Design of a base isolated timber building in the historical center of an high seismic hazard area of Italy

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ABSTRACT: This paper deals with the design of an innovative school building under construction in the historical center of Ariano Irpino (Italy). The building has been designed to be integrated into the historical Town, with very peculiar and innovative structural aspects. The very characteristic heritage location, with small access roads and typical historical buildings, and the site topography, at the top of the hill characterized by sloping sides and high retaining structures, with high seismic hazard, strongly influenced the structural and architectonical solution. In order to deal with the site complexity, and realize a sustainable building, the designers developed an innovative solution: the substructure is a reinforced concrete (r.c.) volume on three sides underground, the superstructure is composed by a couple of timber buildings. Between the base and the timber buildings a base isolation system is placed (which results above the third floor of the complex). The use of cast onsite concrete offer an optimal solution for the basement, with the multiple function of soil retaining system, foundation and location for several fundamental functions (gym, conference hall and restaurants), whereas the use of timber frames and cross-laminated timber (CLT) elements, for the buildings in elevations, allows to obtain a low energy consumption and eco-sustainability, not requiring big construction machines, notwithstanding the use of prefabrication. In this paper the architectural and structural solutions are presented discussing functionality, safety and sustainability issues.

1 INTRODUCTION

1.1 *The project*

This paper deals with the design, considering both architectural and structural issues, of an innovative school building which will host the hospitality training and agri-food school complex of excellence of Ariano Irpino (Avellino, Italy).

The architectural and functional concept of the school complex is strongly connected to the urban and topographical nature of the site. The building (Figure 1, 2) is characterized by a unitary conception articulated by a basement (a reinforced concrete underground volume of three levels hosting several functions) that compensates the altimetric differences (Figure 3) between the two main sides of the building site: 10 meters underground on north side and road level south side, and by two emerging timber buildings that rise up from the cited basement. These latter two buildings are conceived as two similar structures, with a large staircase in between with the public function of connecting the upper square Piazza San Francesco and the lower street Via D'Afflitto (Figure 1).

The didactical spaces are mainly located inside the two timber buildings, which are more easily illuminated thanks to their solar orientation, whereas the main entrance is located in the basement block (ground floor from Via D'Afflitto), in correspondence with a gallery connecting the gym area and the laboratories. Above the gym, an appealing conference hall is located (Figure 5).

The use of the two different construction structural materials: reinforced concrete for the basement and structural wood for the two buildings ensures the achievement of several design targets: durability stiffness and strength for the partially underground part, architectural appeal, structural and energy efficiency for the elevation.

As described in Figure 2 and 3, the building develops starting from a base, characterized by reinforced concrete (r.c.) arches and shear walls, which have the function of contrasting pile retaining wall that sustains the excavation front (Figure 4), from which the buildings rise with wooden structure, helping horizontal resistence. Underneath the timber buildings a seismic isolation system is interposed between level 1 and level 2 (level 1 is the first order of timber/steel elements, therefore the level 2 floor is the first isolated level). The sustainability from energetic point of view of the work is guaranteed by the choice of both the structural materials and the technical solutions adopted: the ventilated envelope with external coating in natural materials, the timber structures made of glulam timber frames and CLT panels.

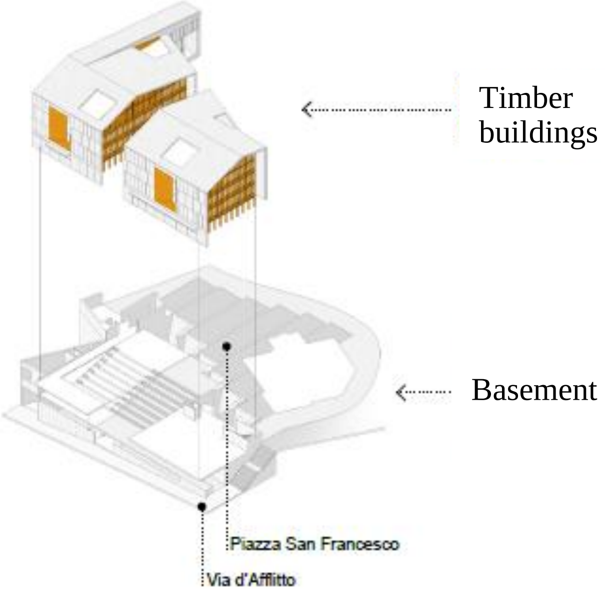

Figure 1. The school building: decomposition according to the main structural systems

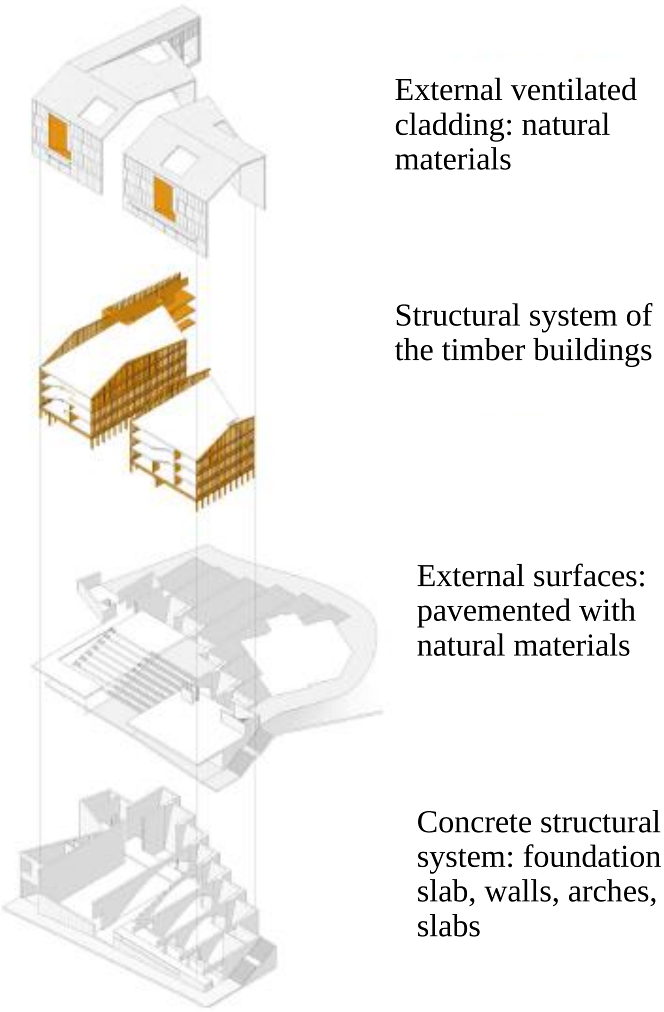

Figure 2. The school building: decomposition according to the main structural and architectural systems

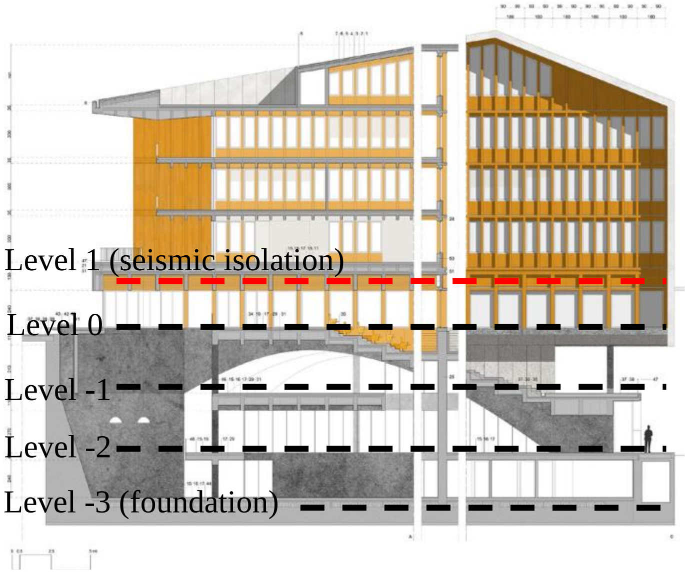

Figure 3. Architectural section of one of the two buildings

Figure 4. Building site, the altimetric gap: view from the existing ground level (almost other 3 m of excavation are expected)

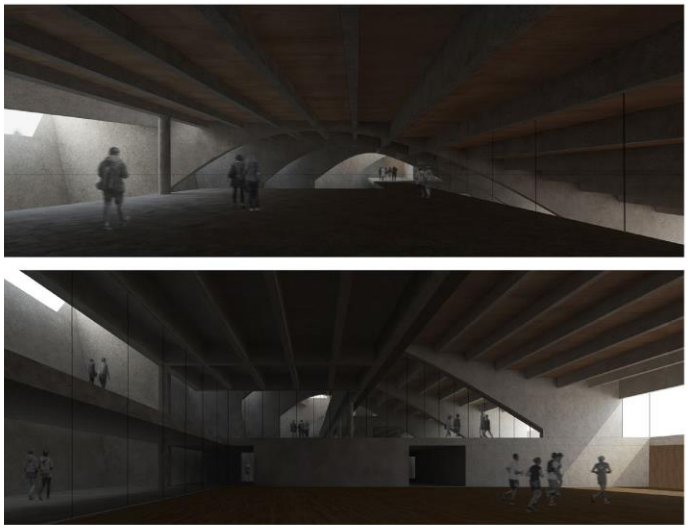

Figure 5. Internal view of the concrete basement: the gym at level -2 (bottom) and other spaces at level -1, under the conference hall (upper)

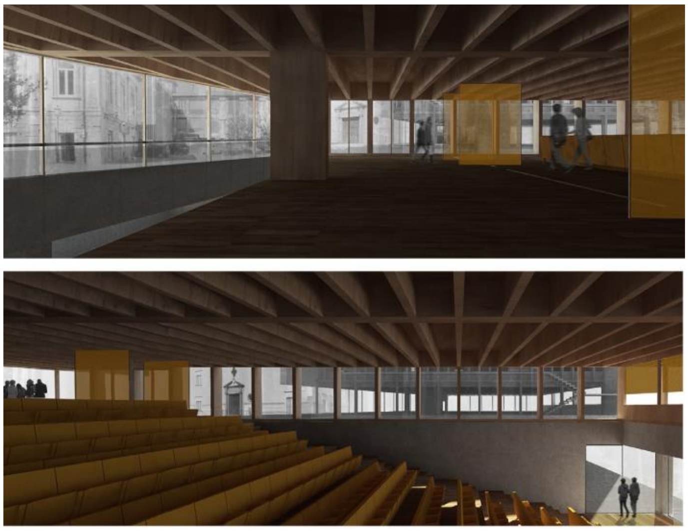

Figure 6. view of the timber building: the conference hall at level 0 (bottom) and the atrium (upper)

Figure 7. North Side Rendered view. Section of: (i) basement: bulkhead and foundation slab, (ii) upperbuidings: timber-steel columns, isolation and the timber structure.

2 TECHNICAL SOLUTIONS AND SUSTAINABILITY

The base of the school complex is extended for the entire intervention area (Figure 8, 9) between the downstream road and the excavation front supported by a piles bulkhead (Figure 7) counteracted by the concrete structure itself.

The reinforced concrete structure starting from the foundation level (-3), has two intermediate storeys (Figure 3) and one at the top supported by the system of reinforced concrete arches which have also the function of supporting part of the horizontal forces acting on the piles bulkhead system.

Over the basement block two emerging buildings rises. They have similar structures. The first storey are made of concrete walls (around stairs), steel and glulam columns with bracings, with an horizontal timber floor. Over the steel columns at level 1 an isolation system is placed which sustain a steel grid above which the upper four storeys rise composed by glulam timber frame structure and CLT walls, with timber horizontal slabs in crosslam. Thanks to the adopted solution the upper part of the buiding is structurally disconnected from the basement for horizontal forces.

According to the specific condition of the building site, the use of modern wood technologies allow flexibility and controlled management of the construction; furthermore, the innovation in the production and structural design of wooden structures components leads to reduced times of erection resulting in cost savings. Moreover, once again the use of an innovative solution, the seismic isolation, allows the achievement of elevated seismic performances and therefore damage prevention and life safety.

Figure 8. The building site: aerial view

Figure 9. Rendered view of the building: aerial view

The building reaches elevated performances also in terms of sustainability and energy efficiency. Internal partitions and external claddings respond to the different conditions of orientation and exposure to daylight, ensuring good levels of thermal insulation, control of environmental quality and shading. The external finishes are characterized by the use of durable natural materials, integrated with the context, capable of ensuring durability over time and limited maintenance costs. The external opaque cladding is made with reinforced fibrocement panels, plastered and colored in paste, on an insulated wooden substructure.

The building conception was finalized to achieve an almost zero energy model. The building has very high energy performance; the following technologies have been adopted.

For the production system:

• low temperature, geothermal heat pumps for heating and cooling;

• heat generator fueled with vegetable biomass for the production of domestic hot water (DHW) and integrated with heat pumps.

For internal terminals:

• radiant floor panels for the areas of the teaching area;

• all-air systems for high crowded environment;

• LED technology with regulation of the luminous flux for the control of natural and artificial light in the room.

Being the construction sector, one of the least eco efficient in Europe responsible for 30% of the region's total energy consumption and for 25% of emissions of CO_2 into the atmosphere, it is easy to understand how policies aimed at promoting energy efficiency and the use of natural technologies and materials are needed. Therefore, the issue of sustainability and the eco-efficiency of buildings is the fulcrum of the policies for public buildings in Europe.

Following this philosophy the use of wood, coupled with concrete in order to optimize the structural efficiency according to the building site morphology, was a primary choice for this project. Furthermore, wood plays a fundamental role in the fight against climate change, by producing forests wood, reduce the amount of carbon dioxide present in the atmosphere by fixing the carbon through the photosynthesis process; in addition, the use and transformation of wood into manufactured products and construction products require much less energy and CO_2 emissions than the production and transformation processes of other structural materials.

Therefore, the approach of the project team, was from the beginning focused on selecting, as much as possible, natural and low environmental impact technologies and materials. With this aim, the choice was to use glulam beams and columns for the timber frames and the floor construction, and CLT panels for walls and floors. Moreover, also in order to meet the sustainability criteria required by the Italian standard for public procurements, the design choice for the timber structural elements was to prefer productions marked with PEFC or FSC forest certification that means wood originating from forests managed with sustainability criteria.

3 STRUCTURAL DESIGN

Since the early stages of the design, the structural team focused his attention on the following issues:

- seismic, static and geotechnical safety;
- durability and functionality;
- energy saving and impact with the urban context.

According to the specific configuration and function of this building, some issues of particular importance have been identified and managed with innovative solutions:

- the morphology of the area;
- the high seismic hazard of the site;
- the building site located in the heart of the historic center.

Additional requirements considered are: flexibility, inevitably required by the intended use, and simplicity and speed of construction actually imposed by the building site condition.

As already mentioned, the building consists of two main portions (Figure 10): the basement block, which goes from the foundation, located just below the elevation of the valley road, up to the elevation of the square.

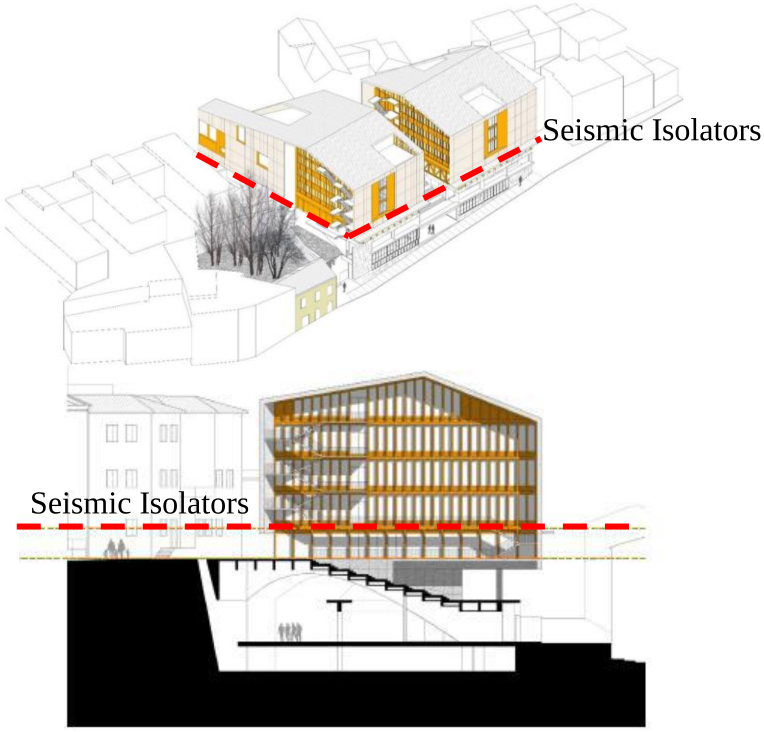

Figure 10. Building section: position of the seismic isolators.

As anticipated the conceptual design of the building was strongly determined by the needs: (i) of resisting high horizontal trust of the 10 meters wall toward north, including seismic action, (ii) the minimization of horizontal rseismic response of the upper buildings. The idea was that, during construction, seismic action can be disregarded, given the short construction time, while the vertical load induced by the upper new buildings have a positive stabilizing effect for the retaining walls, once the structure is completed. At the same time, isolation strongly reduces the horizontal effect of the upper buildings. The reduction obtained ranges from 3 to 5 times with respect to a conventional solution, without isolation and timber adoption.

The structural analysis of the building has been carried out with the software ETABS (Computer and Structures Inc.) and SAP 2000 (Computer and Structures Inc.) with the help of a pre and post-processing software specifically developed by Tecnisoft (Modest version 8.15). The numerical model was developed considering the entire building structure and, in order to correctly consider the seismic response of the seismic isolators, the analysis have been conducted considering the non-linear behaviour of the devices (friction pendulum).

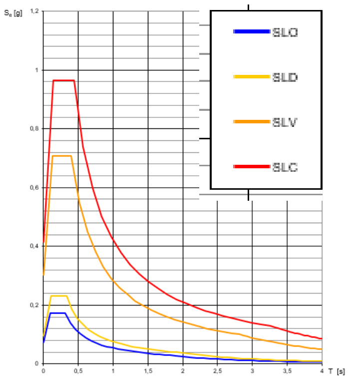

Figure 11. Response spectra: SLV (life safety), SLC (collapse prevention), SLD (damage prevention), SLO (operativity)

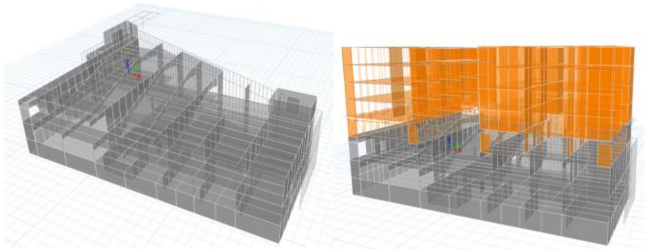

Figure 12. Numerical model of the building: a) entire building; b) concrete basement

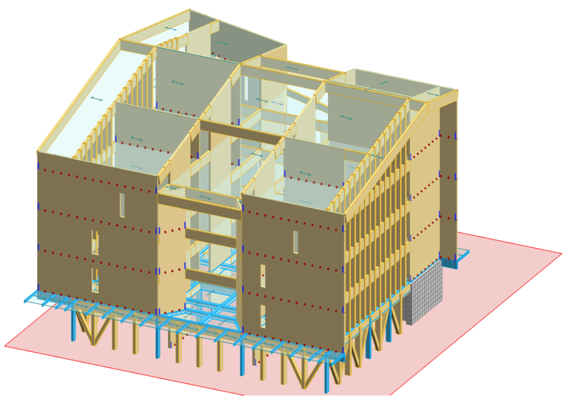

Figure 13. Numerical model of the building: steel, concrete (only at the first story) and timber structural system of one of the two emerging buildings.

The numerical model of the CLT building for linear analysis is composed by three types of elements which are utilized to represent the structural components, namely: (i) shell elements for the wall panels, (ii) truss elements for the connections among wall panels, and (iii) beam elements for the lintels connecting the walls above the window and door openings. All the structure, both the concrete elements and the timber ones , resists seismic action remaining elastic. This important performance occurs thanks to the high rigidity of the structures of the basement block defined on three sides by retaining walls and large wall/arch in north-south direction which contrast the north retaining wall and sustain the upper buildings and free only on the downstream side. This very stiff structure does not amplify the seismic motion from foundation to seismic isolation level with consequent fully compatible resistance requests with geometries.

3.1 *Design of the r.c. structure*

The concrete basement was designed in reinforced concrete cast on site according to the Italian technical code (NTC 2018). The use of concrete, for this portion of the entire building, was the optimal solution according to structural requirements and constructive capacity.

It carries out multiple functions: it is a building hosting many functions of the school, it is the foundation of the timber buildings, and sustains the soil horizontal trust on the north side wall.

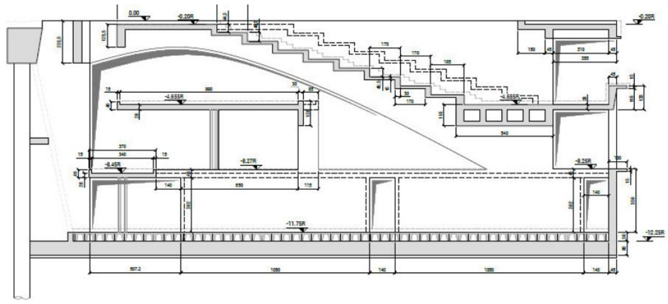

Figure 14. Concrete basement: typical section where one of the concrete arches converge into the retaining structure collaborating supporting the horizontal load

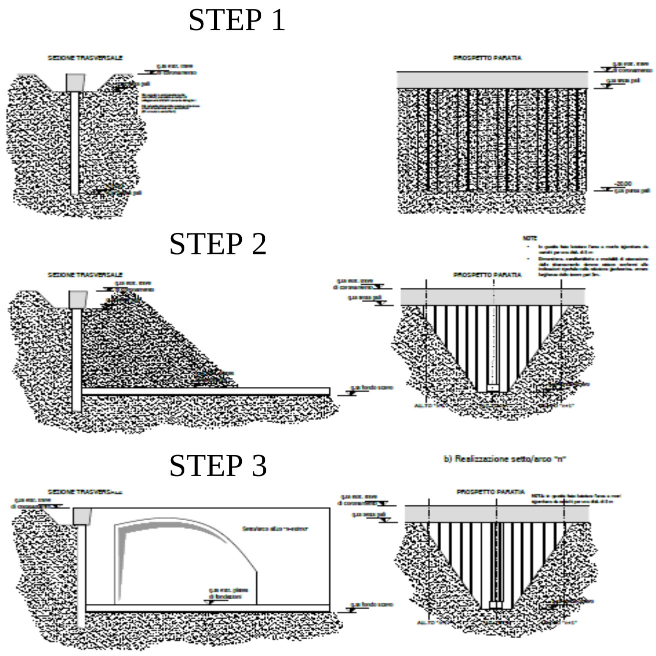

Figure 15. Constructive phases of the bulkhead: step 1- piles; step 2 – excavation; step 3 – construction of the arches

Dealing with this latter point, the height of the bulkhead, 10 meters, made by piles in a high seismic hazard area, on the top of a hill, required the use of a contrast structure.

The basement block concrete structure (Figure 13) made of large wall/arches guarantees the contrast of the retaining wall, with large safety in terms of stability and absence of significant displacements of the retaining wall in all the possible situations, from construction to full exercise even for very large seismic actions. The constructive phases of the bulkhead are detailed in Figure 15.

As a consequence of the specific geometry of the vertical elements rising from the lower level, the foundation is a continuous ribbed slab (Figure 16).

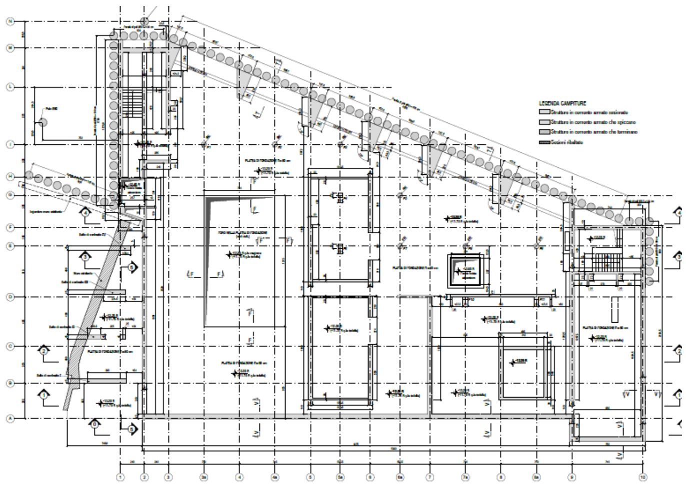

Figure 16. Foundation slab: plan

3.1 *Design of the timber isolated structure*

As already mentioned in §1, the supporting vertical structure of the first story of the two timber buildings is made with a combination of concrete walls for the staircases and elevator shafts, internal glulam and steel columns, and glulam columns and bracings along the four external sides.

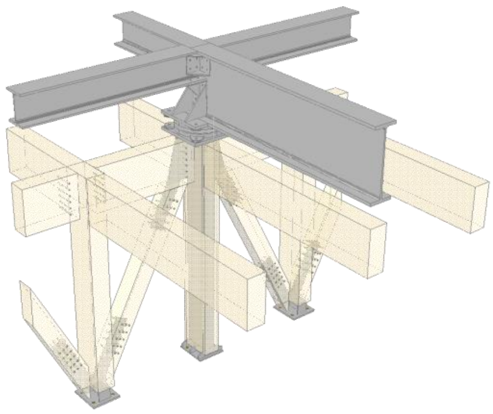

Figure 17. Detail of the steel columns, covered by wooden panels, supporting the double curved sliding isolators, the glulam columns and bracings and the lower timber floor and upper lattice steel floor.

The steel columns, which for architectural reasons are covered with timber panels which contribute also to the fire protection of steel, are needed in order to support the 49 double curved sliding isolators and are made with a box cross-section. All the other columns at the first story are made of glulam.

The first floor placed on top of the steel and glulam columns and below the seismic isolators is made of glulam beams and upper 100 mm 5-layers CLT panels. The second floor placed above the seismic isolator, is made with a very stiff steel lattice made of respectively 900mm and 400 mm, 700 and 300 mm deep H an C-shaped steel beams for the two buildings and again upper 100 mm 5-layers CLT panels.

The very stiff steel lattice floor plays a double role: (i) supporting the vertical components of the primary structure of the four stories above (CLT walls and glulam columns) which for architectural reasons are interrupted below the first level, and (ii) distributing the gravity loads and horizontal actions from the higher levels (timber structures) to the isolators system.

The supporting structure of the 4 stories above the isolation level is made of timber frames made of 180x320 mm glulam columns and 180x360 mm glulam beams spaced at 850 mm for the external walls and internal 5-layer 140, 180 and 200 mm CLT shear walls as primary horizontal and gravity loads resisting system. The intermediate floors and the roof structure are made of 180x360 mm glulam beams spaced at 850 mm and upper 100 mm 5-layers CLT panels.

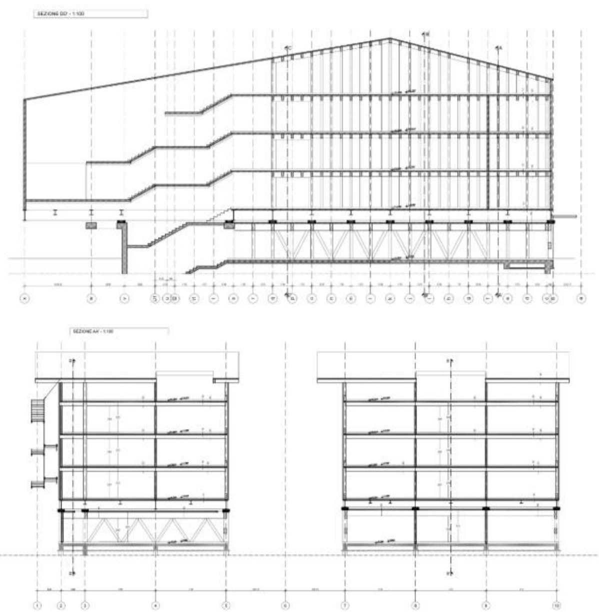

Figure 18. Longitudinal structural section of one of the two buildings (above) and transversal structural section of the two buildings (below).

The internal stairs are made of 200 mm 5-layer CLT ramps and landing and the wooden steps are placed and connected above the CLT panels. The elevator shafts are made of 120 mm, 5-layer CLT panel for the four wooden stories above the elevation level and of a steel trussed structure rigidly connected to the stiff steel floor for the stories below the isolation level, in order to allow the free displacement of the elevator shaft together with the wooden structure placed above the isolation level, when the seismic input occurs.

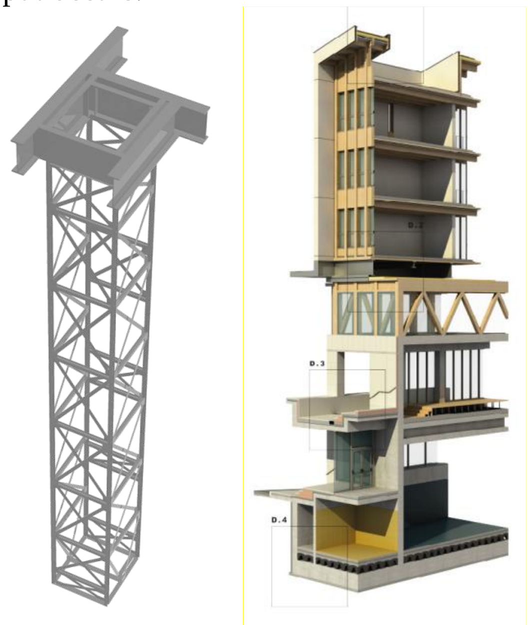

Figure 19. a) Detail of the steel trussed structure of the elevation shaft for the stories below the isolation level rigidly connected to the stiff steel floor; b) Exploded detail of the structures, reinforced concrete walls and floors below the ground level, the first story made of steel and glulam columns and bracings, the double timber and steel floor at the isolation level and the timber structure of the four stories above made of timber frames and CLT walls.

Finally the project includes also two external safety stairs made with steel tie rods attached to the external facades and floors made with steel beams for ramps and landings.

The two timber buildings are designed to remain in the elastic field thanks to the adoption of the seismic isolators, thus ensuring the integrity of the structures and keeping at the same time the functionality, due to the limited amplifications of the seismic action.

The timber buildings are designed with an isolation period between 2.0 and 2.5 seconds so that the horizontal forces due to the earthquake are very low. The horizontal actions resisting system is made of CLT shear walls coupled with the external timber frames. Generally, the connection of CLT walls is made with angle brackets or steel plates with nails and screws are used for the base connection and angle brackets are used for the inter-story connection. This solution allows the advantage of a limited presence of primary resistant structural elements thus enhancing the flexibility of internal spaces (for further details about the design of multi-story CLT buildings see Vassallo et al., 2018).

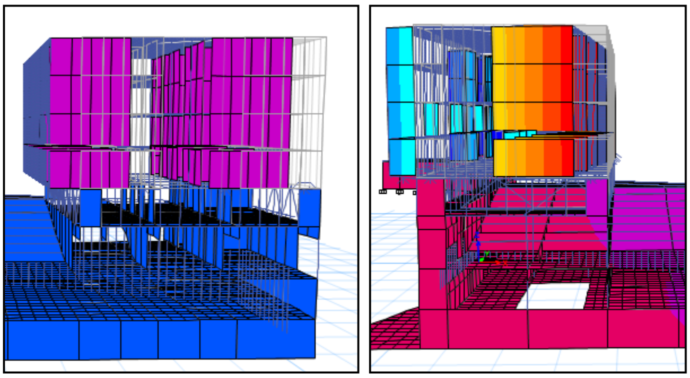

Figure 20. Modal shapes (main modes): a) Mode 1- translation of the est isolated timber building (T = 2.71 sec); b) Mode 2 - translation of the west isolated timber building (T = 2.546 sec)

Moreover, thanks to the adoption of seismic isolation system and to the lightness of the structure placed above (in comparison for example to a reinforced concrete alternative), the horizontal forces transferred by the isolated buildings as well as the vertical seismic actions are very small and therefore do not affect significantly the structural design of the reinforced concrete structures underneath.

Even if not strictly necessary considering the elastic design, the design provisions for the seismic design of timber buildings given in a recent proposal of modification of the chapter for the seismic design of timber buildings within Eurocode 8 were followed (Follesa et al., 2018)

As already mentioned in §1, the choice of the timber structure was due also to the quick construction process resulting in reduced man-made safety hazards at the building site and reduced construction times and costs. These advantages are given by the possibility of prefabrication of the wooden structural components which are at the same time light and easy to handle, which was an important issue in the context of the building suite in Ariano Irpino, characterized by narrow and steep streets.

Different choices, considering the significant dimensions of the construction, would have led to a significant impact on the historic center. On the contrary, the choice of prefabricated wooden structural element would lead to the reduction of discomfort for the surrounding environment during the construction time.

The maximum width of the CLT panels will be 2.40 m in order to ease the transportation, which can be made by placing the panels in flat position within the containers and speed the construction. Also, the maximum length of CLT panels and glulam beams will be limited to 11m in order to allow the transportation with small-size vehicles and ease the assembling procedure. Moreover, all the panels will arrive in the building site already equipped in the production factory with openings for doors and windows and installations and will be assemble according to the order decided in the assembly plan.

Also, the timber frames will be partly pre-assembled in factory and will be connected together by means with slotted-in steel or aluminum plates and dowel type fasteners which will be protected with wooden plugs in order to ensure the required fire protection of 60 minutes. Regarding the fire design, the required fire resistance was reached considering bot the protection given by the internal gypsum counter-walls and the fire resistance of the timber elements itself.

Finally, particular care has been paid to the study of construction details related to durability. The possibility of wetting due to moisture caused by interstitial condensation will be prevented by using breathable insulating sheets and materials and ventilation cavities on the roof in order to allow the drying of the structural elements potentially affected by these phenomena. All the timber structures in the external timber frames are made of larch (a wood species with high natural durability) glulam elements and are protected with 80 mm covering larch planks.

In order to protect as much as possible the wooden walls from the possibility of infiltration from the foundation plane, a concrete base beam will be made covered by bituminous sheet so as to allow the laying surface of the wooden walls to have a safety margin of 10 cm with respect to the internal floor finish in case of any flooding. The maintenance of the structures will also be made particularly easy by the presence of non-structural gypsum counter-walls which therefore allow easy access to the building structures.

4 CONCLUSIONS

The paper presents the design of a new building under construction in an historical center in central Italy. The location: top of an hill, and high seismic hazard, more than 0.4g of peak ground acceleration, with the need of an high retaining wall on one side of the building lead to an innovative conceptual design. The basement block of the building sustains the horizontal trust of the high retaining wall, 10 meters of height, and the vertical loads of the emerging timber buildings. These latter consisting of five floors, four of which stands on a seismic isolation systems. The advantages of the solution adopted, which represents a novelty in the state of the art and of the practice of buildings, are discussed under various point of view: architectural-functional, installation-energy-saving, construction-structural design.

5 ACKNOWLEDGMENTS

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REFERENCES

Bergami A.V., Forte A., Lavorato D., Nuti C. *Proposal of an Incremental Modal Pushover Analysis (IMPA)*. Techno Press, Earthquake & Structures, Vol. 13, No. 6 (2017) 539-549, ISSN: 2092-7614 (Print).

Bergami A. V., Forte A., Lavorato D., Nuti C. Non linear static analysis: application of existing concrete building. Atti di ITALIAN CONCRETE DAYS, 2016. 27 - 28 october 2016, Roma.

Bergami, A.V., Nuti, C., Liu, X. *Proposal and application of the Incremental Modal Pushover Analysis (IMPA)*. IABSE Conference, Geneva 2015: Structural Engineering: Providing Solutions to Global Challenges - Report pp. 1695-1700

Bergami A.V., Lavorato D., Nuti C., Fiorentino G. *Proposal of a non linear static analysis procedure for bridges: the Incremental Modal Pushover Analysis for bridges*. Assessing and Extending the Service Life of Bridges, a special issue of Applied Sciences (ISSN 2076-3417), 2020. DOI: 10.20944/preprints202002.0210.v1

Lavorato D, Fiorentino G, Pelle A, et al. A corrosion model for the interpretation of cyclic behavior of reinforced concrete sections. Structural Concrete. 2019;1–15. https://doi.org/10.1002/suco.201900232

Bergami, A.V., Nuti, C. (2015). Experimental tests and global modeling of masonry infilled frames. Techno Press, Earthquake & Structures, ISSN: 2092-7614, Vol. 9, No. 2, pp. 281-303.

Bergami, A.V., Nuti, C. (2014). Design of dissipative braces for an existing strategic building with a pushover based procedure. Journal of Civil Engineering and Architecture, USA, ISSN: 1934-7359, Vol. 8, No. 7 (Serial No. 80), pp. 815-823

Bergami, A.V., Nuti, C. (2013). A design procedure of dissipative braces for seismic upgrading structures. Techno Press, Earthquake & Structures, ISSN: 2092-7614, Vol. 4, No. 1, pp.85-108.

Follesa, M.; Fragiacomo, M.; Casagrande, D.; Tomasi, R.; Piazza, M.; Vassallo, D.; Canetti D.; Rossi, S. "The New Provisions for the Seismic Design of Timber Buildings in Europe". Engineering Structures 168 (2018) 736–747.

Vassallo D.; Follesa, M.; Fragiacomo, M. "Seismic Design of a six-story CLT building in Italy". Engineering Structures 175 (2018) 322–338.