PARAMETRIC APPROACH TO THE RECONSTRUCTION OF TIMBER STRUCTURES IN CAMPANIAN ROMAN HOUSES

PROCEDIMIENTO PARAMÉTRICO DE RECONSTRUCCIÓN DE ESTRUCTURAS DE MADERA EN LAS CASAS ROMANAS DE CAMPANIA

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Highlights:

- Proposal of a structural model for the dimensioning of timber floor beams in domestic spaces based on archaeological and literature information

- Parametrical interpretation of the model in Grasshopper for Rhinoceros software and optimization analysis of the structural parameters involved

- Application of the model to the reconstruction of floor frames in a house in the Sarno Baths complex, Pompeii.

Abstract:
The virtual reconstruction of ancient architecture aims at describing the 'original' elevation and volume of a disappeared building. The feeble archaeological traces, often limited to their house foundations, impair the reinstating of their image, in contrast to public buildings massive structures. A twofold problem arises when dealing with timber structures during a reconstruction procedure: at the local scale of the individual beam (e.g. joists or rafters), one must define a beam's cross-section given its span; at the overall scale, the shape of a building results from that which its structures allowed it to have been. Consequently, this work proposes a procedure to deal with the 'local' problem, i.e. the definition of a beam's cross-section from its span. To that end, a simplified, parametric structural model is required. The available bits of information are organized into inputs, parameters and outputs of the analytical problem by matching each piece of information with a structural quantity (load, cross-section, spacing, etc.). Two mathematical relationships among them are proposed, which express two equally possible dimensioning criteria, based either on joists' strength or deformability. It seems that the joist's strength was the option for lightly loaded joists, as in roofs or tightly spaced floor frames; conversely, heavily loaded joists conformed to the deformability criterion. Both dimensioning procedures are translated into a visual algorithm in Grasshopper, a plugin for Rhinoceros modelling software, which enables the parametric definition of objects. Finally, the proposed procedure is tentatively applied to automatically reconstruct the floor and roof frames that belonged to the domus on top of the Sarno Baths in Pompeii. The algorithm automatically picked the dimensioning criterion in relation to each frame's span and hypothesized loads and determined joists' orientation and minimum cross-sections. The obtained floor frames, whose structural conditions are considered as sensitive, will be adopted in the overall virtual reconstruction proposal of the ruins, also based on the analytical evaluation of masonry structures.

Keywords: timber structures; reconstruction; parametric modelling; Roman house; Pompeii; Sarno Baths

Resumen:

La reconstrucción virtual de la arquitectura antigua tiene como objetivo describir la altura y el volumen 'originales' de un edificio desaparecido. Los vestigios arqueológicos débiles que dejan las casas, a menudo limitados a sus cimientos, dificultan el restablecimiento de su imagen, en contraste con lo que es posible gracias a las estructuras macizas de los edificios públicos. Surge un problema doble cuando se trata de estructuras de madera durante el procedimiento de reconstrucción: a la escala local de la viga individual (por ejemplo, viguetas o travesaños), se debe definir la sección transversal de una viga dada su luz; a escala general, la forma de un edificio resulta de lo que sus estructuras permitieron que fuera. Por todo ello, este trabajo propone un procedimiento para abordar el problema 'local', es decir, la definición de la sección transversal de una viga a partir de su luz. Para ello, se requiere un modelo estructural paramétrico simplificado. Los bits de información disponibles se organizan en entradas, parámetros y salidas del problema analítico haciendo coincidir cada información con una cantidad estructural (carga, sección transversal, espaciado, etc.). Se proponen dos relaciones matemáticas entre ellas, que expresan dos criterios de dimensionamiento igualmente posibles, basados en la resistencia o deformabilidad de las viguetas. Parece que la resistencia de la vigueta fue la opción para viguetas con poca carga, como en techos o marcos de piso con espacios reducidos; por el contrario, las viguetas muy cargadas se ajustaban al criterio de deformabilidad. Ambos procedimientos de dimensionamiento se traducen en un algoritmo visual en Grasshopper, un complemento para el software de modelado Rhinoceros, que permite la definición paramétrica de objetos. Finalmente, el procedimiento propuesto se aplica provisionalmente para reconstruir automáticamente los marcos de piso y techo que pertenecían a la Domus en la parte superior de los baños de Sarno en Pompeya. El algoritmo eligió automáticamente el criterio de dimensionamiento en relación con el tramo de

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cada marco y las cargas hipotéticas y determinó la orientación de las viguetas y las secciones transversales mínimas. Los marcos de piso obtenidos, cuyas condiciones estructurales se consideran sensibles, se adoptarán en la propuesta de reconstrucción virtual general de las ruinas, también en base a la evaluación analítica de las estructuras de mampostería.

Palabras clave: estructuras de madera; reconstrucción 3D; modelado paramétrico; casa romana; Pompeya; baños de Sarno

1. Introduction

The virtual reconstruction of ancient architecture aims at either documenting its remains or at describing the 'original' volume and elevation of a building (Bennoui-Ladraa, Chennaoui & Ainouche 2020). The latter task may be supported by either the well-preserved vestiges or the very nature of the ruins: in dressed-stone monuments or large public buildings of the Greek and Roman Age (baths, markets, palaces, warehouses, etc.) the traces of the original techniques are evident, even in the details of their builders' practice (Adam, 1990; Bianchini, 2010; Choisy, 1873; Ginouvès, 1992; Giovannoni, 1925; Giuliani, 2006; Malacrino, 2013; Oleson, 2009; Vitti, 2016). Moreover, one may read the choices that ancient builders made to face structural problems. All these traces, which suggest how individual elements were assembled to form the whole structure, help scholars to imagine the complete shape of these buildings (see e.g. Adembri et al., 2016; Dawn & Biswas, 2019; Demetrescu & Ferdani, 2021; Margueron & Gransard-Desmond, 2012).

This is generally not the case of ancient common dwellings, whose structures, i.e., rubble masonry walls and timber floors and roofs, are much weaker than those of public buildings and monuments and therefore left just feeble traces. Consequently, the reconstruction of such buildings is burdensome, and it may lead to different interpretations, even in the case of (presumably) well-preserved remains. In traditional masonry buildings, timber structures are fundamental: a systematic approach to these elements is crucial also for a more complete understanding of how the overall structures appeared. Detailed survey campaigns on archaeological ruins (see e.g. Lorenzoni, Valluzzi, Salvalaggio, Minello, & Modena, 2017; Valluzzi, Lorenzoni, Deiana, Taffarel, & Modena, 2019) yield precious information of the empirical understanding of construction science in Antiquity applied to masonry structures; therefore, their results may be exploited when dealing with the overall reconstruction of a building (e.g. Salvalaggio, Bonetto, Zampar & Valluzzi, 2021).

In general terms, the reconstruction problem concerns the logical combination of the available pieces of information, coming from the archaeological site itself (direct information) and other sources (indirect information, e.g., texts, epigraphy, analogy), within a model. In addition to the features pointed out by Margueron & Gransard-Desmond (2012) and Demetrescu & Ferdani (2021), such model must be:

- Complete, i.e., it can manage all the selected variables
- Universal, in order to be generally applicable
- Adaptable to site-specific situations
- Simple, not requiring strictly discipline-specific input data

- Versatile, allowing to change the role of data considered or to combine pieces of information coming from different sources.

These features allow us to explore as many solutions as possible in order to find the most suitable one to the specific boundary conditions. To that end, one also needs a hierarchy among the available pieces of information (e.g. probable position and use of timber elements inside a building). Indeed, they may be organized in: a) *inputs*, which are the data obtained from archaeological investigations and which therefore are site-specific; b) *parameters*, which are common conditions, shared among different buildings/cases and which may be obtained from various sources; c) *outputs*, which are the unknown quantities, a function of the first two groups of variables.

This paper aims at applying this methodological approach to the reconstruction of timber structures in Roman domestic architecture in Italy, namely in Pompeii. The results are propaedeutic to a more comprehensive approach to the overall reconstruction of these buildings, which will also consider the masonry structure.

1.1. Archaeological evidence

Differently from masonry walls, which leave behind evident traces of their nature, information on ancient timber structures is much more uncertain and often based on indirect studies, e.g. palynology (Dimbleby & Grüger, 2002), epigraphy and iconography (Adam, 1990; Ulrich, 2013) or the observation of their traces where possible, like in Pompeii and Herculaneum (Stellacci & Rato 2021). The development of tools and repositories of such data is a field still in progress (Dessales & Tricoche 2018; Napolitano et al., 2019). Herculaneum, owing to the particular nature of the volcanic deposit in the 79 CE eruption, offers well-preserved specimens of timber, which gave interesting information on the supply of timber for construction at those times. The works by Moser, Allevato, Clarke, Di Pasquale & Nelle (2013) and Moser, Nelle & Di Pasquale (2018) allow us to hypothesize the survival of fir forests, as well as cypress brushes, in Southern Italy and the Mediterranean area and their usage in building sites (see e.g. Camardo & Notomista, 2015).

Data collected by Adam (1990) and recently confirmed by Moser, Nelle & Di Pasquale (2018), Centola (2018), Ruggieri (2017) suggest that in Pompeii and Herculaneum the single joist frame was the usual way to build floors. If compared to the double-framed system, the single framed one consumes more timber, since it requires many long and slender elements which can be easily obtained just from spruces or firs. As a result, it survived through the Middle Age to the Modern Era in northern Italy only, where larger softwood supplies were available (Barbisan & Laner, 1997). Conversely, in southern Italy, this system was substituted by double framed floors which could take advantage of the more

(a)

(b)
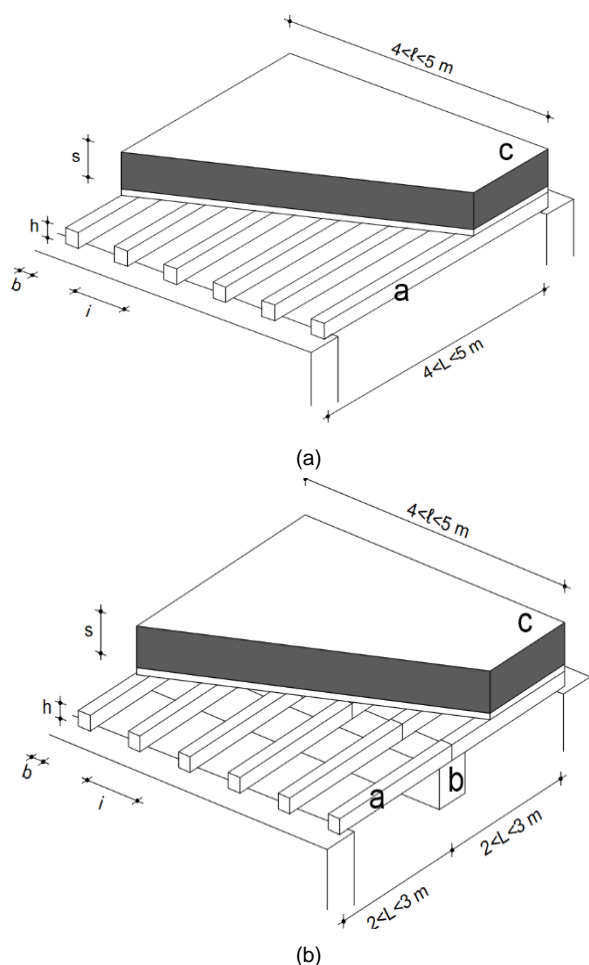
Figure 1: Possible configurations of traditional timber floors: a) single framed floor; b) double layer floor. Legend: (a) joist; (b) girder; (c) concrete slab.

the 62 CE earthquake (Dessales, 2011) Pompeian traditional building materials are of volcanic origin: lava, tuff, and lava foam (*cruma*) the commonest types (Pesando & Guidobaldi, 2006). Their usage might have extended from walls also to the composition of floor slabs.

Figure 2: Sockets left by floor joists in a wall, Pompeii.
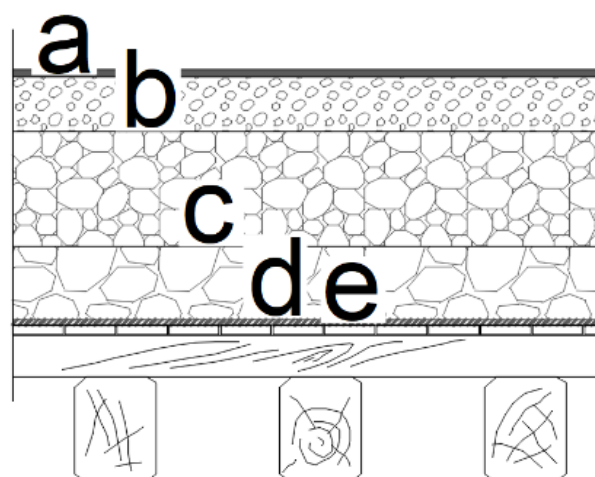
Figure 3: Roman 'terrazzo' floor according to Vitruvius (D.A. 7,1): a) *pavimentum*-upper floor finishing, e.g., mosaic; b) *nucleus*-crushed bricks and lime mortar; c) *rudus*-gravel ballast and lime mortar; d) *statuminatio*-stone rubble; e) detaching layer (straw) for a total thickness of 45-50 cm.

irregular hardwood elements which were left by the Roman exploitation (Fig. 1). Adam (1990), Centola (2018), Ruggieri (2017) and Ulrich (1996) observed that cross sections are often generously sized (about 1/18-1/24 of joist's span) and that they tend to be squat, with the base being about two thirds of the height (Fig. 2). In some cases, joists are circular or used in an unfavourable way, i.e., bent on the minor inertia axis. The spacing between the joists ranges between 30-60 cm (Centola, 2018; Ruggieri, 2017, 2018). The Campanian use differs from that found by Ulrich (1996) in Ancient Ostia, where floor beams were placed some 1.50 m apart.

Floor finishes depend on the social level of the owner of a house, although they may be described as variations on the terrazzo, i.e., a concrete fill whose aggregates become coarser with the depth of the fill (see e.g., Giuliani (2006), Fig. 3). This solution may be observed in the so-called *Casa dei Casti Amanti* (IX, 12, 6-8; Ruggieri (2017)). In the richest houses the *terrazzo* might have been completed on top with a mosaic, as described by Vitruvius in *De Architectura* (*D.A.*) (trans. 1997) in his treatise; in poorest dwellings just a thin cast was used with a simpler stratigraphy (Guidobaldi, Camardo, Esposito, & Tommasino, 2008; Ruggieri, 2017).

Apart the so-called *Calcare del Sarno*, which is a soft travertine, and terracotta tiles, which appeared after

1.2. Written sources

Ancient treatises, mainly the *Naturalis Historia* by Pliny the Elder (trans. 1988) and Vitruvius's *De Architectura* (trans. 1997), are often considered as a reference in archaeological reconstruction but they lack of the specific structural aspects of their topic, e.g., in timber construction, connections, dimensioning procedures. These themes probably were a specific heritage of craftsmen and builders and fell outside the interest of the educated readers.

One may find some specific indications in early modern treatises (Milizia, 1781; Palladio, 1570; Scamozzi, 1615), whose authors were also builders and designers and therefore versed in practical aspects.

To find a precise statement of empirical dimensioning rules, one must examine the 19th century building manuals (Cantalupi, 1863; Cavalieri San-Bertolo, 1832; Curioni, 1872; Donghi, 1906; Mazzocchi, 1871; Rondelet, 1832). However, their discussion grounds on

the result of the arising building science, which was unknown to Roman builders, who conversely worked their solutions out of experience and empiricism (Benvenuto, Corradi, Foce, & Becchi, 2012). Consequently, not every bit of it can be used in the current work. Luckily, these works also report the heritage of common building practice, and the empirical dimensioning rules of timber beams, which obtain their height as a fraction of their span, is included. These criteria are given for the best-known Italian treatises in Table 1.

Table 1: Dimensioning rules of timber floor beams in Italian historic manuals.

Treatise	Beam cross-section height (as a fraction of span)
Rondelet, 1832	1/24-1/18
Milizia 1781; Cavalieri San Bertolo, 1832	1/24-1/18
Donghi, 1906	1/20-1/30
Cantalupi 1862	1/24-1/18

The ordinary value is 1/24 of the span, and applies to joists (Fig. 1a), but for more loaded members, such as girders (Fig. 1b), it can be increased to 1/18; eventually, for secondary members it can be reduced to 1/30 (Cavalieri San-Bertolo, 1832; Donghi, 1906; Rondelet, 1832). Not surprisingly, they are comparable to the experimental data from Pompeii and Herculaneum (Author1 et al., 2018; Ruggieri, 2017). Adam (1990) notes the survival of the ancient tools traditionally used to work timber to modern times: inside builders' guilds, something similar can be also envisaged for the rules-of-thumb of construction practice.

2. Definition of an analytical model

If a site's elevation is not preserved, the possible sources (i.e. the ruins themselves, the analogies and comparison with similar sites, the written sources, both ancient and modern) do not give precise information on horizontal structures, but rather on their general scheme, see e.g. (De Martino et al., 2020). However, to deal with these bits of information in a structural model, such parameters may be expressed either by i) numerical values or ranges, or ii) a set of rules or boundary conditions, or iii) structural roles.

Apart from exceptional cases, an archaeological site, by itself, gives just the shapes of the rooms into which a building was subdivided. The lengths of their sides are assumed as the structural spans of their horizontal structures and therefore stand for the *input* of the problem. Another known factor is a site's geographical collocation, which determines the wind and snow loads on superstructures. However, as one must refer to present technical standards for their rough approximation in past times, they are more properly definable as *parameters*. Other parametric factors of the problem are:

- Structural system: in ordinary buildings whose rooms span less than 5 m, a single framed floor is the customary option. A double floor is applied either to spans larger than 5 m or to answer to regional customs (Mazzocchi, 1871; Ulrich, 1996). Joist bays range typically between 30-60 cm.

- Loads: they are distinguished in i) dead loads, that is the self-weight of construction works, coming from structural elements themselves and the finish used above; ii) live loads, due to imposed loads, coming either from the normal use of the floor/roof or from wind and snow (CEN, 2002). Dead loads are site-specific, as they are a function of a floor slabs' stratigraphy and materials (i.e. specific weight), which are a function respectively of a house's architectural functionality, as well as its social level, and available building materials. In other words, a mosaic would have suited a wealthy house or its main rooms; a coarse slab was enough for a lower-class dwelling (Guidobaldi, Camardo, Esposito, & Tommasino 2008) or in ancillary rooms (Centola, 2018). In Campanian towns, mortar and stones are often of volcanic origin and therefore tendentially lightweight, i.e. less than 2000 kg/m^3. Therefore, depending on the slab's thickness, dead loads range between 150-300 kg/m^2. Live loads can be roughly estimated in 100-200 kg/m^2 for residential buildings (Mazzocchi, 1871), i.e. a little less than those values given by present standards (e.g. MIT, 2018).

- Beam shape: rectangular, square, or circular are equally possible. Their choice depends on i) the available economic means; ii) the supply of building materials and iii) functionality, i.e. whether beams are used in roofs or floors, and, in the latter case, which kind of floor (principal or ancillary room).

- Materials: fir for structural timbers and cypress for architectural ceilings seem the most suitable choice for simple framed floors; oak and chestnut for double framed ones instead. Their mechanical properties can be approximated, in absence of any testing, by current standardized values (e.g. UNI, 2010 for Italian conditions or CEN, 2016 for a broader European context), possibly reduced according to service and load duration classes (CEN, 2004). Recent studies found an average specific weight of about 2000 kg/m^3 for lava specimens (Autiero, De Martino, Di Ludovico, & Prota, 2019b), about 1200 kg/m^3 for mortars (Autiero, De Martino, Di Ludovico, & Prota, 2019a; Miriello et al, 2010). These values may be extended also to the calculation of floor slabs weight.

Once each parameter is chosen, the only factors which are still unknown are the actual measures of a joist's cross-section. If one considers that the section's base can be expressed as a fraction of its height ($b = \xi h$), the problem depends just on a single unknown quantity, which is the desired *output*. The problem to determine a joist's height as a function of its span between the supports and the superimposed loads has already been dealt with by Giordano, Ceccotti, & Uzielli (1999) and Mazzocchi (1871), and more recently by Sbrogiò (2016). There are two possibilities:

$$h_{Str} = [3rl^2 / (4\xi f_d)]^{1/3} \tag{1}$$

$$h_{Def} = [5Krl^3 / (32\xi E_d)]^{1/4} \tag{2}$$

where:

l = structural span

r = superimposed load per unit of length

h = height of the cross section (rectangular)

b = base of the cross section (rectangular)

ξ = aspect ratio (as b/h).

f_d = bending strength

E_d = tensile elastic modulus parallel to the grain

K = maximum deflection of the beam (scalar)

Eq. (1) is governed by the strength of the material (f_d), that is the failure of timber; in Eq. (2) the deformability of timber is considered instead, i.e. the compatibility between a beam's sagging and its use and finish of which that is placed above it. In modern structural terms, the former represents a structural ultimate limit state (ULS) and the latter a serviceability limit state (SLS).

Both expressions are also valid for chamfered rectangular sections, provided the chamfer does not exceed 1/8 of the side of the rectangle (Giordano, Ceccotti & Uzielli, 1999). Similar formulations can be found for circular cross-sections (Mazzocchi, 1871).

In both expressions, geometrical information on the configuration of a frame appears in the terms of span and loads. Beam's span represents the input of the problem, but the load values convey a large part of parametrical information as it combines the bay spacing and the use and finish of a room.

The cross-section's aspect ratio relates to the criterion which is followed to dimension a beam. Indeed, it results from a minimization problem of, respectively, the bending stress at the edges of the cross-section and the deflection at midspan (Sbrogiò et al., 2018). In the former case a squat section is obtained (ξ=0.71, 'strength dimensioning') in the latter a slender one (ξ=0.57, 'deformability dimensioning'). Both shapes can be easily obtained on a log with a simple geometrical construction (Fig. 4) (Donghi, 1906).

The structural properties involved are timber bending strength (Eq. (1)) and deformability (Eq. (2)) expressed by the elastic modulus parallel to the grain. Finally, K value represents the maximum allowable deflection at midspan as a fraction of a beam's span according to use classification (Table 2). The higher its value, the lower the deformation and therefore the stiffer the beam.
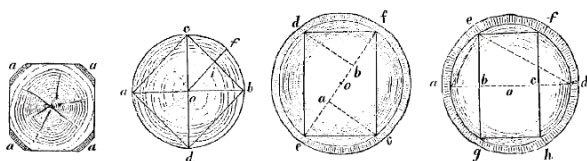
Figure 4: Beams shapes that can be obtained from a log: (a) hand-hewn; and (b, c, d) sawn sections. b) square; c) squat rectangular (strength dimensioning); d) slender rectangular (deformability dimensioning); from Donghi (1906).

2.1. Model validation

The results of these expressions have been systematically compared to real timber beams investigated in Herculaneum by Centola (2018) showing a general 'under-sizing effect'.

From a structural point of view, the strength rule is not equivalent to the deformability one. A beam dimensioned to exactly reach its limit strength is not safe, as either any minimum increase in superimposed loads or a defect of the material, which reduce the estimated strength (Giordano, Ceccotti, & Uzielli, 1999), would

cause the beam's failure. In a beam conforming to deformability criteria, if the load increases or defects appear, it will deflect more than expected but it will not yield under the weight. As the former condition is the most critical for the continuity of use and the overall safety of the structure, in design procedures a so-called 'safety factor on the material', which is used to reduce materials' strength, is commonly adopted.

The comparison between inspected and calculated timbers show that the under-sizing effect is more evident in those obtained from the strength rule. In fact, in Centola (2018) the calculations adopted: i) the lowest strength classes of solid timber of present standards (Table 3); ii) the reducing factors considered in modern standards to compute use and climate impact on timber for non-heated interiors of a house (Table 4). Indeed, both elastic and strength properties appear in the denominator of both Eq. (1) and (2) and therefore their reduction reflects in an increase of a joist's height. Those reducing factors by themselves, applied to elastic properties of timber, worked satisfactorily in artificially increasing joists' section but they were not enough when applied to strength, in agreement to an empirical understating of structural safety. Therefore, an additional reduction can be obtained with safety factors, which can be estimated in γ_M=1-1.5 for elastic moduli and γ_M=2.5-3.5 for strength properties. The latter values correspond to those inferred by Heyman (1997) for old masonry structures and to those adopted in the 20th century in the allowable stress design, till the adoption of the current limit state approach (Sanpaolesi, 2001). The application of these corrections in Eqs. (1) and (2) improves the compatibility between calculations and empirical values. In the same parametric analyses, the values of K currently assumed (Table 2) resulted also applicable to ancient structures.

Indeed, the empirical dimensioning rules for ordinary structural members (Table 1) seem to be inspired by the deformability rule, since this obtains thicker sections; vice versa that used for the secondary elements conforms to the strength approach, as it yields smaller sections. This can be confirmed by the comparison with old masonry buildings that can be found in Italy. Floor joists, which must bear the weight of the floor above, are more generously sized than roof rafters, which must sustain just the weight of the tiles and, occasionally, of the snow. However, in Northern Italy thin but squat joists are also found in floors, but with tighter spacing between them. In fact, the spacing influences the load on the joists and therefore this parameter may require a specific evaluation.

In mere structural terms, the choice between the two criteria, i.e. strength or deformability, depends on the total quantity of the material used, which may be expressed by its weight.

Table 2: Deformability limits for timber structures (AITC, 2012).

Use classification	K
	(live+dead lods)
Roof (without plaster ceiling)	180
Roof (with plaster ceiling)	240
Floor, ordinary	300-360

Table 3: Mechanical properties of solid softwood timber grown in Italy according to UNI (2010). Only those values of interest in the current work are reported.

Timber type	Bending strength (kg/cm^2)	Mean Elastic modulus (kg/cm^2)
C18	180	105000
C22	220	120000
C24	250	118000

Table 4: Reducing factors for solid timber mechanical properties according to CEN (2004): k_{mod} applies to any strength property and k_{def} to any elastic modulus.

Timber type	k_{mod}	k_{def}
Interior, non-heated	0.6	0.8
Exterior	0.5	2

However, in real applications, other considerations may contribute, e.g. the availability of materials, but this is not considered presently. Weight is proportional to the volume of timber, that is the number of joists along the support side of a floor's frame:

$$w = n\, b\, h \tag{3}$$

where

n = number of joists, defined as

$$n = L/i \tag{4}$$

L = length of the support side of the joist

i = joist spacing

b, h = the two sides of a joist's cross-section

in w, the third dimension L is constant among the joists, and therefore it is neglected. If joists are dimensioned according to Eq. (1), their weight w_{Str} can be expressed by combining Eqs. (1) and (3):

$$w_{Str} = L\, \xi\, [3rl^2 / (4\xi f_d)]^{2/3} / i^{1/3} \tag{5}$$

A similar expression may be obtained if Eq. (2) is used, yielding m_{Def}:

$$w_{Def} = L\, \xi\, [5Krl^3 / (32\xi E_d)]^{1/2} / i^{1/2} \tag{6}$$

where

r = superimposed load per unit of surface

and every other symbol has already been defined.

Joist spacing plays an important role in Eqs. (5) and (6). In Figure 5, the frame weight w (normalized to the respective total value) is plotted against joist spacing i: higher ordinates mean more timber and therefore a more expensive structural solution. At load values used in ordinary floors with the terrazzo finish (>200 kg/m²), the curve of the strength criterion (green line) intersects with that of deformability (red line) at i values somewhere between 40 and 60 cm. This means that the strength rule is more convenient for thigh spacing (<40 cm), and the opposite for larger intervals (>60 cm, Fig. 6). Lightly loaded joists have a squat section, but they can also be loosely spaced (Fig. 7).
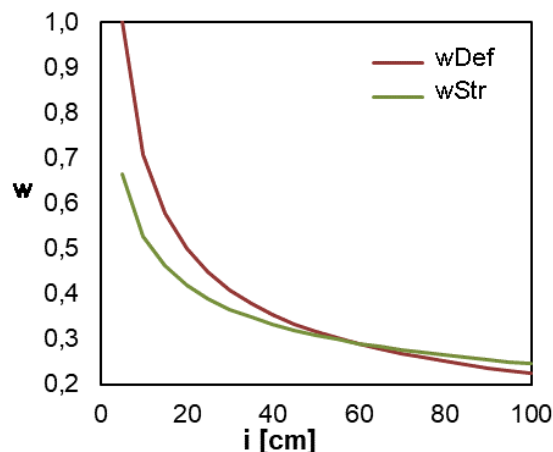
Figure 5: Graphical comparison of normalized 'weight' from strength w_{Str} (green line) and deformability criteria w_{Def} (red line) compared to joist spacing (i). They are obtained for R=300 kg/m², l=300 cm, L=400 cm and C22 timber.
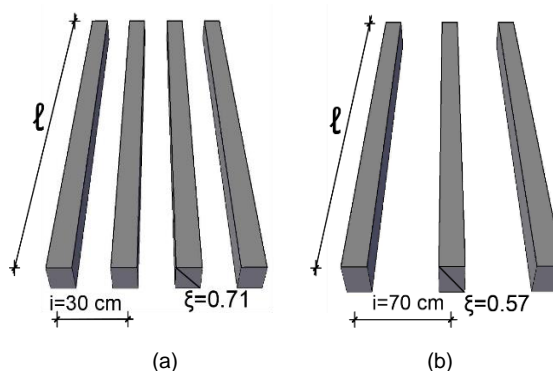
Figure 6: Cross-sections and aspect ratio ξ according to joists' spacing for the same load and span but different bay spacing: a) squat rectangular; b) slender rectangular.
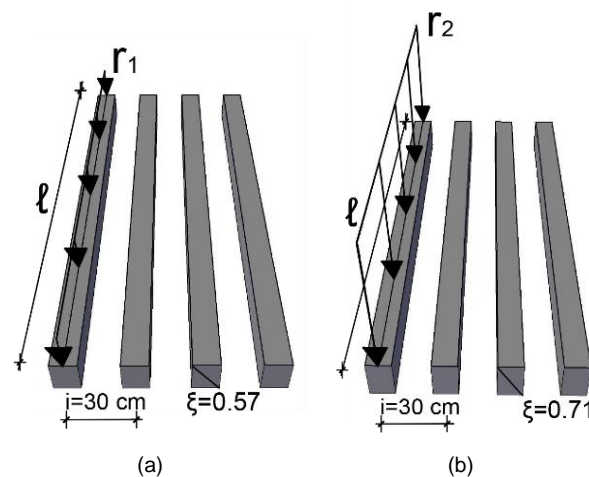
Figure 7: Cross-sections and aspect ratio ξ according to load on joists for the same span and bay spacing: a) squat rectangular (r_1=50 kg/m); b) slender rectangular (r_2=200 kg/m).

A parametrical study working on L, R and i values shows that for the strength criterion (Fig. 5):

- ordinates are smaller than those of the deformability rule at higher load values and smaller spacing;

- ordinates are always smaller than those of the deformability rule at light loads for every value of i.

This is empirically confirmed by the fact that in roofs and those floors finished with a simple wooden board (any joist spacing up to 100 cm) or floors with terrazzo and tightly spaced joists, squat sections are used; in floors whose beams are put at a larger distance (80-100 cm or more) and heavily loaded, slender rectangular cross-sections are adopted (Barbisan & Laner, 1997, 2000; Menichelli & Scappin, 2011); this was observed also in the *Villa dei Misteri* in Pompeii (De Martino et al., 2020). Differences in an owner's social status and usage of the structures may affect real applications as well: at the same strength, slender sections are stiffer but require a bigger log, i.e. more expensive, to be obtained than squat ones. Consequently, either squat rectangular or square sections are common in poor dwellings and in those parts of buildings where they are out of sight or lightly loaded, such as in roofs (Barbisan & Laner, 2000).

3. Parametrization of the analytical model

The sizing procedure, i.e. calculation of a joist's two possible cross-sections and the selection of that which minimizes its weight, was translated into an algorithm for Grasshopper 3D v. 1.0 (Rutten, 2021) plugin for Rhinoceros 3D modelling software (Rhino v. 6.0; McNeel; 2021). Grasshopper is a state-of-the-art piece of software for parametric modelling, i.e. the translation of a design procedure, either geometrical or structural, into a direct acyclic graph (DAG). This is a linear succession of 'components', doing finite operations/manipulations on geometrical objects or mathematical entities; loops are not allowed. Users interact visually with the code, as components appear as icons, which can be dragged and dropped on Grasshopper's working space ('canvas') and which can be connected by wires ('feeding').

Each component receives the results of a previous one and itself feeds one or more following according to the connections established. Inputs may be e.g. geometric objects in Rhino's 3D space, numbers, intervals, lists etc., representing different structural or architectural conditions. Outputs vary in real-time as input changes according to the flow of manipulations. Grasshopper framework, which manages primarily geometric manipulation and object creation, is completed by more specific sets of components, provided by third-party plugins. Plugins are often freely distributed[1], and they deal with several disciplines, among which there are structural and energy analyses; however, any user can develop its components by programming them. Plugins enable the evaluation of the reaction of discipline-specific parameters to changes in geometrical inputs in real-time and the execution of optimization and form-finding analyses based on this capability.

In the current work, structural analysis is powered by a Grasshopper plugin, called Karamba 3D v. 1.3.1 (Preisinger, 2021). This is an additional part of the modelling procedure previously described, which allows an additional control on the results. Thanks to its flexibility, Grasshopper offers a more workable

framework than the Visual Basic environment, in which the procedure described in Section 2 has already been coded (Sbrogiò, 2016). In addition to a more user-friendly interaction with the code, Grasshopper allows users to visualize its results in real-time, which helps in understanding problems and addressing their solutions. In general terms, the procedure was subdivided into three phases: a) input of geometrical data and parameters and display of results; b) calculation of outputs and display of results; c) structural analysis. The first part has in its turn a tripartite structure: a1) definition of a joist frame; a2) calculation of structural loads; a3) definition of materials. The results of the first phase are then fed into the components which calculate the joists' cross-sections according to the optimal criteria for the loading and geometrical conditions. Finally, geometrical objects in Rhino's 3D space (points, lines, surfaces) are transformed, through Karamba, into an analytical model (supports, beams, shells), which may be analysed from a structural point of view. Therefore, displacements, internal forces, nodal reactions, and stresses/strains in each element can be extracted and put into either a validation of results or the reconstruction of the overall archaeological building, comprising its masonry parts.

3.1. Input of data and parameters

3.1.1. Joist frame

The algorithm starts from a set of rectangles that describe each rooms' boundary. The flow of operations described in the following is repeated automatically by Grasshopper for each rectangle, once they have been defined as a 'branch' in the logical tree. The rectangles are exploded in individual segments to find the length and direction of each in the XY plane of Rhino: the shortest side determines both joist's span and direction. Segment lengths are put in ascending order and the shortest one is picked, and the algorithm decides whether it runs in the X or Y axis by decomposing its vector. Thus, boundary rectangles can be oblong in any of the two. Then joists' spacing along the longest side is inputted, to determine the total figure of joists (n). Finally, the boundary rectangles are 'meshed', i.e. subdivided, with no subdivisions in that direction of the shortest side and n subdivision in the other. A Grasshopper component allows selecting the internal edges of the meshed portion of the XY plane, which correspond to the individual joists.

3.1.2. Loads

Structural loads are divided into three load cases: 1) self-weight of structural elements; 2) dead loads; 3) live loads. The first is simply obtained by defining a gravity force field in the global Z-direction of Rhino's 3D space through a specific Grasshopper component. A 'load' component defines cases 2) and 3) as constant linear loads on beams. Their value depends on the load per unit of surface, respectively according to the floor's finish (wood planks, terrazzo, mosaic, etc.) and floor use (residential, roof, etc.), multiplied by joist spacing. Load entity is given by a drop-down list component, which offers a selection of the most common cases. The final value is obtained by a simple multiplication between this value and the bay length. Live and dead loads are merged into one list for each curve, as each room may have a different function/finish;

Gravity is pushed at the beginning of each list. Consequently, each rectangle/room has its own set of load cases. However, differently from the current structural analysis, there is no load combination as it would imply an additional safety level, which is not appropriate for ancient structures.

3.1.3. Definition of materials

The material definition is managed by a Karamba 3D component, since this is already a part of structural modelling. User-defined properties were assigned to a generic isotropic material, as this is a simplified model. A user can pick a timber type (e.g. one of those given in Table 1) from a drop-down list and the algorithm feds the required data into the component. They are already divided by the partial safety factors, which can be chosen within a pre-set range. In its current formulation, the procedure assumes just one material for the entire stock of boundary rectangles, but it may be worked to change it through the set according to the user's needs.

3.2. Outputs: joists' cross-sections

Joists' cross-sections depend on i) the geometrical features of the frame, i.e. its span and spacing as obtained in Section 2; ii) structural loads. Therefore, from a logical point of view, they follow the definition of loads. Thanks to an 'expression' component, it is possible to evaluate Eqs.(1) and (2), by completing them with the parametric values of ξ and K (see Section 2.1). Cross-sections are assumed to be already optimized concerning their aspect ratio, so in Eq.(1) ξ=0.71 and in Eq. (2) ξ=0.57 are used; users however are allowed to change the pre-set values by picking them from a drop-down list. The results of calculations (deformability and strength) are merged, in order to grow as many lists as boundary curves are. Each list contains two values, according to each criterion. Then, a 'weight' parameter is obtained by multiplying the cross-section area by the number of joists in each frame. Finally, the algorithm picks that joist's height which corresponds to the minimum 'weight' value.

3.3. Structural analysis

The 'Assemble model' component transforms the geometrical model so defined into an analytical one, that is, which can be calculated. It is fed by:

- The endpoints of the mesh lines represent joists, which are transformed into the frames' supports by a specific component.
- The elements, i.e. the mesh lines, are changed into 'beams' by a specific component.
- The three load cases merged into one stream.
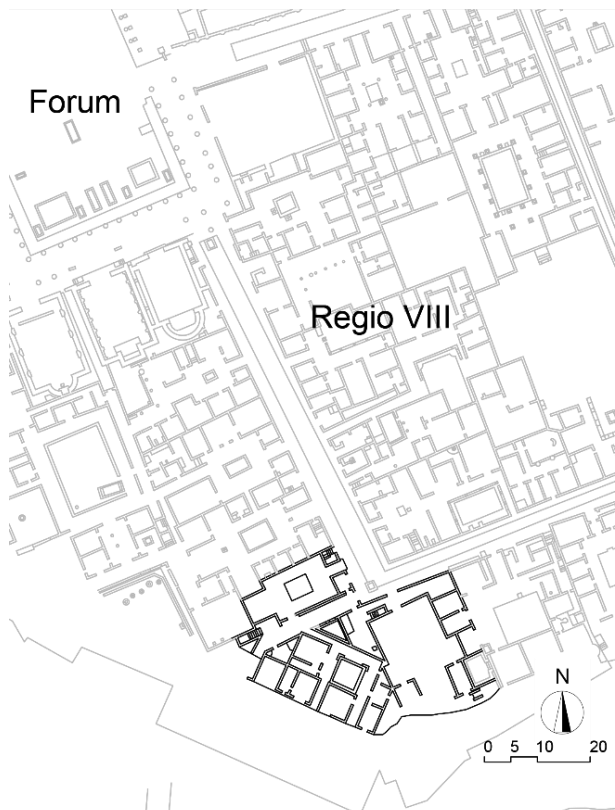- The cross-sections.
- The material.

The resulting 'model' is then fed into an analysis component which yields the structural data of interests (displacements, nodal reactions, section forces, etc.). The algorithm does not consider the structural coupling between joists and the superimposed planks, which may be simulated through a shear connection between the beams and a shell. Indeed, no information is available

on such a subject in existing archaeological remains and, to stay on the safe side, in the dimensioning procedure it is better to exclude such collaboration. As a result, timbers are considered simply supported at both ends.

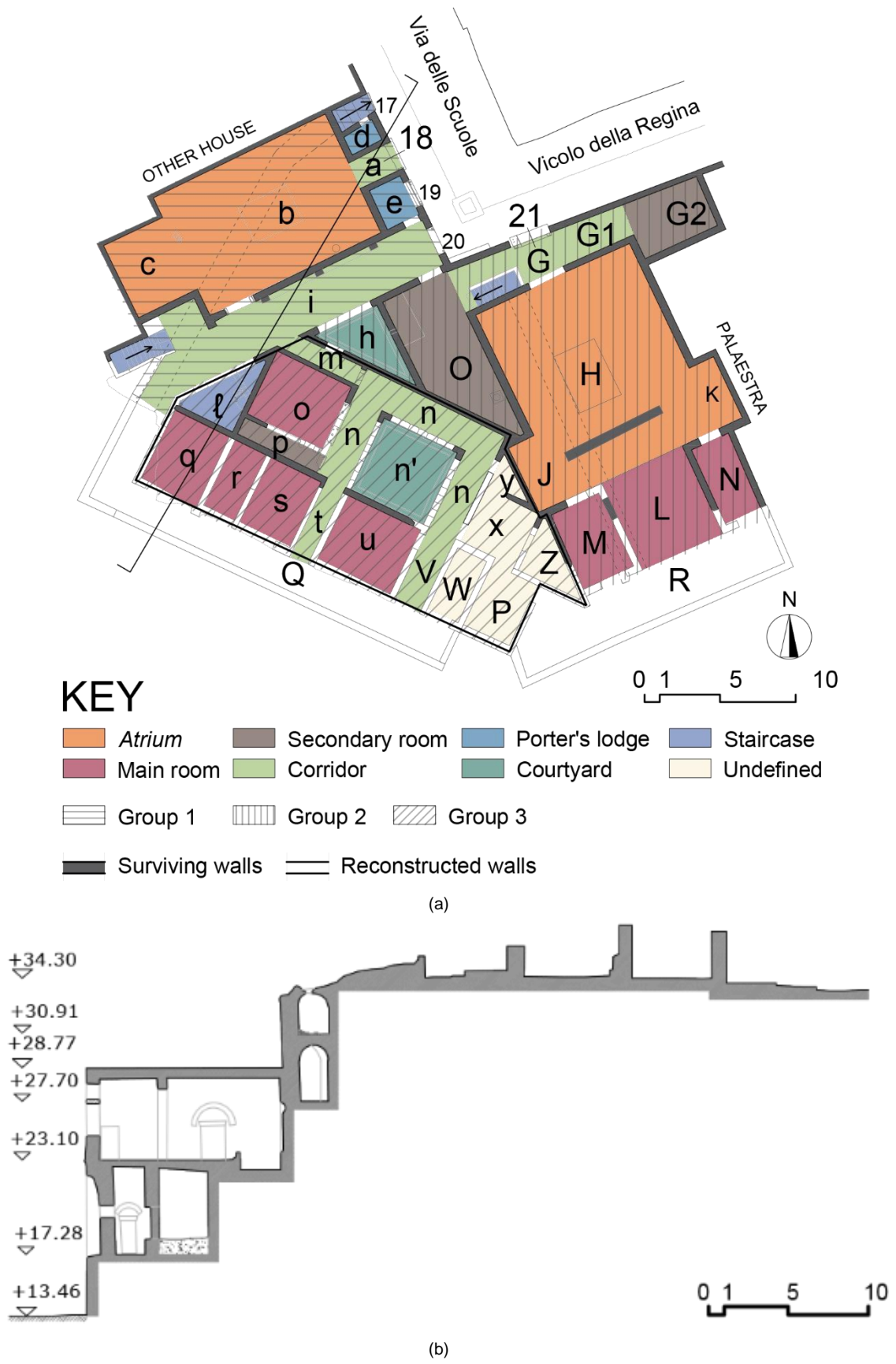## 4. Application: the *domus* on top of the Sarno Baths, Pompeii

The Sarno Baths are placed in *Regio VIII, Insula 2,* at the corner formed by *Vicolo delle Scuole* and *Vicolo della Regina* (Fig. 8). A thorough assessment of the Baths' history, architecture and structures was carried out during the MAHC Project (Multidisciplinary methodological Approaches to the knowledge, conservation, valorisation of Cultural Heritage) led by an interdisciplinary workgroup of experts from the University of Padova (Artioli, Ghedini, Modena, Bonetto, & Busana, 2019). The Sarno Baths are a complex system of dwellings, public baths and their service rooms, which developed for five storeys below the ancient Pompeii's ground level (Fig. 9b), against its ancient cliff. The compound looked towards the ancient seashore and served as a foundation for a large *domus* at the topmost level (Fig. 9a).

The complete reconstruction of the volume of the dwelling can be found in Bernardi et al. (2019), and with higher detail in Centola (2018); therefore, in the following, just that part of the compound is discussed, where it was possible to apply the procedure described in Sections 2 and 3.

Figure 8*: Location of the Sarno Baths complex in Pompeii's Regio VIII (adapted from Morichi, Paone, Sampaolo, & Kockel, 2018).

(a)

(b)

Figure 9: The *domus* on top of the Sarno Baths: a) plan and hypothesized functional layout; b) cross-section of the entire complex, showing the Baths and other rooms below the *domus* with elevations a.s.l. at each storey. In the plan, the thick line delimits the footprint of the portion considered in the reconstruction of the floors (cf. Figs. 11-13).

4.1. Description

Among the dwellings of the complex (Bernardi et al., 2019), that above the Baths comprises three groups of rooms (Fig. 9a), which focus each on a different open space: (a) Tuscanic *atrium*, (b) a peristyle (n'), and another *atrium* (H). The entrance at number 18 from *Vicolo delle Scuole*, surrounded by rooms too tight to be more than a porter's lodge (d, e), leads into the traditional system of *fauces* (a), *atrium* and *tablinum* (c) (group #1). The same happens past the entrance at no. 21, where the *atrium* (H) has its *alae* (J, K) but not the *fauces*, transformed into a corridor (G, G1). The atrium is concluded by a *tablinum* (L), surrounded by two rooms (N, M), only partially preserved. These rooms probably looked toward the sea through a terrace (R), whose profile has been hypothesized from the remains of the Baths below (Centola, 2018) (group #2). The last group of rooms (#3) gathers in the corner between the two *atria* and it follows a diagonal axis. Its layout (referred to as the 'house' in the following), differs from the *atrium-tablinum* scheme, since it depends on a wall in the middle with rooms on its two sides: northern, the peristyle (n'), its portico (n), an exedra (o) and circulation spaces (l, m, p); southern an 'enfilade' of rooms (q, r, s, u), two corridors (t, V) and probably a terrace (Q) above the cisterns of the Baths. The irregular spaces between this 'house' and the two *atria* (h, y, z) were probably left uncovered, although evident traces of a perimetral ditch can be found only in space (h). Spaces (P, x, W, Z) are a proposal by Bernardi et al. (2019) based on the feeble traces left; room (O) has been interpreted as the kitchen of the entire complex. The house had a second storey since in the room (ℓ), the first stone steps of a staircase survive. The other staircases visible in Figure 9 lead to the lower floors of the Baths.

Today one can only guess the distinction between those spaces which were private and those which were public inside the dwelling, since they were intermingled, or decide whether private parts had just one or more owners (Bernardi et al., 2019; Bernardi & Busana, 2019). Presuming that the whole dwelling made just one compound, the two *atria* (groups #1, 2) survived as reception halls and the house (#3) between them hosted the living quarters. The passageways (i) and (G1, G2) served to the general public to reach the other apartments and the Baths below through the staircases.

The superstructures of the house, which are the object of this work, disappeared in the eruption. However, since the surviving walls are generally less than 2 m high, there was no direct archaeological evidence to support the reconstruction process, i.e. the sockets left by joists in walls (Fig. 10).

4.2. Reconstruction of floor frames

4.2.1. Archaeological data and hypotheses

The reproduction procedure described in Section 2 and Section 3 is tailored for simple floor frames and therefore it cannot be applied to the two *atria* (b) and (H) (Fig. 9a) and their ancillary spaces, supposing that they followed the roofing system described by Vitruvius (D.A., 6,3). Based on those schemes and a simplified analytical evaluation (Sbrogiò, 2016), the first reconstruction of their timber structures was proposed by Centola (2018) and an overview of the built volume can be found in

Figure 10: View of the *domus* on top of the Sarno Baths in its current conditions. The picture is taken westward from the entrance of corridor 'i', group #3 is on the left.

Bernardi et al. (2019). As a result, in this work, just the house (group #3, delimited by a thick line in Fig. 9) was taken into account. The only archaeological inputs available are the room sizes and wall thicknesses, as well as the overall architectural layout. Those spaces which were recognized as uncovered, i.e. the peristyle (n') and the irregular triangular spaces (h, y and Z) interpreted as courtyards, were discarded from the interpreting phase. It is worth noting that these courtyards would have been discarded also owing to their shape, which cannot be fitted by the automatic procedure. Room (ℓ) was left partially empty, as the staircase would have interrupted the regular framing of its floor, in addition to its triangular plan. The floor framed a rectangular portion of this room, almost as wide as corridor (p), and served as a landing from the staircase below and probably as a closet, given the presence of a large vertical pipe in the corner of the room Bernardi et al (2019). Overall, the algorithm applied to a set of 15 boundary rectangles (in blue in Fig. 11) with different aspect ratios and orientations: eight delimited actual 'rooms' while the rest described corridors and passageways. Joist frames were automatically oriented according to their shortest side, however, the frame that covers room (u) might have been turned by 90° to match those of the other southern rooms; the fact that the room has an almost square plan would allow such an operation. An overall parametric choice is the height of the portico around the peristyle (n). The central courtyard is obviously discarded, but it is considered surrounded by a two-storey portico according to one of the possible circulation systems for the upper floor proposed by Bernardi et al. (2019). As a result, its beams are calculated as floor joists, but they could have been roof rafters, if the portico had had just one storey. In the latter case, they would be thinner ad more loosely spaced than those calculated with the current procedure. Local parameters are those on which joists' cross-section depends, i.e. loads and spacing. A common joist spacing of 45 cm was applied to every frame as a first guess; this was recognized as a sensible average value based on Centola's (2018) observations in Herculaneum and the observations by Ulrich (1996) in Pompeian shops.

Floor finishes determined the superimposed dead loads on floors, but their nature may be argued from the economic means and, lastly, the social status of the

ancient owner. However, during the MACH campaign, no certainty could be inferred on this subject from archaeological and documentary analyses (Bernardi et al., 2019; Bernardi & Busana, 2019). From the fine paintings found in the Baths (Salvadori, Boschetti, Baronio, & Sbrolli, 2019) and the analogy with other houses, built on that which was Pompeii's cliff towards the seashore (Zanker, 1993), one may hypothesize an upper social level of the dwelling. Consequently, the hypothesized floor finish was a concrete floor slab weighing about 1500 kg/m^3; with a slab about 20 cm thick: the resulting superimposed load is 300 kg/m^2. Finally, live loads were assumed to 150 kg/m^2, according to a generic residential usage of the upper rooms, with light furniture (Mazzocchi, 1871). Loads are distributed on the joists according to their spacing as described in Section 3.1.2. The deflection limit was assumed as 1/300 of the structural span, as a generic floor structure. The structural material considered was a low-grade softwood timber (C22, see Table 3) with partial safety factors γ_E=3 on elastic modulus and γ_f=6 on the bending strength.

4.2.2. Results and discussion

The resulting system of joist frames is shown in Figure 11; walls are omitted since their calculation trespass the limits of this communication. For each joist, the code executes the structural analysis, obtaining e.g. displacements (Fig. 12) or section forces (Fig. 13), which may be used for the revision of the proposal. The single framed floors followed the building tradition of the Campanian towns and the proposed superimposed load was intermediate to the values given by Ulrich (1996). The structural joists' span ranges between 1.6 m in corridors to 4.9 m in the *tablinum* (Table 5) so the single

frame hypothesis should be confirmed in each room. Joist cross-sections vary according to the span, which influences the load on them, as the spacing and the superimposed loads are both constant in this reconstruction. As a result, squat sections are obtained in narrower rooms, such as corridors (m, p, t) and slender sections in larger spaces (e.g. o, u Table 5); this conforms to the studies carried out by Centola (2018) and Ulrich (1996); Adam (1990) reported similar slender cross-sections but without any reference to the span, therefore this latter values could not be compared to those calculated. In general, the ratio between the sides may be imprecise if compared to the 'theoretical' ones (Section 2), but this results from rounding off the results to centimetres. Moreover, for spans narrower than 2 m, the obtained cross-sections may represent a 'structural minimum', as Centola's (2018) observations never reported joist thickness below 10 cm. The calculated deformation (Fig. 12) ranges between 0.40 and 1.70 cm, which exceed the deformability limits assumed only in narrow rooms, where the strength criterion was chosen; these values of deformation can be easily observed in old timber structures.
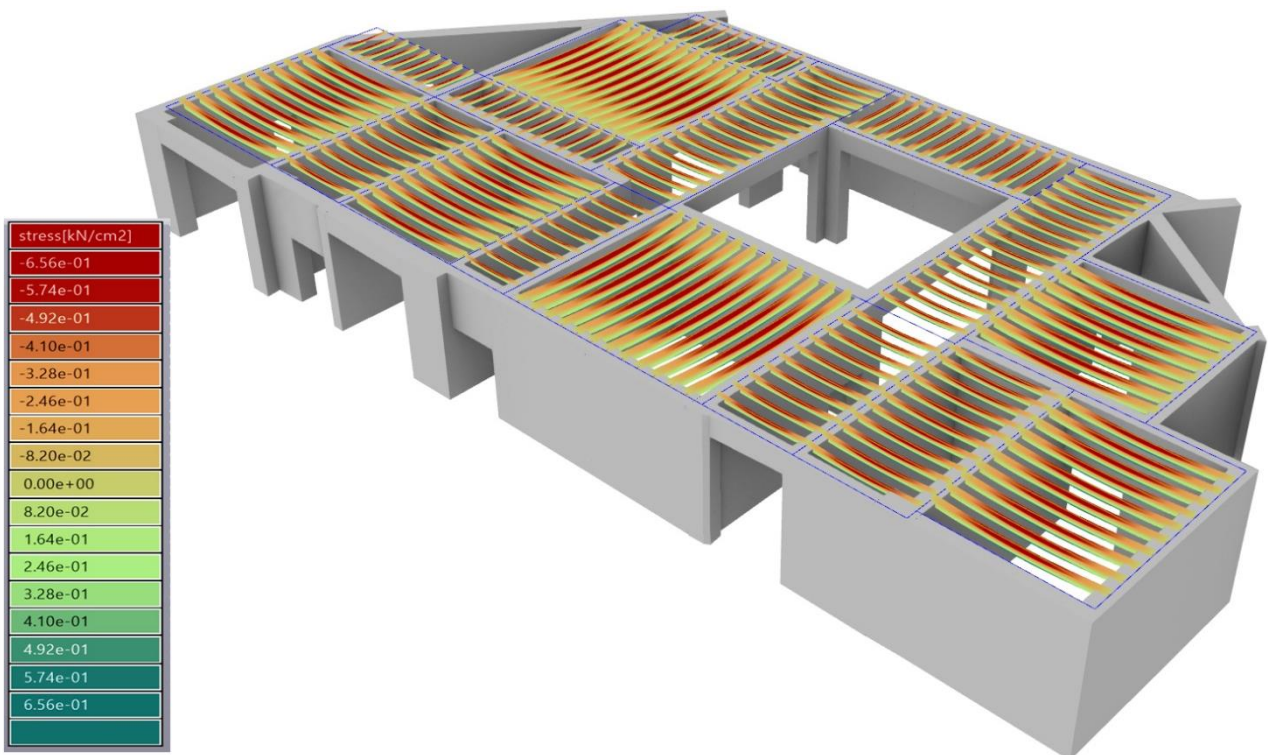
Finally, Karamba 3D plots the utilization ratio (Fig. 13) referred to the 'design' bending strength, i.e. divided by the partial safety factor (see Section 4.2.1), and therefore the high values read in the scale are just an artefact of the software, as they should be divided by 6. Large safety factors were also observed by De Martino et al. (2020). However, joist bending strength is exceeded neither in beams dimensioned on strength nor in those dimensioned based on deformability. The height-to-span ratio ranges between 1/18 and 1/20 for the widest spans, as it was prescribed by construction manuals and observed in Pompeii (Centola, 2018).
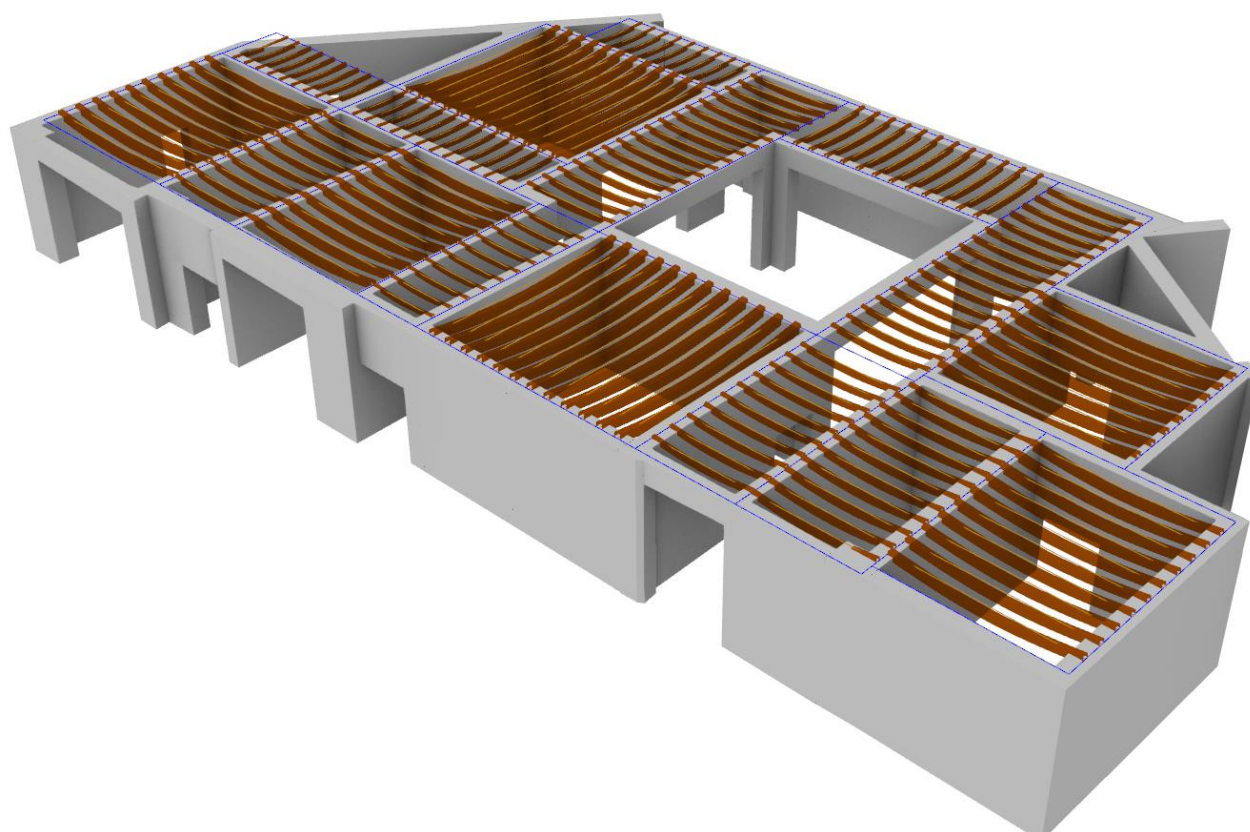
Figure 11: View of joist frames parametrically defined on the portion of the *domus* under study (compare Fig. 9). Bounding rectangles of the rooms are shown in blue; the elevation of the walls is for display purposes only.
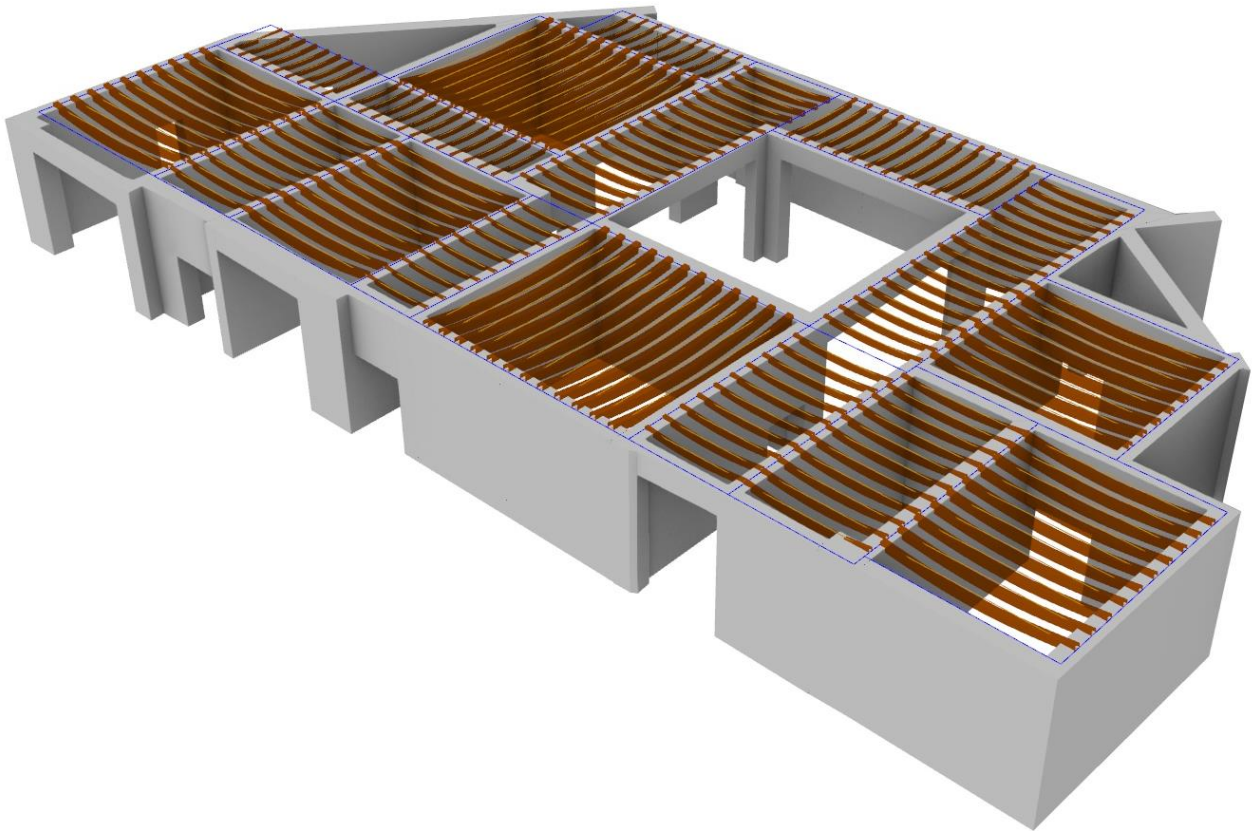
Figure 12: Joist deformations (10x real ones). The bounding rectangles of the rooms are shown in blue.

stress[kN/cm2]
-6.56e-01
-5.74e-01
-4.92e-01
-4.10e-01
-3.28e-01
-2.46e-01
-1.64e-01
-8.20e-02
0.00e+00
8.20e-02
1.64e-01
2.46e-01
3.28e-01
4.10e-01
4.92e-01
5.74e-01
6.56e-01

Figure 13: Joist utilization ratio. The bounding rectangles of the rooms are shown in blue.

Table 5: Features of calculated joist frames per each room: cross sections' heights and bases, height to span ratios, deflections.

Room	Span (m)	b (cm)	h (cm)	Deformation at midspan (cm)
l	164	9	12	0.41
m	164	9	12	0.41
n1	258	12	16	0.80
n2	250	11	16	0.76
n3	228	11	15	0.65
o	493	16	27	1.66
p	164	9	12	0.41
P	367	13	22	1.52
q	451	15	25	1.54
r	266	10	17	0.89
s	392	13	23	1.31
t	175	9	13	0.42
u	493	16	27	1.66
V	229	9	15	0.79
W	264	10	17	0.88
x	421	14	24	1.42

5. Conclusions

In the virtual reconstruction of ancient houses floors and roofs are probably the most uncertain parts, but they play an important role in the definition of the built volume. The paper proposes a methodology for the reconstruction of floor frames of ancient houses, following the criteria that might have applied in Pompeii and Herculaneum prior to the eruption of 79 CE. These Roman towns are privileged sources of information, but they can also stand as validation for theoretical approaches. To that end, an interdisciplinary approach is required to hierarchically organize pieces of information coming from multiple sources (e.g. the archaeological site itself, ancient treatises, hypotheses and analogies, etc.) which contribute to the desired output, i.e. the cross-section of floor joists. Two possible relationships between inputs and outputs were found, based respectively on the strength and deformability of beams. A parametrical study of these mathematical expressions, compared to empirical data coming from Herculaneum and Pompeii, shows that in ancient times:

- The deformability criterion was applied to ordinary floors with high superimposed loads (>400 kg/m^2) and loose spacing of joists (>50 cm).
- The strength criterion was applied in ordinary floors with high superimposed loads (>400 kg/m^2) and tight spacing of joists (≤50 cm) or in roofs and floors with low superimposed loads (<200 kg/m^2) and any spacing distance.
- Empirical design procedures are already considered a safety factor on mechanical properties ranging between 2 and 4.

In addition to these procedural results, case-specific ones were obtained. In fact, the methodological approach was translated into a parametric model, in Grasshopper for Rhino, which was applied to a sector of the Domus on top of the Sarno Baths in Pompeii's Regio VIII. Once a set of 15 boundary rectangles, representing the Domus' rooms, was defined, the algorithm obtained:

- The joists' cross-sections, according to the dimensioning rule that allowed their minimum weight.
- The joists' sagging at midspan.
- The joists' bending moment and stresses along their length.

The results obtained showed good compatibility with actual measures taken on surviving beams in Pompeii and Herculaneum by previous studies. In this work, just cross-sections were the relevant results, as structural quantities were useful in evaluating the general sensibility of the solution.

Further development of this procedure is required to:

- extend it to roof structures, i.e. considering the roof slope;
- include Vitruvius' atrium system;
- locally improve the overall reconstruction, e.g. by adjusting the spacing between joists.

Finally, a more specific evaluation of masonry walls (thickness and type) may suggest a different disposition of floor frames than that here presented.

Acknowledgements

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