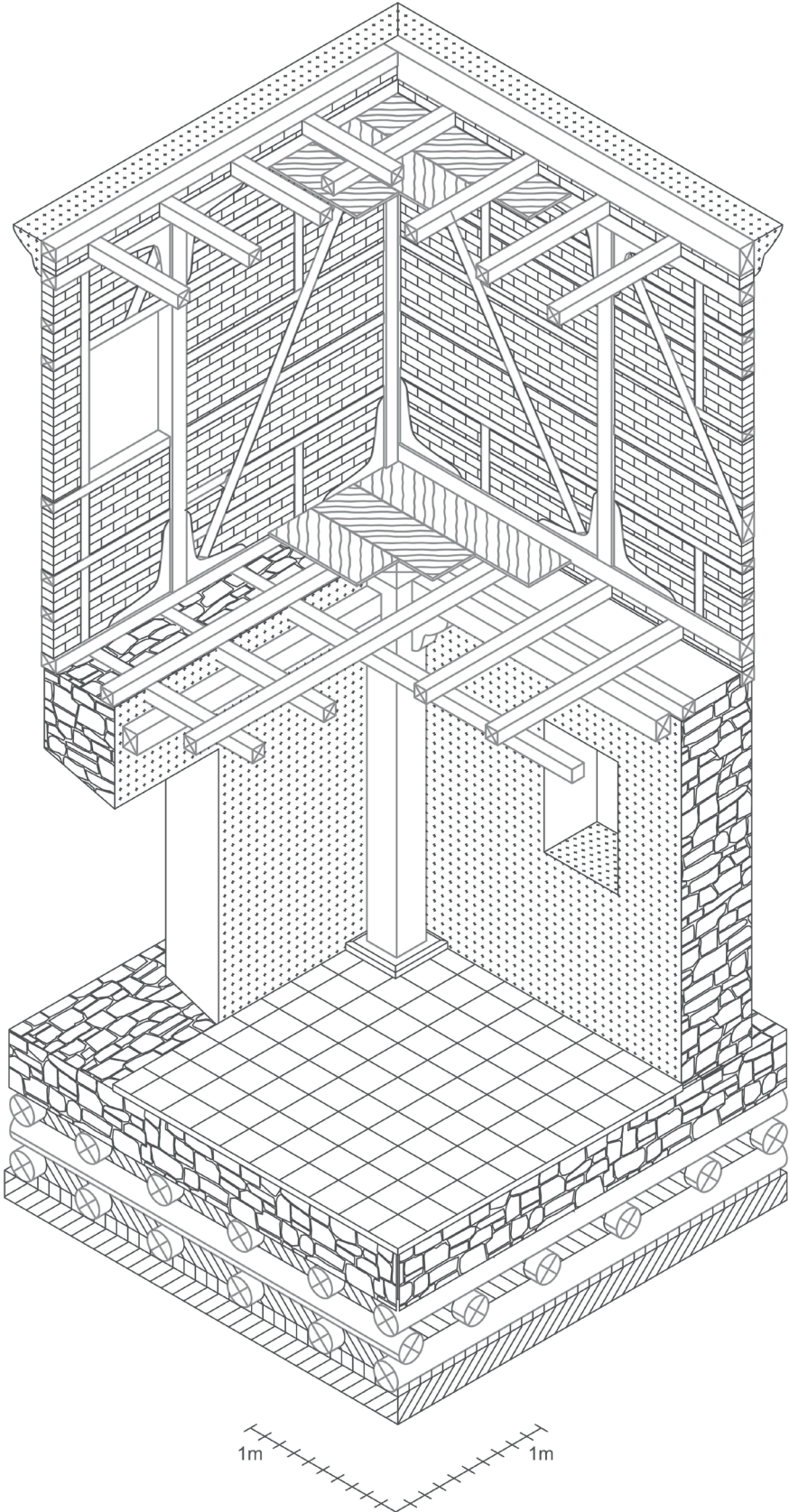
to give an idea of the (not so old) logic behind its rise and development, the same which the most advanced research laboratories on timber structures still adopt today.

2.1.4 FACHWERK



J. Wilhelm, building site of a Fachwerk house, 1668

TIMBER+



2.2 DUAL STRUCTURE

2.2.1 PONTELARISMA

LOCAL SEISMIC CONSTRUCTION
PRACTICE, LSCP

"In the pre-modern age, the concept of preservation was mainly related to the possibility of achieving profits; the decision about restoring derived from the willing of people to keep living their houses and any configuration change was done only if unavoidable. In addition, within a context marked by strong and frequent destructive events, it is interesting to note how conservation may give the way to empirical attempts to improve the construction system.

9 "

The *Leucade* island is an independent entity from the Greek peninsula and it has been under the control of various rulers and administrators: the Venetians (1684-1797), the French (1797), the Turks (1798-1807), the British (1810-1864), until 1864 when it became officially part of the Greek territory. It would be in part wrong to think the *Lefkada* system as a complete vernacular construction, if by vernacular we intend a design not contaminated by educated professionals in any domains of construction.

The *Leucade* region has always being subjected to several attacks from the Crusaders, Bulgarians, Normans, Sicilians and various pirates¹⁰¹¹. This is the main reason why the population has originally retrieved towards the mountainous backcountry. It was during the first domination of the island that locals were relocated close to the shore

in order to build the Venetian fortress. That settlement will later be known as *Lefkada*. At that moment the population was facing far worst constructing conditions than before: apart from the recurrence of earthquakes with magnitude around 6 every 30 years¹², the soil was not purely made of rocks but mainly composed by alluvial deposit, hence more unstable and humid. The Venetians and later the Ottoman Empire contribute to the elaboration of a system which the following administrations, like the British, and especially the local population itself had been keeping it up to date until present days. In fact in 1826, after that the island was struck by several earthquakes, the High English commissioner, general Sir Frederick Adam ordered the edition of a new building code based on the previous system employed by the Venetians and Turks¹³.

It is worthy to note that locals have been trained in naval construction since the establishment of the Venetian costal settlement: the techniques and the construction of naval items have certainly contributed to the creation of a high skilled craftsmanship specialized in wood working.

The authorities adopted new masterplans for the town in order to react to the persistent erosion of the island (the eroded soil is considered of class C of Eurocode 8: "*deep deposits of dense or medium-dense sand, gravel of stiff clay with thickness from several tens to many hundreds of meters*").

The town center is shaped in a way that

9 Multiple research papers's authors, *Historical Earthquake-Resistant Timber Framing in the Mediterranean Area*, Springer (Helena Curz, José Saporiti Machado, Alfredo Campos Costa, Paulo Xavier Candeias, Nicola Ruggieri, José Manuel Catarino, n.d.).

10 P. G. Rontogiannis, "*The Capitals of Lefkada*," 1988.

11 C. Papadatou-Gianopoulou, "*Lefkada Researching [Lefkada Ereunontas](in Greek)*," 1999.

12 Sandra Tonna, Claudio Chesi, "A

2.2.1 PONTELARISMA

heavy rainfalls water can be easily drown towards the sea. Furthermore, the same historical center, which is dating back to the 18th century, was shaped in order to profit of the frequent wind condition blowing N-NW: this helps considerably reducing humidity¹⁴ in the urban area. These preventions against soil erosion and humidity are thoughtful features especially for timber construction: it fulfills the need of timber to dry out, more so important whenever wood is mixed with a masonry system as with the *Pontelarisma* system in question.

Finally, urban blocks and houses were individually build and were independent from each other whenever possible.

Nowadays this building system still cover 34% of the total building stock of the town¹⁵.

DESCRIPTION OF THE BUILDING SYSTEM

The exterior façade of a typical Lefkada house reflects the technological organization of the system: ground floor is stone made, whereas upper stories (up to 4 floors) are built in half-timber construction with clay bricks infills.

Openings at ground level are symmetrically arranged, narrow and regular in order to preserve upper timber floors from ascending humidity and allowing a smooth transfer of load up-bottom (yet it is worthy to note that there are different schools of thought on how to properly distribute openings in anti-seismic buildings).

The ground stone walls present a typical

“sacco” structure (two exterior leaves of masonry made in ashlar whereas the inner core was filled with irregular boulders): the dimensions of the ground floor wall are typically from 0.6 m to 1 m thickness, with a maximal height of 3.0 m.

Foundations excavation were set relatively low, from 80 to 100 cm deep in order to reach the lagoon bottom¹⁶. Whenever possible pozzolan was employed, but if constructors could not dispose of such practical binding powder, they adopted a different method of foundations construction: a grid of crossed hardwood logs was placed underneath the base for the wall realized in lime or in a poor-quality cement. This provided a good behavior and an even base for the upper construction. In fact, in the event of an earthquake, the house would be *shaken* uniformly.

HYPERSTATIC DUAL STRUCTURE OR "PONTELARISMA"

As in many Mediterranean half-timber systems, logs and timber are used inside the masonry in order to boost tensile and shear qualities of the wall. But the real cleverness of this system relies in its dual structure. In other words, the timber frame is autonomous from the main masonry in case of its collapse, but they do work together in a normal static situation. To explain the adoption of this *redundant* technique it becomes necessary to introduce the concept of *building seismic culture*.

Lefkada island is a limited system with

Multidisciplinary Approach to the Analysis of the Traditional Lefkada Houses” (Politecnico di Milano, n.d.).

13 Vinitzileou E, Zagkotsis A, Repapis C, Zeris Ch, “Seismic Behaviour of the Historical Structural

System of the Island of Lefkada, Greece” (2007).

14 Sandra Tonna, Claudio Chesi, “A Multidisciplinary Approach to the Analysis of the Traditional Lefkada Houses.”



Marine

Bernard Juvet

Courtieu, natural deformations for naval construction, extrait of Encyclopédie méthodique marine, p. 103: the influence of (Venitian) naval timber construction is evident on the Pontelarisma technique, see next photos of angular reinforcements.



2.2.1 PONTELARISMA

"L" Connections of frame corners issued of naval techniques ("Seismic behaviour of the historical structural system of the island of Lefkada", 2007, Greece, Author: E.Vintzileou, A.Zagkotsis, C.Repapis, Ch.Zeris. Copyright © 2005 Elsevier Ltd. All rights reserved.)

very few resources, the impact of several earthquakes calls for a pressing need of maintenance and repairing. In the event of a violent earthquake, the aftermath can result even more dreadful than the seism itself. Efficient and economic repairs were the key for the survival of the population.

In addition to the masonry wall an auxiliary post-and-beam system (with a span of app. 2-3m) is connected to a timber slab composed of interlaced beams laid on top of the masonry wall. In a normal situation the masonry wall is the main load-bearing element, especially for the façade. In the case of an important seismic event, the wall collapses after having absorbed part of the seismic energy leaving the columns to sustain the upper floors. The slab does not really provide anti-seismic qualities to the building, nevertheless it assures a stiff connection between the upper floor and the ground floor post-and-beam grid.

This is one of the reasons why the log foundations became progressively more popular: for a better reaction to the seism, posts must rest on the same shaking plan during a seismic event.

Finally, during the aftermath, boulders and bricks can be collected and put in place while the inhabitants can almost immediately reoccupy their homes.

TIMBER DETAILS

As we can see from the axonometric drawing, the frame of the upper floor level is reinforced

and stiffened at corners by four “L” shaped elements called “*bratsiola*”. Today we would create those elements in LVL for example. At the time they were made from oak branches, whose fibers are already naturally arranged to seemingly “L” shape. This detail is helping to enhance the uniform behavior, rigidity and anti-shearing quality of the overhaul timber frame. The logic behind the presence of such elements is the same for which, in modern practice, we tend to brace rib-constructions with OSB or Plywood sheets: to enhance the stiffness of the structure. In addition, it also counter-acts the accumulation of stress in the corners during a seismic event. For the same reasons the very same fasteners are present at the ground level in jointures between posts and beams.

This special treatment of nodes recalls the junction element of a boat planking¹⁷. From this we could assume that the Venitian’s shipwright constructive knowledge has been actively put at use to elaborate the *Lefkadas* system.

The roof connection to the last floor ceiling respects the “box” logic in case of an earthquake and is conceived to counter-act every directional solicitation. The two belt frames are overlaid one on top of each other, connected by either a lateral or a cross lap joint. Furthermore, the two overlap belts are belonging respectively to the last floor and to the roof: this ensures the independent shaking of each story, avoiding in such a way, major deformations. Plus, by doing so it was possible to disassemble the roof and

¹⁵ Triantfyllos Makarios, Milton Demosthenous, “Earthquake Response of Historic Buildings at Lefkas Island” (Departement of civil engineering, Aristotle University of Thessaloniki, n.d.).

¹⁶ “Traditional Building Criteria in the Lefkada

Island: Peculiarities of the Foundation System” (9th international conference on structural analysis of historical constructions, Mexico City, 2014).

¹⁷ Nicola Ruggieri, “Reliability of Timber Framed Constructions in Seismic Prone Areas in the

2.2.1 PONTELARISMA

replace it with an additional floor whenever the inhabitants desire.

It has been calculated that the maximum value of ground acceleration that the overhaul system can sustain is around 0.50 (g units)¹⁸, which is in line with the average of the seismic history of the island. By instance the last earthquake of 2003 was reported to be 0.43g, a value under the general calculated resistance of the system.

PHATOLOGIES OF THE SYSTEM

Following the earthquake of 2003, a detailed survey of the build environment condition was carried out in order to assess the conditions of the town building stock.

Concerning the damages cause by the earthquake, experts were surprised to note that there have been very few out-of-plane collapses regarding the brick infill. Nevertheless, the most serious damages were reported to be in those buildings which were converted from residential to commercial use: one side of the thick masonry ground wall was demolished in order to be replaced by a shop window. By getting rid of one ground-floor masonry wall, the whole system resulted considerably weakened. This is the same reason why we could find entire buildings horizontally shifted due to the collapse of one of the remaining ground walls.

It was also clear that timber elements of upper levels in contact with masonry infills were in

a state of extensive decay (not caused in any way by the earthquake).

There are identifiable reasons behind this phenomenon.

First among all, the decline of local timber stock. In fact, in recent times, the typical wild oak employed in the traditional construction (*Quercus cerris* or “*roupaki*”, its commercial name is *Turkish Oak*) has been running extremely low and there was not enough to supply the recent extension of the urban area (caused by an exponential growth in tourism, the GDP of the island has in fact almost quadrupled in the last few years). This has obliged the population to import Sapwood, mainly from Sweden, for the maintenance and the construction of new *pontelarisma* buildings¹⁹. As said the advanced state of decay for these new buildings was far from being considered as anodyne.

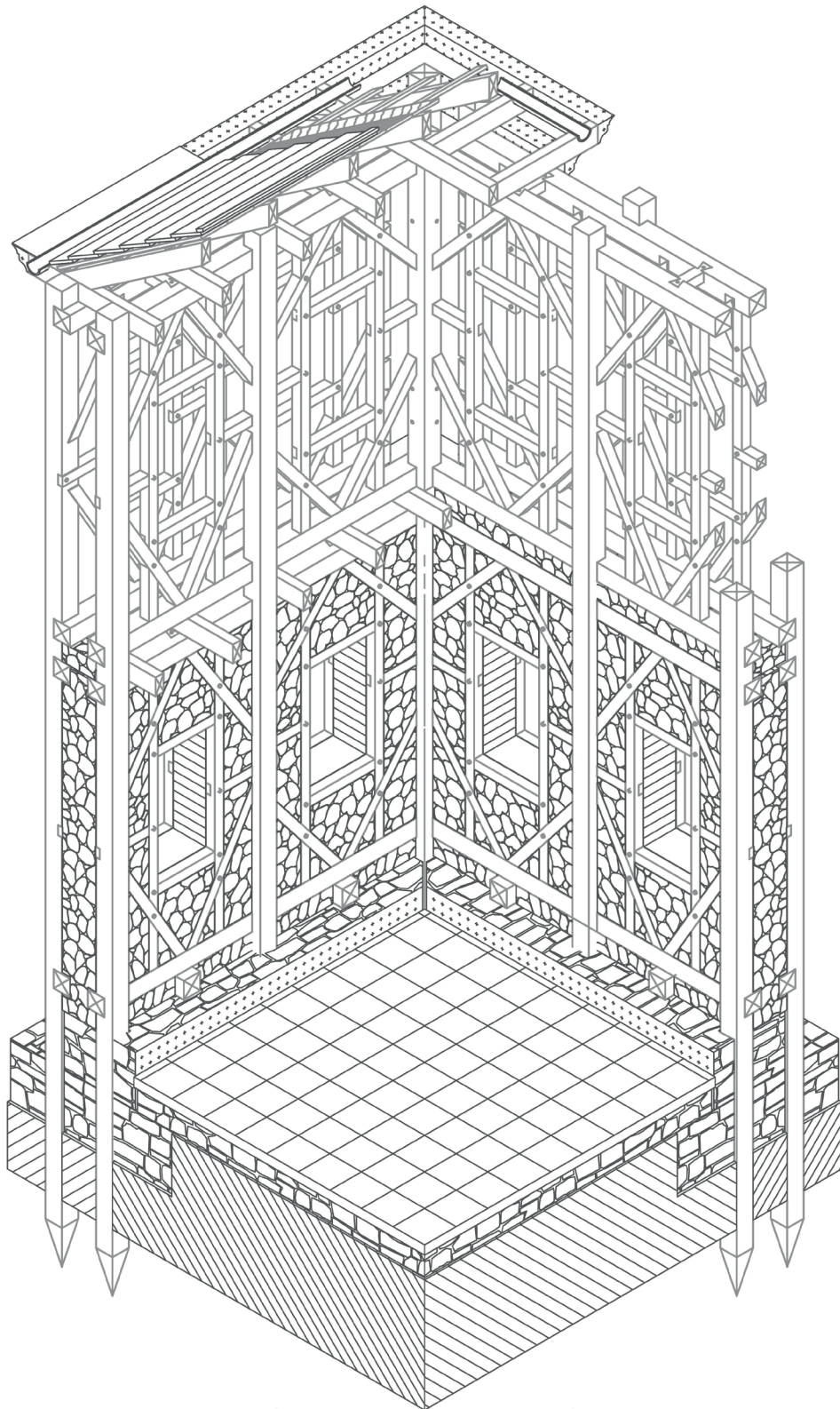
The problem with the importation of northern sapwood can be explained by considering the density of such species in relation to the humid and warm climate of areas like *Leucade* archipelago. In humid and warm conditions (worsened by the alluvial nature of *Lefkada* soil) sapwood species, like Spruce or Douglas Fir, are much more sensitive to moisture attacks than denser and local hardwood species, like the more autochthone *Turkish Oak*.

Practice Codes Issued from 18th to 19th Century” (DIBEST, Università della Calabria, 2016).

18 Sandra Tonna, Claudio Chesi, “A Multidisciplinary Approach to the Analysis of the Traditional Lefkada Houses.”

19 Faye Karababa, Peter Guthrie, “Vulnerability Reduction through Local Seismic Culture,” *IEEE Technology and Society Magazine*, February 2007.

TIMBER+



1m 1m

2.2 DUAL STRUCTURE

2.2.2 BORBONE

A COMPLEX PROTOTYPE

Calabria, an Italian region located in the south of the peninsula, was struck by an earthquake in 1783. Therefore, the *Borbone* government ordered a survey of the economic loss, the state of the building environment and promoted a research on new earthquake-proved building techniques. Among the many experts put in charge of the survey there was Giovanni Vivenzio, volcanologist and doctor of the Royal Household.

In his report, few chapters were devoted to the description of a new half-timber constructing system, three illustrative boards were present as well at the end of his publication²⁰. The text provided data concerning the behavior of the system under a static and especially a dynamic action. Needless to say, the project reflects the *post-quake positivist momentum*²¹ typical of scientific approach to the late 18th century reconstruction, such as the *Pombalino* proposal in Portugal.

Vivenzio imagines a house, designed with the outmost tastes of *beaux-arts* canons, and he introduces two small buildings on the sides of the main central volume, all perfectly square shaped. These two adds-on are considered to contrast the seismic action and stabilize the main body of the complex, in other words they act as buttresses. The perfect cubic proportions of the volumes are another earthquake-proved feature of the design since the building will have a bigger chance to react uniformly to the dynamic

actions of a seism. In addition, he describes and draws the composition of the façade in order to install a regularity which could help not only a smooth vertical flow of charges, but also a compact response during a possible earthquake (here, once again, there are contrasting theories about whether or not, the equal distribution of openings makes the building more anti-seismic).

As in the best spirit of *beaux-arts*, *poché* drawings are always put in comparison to a technological and constructive analysis.

The interior subdivision of the plan is seen as a chance to interlock volumes in all directions thanks to the close and homogeneous distribution of partitioning walls.

Although, hyperstability is often a winning strategy for the design of an earthquake-proved structure (e.g. Lefkadas). In this case the structure appears to be extremely redundant. It is not the structural conception *per se* which results excessive but more the hypothetical manufacture of the proposal. We do not have to forget that this is a prototype proposed for the reconstruction of a Mediterranean area which, apart from the local naval craftsmanship, cannot boast a high level of craftsmanship in the construction of wooden buildings. This is perhaps what makes this prototype extremely correct and theoretically fulfilled under such many aspects, but completely unfit to practical applications. Vivenzio describes and details a doubled timber frames braced by dove-tailed connectors at each panel and reinforced

20 *Istoria e Teoria de 'tremuoti Ed in Particolare Di Quelli Della Calabria, e Di Messina Del MDCCCLXXXIII* (Napoli: Stamperia Regale, 1783).

21 Stefania Stellaci, Francesca Geremia, Enrico

Pagano, Nicola Ruggieri, Ginevra Salerno and Michele Zampilli, "Urban Planning and Building Reconstruction of Southern Italy after the 1783 Earthquake: The Case of Mileto: The Case of Mileto" (ISCTE-Istituto

2.2.2 BORBONE

by a couple of sub-grids, composed by vertical, horizontal and diagonal elements for extra stability. Differently from many other contemporary frame timber structures, which are mainly *platform frame*, Vivenzio takes a bold approach by designing no more a *platform* but a *balloon frame* structure (at least for the central building): the posts run from the bottom foundation level up until the roof without any seizures (it is unclear how he suggests to solve the structural continuity of those vertical members).

The compound pillars are formed by four vertical elements locked by the same dovetail connectors used for the horizontal elements, "*affinche dette travi non cedino da qualunque parte*"²².

Moreover, he suggests detaching the ground floor from the ground with a basal layer of rocks in order to avoid any moisture decays for the timber frame and, to reinforce the building life, he suggests to employ oak.

All the connections and knots on top of being either over-lap or cross-lap, are shored up by dowels or wooden nails. As we can see from the *planche*, the complexity of the joinery would be only overcome by the amount of labor to manufacture it.

GERMANIC INFLUENCE

It is probably no coincidence that such level of complexity could evoke more Nordic typologies of timber construction such as the *Fachwerk* (German/Austrian version of half-timber construction). Calabria was in fact

occupied by Normans (literally *man from the north*) during the 9th century. This population was mainly Germanic and during their stay they promoted the extensive use of *fachwerk*, especially for civil buildings²³, but it seems that timber frame construction can date even before the Norman immigration (see chapter *Casa Baraccata*).

In the 8th century Calabria came under the jurisdiction of the *Regno delle due Sicilie* ruled by Ferdinand IV, head of the Borbone dynasty. His wife on the other hand was Maria Karolina from Austria, belonging to the Asburgo-Lorena lineage, much up north. Vivenzio addresses the report, the one in which the system is described and drawn, to the Queen herself.

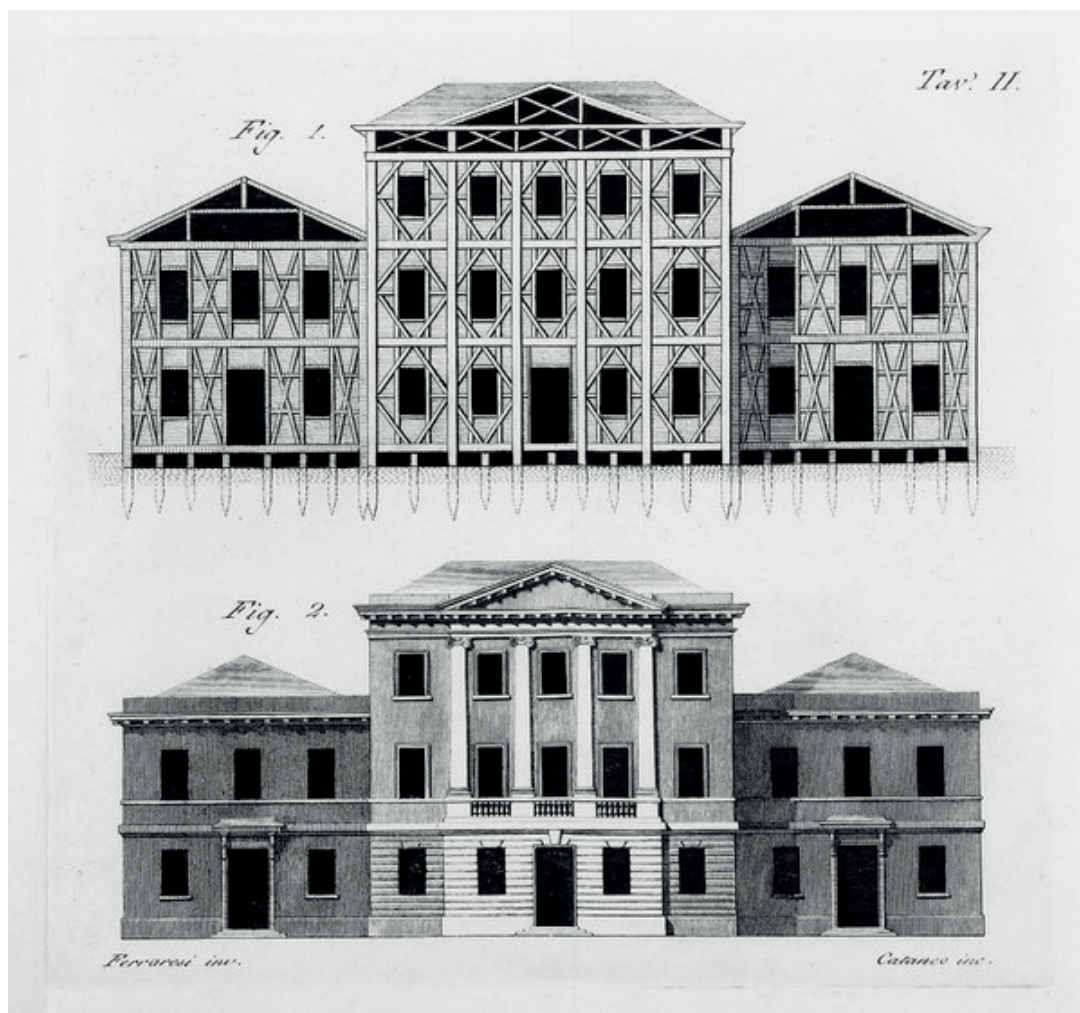
It is no chance that we can find several examples of the same type of framing employed by Vivenzio in Northern Europe, by instance in the Town Hall of Mons, Belgium whom "*frames [are] stiffened by inclined timber members*"²⁴. Another similar framing is found in an engineering manual quite famous at that time in Europe, it would not be hard to imagine Vivenzio having read it. The book in question is a showcase of (mainly wooden) bridges construction and technics from Northern Europe²⁵ (an example of Venitian bridge is included as well).

Furthermore, the presence of a such high number of diagonals (app. eight per frame division) has very little to do with the half-timber culture of the Peninsula, by instance in Calabria they were completely absent

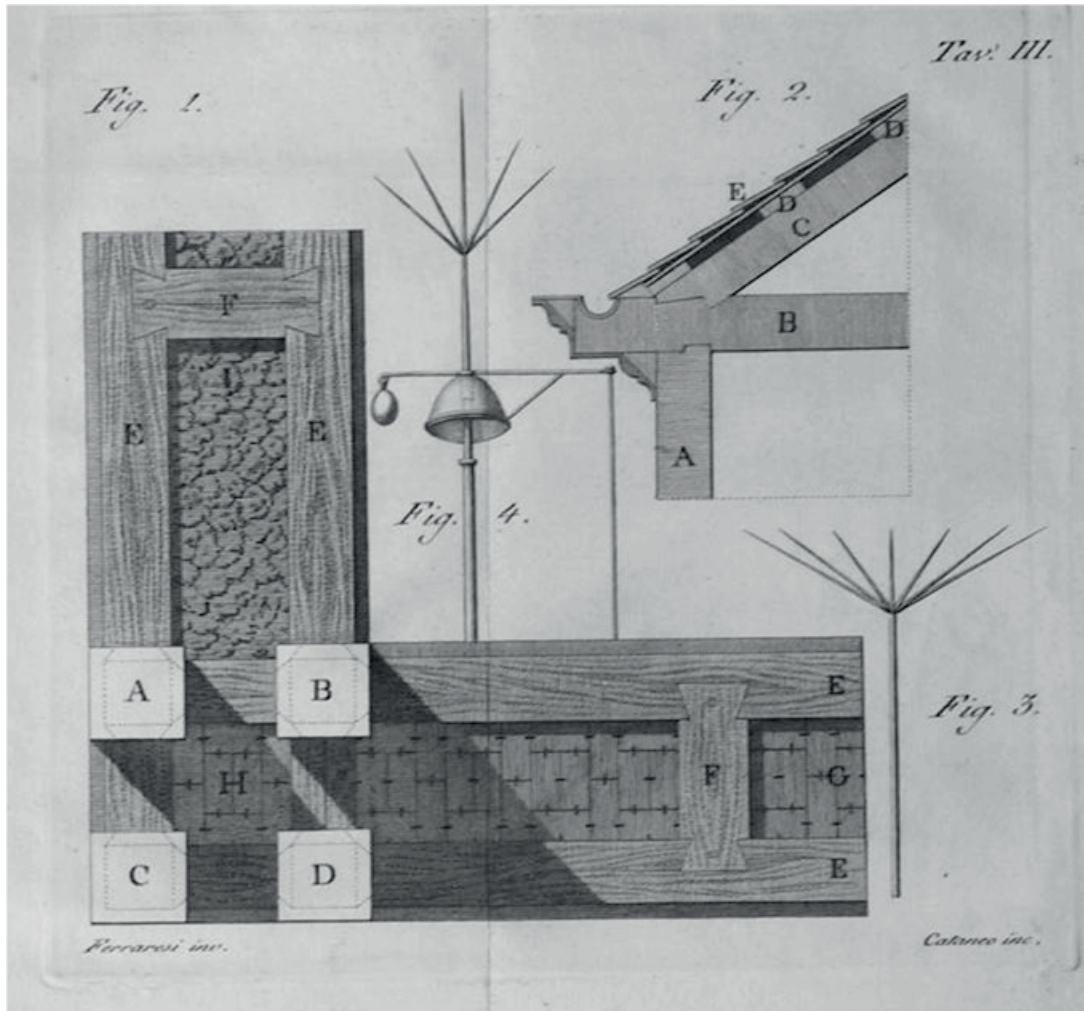
Universitário de Lisboa, DINÂMIA'CET-IUL,
Dipartimento di Architettura Università Roma Tre, n.d.).
22 Istoria e Teoria de 'tremuoti Ed in
Particolare Di Quelli Della Calabria, e Di Messina Del

MDCCLXXXIII.

23 Nicola Ruggieri, "Il Sistema Antisismico
Borbonico Muratura Con Intelaiatura Ligna Genesi e
Sviluppo in Calabria Alla Fine Del '700," n.d.



Hidden structure and illustration of the façade appearance, drawings by Vincenzo Ferraresi from Istoria e Teoria de 'tremuoti Ed in Particolare Di Quelli Della Calabria, e Di Messina Del MDCCLXXXIII.



Detail of the wall composition from Istoria e Teoria de 'tremuoti Ed in Particolare Di Quelli Della Calabria, e Di Messina Del MDCCLXXXIII.

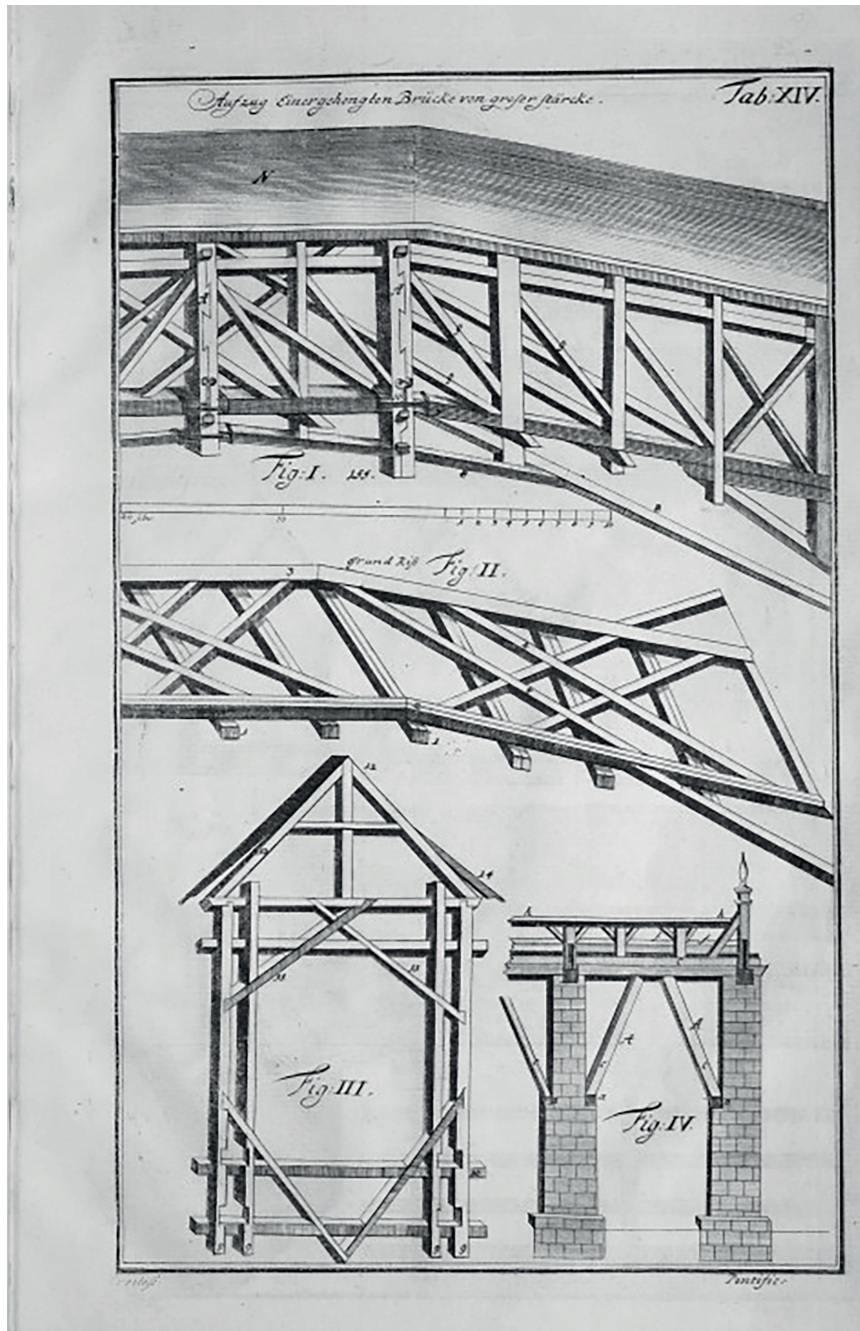
in the vernacular half-timber construction. Probably such bracing was not needed in Italic territories due to the abundance of good quality and locally available pozzolan, whereas up-north diagonals have revealed themselves necessary in order to properly brace the framing in standard static situations. The fact remains that Vivenzio tends to favor diagonals over good quality masonry considering the dynamic loads of the structure. So much effort is put into wooden detailing that fillings of quads are briefly described as *opus incertum*, a terminology employed by ancient Romans to designate a masonry mass which contains neither specific recognizable, nor valuable or resistant stones. The strategy he adopted, and which he probably brought to ideal extremes, is giving priority to timber frame more than masonry.

Later, Vivenzio's treaty will become famous in all the Kingdom and it can be credited for having shown the engineered version of the much simpler local culture of *Casa Baraccata*.

24 Nicola Ruggieri and Raffaele Zinno, "Mechanical and Constructive Interpretation of the Giovanni Vivenzio's Model" (University of Calabria, Rende, Italy, 2015).

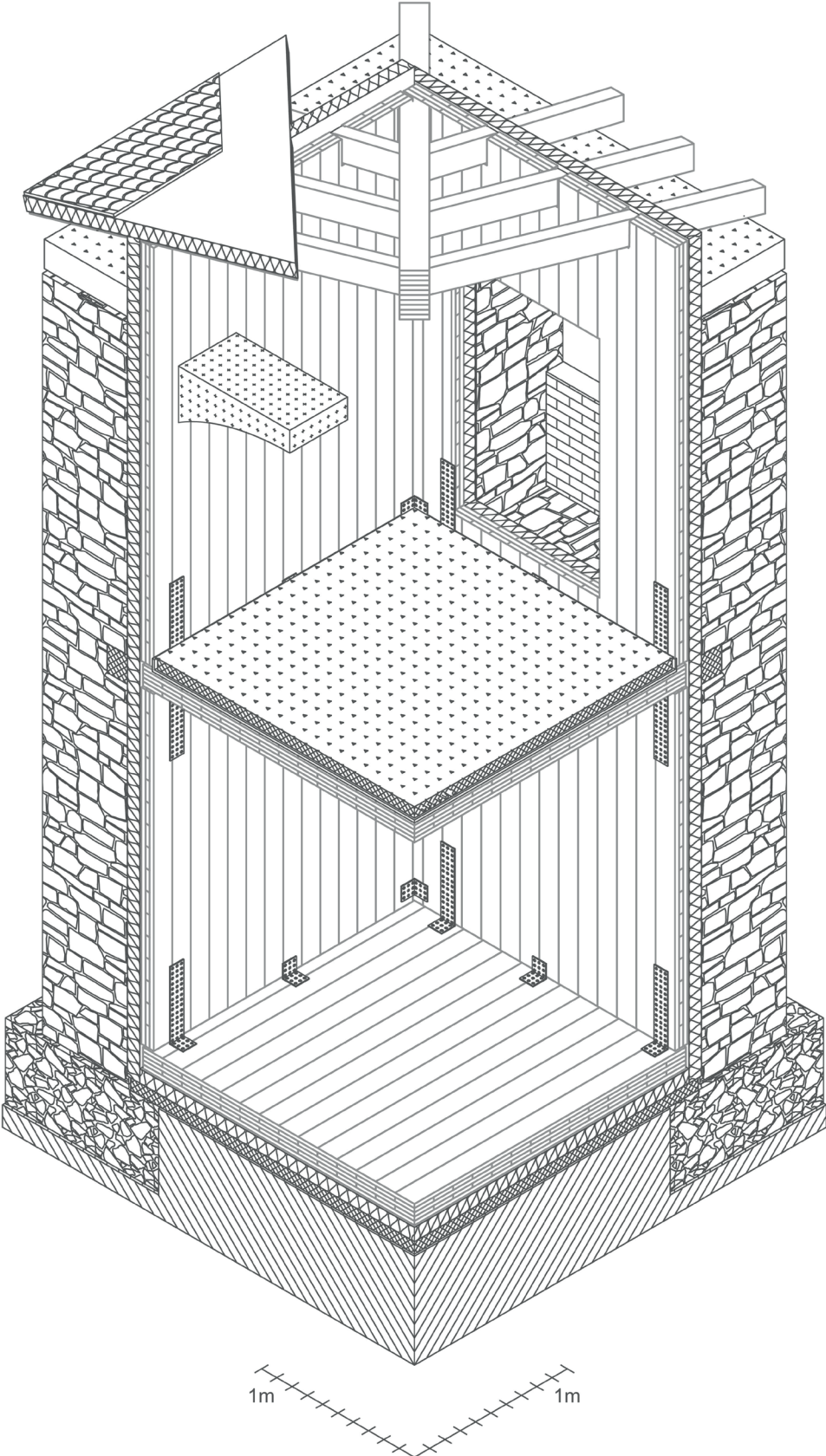
25 Leupold Jacob, *Theatrum Pontificale: Oder Schau-Platz Der Brücken Und Brücken-Baues*, Bernard Christoph Breitopfs (Leipzig, 1774).

2.2.2 BORBONE



Leupold Jacob, *Theatrum Pontificale: Oder Schau-Platz Der Brücken Und Brücken-Baues*, Bernard Christoph Breitopfs (Leipzig, 1774): detail of timber bridge, transversal cross section framing similar to the one employed by Vivenzio in his prototype.

TIMBER+



2.2 DUAL STRUCTURE

2.2.3 CLT SHELL

SHELL STRATEGY

The isometric drawing is referring to a small 3-storey dwell built by an Italian wood construction company (L.A.Cost) nearby the city of L'Aquila, in Ovindoli. Until now, this technique has been used only for retrofitting interventions. Nevertheless, its CLT interior shell embodies the earthquake-proved principle of the “safe cage” employed in all the tradition of “*casa baraccata*” in *Calabrian* region in Italy (see *Mileto system*). In a nutshell: in case of a seismic hazard the absorbs most of the energy and eventually collapses, leaving the interior CLT intact or affected by minor damages.

A study shows the excellent thermal performances of this system²⁶. Admitting a rigid insulation of 40mm (between the CLT panel and the masonry), a wall of 280mm thickness, and a CLT of 950mm, the entire wall obtains a thermal transmittance value of 0,225 [W/m²K]. What the study does not consider is the interior comfort given by the strengthened thermal inertia provided by the heavy perimetral masonry walls. In fact, a major weakness of timber construction is certainly given by its low thermal inertia value, which directly influences its performance in buffering the interior temperature during different times of the day, the add-on masonry fully compensates this lack.

Although a prior intensive work on site is required (emptying the volume of the building from debris or slabs), the installation phase

is relatively simple due to the high degree of prefabrication of CLT. It is possible to match all the possible irregularities and present opening of the system; components can be fitted inside the existing masonry at ease thanks to the light weight of the components.

The main body is then completed with a cover, for instance in the isometric drawing, the roof is made of glulam ridges and rafters.

This system is particularly advantageous in retrofit operations since it leaves the exterior appearance of the building completely untouched and it gives the possibility of building another storey.

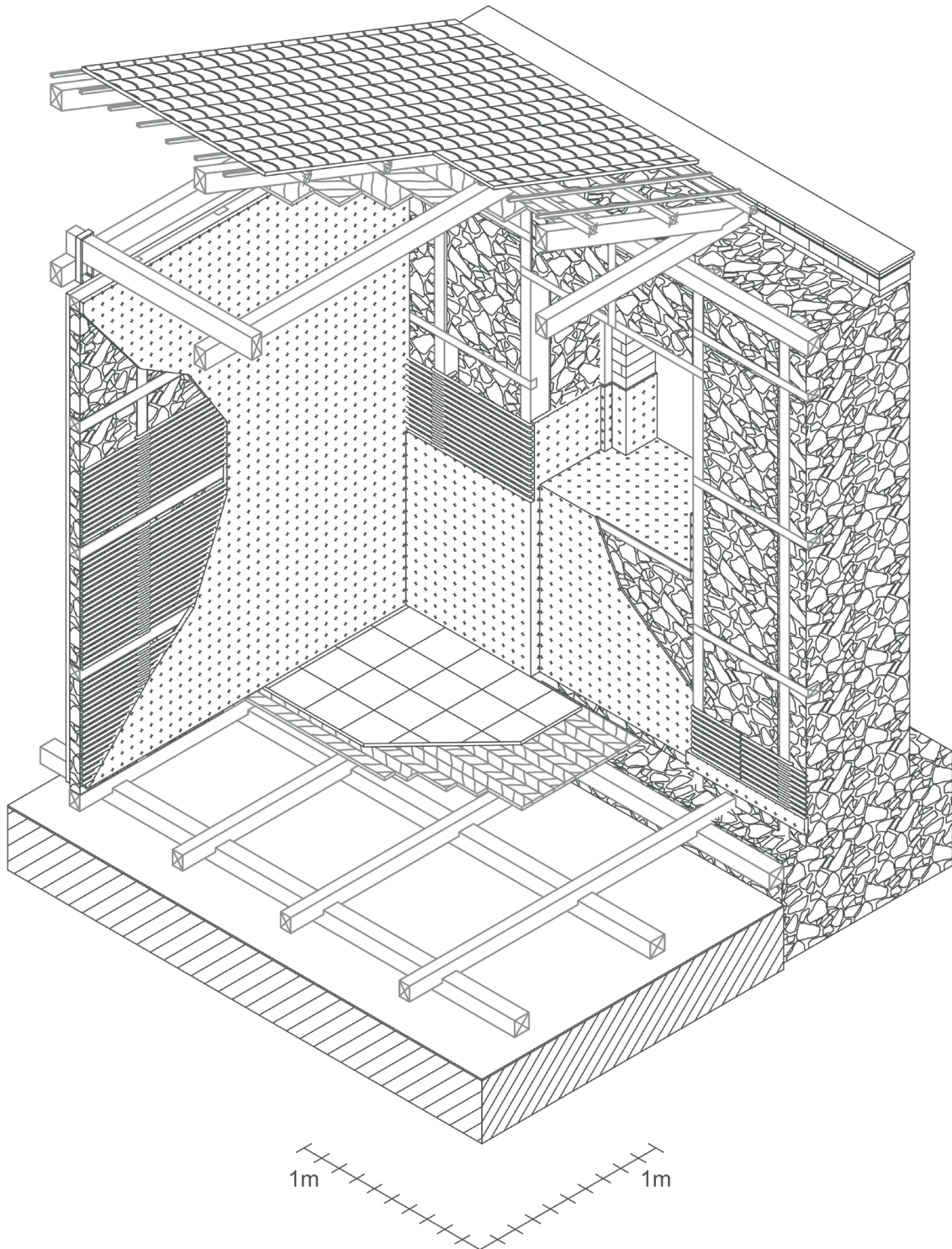
Another possible application is when the building code does not allow the complete demolition of the existing masonry. The project *S(ch)austall*, by *FNPA Architekten*²⁷ exploited this possibility by doubling and detaching the new volume from the existing one. In this scenario, as it often happens for such *week-end* houses, thermal proficiency is not the focal point of the project (the wall is composed just by one layer of LVL panel). Nevertheless, the design takes advantage of the existing masonry to provide an extra (thermal) shelter to the timber shell. Moreover, it is worthy to note that the panels employed are LVL panels, thus, due to their laminar compositions, further attention should be put into water-proving the whole timber core.

²⁶ Moro Bioedilizia, “Procedimento di ristrutturazione di edifici Recupero Rinforzo Risparmio,” n.d., 6.

²⁷ “Home,” Flubacher_Nyfelner_Partner, accessed October 14, 2019, <https://fnp-architekten.ch/>.

2.2.3 CLT SHELL

TIMBER+



2.2 DUAL STRUCTURE

2.2.4 CASA BARACCATA

FERRARI'S PLAN

The Bishop's Palace located in Mileto is part of a much larger masterplan for the reconstruction of the town of Mileto, Calabria, Italy. The Borbone administration commissioned the reconstruction to the royal architect Vincenzo Ferraresi, who after a survey and an estimation of the seismic vulnerability, he designed, on the basis of engineers Winspeare, La Vega and Frangipane, a regular urban grid applicable to all the towns destroyed by the earthquake of 1783 and in need of relocation.

Although the masterplan was well established and studied into the smallest details, it was only partially achieved due to the resistance of the local population to adopt new housings and a brand-new redistribution of properties (the society of the backward province was still influenced by feudal principles).

THE EPISCOPAL PALACE

The construction system in question was adopted for the construction of the Episcopal residence, the building was only partially achieved but it was meant to be part of Ferraresi's reconstruction plan as a showcase for proper earthquake-proved construction technics. It was probably designed by an unknown student of *Ferraresi*, most likely an architect from Gallipoli.

The structure is much closer to the typology of the *casa Baraccata*²⁸ (the vernacular half-timber construction, probably introduced in Italy by Greek-Albanese migrants after the

fall of the East Roman empire in 1453²⁹) than the prototypes proposed by *Vivenzio*³⁰ drawn by *Ferraresi*. Even though, the system presents some engineered details such as diagonals for extra bracing, or diaphragmatic walls as in *Ferraresi*'s drawings or like in the *Pombalino* system.

It was in 1683, after the earthquake of *Calabria Ulteriore*, that the *casa baraccata* was employed for the first time by engineers in order to momentarily shelter the refugees. It is not clear if the frame was placed on the interior leaf like in the case of *Mileto* or it was a more common half-timber construction typology (a *monostructure*, if we want to refer to the categorization of this *Atlas*). What is certain is that it was made from a quickly executed timber frame and rammed earth infills. The name *baracca* has in fact a pejorative nuance in Italian: a poor build hovel made from junks.

THE SYSTEM IN DETAIL

The wooden frame made in chestnut (*castagno calabrese*) is always positioned on the interior leaf of both back and street-oriented wall. The exterior masonry is much more refined: ashlar, *cotto* gables, sandstones, and re-employed debris for the pilaster basis³¹. Whereas the innyard wall masonry is made of rubbles mixed with cement with few transversal stones called *diatoni*. Plus, partitioning walls are realized with the same technique of the back walls, including quad infills made of irregular stones.

28 Olimpia Niglio, "La Casa Baraccata," *Bio Architettura*, July 27, 2004.

29 I. Mazziotti, *Immigrazioni Albanesi in Calabria Nel XV Secolo e La Colonia Di San Demetrio*

Corone (1471-1815), n.d.

30 *Istoria e Teoria de 'tremuoti Ed in Particolare Di Quelli Della Calabria, e Di Messina Del MDCCCLXXXIII (Napoli: Stamperia Regale, 1783).*

2.2.4 CASA BARACCATA

Concerning these interior walls, they might seem to cover a role of diaphragms, but in fact they have no connection with the timber frames of the interior leaves of exterior walls, nor with the roof beams. This is specifically the case of the Mileto building which has just one ground floor.

As always, timber must be kept dry. Here, in order to enhance the stability performance of the frame, some posts reach the mid-basement. This poses the problem of exposure to moisture decay, even more so in this specific case because it is not the long grain edge which is exposed but the top end grain, the most sensible hygrometric area to suck water up from the foundations.

The roof trusses (as in the *Lefkadas* system) transfer very little thrust to the vertical timber frame, instead they lay on top surface of the masonry wall, transferring to this most of the static charge. In case of out-of-plane failures, the masonry overturns, leaving the interior timber shell intact. Here, once again as in *Lefkadas*'s case, structural redundancy pays off: in case of partial or total destruction of the exterior walls, the inhabitants, while occupying the same house, can immediately start the reconstruction of the exterior masonry wall without leaving their dwells.

Moreover, it is fair to say that a masonry wall is far easier to be repaired than it is a timber structure. This principle is still valid today, even for much advanced wood products like CLT structures by instance. Once the

panels are no more plumbed and the steel fasteners are tear out from the panels, it is quite complicated afterwards to repair it. In most of the scenarios, the only solution is to demolish the entire building.

During the 19th century the *casa baraccata* became a well-established solution for popular building seismic areas. So that, in the beginning of 20th century, more than 54 patents on variations of this technique were registered³².

PRESERVATION AND MAINTENANCE

In a description of the *casa baraccata* systems applied in the city of *Reggio Calabria*, the chief commander of the *Genio Civile*, *Giovan Battista Mori* provided a series of recommendations to preserve timber elements in contact with the masonry: “*In order preserve and protect timber in embedded with the masonry from decay, the logs will be well dry, cut down at the right moment, and it will be mandatory to discard the cork and burn the surface, or pitch it.*”³³

This preservation technique is mainly known to be employed in Baltic regions and Japan (*shou sugi ban* in Japanese, but already *Vitruvio* in his *Dieci Libri* was suggesting to burn timber embedded in masonry). This because it creates a carbonized layer of no more of 5 mm which acts as a durable and water-resistant insulation for timber.

This preservation technique confirmed by other witnesses like the one from Eng. Luigi Peggio (XX century), in the *Turin* magazine

31 Stefania Stellaci, Francesca Geremia, Enrico Pagano, Nicola Ruggieri, Ginevra Salerno and Michele Zampilli, “Urban Planning and Building Reconstruction of Southern Italy after the 1783 Earthquake: The

Case of Mileto: The Case of Mileto” (ISCTE-Instituto Universitário de Lisboa, DINÂMIA’CET-IUL, Dipartimento di Architettura Università Roma Tre, n.d.).
32 C. Barucci, *La Casa Antisismica. Prototipi e*

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2.2.4 CASA BARACCATA

Episcopal Palace now abandoned, interior view, 2004 (photo credits to the author; found in Tonna, Sandra; Ruggieri, Nicola; Chesi, Claudio; 2016, "comparison between two historical timber framed solutions representing both tradition and pre-modern earthquake resistance concepts")

Memoria: "[...] the chestnut elements are burnt in order to preserve them from humidity and insect (attacks) [...]"

Calabrian timber construction has a rich set of technological precautions to insulate timber from humidity. This is even more legitimate when we consider the hot climate of such regions, which fosters the chance of insect and fungi attacks.

Another technique of preserving the masonry from humidity was the same present in the very *Mileto's* palace. It consisted in a grid of thin wooden sticks overlaid by a one made from split canes, and a robust plaster thickness on top.

As we know, the 20th century has been a period ruled by concrete in construction. During the first half of the century number of cases *baraccate* were partially replaced by concrete infills or destroyed in favor of post-and-beam structures. But unlike more urbanized and industrialized cities, Mileto, as a result of its isolated position, had been maintaining and preserving most of the original masonry. The reason is attributable to the expensive costs of acquiring good quality sand and clay for the concrete mixture. Dispendious use of water for reinforced concrete could have played a role as well for such hot and isolated territory.

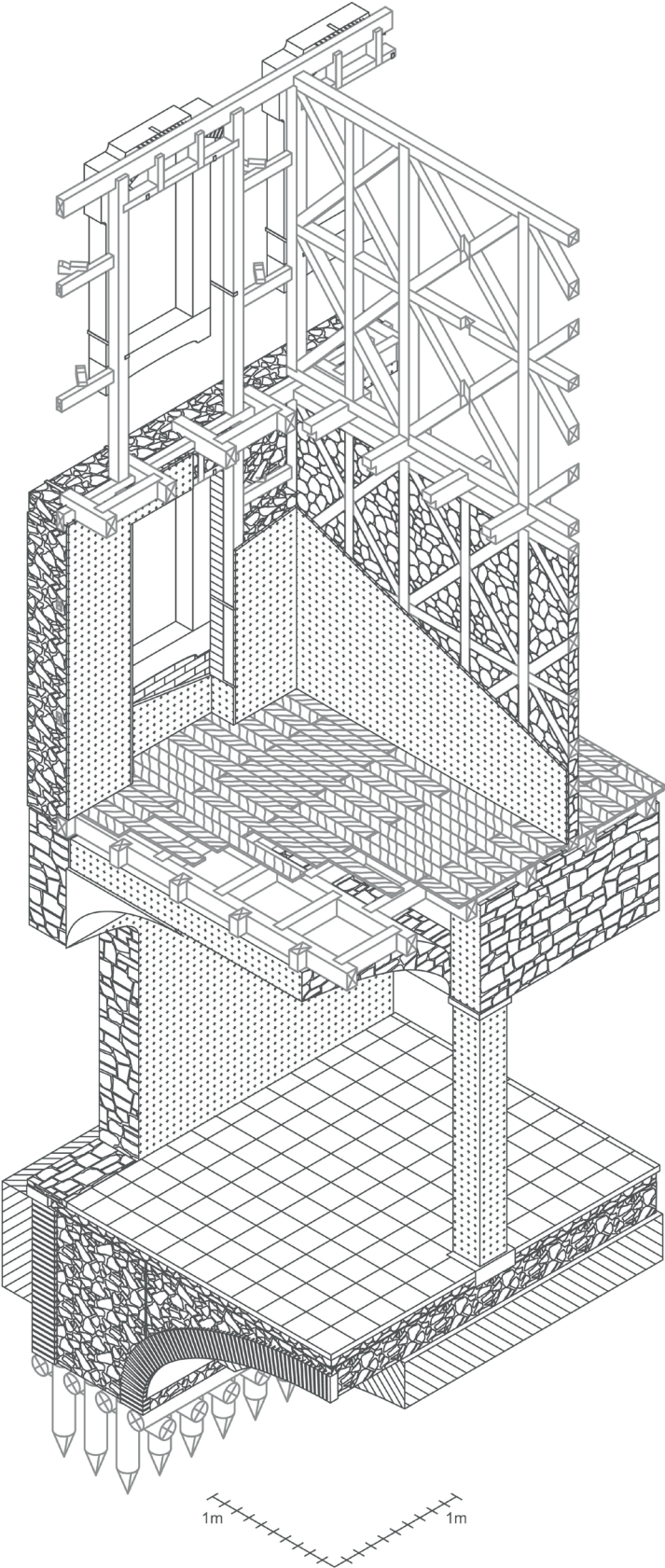
The sustainable feature of such half-timber system, which requires low resources but high labor in construction and repairs, did not make it through the 20th century due to the globalized wide spread of concrete construction.

Brevetti. Materiali per Una Storia Delle Tecniche e Del Cantiere (Rome, 1990).

33 *C. Barucci, La Casa Antisismica. Prototipi e Brevetti. Materiali per Una Storia Delle Tecniche e Del Cantiere (Rome, 1990).*

2.2.4 CASA BARACCATA

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2.2 DUAL STRUCTURE

2.2.5 POMBALINO

THE GREAT EARTHQUAKE OF LISBON

In 1755, Lisbon experienced one of the most destructive seismic events in the whole European history. On Sunday 1st of November (All Saints Day for Catholics) at 9:40 am, there was a strong earthquake that lasted between 3 and 6 minutes. Most of the buildings were turned into rubble and immediately after, rampaging fires spread throughout the city due to the overturning of stoves. After approximately 40 minutes, as a consequence of a sudden volume of waterbrought into the canals by a Tsunami, the city almost entirely flooded. At the end of this catastrophic series of events, 80% of Lisbon building stock was lost and between 40,000 and 60,000 people lost their lives³⁴.

The king fled the destruction and left the *Marquis of Pombal*, a member of his government, to organise the necessary emergency measures and the reconstruction. The *Marquis* invited a military engineer, *Manuel da Maia* to elaborate a new Masterplan and building system for Lisbon. The chief engineer and his equip, mainly composed by military architects and engineers, were influenced not only by the contemporary Enlightenment *esprit*, but also by a solid experience and training in over-sea fortifications, edification of new settlements and urban infrastructures in the Portuguese colonies^{35 36}. Their design will reflect this practical background: replacing old traditional techniques and urban pre-existing figures with innovative concepts, introducing

unconventional logics of masonry like the one that employs weak mortar (almost dry).

The very first problem that engineers had to face was the enormous amount of rubble occupying downtown areas. Thereby they elaborated a timber frame system which could quickly absorb part of the rubble by infilling it into each nob (*hole*) of the frame. Carpenters were immediately called from all over the country, since the timber "*framework*" had to be built before the masonry. In reason of this "*cage*" principle, the system took the name of *Gaiola* and it would be mainly used in multi-story tenements (up to 5 floors) within 10 m width and length which could vary between 8 and 16 m³⁷.

Although central European half-timber constructions might have influenced the *Gaiola* system (Fachwerk, Colombage, Half-timber), *Pombal's* engineers may have been also inspired by the more local *Taipa de rodizio*. Cities of *Porto*, *Vila Real*, *Braga* and *Guimaraes*, all present buildings following this constructing technique: a local half-timber construction characterized by an extensive use of St. Andrew's crosses, dating back to the 15-17th century³⁸.

WEEK MASONRY BINDER

The *Gaiola* or *Pombalino* (from the name of the *Marquis*) system can be technically described as a composite timber-framed masonry, which eventually falls into the second category of the 3 families established

³⁴ Kozak J., Cermak V., *The Illustrated History of Natural Disasters* (London: Springer Publishing, 2010).

³⁵ AD Silva, *Supplemento à Collecção de Legislação Portugeza Ano 1750 a 1762* (Lisboa,

Portugal: Typografia de Luiz Correa de Cunha, 1842).

³⁶ Alice Tavares, Anibal Costa and Dina D'Ayala, "*Possible Precursors of Pombalino Cage*" (University of Aveiro, University College of London, 2016).

2.2.5 POMBALINO

for the *Atlas: Dual system constructions*.

The main structure is characterized by a timber cage (*gaiola*) made of *Oak, Chestnuts or White Pin*, the facades are realized in irregular calcareous stone or clay masonry (their thickness can reach 50 cm in order to isolate fire spreading between near buildings³⁹) and the exterior leaf was usually cladded in ceramic tiles. This last feature boosted the already flourished ceramic industry, but it reduced the stability of the façade due to their extra weight. *Montessus de Ballore* in 1907 wrote about this Portuguese practice: “[...]we must avoid to] *sovraccaricare le facciate, ornandole di ceramiche, di un bell’effetto architettonico, senza dubbio, ma di cui la caduta è inevitabile tanto è mal assicurato il loro ancoraggio ai muri*”⁴⁰.

The weak nature of the connection between the exterior wall and the interior timber cage is responsible for both the ingenious function of the structure and its related weakness: in fact, it would be fair to say that facades only sustain their dead weight and a very small amount of compression loads from the interior timber cage. Two are the connectors responsible for this designed weakness in binding timber core and facades: metal anchors passing all the way through walls, retaining them to overturn, also thanks to their connection with the slab joists, and the *Mão* (or hands), small timber pins nailed to the exterior cage walls and nested into the façade masonry. It is no coincidence that recent analysis on these buildings discovered

that those elements are the ones suffering the most from decaying and partial failures⁴¹: they are designed to break. They are in fact meant to fail in case of an earthquake, letting the facades to fall out, so that the interior timber cage can remain intact. Inhabitants could quickly retake possession of their dwells and rebuild immediately after the seism. This was considered as the most important anti-seismic feature for a building, a structural compromise to enhance user’s resilience to natural disasters. In fact, contrary to what we could think, the deadliest effects of a seism do not occur in the immediate shaking phase, but instead during the aftermath. The *Pombalin’s* royal engineers bared this in mind during the design of the *Pombalino* prototype. That is the very logic behind a *Dual structure*: the inner timber cage is partially independent from the exterior wall (as said, the facades are still relieving the cage from part of the compression in static conditions). However, in case of partial or complete failure of either one of the other structure, they can both, in alternance, be easily repaired.

GAIOLA OR TIMBER CAGE

As mentioned before, the *gaiola* “is like a birdcage made of vertical and horizontal elements braced with diagonals [...]”⁴². The interior walls (also called *frontal walls*) above the first vaulted floor, are made of timber grids reinforced by cogged St. Andrew’s crosses. Due to the alluvial character of the Lisbon soil, it was important to create an even and uniform platform on which to edify upper

37 Graça Vasconcelos, Paulo B. Lourenço and Elisa Poletti, “An Overview on the Seismic Behaviour of Timber Frame Structures” (ISISE University of Minho, Departement of Civil Engineering, 2015).

38 E. Poletti, G. Vasconcelos & P.B. Lourenço, “Timber Frames as an Earthquake Resisting System in Portugal” (ISSE, Faculty of Engineering, University of Minho, 2014).

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A variation of the Gaiola wall with extra nob partitions, St João (all photo credits reserved to Floret Arquitectos, Porto).

floors. Similarly to the *Pontelarisma* technique (see chapter on *Lefkadas*), foundations are made of interlocked green Pine⁴³ log stakes (piers), on top of which rubble masonry and brick arches create a coherent platform for starting erecting the upper ground floor. Plus, ground-floors were often vaulted and made in ashlar masonry in order to stop any dump moisture and fire propagation to the upper wooden floors.

Timber beams equally contribute as flexible diaphragms, especially under dynamic loads. Slabs are all connected to the stairs cage, which eventually works as an interior anti-shear support⁴⁴.

The outer timber frame (which defines the limits of the *birdcage*) is assembled from simple overlap posts and beams, it's lacking any form of diagonal bracings since “[these walls] do not contribute actively to the structural support of the outer cloth⁴⁵”.

Finally, the pitched roof was made of traditional trusses on which timber boards were laid and then covered by ceramic roof tiles.

All the vertical timber posts have a cross-section which can vary between 10 and 15 cm, whereas the diagonals are usually smaller with a cross-section between 10 and 8 cm^{46 47 48}.

Broadly-speaking, the system stands out for a massive use of connectors, both in metal and wood: diagonals are either blocked by coggled joints, nailed or tied to the main grid frame; slab joists are stiffened by transversal wedges and braced to master

walls by metal clips; the exterior cage walls present overlapped half-joint... The stability of the timber cage is ensured by mechanical fasteners. This gives the system a certain level of tolerance within timber elements can shrink and swell without causing damages. This is the same reason why infills are made of loose masonries, either rubble or clay bricks: strong binders like cement or *Pozzolan* would arm the timber structure by reducing their tolerance to moisture movements. The adoption of a weak mortar can also be justified by its capacity of dissipating energy through friction in the event of an earthquake.

39 Nicola Ruggieri, “Reliability of Timber Framed Constructions in Seismic Prone Areas in the Practice Codes Issued from 18th to 19th Century” (DIBEST, Università della Calabria, 2016).

40 C. Barucci, *La Casa Antisismica. Prototipi e Brevetti. Materiali per Una Storia Delle Tecniche e Del Cantiere* (Rome, 1990).

41 E. Poletti, G. Vasconcelos & P.B. Lourenço,

2.2.5 POMBALINO

“Timber Frames as an Earthquake Resisting System in Portugal” (ISSE, Faculty of Engineering, University of Minho, 2014).

42 Sevket Ersan, *“A Comparative Evaluation of the Results of Two Earthquakes: Istanbul and Lisbon Earthquake in 18th Century” (Faculty of Architecture, Restoration Departement Istanbul, Yildiz Technical University(YTU), Istanbul, Turkey, 2016).*

43 Jorge Mascarenhas, Lurdes Belgas and Fernaando G. Branco, *“Pombaline Buildings - Consequences of Some Rehabilitation Interventions” (Polytechnic Institute of Tomar, University of Lurio, University of Coimbra, 2016).*

44 Rita Bento, Ana Paula Falcão, Ricardo Catulo and Jelena Milosevic, *“Seismic Assessment of Pombalino Buildings” (Universidade de Lisboa, 2016).*

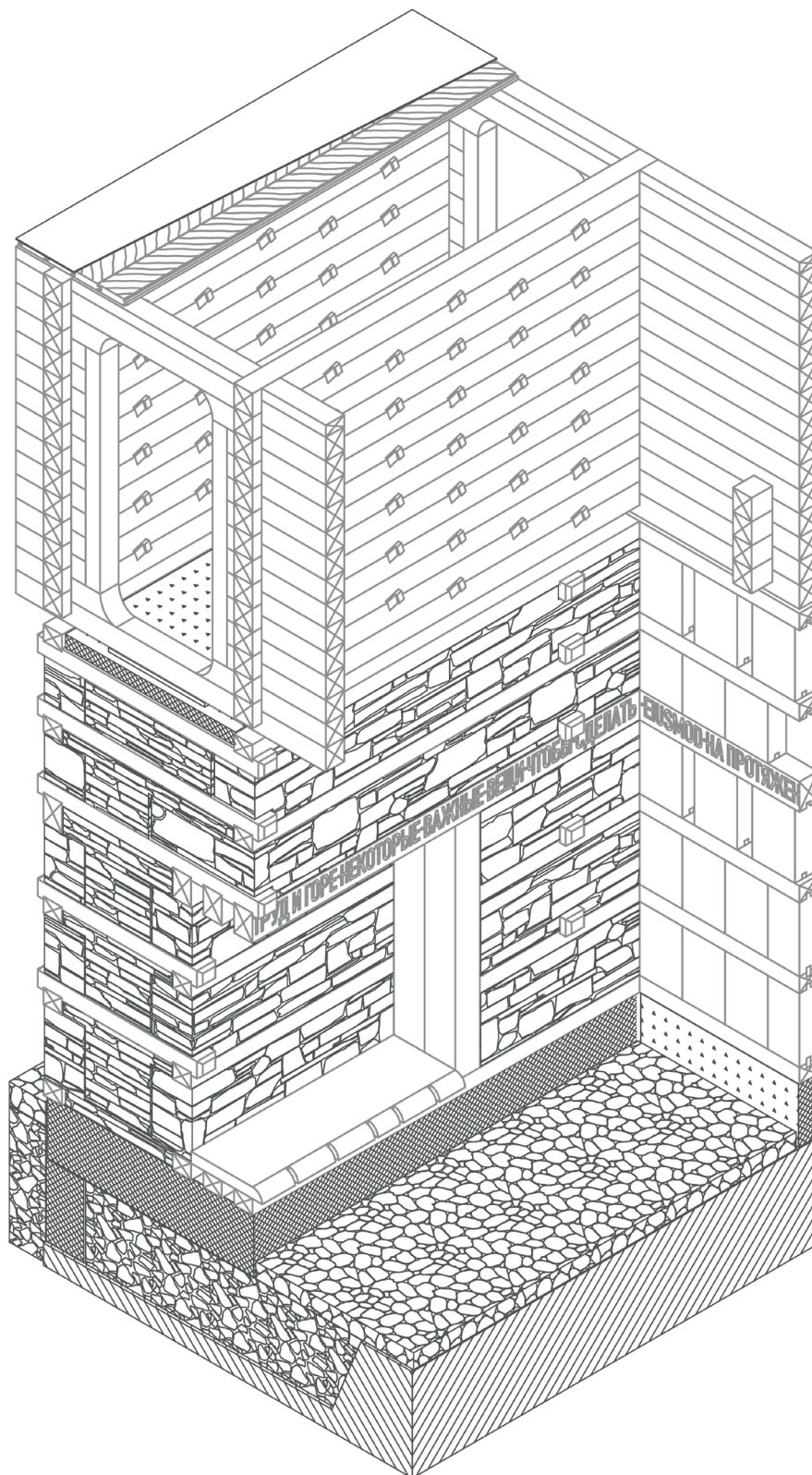
45 G.D. Carlos, M.R. Correia, G. Sousa, A. Lima & F. Gomes V. Lopes dos Santos, *“Lisbon: Downtown’s Reconstruction after the 1755 Earthquake” (CI-ESG Escola Superior Gallaecia & Faculdade de Arquitetura de Universidade de Lisboa, 2015).*

46 E.Poletti, G. Vasconcelos & P.B. Lourenço, *“Timber Frames as an Earthquake Resisting System in Portugal.”*

47 V. Cóias, *Reabilitação Estrutural de Edifícios Antigos, Argumentum (Lisbon: GECOPRA, 2007).*

48 J. Mascarenhas, *Sistemas de Construção (Lisbon, Portugal: Livros Horizonte, 2004).*

TIMBER+



1m 1m

2.3 TIMBER LACE

2.3.1 BÄRENWALDE

SAWN TIMBER AND SLATES

The “*Bear House*” is probably the only contemporary western building which uses timber-lace masonry as a main load bearing element. It was built in 2012 for the *Tierpark Dählhölzli* in Bern, and the design and construction have been led by *Patrick Thurston Architects* (Bern, Switzerland).

The building is composed of mainly three materials: all the wooden parts are made of 180 cubic meters of *European silver fir*⁴⁹, limestone slates for the dry-stack masonries, and punctual reinforcement of concrete for better compression distribution between roof and wall.

The roof system can be considered as a stack-log construction (*blockbau* in German), and it lays on top of the dry-stacked timber-lace walls which are the veritable load bearing components of the structure. For this very reason the stone walls are extremely thick (172 cm wide).

In order to properly receive the roof weight, it is first fastened on steel plates, which are anchored to the last timber belt in-between space, filled with a concrete (12 cm thick) : these two shrewdness enhance the uniform repartition of the static flows down through the dry masonry. In fact, without a continuous concrete plate (which is receiving and uniformly distribute compression), the roof charge could have created points of high pressures on small slates with a consequent failure of part of the masonry.

The roof is thought to have as fewer lateral

charges as possible. With a simple glimpse it is possible to apprehend the incredible robustness of the roof. This is mainly due to the nature and frequency of interlocked cross connections (the over-cross lap joints stiffen the system by avoiding log buckling and bracing the all roof), to the many vertical couples of screws (which fasten couples of logs together), and eventually to the overhaul static height of the roof (280 cm considering the higher pitch).

Plus, the diaphragms are punctually reinforced by inclined double oak pegs. This mechanism confers two qualities to the diaphragms: first, it stops the log shifting movements caused by moisture changes (mainly shrinking and swelling); secondly, it globally reinforces the hole roof diaphragm thanks to the high density of the inter-stacked oak wedges.

Due to the destination of the building, the insulation is not included in the envelope. The roof ceiling is simply realized in *tongue-and-grooved*, watertight planking.

The ground level is composed by two different wall compositions: wooden walls are realised with thick timber frame filled with wooden blocks of 12/26/41 cm, the rest of the walls are mainly made up of dry-stack timber lace masonry.

Each stone layers are 41 cm high, the same partition of the wooden ones. Timber ladders cross-sections (15/12cm) are horizontally placed in order to response with more ductility to sagging behaviour of masonry in time. The corners of the very same timber belts are secured by lap joints anchored by

49 “*Bear’s House in Woods*,” n.d.

50 Eugénié Crété, Santosh Yadav, Milo Hofmann, F. Vieux-Champagne, Yannick Sieffert, Olivier Moles, Philippe Garnier, “*Timber Seismic Bands: Correlating*

Their Characteristics with Local Seismic Activities and Understanding Their Effects under Seismic Loads” (Kastamonu, Turkey, 2018).

2.3.1 BÄRENWALDE

timber pegs.

Approximately every 150 cm the two lintels which compose the timber ladders are notched (around 3cm) by transversal connectors. It is worthy to note that the connectors' top heads have been chamfered on all sides so to make them safer from the inside, and from the outside rainwater evacuates quicker thanks to the sloped sides of the top head.

CONSTRUCTION PHASE

One of the biggest challenges in stacking construction is avoiding uneven change of levels and offsets during the assembly phase. The danger here was double because both the ground floor and the roof level were stacking systems. Therefore, the construction lasted app. 5 months, due to the extreme precision and care degree required by the construction phase. A temporary steel frame shelter was built *in-situ* to provide better work conditions for such extended stacking operations.

In addition, the stones used for the masonry were manually cleaved and adapted by means of simple tools like hammers and chisels. Since no level of prefabrication was introduced for the masonry layers and since each stone had to fit the right position (and be eventually adapted), the realisation demanded for a consistent artisanal labour work.

Nevertheless, it is interesting to note how their realisation has two level of precision required for two different parts of the masonry: the exteriors leaves are larger and well-dressed, whereas the interior presents a less precise

and organic layout.

By partitioning the wall in multiple containments, it is possible to achieve stable and high wall without using cement, nevertheless some measures need to be taken: (as a thumb rule) the ratio height to base width must be at least 1:3 in order to assure a robust equilibrium to the masonry layer. Secondly, each partition must be marked by a timber ladder (better if it loops all the masonry perimeter, in this case we would talk about a timber belt), this allows to reinitiate the wall construction on a new, stable plane and timber ladders must be continuous and transversally fastened. It is proven that this last feature reinforces the wall response to static normal charges⁵⁰.

TIMBER+

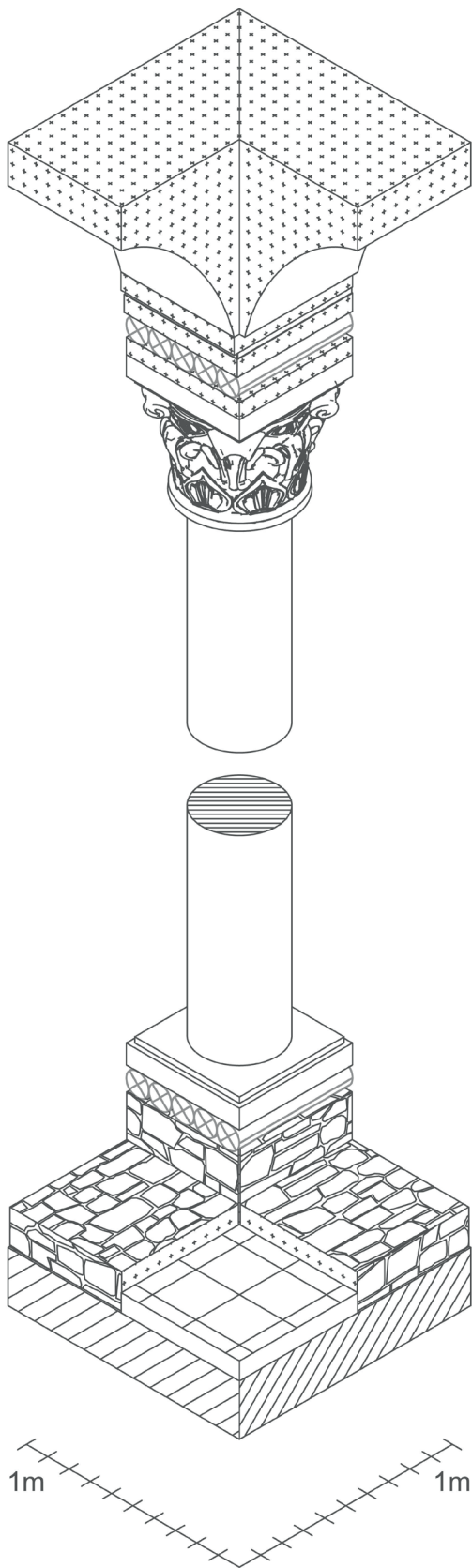




2.3.1 BÄRENWALDE

Bear House in Bern, by Patrick Thurston Architects, 2012.

TIMBER+



2.3 TIMBER LACE

2.3.2 PALACE OF THE DEY

TIMBER ROCKER

This is an example of timber earthquake-proved insulation for columns and arcs. Recent archeological investigations of the Palace of the Dey, in the citadel of Alger have brought to light this particular detail which cannot be found in other parts of the region, aside from this building.

“The palace is part of the most valuable building stock of Medina. It was the largest residential building in the citadel, which also housed two mosques, a second palace and a powder magazine for saltpetre⁵¹”, thus it is no surprise that such care was put into details, like this one. Each floor of the interior patio is composed by a row of columns facing towards the innyard. The isolation of the arcs from the columns guarantees a “box” reaction in case of seismic hazard: arcs and posts are free to move independently. The seizure has been found either at the base of the column or at its top. One or two layers of cypress (Cupressaceae, locally known as *thuya*) or cedar logs are placed just underneath or on top of the column⁵², a superposition of layers of clay bricks and lime mixed with rubbles complete the reinforced device.

The same technique was employed at the lower base of the dome pillars, and in the patio's *collonnades*. The logs cover the function of shock absorbers. Their function is comparable to the rocker we use nowadays in bridges: it improves the tolerance movement threshold of the overhaul system and it isolates it from exterior vibrations.

51 “Qantara - Palace of the Dey of Algiers,” accessed October 6, 2019, https://www.qantara-med.org/public/show_document.php?do_id=468&lang=en.

52 Amina Abdessemed-Foufa, “Historic

Earthquake-Resistant Constructive Techniques Reinforced by Wooden Logs in Algeria” (Lab ETAP, Institute of Architecture and Urban Planning, University “Saad Dahlab” of Blida 1, n.d.).

2.3.2 PALACE OF THE DEY

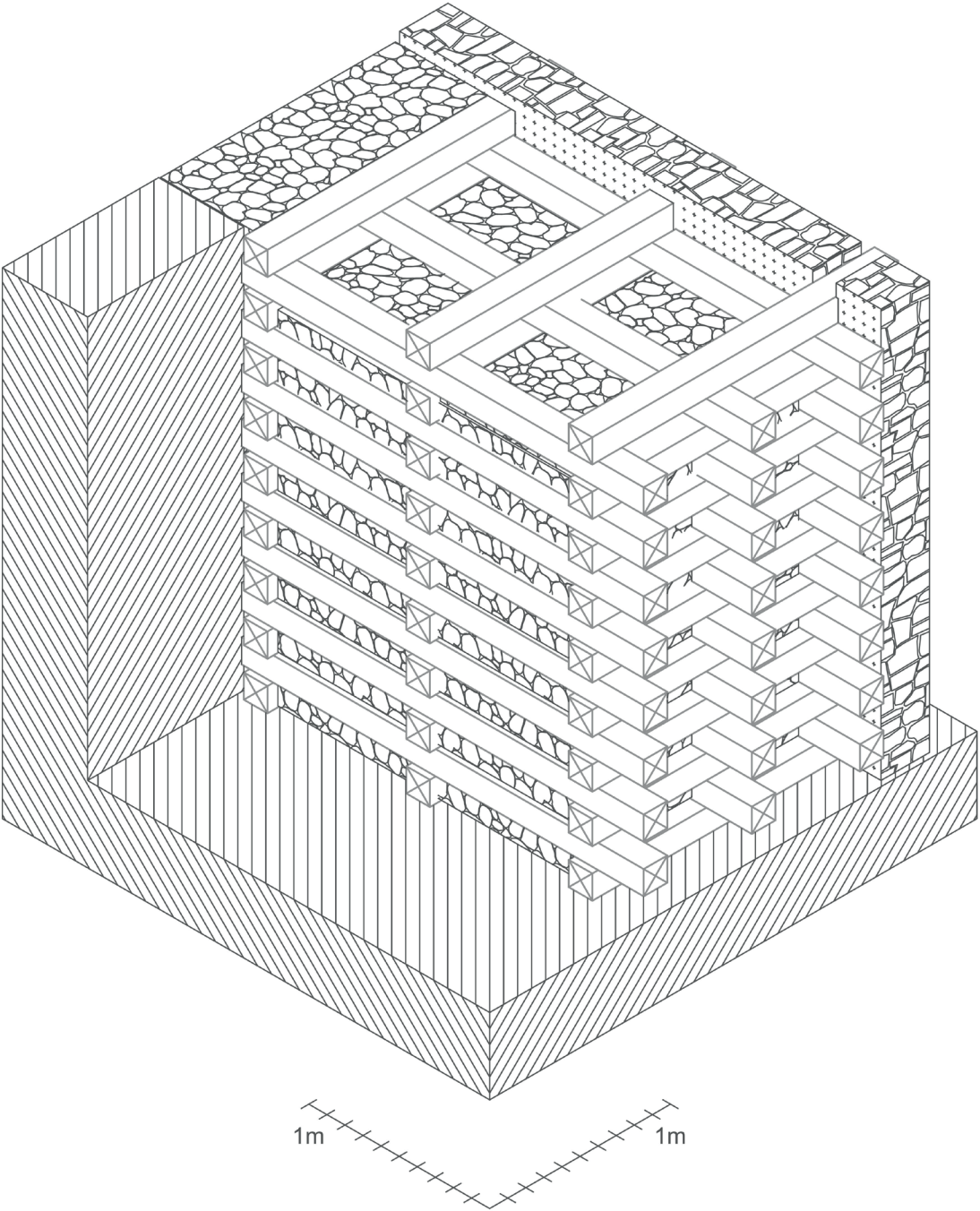


Layer of cedar on top of a column. Palace of the Dey, Citadel of Algiers (All rights reserved to Abdessemed-Foufa, 2005, Amina Abdessemed-Foufa, "Historic Earthquake-Resistant Constructive Techniques Reinforced by Wooden Logs in Algeria" (Lab ETAP, Institute of Architecture and Urban Planning, University "Saad Dahlab" of Blida 1, n.d.).)



2.3.2 PALACE OF THE DEY

Layer of cypress on bottom of a column. Palace of the Dey, Citadel of Algiers (All rights reserved to Abdessemed-Foufa, 2005, Amina Abdessemed-Foufa, "Historic Earthquake-Resistant Constructive Techniques Reinforced by Wooden Logs in Algeria" (Lab ETAP, Institute of Architecture and Urban Planning, University "Saad Dahlab" of Blida 1, n.d.).)



2.3 TIMBER LACE

2.3.3 MURUS GALLICUS

The first Celtic Northern European towns were called *Oppida* (from Latin “enclosed space”). They were typically placed on top of hills in order to overlook the surroundings, especially the biggest ones like *Manching*, in present Southern Germany. They were enclosed by a wall made of interlaced logs (most of the times secured by wooden nails) and rubble fillings. Logs layers were alternated on the exterior leaf by a row of ashlar. This kind of wall composition resulted to be extremely resistant against battery ram shocks (thanks to the ductility of wood and the good weight and compression qualities of stone). They were so resistant to shocks that Romans were obliged to design ramps to overcome this kind of composition instead of destroying it, like in the siege of *Avaricum*. These walls were so proficient that Julius Cesar described this system in his “*Commentarii de bello Gallico*” as a strong and cleaver wooden framework faced with stones and dirt, and he defined it as “*murus gallicus*”.

For the edition of the *Commentari* of 1575, *Andrea Palladio* will realize few lithographs as illustration of the new publication⁵³. He himself will add a description on the qualities of such walls: “[...]perchè què sassi difendono le mura dal fuoco, e il legname le difende dallo ariete, e altri strumenti da battere. Questo legname commesso dalla parte di dentro con travi poste per fila con ispatio di quaranta piedi, non si può nè rompere, nè scommetere”. He says stones protect the wall from the fire and wood protects it from

the battery ram.

Nevertheless, this wall system was already described by Vitruvius in his *De Architectura*: he recommends using olive logs and, in order to preserve the wood, he suggests burning its surface. It was like the one illustrated and described by *Rondelet* later in 1832, who recognized this constructive system as a good solution to raise resistant walls in a short lapse of time⁵⁴. Furthermore, stacking by alternation of timber and rubble layers allowed the builder to construct not only a higher, but also a straighter wall than a similar one made with a mediocre quality of lime or cement.

Superposition and crossed layers of logs are key components to understand the ductility of this kind of wall. This is no different from the principle of Cross Laminated Timber (CLT) panels of recent days in which each layer of lumbers is over-crossed in order to stiffen the panel structure. In both cases the same mechanism assures a perfect bracing on all the three directions. This is the reason why this structure (also thanks to the ductile properties of wood) can absorb dynamic charges without collapsing.

This method of construction will become famous for fortified walls against cannon shocks and fires. For instance *Viollet-Le-Duc* in his *biography of a fortress* reports the good quality of this construction : “mettre le feu à la tour n’était guère possible, car ces ouvrages de bois entremêlés de pierres, ne prennent pas feu facilement”⁵⁵.

53 *Andrea Palladio, I Commentari Di C. Giulio Cesare : Con Le Figure in Rame de Gli Alloggiamenti, de' Fatti d'arme, Delle Circonvallationi Delle Città et Di Molte Altre Cose Notabili Descritte in Essi / Fatte Da*

Andrea Palladio per Facilitare a Chi Legge, La Cognition Dell'historia (Venezia: Pietro de' Franceschi, 1575).

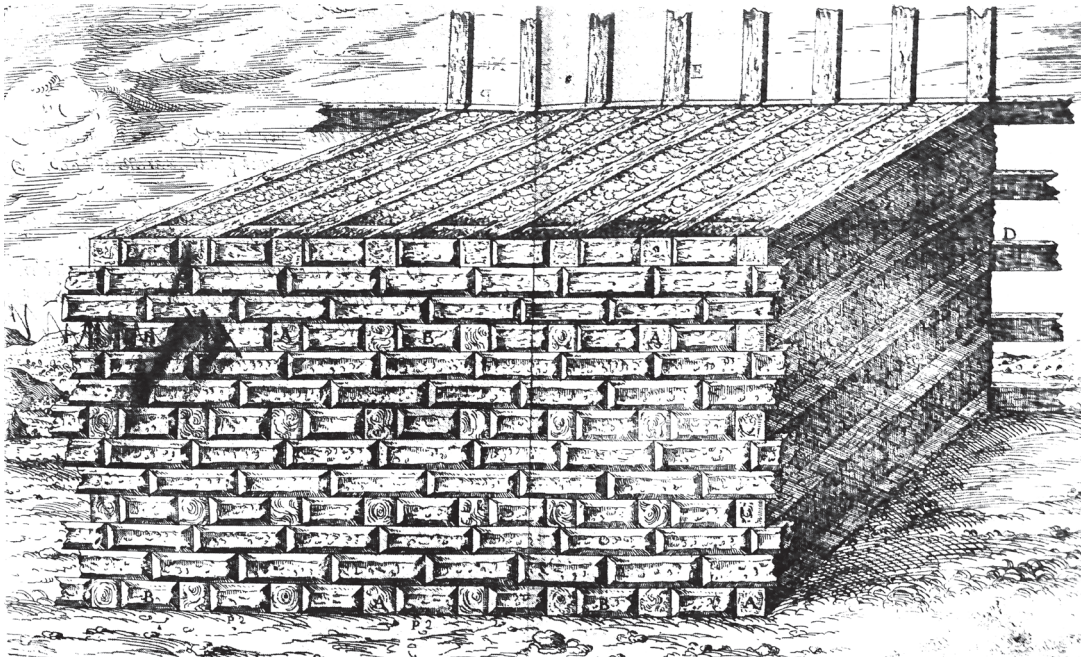
54 *Jean Rondelet, Traité Théorique et Pratique de l'art de Bâtir (Paris: M. A. Rondelet Fils, Architecte,*

2.3.3 MURUS GALLICUS

From this moment it will become interestingly linked to the military construction, and its employment will survive until our days under slightly different forms (see Baltifort chapter). The same system was in use for century in the Ottoman Empire for its excellent anti-seismic properties. The relation between earthquake-proved and military construction does exist whether it is about dissipating cannon balls shocks or seismic waves, the fundamental function of the structure remains the same: dissipate energy.

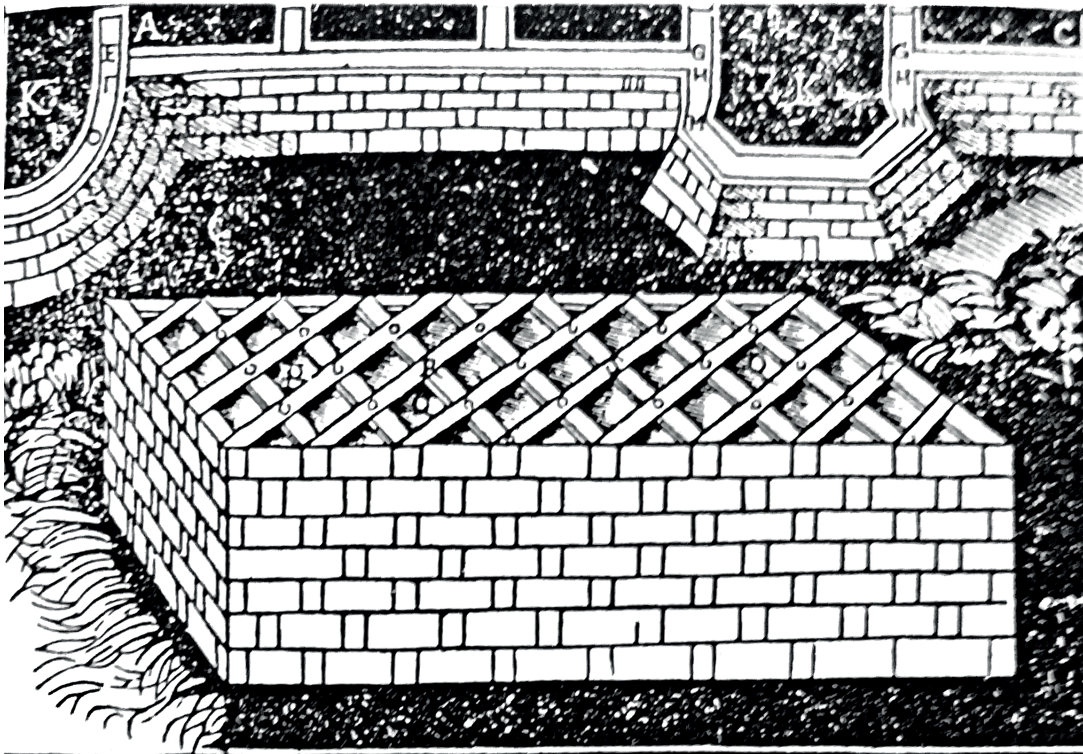
1832).

55 *Eugène Viollet-le-Duc, Histoire d'une Forteresse (Mardaga, 1990).*

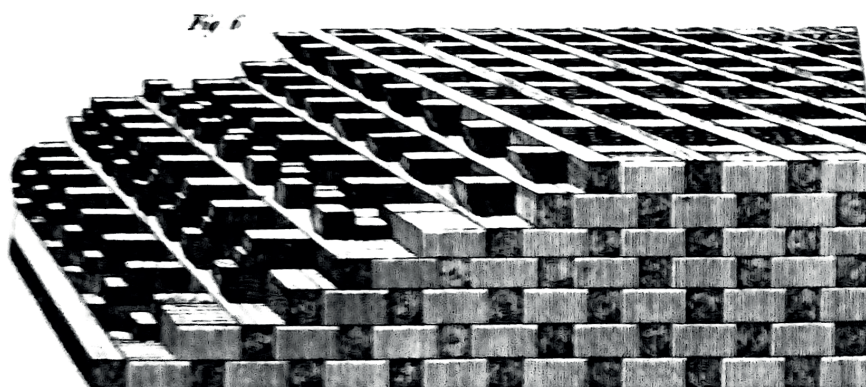
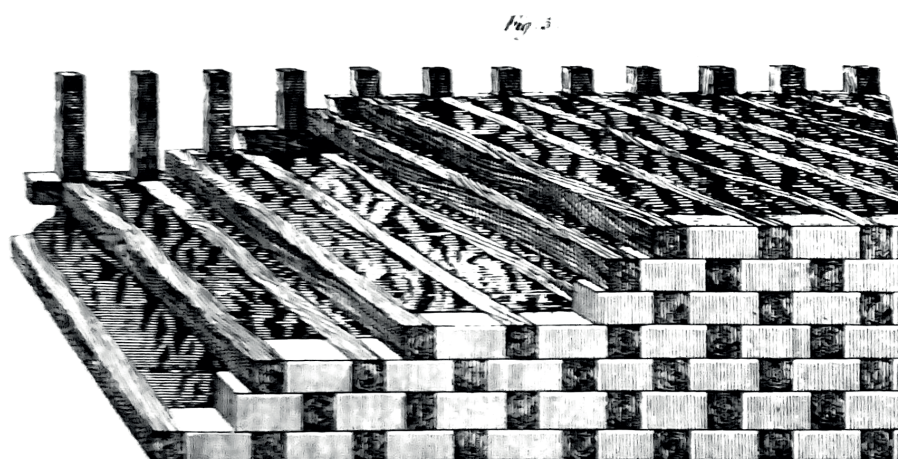
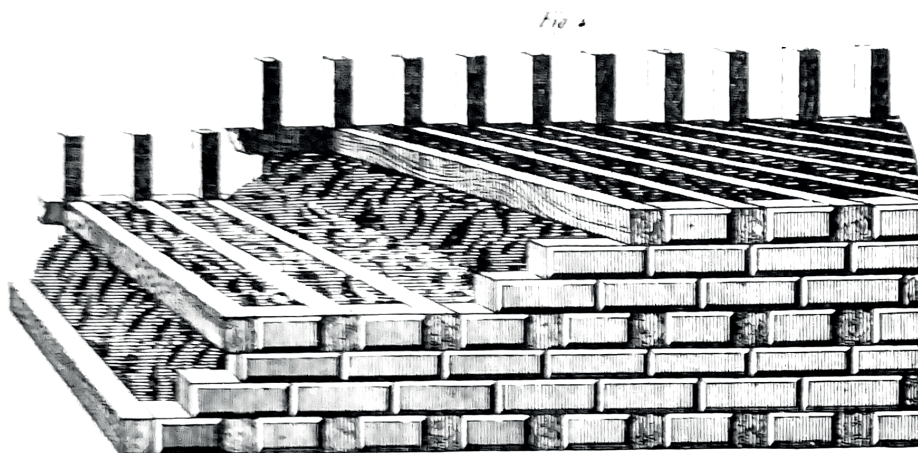


Drawing by Andrea Palladio following Ceasar's description of the murus gallicus (Reproduced from "I Commentari Di C. Giulio Cesare : Con Le Figure in Rame de Gli Alloggiamenti, de' Fatti d'arme, Delle Circonvallationi Delle Città et Di Molte Altre Cose Notabili Descritte in Essi / Fatte Da Andrea Palladio per Facilitare a Chi Legge, La Cognition Dell'historia (Venezia: Pietro de' Franceschi, 1575)".

TIMBER+



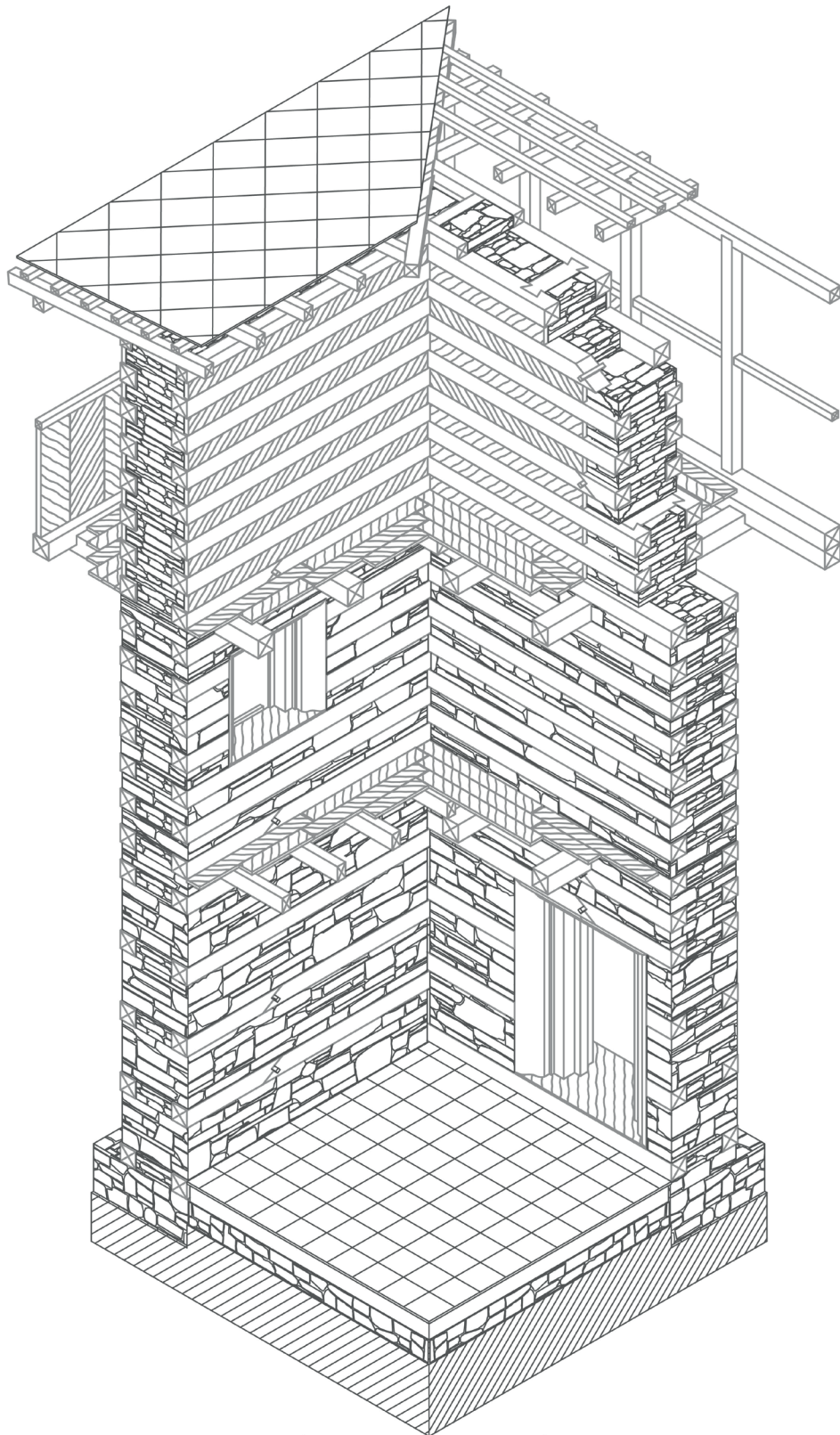
C. Cesarino's illustration to the described version of the murus gallicus by Vitruvio De Architettura, 1521 (Found in C. Barucci. 1990. La Casa Antisismica. Prototipi e Brevetti. Materiali per Una Storia Delle Tecniche e Del Cantiere. Rome).



2.3.3 MURUS GALLICUS

*Framed walls described by Rondelet (Jean Rondelet, *Traité Théorique et Pratique de l'art de Bâtir* Paris: M. A. Rondelet Fils, Architecte, 1832; found in : C. Barucci. 1990. *La Casa Antisismica. Prototipi e Brevetti. Materiali per Una Storia Delle Tecniche e Del Cantiere.* Rome.).*

TIMBER+



1m 1m

2.3 TIMBER LACE

2.3.4 KAT-KI-KUNNI

This constructing system can be defined as *cator-and-cribbage* and it can be mainly found in *Himachal Pradesh* (an Himalayan region that can reach up to 6500 m of altitude⁵⁶). The number of storeys can vary but temples could reach even seven floors. *Kath-Khuni* means “*timber-cornered*”, O.C. Handa (2008) explains the origin of the name: “[...] *combination of two local terms: kath and kuni. The word kath is a dialectal variation of the Sanskrit word kashtth, which means wood, and kuni is again a dialectical variation of the Sanskrit word kona, that is, an angle or a corner. Obviously, the kath-khuni wall implies it should have only wood on its corner or angles.*”⁵⁷

TREE SPECIES

The most employed species are *Duaddar* (*Cedrus deodara*) or *Glindour*⁵⁸, different species of Himalayan Cedar or Pine, they are characterized by strong and durable trunks (up to 50m) and good durability thanks to their incredible amount of resinous heartwood (compared to a *Douglas fir* e.g.).

It is not the unique case of tree presenting such ratio between heartwood and sapwood, in Siberia for example there are pine species which have the same high ration of heart-wood/sapwood. This confers to the final sawn timber not only a better strength, but also a good resistance to moisture (due to the consistent presence of oil and resins in this central part of the trunk). Especially in the case of *Kat-Ki-Kunni* composite construction,

where timber elements are subjected to a constant compression, as well exposed to high degrees of moisture (from the exterior and from the masonry as well), density and durability of wooden components are the key features for the overhaul durability of dwells.

DESCRIPTION OF THE SYSTEM

Foundations are realized in loose rubbles and blocks and their depth depends on the height of the building, it is an important preliminary operation since it provides a water-safe and even ground level to start the construction of the house. Traditional masonries are dry stacked and do not present any use of lime or even mud mortar; on the other hand, the thickness of a wall can vary from 40 to 100 cm⁵⁹.

As in *Taq-bhatar* construction, the two ladder beams are dove tailed by a transversal element. Plus, the corner connection is reinforced by wooden pegs locking one ladder with the inferior one, as a replacement sometimes the ladders are half-lap joined at the corners.

The continuity of the beams is made possible by either a lap joint or in the best scenario by traditional pegged scarf joint. This assures the building to be strapped on during seismic events.

The final storey always presents a balcony (often on the contours of the house) which acts like an extension of the inner living space, it mitigates thermal excursion by

⁵⁶ Bharat Dave, Jay Thakkar, Mansi Shah, Prathaa: *Kath-Khuni Architecture of Himachal Pradesh* (SID Research Cell, CEPT University, 2013).

⁵⁷ O. C. Handa, *Himalayan Traditional*

Architecture (New Delhi, 2009).

⁵⁸ Bernier, Ronald, *Himalayan Architecture*, Madison: Fairleigh Dickinson University Press (London: Associated University Press, n.d.).

2.3.4 KAT-KI-KUNNI

providing shading in summer and thermal insulation in winter, and it protects the bottom walls and exposed timber lintels from drains and sunlight. All the hanging beams are half-lap jointed and locked in a double ladder sandwich. On top of it, the slates roof, made of thick layers of slates, ideal to resist to snow charges in winter.

The intimate understanding of wood construction and its material properties is clearly shown by details reserved to religious buildings, but such attentions can be equally found in the housing stock. The first beam top heads, the one occupying the outer leaf of the wall and closer to the ground (hence the most exposed to moisture and water deterioration) is carefully protected by a panel and a covering stone system.

However, among all the *timber lace* typologies this can be considered as the most laborious and time consuming during the construction phase, but on the other hand it is also the system most prone to progressive maintenance and punctual substitution of elements due to its dual structure (stacked timber and masonry infill).

Finally, *Kath-khuni* works on the same anti-seismic principles of every other *timber laced* structure under dynamic charges (see *Taq-bhatar*). In fact, the ductility conferred to masonry by the timber is reinforced by the absence of mortar and metal nails. In this manner, the building exploits the full potential of frictional energy dissipation offered by the

dry stack masonry.

Doors and windows were as small as possible and despite the common symmetrical recommendations for positioning the openings, here all the windows and doors are staggered in order to avoid vertical continuous weakness on the masonry, plus frames are realized in thick lumbers, and braced by hidden diagonals.

For the same anti-seismic reasons plans ratio is normally included in the 3:2 ratio range and storeys height is kept as low as possible.

TIMBER STACK AND COLUMNS

Although the outer walls are the main load-bearing elements of the structure, it is possible to see interior stacking vertical timber logs of *Cator and Cribbage* houses.

In fact, the way in which wood is employed here is not structurally orthodox.

Wood can be described as a fiber composite material, that means that its structural properties are heterogenous in relation to fibers orientation. Parallely to grain wood, it has robust resistance to compression and excellent quality in tension, on the other hand perpendicularly to it, it does not show great compression properties. However, this is what theory says. The stacked column in *Cator and Cribbage* construction is not the only example of this unusual use of timber.

This system came straight from the original way that local populations employed wood:

59 Rishiraj Das, "Standing Firm: Traditional Aseismic Architecture of the Western-Central Himalayas" (Peoples' Science Institute Dehra Doon, n.d.).

TIMBER+





2.3.4 KAT-KI-KUNNI

One-storey house in Gavas (Photo credits reserved to Mansi Shah & Jay Thakkar: "The Himalayan Vernacular: Kath-Khuni Architecture," Sahapedia, accessed October 25, 2019, <https://www.sahapedia.org/the-himalayan-vernacular-kath-khuni-architecture>).

by stacking it. For such small applications structural safety is not an issue, the problem relies more in durability. Being the horizontal fibers exposed to a constant perpendicular charge, they will have the tendency to consume themselves quicker, starting from the bottom where the charge is the most important. If we add to the equation even a partial moisture exposure, since the grain structure will be progressively delaminated, the stacked column will inevitably and progressively collapse. By instance this is what happened in most of log cabins not properly insulated against moisture transmittance from the ground.

2.3.4 KAT-KI-KUNNI



*Stacked column in Uhl Valley, Himachal Pradesh :
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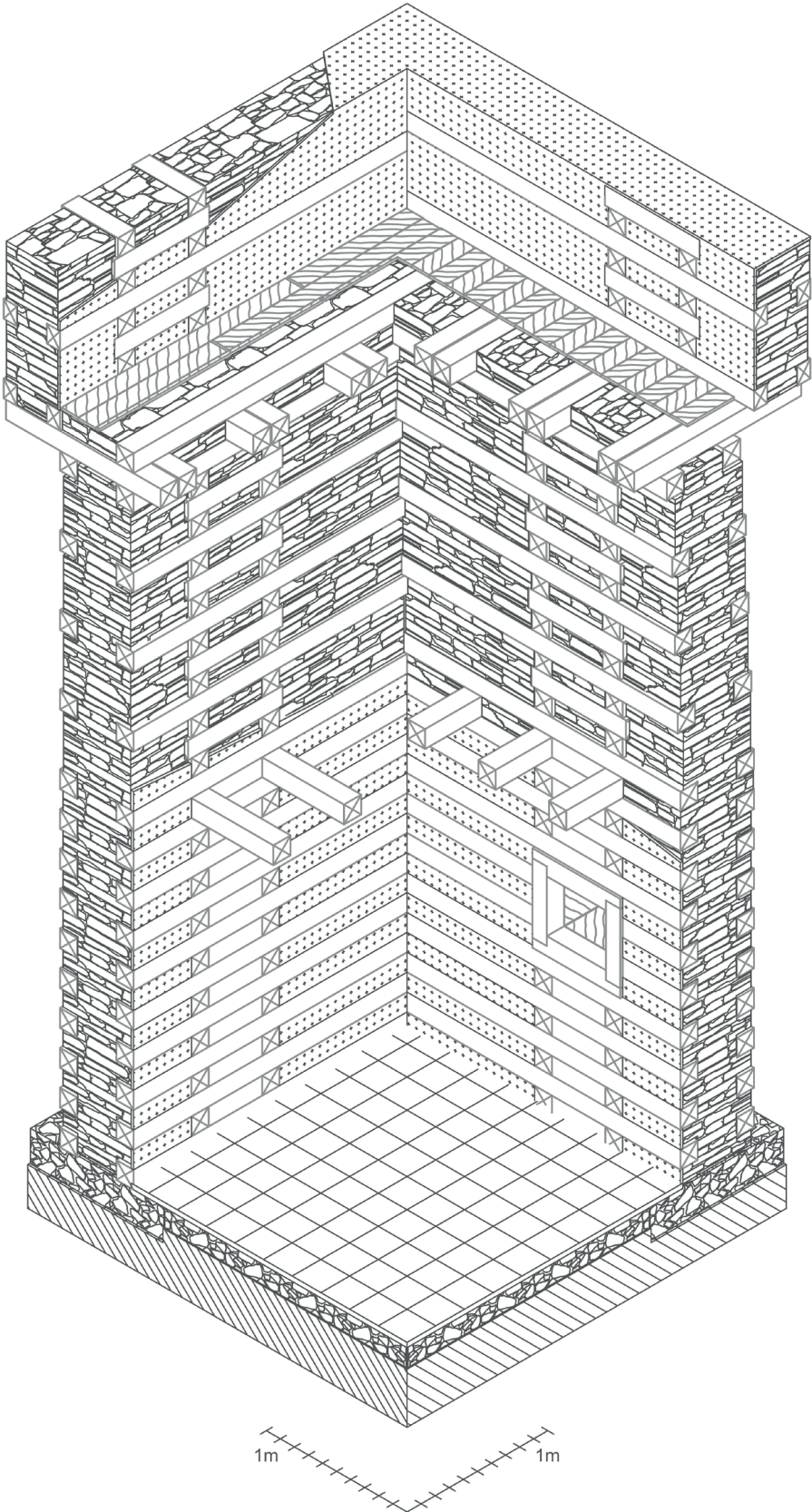




2.3.4 KAT-KI-KUNNI

The first layer beam's top head is carefully protected by water infiltration (Photo credits reserved to Mansi Shah & Jay Thakkar; "The Himalayan Vernacular: Kath-Khuni Architecture," Sahapedia, accessed October 25, 2019, <https://www.sahapedia.org/the-himalayan-vernacular-kath-khuni-architecture>).

TIMBER+



2.3 TIMBER LACE

2.3.5 CATOR AND CRIBBAGE

This system belongs to the family of *Cator-and-cribbage* constructions (the timber horizontal belts are called *cators* in *Balti* language). It can be considered as a hybrid form between log and timber-laced structures. It is possible to find it in *Nuristan*, *Baltistan*, and generally in the Northern area of Pakistan.

This constructing system has been heavily influenced by the Islamic culture in the Kashmiri area⁶⁰ and the use of this technique has been estimated to be 9000 years old⁶¹. In fact, if we accept *Randolph Langenbach's* (one of the biggest experts in vernacular anti-seismic construction) theory whereby all these composite timber systems would have been exported and diffused by the Ottoman Empire, similarities between such distant construction in time and space start to make sense. By instance all these *crator and cribbage* or *taq* and *dhjir dewari* techniques are not present in the Hindu regions of India, but only in the Muslim areas. That would be valid for Greece too (for the case of *Lefkadas*), and more generally for all the territories along the Anatolia's fault.

Timber lacing examples have been found in areas normally missing timber resources like deserts of Iran or Egypt. This means that expensive material as timber was explicitly imported for enhance mainly earthquake-proved features of the building stock⁶².

As in more classic *timber-laced* systems (like *Taq bhatar*) the timber employed in the *cator and cribbage* system counter-acts

most of the masonry defaults under dynamic charges, by instance: the propagation of vertical and diagonal cracks are absorbed and stopped by timber lintels, failure *out-of-plane delamination* or *torsional* collapses are avoided by the belting effects of timber ladders (even more so if the corners are peg or nail-joint) .

MODERN TIMBER LACE IN MILITARY CONSTRUCTION

As we know, *timber laced structures* have been occupying an important role in military architectures. From the *Murus Gallicus* described by Ceasar (see *Murus Gallicus* chapter), passing through Alexander the Great who made use of this technique in Asian campaigns.

Few examples can be found in the modern era too. The British army during their campaign in Northern areas of Pakistan reported the excellent behavior of Nilt fort walls resisting multiple charges of seven pounders (a typical cannon in the English army)⁶³. In fact , timber could absorb and prevent all kind of wall collapses if properly embedded in the masonry. Again, it is no surprise that this technique has been largely used in many areas around the world (see *Taq bhatar* building system) as earthquake-proved system.

Timber lace structures will become progressively less employed in military applications due to the invention of explosive artillery calibers which will turn eventually the use of timber as disadvantageous

1 Kozak J., Cermak V., *The Illustrated History of Natural Disasters* (London: Springer Publishing, 2010).

2 AD Silvia, *Suplemento à Collecção de Legislação Portugesa Ano 1750 a 1762* (Lisboa,

Portugal: Typografia de Luiz Correa de Cunha, 1842).

3 Alice Tavares, Anibal Costa and Dina D'Ayala, "Possible Precursors of Pombalino Cage" (University of Aveiro, University Colle of London, 2016).

2.3.5 CATOR AND CRIBBAGE

(compared to sand or rocks racks), especially considering the damages caused by wooden shards after the impact of a bullet.

In northern areas of Pakistan *cator and cribbage* technique was well established both among the housing stock and the military or public buildings, with the difference that fortifications were built with the outmost attention for detailing for obvious need of extra structural strength during sieges. This is why the *Baltit Fort's* timber structures presents corners joint by wooden pegs and thick, transversal connectors between the two timber lintels, stiff wooden frames for the openings, and like in the case of the fort towers (called *Shikari*), walls are divided in two by an extra set of timber reinforcements in order to avoid torsional collapses or out-of-plane collapses.

The nogs of the structures were carefully plastered in mud mortar, but after the recent renovation, mortar infills were replaced by *Terracrete* which is a mix of soil with a small percentage of hydraulic lime. By the way, this plaster technique can equally be employed as coating layer to enhance durability of adobe, mortar or thick renders.

LOGISTICS

This particular constructing technique also presents some embedded qualities in logistics. First, repairs although frequent, are made possible thanks to timber ladders which provide a temporary support for reparation

and substitution of the damaged element, without extra need for scaffoldings.

Another advantageous feature of the system relies in small foundations, in fact, due to the partitioning and stability of each layer, there is no need for extensive work or dimensions for foundations. This turns to be extremely useful in mountainous areas where hard soil makes extremely laborious any excavation operations. Some towers of the Fort have also been found deprived of foundation systems.

On the other hand, laying stones for so many containments demanded a consistent amount of time and labor.

TIMBER DETERIORATION

The most common species used in these regions are *Duadar* and *Glindous*, Hymalayan Pines. But for very important buildings *Juniper* was punctually used for its extraordinary resistance against moisture and insects attacks.

During the restoration of the Fort, as it is imaginable to happen, timber elements located in the North Façade were the ones most damaged due to high moisture presence. Some external *cators* were also presenting signs of preliminary moisture decay but overhaul the structure was considered sound.

DECLINE AND REBORN

It has been rare to see brand-new construction made in *Cator and Cribbage*,

especially in Northern Pakistan. The causes can be found in part in the development of the concrete industry in the area throughout the 20th century, but mainly in the deforestation of Pakistan and Afghanistan in the past decades⁶⁴. For profit reasons, logs are cut down into smaller lengths, this is making the logs almost unsuitable for the *Cator* system since a lot of splicing joints (like the traditional Pakistani scarf joint) would be needed. In addition to that, logs are not let dry before their use and most of the traditional Pine essences have been replaced by willow and poplar⁶⁵.

Consequently the local population has lost its *now-how* in preserving and repairing rotted lintels. Plus, as often happened in industrial European *Fachwerk* dwells, exterior facades are often entirely plastered and all timber elements result hidden. This harms the wood which is now exposed to moisture condensation and consequent decay. Contrary to the past where the employ of wood was reserved to churches, military structures and noble mansions, wooden parts of the buildings are not more exposed with pride, nowadays, in those regions, it is no more considered as a *status symbol*.

An exception must be noted for Bhutan where a similar constructing technique is still in use today thanks to a persistent culture of preservation and promotion of local traditions.

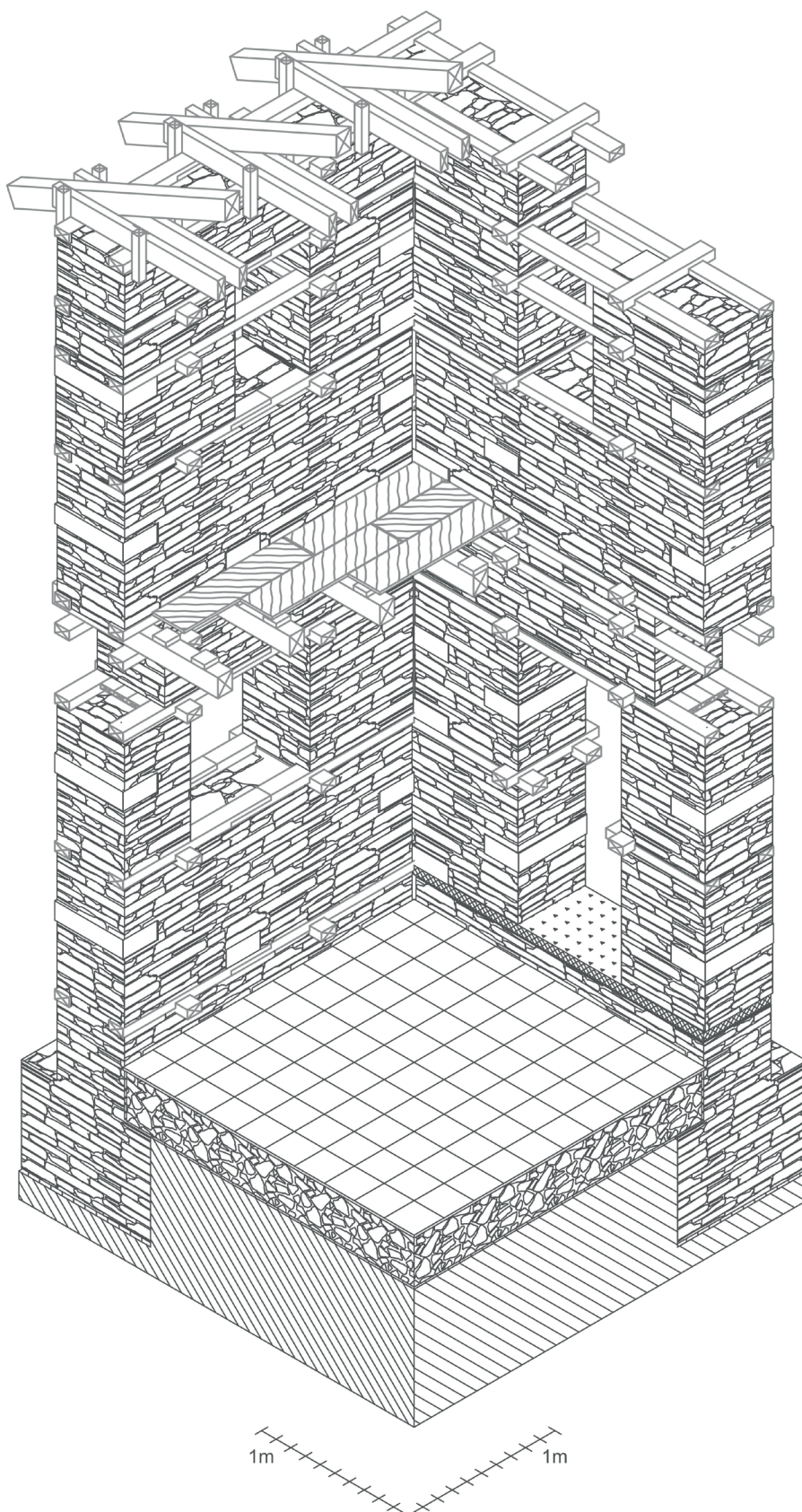
60 “22_TimberTransportFootprintReport.Pdf,” accessed July 17, 2019, https://timbertransportforum.org.uk/attachments/article/22/22_TimberTransportFootprintReport.pdf.

61 “Earthquake Resistant Vernacular Architecture | Analysis,” UKessays.com, accessed October 23, 2019, <https://www.ukessays.com/essays/architecture/earthquake-resistant-vernacular-6765.php>.

2.3.5 CATOR AND CRIBBAGE

62, 63, 64, 65 *Richard Hughes, "Cator and
Cribbage Construction of Northern Pakistan," January
2000.*

TIMBER+



2.3 TIMBER LACE

2.3.6 TAQ BHATAR

MOISTURE AND TIMBER CONSTRUCTION

Taq Bhatar (in Pakistani language *Bhatar* indicates a standard 3”/4” wooden beam) is a timber-laced masonry with load-bearing walls, typical of Himalayan regions. Timber belt are characterized by a ladder-like structure regularly interrupting the stone or brick masonry. The timber essences are mainly hardwoods (*Shorea Robusta* mainly present in Nepal, *Cedrus Deodara*, *Populus Ciliata*), but it is possible to find also sapwoods (*Pinus Wallichiana*). Concerning the masonry stones there are also few typologies such as *limestone*, *sandstone*, *granite*, *dolomite* or *quartzite*. The use of this constructing system dates to the 12th century and it precedes a later system called *Dhajji dewari*, only known from the 19th century⁶⁶. It is worthy to note that this second system, probably influenced by the English presence in the area, it revealed itself unsuitable to mountainous areas as a result of its very thin walls. *Taq bhatar*, on the contrary, can be considered as the most suitable system for mountainous territories of Himalaya and of high regions of Kashmir subjected to temperatures which can vary from -15 C to + 40 C. These areas have always experienced a high seismic activity due to the close presence of the Himalayan fault. In addition, Kashmiri area is characterised by soft eroded soil or prehistoric lakes. As consequence, the employ of timber has been constantly exposed to the problem of moisture: the present-day timber-laced building culture can be in part considered as

a direct technological response to the two previously listed conditions.

THE SYSTEM IN DETAIL

The following description corresponds to the optimal present-day application of the *Taq Bhatar* technique recommended by a study held by the *Swiss Agency for Development and Cooperation* and the *French Red Cross* coordinated by Tom Schaher (2007). Old versions can differ and present multiple variations on the same principles here listed.

Foundations are typically made of stones, by the way, in rural areas, the timber structure is touching the ground and this is the reason why they are suffering from severe moisture decay. This can be in part explained by the fact that dwells are built in the biggest rush after an earthquake occurs. In mountainous environments houses are first build as temporary shelters, with all the inaccurate detailing which that implies.

All the timber elements sections are around 7.5/10 cm. For belts, joists are horizontally placed, or sleeping joists, beams and tie-beams they are instead vertically positioned. Large beams are considered not only dangerously heavy, but also expensive and complex to assemble and transport on site.

All the corners are joint by a half lap joints of no more than 2.5 cm in order to preserve most of the fibres, thus enhancing the strength and life span of timber elements.

66 “Earthquake Resistant Vernacular Architecture | Analysis,” UKessays.com, accessed October 23, 2019, <https://www.ukessays.com/essays/architecture/earthquake-resistant-vernacular-6765.php>.

67 Tolles, E.L., Kimbro, E.E., Webster, F.A. and Ginell, W.S., “Seismic Stabilisation of Historic Adobe Structures” (2000).

68 Raffaele Carabbio et al., “How Can

2.3.6 TAQ BHATAR

Additional, galvanised screws (zinc coated) can be added to strengthen the connections. It is important to make the notch 10 cm away from the top end of the joist so, in case of a dynamic charge or due to wood shrinking, beam will not crack. For the rest of joists connectors (perpendicular to the plane of the wall) a simple coggled lap joint secured by nails is enough.

The continuity between band joists is assured by a lap joint of at least 30 cm, in some cases a traditional Kashmiri scarf joint secured by a peg.

Roof, whenever the climate would allow, was preferably built flat since a trussed roof can exercises a dangerous lateral stress on the masonry, especially in the event of an earthquake. Furthermore, the traditional flat earth roof adds an important thermal mass to the building. Nevertheless, this technique was gradually replaced by pitched roofs, especially in high altitudes, where a pitched roof results sometimes more advantageous due to heavy snowfalls of the region.

Windows and doors should not exceed 1 m of width and they should be regular placed at a distance of at least 1m. The timber belts cover the role of lintels for windows and openings and they are never interrupted except for the entry of the building.

Trusses are composed by rafters clamped into a pair of tie-beams which are themselves nailed to the last couple beams (*bhateri*) belonging to the timber belt.

One of the most resilient properties of this system is the possibility to expand the building with extra rooms. This principle is not new in such stacking timber construction like log construction. In this scenario, corners are dismantled, and each timber belt is extended with a new set of coggled joists. An extra attention should be put as well in avoiding continuous vertical joints in the stone masonry in order to avoid future cracklings of the masonry.

DRY MASONRY AND TIMBER DETERIORATION

As we know, timber-masonry systems may present problems in time that concern wood deterioration and protection. In the case of dry-stack masonry no mortar is present in the masonry. This feature allows the wall to drain water quicker and eventually dry up faster than other types of masonries: timber elements embedded in the wall are less exposed to stagnant water residues.

NO VERTICAL ELEMENTS

At a first glance, this building system results missing two key elements for most of the mix timber structure: vertical elements and mortar.

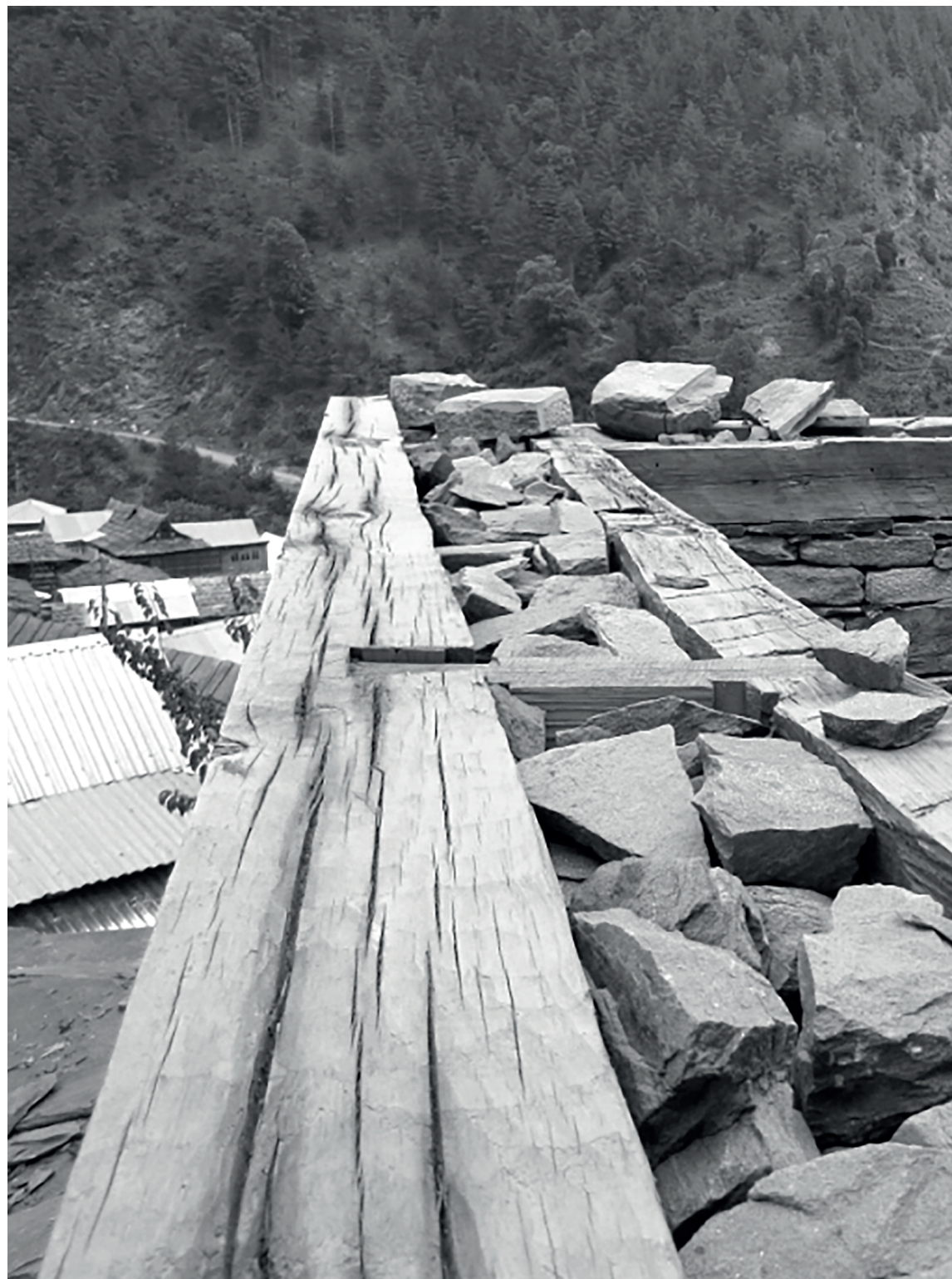
This is because *Taq Bhatar* relies on other structural principles.

In a remote area such Kashmir, every constructive element which was not local had to be brought and transported through

Vernacular Construction Techniques Sustain Earthquakes: The Case of the Bhatar Buildings, "Frontiers in Built Environment 4 (2018): 18, <https://doi.org/10.3389/fbuil.2018.00018>.

69 background + rationale, "Build Back Better - Bhatar," June 2007.

70 Eugénié Crété, Santosh Yadav, Milo Hofmann, F. Vieux-Champagne, Yannick Sieffert, Olivier Moles,





2.3.6 TAQ BHATAR

Wall under construction, it is possible to see the dove-tailed transversal connectors, Devidhar village (Photo credits reserved to Mansi Shah & Jay Thakkar: "The Himalayan Vernacular: Kath-Khuni Architecture," Sahapedia, accessed October 25, 2019, <https://www.sahapedia.org/the-himalayan-vernacular-kath-khuni-architecture>).

impervious topographies at a tremendous human and economic cost. Although, sand-cement or lime mortar relies allows to erect a straight, high wall with very small care or concerns about the stone type employed, it does require an important amount of water, clay and sand. Now, in lack of this component the local population came up with another system to erect straight masonry: *timber laced construction*. This technique allowed for each layer to start on a good erecting plane for the next level of masonry. The technique in question is often employed in different areas to obviate to the use of cement or good quality lime.

The use of sand-cement not only would have had prohibitive costs for the local population, but it is paradoxically not recommended because it diminishes the possibility of the masonry to dissipate energy through friction in the event of a seism. In addition to the hysteric movement of stones, timber belts provide extra ductility to the system which results eventually in a diminished risk of out-of-plane collapses. The out-of-plane failures (but also bending, overturning, delamination) are avoided thanks as well to the high ration of height/thickness of the wall (4 to 6⁶⁷), within this ration the weight is able to ballast the building (despite the fact that the seismic action is proportional to the weight), and to the presence of passing-through stones embedded in the masonry.

It is not yet fully understood how the friction mechanism works. Yet recently, the Barton's model was applied to understand the friction

of the wall, in addition to that a recent research has provided preliminary study (based on references) on possible causes of out-of-plane and bending failures⁶⁸.

Concerning the absence of vertical elements in the structure: “*Inclusion of a continuous vertical connection between the timber Bhatar beams reduces the cap city of the system to dissipate energy through moderate lateral movement of the stone and timber elements. The vertical reinforcement will also carry some gravity loads of the structure, thus reducing compression in the walls, further decreasing the important friction between the stone elements and timber beams.*”⁶⁹ ».

The addition of vertical element could even damage the building due to the differential response to static and dynamic charges of wood and stones. If posts are present, it is merely to support the roof or ceiling of large rooms, but they are traditionally kept independent from the main load-bearing structure (cfr. *Lefkadas* chapter) for the above-mentioned reason.

Finally, timber ladders add several extra qualities to the masonry⁷⁰: they act as lintels in case of a partial failure of the masonry, they also avoid the propagation of vertical and diagonal splitting between masonry layers, and last but not least, the confinements that they create provide the wall extra resistance to compression in a static circumstance. This last feature was already well understood by ancient Romans, who alternated thin layers of bricks to rubble masonry in order to achieve higher heights with smaller wall width.

Philippe Garnier, “*Timber Seismic Bands: Correlating Their Characteristics with Local Seismic Activities and Understanding Their Effects under Seismic Loads*” (Kastamonu, Turkey, 2018).

71 Randolph Langenbach, *Don't Tear It down! Preserving the Earthquake Resistant Vernacular Architecture of Kashmir* (UNESCO, 2009).

2.3.6 TAQ BHATAR

CONTEMPORARY CONSTRUCTION

The masonry stones are as flat as they can be found or cut. They can be dry assembled or stacked with the help of some weak mud mortar. Nevertheless, contemporary masonry is more often composed by rubbles and boulders which limit the frictional potential of the traditional wall. Plus, timber belts are often disconnected between them. The lack of such details in contemporary *Taq* construction results in a consistent weakening of the original design.

Recently there has been an effort in improving this constructive technique by adding steel rebars (coated in concrete) in correspondence of corners. However, it seems that the introduction of a vertical element such steel which has a different coefficient of dilation, reacts badly in time to the stone masonry shifting. This can eventually disrupt and crack the building corners. Plus, any steel reinforcement rust can produce severe damages to other building components like insulation or cladding.⁷¹

3 DEVELOPMENTS

Among all the three structural families of *timber composite systems*, the *dry timber-lace construction* seems to be the most promising for possible contemporary use. The reasons behind its eligibility to contemporary building system are several. In this last part of the work we will try to analyse the conditions and the interests of bringing this vernacular building system to present days.

REDUNDANCY OR CEMENT

First, Dry Timber Lace Construction (henceforth DTLC) is the only technique which requires neither cement/lime nor water. In fact, the main resistance and strength of the wall is given by:

- a. the use of timber belts which allow to achieve plumed walls without the use of any chemical binder;
- b. a low ratio of proportions between height and thickness of the wall;
- c. the partition of the dry-masonry into many containments (traditionally 40 cm high), this has been proved to reinforce the static and seismic resistance to vertical and horizontal static loads⁷²;
- d. the friction between stones and timber is the main source of stability for the wall both in static and dynamic situation (thanks to their capacity of dissipating energies in the event of e.g. an earthquake);

Broadly speaking, structural redundancy seems to be the key feature to avoid use of cement, water and at the same time maintain a tolerant system to repairs and substitutions. Our buildings are now tailored to linear lifespans, once we will acknowledge the global importance of preserving them, rather than discarding them, we will probably accept the expenses of redundant systems such as DTLC.

PROTECTION AND MAINTENANCE

The nature of dry masonry is one of the best environments for a proper use of wood in mixed construction. In fact, due to the absence of cement, the wall does not retain humidity in his joints, hence the timber bands are protected from long-time exposure to residual moistures and water. Plus, the replacement of each timber elements is always possible thanks to the hyper-static structural system: if we take out a portion of the masonry or part of the timber bands, the other timber elements act as lintels by temporarily redistributes charge flows through the surrounding masonry: *"sustainable buildings must be built*

⁷² Eugénie Crété, Santosh Yadav, Milo Hofmann, F. Vieux-Champagne, Yannick Sieffert, Olivier Moles, Philippe Garnier, "Timber Seismic Bands: Correlating Their Characteristics with Local Seismic Activities and Understanding Their Effects under Seismic Loads" (Kastamonu, Turkey, 2018).

⁷³ Markus Hudert and Sven Pfeiffer (Eds.), *Rethinking Wood* (Birkhäuser, n.d.).

3.1 DRY TIMBER LACE CONSTRUCTION, DTLC

differently: The individual construction elements should be joined in such a way that they can be taken apart again. The shearing layers of a construction should be joined in such a way that they can be maintained, repaired, or replaced individually, since they are all subject to different degrees of stress and strain and have different useful lives (Frank Duffy, as cited by Stewart Brand, Brand 1994)⁷³.

MINERAL SLATES

Traces of this construction can be found in ancient Rome, in the Ottoman Empire and in all the mountainous regions of Himalaya and the examples are multiple (for further information see chapters about *Taq Bhatar*, *Kath-ki-kunni* or *Baltifort* constructions). Nevertheless, one constant is shared by all of them: the use of flat irregular stone slates. In the best scenario those stones already had a planar shape thanks to the typology of the stone itself (e.g. *gneiss* or *schist* stones). Otherwise they needed to be manually chiselled and properly dressed in order to obtain at least one flat side.

THERMAL, ACOUSTIC AND FIRE PREVENTION ADVANTAGES

Nowadays clients and architects always aim to label or certificate the sustainability of their buildings. Nevertheless, standard levels set by certifications are often promoting unnecessary use of extra layers of heavy insulating or water-tight materials, resulting in counter-productive behaviour especially for those buildings located in hotter climate areas. Plus, considering the future and in part inevitable raise of temperatures due to climate change, more attention should be put to unconventional but much more effective approaches: choosing a 80cm dry masonry timber-lace wall for its thermal inertia over 15 cm of compact insulation would be one of them for example. Furthermore, dry masonry mixed with timber construction compensates also other lacks of pure timber construction, such as fireproofing and soundproofing.

LESS DOWNGRADING

Engineered wood products (*CLT*, *LVL*, *PSL*⁷⁴, *GluLam*, *Plywood*, *OSB*) represent nowadays the most proficient and reliable set of solutions on the timber construction market. Chemical binders (*Polyurethane adhesive*, *Phenol formaldehyde adhesive*, *Epoxy resins*, and *Melamine formaldehyde adhesive*) have being progressively improved under many aspects, we can now obtain all kind of wood products by just using 0.02 mm of glue layers , but also in terms

⁷⁴ Arfan, "Psl Wood Beam," *New Images Beam (blog)*, December 15, 2017, <http://www.enhancestyleteam.com/psl-wood-beam/>.

of health safety there have been some major refinements. Today there are companies which manufacture a mass production of CLT without any glues or chemical additive, just using hardwood dowels and nails. It is the case of *Küng Holzbau*⁷⁵ (*Alpnach*, Switzerland), which is also exploring also new methods of prefabrication for dry timber components in parallel.

Nevertheless, all wood products already represent a form of *downcycled* material. Sawn massive timber elements can be “*reused, recycled, or downcycled to engineered wood*”⁷⁶. Using as little processed wood as possible means taking the notion of *sustainability* in timber construction seriously up a notch.

3.3.1 CONSUMPTION OF WOOD

As stated before, *DTLC* is thought to be first and foremost employed in the most immediate *transitional economy* where the main goal is to absorb and when possible to stock the embodied energy of mineral waste, in conjunction with a limited use of forest resources.

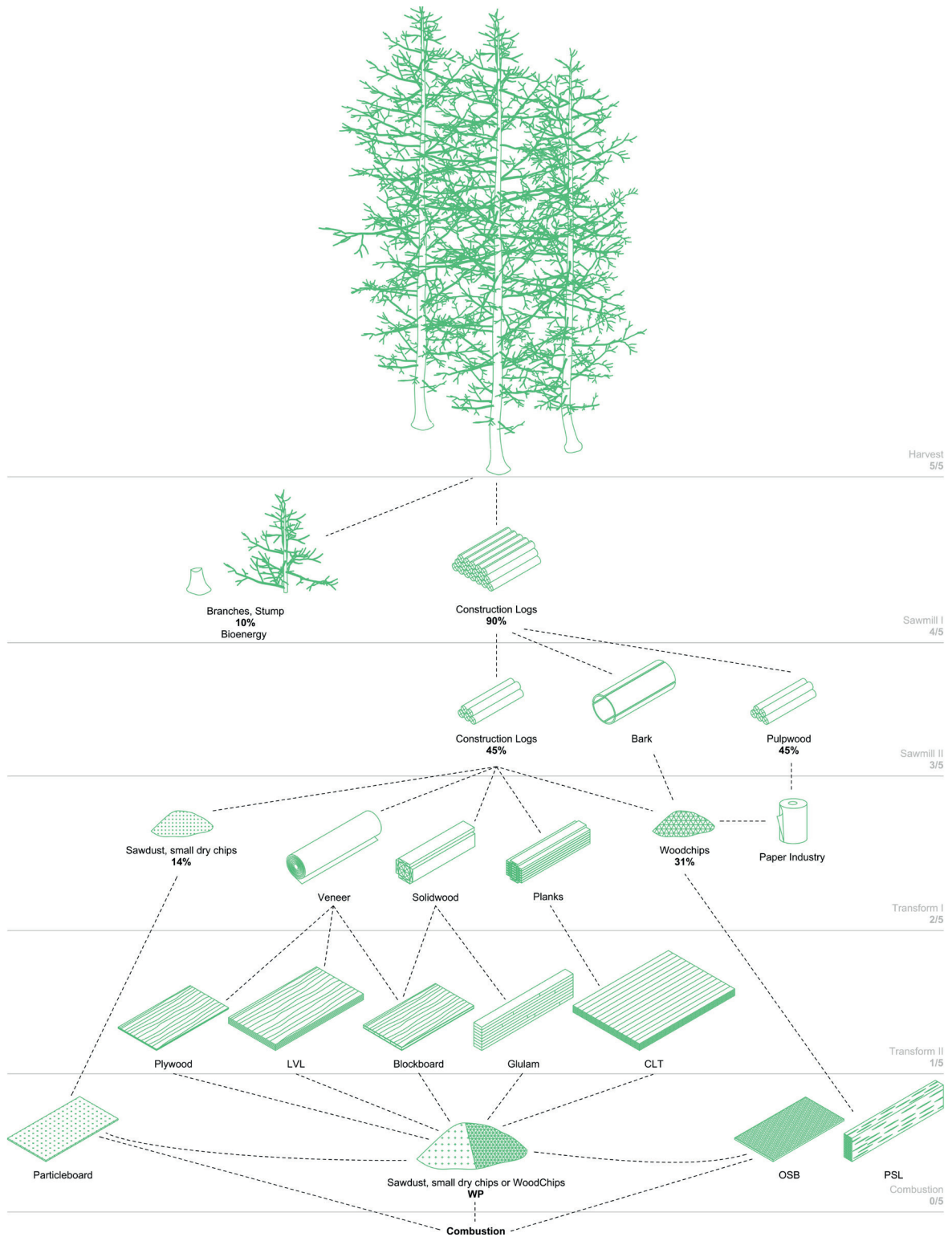
In order to understand the potential of *DTLC* we need to establish some terms of comparison with one of the most competitive products on the timber construction market: CLT. Cross Laminated Timber has conquered the markets since its introduction in Austria and Germany in 90', today it is becoming a very popular choice among designers as a result of its high degree of pre-fabrication, its relatively thin cross-section compared to performance, its stiffness due to the crossed-overlapped layers of fibres, and finally its rapid installation on construction sites. Furthermore, it should be clarified that the purpose of this comparison is not to oppose one system with another, but rather to show their complementary features, suitable for different uses and stages within the same timber lifecycle.

If we take a look at any lifecycle diagram of wood, we quickly realize the wide range of possibilities that this material can offer. Not only in construction but also in paper industry and in the energy field. Nevertheless, within the scope of the present chapter, wood lifecycle will be limited to the construction sector. Although wood can be labelled as *renewable* resource, on condition of a correct and sustainable management of harvesting, there is still room to introduce logics aimed to procrastinate down-cycling. In fact, most contemporary *wood products* or *engineered wood* represent already a down-

⁷⁵ Küng Holzbau AG, “Kontakt,” Küng Holzbau AG, accessed November 7, 2019, <http://www.kueng-holz.ch/de/Unternehmen/Kontakt>.

⁷⁶ Markus Hudert and Sven Pfeiffer (Eds.), *Rethinking Wood*.

3.3 CONSIDERATIONS ON TIMBER



Life cycle assessment for wood, components have been arranged following a parent-child logic of production, but also hierarchically by considering all the possible downgrades for each product (percentages based on “Swedish wood”).





New office in construction of Küngholzbau (Alpnach, Switzerland). They only work with doweled CLT without any use of adhesives. The walls are only composed by CLT, no insulation. The ceiling is realized in CLT Beech. Furthermore they only employ Douglas Fir and Spruce from Switzerland. Küngholzbau truly represent an example of a new circular and intelligent approach to timber construction. (photo by Andrea Settini, 2019)

cycled version of sawn timber.

The majority of *engineered wood* products uses glue (with the exception, as mentioned before, of a few innovative companies⁷⁷ which use of mechanical fasteners entirely made of wood, such as oak screws and dowels). The use of metal fasteners speeds up production, but also reduces the number of times we can *downgrade* such components. Although, as said, it is no longer a question of whether a system can be classified as *high-tech* or *low-tech*, in fact DTLC seems to be place at the centre of these two poles: a balance in which advantages of 3D recognition, robot-aid assembly, and modern prefabrication logic can meet those of local resilience, simple and available materials, intuitive thermal approaches and both mineral and vegetal building components, which can be disassembled and recomposed as many times as possible.

Timber lace elements would fall into the category of *solid timber*, right in the middle of our wood cycle scheme. Few details can be thought in advance in order to facilitate a possible future downgrade of those elements into lower *wood products*, such as a good degree of disassembly, the choice of natural treatment instead of invasive chemical films, the design of less invasive and mass consuming joinery could also help since it allows the element to be maintain relatively intact, hence reusable and, although exposed timber elements may not turn out to be eligible for further downgrades, the interior, sheltered elements certainly will. What is sure is that timber elements employed in DTLC construction will simply return *residue-free* into the natural cycle⁷⁸.

What follows it is a rough estimate of how much volume of wood and consequently how many trees, the same wall of 3 meters by 3, made respectively of DTL (15 x 15 cm lintels, 70 cm of total thickness) or CLT (3-ply, 10 cm, the smallest thickness available on the market) would eventually end up consuming.

According to an estimation provided by the study “*Tree to Lumber*” of the *UW Center for Wood Innovation Studio*⁷⁹ (2016), only “*the 31% of the tree [mature Douglas Fir] is usable as planned, dried lumber*”, and is turned into approximately 0.6 cubic meter of sawn, usable lumber. Bearing in mind that we can approximate the consumption of each wall by 1.4 Douglas Fir, it is important to take some things into account.

77 AG, “Kontakt.”

78 Markus Hudert and Sven Pfeiffer (Eds.), *Rethinking Wood* (Birkhäuser, n.d.).

79 Susan Jones, *Design and Research, Mass Timber*, Oro Editions, 2017.

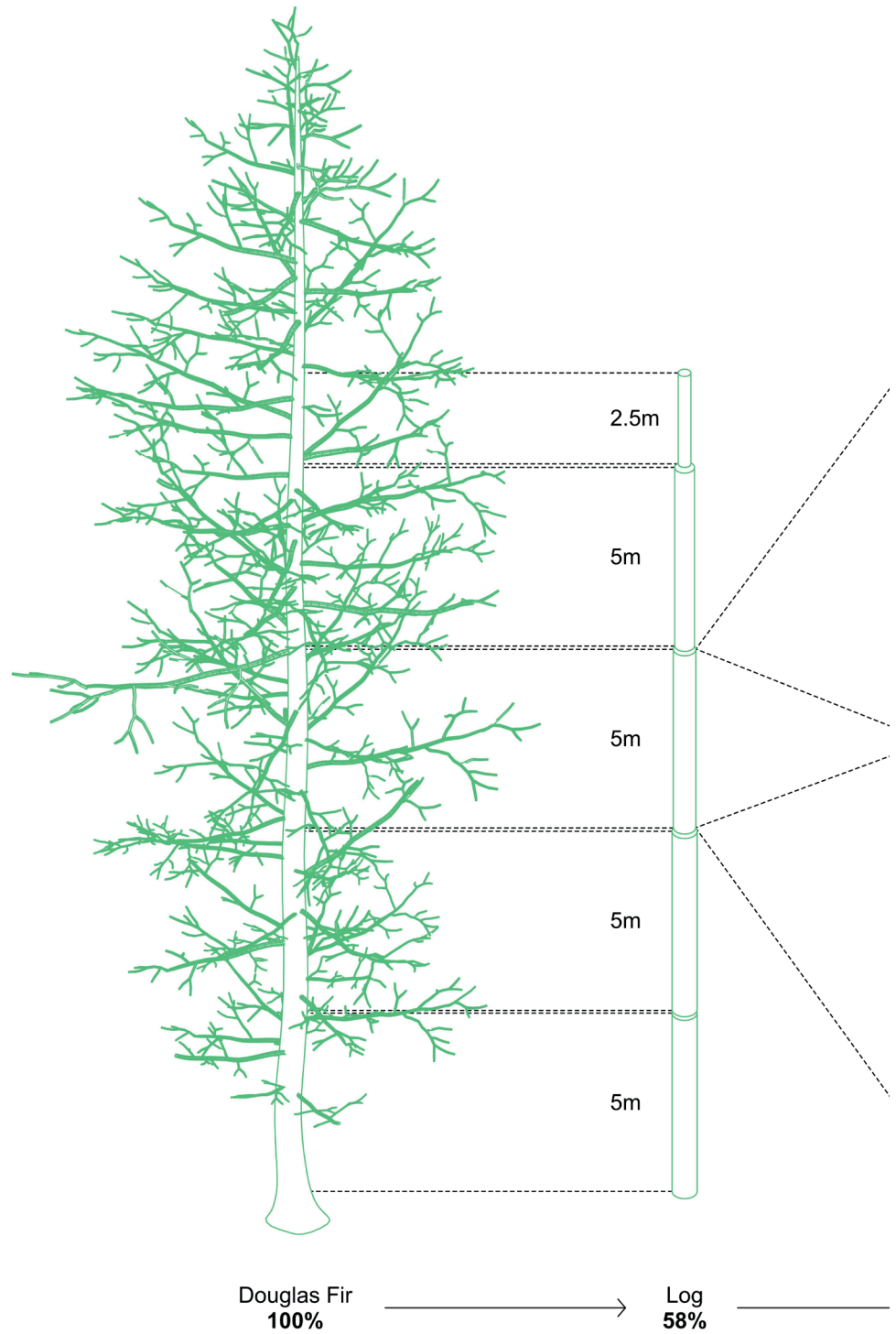
3.3.1 CONSUMPTION OF WOOD

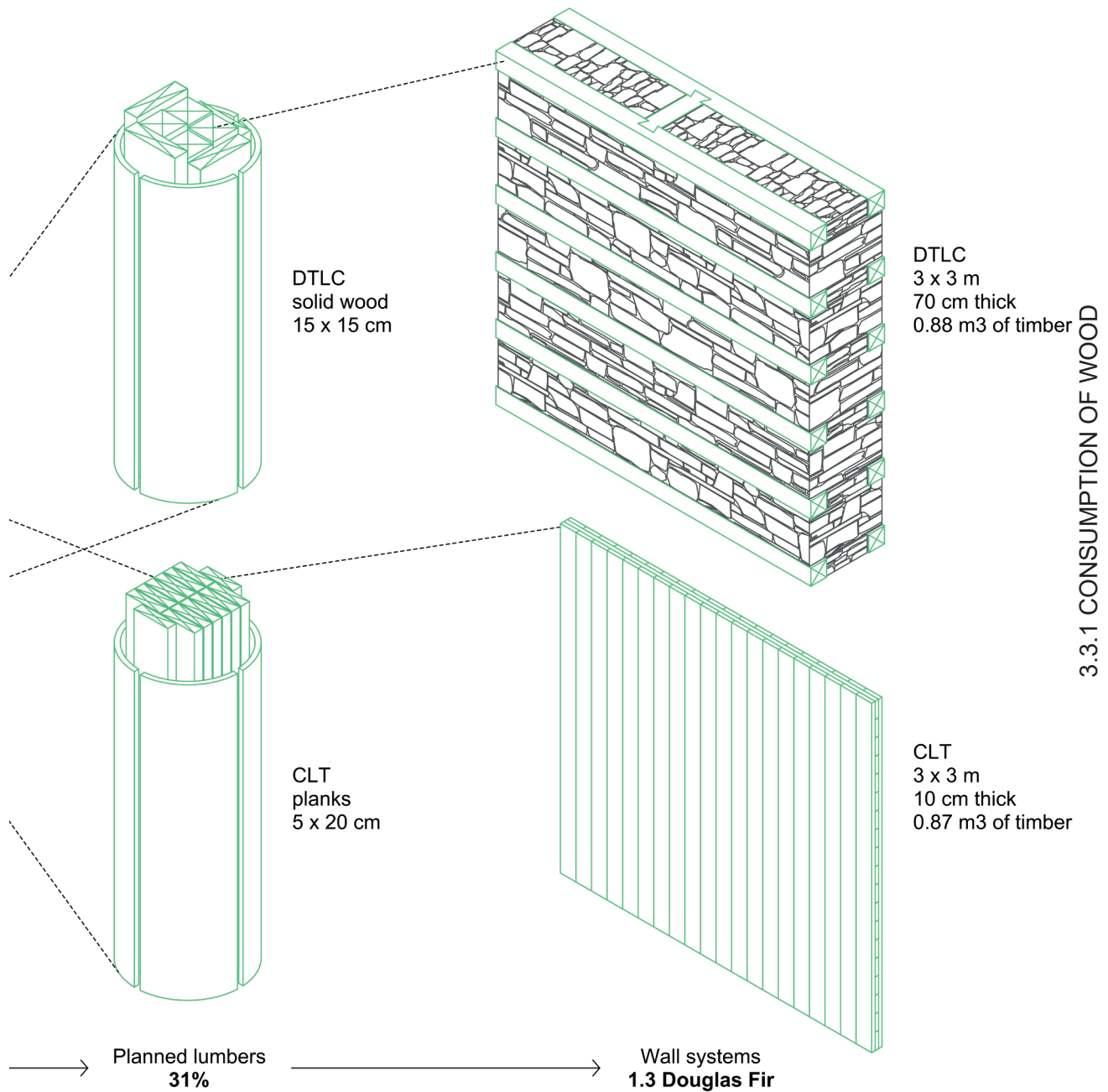
First we must note the fact that dimensions and quality of sawn timber differ for the two walls. CLT has the advantage of using younger trees or shorter portions of lumbers, but with higher sawn losses due to the size and number of planks, whereas in the DTL wall the cross section of each member is bigger (traditionally 15/15, hence fewer cuts and less sawing loss). Moreover, each individual lintel has to present a proper uniform quality. In DTL it is always preferable to use sapwood heartwood (an alternative would be to use a species of hardwood), due to its high density and durability properties against moisture and insect attacks. On the other hand, CLT planks can be used without distinction from any portion of the log cross-section.

Having said that, there is one last important difference between the two walls (in addition to the qualities of DLT listed before): the DLT wall is most probably much less in need of extra layers, insomuch as the CLT wall which requires extra insulation and covering layers.

Wall compositions have for long been assembled (and labelled) following only their thermal performance, which is of course an important step towards contemporary sustainability, but not the only one. In fact, it would be appropriate to include into the concept of performance also the quantity, even more the number of different materials employed. The simpler the macro wall composition, the better. Yet, it is still important to ensure a good thermal proficiency, by starting to add to the equation also the thermal inertia, a quality which will become progressively more appreciated in building comfort due to the unfortunate raising of global temperatures. This means that we will be faced with an increasing need to be able to keep our interiors warm, as well as to be able to cool them down, without electrical installations.

TIMBER+





Calculation of amount of wood employed in a DTLC or CLT wall, based on the research of the UW Center for Wood Innovation.

3.3.2 SPECIES OF WOOD AS STRATEGY FOR DURABILITY

Modern timber market is based on very few species, Spruce, Douglas Fir, and in smaller quantities, Pine, also engineered *wood products* are for the most part produced from Spruce and Douglas Fir. Except for few companies which have recently experimented new wood products (mostly CLT and LVL) from *non-coniferous* trees like Beech⁸⁰, our timber build stock is mainly realized from *coniferous* trees, since these species grow rapidly, their manufacture is relatively easy due to low density coefficients, and for the same reason they are also a good insulator. On the other hand, if we look at which species are used in composite timber constructions (for each example presents in the *Atlas*) we quickly realize that, with the exception of one, they fall into the *medium durable* or *durable* category (according to EN 350-2 classification). The only two buildings using Spruce, which is considered *less durable*, are those built in the last 10 years. There are few reason for this.

First, composite timber constructions, more than traditional northern European full timber constructions (e.g. *Blockbau*), have been constantly exposed to high moisture contact from their masonry components. Local builders have learned to privilege hardwood broadleaved trees or heartwood parts of coniferous trees, as in the case for *dry timber-lace* constructions in Himalaya, in order to prevent wood decay and fungi attacks. When these species were replaced by Scandinavian *coniferous* trees in recent restorations or repairs (see *Pontelarisma* chapter), the outcome was catastrophic, with a consequent overhaul deterioration of the timber structure.

As we can see from the table, the resistance to decay is not only defined by the density of the wood but also by other factors. Let's take the example of European Oak (*Quercus robur*) and the Himalayan Cedar (*Cedar deodara*): even though they have different density coefficients, respectively 710 and 560 [kg/m³], both fall into the same durable category. The presence of *tannins*, *resins*, *crystalline cellulose* can equally enhance the durability of the wood by increasing its resistance to fungi and insect attacks⁸¹: by instance, the Himalayan Cedar has an outstanding heartwood to sapwood ratio, which provides a robust amount of *resins*, this eventually explain its presence among the *durable* category beside denser species like Oak.

Furthermore, the constant presence of hardwood species among composite timber constructions can be explained by looking at the geographical origins

⁸⁰ "BauBuche," accessed December 7, 2019, <https://www.pollmeier.com>.

⁸¹ Ladislav Reinprecht, *Wood Deterioration, Protection and Maintenance* (Wiley Blackwell, n.d.).

3.3.2 SPECIES OF WOOD AS STRATEGY FOR DURABILITY

Durability class	Commercial name	Scientific name	B or C (**)	Density (kg/m3)	Occurrence	Study case
1 Very durable						
2 Durable	Cypress	<i>Taxodium distichum</i>	C	750	Europe, Africa	PalaceOftheDey
	Chestnut	<i>Castanea sativa</i>	B	590	Europe	OpusCraticum Borbone Mileto Pombalino
	Oak	<i>Quercus robur</i>	B	710	Europe	MurusGallicus Pombalino Quincha Fachwerk Mileto
	Himalayan Cedar	<i>Cedar deodara</i>	C	560	Himalaya	DhajjiDewari TaqBathar CatorAndCribbage KathKiKunni
3 Medium durable	Walnut	<i>Juglans regia</i>	B	670	Europe	OpusCraticum Mileto
	Douglas fir	<i>Pseudotsuga menziesii</i>	C	530	Europe	CLTshell
	Turkish Oak	<i>Quercus cerris</i>	B	770	Europe, Middle East	Lefkada
	Pine	<i>Pinus sylvestris</i>	C	520	Europe	Pombalino Fachwerk
4 Less durable	Spruce	<i>Picea abies</i>	C	460	Europe	CLTshell Bärenwalde
5 Non-durable						

(*) (1)Very durable: more than 70 years above ground, under ground more than 40 years; (2)Durable: more than 40 years above ground, under ground more than 25 years; (3)medium durable: between 15 to 40 years above ground, under ground between 15 to 25 years; (4)less durable: between 7 to 15 years above ground, under ground between 5 to 15 years; (5)non-durable: between 0 to 7 years above ground, under ground between 0 to 5 years.(Based on data provided by: "Durability Class | WoodSolutions."
Accessed December 7, 2019.
[https://www.woodsolutions.com.au/glossary/Durability-Class-AND-EN-350-2.](https://www.woodsolutions.com.au/glossary/Durability-Class-AND-EN-350-2))

(**)Broadleaved (B) or coniferous (C)

Table illustrating the tree species for each building analysed in the Atlas. Since most of composite system constructions must deal with moisture, the choice of the right durable species is fundamental.

TIMBER+





3.3.2 SPECIES OF WOOD AS STRATEGY FOR DURABILITY

Dark green: coniferous forests, light green: deciduous forests. Light green, due to future raise in temperatures, will be progressively replace part of coniferous tree stocks (Data from Copernicus, viewed in 2019).

of these systems. They all come from warmer areas, so not only deciduous species were easily available, but once transformed into timber, the latter remains compatible with its native environmental conditions: resistance to heat, UV rays, moisture dump and the consequent insect and fungi attacks.

As we have already said, nowadays we largely build in coniferous timber. In most cases, especially in warm and humid areas, this timber is over-protected under many layers of the most different materials (waterproofing, insulation, claddings, plasters, bitumen), whereas in vernacular timber constructions the first criteria for durability was the choice of the proper tree species.

Now, if we take into account the raise of temperature, due to the climate change, the *coniferous* tree stock of the boreal hemisphere will soon change: this means that *“deciduous trees, which generally only appear as pioneer plants, could potentially dominate the landscape in the long run (MPI of Biochemistry, S. Tautenhahn)”*. It is becoming clear that climate change is transforming Earth, and with it the tree stock we use in our buildings. Even if we manage to stop the raise of temperatures of 2 degrees by the end of the century, the use of hardwood species will not only become a necessity, due to the break-up of *coniferous* species stock, but also the best sustainable building strategy that we can adopt, because once used in a building, those deciduous species will be perfectly adapted to perform in the very same warm climate which originated them.

Within this new perspective, the examples in the *Atlas* can offer an inventory of sustainable building strategies in relatively warm and humid conditions, which even high-latitude areas are about to face.

3.3 CONSIDERATIONS ON TIMBER





Sawn-cut stones: not all these materials will be discarded, app. 60% will be put at use while the remaining 40% will become a by-product of the manufacture chain (credits reserved to Guber Natur Steine, photo by Andrea Settimi)

“[...] Stein hat eine sehr hohe Druckfestigkeit, zum Teil höher als Beton. [...] Uns interessierte die Möglichkeit, den Stein nicht nur flächig, sondern auch strukturell einzusetzen gezielt bei einzelnen tragenden Elementen.”⁸²

SIA 246 , 4.21 defines the material stone as follow: *“pratiquement toutes les pierre naturelles sont composées de diverses matières variant en structure, dureté et couleur. Elles ne sont pas constituées d’une masse homogène compacte. Il arrive souvent qu’apparaissent des dépôts, pointes, veines, particules vitreuses, trous de sel, etc., phénomènes n’altérant pas la nature du matériau et ne constituent pas une dépréciation de sa valeur, pour autant que le traitement ultérieur soit effectué dans les règles de l’art.”*. Stone is not a homogeneous material and its properties depend on orogenesis phenomenon but also on how and in what way these materials are extracted and processed. Since stone extraction and its manufacture too expensive as a massive masonry building system, much cheaper and less laborious systems such as reinforced concrete have gradually made the use of stone worthy only for its aesthetic features in cladding and building *maquillage*. Yet, stone has extremely good structural qualities (among all the high resistance to compression) which are not exploited on large scale because of its prohibitive price.

Timber lace masonries could offer the advantage of exploiting an underestimated branch composed by sub-products, considered in part as waste due to their irregular shape or the fact that they are too small dimension for typical stone products⁸³ (ashlars, *pavé*, wall bricks etc’...). In addition to that, since DTLC has a dry stack masonry, these products can be dismantled, recollected and reassembled an infinite number of times.

This could represent a great opportunity for the stone industries: to partially reorganise their workforce in a more circular man-labour logic. It is surprising, in fact, how the stone industry has preserved, more than all other sectors, an extensive use of man workforce: a human worker is the only asset that can quickly react and give shape to such a heterogeneous material as stone. An experienced quarry worker can quickly react and adapt his or her workflow to the changing characteristics of the stone which he or she is processing, for example splitting a boulder by following the natural seam of the piece or figuring out which is the most profitable point to crack a quarry wall during the very first phase of extraction.

This kind of heritage and know-how could be easily adaptable to pre-fabrication

⁸² Interview Markus Peter, interview: Axel Simon, “Architektur muss etwaas vom Stein wollen,” *HOCH PART ERRE*, 2015.

⁸³ Ladislav Reinprecht, *Wood Deterioration, Protection and Maintenance*.

3.4 CONSIDERATIONS ON MASONRY

of DTL components.

Only in Switzerland it is possible to count a couple of dozens of different types of stones, each quarry of course has its own extraction methods according to the specific morphology of the stone and the demands of the market. Nevertheless, they all produce *waste* or, in other words, *unsaleable* stoneware. In order to clarify what the industry defines as *waste*, it is necessary to take a look at the production cycle of a stone product. Among all the companies I decided to limit the focus to those that sell stones with good or above average structural qualities, moreover, precious stones such as Marble or high-quality Granite are not considered here. The reason why I decided to exclude (for now) precious stones is because their production is closely monitored, even stone dust and minor bits are sold either to cement company or tilers in order to produce top-of-the-range products. For the other stones the management of production and extraction waste is more complicated. In addition, the fact that the concrete industry has always preferred small boulders to sharp-edged gravel for better adherence of cement to the round surface, has further limited the chances of finding a second life for quarry rubble.

DTLC is much more profitable to those companies which extract bulky and resistant stones and try to use their *by-products*.

By instance, stone gabions are designed to meet these needs similarly to DTLC. If a company produces them, it means that the company could be eligible as DTLC supplier. Gabion systems allow in fact, to cover part of the *waste* production by limiting at the same time labour for their production. However, their application is still limited to retaining walls within low heights and the galvanised metal required for the manufacture is, nevertheless, expensive.

Guber Natur Steine fell into the above-mentioned category and was also interested in participating in the study. From now on we will consider their assets and their production in order to establish a life-cycle assessment of all their products and all different type of *wastes*. All prices included do not represent an official price range provided by the company, but only an estimate intended to give a general idea to the reader.

Guber Natur Steine is based in Alpnach Dorf (Central Switzerland) and its extraction site is located at the app. 900 metres above sea level. I would like

to make a premise by saying that the following analysis is in no way intended to highlight an improper behaviour of the company in terms of wastage production. On the contrary, I believe that *Guber Natur Steine* is one of the few companies which is constantly trying to streamline its *by-products* production, which generation is, to a certain extent inevitable. The advantage of quarry waste is that it remains within the exploitation area, just waiting to be used.

Guber's stone, in technical jargon is classified as *litharenite*. More simply, it is a type of stone composed by a lot of *Quartz* (50%), *Sandstone* (40%), *Feldspaths* and other materials (10%). Thanks to these characteristics this stone is particularly resistant, quite compact and can be suitable for outdoor environments. The most famous product of *Guber Natur Steine* is *pavé* tiles, but it also produces other products such as blocks for dry masonry, ground slabs, cladding tiles... The dimensions of the product are influenced and limited by the extraction phase. In fact, quarry wall layers can be divided into three categories: sandstone layers thicker than 40 cm that represent the main source of exploitation, under 40cm thick, layers are mainly composed of *schists*, thereby discarded because of their close seams which produce thin and irregular shaped slabs, the third and last sediment is made of *clay*, hence of no value, indeed its presence makes every extraction operations significantly more difficult. The discarded *schist* layer in addition to the rubble produced to extract the thicker layer of sandstone, is the first type of waste, which I define as "*first degree*" because it originates at the top of the manufacture cycle. These *sub-products* are composed by thin slabs, gravel, and bulkier rocks of no larger than 30-40cm large, and have the main function for the company than serves as a gravel carpet to stabilise the muddy soil of the quarry or as infill mass to cover old extraction sites. It is important to specify that the stone in the *schist* layers is mostly of the same quality as the one in bigger banks, but because of their flat shape and small dimensions it is unworthy for the company to spend extra time and labour to separate them from the rest of excavation rubbles.



Guber Natur Steine: old extraction site(credits reserved to Guber Natur Steine, photo by Andrea Settini).

The larger blocs are then transported to the lower workstation where they can be roughly cleaved by an automatic crusher or by hand, which still represent the quickest option. The trimming operation mainly produces irregular fragments which do not exceed 130-150 cm in length, the smaller and irregular pieces originated by these operations constitute another type of waste. Sometimes it is also possible to find clay bubble within the boulder, if they are smaller than 2 cm, they are aesthetically tolerable, if they are larger, extra trimming is necessary, resulting in more waste. Part of the extraction is reserved to sawn-cut products. If this is the case, the boulder is first cut by a bandsaw, very little of waste is produced during this phase. Subsequently, each slab is further processed by CNC circular saws, polished or burned to obtain a rough, anti-slip top surface. In this phase, on the other hand, a fair amount of planed and orthogonal stone *residues* is produced, normally the dimensions can vary from a minimum of 5-10 cm to a maximum length which should not exceed 180cm. Around 60% of it will be later converted into *pavé* or other cleaved products, the rest will be discarded.

Rough cleaved stones are further trimmed to obtain smaller products such as *pavé*, masonry blocks, slabs for cladding or tiling. During this phase the size of waste becomes reasonably small but always irregular, with dimensions always remaining within 5 and 40 cm.

In the end, considering the whole production and extraction chain, almost half of the initial total extracted material will become an immediate saleable product. Half of what we produce in carries is not considered disposable only due to its irregular shape, since their structural quality remains intact. The generation of waste is simply explained by our need to build with orthogonal elements: their assembly is simpler and less time consuming. Plus, the use of cement has made the bricklaying task even easier by reducing precision and care with which stones are chosen and laid. On the contrary, dry masonries works within a set of opposite values: less material and water, less time consuming, require highly skilled brick layers and precision in return. They allow stones of all sizes and irregular shape to be used: large and squared stone waste can be used for the exterior dressed leaves, whereas extremely irregular rubble can be used as infill for the inner core of the wall.

Stone quarries are not the only source of reusable mineral waste, the most important one comes from demolition rubbles. Yet, it is important to make a few

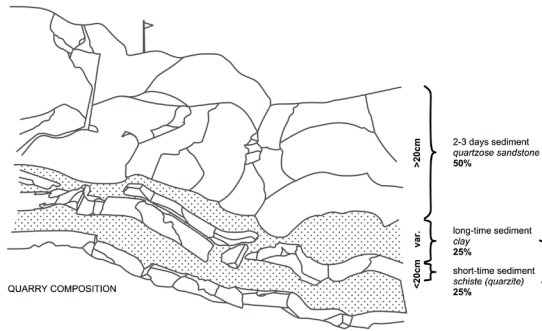
3.4 CONSIDERATIONS ON MASONRY

considerations.

In Switzerland, just right after wastes excavation waste, rubble and demolition gravel represent by far the largest amount of waste produced in the Swiss territory: 15 millions of tons per year⁸⁴. Most of these tons are composed of mineral materials: asphalts, concrete, reinforced concrete, bricks, sand and gravel. To date, all these materials are stocked in landfills reserved only to mineral waste. It would not be difficult to imagine using mineral rubble instead of stone *waste* for DTLC, but there is one basic difference between the two types of *wastes*: stones, despite their size and shape can maintain uniform structural properties, while structural properties of concrete rubble, once sorted from all other of mineral waste, are highly influenced by their shape, material composition and dimensions. For this reason, to overcome these disadvantages, concrete rubble is often turned into powder for cement or into small granulometric formats in order to serve as gravel for new concrete mix. This does not mean that concrete rubble (as masonry blocks) cannot be used in DTLC construction, it may just cover less structurally demanding tasks, but still be used as infill. An example of this approach comes from the Portuguese *Gaiola* construction (see the chapter *Pombalino* system for the complete analysis). After the destructive earthquake of 1755, the royal engineers in charge of the reconstruction devised a constructing system capable of absorbing some of the debris and rubble in which the city was almost entirely covered. The main structural system was a timber frame system (like the Northern European *Fachwerk*), the exterior façade walls were made of the best quality recycled mineral materials and the interior framed wall's nobs were filled with the most heterogenous rubble found in the surroundings. Although they did not have to cover important structural tasks, their dense mineral mass improved the sound insulation, fire resistance and anti-seismic properties (thanks to their energy dissipation trough friction) of the entire building, while at the same time contributing to the waste disposal of the city.

⁸⁴ Dialogue Économie verte, “La Suisse avance dans le recyclage des déchets de chantier,” accessed December 7, 2019, https://www.gruenewirtschaft.admin.ch/grwi/fr/home/Gruene_Wirtschaft_konkret/schweiz-macht-sich-beim-recycling-von-bauschutt-auf-den-weg.html.

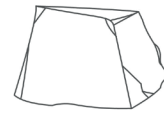
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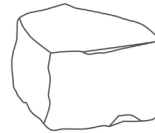
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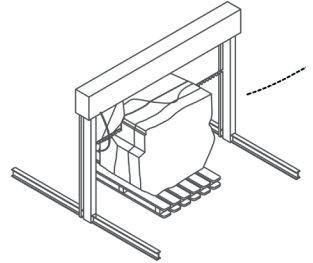


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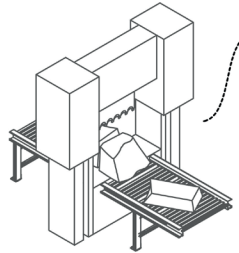


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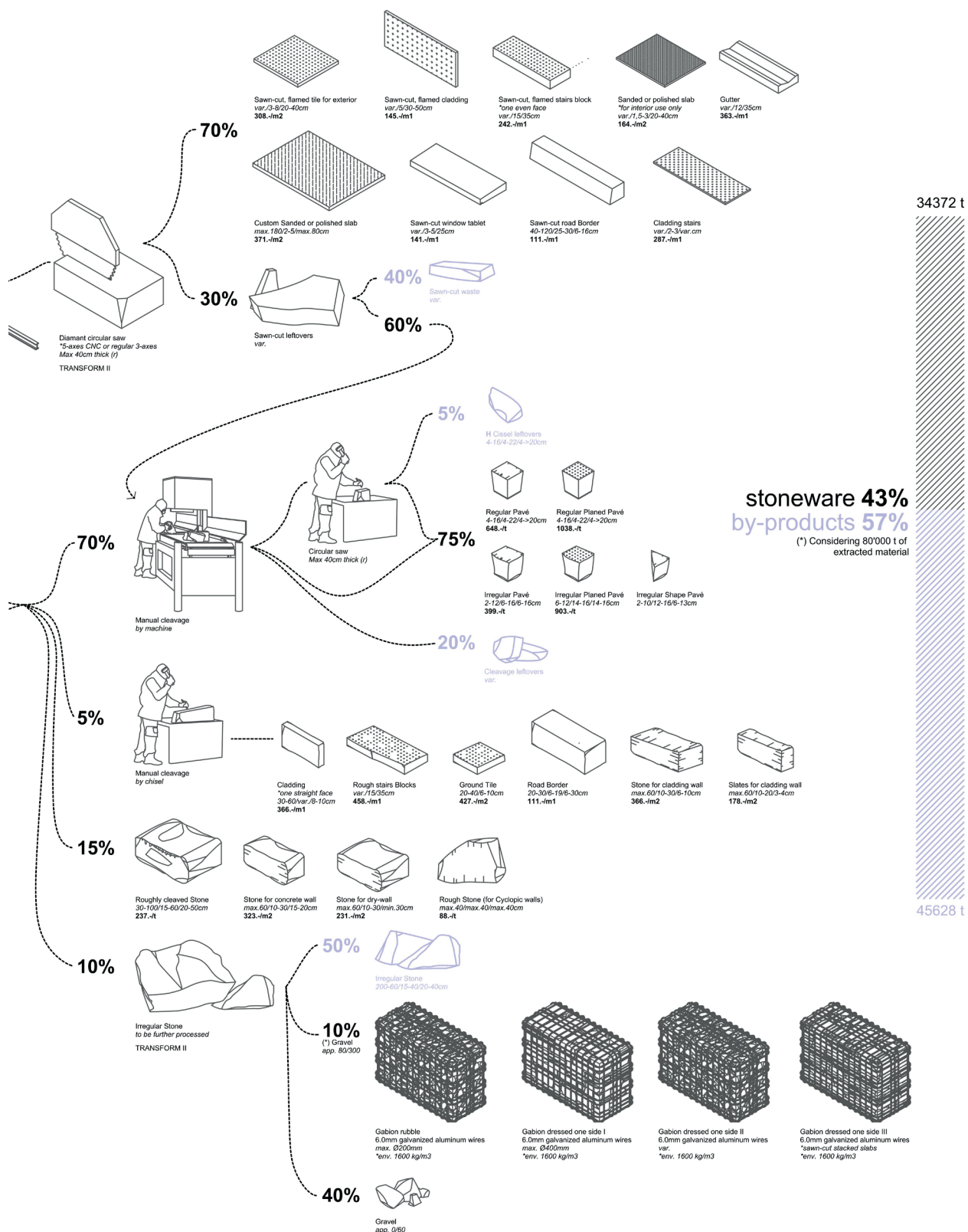
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TRANSFORM I



3.4 CONSIDERATION ON MASONRY

Lifecycle assessment of stoneware and waste produced from extraction to end of the manufacture process
 (*Prices are the result of an average estimate, they are only intended to give an overall picture and do not represent an official price given by the company. ** Percentages and data represent an estimate given by the company, on these data is calculated the overhaul amount of stoneware and waste, it is important to note that it has some margin, nevertheless it allows to give a general picture of the situation).

Traditional DTLC is typically an *in-situ* construction due to the heaviness of the construction, the dry-stacked nature of the masonry and the need to ensure proper continuity between timber-belts.

These are the main challenges related to the transformation of this *in-situ* technique into a pre-fabricated one. In fact, it is difficult to find an example of pre-fabricated masonry because of the very definition of bricklaying: an easy operation made possible by stacking standardised, small, easily transportable and stackable elements. All these features defeat the very purpose of masonry prefabrication. Nevertheless, DTLC does not seem to fit exactly into this working environment. The difference between DTL masonry and standard brick masonry is based on the high precision required for laying assembly, in fact, the laying of dry and uneven stones and rubbles pieces is far more time-consuming. This is due to the attention paid to the correct dressing and finding the right size for each stone/rubble compared to stacking standard and equal bricks. This is of course a repetitive task, but one that requires a customised laying procedure for each piece.

As we mentioned before, there is no universal solution for a sustainable approach when it comes to industrially developing a specific technology. Good results can be achieved by training workers in new tasks. There are of course good results in introducing inexperienced builders to new building technics (e.g. Community Library in *Ambepussa*⁸⁵, by Milinda Pathiraja⁸⁶). *Guber Natur Steine* could also be eligible for prefabrication technique, thanks to their high-skilled workforce.

On the other hand, digital design and machine-assisted fabrication have progressively shown their potential to assist designers and producers in the transition to the circular economy, especially in adapting rigid industrial standards towards more adaptable and resilient manufacturing approaches. It is very unlikely that one trend will completely overcome the other, we are likely to see a coexistence of both. Nevertheless, digital production is likely to be the main feature that will, in the long term, make the production of new *regenerative* building components cheaper and therefore more available to a wider public.

Having made these premises, there are two possible choices for DTL pre-fabrication: the first is partial prefabrication in which all timber containers are partially prefabricated in advance and filled (or stacked) with rubbles directly

⁸⁵ LafargeHolcim Foundation for Sustainable Construction info@lafargeholcim-foundation.org, "Milinda Pathiraja | LafargeHolcim Foundation for Sustainable Construction," LafargeHolcim Foundation website, accessed November 10, 2019, <http://www.holcimfoundation.org/Experts/milinda-pathiraja>.

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on site. The second is full prefabrication in which all units would be fully prefabricated in order to reduce to the bone the operations *in-site*. This is where robot-aid manufacture could play a substantial role during the prefabrication phase (in rubble 3D scanning and laying) and would give an advantage over the *in-situ* strategy (which requires a lot of manpower). The main advantage in rubble-laying robot-aid would be the automation of this irregular process. The logic-chain would be to detect, and 3D scan each rubble or stone, calculate its position in the nest, place it within, capture the new layout and loop the process. It is worth noting that rubble can be manually pre-processed even after the recovery, this is already the case with recycled stone paves which are always sold with only one straight flat face⁸⁷. Furthermore, there is already new research focused on 3D scanning to manipulate irregular objects, which although premature, seem quite promising⁸⁸.

More strategies are possible on how to shape and assemble each unit, depending on the asset available. We must not forget that DTLC remains a type of heavy construction, therefore, a first intuition would be to reduce the size of each unit to take full advantage of canonical prefabrication. In this way it is possible to facilitate transportation, manipulate the units with equipment of reasonable size (to avoid as much as possible the use of specialized cranes), obtain versatile joinery for site assembly, etc.

Finally, some words may be reserved to the option of adding new elements to the DTLC components. The most convenient add-ons would probably be to contain meshes which would eventually contribute to avoid out-of-plane collapses and would also improve safety and manoeuvrability during the transport. Since the meshes in question would work mainly under tension, few materials could be used to the masonry layers in place. The most common choice would fall on metal wire-grid (like in gabion construction), but other options such as reused seat belts, textile grids or even timber lattice structures can also be explored.

⁸⁶ “Milinda Pathiraja – FAR,” accessed November 10, 2019, <https://www.epfl.ch/labs/far/a-demo-by-hd/team/milinda-pathiraja/>.

⁸⁷ “Rotor, Tristan Boniver, Lionel Devlieger, Maarten Gielen, Bruxelles, Belgique,” *Cité de l’architecture & du patrimoine*, accessed November 8, 2019, <http://www.citedelarchitecture.fr/fr/video/>

Timber+ offers an overview of the broad theme of *Composite Timber Construction*. It explains why these constructions have flourished in specific areas of the world and why in some cases they have disappeared. It wants to focus on some clever timber details and sustainable building strategies adopted in these constructions. This third section shows these constructions under the lens of today's building environment. I believe that these constructions have a number of features that we absolutely need today: easily repairable and down-cycling components, any use of cement or water, great expertise in the field of thermal and building comfort, etc.

Timber+ tries also to answer to few questions: are these constructions relevant to today's building environment? Do we have the assets and resources to carry them out? Can *Timber Composite Constructions* offer solutions to today's environmental issues? I hope the reader already has enough information to answer to these questions.

I am sure we would have no difficulty in finding talented technicians, both in the engineering and economic field and in that of building management, to also answer to the following questions: are these constructing systems economically reliable? How many storeys can we build today with *dry timber lace* walls? How could the friction between the stones be modelled? How much would it cost to maintain these structures?

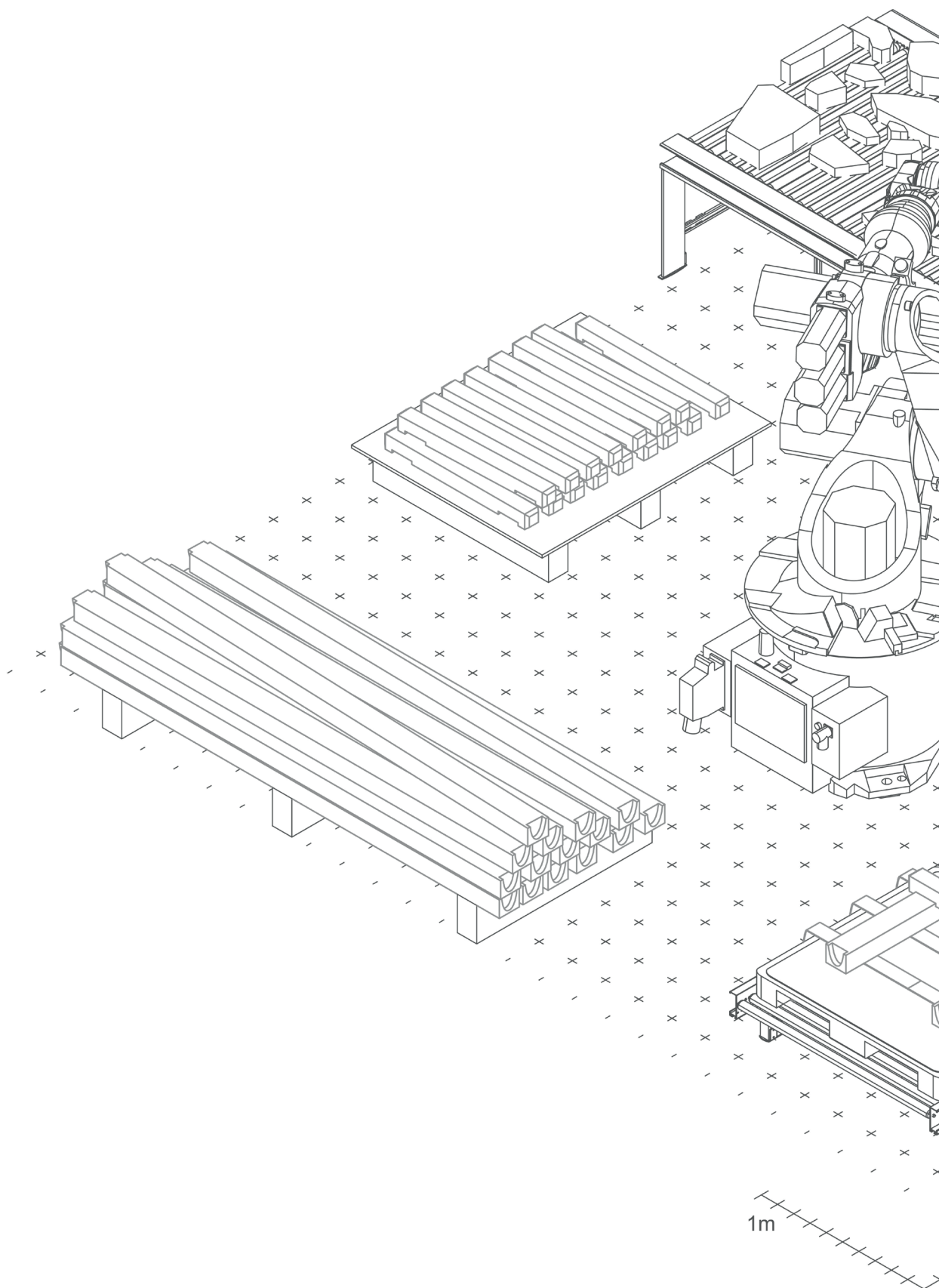
But the true question that *Timber+* should raise is another one: are we willing to experiment technologies based on values other than structural efficiency? What *Timber Composite Constructions* teaches us is that redundancy is the price we pay to generate logistics and mechanisms which ultimately will make our buildings last longer. This last feature won't hardly rime with economical and structural efficiency as we traditionally intend. Hence, in order to continue researches on *Timber+*, we must first of all accept a change in values which eventually ends up making room for other areas of work: for the new generation of designers and developers, thinking globally and acting locally is no longer a slogan, but rather a crucial necessity to be recognized as soon as possible. In fact, the results of technological innovations should be put into perspective from the earliest stages of development and should not be conceived for their temporary nature. Once we recognise these other priorities in construction, we will then find the systems presented in this book worthy of future development.

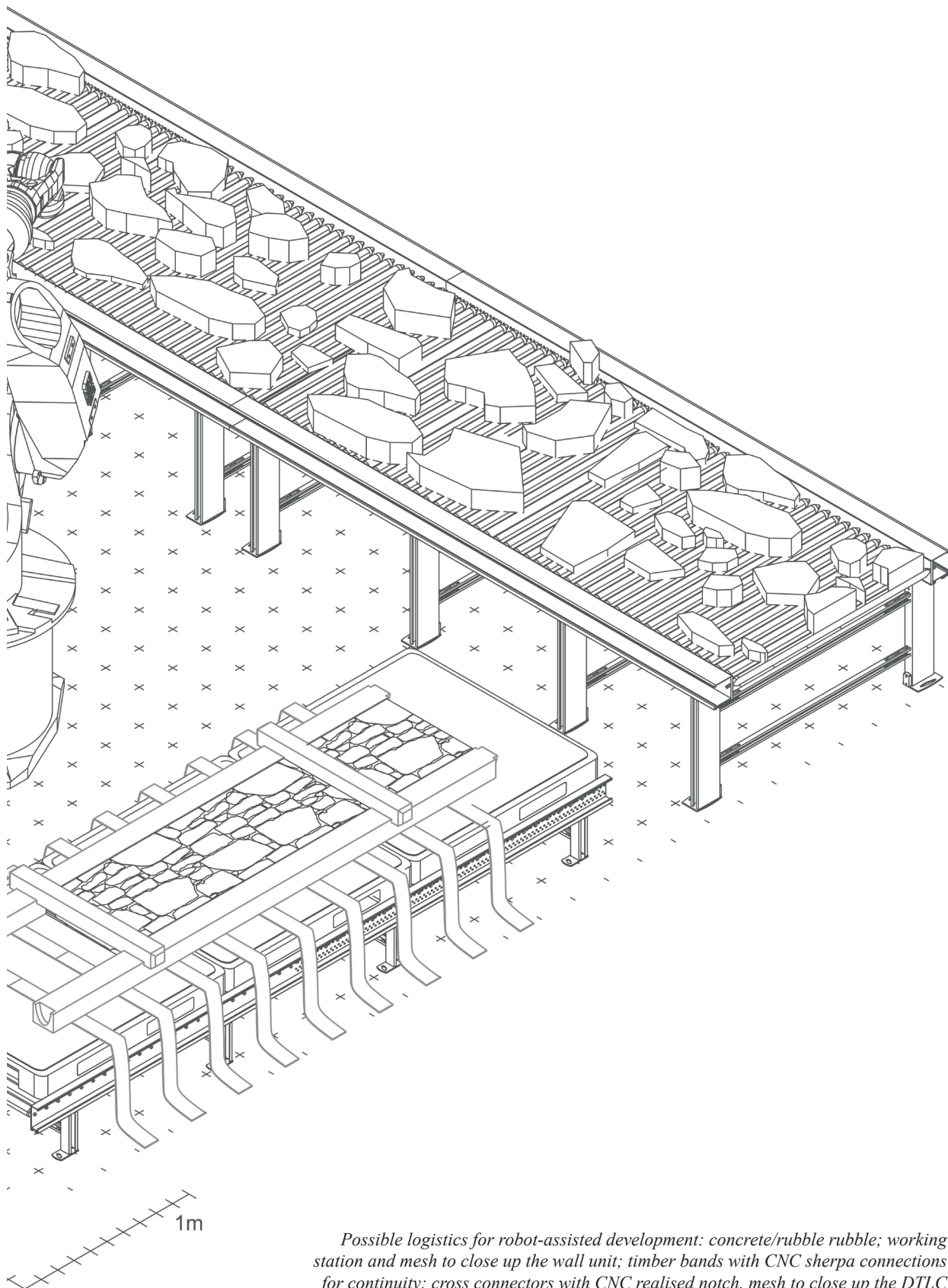
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88 "Robotic Aggregation of Materials with Irregular Geometry | Dfab," accessed November 8, 2019, <http://www.dfab.ch/research/robotic-aggregation-of-materials-with-irregular-geometry/>.

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TIMBER+





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Possible logistics for robot-assisted development: concrete/rubble rubble; working station and mesh to close up the wall unit; timber bands with CNC sherpa connections for continuity; cross connectors with CNC realised notch, mesh to close up the DTLC component.

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