Linear Analysis of an Innovative System for Wooden Arches and Vaults

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Abstract: - The present paper aims to perform a finite element analysis of an innovative construction system for arches made of wooden box-shaped blocks equipped with interlocking joints. This new technology has the objective to favor the use of wood, and at the same time to ensure excellent mechanical performance and rapidity and ease of assembly. The arch model was created with Straus7 software and the analysis process consists of an initial part of pre-processing, where the model has been reproduced, followed by a second phase of processing, that is the actual analysis with the resolution of the problem, and the third and last phase of post-processing with the processing and representation of the solution considering the results obtained from a previous load test using an arch prototype in scale 1: 1..

Key-Words: - Finite Element Modelling, Numerical Analyses, Wooden arches and vaults, Hollow shaped boxes.

1 Introduction

Since ancient times, vaults have been one of the basic types of ancient roofs, gone into disuse with the evolution of construction techniques that, nowadays, can cover the spaces in which we live using typologies and materials different from those used in the past. Similarly, the wood after losing its structural function, has retained its validity as a material for floors and walls. 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. The use of wood in construction, in fact, at least in Italy, has always been decreasing, first with the use of steel as building material, and then of reinforced concrete. Despite this, 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 [1,2]. These lack is due also to a vacuum in the normative code of our country, which has been filled only recently (EC5, DM 2008 and its new version, with new prescriptions for timber structures) [3,4].

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 [5].

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 has 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.

It is also important to consider the degradation in the time of the mechanical characteristics of timber structures depending on the type of wood [6]. 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 only to reduce the excessive displacements.

This paper deals with the study of this new construction system for wood arches and vaults, realized utilizing wooden hollow box-shaped blocks ([7,8]) that, 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.

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; so that it results lightweight and 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 with a hooking system of a male-female type that allows, during the assembly, to use fewer supports. The 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.

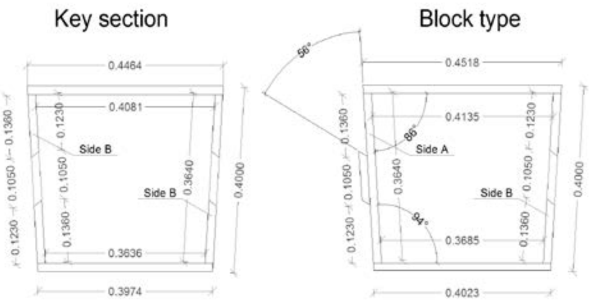

Fig. 1 Executive drawings of the blocks with the connecting system by mean of male-female joints.

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 [8]. The results obtained from the experimental tests have been compared with the results obtained by the numerical modeling.

Figure 2a shows the testing set-up and the collapse for anti-symmetric loads. Figure 2b shows the collapse of the arch prototype under an asymmetric load condition.

a)

b)

Fig. 2 Tested arch. a) details with the low tanks of the positioning of the displacement transducers; b) collapse mechanism and achievement of the hinges in the arch with an asymmetric load condition.

2 Finite Element Model - FEM

The finite element method (FEM), except in rare cases, is not an exact method, but approximated 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..

3 Modelling with *Beam* elements

In this case the FE model consists of 19 beam elements and 20 nodes. It has been developed by Straus7 software [9].

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 3); the second one consists in a global acceleration in Y direction equal to -9.81KN, thus generating the gravitational load from the top downwards.

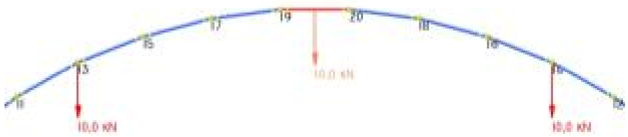

Fig. 3 Detail of the forces applied to the structure

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.

The structure has been restrained with two simple 2D supports, in the 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.

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}

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

Figure 5 shows the bending moment acting on each element of the arch vault.

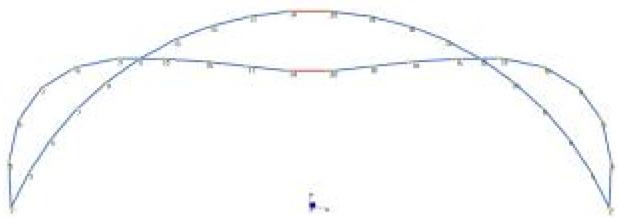

Fig. 4 Deformed shape of the structure (amplified of 5%).

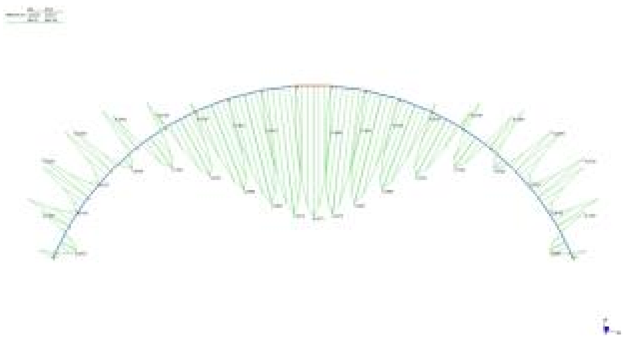

Fig. 5 Bending moment on the arch with a load equal to 24 KN

Figure 6 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.

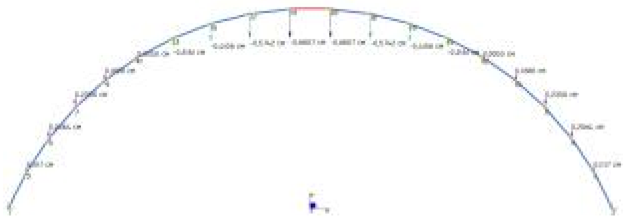

Fig. 6 Lowerings with a load equal to 24 KN

4 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 the fact that the width and the length of each block are much bigger than its thickness.

The choice to utilize such type of finite element 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 7). In total 1976 plate element 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 (see Figure 1), one membrane behavior for the two vertical surfaces. The bending one 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.

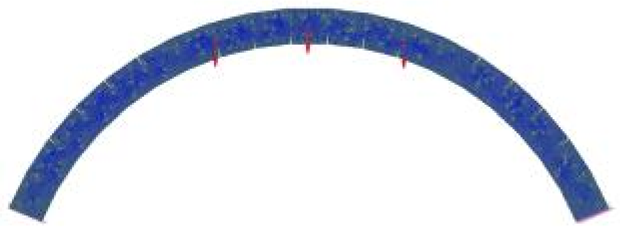

Fig. 7 "Warping" view of the arch with plate elements and applied loads

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 8.

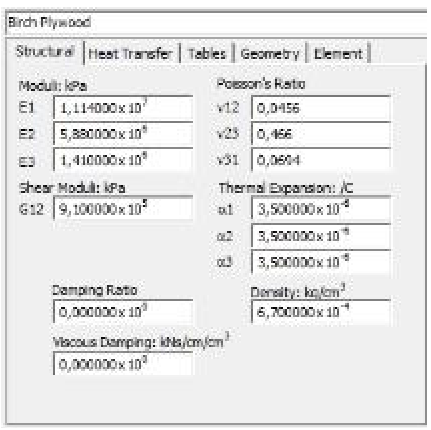

Fig.8 Mechanical characteristics of the wood utilized for the *plate* elements.

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 9). Also in this case the deformations were found to be very similar to those experimental. 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.

Table 2 reports the lowering values of the key block, comparing the experimental test data with the results of the numerical model.

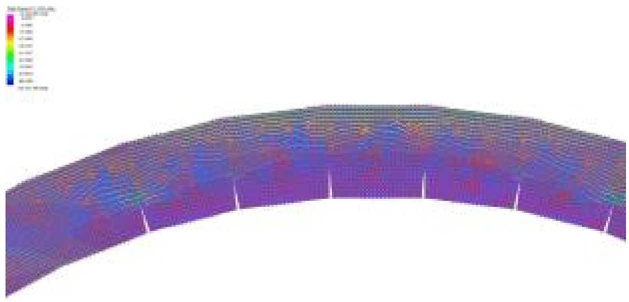

Fig.9 Detail of the stresses acting on the central ashlars

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 10).

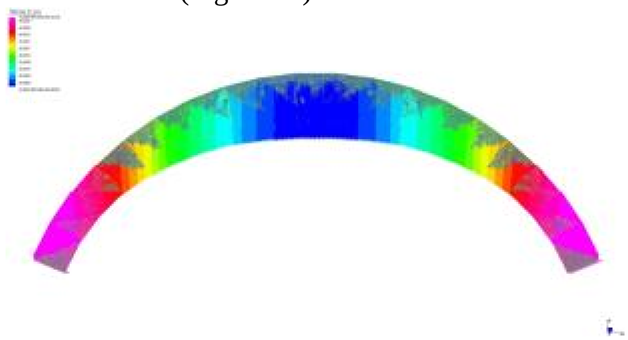

Fig. 10 "Contour" plot of the lowerings

Table 2 Lowerings of the key block in the two modelling cases.

Load (KN)	**Experi-mental tests [mm]**	**Beam Elements [mm]**	**Plate Elements**	**Plate Elements**
			Membrane thickness	
			40 mm	38 mm
	Key Block			
6.00	-18.6	-18.0	-14.3	-15.4
12.00	-28.9	-34.6	-28.1	-30.3
24.00	-69.7	-68.0	-55.4	-60.0
30.00	-81.5	-84.7	-69.7	-74.9
25.00	-64.8	-70.5	-57.6	-62.0

5 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 has allowed us to understand which are 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 system has 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, real problem for lightweight structures.

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