Environmental Safety House Analysis with regard to the structural behavior of wooden construction

R. Stasiak-Betlejewska, M. Bottoni, A. di Taranto

Abstract**—** Sustainability is a contemporary source of several technical and organizational solutions, which provides realization of environmental safety construction development. There are a lot of enterprises initiatives coming toward the sustainable construction promoting in Italy in the frame of environmental safety construction technologies. Italian construction follows the best practices on safety wooden houses practices. The article is interesting because it shows that the structural behavior described in the introduction is due in fact to the rotational behavior of the joint, and not to other dissipative effects (friction in various parts of the structure). The effects described in the introduction are in all cases experimentally observed coupling (curve enveloping non-linear change of stiffness reloading). The curve is symmetric since only the behavior of the joint it is shown.

Keywords**—**sustainable development, wooden construction, friction, multifibre beam, open source software, Code Aster

I. Introduction

Sustainable development is defined as a practice of the environment protecting through constant improvement of human living standards, what is possible owing to an invention and an innovation which are success keys. Invention and innovation for sustainable development isn't just about developing new technology, but includes new processes and new ways of solving old problems - creative thinking is the rubric [2]. Invention stimulates entrepreneurship and overall economic activity. In this meaning, invention means a focused application of the human mind to the world that yields an original creation with practical use. Innovation, as defined here, is the practice of bringing inventions into widespread usage, through creative thinking, investment, and marketing.

That's why basic invention is typically needed to spur innovative activity. To stimulate invention, education should be the centre of action because invention requires a lot of knowledge.

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Invention is a set of interactions between human creativity, technology and the marketplace what leads to economic indicators increase.

Society increasingly imposes a challenge for changing the nature of economic activities in almost every sector of the economy. This structural, long-term reorientation and transformation of economic activities is termed a transition [3].

Construction industry need such a transition, because this sector as a user of energy and materials creates waste and this sector uses about 25% of the wood and produce sulphur oxides. Progress in the sustainable development applying is useful for construction sector what is seen in the benefits and organizational solutions. The best practices in the sustainable construction can be built up only by an effective transfer of knowledge and experience, which can creates the competitive position of the industry on the worldwide marketplace. Transition of knowledge and experience into technical and organizational solutions is created through several kind of actions, which can includes e.g. cluster initiative or creating other network kinds such as associations or technological platform. Italy goes through an economic phase of transition which started in 1992 and it is characterized by [4,5]:

- restrictive policies in public expenditures, set to reduce the great public debt,
- accumulated during the Eighties,
- constant effort of industry to achieve higher productivity rates, as their main strategy in order to participate in the global exchange market.

There are three fundamental issues of a sustainable development strategy in Italy which concerns protection of ecological systems, production growth and environmental damage and change of economic objectives from quantitative growth to qualitative development. Central and Northern part of Italy is a settlement of a large number of small and middle companies. The construction sector is fundamental for the Italian economy. Research reveals that, over the past five years, a few key drivers (legislation, certification, active role of trade associations and green building clusters) have increased the interest and demand for green building products and services in Italy. Currently, best prospects for the Italian green building market include:

- photovoltaic panels (for domestic use),

–solar thermal panels for building heating and hot water production,

–insulation products and energy saving systems for residential and industrial applications,

–wood construction,

–geothermal energy for building heating applications.

Popularity of “green building” in Italy has grown. A major challenge for green builders in Italy is compliance with the Italian legislation that regulates green building, which is starting to be implemented in a uniform manner at the national level only now.

Problem of sustainable building (in Italy – green building) issues are discussed mostly by architects who concerns about the environment and building materials which affects on human living.

An important step towards the promotion of green building issues in Italy was the publishing in 2004 of a *White Paper on Energy, the Environment and Buildings* jointly by FINCO (the Italian Federation of Building Products and Services Manufacturers) and ENEA (the Italian Agency for New Technologies, Energy and The Environment). The main purpose of the document was to demonstrate benefits on energy consumption regulating in building. Document highlighted how building envelopes in Italy generally are usually not energy efficient because of the lack of adequate thermal insulation, especially for those buildings constructed before a 1976 law that set heating guidelines.

II. Research initiatives on Environmental Constructions analysis

Among the various strategies of government intervention capable to stimulate further progress towards sustainable development are the activities of research and development led at the present time by ENEA in the sectors of environmental technologies, the development of renewable sources of energy, of innovation of product and especially in the fields of energy saving and of the application of advanced solar technologies in buildings [4].

Some research results concerns not only technologies but also renewable resources used for green building. In Italy the common opinion about wooden houses is that they are expensive, their behavior in seismic regions is basically unknown, they are very unsafe in case of fire, besides, their behavior over time is not known and therefore not guaranteed.

Since some years Province Trento commissioned a research to Dolomiti Pro Group about wooden houses with the aim of understanding the behavior of such a building after an earthquake and after a fire. Dolomiti Pro Group is partecipated by Duplo Costruzioni, Ille Prefabbricati and Benedetti Sistemi. After such research, it's high time to broaden such research and to go deeper with mathematical models. Software side of the research are be led by Tyto company, which is a partner of Dolomiti Pro Group.

Wooden buildings are frequently associated with energy saving houses, and because of the not brilliant economic situation in Europe, it's a good moment to push researches about energy saving topics, what means:

– to make research grow,
– to increase the 'green mood' in population and, in the mid-long term,
– to increase a new economy based on wooden and energy saving buildings.

Such trend is already visible in the Northern part of Italy all along the Alps, were average temperature is lower and nevertheless, where good weather (and direct sun, for photovoltaic panels) is available very for most of the days in a year.

It's time to let the research to be lead by open source software tools: open source software made giant steps in quality and in the variety of its application fields. Open source software is typically led by a community of programmers and users, and its incubation is frequently situated in some Universities, what means a very quick way of sharing knowledge and both problems and solutions. It means it's the ideal situation for research in general (and specifically for our research).

For such research partners of Dolomiti Pro Group decided to use *Code_Aster* [10], a finite elements software written by EDF (Electricité de France, first energy producer in Europe) for internal use. It comes to be a huge development and study environment, with applications in statics and dynamics, mechanical and hygro-thermal analysis, with a large possibility of non linear computations. To give an idea of such a project, it's documentation covers more than 20000 pages! Moreover, *Code_Aster* is completely free and open source.

A complete description of *Code_Aster* features is out of the topics of this paper. However, a first application to the seismic behaviour of a wood panel under cyclic loading is shown. This is the first step for characterizing the seismic behaviour of a structure or of a structural element. In fact, if it is true that dynamics effect are not included, on the other hand the displacement or force levels are controlled. From the numerical point of view, the static cyclic analysis allows calibration of model parameters, to be used eventually in a second step in a dynamical analysis.

To study a wooden house behavior in case of earthquake is rather different than study the behavior of a concrete building in the same situation. Concrete differs from wood in weight and in the elastic law they follow. Frame follows a different behavior due to totally different technique about joints and other aspects. The study started from experimental data about nail deformation due to an earthquake, what can be seen in Fig. 1.

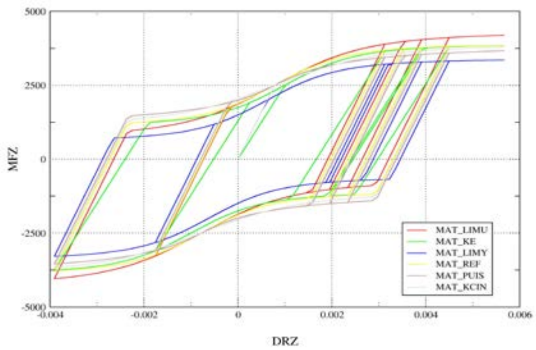

Fig.1. Experimental data about nail deformation during an earthquake.

Then it can be seen a behavior law in Code Aster for plastic hinges. This law had to give a very good approximation of the experimental data of Figure 1. It has to be underlined the fact that the law draws many cycles, widening on an on, both right and left, to simulate the irreversible deformation of the nails in the joints in the wood (Fig. 2).

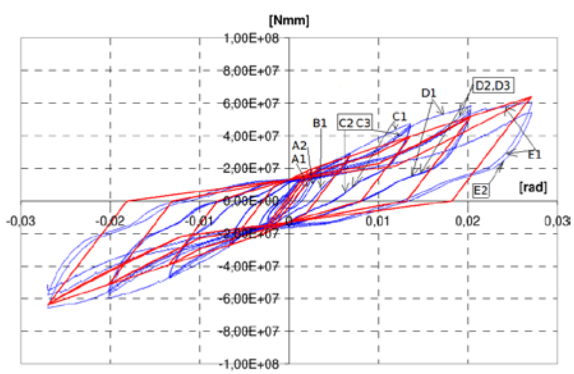

Fig. 2. Behavior law about nails.

Then starting from a sample earthquake we used the preliminary model with an automatic calibration feature of Code Aster for tuning parameters based on experimental data reconstructed. The calibration program has executed hundreds of times the earthquake calculation to find the most suitable parameters to describe the experimental data (Fig. 3).

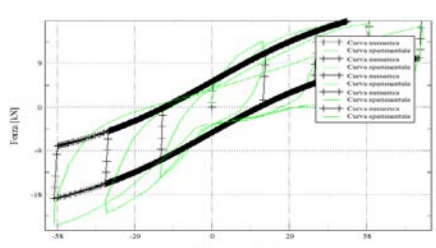

Fig. 3. Experimental data over calibrated law. shift in mm (x axix), force kN (y axis).

In the previous research, a building 1:1 scale was built and tested against 3 different earthquakes. Test was conducted upon a full 'dressed' 3 floors building, it means with furniture inside.

Further steps are scheduled in future: the first one is to test a building with water and sanitary system fully operative: there is no available data about such a test situation so it is natural to understand what happens, there is a big interest on it about the companies. A wall was tested against fire to understand what happens to physical parameters of the wood. Next step the research tries to understand and predict the thermal behavior of a wooden building after an earthquake. To test a thermal behavior on a wooden building it's necessary to have a complete building (1:1 scale or smaller) and to blow smoke into the building at a certain pressure, if the smoke is visible immediately outside it means that there is a crack in the walls.

Further tests will try to check what happens after an earthquake on a the thermal insulation system of a building: If smoke is visible after an earthquake test and such smoke was not visible earlier, it means that earthquake solicitations damaged the building in the frame, or in the nails or in the walls. Tests on wooden buildings were shortly described as if they were so easy and cheap to complete: instead, there must be a great organization to get information from these test, just consider the need of sensors or the need of all the infrastructure to simulate the earthquake or the fire.

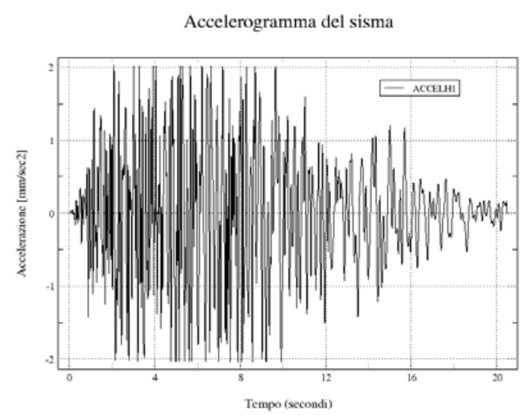

Fig. 4. Test earthquake used to stress the model, time in seconds (x axis) acceleration mm/sec2 (y axis).

So far, all researches pointed their attention to an existing building. But so many doubts arise when the all were dealing with the health of a wooden house after 10, 30, 50, 100 years since its construction, and the idea behind is very simple: if we think about a concrete house, all the historical knowledge makes us so confident that a well build construction will last for long time, let's say a century.

And there were reported two centuries old wooden buildings in Russia and Portugal to compare research results. The problem is that the construction procedures have changed so much, and there is no idea about modern wooden buildings behavior, just think about air pollution or wood mildew. So common opinion keeps are very suspicious about such buildings.

In next step of our research authors would like to point our attention to what happens to a wooden building over time. Wood is a natural element, so it interacts with humidity and its environment in a much more active way than concrete can do. Wood reacts to weather changes, humidity changes, temperature changes. Since it's a living matter it may adjust its position over time in a much different way than a concrete building may do. The idea of a further research about behavior over time comes out of here. The authors have to deal with historical data about the 'matter wood', its behavior with weather changes over time. Just imagine the seasonal changes, or the daily changes, and after collecting all data we need to build a mathematical model with Code Aster to predict what happens to wood, or what happens to nails-wood combination, or what happens to wood-concrete combination close to the foundations.

III. Plastic Hinges

The model refers to a wood, panel-type constructive system of *Ille Costruzioni*, consisting of a load bearing structure of beams and columns completed by the internal wall having both a stiffening function against horizontal forces and a partitioning function [6]. The *Ivalsa institute* performed for *Ille Costruzioni* some experimental cyclic tests on the described panels. Increasing levels of an imposed displacement were applied on the top of the panel, shown in Figure 1a. The same displacement level was applied with alternating sign (from left to right and from right to left). Each level of imposed displacement was repeated three times. The response of the panel in terms of applied force-displacement of the upper beam is shown in Figure 5b (blue curve).

a)

b)

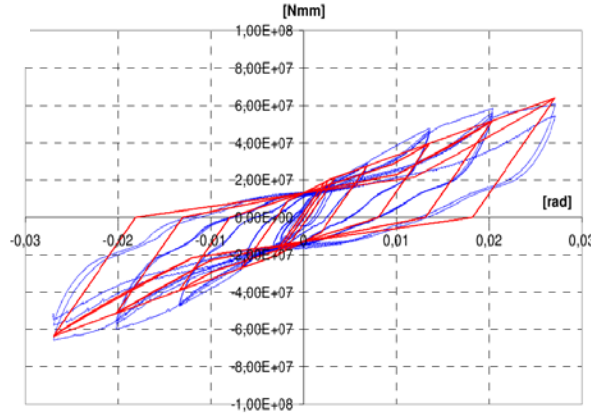

Fig. 5: (a) *Ille Costruzioni* building system (b) Response of the panel under cyclic loading (blue curve) [5].

Figure 5b shows that the structural behavior is strongly nonlinear and dissipative. It may be described in a qualitative manner by means of the following characteristics:

1) A curve obtained for the same load level (same displacement level, applied in the two opposite directions) is symmetrical about the origin for positive and negative displacements.
2) The enveloping curve (which contains the maxima of the cyclic curve) is non-linear, tangent stiffness decreasing with the level of displacement.
3) Reduction of stiffness for the same level of displacement imposed from the second reloading. Let's call DX_i the i-th imposed displacement, and denote by n = 1,2,3 the number of repetition DX_i^n. It can be observed clearly that the curves DX_i^2, DX_i^3 coincide and that the branch load DX_i^1 retraces the entire curve DX_{i-1}^3.
4) Comparing a branch of load with the subsequent reloading, DX_i^1 and DX_i^2, is observed in parallel with the overall loss of stiffness in DX_i^2 that in reality the force level reached is virtually the same.

Other similar tests have been made on other types of frame, more traditional, represented in Figures 6 and 7. In particular, we reported the case of a frame with asymmetric stiffeners (Fig. 6) and of a symmetrical frame (Fig. 7). Consequently, the structural response to cyclic loading respect to the origin is decidedly asymmetric respectively in the first case and approximately symmetrical in the second case. The cycles characteristics (apart from the symmetric/asymmetric property) are those already listed before.

a)

b)

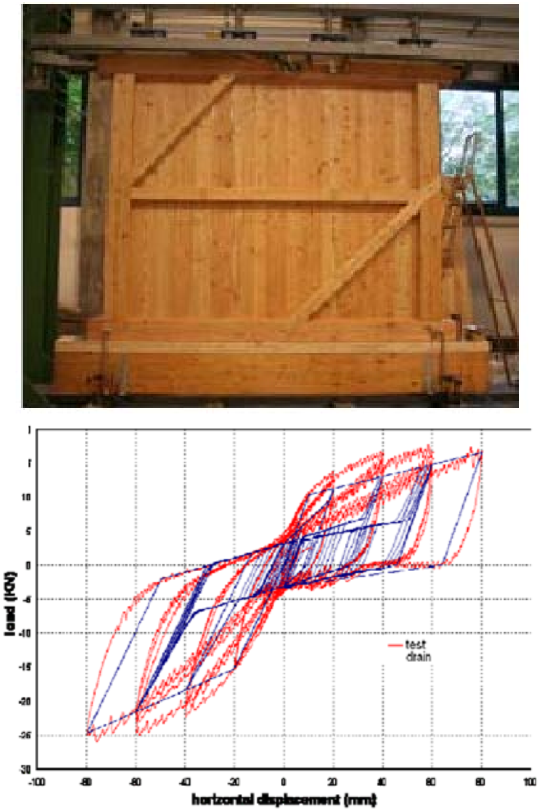

Fig. 6: Experimental tests on an asymmetric traditional frame: (a) panel test system, (b) experimental curve (red) and numerical simulation (blue).

a)

b)

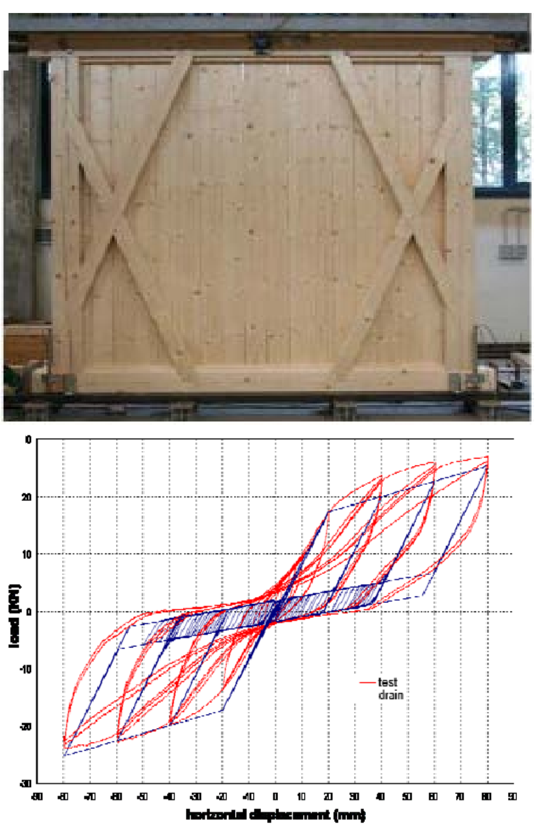

Fig. 7: Experimental tests on a symmetrical traditional frame symmetrical, (a) and panel test system,
(b) experimental curve (red) and numerical simulation (blue).

IV. Previous Modelling (Drain)

Previous modelings at Ille Costruzioni used the finite element program *Drain*, developed at the University of Berkeley. *Drain* specializes in frames, also with non-linear constitutive laws. In addition to beam elements of traditional type, multifibre beam elements can be used, or joints with linear or non-linear behavior. Among the latter, an example is given by the law of Figure 4, developed in [8] and implemented in *Drain*. Drain is a finite element software dedicated to linear and non-linear analysis in civil engineering. Applications are exclusively for frame (columns and beams) structures.

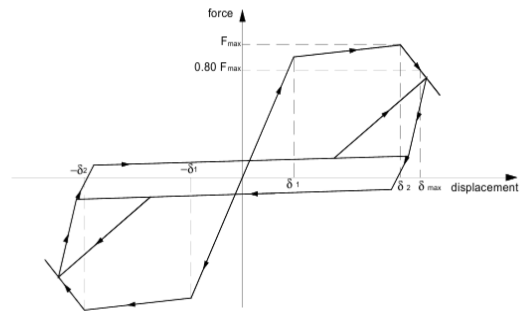

Fig. 8: Example of model used in *Drain*.

For the frame of Figure 5a, beams and columns were simply given a linear elastic behavior, while the structural non-linearity is attributed to the nodes, and modeled with plastic hinges [5]. Plastic hinges are joints with a plastic moment-curvature behavior, similar to that of Figure 8 but in terms of moment-rotation. As for the simulation test of Figure 5, the numerical results are compared to those experimental data in Figure 5b (red curve). You will notice the following characteristics of the model compared with the experimental results:

- the model is calibrated on the power level of the last cycle, nevertheless fails to follow the curve tangent enveloping with descending order (item (2) of the initial list : "enveloping curve"),
- differences between DX_i^1 and DX_i^2, described in paragraphs (4), are not reproduced,
- the experimental unloading branch is not reproduced correctly.

With reference to the initial list, only the characteristic (1), "symmetrical curve", is correctly reproduced. It would be interesting to analyze the results in terms of energy dissipation, which is an important parameter under a seismic point of view, and that with a first impression seems quite correct (amplitude of the cycle).

As for the simulation tests of Fig. 6 and Fig. 7, the model used is able to reproduce the variation of stiffness to the reloading (items (3) - (4) in the list : "reduction of stiffness" and "comparing a branch of load with the subsequent reloading"), but the amplitude of the cycle (and so the dissipated energy!) is much lower than the required level. The items (2) cannot be verified. The symmetrical/asymmetrical character (item (1), the latter is correctly reproduced.

V. Available model in *Code Aster*

In *Code_Aster* a joint type (discrete element) modeling is available, with various types of constitutive laws (viscous, plastic, etc). The wooden frames can be modeled by using plastic hinges, obtained with a discrete element with a plastic behavior on rotation. The law of behavior is called in *Code_Aster* "DIS_ECRO_CINE", and is applied to a discrete element of zero length (a law of the same type, with different parameters, can be applied for all 6 degrees of freedom of translation and rotation) .

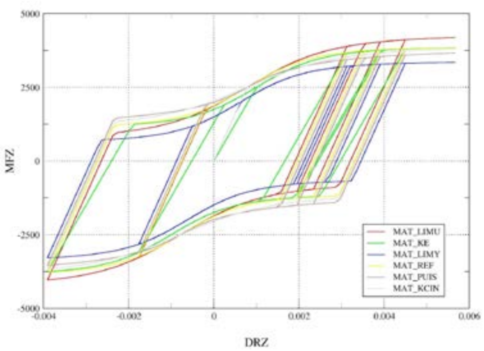

Fig. 9: Example of DIS_ECRO_CINE law used in Code_Aster on the rotation around the z axis (MFZ = moment, DRZ = rotation).

The details of the law are described below. Form of the elasto-plastic law:

1. elasto-plastic relationship:

$$F = K_e (U - U_{an}) \quad (1)$$

2. plastic criterion:

$$f = (F - X) - F_y \quad (2)$$

3. kinematic hardening:

$$X = \frac{K_x \alpha}{\left(1 + \left(\frac{K_x \alpha}{F_u}\right)^n\right)^{\frac{1}{n}}} \quad (3)$$

where:

K_e : elastic stiffness
F_y : elastic limit
K_x : kinematics stiffness
F_u : asymptotic force
n: power

In total there are 5 parameters; α stands for the plastic deformation. The law of behavior is shown in Fig. 9. There are 6 curves depicted, a reference curve (yellow, "MAT_REF" in legend) of parameters:

K_e= 3200000 ; F_y = 2500 ; F_u = 1400 ; K_x = 850000 ; n = 2.25

and other 5 curves with each one parameter changed from the reference curve is shown below in the parameter value close to the name of the curve given in the legend of Fig. 9:

– MAT_LIMU (red curve): F_y = 2000
– MAT_KCIN (gray curve): K_x = 600000
– MAT_PUIS (brown curve): n = 1.25
– MAT_KE (green curve): K_e= 2500000
– MAT_LIMU (red curve): F_u= 1800

It can be already seen that the characteristics of the numerical curve:

– the reloading is made on the same branch of the load curve,
– with increasing rotation, it tends to an asymptote of the moment,
– the unloading is elastic, the stiffness equal to the initial stiffness and intensity equal to two times the elastic limit $2F_y$.

Ultimately, we can already see that the law at present in *Code_Aster*, as for the law already in use in Drain, does not yet have all the features needed to reproduce the experimental data.

Retracing the observations made for Figure 5b (in the introduction with p. 2) with the characteristics made to Figure 5, we can say that the characteristic (2) (enveloping curve tangent with descending) may be reproduced, but they will never the characteristics (3) and (4). With regard to the symmetry with respect to the origin (point (1)), the behavior can only be symmetrical.

VI. Research results obtained with *Code Aster*

We tried to simulate the test [8] using our model in *Code_Aster*. The structural model corresponds to a frame (two beams and two pillars in a closed square configuration and simply supported). At each intersection of beam-column a plastic hinge is inserted (4 in total). The central panel was not modeled.

The tensile strength and stiffness are calibrated by hand directly comparing the response of the numerical simulation to the experimental curve. We have then:

– $K_x = 5 \cdot 10^{10} \, N \cdot mm$
– $F_y = 8 \cdot 10^{6} \, N \cdot mm$

The other parameters were obtained for inverse analysis, using the algorithm of Levemberg-Marquardt, available through the automatic calibration command MACR_RECAL of *Code_Aster*:

- $F_u = 3 \cdot 10^7\, N \cdot mm$
- $K_x = 1.3 \cdot 10^9\, N \cdot mm$
- $n = 2$

As for the elastic properties of the wood, the Young's modulus is equal to 15000 MPa. The curve obtained is shown in Fig. 6.

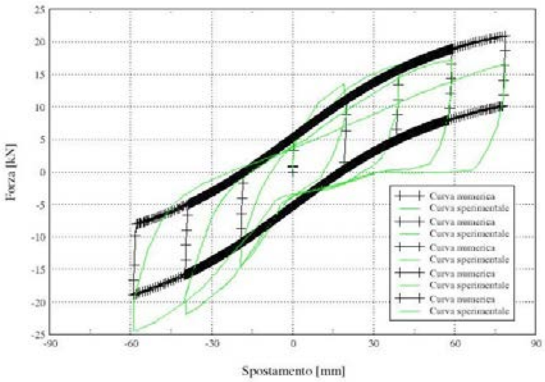

Fig. 10: Numerical curve obtained with *Code_Aster* and experimental curve (in green).

It should be noted that the structural behavior of "asymmetric" is clearly due to the diagonal stiffeners in wood, and not riveted joints. To obtain the structural response correct then it would be necessary to model them, so as for the central stiffening panel.

VII. PERSPECTIVES

There are other studies that focus on the behavior of single joint rather than on the structural response [9]. These authors report experimental curves on riveted unions, and a model that describes the coupling in an explicit way (Fig. 11).

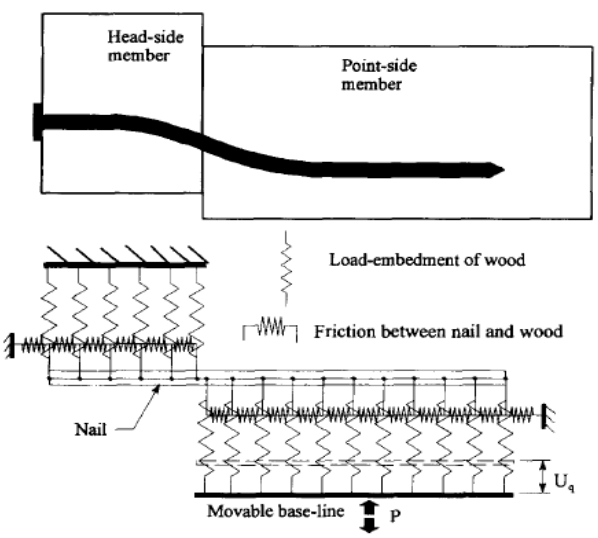

Fig. 11: Scheme of the joint.

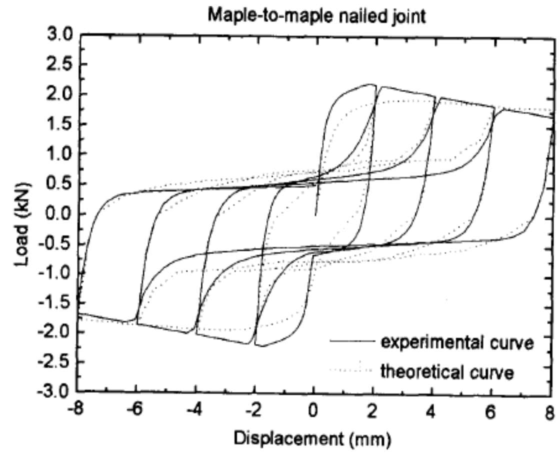

Fig. 12: The experimental result of a cyclic test on the joint and the result of simulation.

As perspective, the experimental data can be used to calibrate a new law behavior of the plastic hinge type. In terms of modeling the panel, it is clear that an explicit modeling of the inner panel including stiffness should be added.

VIII. CONCLUSION

So far, all researches pointed their attention to an existing building. But so many doubts arise when the all were dealing with the health of a wooden house after 10, 30, 50, 100 years since its construction, and the idea behind is very simple: if we think about a concrete house, all the historical knowledge makes us so confident that a well build construction will last for long time, let's say a century.

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Code Aster is able to describe, in a single software environment, what happens to a wooden building overt time.

Researchers didn't mention the possibility to study acoustic behavior, or thermal dissipations, for example. Another field of research is to follow what in France is already exists in practice: to give the customer, together with the new building, a document describing for example the estimated production of CO_2 over all the lifecycle of the building from construction to demolition. As it was said earlier, in France it is a common practice, and the results of such a document are able to determine the interest of a potential customer and, of course, the final price of the building.

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