RELATIONSHIP BETWEEN SHAPE AND STRUCTURE IN CONTEMPORARY WOOD ARCHITECTURE

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Abstract. Our research work deals with the relationship between new wood optimized technological systems and their structural behaviour for the construction of contemporary wood architecture.

The aim of our paper is to work out possible design plans and methodologies able to highlight the relationship between shape and structure in buildings through the definition of specific hypotheses. Starting from the contributions given by Structural Mechanics and the analysis of the link shape-structure which determined the existing technological attitude and the development in wood architecture, it is possible to work out a valid framework able to integrate different approaches and theories from contemporary architecture and the modern Construction Science.

Through Mathematic Models and numerical calculation/analysis software, the dimension of structural elements will be rated to highlight the relationship between the Shape of the building and its Structure.

The work is organized into the followings sections:

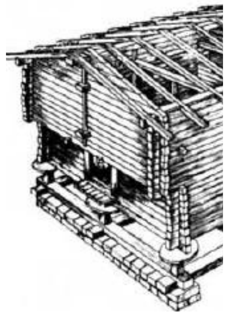
- Living spaces: historical and contemporary wood architecture;
- Technology systems for housing;
- Relationship between shape and structure in wood architecture;
- Main issues of studies on classical Mechanics and on contemporary Mathematic Models about wood structures;
- Structural connections in wood buildings: main typologies in historical buildings compared to contemporary constructive solutions;
- Case studies and design experiences in contemporary wood architecture.

1. LIVING SPACES: HISTORICAL AND CONTEMPORARY WOOD ARCHITECTURE

If we talk about wooden houses, we have to relate to a complex reality which has a long history of about 2000 years. If we refer, for simplicity, only to the constructions of which we have a direct knowledge, from High Middle Age to today we can observ lot of wooden buildings in Europe, USA, China, Japan and so on, and study their constructive technologies and methodologies. Wooden technologies were well studied first in Europe and in Asian Countries and traditional constructions evolved ad developed in many directions and solutions. For example we can think about *fackwerke* (fig.1) in the center of Europe, the *bay system* and the *box frame* in UK, the Norwegian *grind* and the *blockbau system* (fig.2), a typical Eastern-Europe and Russian technology. We can point out that in Western-Europe and in Turkish-Ottoman area the system-frame was the main developed constructive methodology because of the massive presence of pine forests; instead, in the Eastern-Europe, wooden buildings were constructed with logs stacked, like in the blockbau system.

Fig. 1 - The fackwerke system

Fig. 2 – The blockbau system



Around the tenth century, in Northern Russia such as in Novogorod and in Lagoda, all houses and other kind of constructions were made by wood. They had to provide a precise plan and orientation and they were articulated in two or three rooms to be well heated. They were built by farmer themselves, passing knowledge down from father to son. During the Middle Ages and in the later centuries, Northern-Russia houses called *izbe,* were radically changed on their functional and formal conception, but the aggregative criteria of single houses remain unchanged. The *izbe* typology of house were different country by country; the most used typologies were the *brus,* the *glagol* and the *koshel,* but every typology was build using the blockbau system technology. The Finnish and the Norwegian wooden architecture is otherwise influenced by the contest in which they were built. The weather is very cold for the whole year, and people are often not-aggregate into cities. They are usually very small communities, like single-family farms. Houses were built in a precise way, arranging buildings creating a closed court. They consisted mainly in two-floor houses, and they constructive system generally reflected their importance: most representative buildings were built by using the system-frame instead of the less important houses which were built with the blockbau system, a less developed technology. First Chinese wooden buildings date back to around 2000 years ago. Their construction methodology was particularly interesting because of the use of standardized wooden elements, assembled in a simple way. The wood was often used in Chinese architecture and, even if it was not the only material, it was very important for the development of Chinese techniques. The most popular system of houses aggregation was the court; it always followed a precise rooms layout and scheme: on the south was placed the main building, on the east and on the west were built the rooms for children and on the south were located the welcome room and the buildings for servants. The building complex was separated from the outside with a wooden perimetric fence. Form a technical and constructive point of view, wooden buildings could be divided into three classes, according to their construction process: the *Beam in Tiers Structural System* (fig.3), the *Column and Tie Beam System* (fig.4) and the *Log Cabin System* (fig.5). The *Beam in Tiers Structural System* was a frame system made by beams, columns and foundations, arranged according to the plan. A pair of short columns is located on every beam, gradually up to the roof. The main frame is then made of an overlap of different frames, according to the need of the building. The *Column and Tie Beam System* was characterized by a disposition of beams in the deeper dimension of building, and the columns are placed very closed one to each other. Rafters are placed directly on the head of the columns. The frame in made using multiple lines of connection beams (tie beam) which pass though the columns. Some brackets and some connection beams are also placed among different lines, in addiction to rafters, connecting the frame in a longitudinal direction. This typology of structure is equally repeated on different levels of the building, which means a saving of wood compared to the *Beam in Tiers System.* The *Log Cabin System* is a structural system very similar to the blockbau, often used in northern countries and in mountainous regions.

Fig. 3 – The Beam in Tiers Structural System

Fig. 4 – The Column and Tie Beam System

Fig. 5 – The Log Cabin Structural System

Through the development of improved technological systems, which allowed a better understanding of the mechanical behaviour of materials, it was possible to apply the knowledge of Western-Europe traditional structural systems to wooden buildings. The *frame system* is one of the most used structural system and it is composed by repetition in series of "beams and columns" module (Fig. 6). The *new blockbau* is another system currently in use, which name is inspired to the historical one because it starts from the traditional system logs stacked. Through prefabrication methods it's possible to create framed panels (Fig. 7); each panel contains a thin wooden structure and a natural insulation. Construction methods are simple, starting from the completion of the panel in the workshop, trough the storage, the transport on site, the new storage and the final installation. The *massive panels structural systems (X-Lam)* is composed by elements obtained by superimposing and crossing different boards. Each board is linked with the others with screws, glue or wooden pins (Fig. 8). The connection between panels and the other elements of the buildings, such as structural floors, is extremely simple; it is made through metal brackets or with a continuous border connection between panels and roofs.

Fig. 6 – Frame System

Fig. 7 – Insulated Panels Structure

Fig. 8 – X-Lam Panels Structure

3. RELATIONSHIP BETWEEN SHAPE AND STRUCTURE IN WOOD ARCHITECTURE

The study of the relationship between shape and structure in wood architecture, talking about residential buildings, explores the possible methodologies and tools to define the architectural shape through the comprehension of the structural behaviour of the building.

The ongoing research, within the technical-industrial factories which produce architectural elements (walls, floors, roofs), was important to identify structural systems whose task is to transmitting loads to the ground and to divided them into two categories: *massive panels structural systems* (X-Lam) and *lightweight systems* (insulated panels) (Fig. 9). Massive panels (Fig. 10) transmit loads across two main directions of their main plane. They may work as a horizontal slab (for loads perpendicular to the plane of the panel) and as vertical slab (for loads parallel to the plane of the panel) (Fig. 11). Lightweight systems, are composed by structural elements, very similar to "columns and beams" system, which are separated to insulation and closing components. The definition "lightweight construction of wood framed" is derived from the English expression "timber frame"; the backbone of the building, where uprights are fairly close, is then covered with panels to form such a slab (Fig. 12).

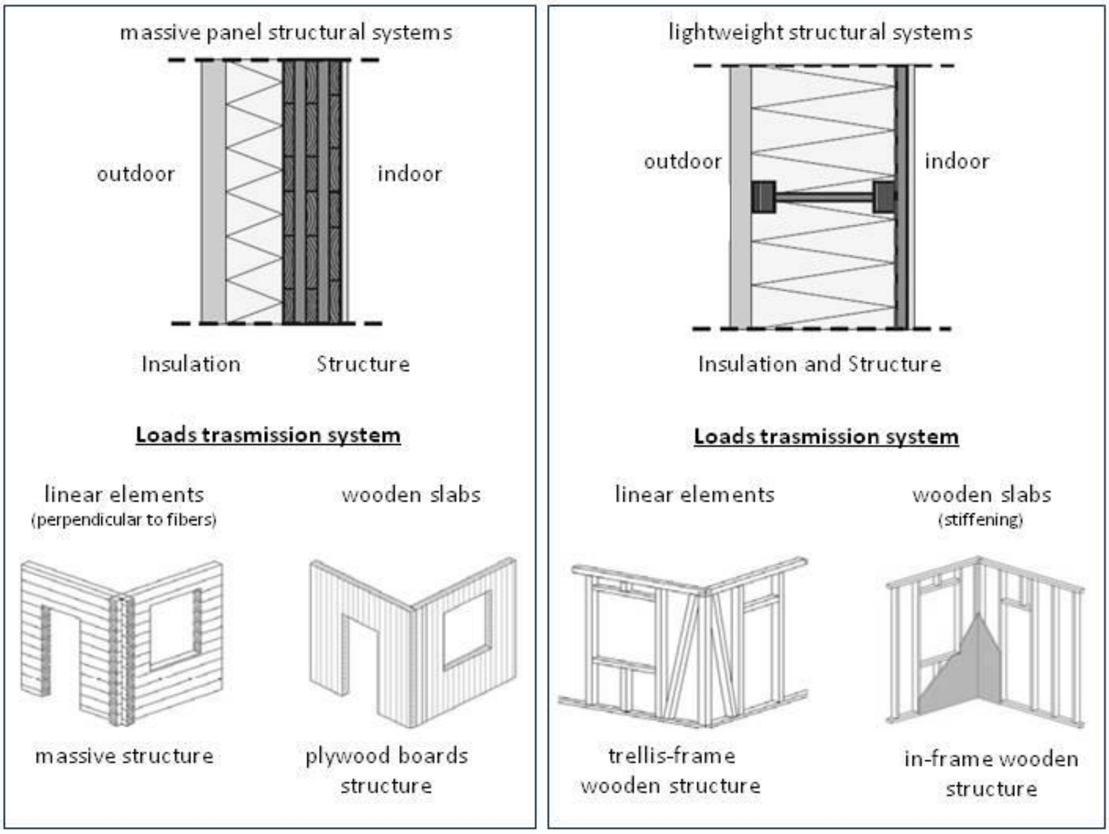


Fig. 9 – Wood structural systems

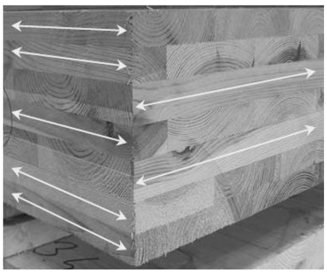


Fig. 10 – Plywood panels – X-Lam

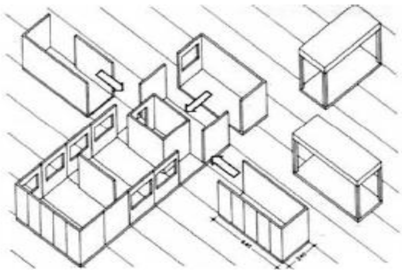


Fig. 11 – X-Lam Structural Panels

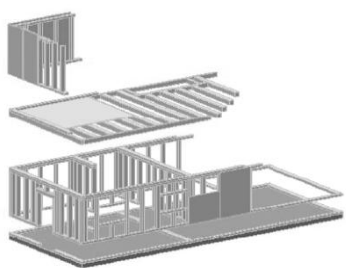
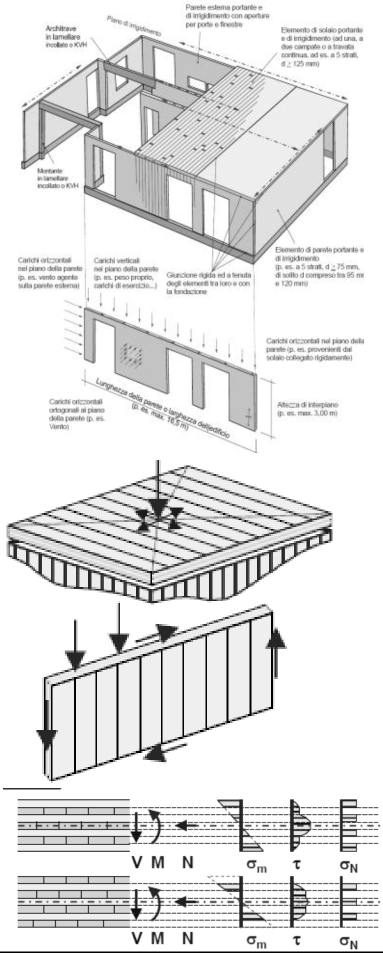
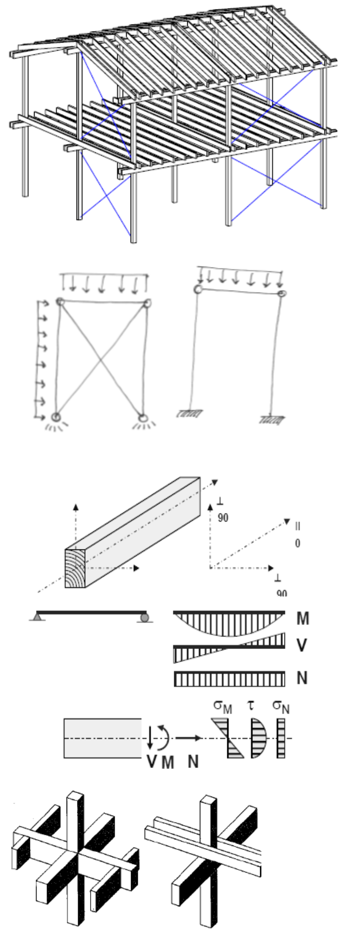
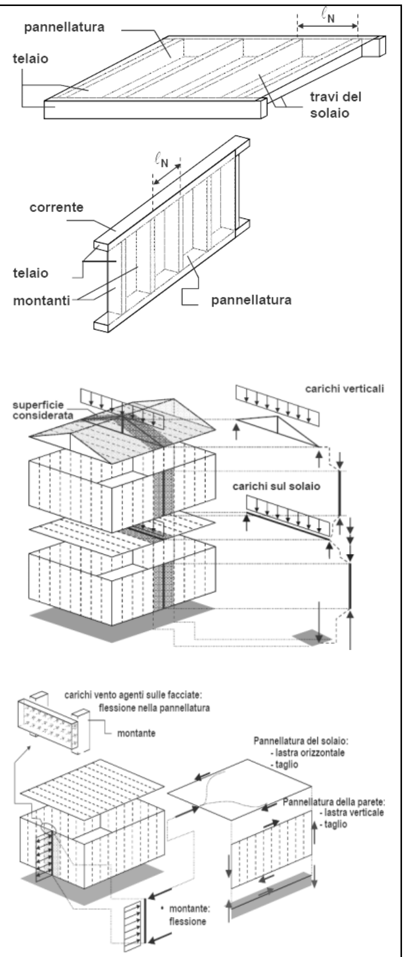


Fig. 12 – Frame-panels Structure

4. MAIN ISSUES OF STUDIES ON CLASSICAL MECHANICS AND ON CONTEMPORARY MATHEMATIC MODELS ABOUT WOOD STRUCTURES.

Starting from the study of these different structural typologies, it's possible to deepen the static behaviour of structural wooden elements, comparing mathematical models to reality. The table below compares the different methods of approach within the three systems most commonly used in wood residential buildings.

		
Massive panels structural systems: panels, composed by elements obtained by superimposing and crossing different wooden boards, work like a slab and transmit loads across two main directions of their main plane. They may work as a horizontal slab (for perpendicular loads) and as vertical slab (for parallel loads).	Lightweight structural systems: structural elements are linear and loads are transmitted by them directly to the ground. Insulation and closing elements can be independent from structure. Frame buildings are composed by a principal structural system, which is defined by colu9mns and beams placed according to the needs of the plan, and a secondary one.	In-Frame structural systems: chassis elements of the upright transmit vertical loads, meanwhile structural floor and roofs transmit horizontal loads. Unlike lightweight structures, frame and closing/insulation elements of the in-frame structure are not separated and they are produced as a slab.

5. STRUCTURAL CONNECTIONS IN WOOD BUILDINGS: MAIN TYPOLOGIES IN HISTORICAL BUILDINGS COMPARED TO CONTEMPORARY CONSTRUCTIVE SOLUTIONS

Connections are devices which transmit loads from horizontal to vertical structures. They are joint mounting systems, made by shaping the top of the structural elements, which provide to the coupling different elements (fig. 13). In historical trellis-structures called *fackwerk*, stiffening structures, which counter horizontal loads like wind, are made by including diagonal elements between frames, connected to them by metallic screws or pins. Contemporary connection systems, starting from traditional structural criteria, are designed by verifying their size and placing through numerical control and mechanical modelling, providing new solutions for carvings and joints. Connection techniques between wooden elements can be divided by their subjected stresses or by material, but the most common classification considers the origin;

This classification identifies two principal typologies: *traditional connections* (fig.14) of wood carpentry, produced by processing contact surfaces (carpentry joint); in this case, loads are transmitted directly to compressive stresses. *Modern mechanical connections* (fig.15) which transmit loads thought glue layers or metallic connectors inserted in the structure to link wooden structural elements (mechanical joint). Modern mechanical connections can be also divided by typology: *stemmed cylindrical metal connectors* (nails, bolts, pins, screws and staples) and *surface metal connectors* (ankles, rings, shaped plates). Connections between wooden elements are often made with shaped slabs or welded metallic slabs. Connections choice has to be defined by static and kinematic properties of them, defined by structural design: *hinge connections* (fig. 17) are not able to transmit bending actions; the most important hinge connection between principal beam and secondary beam is called "metallic shoe connection", a cold-shaped metallic sheet with holes for nails. *Rigid connections* (fig. 17) can transmit blending actions; in this cas, extreme sections of the rods which converge to the junction are forced to undergo the same rotation. In contemporary wood residential buildings, made with plywood boards which bear horizontal loads, connections between panels and other structural elements are often performed with metallic connections (fig.18).

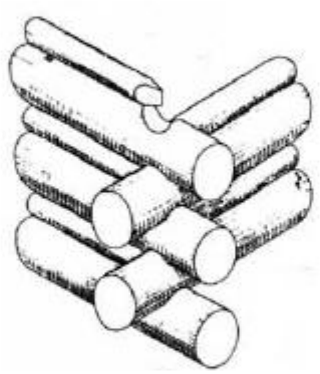


Fig. 13 – Unilateral dovetail connection

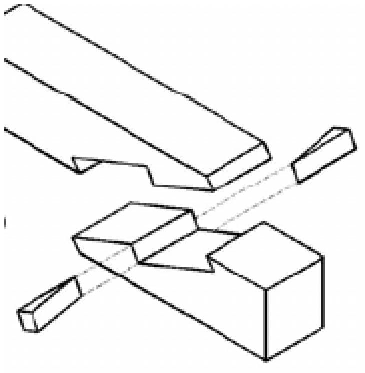


Fig. 14 – Traditional connections

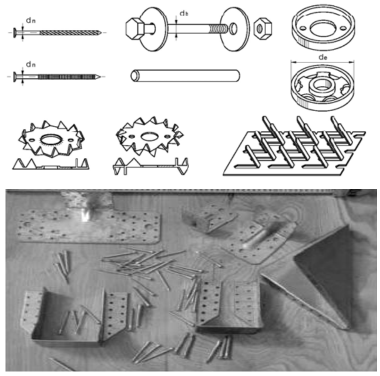


Fig. 15 – Modern connections

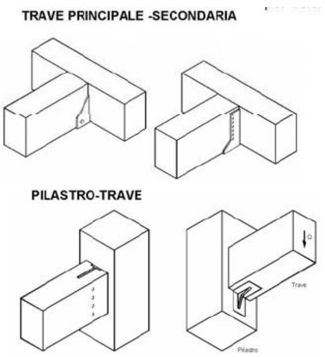


Fig. 16 – Hinge connection

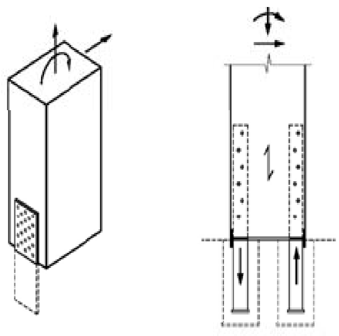


Fig. 17 – Rigid connection

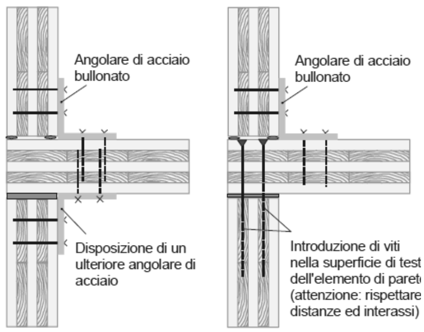


Fig. 18 – Connections betweek plywood panels

6. CASE STUDIES AND DESIGN EXPERIENCES IN CONTEMPORARY WOOD ARCHITECTURE

This case study (fig. 19) highlights a possible approach to the structural design of a small extension of a residential building made by contemporary wood architectural systems. The extension is a small volume with sizes 5x3x3 meter (fig. 20) in contact with the existing building and placed on the roof slab of its terrace. In order to not-overburden on existing structure, the new building is thought to be built with an independent wood frame structure, composed by glulam (glued-laminated timber) beams and columns connected by interlocking joint. The whole structure is then anchored to the base through L-metal-slabs and plates. The structure was sized using a 3D modelling software which can finite-elements-models (fig. 22), then verified by procedure within limit states defined by D.M. Infrastructure of 2008/01/14 (NTC 2008).

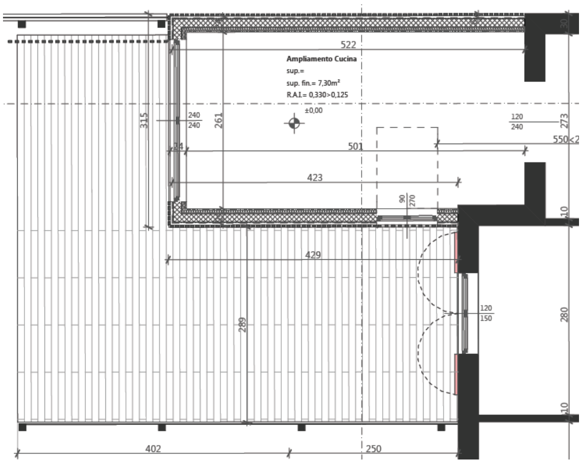


Fig. 19 – Architectural Plan

Fig. 20 – 3D Model

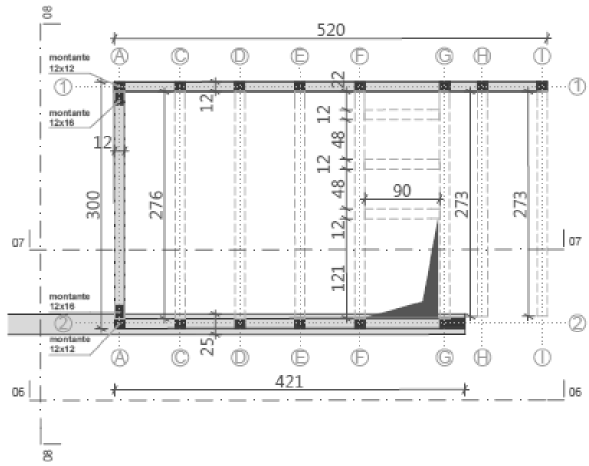


Fig. 21 – Structural Plan

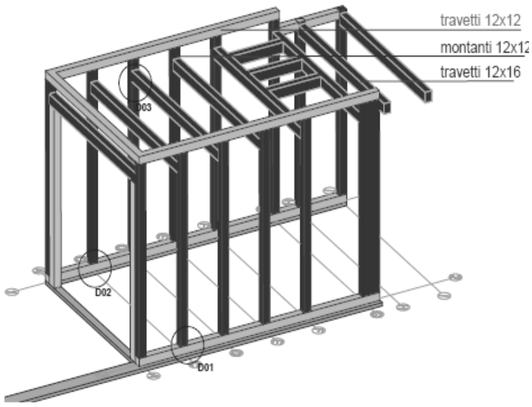


Fig. 22 – Structural 3D Model

Procedures that lead to size structural elements can be summarized through this steps:

- Loads analysis
  - Dead loads (permanent loads) and own-weight loads (ref. NTC2008 - 3.1.2 - 3.1.3): common material loads bear by structure and own-weight loads.
  - Live loads (variable loads - ref. NTC2008 - 3.1.4): they depends on uses of the buildings.
  - Duration of load classes (ref. NTC2008 – 4.4.4):
    - non-removable loads and own-weight loads: permanent duration;
    - permanent loads subjected to changes: long-term class;
    - variable loads: middle-term class;
    - snow load, reported on the ground: related to site features;
    - wind load: instant-load class.
  - Combination of actions (ref. NTC2008 – 2.5.3): defined by combination of loads (between permanent loads, variable loads, live loads and seismic loads) which generated most relevant stresses.
- Finite-elements modelling and calculation of internal forces in structural elements (fig. 23, 24, 25, 26, 27, 28)

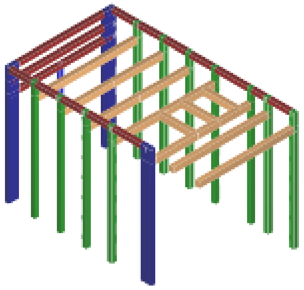


Fig. 23 – Structural-elements 3D model. Setting of the size of single elements and links between elements at the base (joint) and at the top, between beams and columns (hinge).

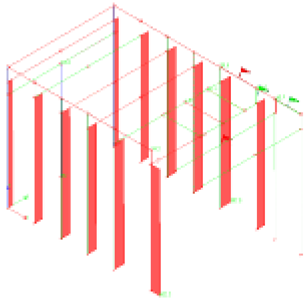


Fig. 24 – Axial-actions Diagram of vertical structural elements, which will be useful to determin their size.

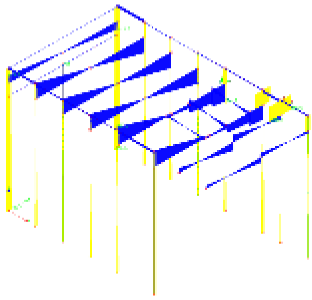


Fig. 25 – Cutting-actions Diagram of structural elements. Values will be useful to design and verfy metal connections between structural elements

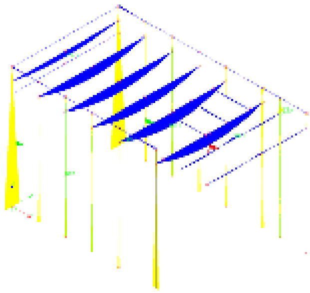


Fig. 26 – Bending-moments Diagram of structural elements. Maximum values otained will be useful to verify the bending of each single elements.

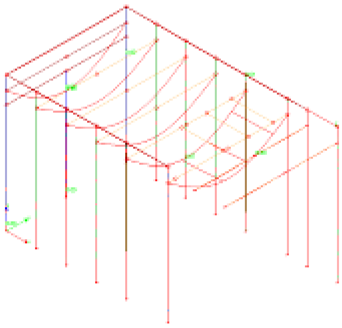


Fig. 27 – Structure subjected to rare snow loads: maximum deflections verified with operational limit states calculation.

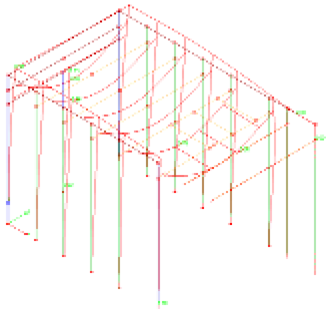


Fig. 28 – Strains diagram of maximum deflection caused by cross wind loads.

- Verification of most-stressed structural elements within ultimate limit states and operational limit states:
  - Bending-stresses verification: $(\sigma_{m,y,d} / f_{m,y,d}) + k_m (\sigma_{m,z,d} / f_{m,z,d}) < 1$
    - $f_{m,y,d}$ it's the calculation resistance to bending-stresses in y-axis;
    - $f_{m,z,d}$ it's the calculation resistance to bending-stresses in z-axis;
    - $\sigma_{m,y,d}$ it's the maximum strength to bending-stresses in y-axis;
    - $\sigma_{m,z,d}$ it's the maximum strength to bending-stresses in z-axis;
    - k_m safety correction factor;
  - Cutting-stresses verification: $\tau_d \leq f_{v,d}$
    - $f_{v,d}$ it's the calculation resistance to cutting-stresses;
    - τ_d it's the maximun shear strength, according to Jourawski theory.
  - Operational limit states verification: maximum deflection values verified with 3D models must be less than values imposed by NTC 2008 .

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