# Comparison of different fem simulations of a modular wooden arch made with hollow blocks

Dora Foti, Giovanni Arrè, and Salvatore Carbone

***Abstract*—**The paper proposes a comparison of different numerical simulations by Finite Element Models (FEM) of an arch made of modular wooden blocks with a hollow shape. Experimental tests have been realized on a prototype of the arch and the results have been compared with the results obtained from the numerical simulations. Three different numerical modeling of the blocks have been assumed in three different models, that is beam elements, plate elements and block elements. They distinguish for the level of accuracy and the level of calculus. Results are interesting to evaluate the better compromise between accuracy and cumbersome calculus to get a reliable modeling of these kind of structures. In particular, the investigations carried out considering different levels of detail allowed to clarify the potential use of wood for structural purposes. The weakest points results to be the connections as the arch collapsed not for failure of the material, but because of its connections and the joints between the various blocks; they have to be improved and modified, especially to face wind and earthquake actions, different from the loads utilized in the present study and dangerous for lightweight structures.

***Keywords*—** Finite Element Modelling, Numerical Analyses, Wooden Arches and Vaults, Hollow shaped boxes.

## I. INTRODUCTION

WOOD was one of the first building materials and has been for the man the mean to solve, for centuries, the most complex structural problems. With the advent of reinforced concrete and steel, its use has been gradually decreasing. Such decline was much greater in Italy than in other European nations, while North America has continued to use it extensively, especially in civil engineering. Only the recent development in architectural design and new construction techniques, as well as the deepening of structural analysis and the strength of wood to fire, together with the introduction of new products able to preserve the wood from degrade, it allowed to regain possession of the varied architectural possibilities, the extraordinary aesthetic and full compatibility with the criteria of sustainable development that a wooden structure has to offer.

It is undoubtedly one of the most suitable materials for green building. Its lightness, the high resistance to compression and tensile stresses, ease of processing, the impregnability by the chemical and environmental aggression and the almost absolute insensitivity to temperature changes, allow the most different structural uses. Wood is also featured by good insulating qualities, both thermal noise and a low electric conductivity.

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The wood is also an eco-friendly material: the energy used in the production process is much lower than that required for the construction of houses in reinforced concrete or masonry. Demolition of wooden artefacts is cheaper and faster, it has a good resistance. It is also a material with a very low stiffness, and this allows the wood to absorb the seismic energy and the whole construction to better respond to the effects of an earthquake.

In addition, from a static point of view the wood can show excellent results also better than masonry, reinforced concrete and steel, thanks to new technical advances [1-3]. However, the decline of wood in Italy was due also to a vacuum in the normative code, which has been filled only recently (EC5, DM 2008 and its new version, with new prescriptions for timber structures) [4,5].

Scientific studies have also highlighted a legislative gap regarding the evaluation of the loads capacities of timber-concrete composite joints exclusively entrusted to standard shear tests on "push out" joints [6].

A key aspect in the design of timber structures deals with the choice of the mechanical and structural models that properly describe the behavior of the materials and the structural systems themselves. According to all code prescriptions of the latest European edition, actions must be assigned to one of the classes of duration of load, which are characterized by the effect of a constant load for a certain period of time of the life of the structure. In this way it is possible to estimate the interaction between the typical temporal variation of the load in the time and the material properties.

The wood is a very particular and efficient material, different from the most commonly building materials, its structure having different and interesting characteristics, almost conflicting, as for example its notable resistance under both compressive and tensile loads that becomes nearly unique if compared with its limited weight density. All this leads to realize structures absolutely suitable also to the seismic safety.

A disadvantage could be the degradation in the time of the mechanical characteristics of timber structures depending on the type of wood [7]. Generally elements in wood, due to the nature of the material, can be subjected to a reinforcement intervention for several reasons: increment of the dead loads, degradation of the mechanical properties of the element or simply only to reduce excessive displacements. In particular, in recent years also techniques born to reinforce masonry elements have been tested on the wood such as Fiber Reinforced Polymers (FRP) [8], which has given excellent results in both construction techniques in the case of structural elements subject to bending.

A common application of wood was for floor and, especially in the past, as a material for arched and vaults. With this in mind, the present paper deals with the study of an innovative construction system for wood arches and vaults, realized utilizing wooden hollow box-shaped blocks ([9,10]). These blocks, due to this characteristic, assure both a considerable saving of material, and the possibility of having compartments for the accommodation of facilities, as well as guarantee lightness and ease of assembly. This innovative product and the research study associated to it, therefore, wants to bring back both the constructive system, and the material used for the structural elements.

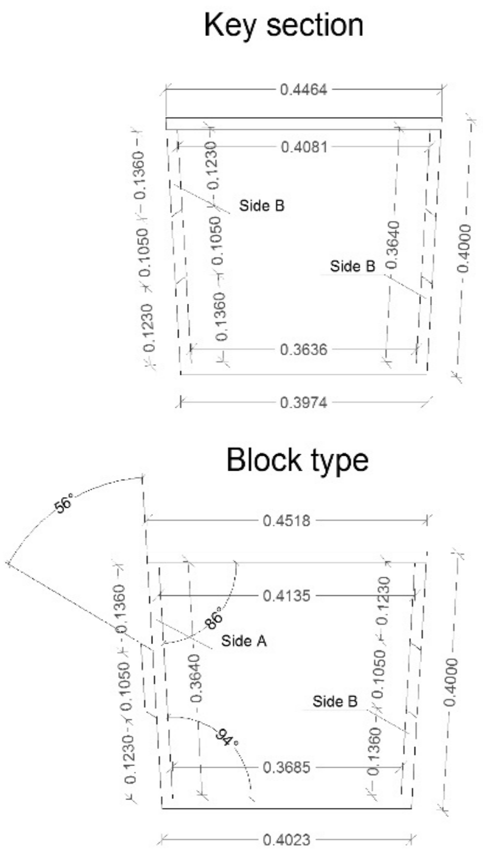


Fig. 1 Executive drawings of the blocks with the connecting system by mean of male-female joints.

The constructive system object of this analysis was designed and produced by Intini S.r.l. enterprise (Noci, Italy). The system is good to satisfy the necessity to cover spans (some of considerable size) with a structure that does not require the inclusion of intermediate supports. In this way it results in a lightweight arch easy to install by mean of its mechanical junctions.

In the constructive system, the ashlars are made of birch wooden panels (13 layers for a total thickness of 18 mm) (Figure 1).

The panels are then arranged together so as to form a closed box-like structure (Figure 2a) with a hooking system of a male-female type that allows, during the assembly, to use fewer supports (Figure 2b). The principal characteristic of the block, in fact, is a perfect modularity, with the exception of the key element designed with two "female" connections, so as to accommodate the “block type” elements.

**a)**

**b)**

Fig. 2 a) Assembling of the wooden panels to form a closed-form ashlar; b) Assembling of the arch.

Experimental studies have been conducted on the base material, on the individual blocks and, thereafter, on an arch built in scale 1:1 to evaluate the displacements, the deformations and the maximum load to failure and to examine its compatibility with the provisions of the code in force [5]. The results obtained from the experimental tests have been compared with the results obtained by the numerical modeling.

Figure 3 shows the testing set-up under a symmetric load configuration. Figure 4 shows the collapse of the arch prototype under an asymmetric load condition.

Fig. 3 Tested arch with details of the positioning of the displacement transducers.

Fig. 4 Collapse mechanism and achievement of the hinges in the arch with an asymmetric load condition.

## II. Finite Element Model - FEM

The need to calculate the static behavior of a mechanical system is satisfied by the analysis in which the finite element discretization of the continuous leads to a mathematical representation making it possible qualitative and quantitative analyses of the characteristics of the system in real conditions of use.

The finite element method (FEM), except in rare cases, is not an exact method, but an approximate one as the convergence of the approximation to the exact solution is derived by numerous parameters. If the model is set up correctly, the solution may be very close to the exact solution, and therefore much closer to the experimental test results. Otherwise, you may run into numerical errors due to inaccuracies of the numerical procedures utilized, errors in its formulation, due to the use of elements that do not adequately describe the physical phenomenon, and discretization errors due to an inadequate mesh, too coarse, with elements distorted, not conformable or too disproportionate.

The realization of the grid (mesh) is a crucial stage in the development of a FEM calculus, because the accuracy and effectiveness of the analysis depends directly on the quality of the mesh. Furthermore, the step of meshing, even if carried out by the latest generation of pre-post-processing software, is the longest phase of the check cycle because, in the simplification of the CAD geometry and the operating contour conditions, the reliability of the simulation and the ashlar complexity have been safeguarded.

A finite element method is based on the concept of describing the state of deformation of a continuous system; the element stiffness matrices and consistent nodal force vectors are immediately assembled to form the master stiffness matrix and the master force vector, respectively, by a process called merge. The results of this assembly process are the master stiffness equations:

$$\mathbf{K}\boldsymbol{u} = \boldsymbol{f} \qquad (1)$$

where **K** is the master stiffness matrix, $\boldsymbol{f}$ the vector of node forces and $\boldsymbol{u}$ the vector or node displacements. Upon imposing the displacement boundary conditions, the system is solved for the unknown node displacements. The equation is valid for any type of linear analysis, especially in structural analysis, the purpose of which is the study of displacements, strains, and deformations in a structure or in a part of it. Therefore, in the structural analysis, $\boldsymbol{f}$ represents the external forces, **K** the stiffness matrix and u the displacements.

The various load conditions act independently each time you run the solver. The model, once created, is solved separately for more constraint conditions and for different load combinations.

## III. Modelling with Beam elements

In the case of a discretization with Beam elements the FE model of the present arch-vault consists of 19 beam elements and 20 nodes. It has been developed by Straus7 software [11].

The aim of the modeling is to give a first interpretation of the response of the structure. To this end two load conditions utilized in the experimental tests have been added, the first represented by three vertical forces, each one of 10 KN (Figure 4); the second one consists in a global acceleration in Y direction equal to -9.81KN, thus generating the gravitational load from the top downwards.

In the model the nodes have been modelled not fixed but with a different stiffness for each element, depending on the values of the bending moment obtained in a preliminary analysis.


Fig. 4 Detail of the forces applied to the structure.

The structure has been restrained with two simple 2D supports, in nodes 1 and 2, which allow a movement of rotation and a translation. The mechanical characteristics of the material of the blocks are shown in Table 1. The geometry is the same of the ashlars utilized to build the prototype for the tests [8].

Table 1 Mechanical characteristics of the material utilized for the wooden blocks (*beam* elements).

| Elastic modulus [kN/mm$^2$] | Poisson's ratio | Density [kg/cm$^3$] | Thermal expansion [/°C] |
|---|---|---|---|
| 1.11 x10$^4$ | 0.0456 | 6.7 x10$^{-4}$ | 3.5 x10$^{-6}$ |

Figure 5 shows a 3D representation of the model of the arch made of beam elements.

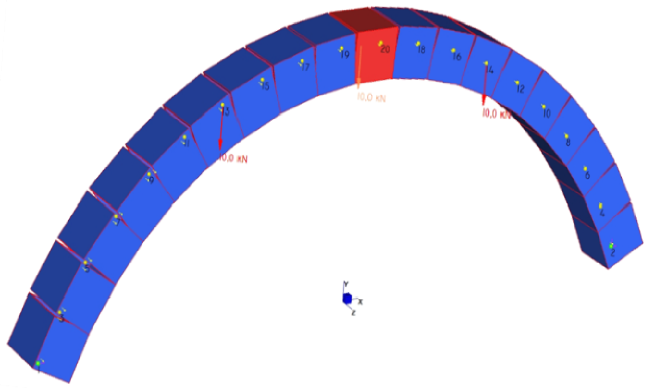

Fig. 5 3D representation of the arch discretized with beam elements.

In the loading phase, similarly to the experimental test, the 10 kN loads have been gradually increased up to the maximum load, then followed by a discharge phase.

For the post-processing, during the evaluation and interpretation of the results of the FE analysis, Straus7 displays the results as "contours" color maps for stresses, strains, and displacements or with graphics, animations, deformed configuration and data lists.

Figure 6 shows the deformed configuration of the structure with respect to the forces and the constraints that have been previously applied.

In the second instance, after realizing that the model gave significant bending stress we set manually the stiffness at the end of the blocks - release- initially unknown, to have a first linear displacement compatible with the experimental one.

The change of stiffness with the release was not uniform, but it was increased in some points where higher values of the diagram of the bending moment were found. In fact, the wood blocks were hinged and supported one another, so that they were able to transfer only compressive forces and not tensile ones.

Figure 7 shows the bending moment acting on each element of the arch vault.

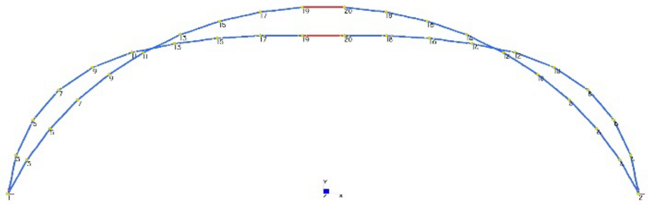

Fig. 6 Deformed shape of the structure (amplified of 5%).

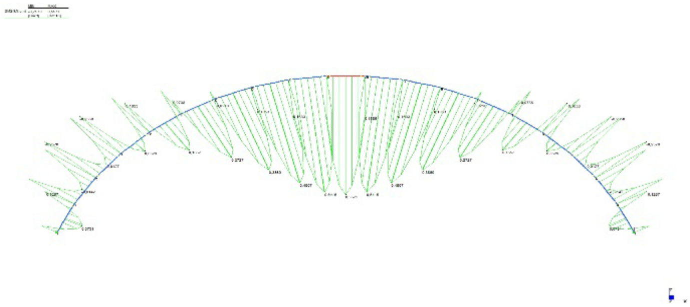

Fig. 7 Bending moment on the arch with a load equal to 24 KN.

Figure 8 shows the "lowering" in the arch when the applied load is equal to 24 kN.

This first modeling, albeit developed in linear analysis, allowed to validate the model in such a way to approach the real structure neglecting the non-linearity. The setting of the beam elements model has been very useful for the comparison with the models created later.

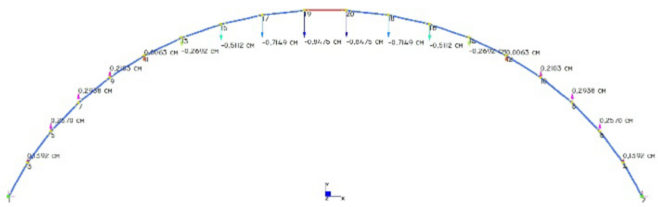

Fig. 8 Lowerings with a load equal to 24 KN.

## IV. Modeling with Plate elements

A second and more detailed analysis was performed using plate elements, as a result of the two-dimensional nature of the problem and because the width and the length of each block are much bigger than its thickness.

The choice to utilize Plate elements for the discretization has been dictated by the type of analysis to be carried out and, above all, by the stress variation within the blocks. In particular, having a linear stress variation a 2D finite element with a number of "sets stress" equal to three has been chosen. Therefore for this modeling the element QUAD6 (QUAD4 with a Bubble function) has been utilized to eliminate the parasite shear stresses that produced a "mesh locking" effect (Figure 9). In total 1976 Plate elements and 2002 nodes have been utilized to model the arch.

Each block of the arch is distinguished by two static behaviors, one bending behavior for the horizontal planes, one membrane behavior for the two vertical surfaces (see Figure 1). The bending behavior is hardly activated respect to the membrane one.

Also in this case, the same constraints, forces and load combinations utilized in the beam elements model have been applied.

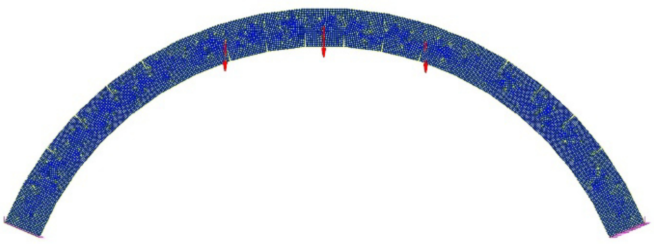

Fig. 9 "Warping" view of the arch with plate elements and applied loads.

In this modeling it has been assumed a 2D Plane Stress. In this case the nodes have only 2 degree of freedom: translation in X and Y directions. It is thus required small displacements and stresses in the linear range.

An equivalent section with a membrane thickness of 38 mm and 40 mm has been utilized. The technical characteristics of the wood have been set as shown in Figure 10.

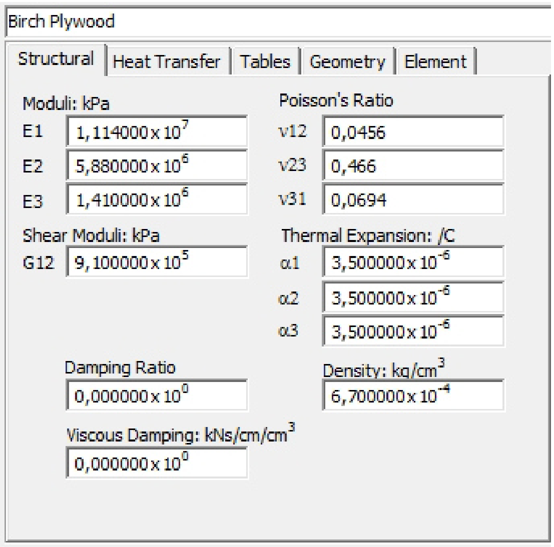


Fig. 10 Mechanical characteristics of the wood utilized for the plate elements.

Since in this case it was interesting to find the maximum axial tensile an compression stresses, it has been helpful the representation of color maps of the axial distribution (Figure 11). Also in this case the deformations were found to be very similar to the experimental ones. The tensile and compression stresses have been analyzed. Subsequently, the nodes have separated in correspondence of the tensile stresses where the segments detached one from the other.

With this representation, results almost coincident with the experimental ones have been obtained in terms of vertical movements, confirming the reliability of the numerical model.

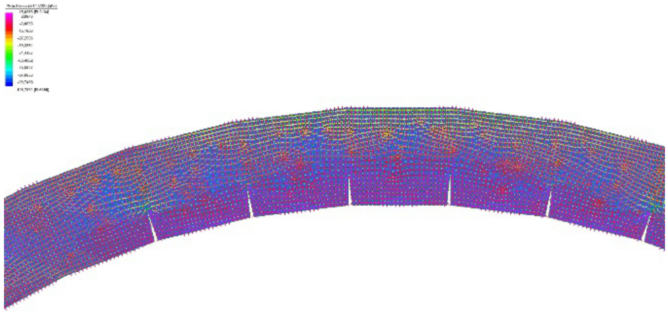

Fig. 11 Detail of the stresses acting on the central ashlars.

The values of the lowerings at the key section have been tabled, comparing the data of the experimental test with the results of the modelling with beam and plate elements (Table 2).

Table 2 Lowerings (measured in mm) at the key section (Pot 4) and deviations % (in red).

| **Load (KN)** | **Exp. stress** | **Beam Elements** | **Plate elements** | | **Plate elements** | |
|---|---|---|---|---|---|---|
| | | | **Membrane thickness** | | | |
| | | | 40 mm | | 38 mm | |
| | *Key Block* - Pot 4 (mm) | | | | | |
| 6.00 | -18.6 | -18.0 | -14.3 | 0.23% | -15.4 | 0.17% |
| 12.00 | -28.9 | -34.6 | -28.1 | 0.02% | -30.3 | 0.04% |
| 24.00 | -69.7 | -68.0 | -55.4 | 0.20% | -60.0 | 0.13% |
| 30.00 | -81.5 | -84.7 | -69.7 | 0.14% | -74.9 | 0.08% |
| 25.00 | -64.8 | -70.5 | -57.6 | 0.11% | -62.0 | 0.04% |

The values are referred to Pot 4 element that is the key element (Figure 12).

From Table 2 it is possible to notice that the deviation in percentage terms respect to the experimental values is much less than 1% thus validating the results of the modelling.

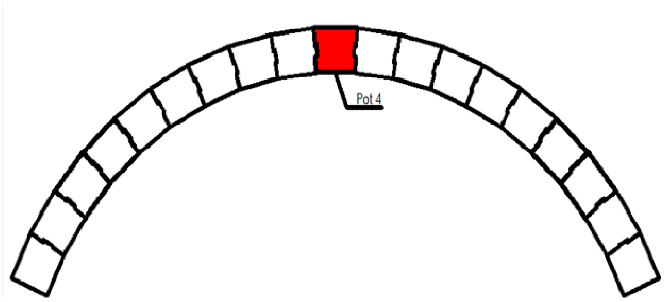


Fig. 12 Position of Pot4 element.

It was also possible to read the stress peaks in the mesh, trying to capture both the most stressed areas, likely local crisis zones, both the coincidence between the maximum stress with the ultimate stress of the material (Figure 13).

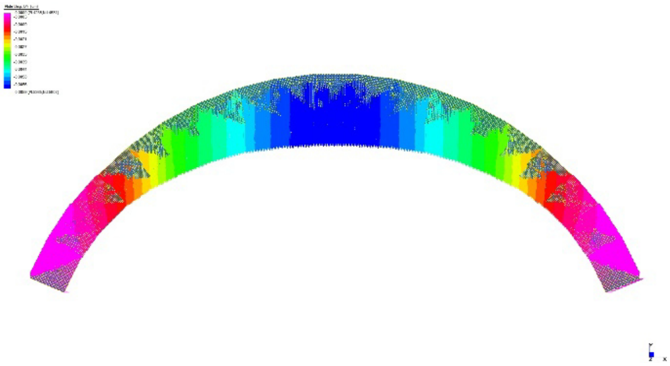

Fig. 13 “Contour” plot of the lowerings

## V. Modeling with Brick elements

The modeling with Brick elements refers to a 3D model of the arch structure.

To analyze the 3D model, we have considered the "sub-modelling", applying the "structural zooming" on the 2D plane stress elements, where the subdivision in elements adopted was enough dense for the whole response (Fig. 14).

It was possible to further the investigation by analyzing more in detail just a part of the arch and not the whole model. Specifically the keystone and the contiguous blocks have been considered for the 3D model.

After implementing the global model, it has been paid more attention to the peak stress at the interface between the ashlars in the compressed zones.

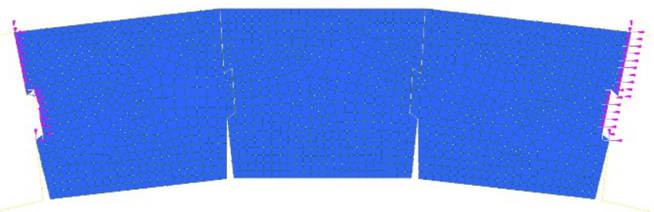

Fig. 14 “Structural zooming” of 2D plane stress elements.

In particular, we have also assessed the possible transverse stresses inside the wooden tooth, then enlarged models were made of a few blocks going from flat elements, Plate, to 3D elements, Brick (Fig. 15).

One of the most common ways to reduce the size of a finite element model, where possible, is to use the symmetry conditions. In the present case, because of its geometry, it had been possible to take into consideration one of the symmetry axes of the arch, thus agreeing to only half of the structure.

However, to analyze, the 3D model, it had to be used the "sub-modeling", by performing the so-called "structural zooming", first performed on 2D plane stress elements, in which the division into elements adopted was sufficiently fine for the overall response. It was possible to further the investigation without having to re-mesh and re-launch the entire model and analyzing specifically the keystone and the contiguous blocks.

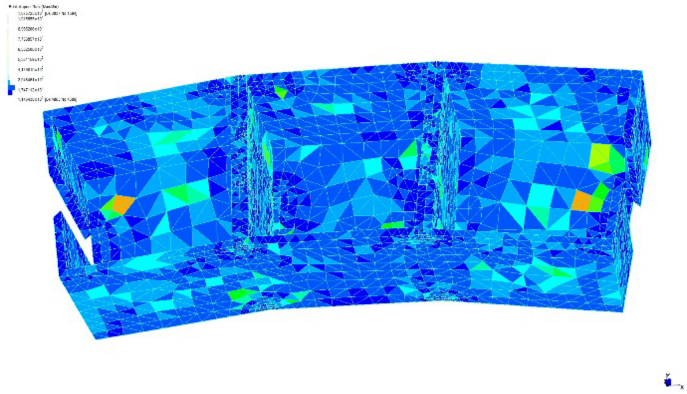

Fig. 15 Brick aspect ratio (Max/Min).

The analysis confirmed the experimental findings: the “teeth” of the ashlars are the most stressed areas.

## VI. Conclusions

The present article proposes a different approach to the study of an innovative system for roofing structures in wood, that assure the demands in terms of code standards, especially with regard to eco-compatibility.

Wood is a perfectly eco-friendly material, from its extraction, through production and processing, to the use and disposal. The construction of halls or rooms with vaulted wood roofs with this new construction technique would combine the high assembly capacity and would take advantage of the low thermal conductivity of the material, which ensures excellent thermal insulation.

The system offers many fields of application ranging from simple use for aesthetic purposes, to the use for structural purposes. It is easy to see how the system is aesthetically pleasing. Moreover, if properly introduced in certain contexts, it also enables the recovery of techniques of traditional building materials. The system is able to accommodate loads in safety, at least as regards the more favorable loading condition for this type of arch structures, or that of a uniformly distributed load; so it would not be ruled out its use even in the structural field, placing itself in competition with the laminated wood structures at least for certain applications such as large rooms, i.e. for dining or sporting activities.

The analyzes carried out have enabled us to highlight different information useful for understanding the behavior of these structures. In particular, the investigations carried out considering different levels of detail allowed to clarify the potential use of this material for structural purposes.

Model validation performed on tests conducted on-site allowed us to identify the critical points of the structure collapse. A more accurate modeling can be done via a non-linear analysis, possibly with mechanisms of damage of the material and considering the non-linearity resulting from the degree of ductility of the connections together with further experimental data. In fact, in this work, the damage mechanism considered provides a boundary surface defined by the parameters of tensile and compressive strength of the wood.

Globally, the knowledge gained from the present research work constitutes the beginning and the basis for analyzes to identify possible interventions of structural improvement. For more and more specific structural analyzes both in nonlinear and dynamic fields it is appropriate to conduct experimental investigations that capture the deformation capacity and strength of the joints such as to formulate reliable calculus methodologies for wood species not currently certified as structural wood.

The present system here considered, in fact, collapsed not for failure of the material, but because of its connections and the joints between the various blocks that will have to be improved and modified.

For structural uses it is necessary to observe that the arch system behaves in a less efficient way for loading conditions different from the one treated in this study, however, and covered in the code. Just think about the effects of an earthquake, but especially the effects of wind, a real important problem for lightweight structures.

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