Andalusian Timber Roof Structure in Chefchaouen, Northern Morocco: Construction Technique and Structural Behavior

Original Citation:

Andalusian Timber Roof Structure in Chefchaouen, Northern Morocco: Construction Technique and Structural Behavior / Galassi, Stefano; Dipasquale, Letizia; Ruggieri, Nicola; Tempesta, Giacomo. - In: JOURNAL OF ARCHITECTURAL ENGINEERING. - ISSN 1076-0431. - ELETTRONICO. - 24(2018), pp. 1-17. [10.1061/(ASCE)AE.1943-5568.0000315]

Availability:

This version is available at: 2158/1128132 since: 2021-04-07T11:48:22Z

Published version:

DOI: 10.1061/(ASCE)AE.1943-5568.0000315

ASCE Author Proofs

Important Notice to Authors

Attached is a PDF proof of your forthcoming article in **Journal of Architectural Engineering**. The manuscript ID number is **AEENG-730**.

No further publication processing will occur until we receive your response to this proof. Please return any corrections within 48 hours of receiving the download email. Your paper will be published in its final form upon receipt of these corrections. You will have no further opportunities to review your proof or to request changes after this stage.

Information and Instructions

- The graphics in your proof have been down-sampled to produce a more manageable file size and generally represent the online presentation. Higher resolution versions will appear in print.
- Proofread your article carefully, as responsibility for detecting errors lies with the author.
- Mark or cite all corrections on your proof copy only.
- Corrections should be sent within 48 hours after receipt of this message.
- If no errors are detected, **you are still required to inform us that the paper is okay** to be published as is.
- You will receive a message confirming receipt of your corrections within 48 hours.

Color Figures

Figures containing color will usually appear in color in the online journal. All figures will be grayscale in the printed journal unless you have agreed to pay the color figure surcharge and the relevant figure caption indicates “(Color)”. For figures that will be in color online but grayscale in print, please ensure that the text and captions do not describe the figures using the colors of the online version.

If you have indicated that you will be printing color figures in color (or choosing Open Access), you will receive an email from ASCE Author Services with a link to the publication fee payment system. Until payment is received, your article will not be published.

Reprints

If you would like to order reprints of your article, please visit http://www.asce.org/reprints.

Questions and Comments to Address

The red numbers in the margins correspond to queries listed on the last page of your proof. Please address each of these queries when responding with your proof corrections.

Return your Proof Corrections

- Web: If you accessed this proof online, follow the instructions on the Web page to submit corrections.
- E-mail: Send corrections to ASCE.Production@cenveo.com. Include the manuscript ID **AEENG-730** in the subject line.

ASCE Open Access

Authors may choose to publish their papers through ASCE Open Access, making the paper freely available to all readers via the ASCE Library website. ASCE Open Access papers will be published under the Creative Commons-Attribution Only (CC-BY) License. The fee for this service is $1,750, and must be paid prior to publication. If you indicate Yes, you will receive a follow-up message with payment instructions. If you indicate No, your paper will be published in the typical subscribed-access section of the Journal.

Selecting Yes does not commit you to publishing your article as Open Access. You will have the option to cancel the Open Access process later. If you are unsure, we recommend selecting Yes. If you select No now, your paper will be published online shortly after your proof corrections are received, and you will no longer have the ability to publish your article as Open Access.

If you have indicated that you will be choosing Open Access, (or printing color figures in color), you will receive an email from ASCE Author Services with a link to the publication fee payment system. Until payment is received, your article will not be published.

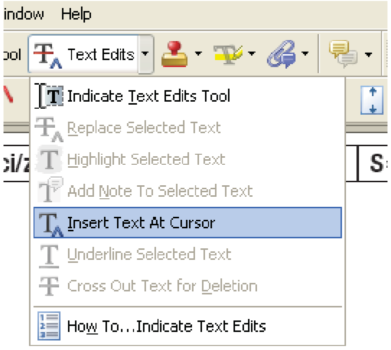
Adding Comments and Notes to Your PDF

To facilitate electronic transmittal of corrections, we encourage authors to use the comments and notes features in Adobe Acrobat or the free Adobe Reader software (see note below regarding acceptable versions). The PDF provided has been "comment-enabled," which allows you to use the text editing and annotation features.

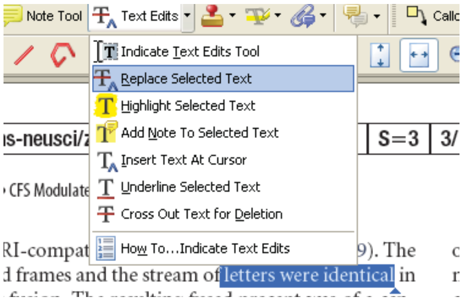
When you open your PDF in **Adobe Acrobat**, the comments/notes/edit tools are shown on the top tool bars (icons may differ slightly among versions from what is shown below). The important features to know are the following:

Use the **Text Edits** tool (Text Edits ▾) to insert, replace, or delete text.

- To **insert text**, place your cursor at a point in the text and select "Insert Text at Cursor" from the text edits menu. Type your additional text in the pop-up box.



- To **replace text**, highlight the text to be changed, select "Replace Selected text" from the text edit menu, and type the new text in the pop-up box.



- To **delete text**, highlight the text to be deleted and select "Cross Out Text for Deletion" from the text edits menus (see graphic above).

Use the Sticky Note tool (Note Tool) to describe changes that need to be made (e.g., changes in bold, italics, or capitalization use; altering or replacing a figure; general comments) or to answer a question or approve a change that was posed by the editor. Beware that comment bubbles can shift. They are not recommended as a primary text editing tool.

Use the **Callout tool** (Callout Tool) to point directly to changes that need to be made. Try to put the callout box in an area of white space so that you do not obscure the text, as in the example below:

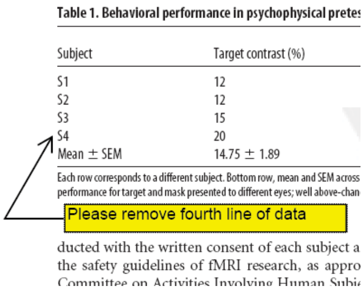


Table 1. Behavioral performance in psychophysical pretes

Subject	Target contrast (%)
S1	12
S2	12
S3	15
S4	20
Mean ± SEM	14.75 ± 1.89

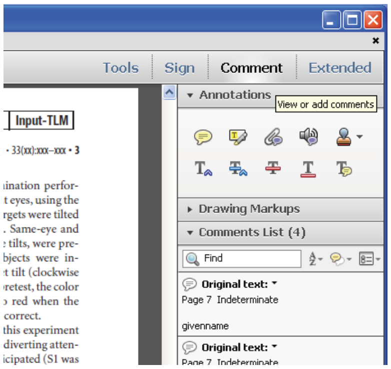
Each row corresponds to a different subject. Bottom row, mean and SEM across performance for target and mask presented to different eyes; well above-chan

Please remove fourth line of data

ducted with the written consent of each subject a the safety guidelines of fMRI research, as appro Committee on Activities Involving Human Subj

- Use the **Highlight tool** ( ) to indicate font problems, bad breaks, and other textual inconsistencies. You can describe the problem with the Callout tool (above), a sticky note, or by double clicking highlighted text (a pop-up window will appear where you can add your comment).

To access the annotation tools in the free **<u>Adobe Reader</u>** software, select the “view” menu and then “Comment” as shown below. You can also access the text edit tools in Adobe Reader through the “View” menu.



<u>Note:</u> To use the comments/notes features on this PDF you will need Adobe Reader version 10 or higher. This program is freely available and can be downloaded from http://get.adobe.com/reader/.

Andalusian Timber Roof Structure in Chefchaouen, Northern Morocco: Construction Technique and Structural Behavior

Stefano Galassi[1]; Letizia Dipasquale[2]; Nicola Ruggieri[3]; and Giacomo Tempesta[4]

Abstract: This article presents the results of an investigation on the building system of the Andalusian timber roof, which is widespread in northern Morocco. The structural behavior of the Andalusian timber roof structures surveyed in the medina of Chefchaouen is analyzed in depth. The analysis, carried out using finite-element models, allowed for assessment of the structural behavior of the structure but also highlighted some weaknesses that are inherent to this building system. These weaknesses are primarily due to the presence of unilateral connection elements that ensure efficiency only under specific stress conditions and also to the lack of efficiency of the connection between load-bearing elements of the roof and the surrounding walls. The detected horizontal displacement of supports explains the cracking pattern that is usually visible at the top of walls just under the level of the gutter. A parametric analysis was performed, revealing that the weaknesses of the system do not present specific criticalities in the geographic context in which the system is developed. Nevertheless, some crucial strengthening interventions are proven to be necessary for esuring that all timber elements can suitably contribute to the overall equilibrium of the structure in the case of an earthquake. **DOI: 10.1061/(ASCE)AE.1943-5568.0000315.** *© 2018 American Society of Civil Engineers.*

Author keywords: Andalusian roof; Vernacular timber roof; Timber roof–masonry interaction; Règlement de construction parasismique RPS2000; Strengthening interventions; Seismic vulnerability assessment.

Introduction

Due to its refined and complex distinctive traits, noticeable in the geometric features of the structural elements, their organization, and the solutions adopted for the nodes, the Andalusian-type collar roof, widespread in the medina of Chefchaouen, has been the object of research, of both a historical and technological nature, and of surveys aimed at defining its construction traits (Dipasquale and Volpi 2009; Tampone 2001).

Important in-depth analysis was also carried out regarding the mechanical features of the walls of the buildings in which the Andalusian collar roof system is generally used (Rovero and Fratini 2013).

Rovero and Fratini (2013) identified three masonry types in the medina of Chefchaouen: MT1, MT2, and MT3. Type MT1 is a stone masonry made of hard limestone blocks, roughly hewn and irregular in shape. Some stone blocks running through the wall for approximately two-thirds of the thickness allow a certain transversal connection. Type MT2 is a three-headed load-bearing brick masonry with usual block sizes of $21 \times 10 \times 2.5$ cm or $22 \times 10 \times 3$ cm, and the cross section of the wall is approximately 35 cm thick. Type MT3 is a mixed stone and brick masonry with a core of fine filling material and mortar in the wall section. With the aim of regularizing the wall structure and providing a connection between the internal and the external wall fabric, rows of bricks placed every 60–80 cm are generally present. In all masonry types, blocks are bound with a lime–earth mortar, executed by mixing a part of lime binder and a part of clay. The compressive strength of this mortar was evaluated to be approximately 25 $\mathrm{N/mm^2}$. Lastly, walls are protected by plaster, usually of earth and lime, and painted in a thousand shades of indigo. This practice demonstrates the concern for ensuring maintenance and adequate protection of the earthy mixture against rain, without which the whole masonry system would be subjected to decay.

In this study, numerical investigations were carried out to deepen the knowledge of the overall structural behavior of the constructive typology of the Andalusian timber roof. The analyses both highlighted some inherent critical elements due to the adopted technological solutions and allowed the assessment of its vulnerabilities, not only regarding gravitational loads but also with respect to seismic actions (Parisi et al. 2011; Parisi and Chesi 2014; Ruggieri et al. 2018). The results allow for the provision of targeted solutions for conservation and safeguard.

The medina of Chefchaouen, situated in the north of Morocco, was founded by the Andalusian Arabs in 1471, who chose to build a fortified city in a strategic position to defend the region from the Portuguese invasion, not far from the source of the Ras el Maâ River. Chefchaouen had its greatest period of development in the sixteenth and seventeenth centuries as a result of the fall of the kingdom of Granada in Spain (1492), which caused the incoming of large numbers of Arab Andalusian refugees who settled in this area, attracted by the fertility of the land and its strategic position (Dipasquale et al. 2008).

It is precisely due to the influence of the Spanish Andalusian culture, and to the fortunate integration with local Berber and Islamic

---

[1] Dept. of Architecture, Section of Materials and Structures, Univ. of Florence, Piazza Brunelleschi, 6, Florence 50121, Italy (corresponding author). ORCID: https://orcid.org/0000-0003-2341-8031. Email: stefano.galassi@unifi.it

[2] Dept. of Architecture, Section of Industrial Design, Univ. of Florence, Via della Mattonaia, 8, Florence 50122, Italy. Email: letizia.dipasquale@unifi.it

[3] Parco Archeologico di Pompei, Via Villa dei Misteri, 2, Pompei 80045, Italy. Email: nicola.ruggieri@beniculturali.it

[4] Dept. of Architecture Section of Materials and Structures, Univ. of Florence, Piazza Brunelleschi, 6, Florence 50121, Italy. Email: giacomo.tempesta@unifi.it

Note. This manuscript was submitted on July 31, 2017; approved on January 30, 2018; published online on [redacted]. Discussion period open until [redacted]; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Architectural Engineering***, © ASCE, ISSN 1076-0431.

traditions, that the medina of Chefchaouen efficiently represents the process of development of an architectural and urban culture with original and particularly significant traits.

The most recurrent traditional roofs in the medina of Chefchaouen are of the double-pitched type. These roofs, as can be deduced from observation, in-field surveys, and interviews with local master builders (*maâlem*), are classifiable into two structural categories: the Berber structure and the Andalusian structure.

The former (Fig. 1) is the simplest and also the oldest one. The ridge beam is supported by a bearing structure composed of very close sloping rafters. The pitch slope is between 30 and 40%. In the case of wide spans to be covered (more than 5 m), the Berber system is aided by additional elements, namely, two principal rafters joined to a horizontal beam. The king post is directly joined to the tie-beam, constituting a not-beneficial concentrated load for the tense element. Hence, this configuration makes the static behavior of this constructive typology ineffective, which indeed always shows very deformed structural elements. The behavior of the Berber structure is currently under analysis, and the results of the investigation will be provided in a following paper.

The Andalusian structure is more complex and interesting from the constructive point of view; it uses well-squared and often finely decorated wooden elements (Dipasquale and Volpi 2009). The most widely used wood species in Chefchaouen, all from local sources, are cedar (*Ærz*), fir (*soha*), and red fir (*sanawbar*). Whereas cedar is often used for decorations, fir and red fir are mainly used to build roof structures.

A key element in Moorish architecture, the Andalusian roof is a recurrent building system in central and southern Spain (Anderson and Rosser-Owen 2007), where it is called *armadura de par y nudillo*, meaning a structure of rafters (*pares*) and collar beams (*nudillos*). During the period of Arab domination (711–1492), this region was known as Al-Andalus and received architectural and artistic influence from the Muslim culture and from the North African Berbers and the classical Roman tradition already present in Andalusia. In this area, it is still possible to find examples of *armadura de par y nudillo*, especially in religious buildings converted into churches and in noble palaces (Nuere 1989; Candelas Gutiérrez 2003). In the medina of Chefchaouen, the Andalusian-type wooden structure was imported by the Andalusian master builders who settled there and was widely used—with substantial modifications regarding the constructive technique mostly used in Spain, which are not noticeable at first sight—for the roofs of the rooms of the courtyard house and the bays of mosques. A very similar structural organization is also emphasized in many church roofs in the Sicily region (Copani 2006). An eminent example is the Nicosia cathedral (Catania) that dates back to the fifteenth century and derived from the Arab domination (ninth to eleventh centuries) and consequent constructive culture influence on the Sicily region (Tampone 2005).

The article is organized as follows: The constructive system of the Andalusian timber roof structure is described in the second section, and a fundamental comparison between the Moroccan and the Spanish Andalusian version is also provided. The third section is devoted to the reference case study of an ancient courtyard house in the medina of Chefchaouen, in which the structure type under analysis is found. The role of each timber element is investigated, and the structural behavior is assessed. In the same section, the results of the analyses, which highlight some inherent weaknesses of this type of structure, are summarized. The results explain and are coherent with the external cracking pattern detected. The fourth section deals with the seismic behavior assessment of the structure, taking into account, as a reference, the provisions in the local regulations. The final section presents concluding remarks.

Construction Analysis

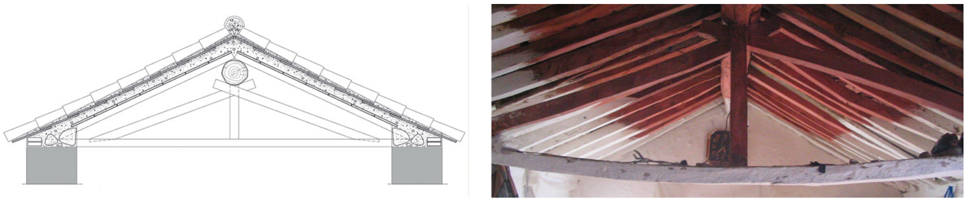
The structure of the Andalusian-type roof is constituted by a single-frame double-pitched roof, made with the use of coupled rafters placed with a slope of approximately 85% and oriented in accordance with the shorter side of the room to be covered. The span varies from 3 to 4 m, in courtyard houses, up to 7 m, in the case of mosques.

The coupled rafters are counterposed and connected at the ridge with the use of a plank, which is particularly useful during the phase of setting the structure with the aim of maintaining the spacing established for placing the other elements. Therefore, the roof carpentry work does not include an actual ridge beam. Every coupled rafter includes a transversal connection timber element (collar beam) with a section of 5–7 by 10 to 15 cm and a length of approximately 60 to 65 cm, whose far ends are adequately shaped and carved so as to provide suitable support for the connecting joints (Fig. 2).

The collar beams, placed in the upper part of the structure at a distance from the ridge of about one-fifth of the rafters' length, support wooden planks that, with their thickness, are wedged into the grooves carved in the rafters. In that same spot, additional planks completing the connecting system are placed, orthogonally arranged to the roof surface and wedged into the corresponding grooves in the collar beams [Figs. 3(a and c)].

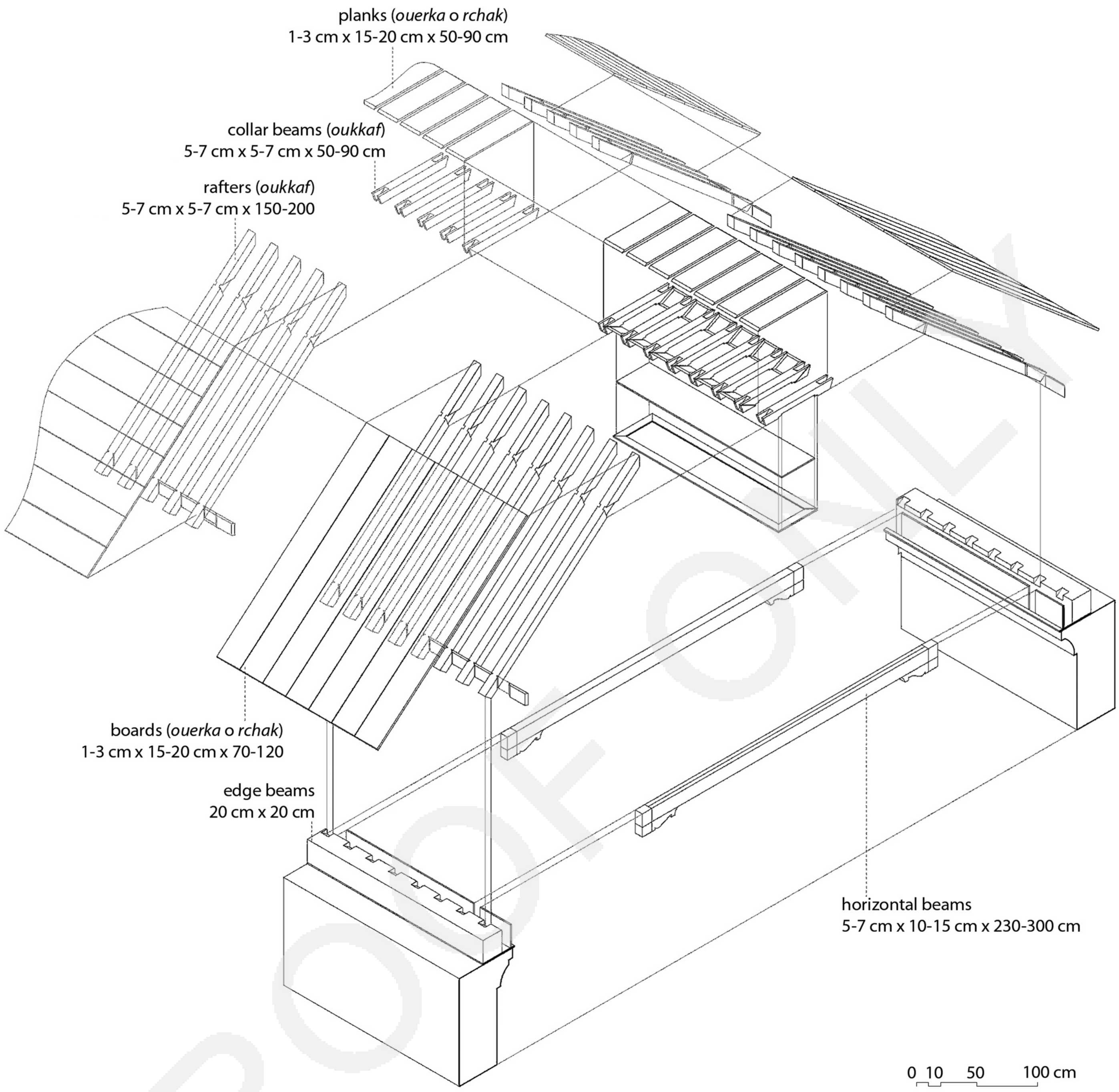
The central part of the roof presents an additional set of boards at the lower edge of the collar beams, wedged to the collar beams and nailed to the boards [Fig. 3(b)]. The ensemble of these elements constitutes the *bsat* (Dipasquale and Volpi 2009).

From the geometric and constructive features of the joint between the collar beam and the rafter, it can be noticed how that device provides only a unilateral connection, capable of transferring compression forces but inefficient if subjected to tensile forces [Figs. 3(b and c)]. In the constructive technique of the aforementioned structural system, the boards that constitute the external deck of the roof, which are directly nailed to the rafters, assure a good overall stiffness and, at the same time, nullify the tendency to stack the individual structural units, preserving the spacing between them unchanged (Tampone and Ruggieri 2016).


(a) (b)

F1 : 1

Fig. 1. (a) Sectional elevation; (b) Berber roof structure (image by Letizia Dipasquale).



F2 : 1

Fig. 2. Exploded view drawing of the Andalusian-style roof: Procedure of assembly of the elements.

The bases of each couple of rafters are connected to two edge beams with the rectangular cross section, placed at the top of the longitudinal walls, which provide support for the roof structure and allow a good distribution of the actions transmitted on the masonry walls. The connection between the main elements of the roof and the edge beams is obtained through a half-lap joint, that is, a cavity hollowed out on the upper corner of the edge beams, which holds the head of the rafter [Fig. 3(d)]. The edge beam thus has a square and beveled section alternately. The general carpentry elements are presented in Table 1.

With the purpose of providing the roof deck for both pitches, wooden boards are nailed to the upper edge of a couple of rafters, arranged transversally to the room at the center and longitudinally at the ends (Fig. 2).

The deck provides support for the screed and for the roofing tiles. The screed, with a thickness between 5 and 12 cm, is constituted by a mix of earth, lime, pebbles, and fragments of bricks. The curved tiles (which are made of a mix of clay, sand, straw, and organic elements, molded by hand and baked in traditional wood ovens) are placed in two superposed inverted layers directly on it. Fig. 4 shows the covering and the arrangement of the tiles to provide two typical gutter systems, the simple and the protruding gutter. These systems are aimed at directing the rainwater away from the masonry walls and preserving the earth mortar and plaster.

Additional horizontal beams (Fig. 5) are often placed at the level of the edge beams, with a rectangular cross section of approximately 7 by 15 cm, arranged transversally to the room without a structural connection with the edge beams, and are thus unable to

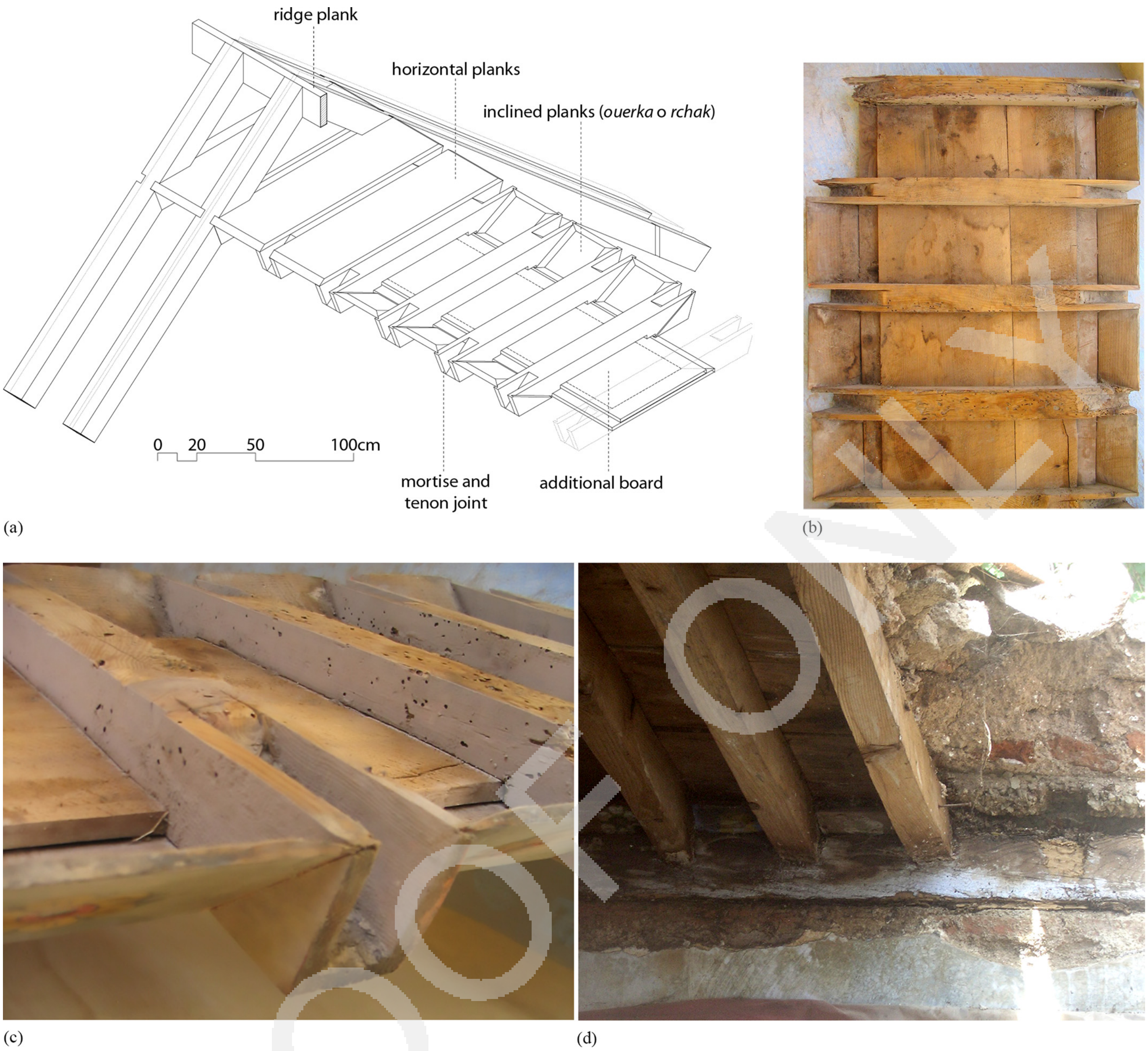
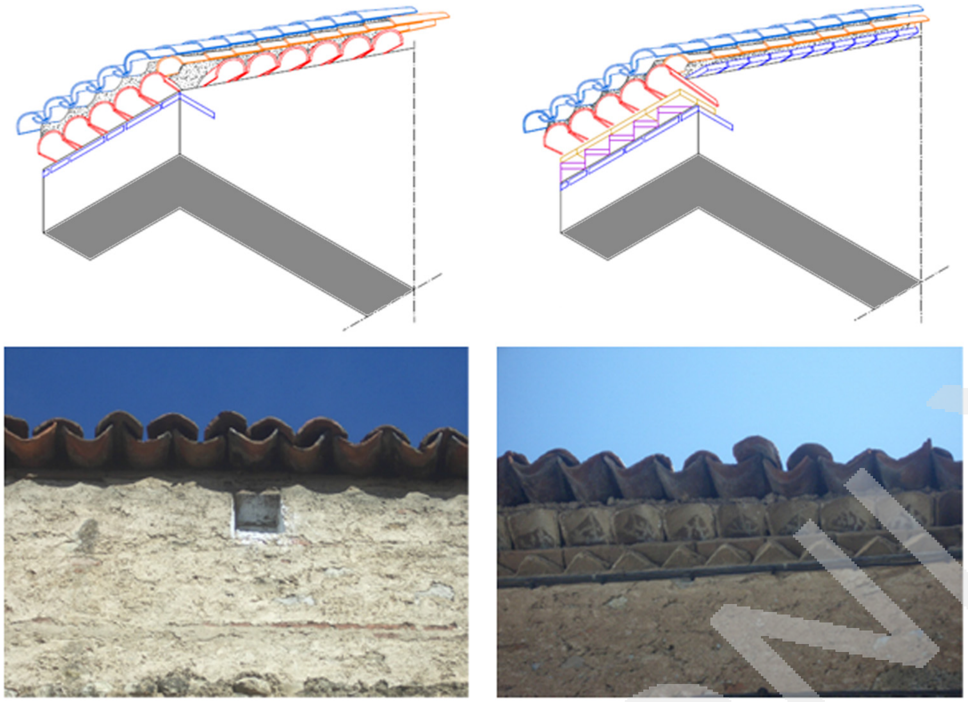


Fig. 3. (a) Schematic representation of the longitudinal connection of the structural system's coupled rafters–collar beam with the use of inclined and horizontal planks placed into grooves carved on the heads of the collar beam and in the tenons on the rafters; (b) set of boards at the lower edge of the collar beams; (c) detail of the mortise joint on the collar beams; (d) detail of the node between rafter and edge beam. [Images (b–d) by Letizia Dipasquale.]

Table 1. Dimensions of the carpentry elements

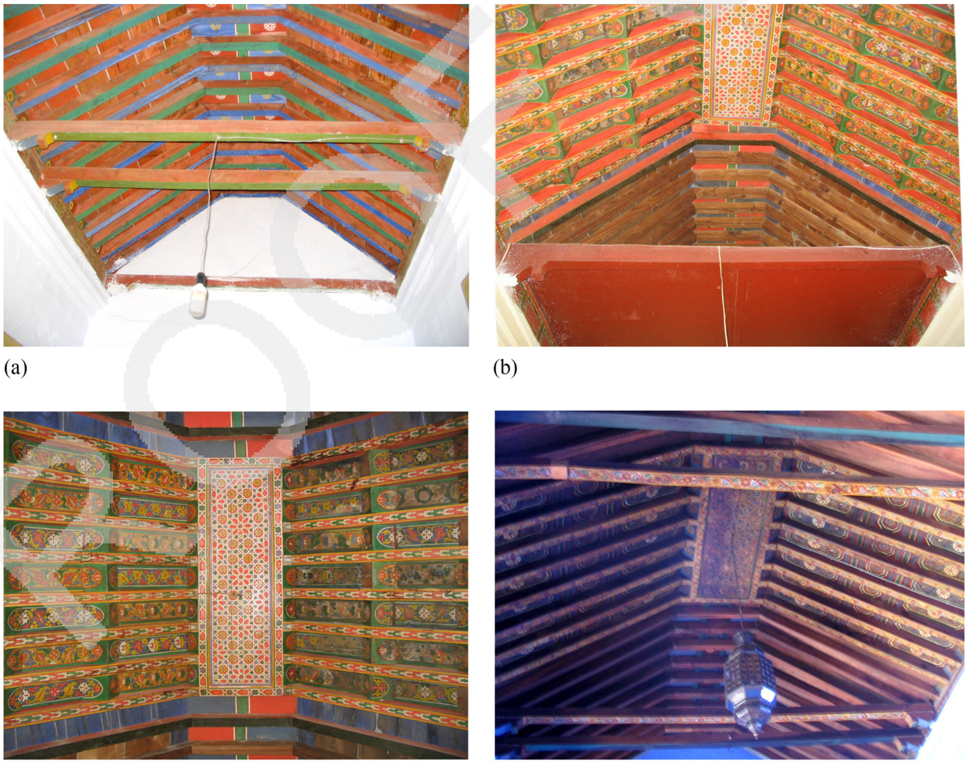
Wooden elements	Size (cm by cm)
Rafter (*Oukkaf*)	5–7 by 5–7
Collar beam	5–7 by 10–15
Ridge plank	4–5 by 10–12
Planks	1–3 by 15–20

provide contribution to bear the thrust from the roof structure, unlike a traditional king post roof truss or the *par y nudillo* timber roof in Spain, from which the Moroccan version was derived. In fact, in the Spanish Andalusian system (Nuere 1989), the transversal beams can behave as tie-beams, given their U-shaped grooves where the longitudinal edge beams are placed, forming a crosslap joint (compare Figs. 2 and 5 with Fig. 6). Instead, in the Moroccan version, the transversal beams do not work as actual ties because the connection with the edge beams is not sufficient to assure such a role because the link, which is not present in all cases, is made of simple metal brackets or nails with a wooden corbel. Considering this node geometry, although a pair of nails is usually present, the connection cannot transfer the tensile force from the transversal beams to the edge beams. These beams, usually placed in couples [Figs. 5(a and d)], with a variable spacing, usually alternate, of approximately 1.30 and 0.45 m, have only the function of providing support for a possible attic, usually used as a storeroom or garret [Fig. 5(b)]. With the aim of reducing the span of these beams and providing a suitable end support, the walls include a series of bricks that protrude approximately 15 cm, with the addition of the aforementioned wooden corbel.



(a) (b)

F4 : 1 **Fig. 4.** Gutter systems: (a) simple gutter; (b) protruding gutter. (Images by Letizia Dipasquale.)



(a) (b) (c) (d)

F5 : 1 F5 : 2 **Fig. 5.** Internal view of an Andalusian-type roof with floral and arabesque decorations: (a) without mezzanine attic; (b) with mezzanine attic; (c) details of the colored decorations; (d) details of the transversal beams. (Images by Letizia Dipasquale.)

The system is characterized by great simplicity of execution. In fact, retracing the main construction phases, first the edge beams are placed on the side walls, then each pair of rafters is erected and placed together with the transversal connecting element. The base of the rafters is joined to the edge beams by way of the notch carved into the edge beams themselves, without nails. The next pair could

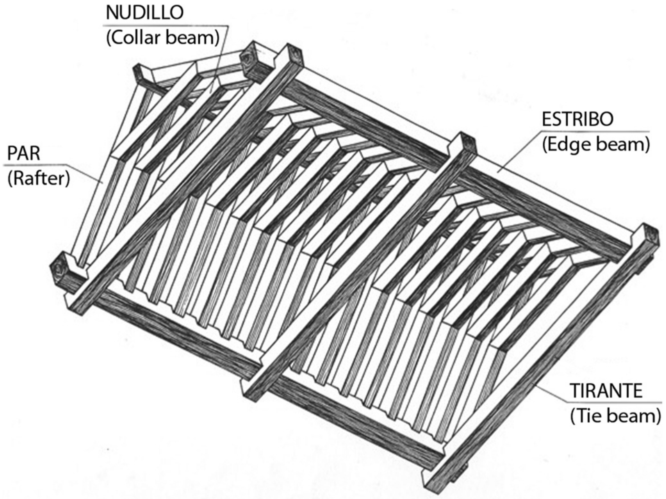


Fig. 6. Andalusian-type roof in Spain (with tie-beam elements) known as *armadura de par y nudillo*.

be placed after the insertion of both the inclined and horizontal planks, which connect them to the previous pair. The spacing between the rafters, very reduced (between 10 and 20 cm), corresponds approximately to double their width. The building procedure just described is very similar to a sort of modern prefabrication system. The site was always headed by a *maâlem* (i.e., master builder), who had an excellent knowledge of geometry and was capable of drawing and representing, by in-scale models, the structure of the roof to be built. It was the *maâlem* himself who established the dimension and spacing of the elements, based on the size of the room and the slope of the roof.

The inner surface of the Andalusian-style roof is often painted with geometric, floral, and arabesque patterns and framed by additional wooden planks [Figs. 5(b–d)].

Case Study

With the purpose of assessing the safety of the structural system used in the configuration of the Andalusian roof and in attempt to highlight its vulnerabilities (Cruz et al. 2015), both inherent and deriving from possible seismic events, a series of numerical simulations was carried out with the finite-element method (FEM) software Straus7. The reference case study of the Raissouni *dar* was examined, which is the oldest courtyard house in the medina of Chefchaouen. Built by the founder of the city, Moulay Ali Ben Rachid, the house underwent several transformations throughout the years, and today the building represents an example in which the constructive solutions adopted are among the most refined, technologically more advanced and structurally more correct. In particular, the roof analyzed is that of the *ghorfa* (bedroom), the common space in which the family nucleus spends most of its domestic life.

Dimensions of both masonry walls and roof timber elements were ascertained by on-site inspections during surveys. The covered room is an 8.60 × 2.90 m rectangular space with 0.35-m-thick walls in stone and bricks set in a mortar of mixed lime and earth.

The load-bearing structure of the roof, arranged according to the typical Andalusian configuration, is constituted by the usual sequence of counterposed couples of rafters set with a slope of 72.5% (approximately 40°) and placed with a spacing of 0.215 m (Fig. 7).

The mechanical and dimensional characteristics of the elements that form the structure, assumed in the numerical models, are presented in Table 2 and Fig. 7. Because experimental data were not available for the mechanical features, reference was made to conventional values from the standard UNI 11035–3:2010 (UNI 2010). These values, and in particular the specific weight, coincide with those provided by Eurocode 1 (CEN 2002) relative to the timber strength class C18 reported in the standard UNI EN 338:2009 (UNI 2009), which are obtained for timber at a moisture content consistent with a temperature of 20°C and a relative humidity of 65%. Such values were assumed in this study because they are coherent with the typical Mediterranean climate of Chefchaouen, characterized by high humidity and quite high temperatures (the mean temperature is equal to approximately 17°C).

In the structural model, the transversal beams that provide support for the attic deck were considered due to the effective lack of connection with the edge beams of the roof detected.

Table 3 shows the incidence of self-weight loads acting on each rafter, listed both per unit area and as load uniformly distributed on the axis of the element.

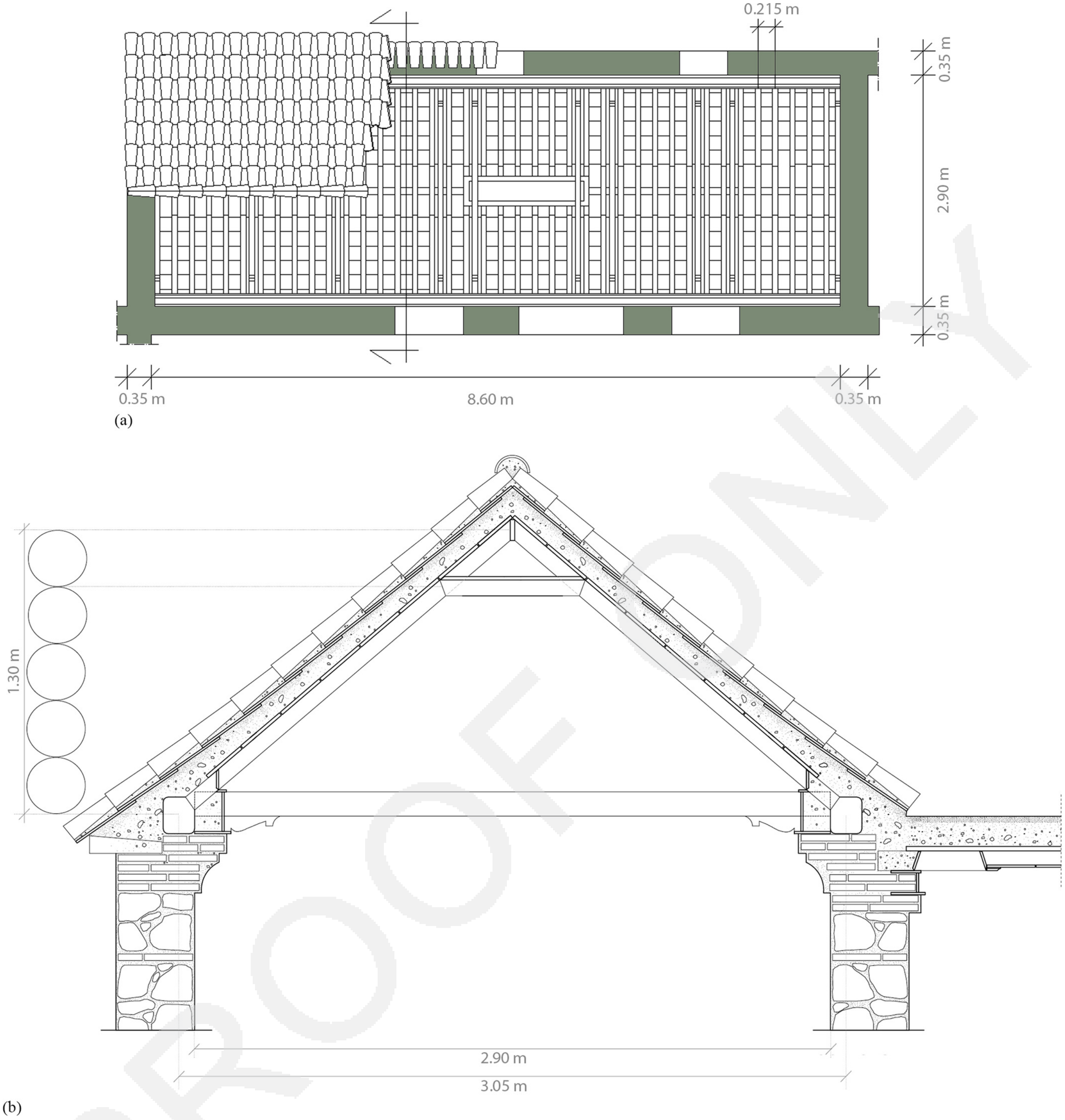
Structural Behavior Assessment of the Timber Elements

Because the roof structure is generated by a repetitive elemental frame, composed of a couple of sloping rafters and the collar beam, a fundamental investigation to detect the exact function of each timber element was carried out by the analysis of very simple two-dimensional (2D) models. Three configurations of this model were conceived, where only the external supports were changed. All geometric and dimensional features of the elements were preserved, as were the rafter-to-rafter and rafter-to-collar beam links, assumed as internal hinges. The collar beam was considered as a truss, capable of transmitting the axial load but also subjected to the bending moment due to its self-weight.

Through direct site inspections, it was ascertained that the roof system is simply supported on the room walls, by means of the edge beams, without fasteners. Based on this observation, a first model was conceived (Model FEM_1) as supported on a roller and a pinned support, respectively. As expected, in this model the collar beam is necessarily subjected to a tensile force, taking the role of the lacking tie-beam at the base of the system. However, it is not coherent with the technological solution adopted in the tenon and mortise joints between the collar beam and the coupled rafters (Parisi and Piazza 2000); therefore, the boundary conditions of this model cannot effectively describe the behavior of the actual structure. In Fig. 8, the results of the analysis are shown; specifically, it is worth noting the following:

1. The structure transfers to the walls an exclusively vertical action equal to 0.73 kN.
2. The tensile force in the collar beam, equal to 2.07 kN, is certainly not negligible.
3. The very high horizontal displacement of the roller support equal to 4.40 cm directed toward the exterior of the room, which is also lowered by the chain effect of the collar beam according to the assumed hypotheses of this model, actually would detach the collar beam from the couple of rafters and transform the structural system into a collapse mechanism due to the spreading of the two pitches.

Therefore, from the considerations summarized in the previous list, it can be easily deducted that the structure was originally intended by the Moroccan master builders (*maâlem*) as a statically indeterminate system whose supports on the walls work as two pinned joints. Furthermore, because the two supports of the roof to the walls are of the same type, it should not be correct to assume



F7 : 1

Fig. 7. *Ghorfa* roof structure in the Raissouni *dar*: (a) plan; (b) transverse section.

Table 2. Mechanical and dimensional characteristics assumed for the timber elements of the roof structure

FIR elements	Size (cm by cm)	Specific weight ($\text{kN}\cdot\text{m}^3$)	Elastic modulus (N/mm^2)	Flexural strength (N/mm^2)
Ridge plank	5 by 10	3.8	7,200	28
Rafter	6.5 by 7.2			
Collar beam	6.5 by 7.2			
Edge beam	14.5 by 16.5			

Source: Data from CEN (2002); UNI (2009, 2010).

Table 3. Self-weight load acting on each rafter

Roof floor	Description	Thickness (cm)	Incidence of load per unit area (kN·m^2)	Uniformly distributed load (kN·m)
Deck planking	Wooden boards	1.5	0.057	0.012
Screed	Mix of earth, lime, pebbles, and fragments of bricks	8	0.96	0.21
Covering tiles	Mix of clay, sand, straw, and organic elements, molded by hand	—	0.6	0.13

one as a hinge and the other as a roller. Accordingly, a second model (FEM_2) was made that considers these supports (Fig. 9).

The analysis of this second model underlined that the collar beam behaves as a strut under a compression force equal to 0.75 kN, in agreement with the technological solution adopted for building the joint under study, and that the structure transfers to the walls a horizontal thrust equal to 0.59 kN and a vertical action of 0.73 kN.

Furthermore, the stress state of the structural elements was found to vary in a very reduced range, between −1.33 and +1.22 N/mm^2, values that are much lower than the limit values of the fir wood. The most stressed areas were detected at the midspan of the rafter and near the joint with the collar beam. The maximum vertical displacement, detected at the midspan of each rafter, was equal to 0.05 cm, a value that is much lower than the limit value (0.53 cm, i.e., 1/300 of the span). Therefore, in this model the strength and serviceability verifications are also satisfied.

According to the results just presented, the behavior of the second model could match the actual behavior of the real structure. However, it is necessary to note that the thrust provoked by the rafters on the masonry walls must rely only on the friction reaction that is produced in the timber–masonry interface, between the edge beam and the wall, due to the lack of the tie-beam at the base of the roof system.

A shear-sliding verification was, therefore, carried out at the timber–masonry interface. The criterion of Coulomb's friction cone was adopted, and the value of the static coefficient of friction was taken from the technical literature.

Because the value of the actual friction coefficient was not available, reference was made to values from the technical literature, which range from 0.4 to 0.7 (Du Bois 1902; Mastrodicasa 1948; Murase 1984; Blau 1996; Grigoriev and Meĭlikhov 1997; Elert 2017; Gorst et al. 2003; Lee et al. 2005). The highest value of 0.7 was chosen as the reference value to assess if the roof structure had the propensity to slip on the walls already in the optimal condition due to the highest friction reaction.

The computed shear force (i.e., the horizontal thrust transmitted by the structure of the roof to the wall), equal to 0.59 kN, is slightly higher than the maximum value of the friction reaction that the beam-wall joint can exert ($f \cdot N = 0.7 \times 0.73 = 0.51$ kN). Therefore, this condition would highlight the propensity of the structure to suffer a horizontal displacement exactly in correspondence to the edge beam.

To deepen this phenomenon, an additional analysis was carried out in a further model (FEM_3), simulating the presence of a horizontal inelastic displacement at the level of the edge beams.

The third model (Fig. 10) was analyzed using a step-by-step procedure of increasing inelastic displacements applied to the external supports (Galassi et al. 2013; Orlando et al. 2016). The process was interrupted at the step in which the axial load in the collar beam became positive (traction) and, therefore, incompatible with the actual performance of the element. The results of this parametric analysis are presented in Table 4. The values reported in Table 4 are also graphically represented in Fig. 11.

The diagrams presented in Fig. 11 highlight that, for a value of the inelastic displacement equal to 0.30 cm for both supports, the horizontal thrust transmitted by the structure on the edge beam is exactly equal to the friction reaction, which ensures the equilibrium of the system. This means that, in correspondence to that value, the sliding of the edge beam toward the exterior stops, and the structure finds a new equilibrated configuration.

The last displacement considered in the parametric analysis (approximately 0.6 mm), at which the axial load in the collar beam changes sign, corresponds to the collapse of the structure, which transforms into a mechanism. The ultimate displacement detected is twice the displacement at which the thrust on the wall is balanced by the friction force. This highlights considerable safety in the case of gravitational loads.

Discussion of Results and Strengthening Interventions

The timber roof structure of the Raissouni *dar* represents a case study that is sufficiently representative of the Andalusian-type roof in Morocco.

The numerical analyses carried out highlighted the structural behavior of the timber structure in which a significant role is played by the collar beam that connects, in proximity of the ridge of the roof, the two counterposed rafters that form the covering surface. It was ascertained that, given the peculiar tenon and mortise joint, the horizontal beam must behave as a strut and contributes, on the one hand, to containing the flexural deformation of the roof and, on the other, confers a higher degree of safety to the efficiency of the hinge-joint between the two rafters near the cusp, especially in the presence of nonsymmetrical actions.

In detail, it was proven that the Moroccan-type Andalusian roof system shows a general structural consistency and a sufficient level of safety in the case of gravitational loads, even if the structure is in a state of unstable equilibrium ensured only by the friction between the edge beam and the masonry.

The main reasons can be listed as follows:

- The spacing between the rafters is moderate (21.5 cm).
- The high slope of the roof pitch and, therefore, of the elements that constitute the load-bearing structure (over 70%), together with the low incidence of the dead loads as a result of the moderate spacing between the rafters, determines a very low horizontal thrust on the wall.
- Given its location in Morocco, variable loads cannot reach significant values; snow, for example, is not a possible load condition. Thus, any increase over time in the stress on the load-bearing timber elements and of the thrust on the walls is not possible.

However, negative characteristics of the roof affecting the safety for gravitational loads and meaningful critical elements are identified as follows:

- The approximately 8- to 10-cm-thick screed over the planks is an extremely heavy load, but its distribution on each element does not reach very high values thanks to the reduced spacing.
- The tenon and mortise joint between the collar beam and the timber elements of the pitch acts as a unilateral connection.
- There is a lack of an actual ridge beam.
- The edge beams are simply supported on the masonry walls without fasteners.

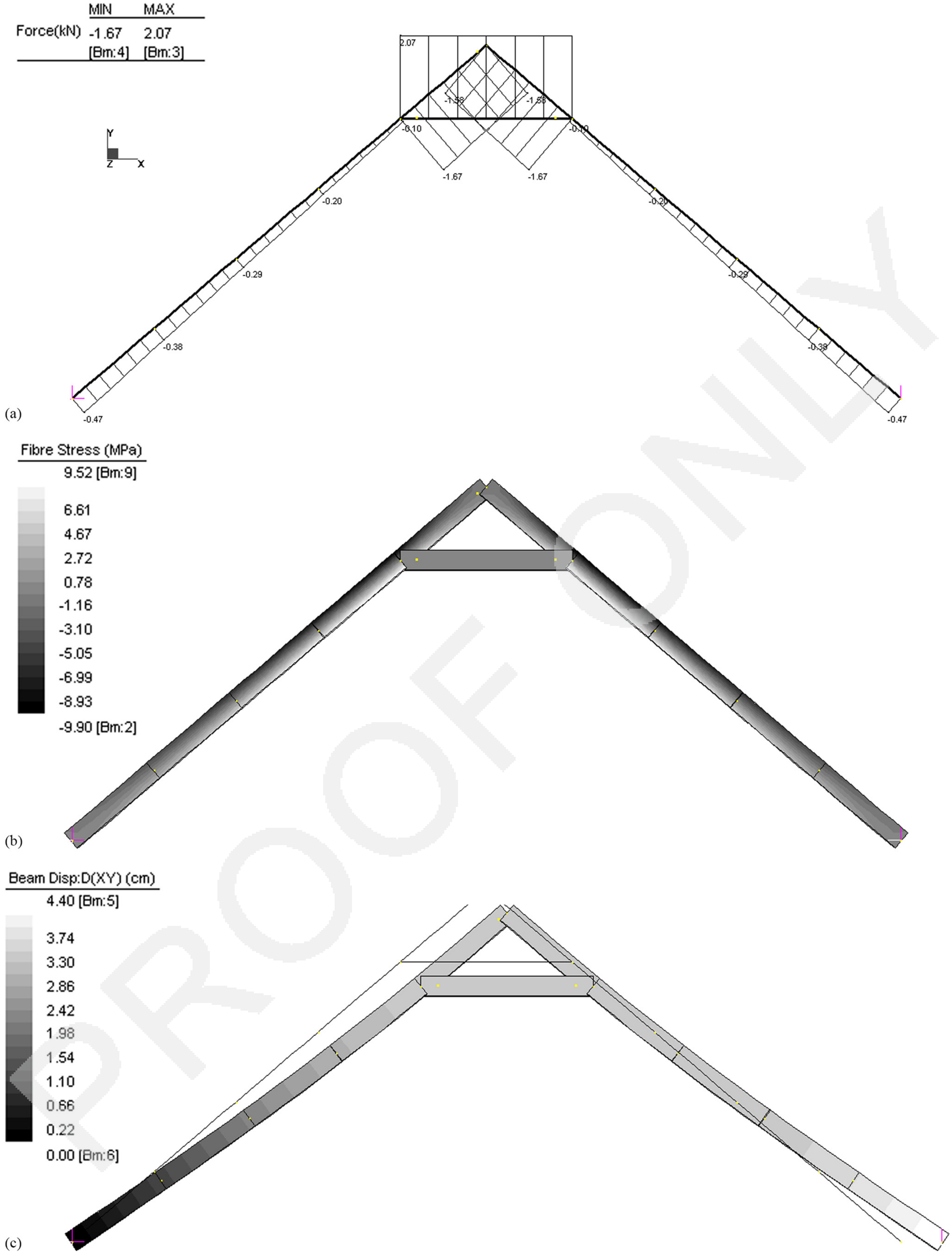


Fig. 8. FEM_1 Model—statically determined structure joined to the walls by a pinned and a roller support: (a) axial load; (b) stress state; (c) horizontal and vertical node displacements.

Fig. 9. FEM_2 Model—statically indeterminate structure joined to the walls with pinned supports: (a) axial load; (b) stress state; (c) horizontal and vertical node displacements.

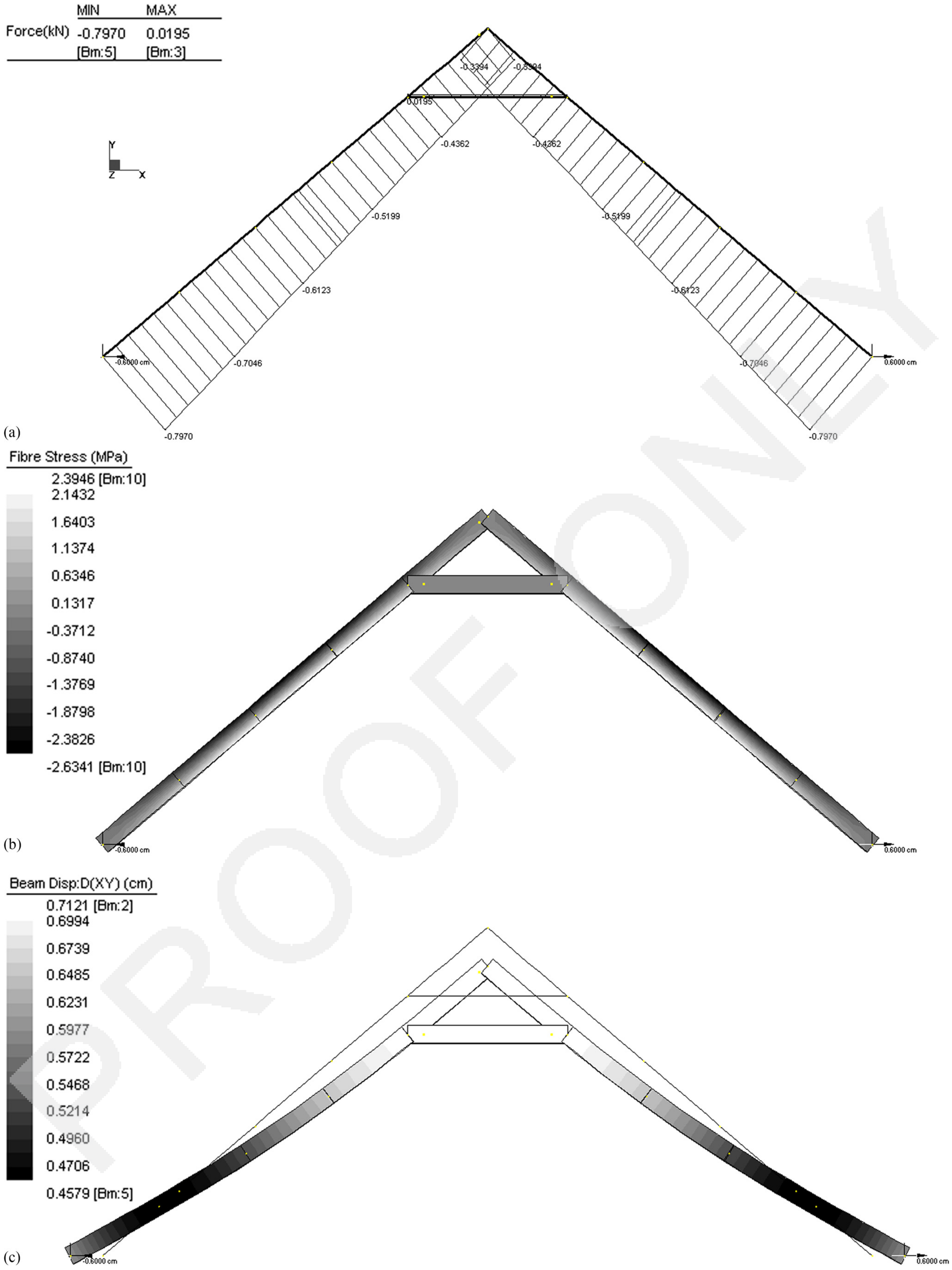


Fig. 10. FEM_3 Model—statically indeterminate structure joined to the walls by pinned supports subjected to inelastic displacements of approximately 0.6 cm: (a) axial load; (b) stress state; (c) horizontal and vertical node displacements.

- The horizontal beams arranged transversally to the room are not connected to the longitudinal edge beams.
- There is a lack of actual tie-beams.
- The connection between each pair of rafters in the longitudinal direction relies only on horizontal and inclined planks wedged into grooves carved in the rafters and does not realize a perfectly three-dimensional (3D) structure behavior.
- The node between the rafters and the edge beams is obtained through a simple cavity hollowed out on the upper corner of the edge beams where the rafters are inserted.
- The connection between the roof structure and the walls at the level of the longitudinal beams that are simply placed (as sleeper beams) on the top of the walls without fasteners, which does not offer the possibility of providing a joint with a higher level of safety, is yet, however, sufficiently efficient in the examined context. In fact, even if the inevitable small horizontal displacement toward the outside of the edge beam on the wall is confirmed by a horizontal crack that is visible on the outside wall of the room of the *ghorfa* at the roof–wall interface [Fig. 12(a)], it nevertheless does not seem to put the overall stability of the system at risk. In particular, it is worth highlighting that the masonry typology of the building is a mixed stone and brick masonry, bound with lime–earth mortar, that does not provide an efficient monolithic behavior due to both the hard and scarcely hewing stones and the poor mortar with a low amount of lime. Furthermore, as reported by Rovero and Fratini (2013), the average values of the mechanical properties of this masonry are rather low: compressive strength 2.9 N/mm^2, Young modulus 1,340 N/mm^2, shear stress approximately 0.05 N/mm^2.

This type of damage, in fact, has been acknowledged and highlighted by the most recent Moroccan regulations, *Reglement parasismique des constructions en terre* (RPCT 2011) [(Fig. 12(b)]. The same regulations suggest, in fact, some reinforcement interventions aimed precisely at improving the connection between the edge beam of the Andalusian-type roof and the walls of the room (Fig. 13).

Table 4. Parametric analysis: Wall thrust and collar beam axial load as a function of the inelastic displacement of the supports

Inelastic displacement (cm)	Wall thrust (kN)	Collar beam axial load (kN)
0	0.59	−0.75
0.10	0.56	−0.62
0.20	0.53	−0.49
0.30	0.51	−0.37
0.40	0.48	−0.24
0.50	0.45	−0.11
0.58	0.43	−0.0062

Seismic Vulnerability Assessment

The state of unstable equilibrium based on friction, discussed previously, which was ascertained under the assumption of only gravitational loads and the value of 0.7 for the static coefficient of friction, could also be overestimated, and the structure could be, instead, in a condition of higher risk because of the arbitrariness with which this coefficient can be assumed. In fact, according to the technical literature, reference to the dynamic coefficient of friction of 0.25 at the timber–masonry interface, which is less than half of that considered, should be made in the case of an earthquake (Rizvi 2005). This reduced value is due to the seismic actions that provoke the relevant vibrations of the structure. This is the main reason why the Moroccan-type Andalusian timber roof, as-is, cannot be considered safe with respect to possible earthquakes.

Therefore, to assess the seismic vulnerability level of the Andalusian roof, reference was made to a structural model where all the rafters were considered as perfectly pinned at the base, therefore assuming a theoretical condition of poststrengthening so as to prevent any displacement, in accordance with the RPCT (2011) recommendations. Under this assumption, reference to the dynamic coefficient of friction is omitted in this article because the sliding failure is considered prevented by fasteners.

For this reason, an additional analysis was carried out with the creation of a 3D model (FEM_4) to assess the response of the roof structure when subjected to a seismic action (Pugi and Galassi 2013). This model included both the load-bearing elements of the structural system, using monodimensional elements of the beam type and the wooden deck that supports the covering of the roof through plane plate-type elements.

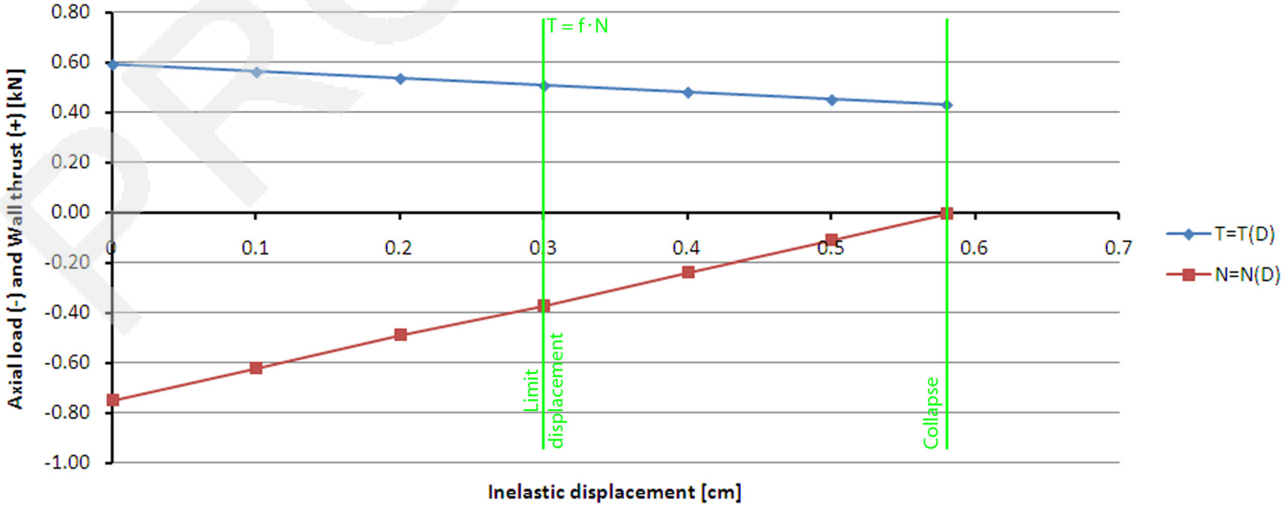
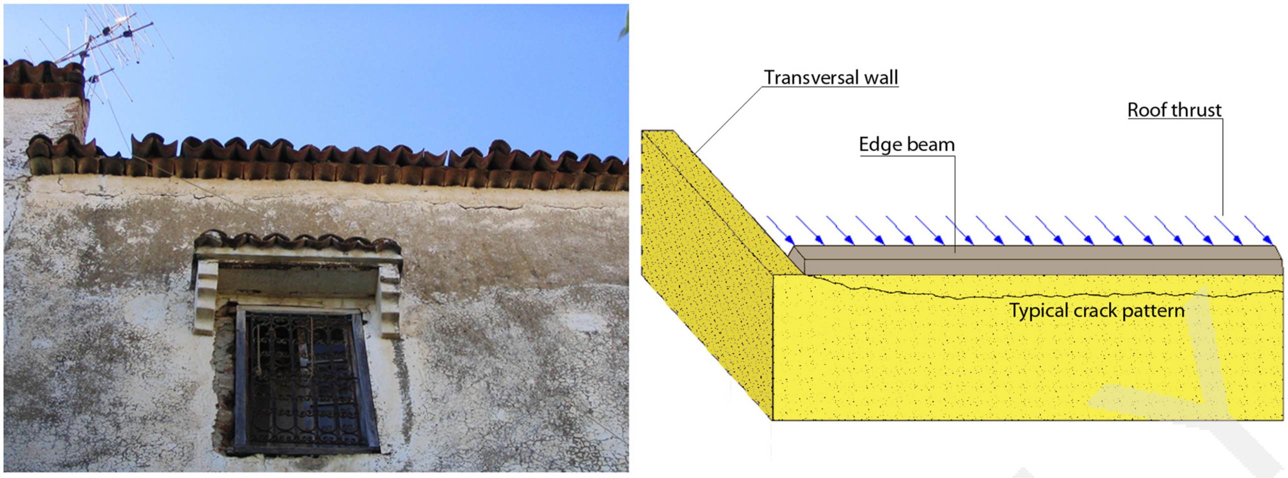
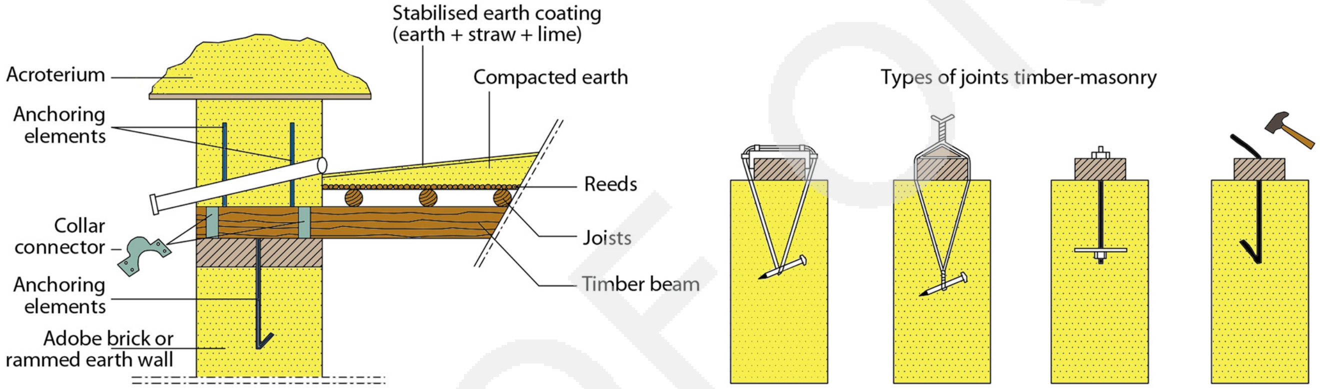


Fig. 11. Results of the parametric analysis: wall thrust T and collar beam axial load N as a function of the inelastic displacement D of the supports.



(a) (b)

Fig. 12. Horizontal crack on the wall due to the horizontal displacement of the roof's support beam: (a) *ghorfa* of Raissouni *dar* (image by Letizia Dipasquale); (b) crack scheme (adapted from RPCT 2011).



(a) (b)

Fig. 13. (a) Reinforcement intervention for improving the connection between the edge beam of the roof and the wall of the room; (b) types of joints of the edge beam to the wall. (Adapted from RPCT 2011.)

Two load conditions, in addition to the one due to gravitational loads, were formulated: seismic action in the transversal direction (*X*-direction) and seismic action in the longitudinal direction (*Z*-direction).

To compute the seismic action, reference was made to the Moroccan *Règlement de Construction Parasismique RPS 2000—Version 2011* (RPS 2000). According to these regulations, the national territory of Morocco is divided into five homogeneous seismicity zones (from 0 to 4) that present approximately the same level of seismic risk, with a probability equal to 10% in 50 years for the recurrence of a seismic event.

The probability of 10% in 50 years was adopted by the regulations envisaging a seismic event of medium intensity that can occur several times during the life span of a structure. Fig. 14 presents the map of the seismic areas of Morocco and shows the location of Chefchaouen.

The city of Chefchaouen is situated in homogeneous Zone 3, which is characterized by an expected seismic acceleration equal to $0.18g$.

The combined effect of gravitational loads with the horizontal seismic action evaluated as an equivalent static force, in perfect accordance with the provisions of the Moroccan regulations, was considered. In particular, the seismic action was inserted into the model by applying an additional load condition with a horizontal acceleration equal to $0.18g = 176.58\ \text{cm/sec}^2$.

The analysis of this fourth model (Fig. 15) clearly highlights that the seismic action does not significantly increase the thrust transmitted to the wall, nor does the axial load on the collar beam. Therefore, considering an earthquake of medium intensity but with a high probability of occurrence, the Andalusian-type roof shows a good level of safety with respect to the possibility of seismic events.

It is worth highlighting that the axial compression load on the collar beam obtained in the 3D model (–0.36 kN) is approximately half of that obtained in the 2D model. This is due to the presence of plate elements, inserted to simulate the deck of boards placed as lozenges studded to the extrados of the elements of the roof, which evidently increases the stiffness of the overall structure.

Furthermore, the stress state is very low and therefore is not capable of putting the structure at risk [Fig. 15(b)].

The longitudinal effect of the seismic action has an even lesser influence because the structure presents a great longitudinal stiffness due to the dense repetitiveness of the timber elements that constitute the structural system of the roof, made even more efficient by the reciprocal connection carried out by the continuous deck of boards.

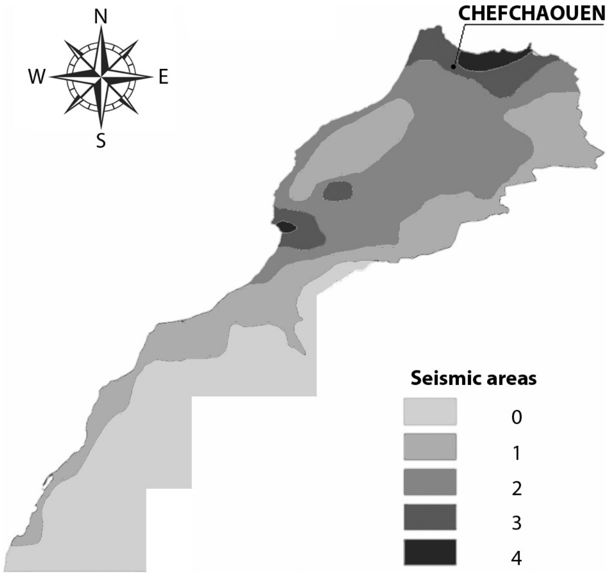


Fig. 14. Map of the homogeneous seismicity zones of Morocco as a function of the peak accelerations. (Adapted from RPS 2000.)

The results of the analysis for gravitational loads and seismic action are presented in Table 5.

Lastly, it is necessary to note that, in the authors' opinion, the strengthening interventions proposed by the Moroccan regulations consisting of the use of fasteners to anchor the timber roof (i.e., the edge beams) to the walls is effective only in the case of good-quality masonry, capable of supporting both the horizontal and vertical thrust provided by the roof. However, in traditional buildings of the medina, such as in the case of Raissouni *dar*, the walls are often made of irregular blocks laid down without shaping due to the hardness and assembled with clay mortar. For this reason, despite the strength of the stone (which is relatively high), the overall strength of the masonry is not high because it is not guaranteed a structure capable of stress uniformity or of monolithic behavior (Rovero and Fratini 2013). Therefore, because the seismic vulnerability of the roof is a function of the anchorage of the roof itself to the walls, which can improve the seismic response of the whole building, the authors are convinced that the proposal of the building regulations is not quite adequate and that, instead, the better way to provide anchorage of the roof structure to the wall could be to link the edge beams to the transversal beams of the attic. In this way, the horizontal thrust, which, regardless of seismic action, is yet provoked by the gravitational loads due to the heavy screed over the deck planking, can be nullified, and the shear failure or the overturning of the walls can be prevented.

Conclusions

This article presents an in-depth analysis of the structural system of the Andalusian-type roof for the courtyard house, a typical building typology in northern Morocco. The analyses have been performed using numerical simulations with both 2D and 3D models carried out with the finite-element software *Straus7*.

In particular, the role that each structural element plays within the roof system to ensure its equilibrium was highlighted using 2D models. At the same time, it was possible to ascertain that the building system presents some inherent vulnerabilities due to the particular building technique adopted, which relies on unilateral-type joints and elements and on frictional supports.

These vulnerabilities, however, have proven to be not significant if the Andalusian structure is constructed in the context of the Moroccan territory because the climate conditions do not make it probable to have important increases in terms of load due to snow.

However, the simplicity and the typology of the connection joints among the elements of the roof structure provoke a thrust on the perimeter masonry walls that cannot be prevented. The thrust cannot be entirely balanced by the support reaction exerted in correspondence to the interface between the edge beam and the masonry wall, which is only based on the friction force. Therefore, a slight horizontal sliding toward the outside inevitably occurs. The visible horizontal damage on the external wall at the level of the connection between wall and roof clearly shows the aforementioned phenomenon.

Local building regulations codified this type of crack as a recurring type of damage in Moroccan buildings where the Andalusian-type roof is used and indicate possible and specific techniques for reinforcing and improving the joint. Taking inspiration from the recommendations of the local building regulations, which propose devices for the anchorage of the roof to the walls, the seismic analysis was performed considering pinned supports that cannot move in a 3D model. It has been demonstrated that the effects of a seismic action, with levels of intensity predicted by the regulations, are not capable of modifying, in any significant way, the equilibrium and stability of the structure.

However, because the authors do not share the anchorage device proposed by the Moroccan regulations, to prevent the thrust of the roof on the masonry walls and reduce the seismic vulnerability, a strengthening intervention based on an effective connection between the transversal and the edge beams was proposed. Indeed, as mentioned previously, the actual seismic vulnerability depends on the anchorage of the roof to the walls, which is affected by the geometric and mechanical characteristics of masonry, which, in the specific case, has proven not to provide, in any way, a monolithic behavior or a high strength.

Finally, a parametric analysis was carried out to compute the limit value of the horizontal displacement that can turn the structure into a mechanism. The analysis highlighted the fact that the limit value is never actually reached in the case of gravitational loads. In fact, the horizontal displacement, once it has begun, stops when the thrust on the edge wall decreases and is balanced by the timber–masonry friction force of supports, as a consequence of the new configuration of the structure due to the displacement itself.

In this regard, it is worth noting that this article is a first contribution to the knowledge of the structural behavior of the Moroccan Andalusian timber roof. A fourth-step analysis based on an additional numerical model that also takes into account the masonry walls could be a very realistic analytical simulation to be performed to provide a more in-depth understanding of the behavior of each timber element of the roof structure. But, as might be expected, in this model, the behavior of the collar beam (i.e., if subject to compression or tensile axial load) would be the consequence of the deformability of the wall rather than the rigid sliding of the edge beam on the walls, whereas, instead, the horizontal crack detected on the wall exactly under the edge beam of the roof has clearly proven a rigid-cracking behavior of masonry due to the sliding failure. Because such a model would need a more accurate assessment of the mechanical properties of both timber and masonry, in addition to general knowledge regarding the geometric features of specific analyzed buildings, this issue will be addressed in a further study.

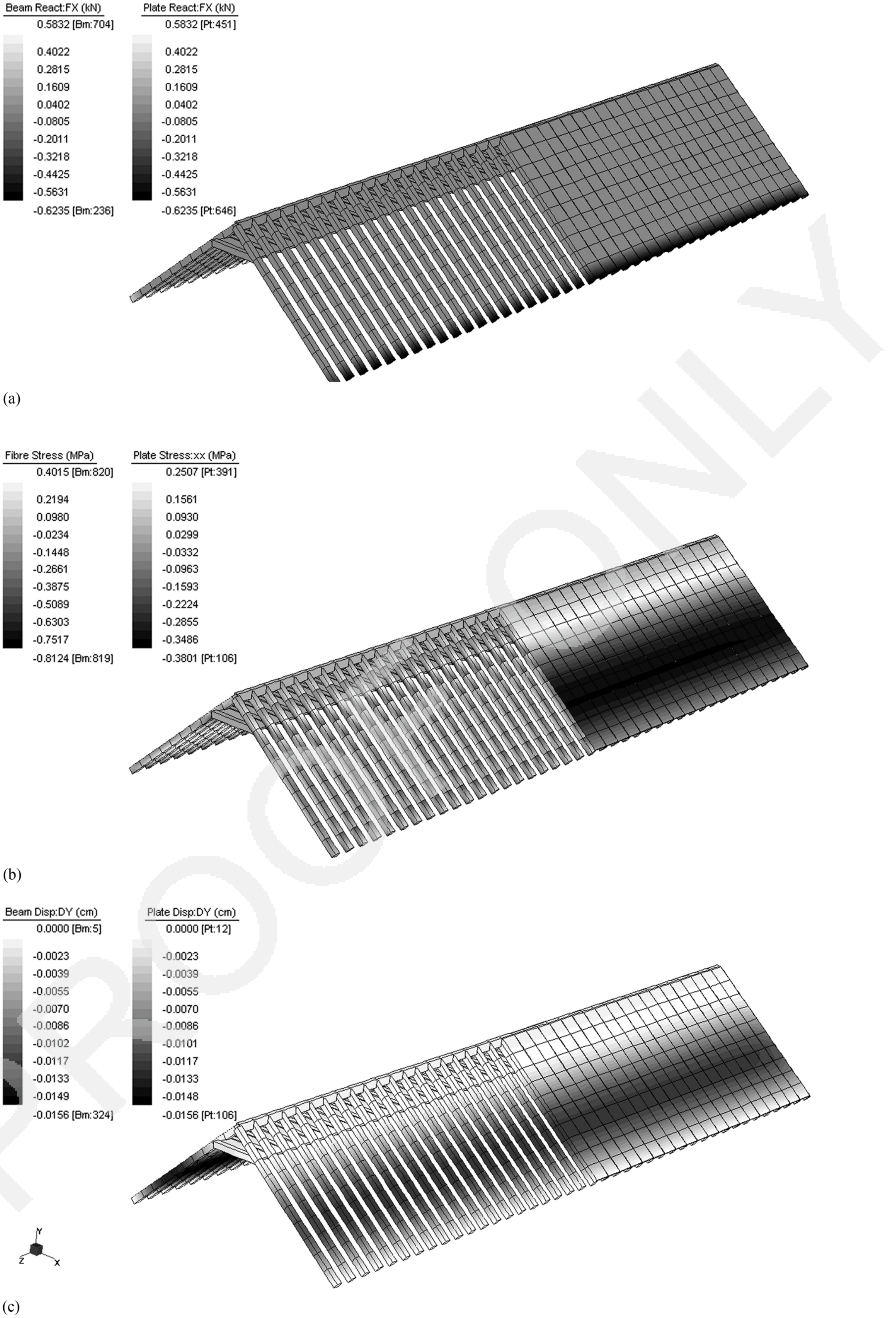


Fig. 15. FEM_4 Model—3D model of the Andalusian-type roof for seismic analysis. Results regarding the gravitational load combination with the seismic action in the transverse direction: (a) thrust transmitted to the walls; (b) stress state; (c) vertical displacements.

Table 5. Summary of the results of the analysis of the Andalusian-type roof for gravitational loads and seismic action

Thrust transmitted to the wall versus collar beam axial load	Load Combination 1 (gravitational loads)		Load combination 2 (gravitational loads + Earthquake X)		Load combination 3 (gravitational loads + Earthquake Z)	
	Edge frame (kN)	Central frame (kN)	Edge frame (kN)	Central frame (kN)	Edge frame (kN)	Central frame (kN)
In plane thrust (X)[a]	0.34	0.6	0.36	0.62	0.37	0.6
Vertical thrust (Y)[b]	0.44	0.78	0.46	0.79	0.47	0.78
Out-of-plane thrust (Z)[c]	0.0047	0	0.0042	0	0.013	0.023
Collar beam axial load	−0.3	−0.37	−0.3	−0.36	−0.31	−0.37

Note: Medium-intensity earthquake as defined by RPS (2000).
[a] Room transversal direction.
[b] Gravitational load direction.
[c] Room longitudinal direction.

For the aforementioned reasons, the authors will use their specific software *BrickWORK* (Galassi and Paradiso 2014; Galassi and Tempesta 2018), already used to perform the analysis of masonry constructions in earlier works (Paradiso et al. 2013, 2014a, b) and suitably developed to model the walls by rigid blocks, even assembled with heart-based mortar joints that are characterized by an elastic behavior under compressive forces and a rigid-cracking behavior under tensile forces, in agreement with the effective performance of the masonry that has proven not to provide a monolithic behavior. The results will also be compared to those provided by the use of *Straus7*, herein used to perform the analyses. It is expected to realistically describe the effect of the spreading roof on the side masonry walls and, therefore, the overall behavior of the roof–wall structure.

References

Anderson, G. D., and M. Rosser-Owen. 2007. *Revisiting al-Andalus: Perspectives on the material culture of Islamic Iberia and beyond.* Leiden, Netherlands: Brill.

Blau, P. J. 1996. *Friction science and technology*. Boca Raton, FL: CRC.

Candelas Gutiérrez, A. L. 2003. "On the origin of some 'whiteness' carpentry rules." In *Proc., 1st Int. Congress on Construction History*, edited by S. Huerta, 505–512. Madrid: Instituto Juan de Herrera.

CEN (European Committee for Standardization). 2002. *Actions on structures, part 1.1*. Eurocode 1. Brussels, Belgium: CEN.

Copani, P. 2006. "Ancient wooden roofs in Sicily: The heritage of Taormina." In *Proc., 2nd Int. Congress on Construction History*, 817–835. Exeter, UK: Short Run.

Cruz, H., D. Yeomans, E. Tsakanika, N. Macchioni, A. Jorissen, M. Touza, M. Mannucci, and P. B. Lourenço. 2015. "Guidelines for on-site assessment of historic timber structures." *Int. J. Archit. Heritage* 9 (3): 277–289. https://doi.org/10.1080/15583058.2013.774070.

Dipasquale, L., S. Mecca, L. Rovero, and U. Tonietti. 2008. "Technical knowledge and traditional architecture in medina of Chefchaouen (Morocco)." In *Proc., 2nd Int. Conf. on Mediterranean Heritage (RIPAM)*. Marrakech, Morocco: Universitè Cadi-Ayyad.

Dipasquale, L., and V. Volpi. 2009. "*Le coperture*." In *Chefchaouen. Architettura e cultura costruttiva*, edited by S. Mecca, L. Dipasquale, L. Rovero, U. Tonietti, and V. Volpi, 167–181. Pisa, Italy: Edizioni ETS.

Du Bois, A. J. 1902. *The mechanics of engineering*. New York: Wiley.

Elert, G. 2017. "Friction." *The physics hypertextbook*. https://physics.info/friction.

Galassi, S., and M. Paradiso. 2014. "BrickWORK software-aided analysis of masonry structures." *IERI Procedia*, 7: 62–70. https://doi.org/10.1016/j.ieri.2014.08.011.

Galassi, S., M. Paradiso, and G. Tempesta. 2013. "Non-linear analysis of masonry structures subjected to external settlements." *Open J. Civ. Eng.* 3 (2A): 18–26. https://doi.org/10.4236/ojce.2013.32A003.

Galassi, S., and G. Tempesta. 2018. "Analysis of masonry block structures with unilateral frictional joints." In *Proc., 2nd Int. Conf. on Materials, Manufacturing and Mechanical Engineering (MMME2017)*. Dubai, United Arab Emirates: Emirates Research Publishing.

Gorst, N. J. S., S. J. Williamson, P. F. Pallett, and L. A. Clark. 2003. *Friction in temporary works*. Research Rep. 071 Prepared for Health and Safety Executive. Birmingham, UK: Univ. of Birmingham, School of Engineering.

Grigoriev, I. S., and E. Z. Meĭlikhov. 1997. *Handbook of physical quantities*. Boca Raton, FL: CRC.

Lee, S.-H., S. Harari, H. Wong, and V. Kapila. 2005. "Friction experiment." *SMART—Science and Mechatronics Aided Research for Teachers 2003–2005*. http://engineering.nyu.edu/mechatronics/smart/pdf/experiments/Project3.pdf.

Mastrodicasa, S. 1948. *Dissesti statici delle strutture edilizie. Diagnosi e consolidamento*. Milano, Italy: Hoepli.

Murase, Y. 1984. "Friction of wood sliding on various materials." *J. Facil. Agric. Kyushu Univ.* 28 (4): 147–160.

Nuere, E. 1989. *La carpintería de armar española. Editores instituto de conservación y restauración de bienes culturales.* Madrid, Spain: Ministerio de Cultura, Instituto de Conservacion y Restauracion de Bienes Culturales.

Orlando, M., L. Salvatori, P. Spinelli, and M. De Stefano. 2016. "Displacement capacity of masonry piers: parametric numerical analyses versus international building codes." *Bull. Earthquake Eng.* 14 (8): 2259–2271. https://doi.org/10.1007/s10518-016-9903-x.

Paradiso, M., S. Galassi, A. Borri, and D. Sinicropi. 2013. "Reticolatus: An innovative reinforcement for irregular masonry. A numeric model." In *Structures and architecture: Concepts, applications and challenges*, edited by P. J. S. Cruz. Boca Raton, FL: CRC.

Paradiso, M., S. Galassi, and D. Sinicropi. 2014a. "Il caratteristico Forte di San Fernando de Bocachica, Colombia." In *Proc., Congress on Construction Pathology, Rehabilitation Technology and Heritage Management (Rehabend 2014)*, edited by L. Villegas, I. lombillo, C. Liano, H. Blanco. Santander, Spain: Gráficas Iguña.

Paradiso, M., S. Galassi, and D. Sinicropi, 2014b. "Stabilità di archi e volte in muratura: Metodi tradizionali e calcolo automatico." In *Proc., Congress on Construction Pathology, Rehabilitation Technology and Heritage Management (Rehabend 2014)*, edited by L. Villegas, I. lombillo, C. Liano, H. Blanco. Santander, Spain: Gráficas Iguña.

Parisi, M. A., and M. Piazza. 2000. "Mechanics of plain and retrofitted traditional timber connections." *J. Struct. Eng.* 126 (12): 1395–1403. https://doi.org/10.1061/(ASCE)0733-9445(2000)126:12(1395).

Parisi, M. A., and C. Chesi, 2014. "Seismic vulnerability of traditional buildings: The effect of roof-masonry walls interaction." In *Proc., 10th US National Conf. on Earthquake Engineering*, Oakland, CA: Earthquake Engineering Research Institute.

Parisi, M. A., M. Piazza, and C. Chesi. 2011. "Seismic response of traditional timber elements and roof structures: Learning from the L'Aquila earthquake." In *Proc., 11th Int. Conf. Structural Health Assessment of Timber Structures*, 1–9. Lisbon, Portugal: Laboratorio Nacional de Engenharia Civil.

Pugi, F., and S. Galassi. 2013. "Seismic analysis of masonry voussoir arches according to the Italian building code." *Ing. Sism.* 3: 33–35.

Rizvi, M. A. 2005. *Effective technical communication.* New Delhi, India: Tata McGraw-Hill Education.

Rovero, L., and F. Fratini. 2013. "The medina of Chefchaouen (Morocco): A survey on morphological and mechanical features of the masonries." *Constr. Build. Mater.* 47: 465–479. https://doi.org/10.1016/j.conbuildmat.2013.05.025.

RPCT (Royaume du Maroc, Ministère de l'Interieur, Ministère de l'Equipement et du Transport, Ministère de l'Habitat, de l'Urbanisme et de la Politique de la Ville). 2011. *Règlement parasismique des constructions en tierre*. RPCTerre 2011. Rabat, Morocco: RPCT.

RPS (Royaume du Maroc, Ministère de l'Habitat et de la Politique de la Ville). 2000. *Règlement de Construction Parasismique*. RPS 2000—Version 2011. Decreto n. 2-02-177 du 9 hija 1422 (22 febbraio 2002). Djibouti, Africa: RPS.

Ruggieri, N., S. Galassi, and G. Tempesta. 2018. "Pompeii's Stabian baths. Mechanical behaviour assessment of selected masonry structures during the 1st century seismic events." *Int. J. Archit. Heritage.* https://doi.org/10.1080/15583058.2017.1422571.

Tampone, G. 2001. "Acquaintance of ancient timber structures." In *Proc., 3rd Seminar on Structural Analysis of Historic Constructions*, edited by P. B. Lourenço and P. Roca, 117–143. Guimaraes, Portugal: Univ. of Minho.

Tampone, G. 2005. "Il complesso lignario della Cattedrale di Nicosia." In *Proc., Int. Conf. on Conservation of Historic Wooden Structures*, 144–154. Florence, Italy: Alinea.

Tampone, G., and N. Ruggieri. 2016. "State-of-the-art technology on conservation of ancient roofs with timber structure." *J. Cult. Heritage*, 22: 1019–1027. https://doi.org/10.1016/j.culher.2016.05.011.

UNI (Ente Nazionale Italiano di Unificazione). 2009. *Structural timber. Strength classes*. EN 338:2009. Brussels, Belgium: UNI.

UNI (Ente Nazionale Italiano di Unificazione). 2010. *Structural timber. Visual strength grading. Part 3: Timber Uso Fiume and Uso Trieste*. UNI 11035-3:2010. Milano, Italy: UNI.

AUTHOR QUERY FORM

AQ1: ASCE Open Access: Authors may choose to publish their papers through ASCE Open Access, making the paper freely available to all readers via the ASCE Library website. ASCE Open Access papers will be published under the Creative Commons-Attribution Only (CC-BY) License. The fee for this service is $1750, and must be paid prior to publication. If you indicate Yes, you will receive a follow-up message with payment instructions. If you indicate No, your paper will be published in the typical subscribed-access section of the Journal.

AQ2: Please provide the ASCE Membership Grades for the authors who are members.

AQ3: Please add job titles/roles (e.g., Professor, Graduate Stduent) for all authors to author footnotes.

AQ4: Please add access dates for the URLs in Elert (2017) and Lee et al. (2005) in the reference list.