

# Structural Integrity Modelling of an Early Bronze Age Corridor House in Helike of Achaea, NW Peloponnese, Greece

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## Abstract

Structural integrity modelling and simulation studies were performed on the Helike Corridor House (HCH), a monumental building excavated at the Early Helladic (EH) site of Ancient Helike on the NW Peloponnese, Greece. The aims of the research were to explore building materials and plan alterations of an earlier phase into an EH II-III period Corridor House. Static load analysis followed by buckling (failure) analysis was simulated using ANSYS. Results demonstrate that buckling would develop in the narrow corridor area, being the critical spot in the structure due to its configuration of long tall sidewalls. It is shown that when stairs are introduced, the structure becomes less susceptible to buckling. We conclude that the doubling of the outer walls was a high structural and functional technical innovation which required specialized knowledge on planning and construction highlighting the critical role architecture played in response to upcoming social transformations.

**Keywords:** Helike, Corridor House, Early Helladic Architecture, Structural Integrity, Finite Element Analysis

## 1 Introduction

The Helike Corridor House (HCH) excavated foundations (Katsonopoulou, 2011) reveal an outstanding and monumental house prototype of the late Early Helladic (EH) II-early III (mid- to second half of the 3<sup>rd</sup> millennium BC), fitting with the mostly debated architectural template of the Greek mainland in this period. This paper investigates analytical modelling and simulation studies on the HCH to test the way innovative features were incorporated to guarantee its structural integrity, and assess the significance of such architectural innovations to proto-urban setting.

More specifically, reviewing older research in the southern Greek mainland, the corridor feature has been associated with various material transformations and innovations in the EH period (Peperaki, 2004; Maran and Kostoula, 2014). Although it emerged individually as a widespread but distinct architectural trait in several sites (Hägg and Konsola, 1986; Harrison, 1995; Wiersma, 2013), it was adopted with a patterned arrangement along the side walls of certain houses for the configuration of this innovative and complex kind of building, called the ‘Corridor House’, at some stage of the EH II (Shaw, 1987; 1990; 2007). One aspect of the complex debate about establishing these external corridors has derived from the implication that they hosted stairways leading to an added second storey. More than that, the recovery of precious equipment and distinct accessories from these houses, along with their presence as unique examples inside the settlements, has promoted arguments for their possible centralized administrative role and the rapid advance of the EH society towards hierarchical pre-state modes (Maran, 1998; Pullen, 2008).

On account of these regional and cultural connotations, further definition of the detailed material data of the known corridor houses has been long-attempted by an array of scholarly analysis of their design, purpose, construction techniques and material equipment (Themelis, 1984; Pullen, 1986; Aravantinos, 1986; Shaw, 1987; 1990; Wiencke, 1989; 2000; Kalogerakou, 1999; Maran and Kostoula, 2014), always with an eye to verify the broader social advances of the period. Within this integrative framework, the present material and structural analysis of the particular HCH is expected to provide research on Helike with challenging implications that will go beyond the house's individual features and will contribute to understanding the social and economic significance of the settlement itself and also the rise of this long-debated building type in the wider mainland context.

The HCH was revealed during excavation work carried out by the Helike Project (Katsonopoulou, 2011), a interdisciplinary and cross-cultural landscape archaeology and geomorphology project conducted in the major Helike area in Achaia, NW Peloponnese (Katsonopoulou, 1998; 2005; Soter and Katsonopoulou, 2011) from 1988 onwards. Although the particular structure was excavated along its western section only, as the rest of it extends into non-excavated neighbouring fields, its 'corridor' plan is testified by the arrangement of narrow corridors along the preserved external sides of an axially placed rectangular structure composed of a series of adjoining rooms.



**Figure 1:** The geographic location of the corridor houses at Helike, Lerna and Aegina

In this paper we propose a tentative reconstruction of the HCH based on comparable reconstructed corridor house plans as assumed by Shaw (1987). In particular the closer association of the HCH should be established with the EH II 'House of the Tiles' at Lerna in the Argolid (Caskey, 1959; Wiencke, 2000), and the 'Weisses Haus' (though this one is more complex) at Kolonna in Aegina

(Walter and Felten, 1981), whose plans Shaw (1987) has very critically assessed. The geographic locations of the mentioned sites are indicated in Figure 1. In a brief account of the HCH, the reconstruction of the missing east long sidewall in terms of length and openings are mirrored on the excavated west walls as shown in the conjectural plan. The entrance, outside openings and blind rooms are hypothesized on the basis of the above equivalent houses. More noticeable parallels between the HCH and the latter include the interior rooms varying in width -the side chambers being wider than the intermediate area-, and the non-axial arrangement of the interior doorways. Certainly one has to consider that other versions may be plausible for the reconstruction of the HCH in terms of minor features.

The account of rich interior items in the HCH and the evidence to the fact that it was modified from an earlier simpler long rectangular building are highly significant for the research questions posed in this paper. A large number of cooking and drinking vessels were revealed in the central rooms together with a remarkable assemblage of big storage jars in the side area placed in a row along the wall and bordering pebbled floor areas (Katsarou, 2011). Hearths and a rich collection of tableware from the centre of the chamber were also revealed. The changing plan therefore may in the first place indicate the addition of the corridor areas to the long and narrow sides in order to accommodate the storage facilities on the ground floor. Furthermore it implies the addition of a stairway to the upper floor, sheltered entrance, balcony appendages, and other side rooms to acquire increased space and monumentality.

We should also note that the EH settlement of Helike has revealed a number of free-standing long rectangular houses built across an area of about 30 hectares (Katsonopoulou, 2011). The buildings are arranged in poleodomic insulae and are aligned with long straight crossing cobbled roads, even featuring the presence of at least one open plaza (Katsonopoulou, 2011), all of which seem to have cut across an earlier plan of the settlement. The clear-cut town planning of Helike is strongly indicative of a collective communal project and thus of an administrative regime to organize its accomplishment before putting it into practice. The precious possessions of several houses in gold and silver and intimate exotic clay imports as implied by the unique *depas* cup (Katsonopoulou, 2011), strengthen the view that EH Helike constituted a rich trading community on the southwestern coast of the Corinthian Gulf. Within this context, the attribution of an administrative or socially differentiated role to the HCH, as assumed for corridor houses from other sites (Peperaki, 2004; Maran and Kostoula, 2014) are strongly justified. The above considerations provide an interpretative context for the HCH 3D reconstruction, materials characterization and structural analysis simulations described in the next sections.

## 2 Research Aims and Methodology

Reconstruction modelling, sometimes called ‘solid modelling’, ‘three-dimensional modelling’ or ‘Virtual Reality modelling’, has been used in archaeology since the late 1980s (Lock 2003, 152) and is now commonplace. The resultant ‘constructs, simulations and hyperreal worlds’ (Goodrick and Gillings 2000) have largely moved on from attempting to offer objective and accurate representations of the past as was claimed for many early models, to being a more exploratory method of thinking about what the past may have entailed. It is within this context of ‘what if modelling’ that we present this work based on an aspect of reconstruction that is relatively new to archaeology, that of testing the structural integrity of buildings.

Structural analyses through computer models are widely used in architecture and engineering to study the behaviour of real world structures (Lawrence, 2012). These studies can replace real experimentation and measurements as the simulations are based on precise physical models allowing the specification of materials, geometries, and their ability to withstand a large variety of loads. Structural analysis requires thus, the specification of materials, their physical and mechanical properties, geometry, and the loads acting on the structures. This kind of analysis has been used

before in connection to cultural heritage. For instance, finite element analysis has been employed to assess seismic vulnerability as a way to predict ruptures in the case of earthquakes (Shakya *et al.*, 2012; Dowling, 2004), as a guide to the restoration of monastic buildings (Miles, 2014), to study the durability of materials (Varum *et al.*, 2011; Ruano *et al.*, 2012), and to test historical masonry structures for the restoration of the Bam Citadel destroyed by an earthquake in 2002 (Hejazi and Saradj, 2014).

This research is based on ANSYS (Lawrence, 2012; Sharpe, 2008), which is a sophisticated modelling and simulation platform for testing and validating the physical behaviour of structures based on Finite Element Analysis and mechanical properties of materials. ANSYS provides a number of tools and utilities integrated and deployed from a single workbench. The HCH is the first Early Helladic corridor house to be analysed by this methodological tool.

The aims of the research are to formulate and validate hypotheses based on finite element modelling to test the structural integrity of the HCH. Results and conclusions would be directly relevant to similar buildings where evidence is scanty (e.g. mostly foundation walls). Related research questions include:

- What is the structural value of the added corridors to the monumentality of the building, i.e. in terms of load bearing, can a clear indication be provided of whether or not a second floor might have existed?
- On what structural properties was the choice of construction materials based?
- Why and how was the plan of the earlier house modified resulting in long narrow corridors and their relationships to facilities on the ground and upper floor?
- How does the HCH compare with the ‘House of the Tiles’ at Lerna and the ‘Weisses Haus’ at Kolonna, Aegina, in terms of isometric relationships and building materials?

The modelling and simulations reported in this paper involves static structural analysis followed by linear buckling analysis, which aims to determine at which level the load (i.e. the weight of the roof and other structural components) renders the structure unstable. Developing such a simulation and analysis in ANSYS involves the following steps:

- Select the analysis to perform (e.g. linear buckling)
- Specify materials engineering data, i.e. their mechanical properties which include the material’s density, compressive and tensile yield strengths, Young’s modulus of elasticity and Poisson ratio. Other properties such as the bulk and shear modulus are derived from Young’s modulus and Poisson ratio
- Define the geometry of the structure as a solid 3D model
- Specify the physical model and assign materials to various parts of the structure
- Set up the initial forces and loads acting on the structure
- Select a solution to perform (e.g. stress). The APDL (ANSYS Parametric Design Language) is used to solve the physical model and perform the simulations
- Display the results in graphic and text report formats.

These steps are described in Sections 3 and 4.

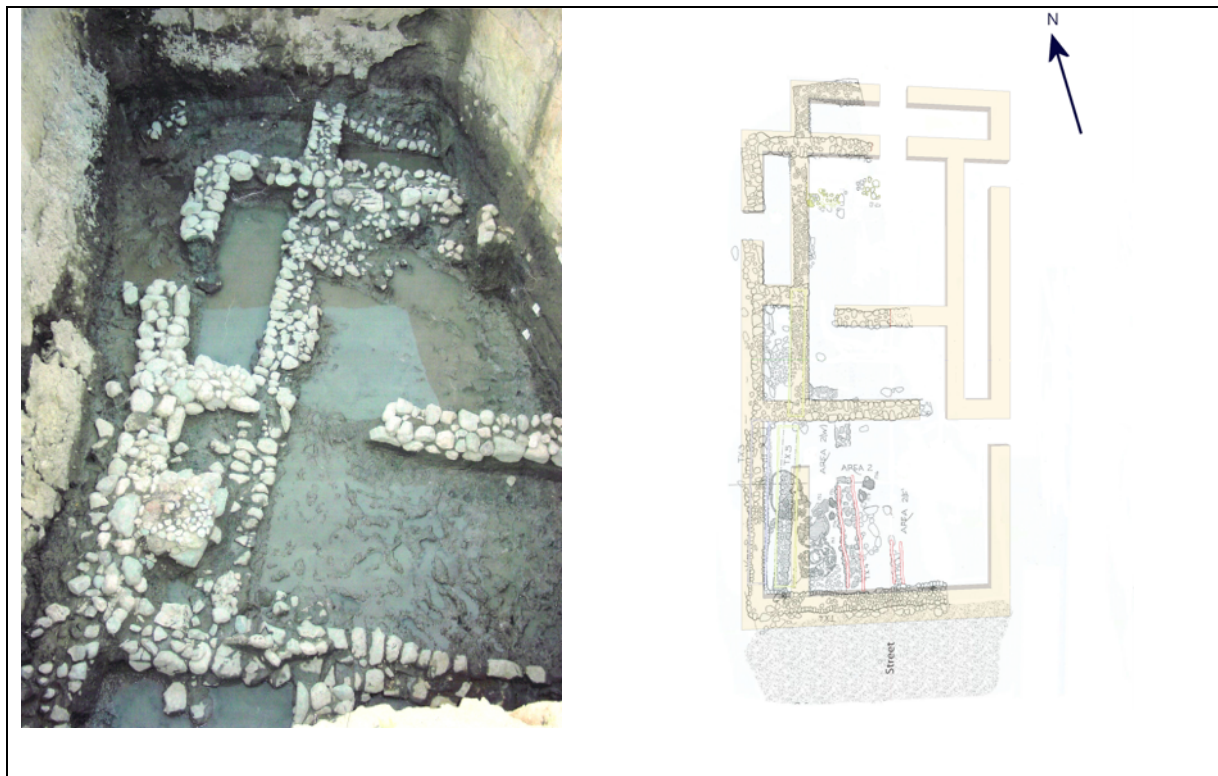
## 3 Geometry and Materials Characterisation

### 3.1 Geometry Modelling

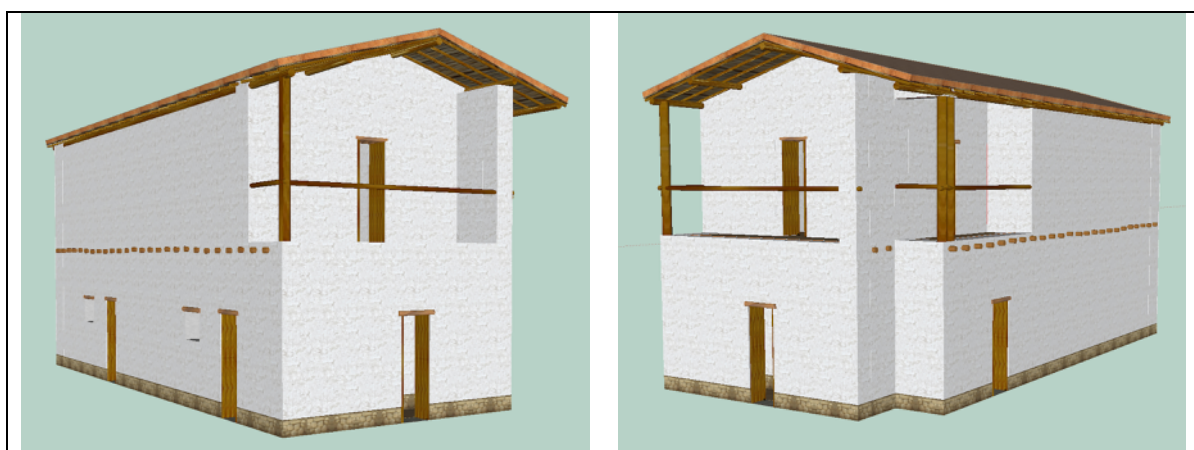
The ANSYS Design Modeler is a geometric modelling package with predefined geometric shapes and operations such as extrude, revolve and sweep together with advanced operators such as logic Boolean and blending. However, a number of operations are not intuitive and require various steps to complete and for this reason the 3D models of the house structure were drawn using SketchUp (2015), which provides a finer level of control and is more user-friendly. The models are then

exported from SketchUp to a standard 3D file format and imported directly into ANSYS Design Modeler providing a full integration into ANSYS Mechanical APDL.

The house plan geometry is derived from accurate measurements of the excavated foundation walls at the EH Helike site. Figure 2 shows part of the excavated foundation walls during the 2003 season and a corresponding drawing of the HCH with added conjectural plan that was used to guide the 3D reconstruction. Figure 3 illustrates two views of the 3D reconstructed house performed in SketchUp.



**Figure 2:** Left: view of the north western part of the HCH during fieldwork in 2003; right: full drawing of the ground plan.



**Figure 3:** The 3D model of the HCH, based on the house plan of Figure 2.

### 3.2 Materials Characterisation

The stone foundation walls of the HCH have been buried for the past 4,000 years at a depth of about 3 to 3.50m below present surface. Other structural materials such as complete bricks, wooden structures and roof tiles have not survived. Excavation shows that the house walls were built of adobe (sun dried mud brick), few samples of which have been recovered. Other assumed building materials are wood (*Pinus halepensis* and *Olea spp*) and reed (*Arundo donax*), their mechanical properties are characterized as follows.

The Young's Modulus of elasticity is a measure of stiffness of an elastic material when stretched or compressed. The Poisson Ratio is the decrease in lateral measurement to the increase in length in a sample of material that is elastically stretched. The higher the Poisson ratio, the more elastic the material is. The tensile strength is the maximum amount of tensile stress a material can take before failure; it is defined as the ratio of *stress* (force per unit area) along an axis to *strain* (ratio of deformation over initial length). The compressive strength is the capacity of a structure to withstand loads in the elastic region.

The mechanical properties of materials are normally obtained through standardized destructive and non-destructive tests (Hibbeler, 2013). In order to determine the compressive and tensile strengths of mud bricks together with their modulus of elasticity and Poisson ratio, it would be necessary to run destructive tests on a number of samples. Since only eroded samples of brick are available from the site, and these certainly cannot be subject to destructive tests, image-based analysis was performed yielding estimated composition of 30% gravel, 53% sand, silt and clay and 17% straw (Iliopoulos, 2014). This led to density estimates and comparison with known properties of ancient mud bricks and other building materials elsewhere for the required mechanical properties (King, 1996; Keefe, 2005; Houben and Guillaud, 1989). The adobe brick mean density was estimated at 1,737kg.m<sup>-3</sup>. The Young's modulus of elasticity was assumed 54.7Mpa (Adorni *et al.*, 2013). The Poisson ratio was 0.17, the compressive strength 1.2MPa and the tensile strength 0.04MPa (Hejazi and Saradj, 2014; Academia, 2015). Table 1 shows the assumed mechanical properties of adobe brick together with other materials discussed below.

**Table 1:** Mechanical properties of building materials.

	Density <b>Kg.m<sup>-3</sup></b>	Young's Modulus <b>MPa</b>	Poisson Ratio	Compressive Strength <b>MPa</b>	Tensile Strength <b>MPa</b>
Adobe Brick	1,737	54.7	0.17	1.2	0.04
<i>Pinus halepensis</i>	600	10,770	0.17	61	81.6
<i>Olea spp</i>	990	17,770	0.25	62	31
Reed <i>Arundo donax</i>	234	9,000	0.25	665	321.7

The upstairs floor structure of the HCH was assumed according to interpretations in the literature (Wiencke, 2000) to be composed of three layers: a wooden supporting structure, a layer of reed and a layer of mud or rammed earth. The wooden component of the floor discussed in terms of the doorways at the 'House of the Tiles' (Maran and Kostoula, 2014) would likely to have been constructed from transversal and longitudinal beams of the local species *Pinus halepensis* with mean diameter of 110mm and 180mm respectively. *Pinus* is also assumed for the construction of stair structure between ground floor and first floor. Evidence for *Pinus halepensis* can be found on the northwestern coast of Peloponnese during the Holocene (Lazarova *et al.*, 2012). Radiocarbon analysis of sediment cores indicate that pine communities dominated the landscape during the Neolithic period but, possibly as a result of human intervention, were strongly reduced during the Early Bronze Age (Lazarova *et al.*, 2012). The mechanical properties of *Pinus halepensis* quoted in Table 1 were determined by mechanical testing (Correal-Modol, 2012; Zanne *et al.*, 2009) and by similarity to related species (Ozkaya, 2013).

Pollen diagrams also show evidence for cultivation of *Olea spp* in the northern Peloponnese in the Holocene (Lazarova *et al.*, 2012). The use of *Olea spp* in the form of reinforcing beams above doors

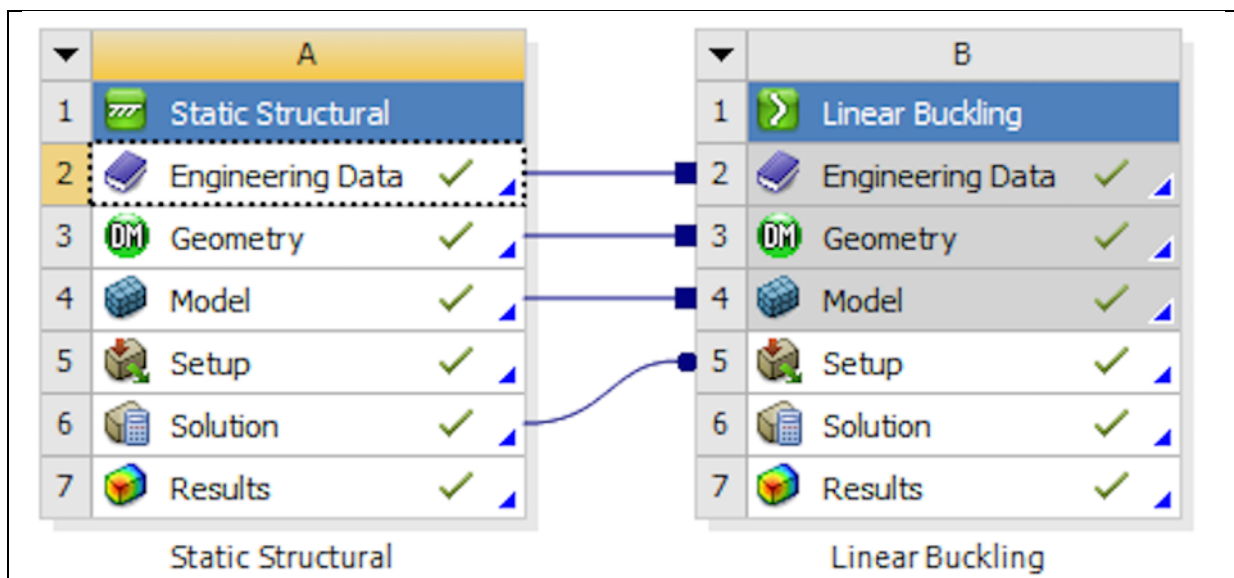
and window frames inside the upper floor wooden component is observed at the Cycladic Bronze Age settlement of Akrotiri, Thera, Greece (Palyvou, 2005). In the HCH we may equally consider the possible use of reinforcing longitudinal beams from *Olea spp* beneath the *Pinus halepensis* floor structure, and also in the construction of the steps in the stair structure. The assumed mechanical properties (The Wood Database) are quoted in Table 1.

Reeds are a building material widely used since ancient times mainly to support and hold mud or clay on floor and roof structures and fences. They are well adapted to saline environments (Koutsios and Kontopoulos, 2011) and exist in abundance in the area of Helike to this day. It is assumed that the local species *Arundo donax* (Cartwright & Taylor, 2011) is the mostly likely to have been used in the floor substructure. Its mechanical properties (Barreca, 2012; Spatz *et al.*, 1997) are quoted in Table 1.

The roof structure of the HCH is also conjectured as being of similar construction and materials as the upstairs floor: a wooden structure made out of supporting *Olea spp* beams overlaid by *Pinus halepensis* beams followed by a layer of reed *Arundo donax*. A layer of rammed earth would cover the reeds. The roof would have an added topmost layer of tiles. The mechanical properties of the roof structure were not tested as such; instead their equivalent weight acting on the supporting wall structure was used in the simulations reported in the next section. The total weight of the roof structure was calculated from the density of each material multiplied by their volume. The volume was directly obtained from the solid models generated in SketchUp.

## 4 Structural Integrity Simulation Settings and Results

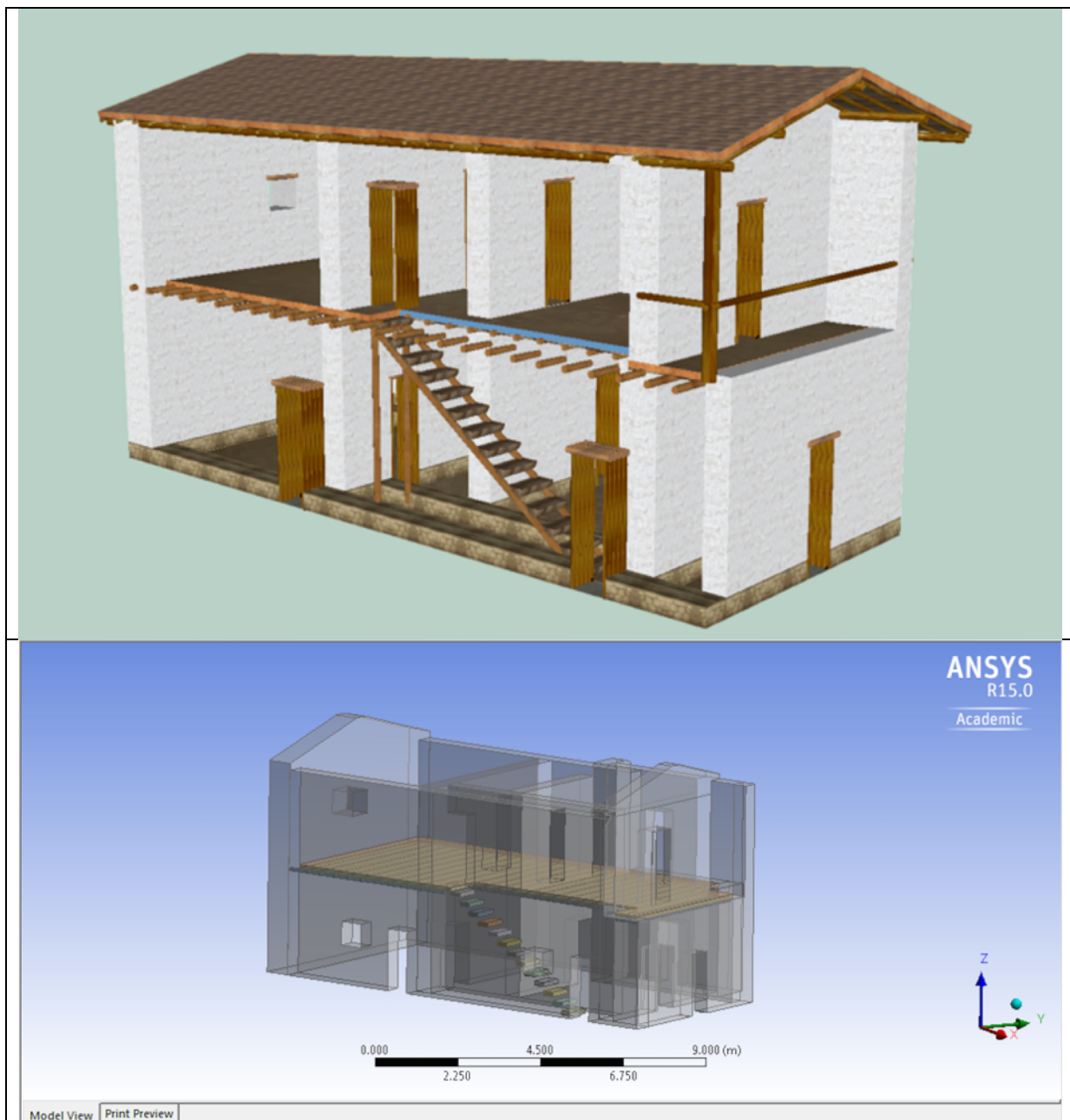
Figure 4 shows the top level ANSYS schematic program to perform static structural analysis followed by linear buckling. In order to build a simulation model, one must work the way down from the top by first specifying engineering data. These are the mechanical properties for each material as defined in Section 3, which are added to the standard ANSYS database of material properties. The solution to static structural analysis is then used as input to linear buckling analysis as shown in Figure 4.



**Figure 4:** ANSYS schematic program.

Following *Engineering Data*, the *Geometry* of the structure is specified. All 3D geometries developed in SketchUp were exported as solid models in IGS, which is a data format designed to exchange 3D information. These were then directly imported into ANSYS. The 3D models were divided into

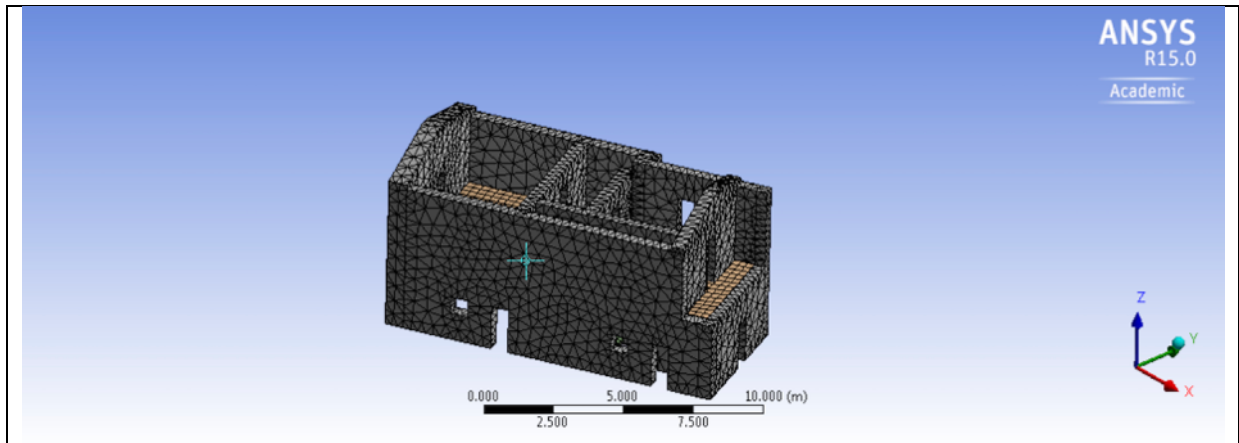
groups as follows: 1) Foundations, 2) Walls, 3) Floor: wooden structure, 4) Floor: reed structure, 5) Floor: mud layer, and 6) Stair structure.



**Figure 5:** Top: visualization of the 3D model (with some walls removed to show interior); bottom: ANSYS model with roof removed.

Figure 5 top shows the SketchUp model with two walls removed so that the interior floor and stairs could be visualized. Figure 5 bottom shows the imported geometric structures into ANSYS. It is necessary to specify the bonding of various structures before the physically based simulation, that is, whether the various walls are allowed relative motion or not. In the simulations of the HCH we specified that all structures are bonded together and no relative independent motion is allowed.

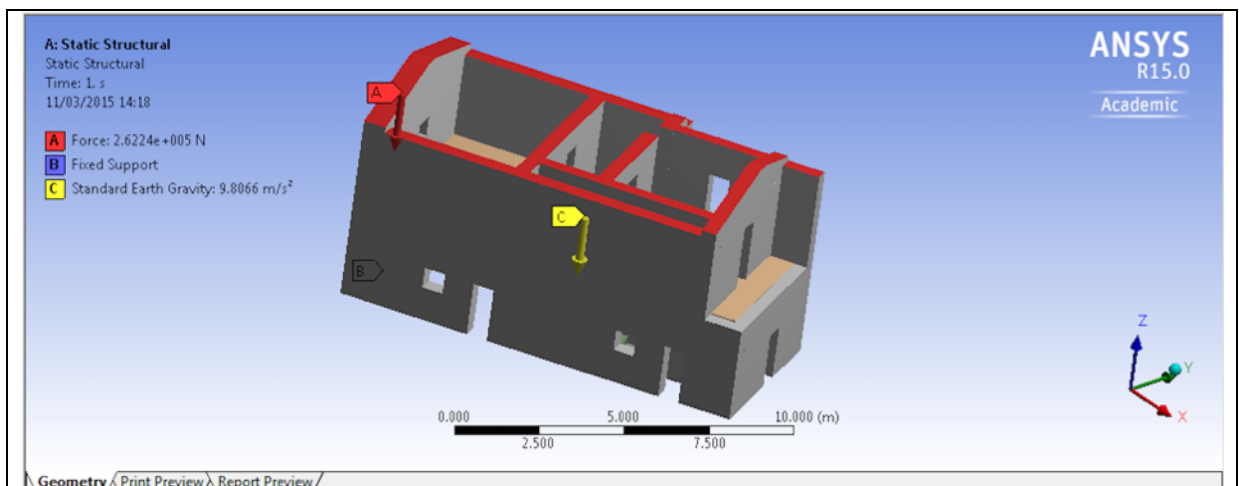




**Figure 6:** Tetrahedral meshing operation on the 3D structure.

Having imported the geometry, the mechanical *Model* is specified starting from meshing the 3D structure and assigning materials to their respective geometries. ANSYS has a range of meshing tools and mesh refinements to ensure simulations will accurately validate the physical model. We used tetrahedral meshing as depicted in Figure 6. ANSYS has a ‘physics preference setting’ to ensure the most appropriate mesh is generated for each simulation. The size of each element of the mesh can be controlled by the user: the smaller the (finite) element, the more precise the answer, but the price to pay is that of higher computational costs.

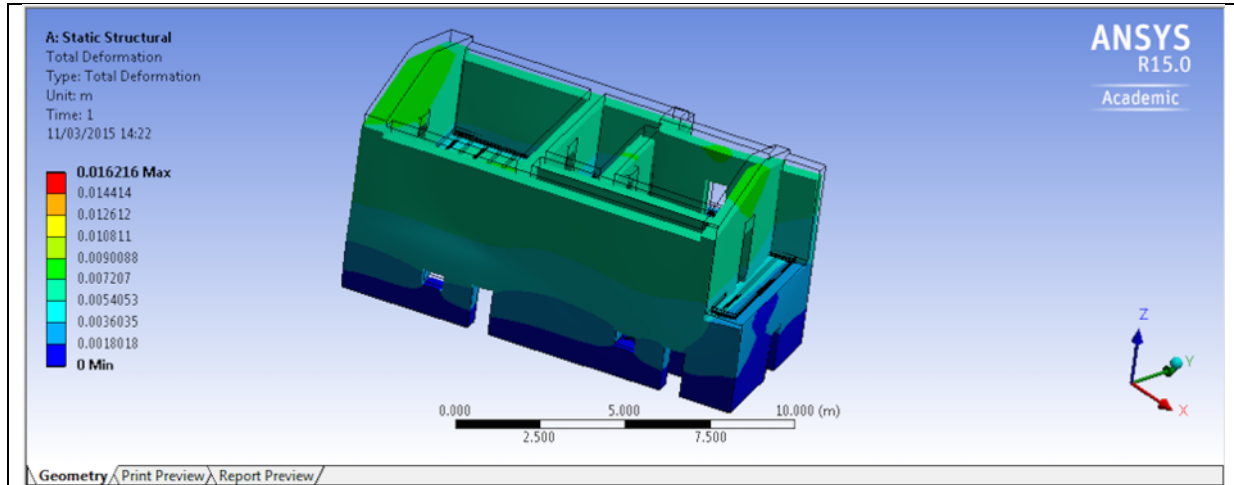
In the *Setup* step the parameters of the analysis, namely all loads, forces and support acting on the structure are specified. Only a single compression force is required given as the total weight of the roof plus the live load. The weight of the roof is carefully calculated from the geometry of its various components using their respective densities. A live load is added equivalent to 1ton (~9,800N) to represent people and furniture, yielding a total downward force of 262,244N acting on the surfaces indicated in red in Figure 7. Inertial forces were also included using the standard gravity acceleration (in yellow), so the weight of the wall acting on every element is also taken into consideration. When considering compression forces due to weight integration effects, note that the bricks at the bottom of the wall near to the ground are placed under considerably higher compression than the ones touching the roof.



**Figure 7:** Load setup showing downward forces acting on the surfaces in red.

Finally, a fixed support is added to ensure that wall structures are fixed to the foundations and are constrained in all directions, that is, the bottom surfaces of the walls are not allowed to slide or move along the  $x, y$  or  $z$  axes. ANSYS then solves the analysis (the *Solution* step) using the Finite Element Method by applying the specified loads and constraints propagated to each element of the mesh and

then integrating the results, which can be reviewed using a range of graphical tools and tabular formats. The results for total deformation from static structural analysis are depicted in Figure 8. The maximum deformation for the applied load is 16mm. This would be difficult to show on a 6m tall wall, so the deformation relative to the original outline in Figure 8 is exaggerated for the purposes of visualization.



**Figure 8:** Total deformation in static structural analysis (exaggerated for visualization).

Buckling analysis is used to determine the buckling loads, or the loads in which the structure becomes unstable (Hibbeler, 2013). It is justified and widely used to test slender structures such as walls and columns. The technique seeks to determine the load level at which the structure becomes unstable, and this is achieved by gradually increasing the load. The classic Euler formulation for a column is defined as:

$$F = \frac{n\pi^2 EI}{L^2}$$

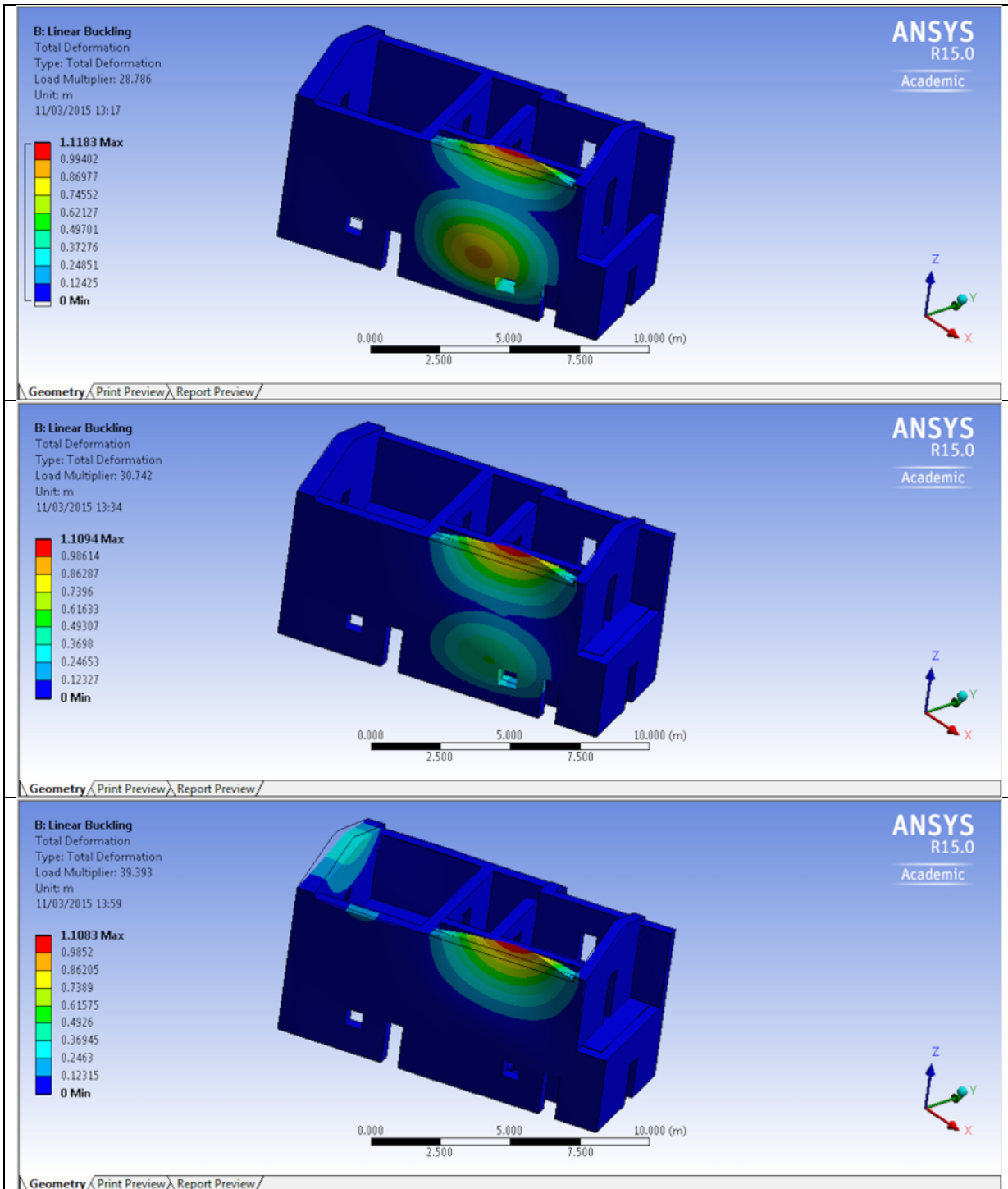
where  $F$  is the allowable load,  $n$  is the number of end conditions,  $E$  is the modulus of elasticity,  $L$  is the length of the column, and  $I$  is the moment of inertia. At the onset of instability (buckling) the structure will have a very large change in displacement with no change in applied load. To estimate this condition, the linear buckling analysis predicts the theoretical buckling strength by solving for the load multiplier  $\lambda_i$  as a function of the applied load:

$$([K] + \lambda_i[S])\{F_i\} = 0$$

where  $K$  and  $S$  are constant and the response based on the loading  $\{F_i\}$  is a linear function of  $\lambda_i$ . The critical load specified through the load multiplier must be treated only as a prediction as the load multiplier is not a safety factor. In order to find the actual critical load, a non-linear analysis would be required. The research reported in this paper focuses on linear buckling only and thus, uses the load multiplier as a prediction of structure stability.

Simulations were performed on the HCH 3D model by including or removing various elements of its structure resulting in three relevant what-if scenarios as follows.

1. The house structure as defined by external and internal walls only.
2. The house structure with the addition of the upper floor components including the wooden structure, and the layers of reed and mud.
3. The house structure with the addition of the NNE long side stairway.



**Figure 9:** Top: buckling of the HCH structure defined by the walls only; middle: buckling with addition of the upstairs floor; bottom: buckling with the addition of upstairs floor and stairs.

Figure 9 depicts the results of linear buckling analysis for the three cases considered. It can be seen that the weakest area of the house is the external wall of the corridor containing the staircase. The respective buckling load multipliers are 28, 30 and 39 where normally the higher the multiplier the more rigid and stable the structure. The simulations clearly demonstrate the relative importance of the stairs as a structural element as is evident in the highlighted areas of the model and by the change in load multiplier: by adding the upstairs floor, the multiplier goes from 28 to 30 but when stairs are added it goes from 30 to 39. Although these are rough predictions, it is clear that the structure would not collapse under the applied loads in normal circumstances – i.e., in the absence of large external disturbances such as an earthquake.

The interpretation of the results leads to the following assertions:

- The design inferred from the foundation walls is capable of supporting a second floor.
- The wall most susceptible to buckling is the outside wall to the stairs, along the NNE side of the house.
- The addition of the upper floor structure provides the HCH with the advantageous side effect of making the external NNE wall more rigid, and thus reducing the magnitude of buckling.
- The addition of the stairway makes the external NNE wall even more rigid and totally removes the probability of buckling on the ground floor.
- The designers have solved structural buckling issues by adding internal transverse walls at 90 degrees to the double NNE wall and to the west façade corridors, which made the structure more rigid and less susceptible to buckling. Instead of providing access to the second floor, these corridors may have accommodated supplementary rooms in the periphery of the ground floor and a more complex entrance, and had possibly supported one or more upper floor balconies.
- The wall on the south façade was built thicker than any other wall (700mm against 470mm and 400mm of other walls), which also has the effect of reducing its susceptibility to buckling. Had it been built with the same thickness as the other walls, our simulations show that it would be as prone to buckling as the NNE external wall.

## 5 Discussion and Conclusions

The present project has created a 3D model of the HCH from the measurements and plan inferred from its excavated foundation walls. The house plan was compared with the plans of corridor houses at Lerna and Aegina to enable interpretation of missing components. The model was exported as a 3D solid and loaded into ANSYS for structural analysis. All construction materials were carefully defined concerning their dimensions and respective mechanical properties, namely density, Young's modulus of elasticity, the Poisson ratio, compressive and tensile strengths. These parameters were used to perform finite element-based structural simulations to study the behaviour of the structure and to verify whether or not it would be able to support a second floor.

The models have proved that the modification of an earlier EH II rectilinear ground floor house into a corridor type of building by transforming its sides into the form of double walls or corridors to accommodate the stairway access to the upper floor and auxiliary peripheral rooms, would have met perfectly the structural prerequisites for the HCH to achieve increased space and a monumental height. The suitability of the assumed building materials has been validated by successful structural integrity tests for their loads under normal circumstances. A static structural model followed by linear buckling analysis revealed the areas of the building more susceptible to buckling. It however verified that linear buckling would not develop under the imposed static loads, and the structure would be able to support a second floor thanks to the added 'corridors' and more subtle architectural choices.

Our research points to the specialization of Helike builders on planning and creating architecture. It is interesting to note the number of similarities between the HCH and the 'Weisses Haus' at Aegina, and the 'House of the Tiles' at Lerna. The scale is intriguing: the 'Weisses Haus' is about 1.5 times larger than the HCH while the 'House of the Tiles' is twice as large. This scale applies to length, width, and wall thickness. The HCH measures 6.25x12.50m with wall thickness ranging from approximately 0.45-0.55m, 'Weisses Haus' 9x18.5m with wall thickness of 0.60m while the 'House of the Tiles' measures 12x25m with wall thickness of 1m. The analogy looks too coincidental and may suggest that the sites shared architectural plans as suggested by Shaw (2007) in terms of size and internal arrangements. This may also strengthen the argument for similar engineering practices and construction materials, as half the size would call for half as thick wall as observed in the three houses. The observation may also account for the scenario according to which the plan and building techniques were optimized and then re-used across the region.

The HCH project suggests rapid architectural changes and technological advances through modifications of an earlier design into a monumental corridor house. The employment of standardized architecture such as the corridor type structure at Helike and the broader EH region is the result of social changes such as the need for accommodating a rising number of residents, an administrative centre, an assembly hall, a kin group or communal storage place. Such a social context would lead to the development of larger households and other buildings for public use.

The EH Helike was destroyed by an earthquake accompanied by fire resulting in its immediate abandonment, leaving the contents of its buildings intact and sealed under mixed terrestrial, marine and lagoonal deposits. Further research will address the structural weaknesses of the adobe brick walls of the free standing, two storeys HCH to the effects of an earthquake (Varum *et al.*, 2014) as well as palaeo-seismological data to determine the magnitude of the earthquake that would have been sufficient to destroy the house. These are working hypotheses to be tested in the next stage of our research.

## References

Academia.edu. (2015). *Some Useful Numbers on the Engineering Properties of Materials (Geologic and otherwise) Angle of Internal Friction.* [Online] [http://www.academia.edu/4156626/Some Useful Numbers on the Engineering Properties of Materials Geologic and Otherwise Angle of internal friction.](http://www.academia.edu/4156626/Some_Useful_Numbers_on_the_Engineering_Properties_of_Materials_Geologic_and_Otherwise_Angle_of_internal_friction) [Accessed: 3<sup>rd</sup> November 2014]

Adorni, E., Coisson, E. and Ferreti, D. (2013) In situ characterization of archaeological adobe bricks. *Construction and Building Materials*. 40 (March 2013). p.1-9.

Aravantinos L. (1986) The EH II Fortified Building at Thebes: Notes on its Architecture. In: Hägg, R. and Konsola, D. (eds) *Early Helladic Architecture and Urbanization*. Göteborg: Paul Åströms - Förlag.

Barreca, F. (2012) Use of giant reed *Arundo donax* L. in rural constructions. *Agricultural Engineering International: CIGR Journal*. 14 (3). p. 46-52.

Cartwright, C. and Taylor, J. (2011) Investigating technological and environmental evidence from plant remains and molluscs in cuneiform tablets. *The British Museum Technical Research Bulletin*. 5 (2011). p. 67-72.

Correal-Modol, E. (2012): Properties of clear wood and structural timber of *Pinus halepensis* from northeastern Spain, *World Conference on Timber Engineering*. Auckland, New Zealand. 2012.

Dowling, D. (2004) Adobe housing in El Salvador: Earthquake performance and seismic improvement. In: Rose, I., Bommer, J.J., López, D.L., Carr, M.J. and Major, J.J. (eds) *Geological Society of America Special Papers*. p. 281-300.

Goodrick, G. and Gillings, M. (2000). Constructs, simulations and hyperreal worlds: the role of Virtual Reality (VR) in archaeological research. In: Lock, G. and Brown, K. (eds) *On the Theory and Practice of Archaeological Computing*. Oxford: Oxford University Committee for Archaeology Monograph (51). p. 41-58.

Hägg, R. and Konsola, D. (eds) (1986) *Early Helladic Architecture and Urbanization*. Göteborg: Paul Åströms - Förlag.

Harrison, S. (1995) Domestic Architecture in Early Helladic II: Some Observations on the Form of Non-monumental Houses. *British School at Athens* (90). p. 23-40.

- Heath, M.C. (1958) Early Helladic Clay Sealings from the House of the Tiles at Lerna. *Hesperia* (27). p.81-120.
- Hejazi, M., Saradj, F.M. (2014) *Persian Architectural Heritage: Structure*. Southampton: WIT Press.
- Hibbeler C. R. (2013). *Mechanics of Materials*. 9<sup>th</sup> edition, N.J.: Prentice Hall.
- Houben, H. and Guillaud, H. (1994) *Earth Construction, A comprehensive guide*. Rugby Warwickshire: Practical Action Publishing.
- Iliopoulos, I. (2014) *Image Analysis, Samples H61 and H21* [email]. Message to: Katsarou, S. 29 October 2014.
- Kalogerakou, P. (1999) 'Ta protoelladika II "Oikodomimata me diadromous": protaseis gia ti leitourgia kai ti simasia tous' In: Kilian-Dirlmeier (ed.) *Eliten in der Bronzezeit: Monographien des Römisch-Germanischen Zentralmuseums* (43). Mainz: p. 87-101.
- Katsarou-Tzeveleki, S. (2011) Morphology and distribution of pottery at the Early Helladic settlement of Helike, Achaia. In: Katsonopoulou, D. (ed.) *Helike IV. Ancient Helike and Aigialeia. Protohelladika: The Southern and Central Greek Mainland*, Athens: The Helike Society. p. 89-126.
- Katsonopoulou, D. (1998). The first excavation at Helike: Klonis field. A preliminary report. In: Katsonopoulou D., Soter S., Schilardi, D. (eds.) (1998) *Helike II. Ancient Helike and Aigialeia*, Aigion, 1-3 December 1995, Athens: The Helike Society. p.125-145.
- Katsonopoulou, D. (2005). Test excavations in the Helike Delta in 2000. In: Katsonopoulou, D., Soter S., Koukouvelas I. (eds.) *Helike III. Ancient Helike and Aigialeia. Archaeological Sites in Geologically Active Regions*, Nikolaiika, Diakopton, 6-8 October 2000, Athens: The Helike Society. p. 33-65.
- Katsonopoulou, D. (2011). A Proto-urban Early Helladic settlement found on the Helike Delta. In: Katsonopoulou D. (ed.), *Helike IV. Ancient Helike and Aigialeia. Protohelladika: The Southern and Central Greek Mainland*, Athens: The Helike Society. p. 63-86.
- Keefe, L. (2005) *Earth Building. Methods and materials, repair and conservation*. New York: Taylor and Francis.
- King, Bruce P.E. (1996) *Buildings of Earth and Straw*. Vermont: Chelsea Green Publishing Company.
- Koutsios, A. and Kontopoulos N. (2011). Middle to Late Holocene Record of Environmental Changes in the Coastal Area of Helike, NW Peloponnese, Greece. In: Katsonopoulou, D. (ed.) *Helike IV. Ancient Helike and Aigialeia. Protohelladika: The Southern and Central Greek Mainland*, Athens: The Helike Society. p. 185-198.
- Lawrence, K.L. (2012) *ANSYS Workbench Tutorial Release 14*, SDC Publications.
- Lazarova, M., Koutsios, A. and Kontopoulos, N. (2012) Holocene vegetation history of the Kotihi lagoon (northwest Peloponnesus, Greece). *Quaternary International* - Elsevier. (261). p.138-145.
- Lock, G. (2003) *Using computers in archaeology. Towards virtual pasts*. London: Routledge.
- Maran, J. (1998) Kulturwandel auf dem griechischen Festland und den Kykladen im späten 3. Jahrtausend v. Chr. Studien zu den kulturellen Verhältnissen in Südosteuropa und dem zentralen sowie östlichen Mittelmeerraum in der späten Kupfer- und frühen Bronzezeit. *Universitätsforschungen zur prähistorischen Archäologie*. Bonn: R. Habelt.

- Maran, J. and Kostoula, M. (2014). The spider's web: innovation and society in the early Helladic 'Period of the Corridor Houses'. In: Galanakis, Y., Wilkinson T. and Bennet J. (eds.) *AΘYPMATA. Critical Essays on the Archaeology of the Eastern Mediterranean in Honour of E. Susan Shettatt*. Oxford: Archaeopress. p. 141-158.
- Miles, J., (2014) Integration of laser scanning, photogrammetry and building surveying within the virtual reconstruction of Winchester Cathedral and its precinct buildings. *CAA 2914 Paris. Book of Abstracts*. [Online] [http://caa2014.sciencesconf.org/conference/caa2014/pages/BOACAA\\_2016.pdf](http://caa2014.sciencesconf.org/conference/caa2014/pages/BOACAA_2016.pdf) [Accessed: April 2014].
- Ozkaya, K. (2013) Determination of some physical and mechanical properties of Calabrian pine (*Pinus brutia* Ten.) trees grown in the Denizli area of Turkey. *International Journal of Physical Sciences*. 8(46). p. 2063-2068.
- Palyvou, K. (2005) *Akrotiri Thera: An Architecture of Affluence 3,500 Years Old*. Philadelphia: INSTAP Academic Press.
- Peperaki, O. (2004) The House of the Tiles at Lerna: Dimensions of Social Complexity. In: *The Emergence of Civilisation Revisited*. (ed) Barrett J.C., and Halstead, P. Sheffield Studies in Aegean Archaeology (6). Oxford: Oxbow. p. 214-231.
- Pullen, D. (2008) The Early Bronze Age in Greece. In: Shelmerdine C.W. (ed) *The Cambridge Companion to the Aegean Bronze Age*. Cambridge: Cambridge University Press. p.19-46.
- Pullen, D. J. (1986) A "House of Tiles at Zygouries"? The function of monumental Early Helladic architecture. In: Hägg, R. and Konsola, D. (eds) *Early Helladic Architecture and Urbanization*. Göteborg: Paul Åströms Förlag. p. 79-83.
- Ruano, A., Costa, A.G. and Varum, H. (2012) Study of the common pathologies in composite adobe and reinforced concrete constructions. *Journal of Performance of Constructed Facilities*. doi 10.1061/(ASCE)CF.1943-5509.0000200. 26(4). p. 389-401
- Shakya, M., Varum, H. Vicente, R. and Costa, A. (2012): Structural Vulnerability of Nepalese Pagoda Temples, *15 World Conferences on Earthquake Engineering*. Lisbon. [Online] [www.iitk.ac.in/nicee/wcee/article/WCEE2012\\_2919](http://www.iitk.ac.in/nicee/wcee/article/WCEE2012_2919). [Accessed: 28<sup>th</sup> October 2014].
- Sharpe, W.N. (ed) (2008) *Springer Handbook of Experimental Solid Mechanics*. Heidelberg: Springer.
- Shaw, J.W. (1987) The Early Helladic II Corridor House: Development and Form. *The American Journal of Archaeology*. (91). p.59-80.
- Shaw, J.W. (1990) The EH II "Corridor House": problems and possibilities. In: Darque, P. and Treuil, R. (eds). *L'Habitat égéen préhistorique BCH*. (19). Paris. p. 231-254.
- Shaw, J.W. (2007). Sequencing the EH II Corridor Houses. *British School at Athens*. (102). Athens. p. 137-151.
- SketchUp Pro. (2015) SketchUp main web page: Available from: <http://www.sketchup.com/>
- Soter, S. and Katsonopoulou D. (2011) Submergence and Uplift of Settlements in the Area of Helike, Greece, from the Early Bronze Age to Late Antiquity. *Geoarchaeology*. 26 (4). p. 584-610.
- Spatz, H.Ch., Beismann, H., Bruchert, F., Emanns, A., and Speck, T. (1997) Biomechanics of the giant reed *Arundo donax*. *The Royal Society*. B (352). London. p. 1-10.
- THE WOOD DATABASE. (2008) [Online] <http://www.wood-database.com/lumber-identification/hardwoods/olive/>. [Accessed: 20<sup>th</sup> February 2015]

Walter H. and Felten F. (1988) *Alt-Ägina Felten III.1: Die vorgeschichtliche Stadt: Befestigungen, Häuser, Funde*. Mainz: Verlag Philipp von Zabern.

Themelis, P. G. (1984) Early Helladic monumental architecture. *Athenische Mitteilungen* (99). p. 335-51.

Wiencke, M. (2000) Lerna, a Preclassical Site in the Argolid; The Architecture, Stratigraphy, and Pottery of Lerna III. *Results of Excavation by the American School of Classical Studies at Athens*.(4). Princeton.

Wiencke, M. (1989) Change in Early Helladic II. *American Journal of Archaeology*. (93). p. 495-509.

Wiersma, C. (2013) *Building the Bronze Age. Architectural and Social Change on the Greek Mainland During Early Helladic III, Middle Helladic and Late Helladic I*. Oxford: Archaeopress.

Varum, H., Figueiredo, A., Silveira, D., Martins, T., Costa, A. (2011) Outputs from the research developed at the University of Aveiro regarding the mechanical characterization of existing adobe constructions in Portugal. *Informes de la Construcción*. doi: 10.3989/ic.10.016. 63(523). p. 127-142.

Varum, H., Tarque, N., Silveira, D., Camata, G., Lobo, B., Blondet, M., Figueiredo, A., Rafi, M.M., Oliveira, C., and Costa, A. (2014) Structural Behaviour and Retrofitting of Adobe Masonry Buildings. In: A. Costa et al. (eds) *Structural Rehabilitation of Old Buildings, Building Pathology and Rehabilitation 2*. Heidelberg: Springer-Verlag. p. 37-75.

Zanne, E., Lopez-Gonzalez G., Coomes A., Ilic J., Jansen S., Lewis, L., Miller, B., Swenson G., Wiemann C., Chave J. (2009) Global Wood Density database. *Dryad Digital Repository*. [Online] <http://dx.doi.org/10.5061/dryad.234>. [Accessed: 8th November 2014].