**Structures and Buildings**
Volume 164 Issue SB3
**Timber-reinforced structures in Greece: 2500 BC–1900 AD**
Vintzileou

ice | proceedings

**Proceedings of the Institution of Civil Engineers**
Structures and Buildings 164 June 2011 Issue SB3
Pages 167–180 doi: 10.1680/stbu.9.00085
**Paper 900085**
Received 15 October 2009 Accepted 28 July 2010
Published online 24/05/2011
**Keywords:** history/seismic engineering/timber structures



ice
Institution of Civil Engineers
publishing

# Timber-reinforced structures in Greece: 2500 BC–1900 AD

**E. Vintzileou** Dr Ing
Professor, Faculty of Civil Engineering, National Technical University of Athens, Greece

**The survey of numerous monuments and historic structures in Greece – a country situated in the most earthquake-prone area of the eastern Mediterranean – has revealed a systematic and continuous through-centuries use of timber elements within masonry. The extent of the use of timber in the structures, the contribution of the timber to the overall structural system, the specific measures taken to protect timber from decay and, hence, the efficiency of the developed structural systems present a vast variety, associated with social and economical factors. This extensive use of timber makes it legitimate to assume that our predecessors were aware of the effect of timber-reinforcing systems on the seismic behaviour of structures. This paper provides information on the use of timber in structures in Greece ranging from the Minoan Crete 2500 years BC to Akrotiri, Thera sixteenth century BC, to Byzantine churches and monasteries, and finally to more than 70 urban nuclei within the country that were developed in the eighteenth and nineteenth centuries.**

## 1. Introduction

For any historic structure, the bearing system, developed to withstand and safely transfer actions to the earth, constitutes an integral part of the structure and hence is among the values to be preserved for the structure.

Throughout Greece, the work of archaeologists, architects and engineers in numerous archaeological sites, in individual monuments, as well as in historic centres has brought to light numerous structural systems developed by smaller or larger communities over the course of almost 5000 years (Figure 1). The level of sophistication of each structural system depends on the use of each individual building, on the social organisation of the community, on its wealth and so on. The size of buildings varies depending on their use (church, palace or residential house). Thus, there are buildings with plan dimensions varying from some metres to some tenths of metres.

It is, however, remarkable that independently of the local conditions under which these structural systems have been developed, a systematic use of timber elements is recorded throughout the history of civilisation in Greece.

## 2. The Minoan palaces and villas

The oldest architectural remains found in the island of Crete date back to the late Neolithic era (fifth millennium BC); a complex of residential houses, dating back to the fourth millennium BC, was brought to light thanks to the excavations by Evans (Evans, 1921). The early Bronze Age is marked by intensive activity in various fields in Crete. A characteristic specimen of a residential settlement of that period (termed as the pre-palatial period) was excavated in Vassiliki (Ierapetra). The settlement, organised as a functional entity, bears witness to the high level of architectural design reached by the Minoans already in the second millennium BC. Excavations in major sites (such as Knossos, Festos, Malia and Zacros), as well as in numerous other locations throughout the island, demonstrate that during the second millennium BC there was a very dense network of settlements. Furthermore, there are clear signs of extensive destruction of buildings and entire settlements owing to earthquakes. Tsakanika (Tsakanika, 2006) documents a comprehensive study of the bearing structures of palaces and villas (noble houses) in the Minoan Crete of the late Bronze Age. The systematic use of timber elements is also evident at other locations including Mycenae and Thivai. Tsakanika's work (Tsakanika, 2006) constitutes a corpus of more than 14 000 images that document the structural systems of the studied buildings at more than ten locations. The available documentation points to the use of timber as both horizontal and vertical load-bearing elements including main and secondary beams, floor joists, roofs, staircases, door and window lintels and frames, pillars, timber-framed piers filled with rubble stone masonry, along with vertical and horizontal reinforcing of rubble or cut stone-masonry walls. Many of these timber elements have not survived to the present day, but their existence, location and dimensions are evidenced by vertical, horizontal or oblique holes in the masonry. The use of cypress wood was identified in various sites (including Knossos). Nevertheless, the use of other types of wood cannot be excluded.

As even a concise presentation of the available documentation is impossible, in this paper only some illustrations (Figures 2 to 6) are reproduced from Tsakanika (Tsakanika, 2006). Some key remarks regarding the studied structural system are outlined below.

(*a*) Economy in construction effort is observed. The Minoans were using local materials to avoid massive transport from


**Figure 1.** Map of Greece. Location of investigated archaeological sites and historic centres

other locations (Tsakanika, 2006). Nevertheless, stronger stones were used in exterior walls, as well as in pavements. Stones are cut only on the exterior faces of structural members, as well as in faces that are in contact with timber elements. Needless to say that an exemplary organisation of the site is a prerequisite for such a sensible use of local and imported materials.

(*b*) A peculiar characteristic of the Minoan architecture is that transversely meeting masonry walls are not interconnected. As shown in Figure 5, it seems as though the perimeter walls parallel to one of the main directions were constructed first, followed by those parallel to the other main direction. The integrity of the system was ensured by timber-framed piers, arranged at all corners and at free-ends of walls. Rubble


Figure 2. Old palace in Festos. Location of horizontal longitudinal and transverse timber elements in rubble stone masonry (Tsakanika, 2006)

Figure 3. Villa in Ag. Triada, Room 4, northwest wing. Retaining wall with vertical timber reinforcement. The wall was covered with plaster elements. Timber elements were unplastered and, hence, protected from concentration of humidity (Tsakanika, 2006)

stone masonry fills the space between consecutive stronger vertical elements.

(*c*) Special care is given to the foundation of the bearing system. All structural members were made of cut stones. Also, piers between openings are resting on cut stones (Figure 6). The arrangement of those stones coincides with critical locations (such as free ends of walls, intermediate locations where masonry is subjected to high loads, locations of timber frames of doors etc.); it seems therefore legitimate to assume that the entire plan of the building, as well as the scheme of the bearing system, were fully designed before the commencement of the construction process.

(*d*) The systematic use of timber or timber-framed elements at critical locations (such as locations of high vertical loads, in corners and free-ends of walls, as well as in piers between openings), along with the elaborated system of forming those

Figure 4. Timber frames of doors in the restored double axes hall of the palace of Knossos (Tsakanika, 2006)

elements that are interconnected at floor and roof levels, insinuate that the Minoan technicians were aware of the fact that their constructions had to face seismic events. Even severe damages and partial collapse of the (rather weak) rubble stone masonry would not cause collapse of the entire building, since the (stiff and strong) timber ‘skeleton’ of the structure was able to resist the seismic actions and to bear vertical loads until rubble stone masonry was repaired after an earthquake. It should be noted that a structural system that follows similar design logic is still in use on the island of Lefkada.

## 3. Structural systems in the prehistoric town of Akrotiri in Thera

Akrotiri, a flourishing town on the island of Thera-Santorini, was destroyed by a volcanic eruption circa 1500 BC. The construction system of the site in Akrotiri (preserved under volcanic material), almost contemporary of the structural system in Crete, was exhaustively studied by Palyvou (Palyvou, 1999). Similar to palaces and villas in Cretan sites, walls and piers in Akrotiri are founded on the rock. In numerous cases, the rock is worked with the purpose to form a horizontal plane; in other cases, a cut stone is placed between the rock and the masonry element (Figure 7).

In Akrotiri, 2- and 3-storey buildings are mainly made of rubble stone masonry. Better-quality masonry is apparent in zones that are critical for the bearing capacity of the structure, such as the corners of the building (meeting walls are tied and, hence, box action of the building is ensured), around openings (reinforcement of walls that are weakened because of the openings), and at free-ends of walls (sensitive to out-of-plane actions owing to the lack of transverse collaborating wall). In those locations, larger dimension stones with elaborated faces are used. Rubble stone masonry is systematically reinforced using timber ties: As a rule, nets of horizontal timber elements are incorporated within the masonry at various levels; there are, however, some cases of


**Figure 5.** Knossos palace, queen's apartments. Part of the excavation drawing (Tsakanika, 2006)

**Figure 6.** Palace of Festos during excavations (Mont. Ant., vol. XIV, Tabl. XXXIII, taken from Tsakanika, 2006). Cut stone bases and pavement

**Figure 7.** Section D, room D15, northwest exterior corner. The foundation of cut stones (Palyvou, 1999)

vertical timber elements that will be referred to separately. As shown in Figure 8, branches of trees were used to form the net of horizontal wooden elements. Normally two longitudinal timber elements are running around the entire room and, quite often, around the entire building. In some cases, in the connection zone between a longitudinal and a transverse wall, three timber elements are arranged. Transverse timber elements are resting on the longitudinal elements; they are either perpendicular to them or oblique (typically in the corners of the buildings). As the available length of branches could not cover the entire length of the walls, longitudinal timber elements consist of several branches, either placed one next to the other or spliced. Horizontal nets of timber elements are arranged typically close to the lower level of the wall, below openings and at the level of lintels. In some cases, a fourth net of timber elements was identified at floor level. As the imprints of wooden elements on the volcanic ash were not preserved, available information on the types of wood used in the buildings is limited. Although various kinds of trees were identified in other locations on the island of Thera (namely, Tamaris, Pistacia lentiscus L., Olea europae, Phoenix Dactylifera I. etc.), there is no evidence to exclude or certify their use in Akrotiri.

Vertical networks of timber elements were identified in three buildings in Akrotiri, thanks to the holes left within the volcanic material when the wood disintegrated. Note that only parts of some of the buildings in Akrotiri have been excavated. Figure 9 shows the restored façade of Xeste 2, where the disintegrated timber elements were substituted by reinforced concrete ones; the

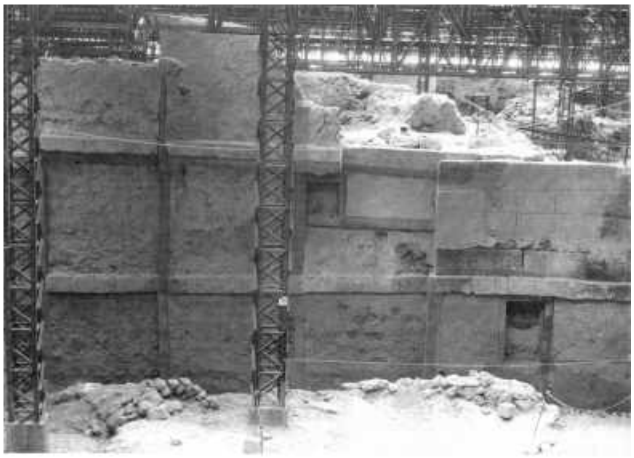


**Figure 9.** Xeste 2, north façade (Palyvou, 1999)

arrangement of a net of (rectangular in section) horizontal and vertical timber elements is apparent. Unfortunately, as this wall was discovered and restored during the early stage of excavations (when the structural system of Akrotiri was unknown to archaeologists), no information was gathered regarding the length of timber elements or their connections. The interior of Xeste 2 has not yet been excavated. Therefore, there is no information as to whether a similar network of timber elements is arranged on the opposite face of the wall. Nevertheless, one may assume that this is the case, on the basis of similar findings in other (partly excavated and not yet restored) buildings. The south exterior wall

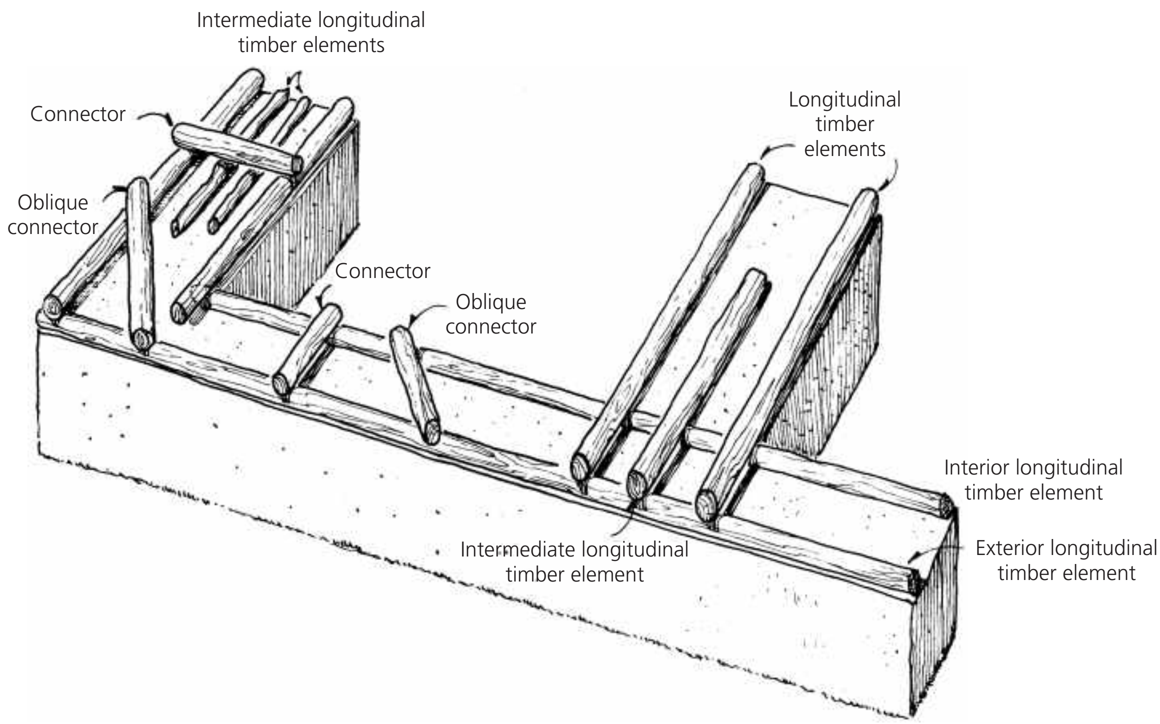
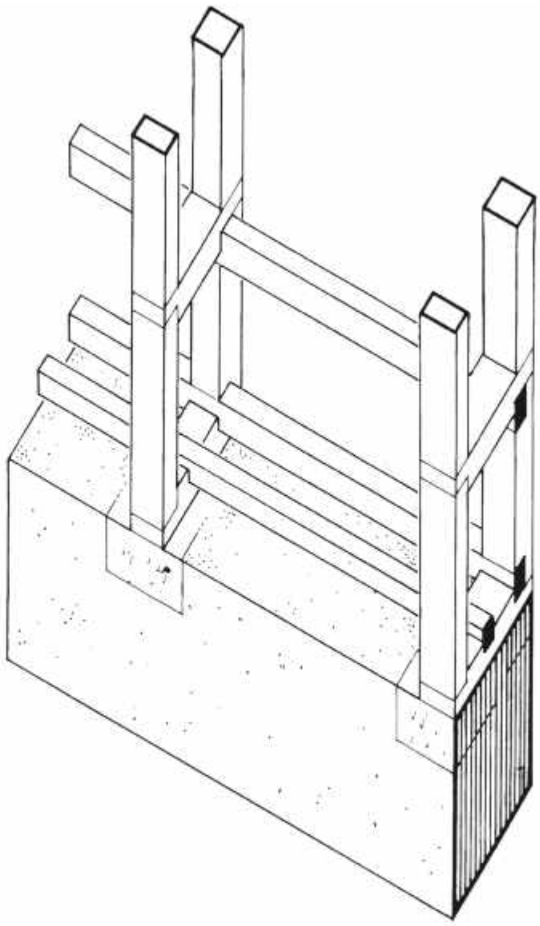



**Figure 8.** Horizontal timber ties, typical detail (Palyvou, 1999)

of Xeste 3 (Figure 10(a)) allows for the system of vertical nets of timber elements to be identified and represented (Figure 10(b)).

Among the numerous interesting findings related to the cut stone masonry walls, pillars, floors and staircases, it is of special interest to focus on the three-dimensional (3D) timber frames of exterior and interior doors and windows (Figure 11). The effort of the constructors in Akrotiri to form timber frames that were stiff enough and able safely to transfer vertical loads is apparent. Other than that, the arrangement of a series of wide openings around the interior courtyard of the buildings allowed for lighting and for organisation of family life within the house.

(a)



(b)

**Figure 10.** (a) Location of vertical timber elements in north exterior wall of Xeste 3 and (b) axonometric representation of vertical timber ties (Palyvou, 1999). Wall thickness ~0·80 m; distance between consecutive timber frames ~1·50 m

In conclusion, it can be stated that, although there are some similarities with the system developed by the Minoans, the structural system of Akrotiri is locally developed. Timber ties arranged within rubble stone masonry served as reinforcement of the low tensile strength masonry. Furthermore, the horizontal and vertical timber ties together formed a robust 3D system which confined and so enhanced the deformation capacity of the masonry. The timber elements were also able safely to withstand vertical loads, in case masonry was damaged or even partially collapsed, thus allowing buildings to survive until masonry was repaired. Finally, the elaborate 3D system of timber frames in multiple windows and doors constitutes a sophisticated solution of substitution of masonry with the purpose of serving functionality while respecting the rules of 'seismic design'.

## 4. Timber ties in Byzantine architecture

The traces of the use of timber reinforcement in buildings are found in numerous structures (residential houses, churches and towers) of the Byzantine era. It is interesting to observe that timber ties are widely known under the term of 'imandosis',

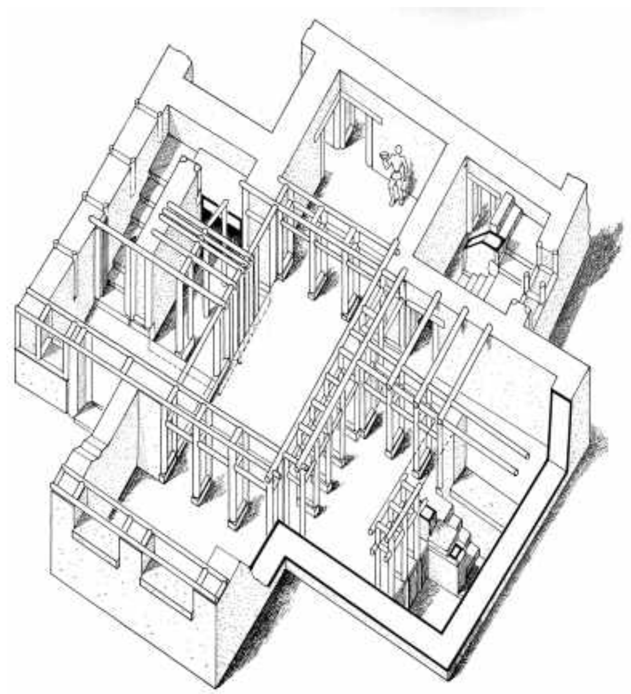
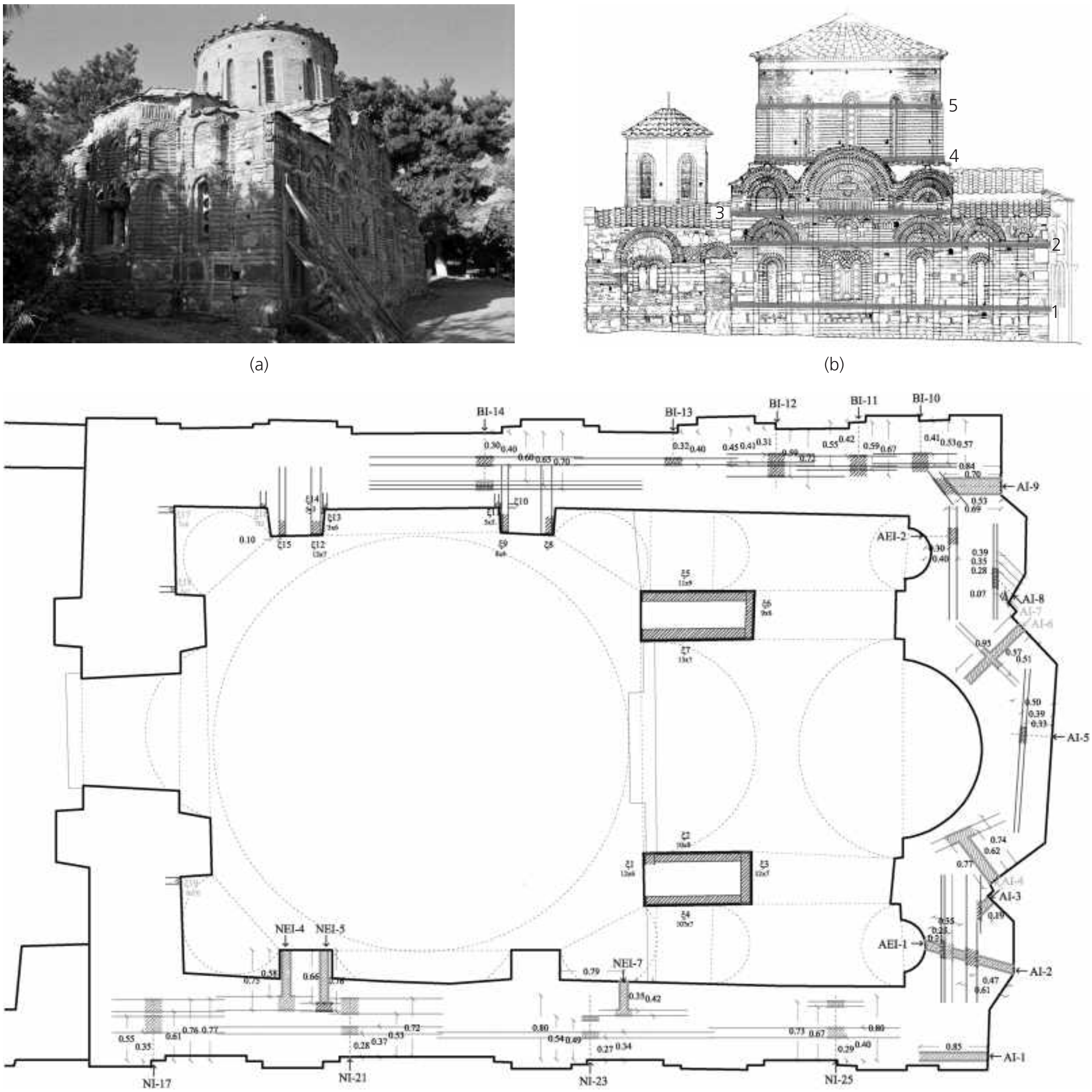


**Figure 11.** Xeste 3, axonometric representation of rooms 1 to 8 (Palyvou, 1999)

which comes from the Greek word 'imas'–genitive 'imandos': strap. In the ninth-century dictionary of Patriarch Photios (Photios I, 2004) and the tenth-century dictionary of Suda (Suda On Line, 2011), 'imandosis' is defined as a tying system ; it ties together timber elements embedded in buildings. The beneficial effect of timber ties is recognised and mentioned even in texts not related to construction. For example, St. John Chrysostom (349–407 A.D.), in his epistle to the people of Antioch (Homily VI) (St. John Chrysostom, 1842) writes; '. . .for what the stay-beams (εν ταις οικίαις των ξύλων αι ιμαντώσεις – literally; in houses,




(a) (b) (c)

Figure 12. (a) The church of Panaghia Krina in Chios and (b) east-west section of the church. Five levels of timber ties are indicated (1 to 5). (c) Part of the plan at the level of the lower timber tie. Note that in some locations timber elements are completely disintegrated, whereas in others timber elements still exist (Vintzileou, 2006)

timber strappings) are in houses, that rulers are in cities; and in the same manner as if you were to take away the former, the walls, being disunited, would fall in upon one another ... (αν εκείνας ανέλης, διαλυθέντες οι τοίχοι συμπίπτουσιν αλλήλοις αυτόματοι)'.

Among the numerous examples of the use of timber in the Byzantine architecture, two cases are selected for this paper, namely the church of Panaghia Krina (in the island of Chios) and the Doheiarion monastery in Mount Athos. The church of Panaghia Krina (Figure 12(a)), built in the twelfth century AD, has survived several earthquakes. The monument being in a critical state, the Hellenic Ministry of Culture has funded a research programme (Vintzileou, 2006) to investigate the structural system of the monument, to assess the available margins of safety and to explore possible intervention techniques. Within the programme, the construction type of masonry was also investigated, mainly through boroscopy, a technique consisting of drilling a hole of small diameter in the masonry and observing the interior of the masonry using an optical fibre device. The investigation demonstrated that the monument was reinforced by means of timber ties at five levels within the height of the walls as shown in Figure 12(b). Figure 12(c) shows the arrangement of timber elements (both longitudinal and transverse) in one of the levels.

One of the main problems that arises when timber ties are identified within masonry in monuments is that timber elements are completely (or, even worse, partly) disintegrated. As in the normal case, timber ties are located away from masonry surfaces (for reasons of protection from humidity changes), it is extremely difficult, if not impossible, to replace the rotten wooden pieces and to ensure connection between longitudinal and transverse timber elements. Quite often, substitution of timber ties by external or internal metal ties is attempted. Nevertheless, metal ties can only replace the longitudinal timber elements. Transverse connections, provided in the original timber ties at distances not exceeding one to two times the masonry thickness, cannot be substituted and connected to the longitudinal metal ties. Although research on this subject is on-going, the urgent need to preserve historic structures and monuments imposes alternative solutions to be invented and applied. The problem is solved on a case-by-case basis, by enhancing the bearing capacity of the masonry itself (e.g. through grouting), by enhancing box action of the building by providing (preferably, timber) diaphragms at floor and roof levels, and so on.

The Doheiarion monastery in Mount Athos (Figure 13) was founded in the tenth century. The investigation of the complex of buildings (Touliatos, 2009) has shown that timber ties (both visible and invisible) are used in the Katholikon (main church), in the cells, as well as in the tower of the monastery. Figure 14 shows the levels at which timber ties were identified. One may observe that (visible) timber elements are used as ties in the origins of arches and vaults, as well as within masonry along the perimeter walls in the form of timber ties (imandosis). The fact that the constructors of the monastery were aware of the importance of timber elements is demonstrated also by their care to protect them from humidity. Figure 15 shows a detail of the timber tie located within the masonry of the cells: Below timber elements, a recess was formed using stones. This recess (20 to 30 mm deep) covered with lime mortar, plays the role of drainage for the timber elements, thus keeping their humidity constantly below the biological attack level.

**Figure 13.** Doheiarion Monastery in Mount Athos (Touliatos, 2009)

Finally, it is very interesting to look at the findings concerning the tower of the monastery (Figure 16). A system of horizontal timber ties was detected at floor levels, as well as at intermediate levels (at the bottom of openings). At intermediate levels, the connection among longitudinal timber pieces is ensured by means of diagonally placed stiffening elements. At floor levels, timber ties (located within the thickness of masonry) are connected to the timber beams of the floors. Timber pavements fixed onto the floor beams ensure a diaphragm action of the floors, thus forcing the walls to deform jointly in case of an earthquake. The concern of the constructors about the seismic behaviour of the tower is also demonstrated by the fact that, as shown in Figure 16(b), the floor beams are positioned along the $x$- or along the $y$-direction every other floor. In this way, a uniform behaviour of the tower is sought, independently of the predominant direction of the seismic motion.

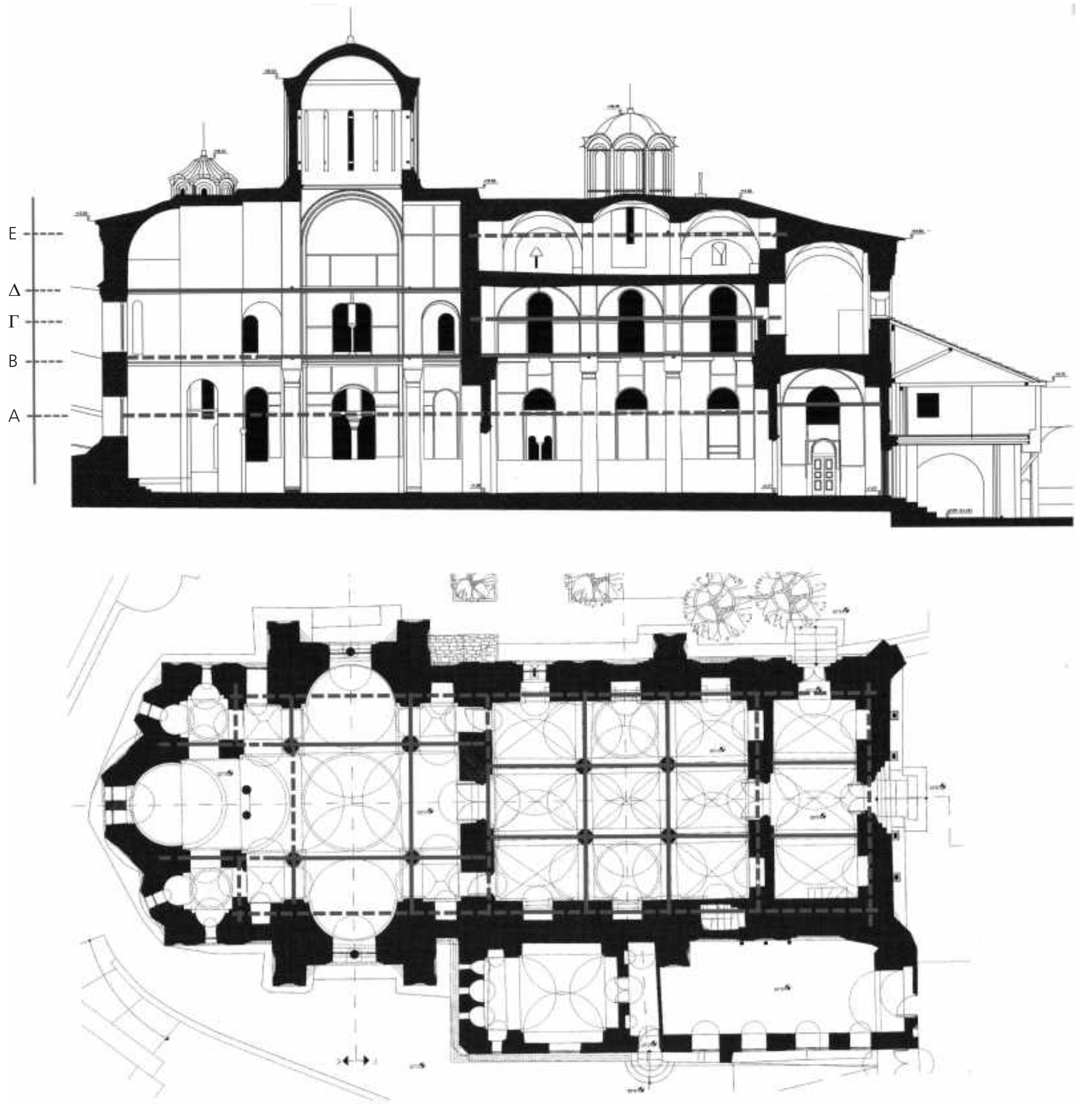



Figure 14. Doheiarion Monastery. Visible and non-visible timber ties in the Katholikon (main church) (Touliatos, 2009)

## 5. Historic structural systems (eighteenth and nineteenth centuries)

The survey of historical structural systems throughout Greece has shown that practically in all of them (more than 70 historical structural systems) timber reinforcement (made of wood from olive or chestnut trees in many cases) is used within the thickness of masonry (Figures 17 and 18). The typology of timber ties (location, dimensions of wood elements, arrangement within masonry thickness (Figure 19) and along the height of walls, splices in longitudinal timber elements (Figure 20), connections between longitudinal and transverse elements (Figure 21) etc.), their effect on the seismic behaviour of buildings, the typical pathology of those systems, as well as possible intervention techniques, were investigated within a research programme (Vintzileou, 2008).

The main findings of that research (that are in accordance with

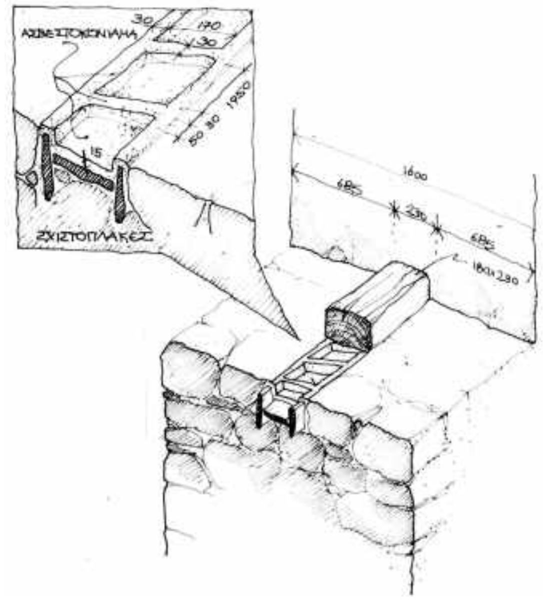



**Figure 15.** Detail of the timber tie within masonry (Touliatos, 2009)

**Figure 17.** Paleos Panteleimon, Macedonia

the observed behaviour of historic structures) confirm the positive effect of timber ties in (moderately) enhancing the compressive strength of masonry owing to confinement, in significantly enhancing the deformability properties of masonry, thus permitting the buildings to sustain large deformations (owing to earth-

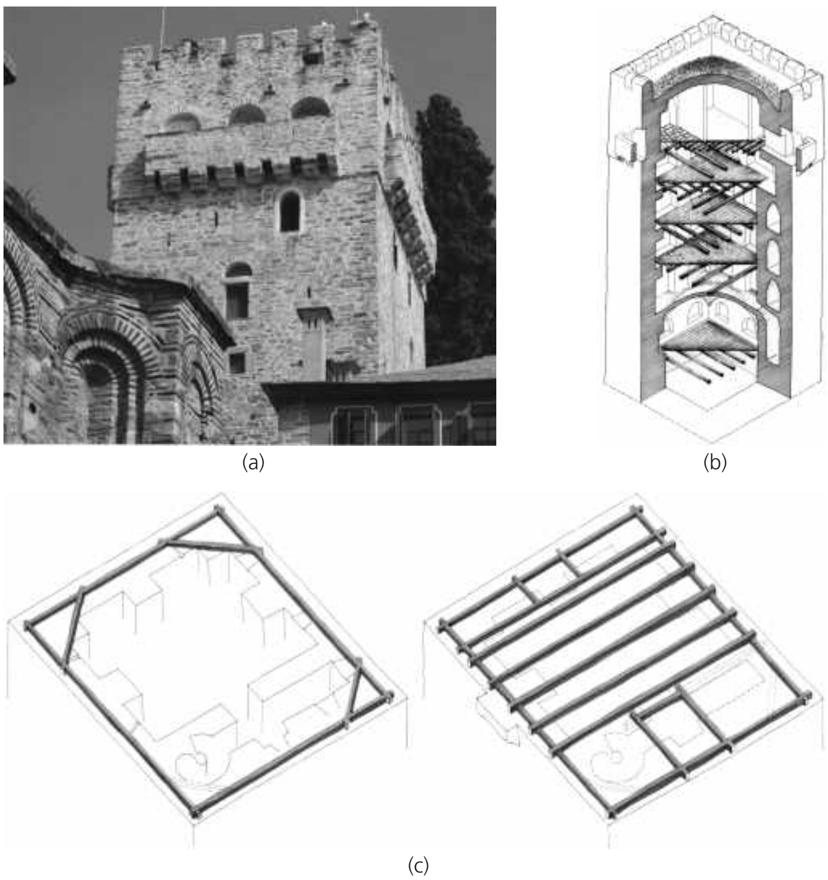



**Figure 16.** (a) The tower of the Doheiarion Monastery, (b) axonometric section of the tower and (c) timber ties between floors and at floor levels (Touliatos, 2009)

Figure 18. Zagori (Epirus)

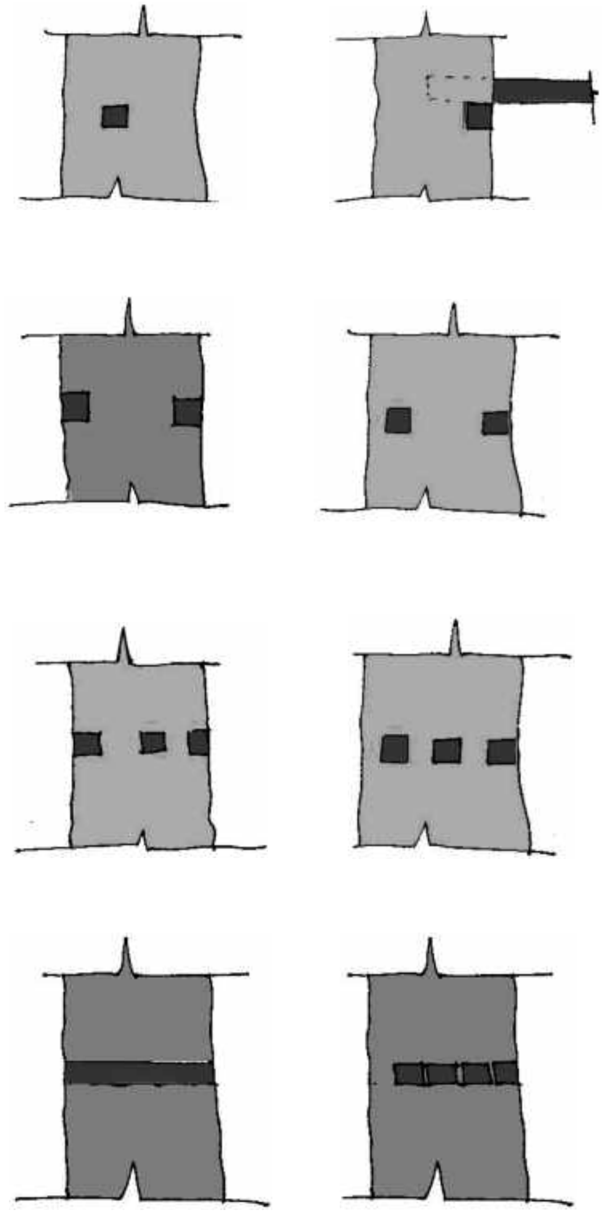


Figure 19. Number and location of longitudinal timber elements along the thickness of walls (Vintzileou, 2008)

quakes or land slides) without disintegration and collapse. More specifically, the compressive strength of masonry (as low as $0{\cdot}47\ \mathrm{N/mm^2}$) was enhanced by 10% to 20%. The vertical strain at attainment of maximum resistance was increased from 0·0062 (for plain masonry) to 0·0124 and 0·0201 for timber-reinforced masonry. The effect of timber reinforcement on the shear strength of masonry was rather spectacular: depending on the arrangement of timber ties, strength enhancement varying from 134% to 400% was recorded. The shear deformation corresponding to the maximum shear resistance was increased by 300% to almost 500%. Furthermore, thanks to the presence of timber ties acting as reinforcement to the masonry, the action effects on masonry owing to seismic events are reduced, while at the same time the respective bearing capacities of masonry elements in shear and in out-of-plane bending moments are increased by as much as up to an order of magnitude (Vintzileou and Skoura, 2009).

As a final example of use of timber in historic structures in Greece, mention should be made of the structural system developed (and still in use) in the Ionian island of Lefkada, situated in the most earthquake-prone region of the country. That system (Vintzileou *et al.*, 2007), seems to fulfil most of the requirements of current Codes for the conceptual design of earthquake-resistant structures: (a) symmetry in-plan and in-elevation is ensured; (b) mass and stiffness are concentrated in the ground floor (made of rubble stone masonry), while in the upper storey(s) mass (but not stiffness) is reduced thanks to the construction of timber framed walls. The peculiarity of this structural system, which has sustained several strong earthquakes, lies in the secondary timber structural system provided to all buildings (Figure 22). As demonstrated by survey and calculations, the secondary system (too flexible to contribute to the seismic behaviour of the building) is able safely to sustain vertical loads, in case the masonry of the walls between ground and first floor is severely damaged or even collapsed owing to a seismic event. Thus, the structure remains safe and gives the population the time that is necessary for repair or reconstruction of the damaged masonry.

## 6. Conclusions

From this (though inexhaustive) description of structural systems developed in Greece through centuries and millennia, the following observations apply.

(*a*) Constructing has always been an important activity of the inhabitants of this part of the globe. To ensure safe shelters for their private and social activities, our predecessors invented clever structural systems able to sustain the actions imposed by nature.

(*b*) The use of timber (in various alternative forms and arrangements) in buildings seems to be continuous through

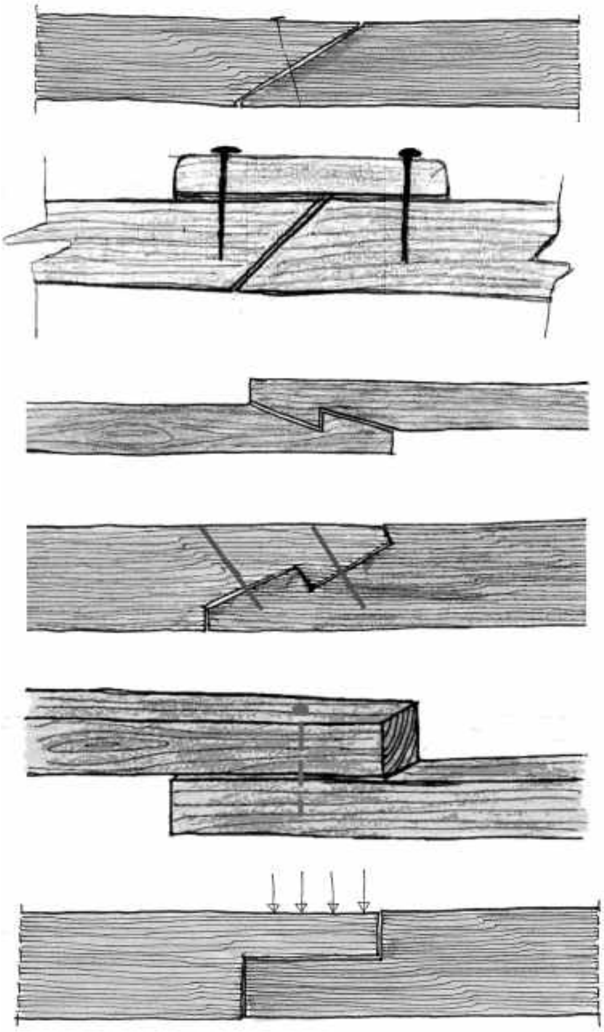


Figure 20. Typical splices of longitudinal timber elements (Vintzileou, 2008)

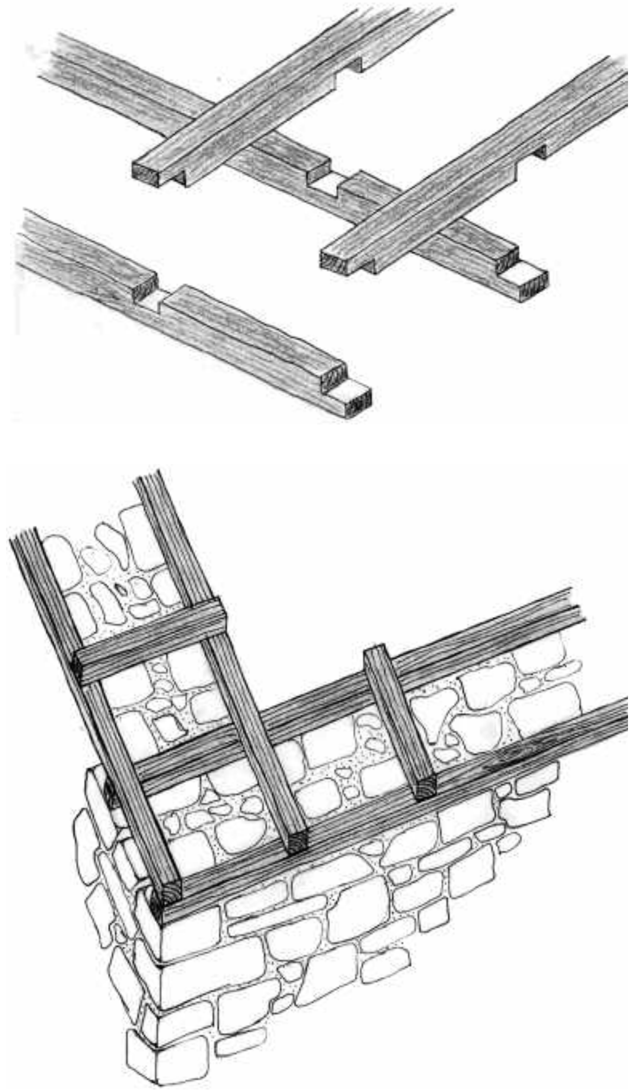
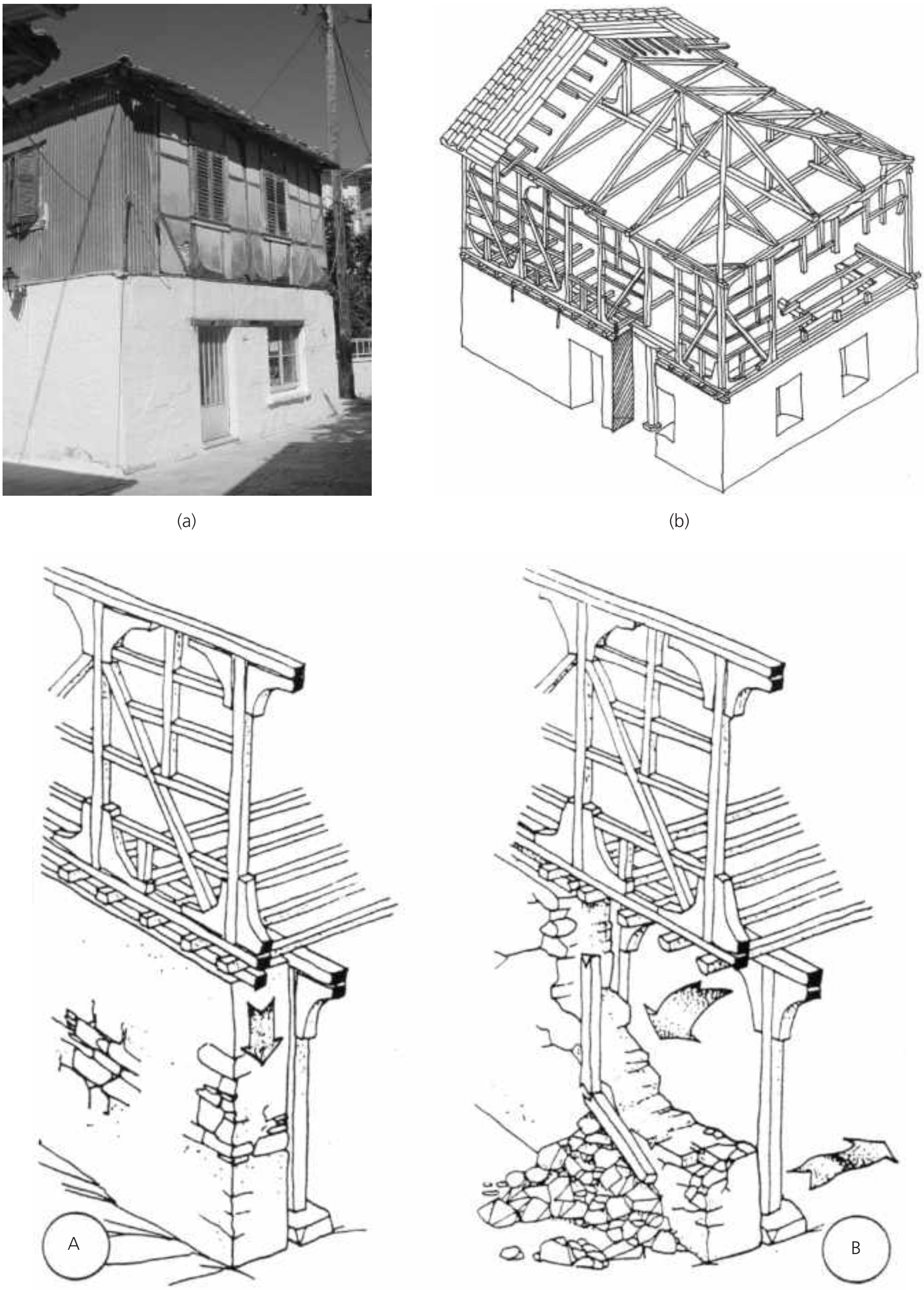


Figure 21. Typical connections between longitudinal and transverse timber elements (Vintzileou, 2008)

many centuries. It was a common belief that the high tensile strength of wood (as compared with the extremely low tensile strength of masonry) contributes to the enhancement of the bearing capacity of masonry elements; the use of the term 'imandosis' proves that they knew by experience that timber elements are able to tie together the perimeter walls of buildings, the leaves of masonry within the wall thicknesses, the floors and the roof to the walls and so on. These timber ties enhanced the 'box action' of the masonry structures – a major characteristic of safety against earthquakes. These well-tied boxes are less deformable and, hence, less liable to disintegration and to collapse than are other 'open' forms of structures.

(*c*) It is fascinating, however, to observe that the respect of the 'rules' for satisfactory seismic behaviour did not lead to uniformity in architecture. On the contrary, even the few examples presented in this paper show a vast variety of architectural forms; the respective structural solutions (obviously conceived together with the architectural forms) are far from being conventional and conservative. To mention the example of Minoan villas and that of residential houses in Akrotiri, large open spaces are created within the buildings. In those cases, 3D timber structures are provided; they enhance the bearing capacity and the stiffness of masonry, while serving functionality and allowing for innovative architectural design.

(*d*) It has to be noted, however, that although timber is quite durable under certain conditions, timber elements within masonry are not everlasting. This is one of the major problems the modern structural engineer has to face in the effort to preserve timber reinforced historic structures. Although several solutions are available, the problem still asks for more alternative solutions and for better documentation of those that are available.




(c)

**Figure 22.** Historic centre of Lefkada: (a) typical house, (b) the bearing system (schematic, sketch by P. Touliatos) and (c) the function of the secondary timber system (schematic, sketch by P. Touliatos)

**REFERENCES**

Evans AJ (1921) *The Palace of Minos: A Comparative Account of the Successive Stages of the Early Cretan Civilization as Illustrated by the Discoveries at Knossos*. Volume 1: The Neolithic and Early and Middle Minoan Ages. McMillan and Co., London.

Palyvou C (1999) *Akrotiri-Thera: The Art of Construction*. Library of the Archaeological Society of Athens, No 183, in Greek.

Photios I (2004) *Λέξεων Συναγωγή (Collection of Words)*. Volume B (E–O), Kaktos, Athens, in Greek.

St. John Chrysostom (1842) *The Homilies On the Statues; or to the People of Antioch*. Members of the English Church, reprint from the book published in Oxford, John Henry Parker, J.G.F. and J. Rivington, London.

Suda On Line (2011) Adler number: iota, 332 (headword: *himantes* – straps). See http://www.stoa.org/ (accessed 20 May 2011).

Touliatos P (2009) *The Doheiarion Monastery in Mount Athos – The Architecture of the Katholikon and the Tower*, National Technical University of Athens, 2009, 134 pp. (in Greek).

Tsakanika E (2006) *The Structural Role of Timber in Masonry of Palatial Type Buildings in the Minoan Crete*. Doctor Thesis, National Technical University of Athens, in Greek.

Vintzileou E (2006) *Panaghia Krina in Chios: Identification of Timber Reinforcement, Assessment of Current State and Related Interventions*, Research Report, in Greek.

Vintzileou E (2008) The effect of timber ties on the behaviour of historic masonry. *ASCE, Journal of Structural Engineering* **134(6)**: 961–972.

Vintzileou E and Skoura A (2009) Seismic behaviour of timber reinforced masonry buildings. *Proc. of the 1st International Conference on Protection of Historical Buildings, PROHITECH, Rome*, in electronic form.

Vintzileou E, Zagotsis A, Repapis C and Zeris Ch (2007) Seismic behaviour of the historical structural system of the island of Lefkada, Greece. *Construction and Building Materials* **21(1):** 225–236.

**WHAT DO YOU THINK?**