Glulam Architecture: between sky and rails - The wooden structure of the metro station Napoli Centro Direzionale

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1. The wooden structure of the Metro Station of the Directional Center of Naples

Figure 1: Project rendering, exterior - front view

With its 5825 sqm covered area, of which 761 sqm of fixtures, the glulam structure and X-Lam for the coverage of the metro station of the Directional Center of Naples is now in construction step.
The project is the result of a long work starting from a preliminary-executive handed over to the buyer already in 2009: many years of management and estimation have passed since the first approaches to the feasibility study in 2007.
The great architectural project is a work of the EMBT Miralles-Tagliabue studio in Barcelona; the Metropolitana di Napoli S.p.a. is a concessionaire for design and construction; the Naples Metro Engineering s.r.l. is a concessionaire for design and work management.

1.1. Architectural design and compatibility with Wood material

The idea behind the work is to "*get to the Centro Direzionale, with the trains of the subway, a piece of real Naples, give that area an identity that puts it in the city ... In the Directional Center the city is not recognizable, it is impossible to find any of its historical or cultural features, so the main purpose of the project is to break the physical and mental barriers between the historic center and the directional center, past and present... The metro station become a sort of lava bubble that splits and explodes by connecting the under with the above*" [cit. Arch. Benedetta Tagliabue].

The complex structural system at the base of the architectural design has found the use of wood material the perfect combination winning. In fact, the great mechanical strength, with extreme lightness, with the structural versatility of the shape and size of the structural elements, has allowed an easy design of the structure in full respect of the architectural idea.
Certainly, the many possibilities of connection and the opportunity to make long, curved, and composed elements were fundamental. Likewise, industrial precision (including advanced numerical control machinery) in the production of the elements and the guarantee of the expected performance were the basis of a structural design that had more chance of respecting the architectural design.

2. Executive design

2.1. Description of the work

The basic concrete structure consists of four buildings up to three main elevation floors: rail floor +1.85 m, middle floor at +8.50 m and square floor at approx. 11.85 m above sea level.
The structures are continuous at the foundation level and rail level, while in height they are separated by joints between the frames of columns side by side.
The wood structures are integral to three of the four concrete buildings and are made as follow:

- a main structure grid formed in transversal direction (X) by curved and / or straight beams and in the longitudinal direction (Y) by rectilinear and composed double horizontal beams. These main structures are supported by pillars, generally consisting of 2 single inclined pillars supporting the horizontal main beams and 2 pairs of inclined and spaced pillars supporting curved main beams. All of these inclined pillars are rigidly connected to the base of the steel pillars embedded in the concrete structure;
- a secondary structure, in Y direction, consisting of straight beams, overlaid on the curved beams until to reach the perimetral main beams;
- four glulam structures "skylights" with glazed windows interposed between the roof beams. Two skylights are at the same level of the curved roof (skylights A and C), the other two skylights (skylights B and D) are emerging and let to reach the maximum height to the whole strucure to about 22 meters;
- a structural covering package consisting of straight and curved Cross-Lam panels.

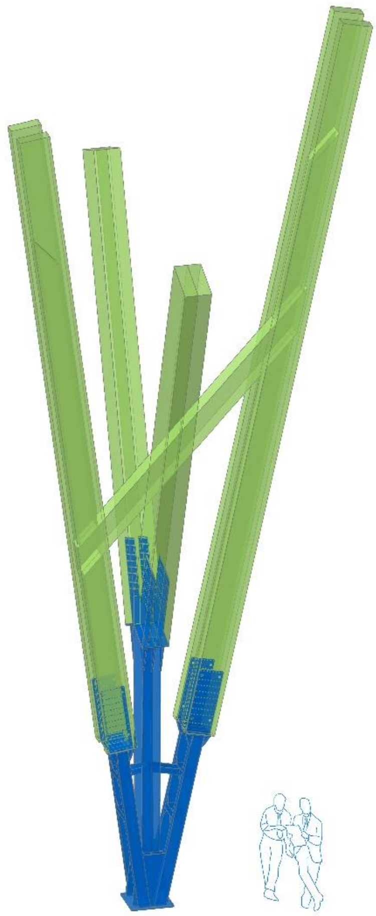

Figure 2: Pillar type, isometric view. It is possible to distinguish the steel frame structure (which will be later covered) and the inclined columns in glulam with bolted and dowelled connections

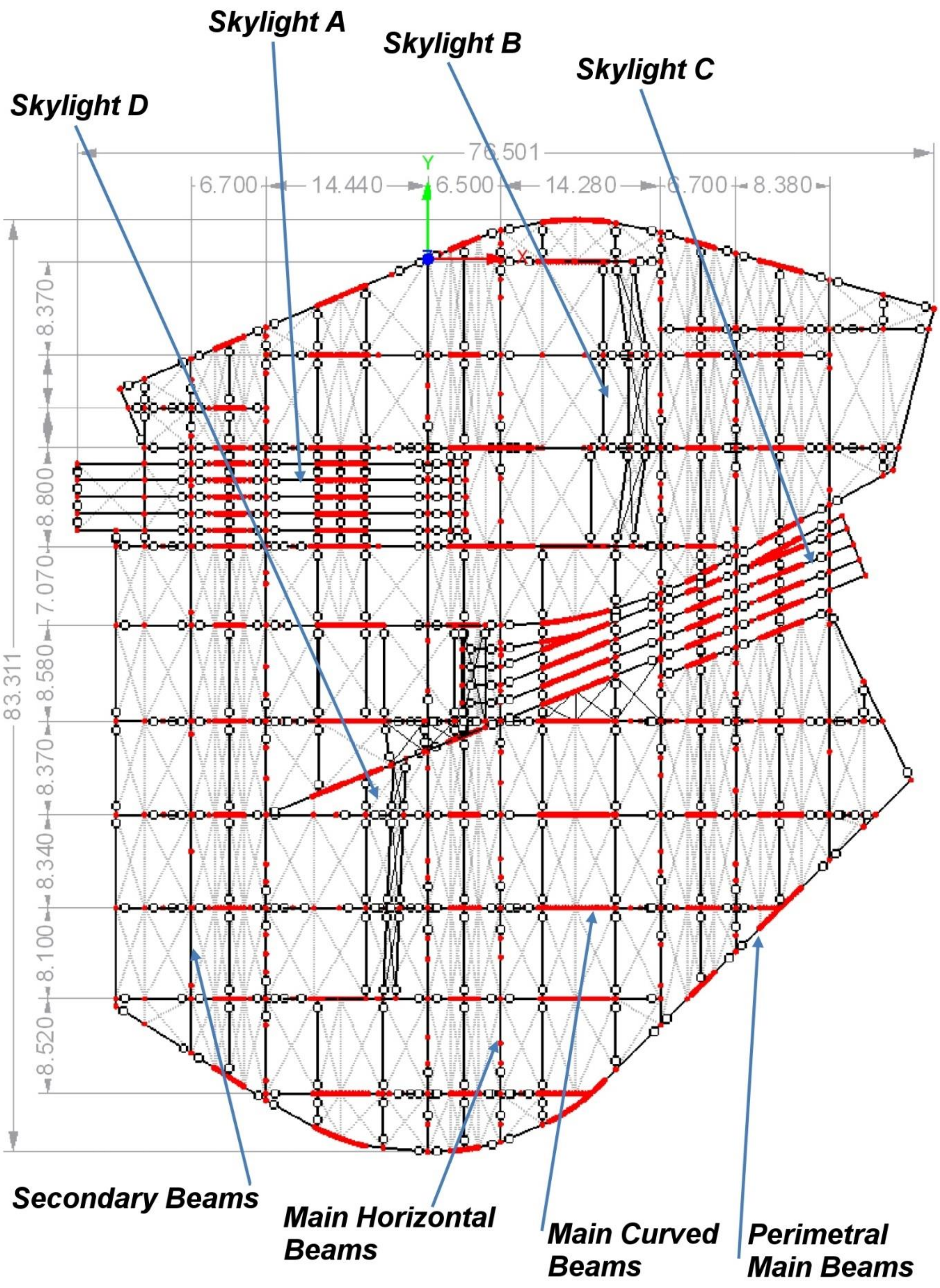

Figure 3: Planimetric scheme of structures and identification of the members

The static scheme adopted in the structural design is spatial (3D):

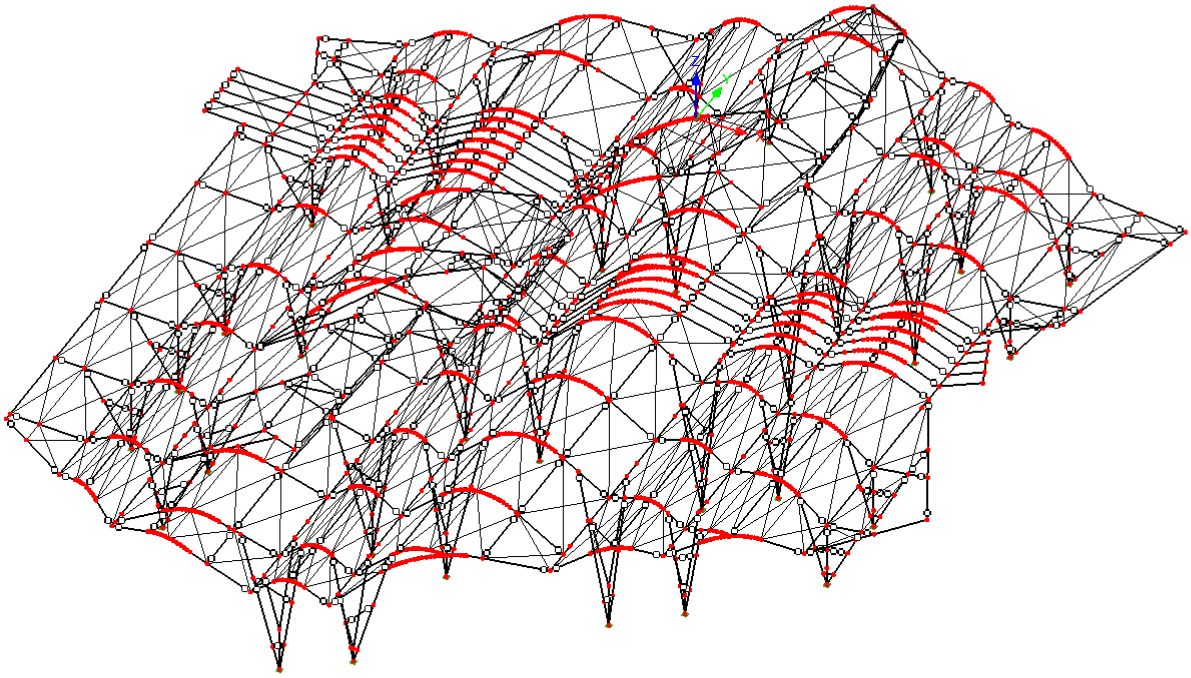

Figure 4: Spatial structure model, isometric view

Curved beams are modeled as hinged elements to the ends and linked with the main horizontal beams. Curved beams are connected between them, out of their plane, by compression/tension secondary beams.
Curved beams are also supported in X direction by the inclined double pillars, which are then rigid linked to the base structure of the steel pillar.
The horizontal main beams are glued 2+2 with a central member, they are rigidly linked to the length and are continuous on multiple supports represented by the inclined double pillars in Y direction, then rigid linked to the base structure of the steel pillar.
The pillars are modeled with a welded connection to the base.

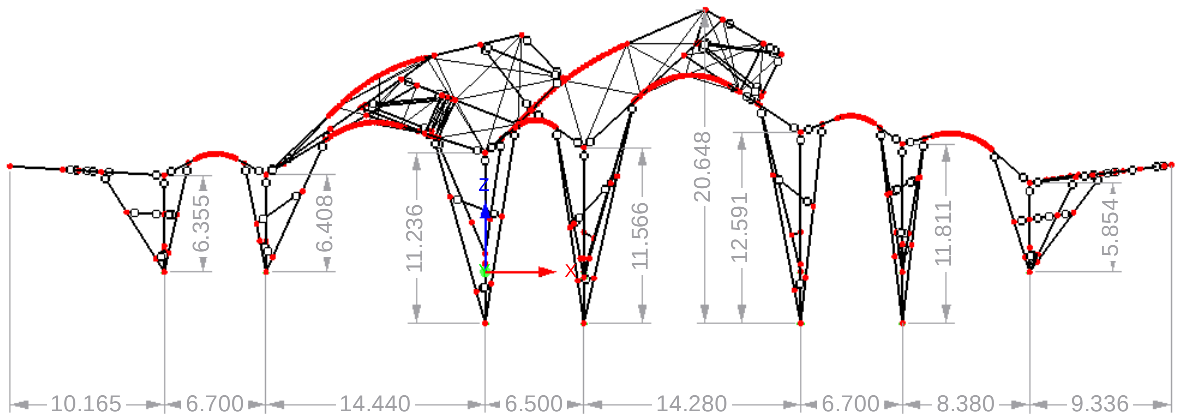

Figure 5: Spatial structure model, frontal view

2.2. The influence of the site on structural design

The design of this structure has been extremely binding on the state of the site, which is located in the heart of the city center into the Directional Center, nestled amongst the large palaces on a multi-level square. In particular the road that can be reached to reach the site is subject to a lower part of the square.
The main tower crane, which is strategically positioned at the center of the roof, has limits due to interference with the surrounding skyscrapers and buildings.

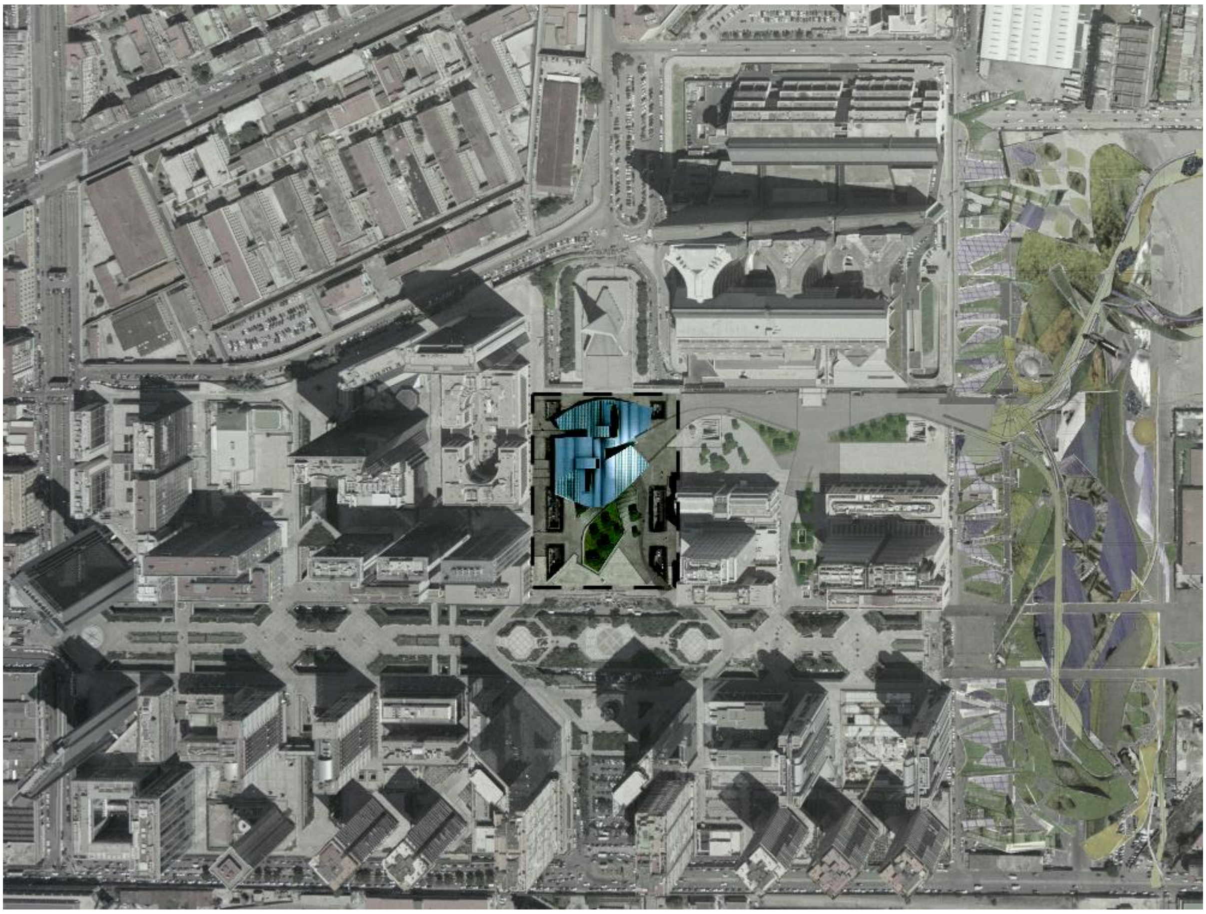

Figure 6: Project plan with site identification (dotted perimeter), we can see the size of the adjacent buildings and the positioning of the "slots" (rectangles and trapeziums on the two sides of the roof)

The beams and pillars can reach the site crossing a "slot in the square" that limits its size and weight.
Then, in the structural design, there are also the joints between the continuous elements that take into account the capabilities of the crane at each specific distance in which the crane operates and, of course, the size of the "slot". This single example clearly shows how the construction site conditions affect design. In the case of this structure, no margins of indeterminacy can be granted, and the in-depth study of the site even the assembly plan becomes a necessary condition for the success of the work.

2.3. Anti-seismic structural behavior and design strategy

Probably, just when one carry out a seismic analysis of a wooden structure, one can understand really how the use of this material in constructions is extremely effective.
The intrinsic lightness of the materials used in a construction already positively influences the masses excited by the seismic event, reducing the forces that consequently come into calculation. To complete the question there is also the best ability of the wood to withstand the instantaneous stresses, such as those caused by seismic action.
However, for such a complex and important structure as this, is not correct to "just to satisfy" to achieve adequate resistance to seismic actions. In fact, it is necessary to understand and optimize the seismic behavior of the structures. Wood, as the experience teaches us, is a material that, when the resistance reaches the elastic limit, such as a branch after being bent, even with great deformations, comes to break. The best seismic behavior is the ductile, which still leaves resistance even after the elastic limit reaches through the plasticization of the material. To allow for the best ductile behavior of the structure, we have to work on the connections, to whom are entrusted with the task of dissipating the energy before the elastic limit to the wood can be reached.

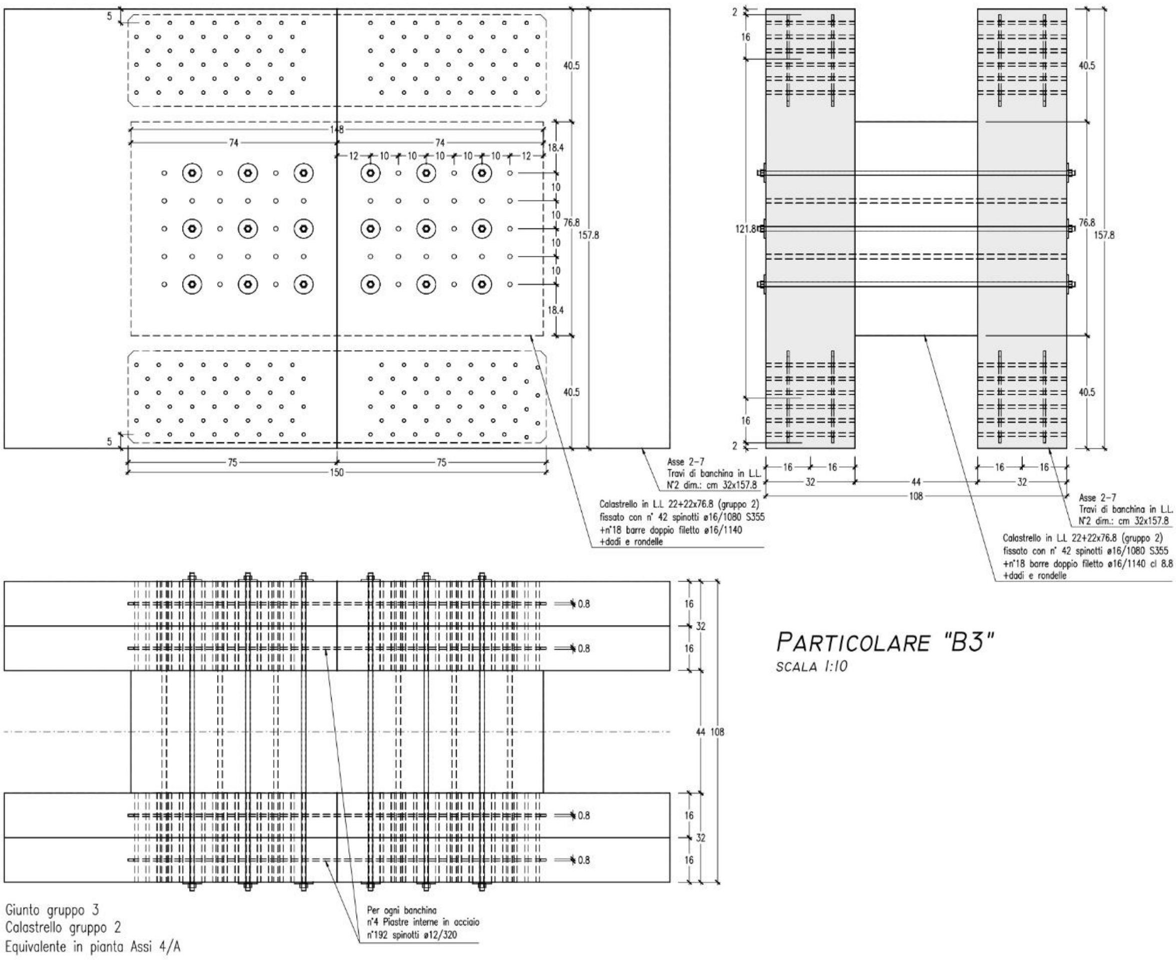

Figure 7: Abstraction from design drawings, rigid joint between the horizontal main beams (side view, section view and top view)

For example, all the continuity joints planned to limit the dimensions of the beams for the passage from the "slot in the square " mentioned above, have been studied as dissipative joints. This has optimized a limit and made it an opportunity. Perhaps this is a good example to express the strategy that has accompanied the entire structural design process.

3. From design to realization

Figure 8: Scale model, Miralles Tagliabue EMTB - Barcelona - Spain

The organization at the base of the construction of a prefabricated structure can not ignore the careful study of the production, pre-assembling and construction site operations. One of the most important advantages of this constructive typology is that of designing every aspect of both technical and organizational design. In this way, the actual building phase is reduced to a predetermined sequence of ordered steps, where the necessary material is always available and ready to be assembled. Operators know exactly what to do, how and how long. Thus the assembly teams will be suitably sized and placed on site as needed.
Unforeseen events will be minimized, and adverse meteorological conditions will also be covered in the hypothesized scenarios.

Figure 9: Design rendering, interior – internal view

3.1. Mock-up

Between the Project and the Realization (still in the design phase), it was indispensable to organize multiple coordination meetings of the design phase with all the subjects involved.
In particular, it was useful to prepare various real-size Mock-ups to support the executive solutions.
Below are the two main Mock-ups (only by way of example);

– Portion of horizontal main beam (half of the upper side)

Figure 10: Mock-up of a main horizontal beam (half of the upper side with roof) aimed at studying the gutter channel and the waterproofing covering

– Portion of roof (secondary beams and Cross-Lam)

Figure 11: Mock-up of a roof portion (secondary beams and Cross-Lam) aimed at the study of the waterproofing covering and interference with joints and connections on the roof

3.2. Production and pre-assembly

The production of a single order with significant volumes of material is generally optimized in the programming of the factory in order not to compromise the progress of the other orders in progress. In the specific case of a large and complex project such as the Naples underground metro roof, production was also phased as to eliminate the risk of material unavailability in subsequent operations. So the production, pre-assembly and assembly programs have been integrated into a single chronoprogram that scans and optimizes the time.

Figure 12: Factory of Rubner Holzbau Sud a Calitri (AV) Italy, glulam beams ready to be pre-assembled

For ordinary works, pre-assembling is often postponed to the site because it has a relatively small incidence of installation jobs. In the case of this structure, the large number of connections, the important dimensions of the elements (especially those of the main beams) and not least the small space available on site, make it necessary to organize and optimize even the pre-assembly phase in the factory. To understand the complexity of the operations, just imagine the preparation from gluing to the installation of a real example of a horizontal main beam:

- 4 straight single members 16 × 160cm and 2 straight pieces 22 × 80cm and planing;
- double glued of 4 elements together to get 2 pieces 32 × 160cm and 2 elements to get 1 piece 44 × 80cm and finishing;
- assembly with glue and bolts of the 2 pieces 32 × 160cm with 22 × 80cm piece in middle and finishing;
- head milling for the steel plates housing, predrilling for the housing of connectors;
- inserting the steel plates with the connectors on a composed beam in head side.

It is therefore evident that the complexity of repetitive steps for a significant number of elements, although seriously engaging an "ad hoc" factory, if takes place at the factory eliminates all the unforeseen, not the last, meteorological events that may occur at the site.

3.3. Installation plan

The installation of the structure, thanks to the previous pre-assembling phases in the factory, can take place with the smallest number of in site operations. Among the most obvious advantages are the following:

– installation speed;
– precision of execution;
– site work control;
– safety.

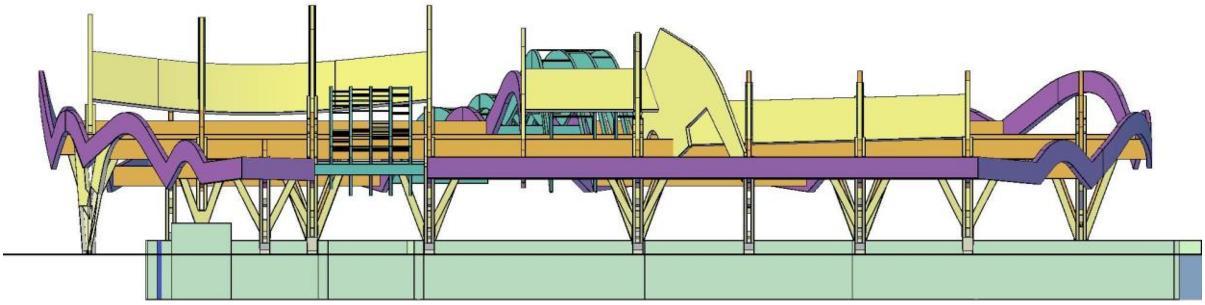

Figure 13: lateral view, main beams and columns (in this view the roof cross-lam panels and the secondary beams are concealed)

The installation phases were studied by dividing the construction in steps. Each step and each intermediate stage is supported by static calculations that show stability to the most severe actions that may occur (with particular attention to wind load).

The installation starts with the placement of all the steel pillars (Ref._a_ Figure: Main Stages of Installation), allowing first verification of the alignments and distances. At this point, when the expected geometry is reached, there is a valid setting that allows the correct mounting progress.
Thus, it is possible to connect the glulam columns, inclined or vertical, (according to the design drawings) on the steel pillars (Ref._b_ Figure: Main Stages of Installation) and after it is possible the placement of the horizontal main beams (Ref._c_ Figure: Main Stages of Installation).
The first step is complete with the installation of the connecting curves main beams between the horizontal main beams of the first two alignments. These are located in the area where the cover has a minimum height difference with the plane of the square, resulting in more rigidity.
With the placement of secondary beams and provisional wind bracing, a whole independent structure section will be created that can be entrusted with the task of countering the elements in subsequent steps.
This is done, with the same sequence setting, for the installation of the additional spans and perimeter beams (ref._c, d, e, f, g_ Figure: Main Stages of Installation).
At the end of all the fixings of the main beams, the secondary beams can be completed (Ref._h_ Figure: Main Stages of Installation) and then also the Cross-Lam roof (Ref._i_ Figure: Main Stages of Installation).
At this point, the entire structure reaches the carrying capacity sufficient to eliminate all the provisional wind bracing systems foreseen in the design of the installation steps. This makes it possible to safely mount the emerging skylights, which will find at their base a complete and perfectly functioning structural system.
The installation ends with the removal of the tower crane, with an additional cranes (MC) to be positioned outside the site area. This mobile crane need also to close with the last X-Lam panels the roof portion previously occupied by the tower crane.

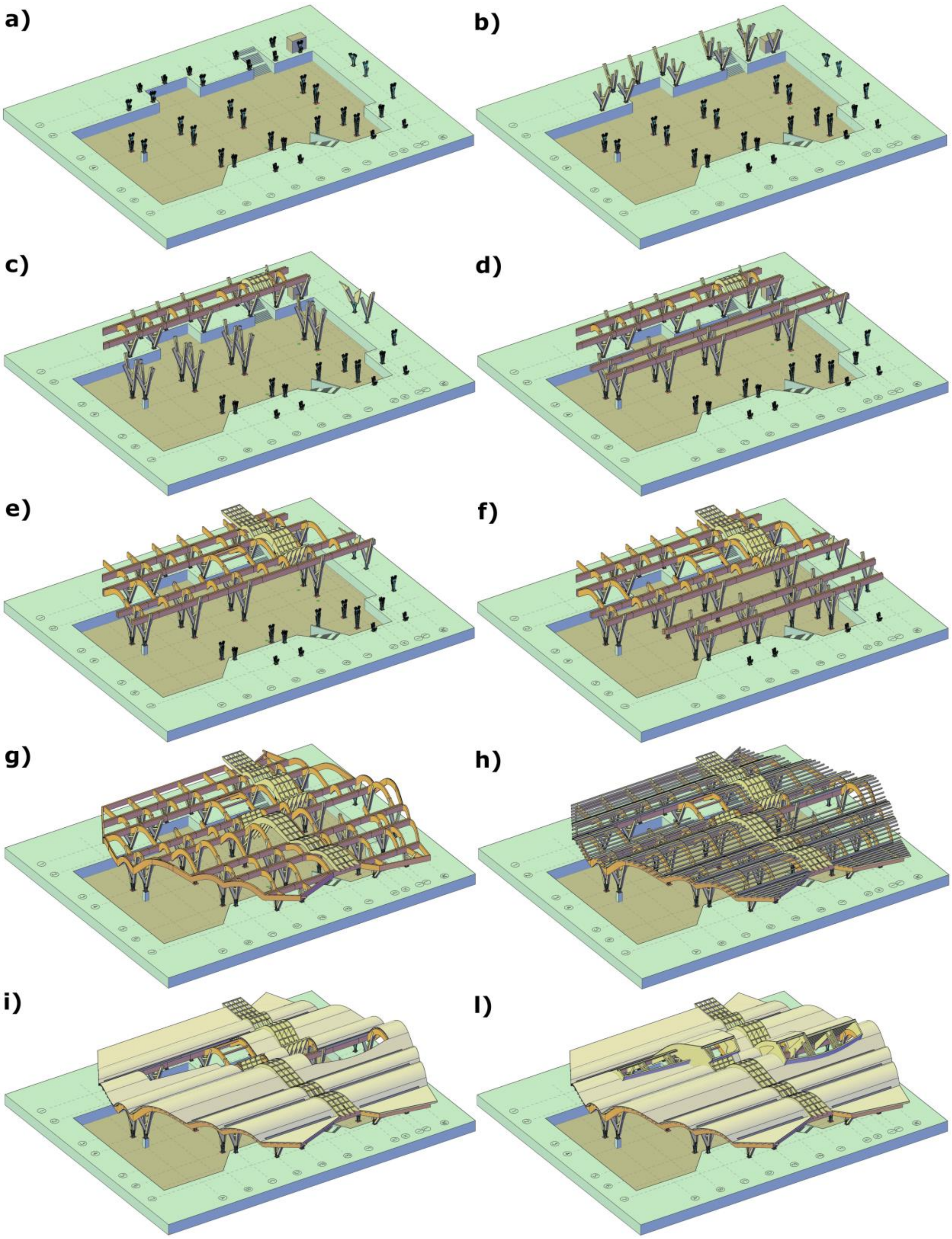

Figure 14: Main Stages of Installation, a) installation of the steel pillars; b) installation of glulam columns (inclined or vertical) to steel pillars; c) connecting the horizontal main beams to the pillars and the arches to the horizontal main beams, including the the provisional wind bracing systems; the beginning of the connection of the glulam columns to the steel pillars of the next span; d) installation of the horizontal beams to the glulam columns; e) connecting the arches to the horizontal main beams, including the wind bracing system for the stability of the structure; installation of the arches and curved beams to the horizontal main beams; connecting the cantilever beams from the first span; f) installation of glulam columns for the last pillars; g) completing the installation of the main beams; h) completing the installation of secondary beams; i) positioning and fixing of the Cross-Lam structural roof pannels; l) installation of emerging skylights and work completion

4. Data and information about the Project

General data	
Architectural designers	*Studio Miralles Tagliabue – EMBT – Barcelona - Spain*
Structural design	*Rubner Holzbau Sud S.p.a. – Ing. Dario Curlante*
Technical drawings	*Rubner Holzbau Sud S.p.a. – P.I. Giuseppe Zicola, Geom. Angelo Sista*
Contractor	*I.G.R. S.r.l. - Napoli*
Use	*Underground station*
Typology	*Roof and pillars*
Location	*Napoli – Centro direzionale* *Latitude: 40.8636* *Longitude: 14.2854*
Height above sea level	*17 m*
Covered surface	*5825m²*
Glulam	*2120m³*
Cross-Lam	*355m³*
Steel	*124.000kg*
maximum size	*Lx=80,0m Ly=88,0m H=21,0m*
Year start of work	*2017*
Year end of work	*2018 (for wood structures)*
Structures description	
Concrete substructures	The basic concrete structure consists of four buildings up to three main elevation floors: rail floor +1.85 m, middle floor at +8.50 m and square floor at approx. 11.85 m above sea level. The structures are continuous at the foundation level and rail level, while in height they are separated by joints between the frames of columns side by side.
Wood structures	The wood structures are integral to three of the four concrete buildings and are made as follow: - a main structure grid formed in transversal direction (X) by curved and / or straight beams and in the longitudinal direction (Y) by rectilinear and composed double horizontal beams. These main structures are supported by pillars, generally consisting of 2 single inclined pillars supporting the horizontal main beams and 2 pairs of inclined and spaced pillars supporting curved main beams. All of these inclined pillars are rigidly connected to the base of the steel pillars embedded in the concrete structure; - a secondary structure, in Y direction, consisting of straight beams, overlaid on the curved beams until to reach the perimetral main beams; - four glulam structures "skylights" with glazed windows interposed between the roof beams. Two skylights are at the same level of the curved roof (skylights A and C), the other two skylights (skylights B and D) are emerging and let to reach the maximum height to the whole strucure to about 22 meters; - a structural covering package consisting of straight and curved Cross-Lam panels.
Loads	

Dead Loads	*g=0,50kN/m² (without selfweight)*
Live Loads	*q=0,50kN/m² (Maintenance on roof)*
Snow	*s=0,96kN/m² (maximum load for accumulation snow)*
Wind	q_b*=456,29N/m²*
Seismic analysis	
Type of analysis	*dynamic and linear*
Structure factor	*2,4*
Topgraphical category	*T1*
Underground category	*D*
Use class	*III*

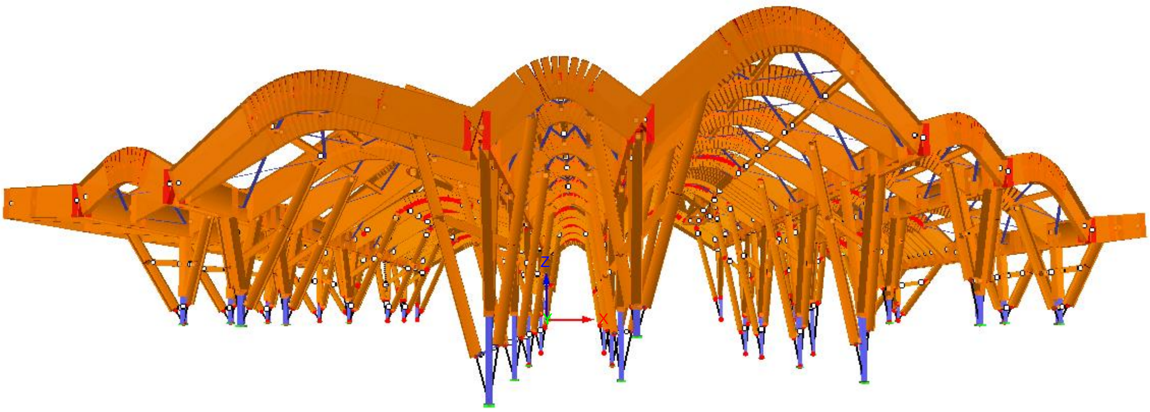

Figure 15: Calculation 3D model, frontal perspective view

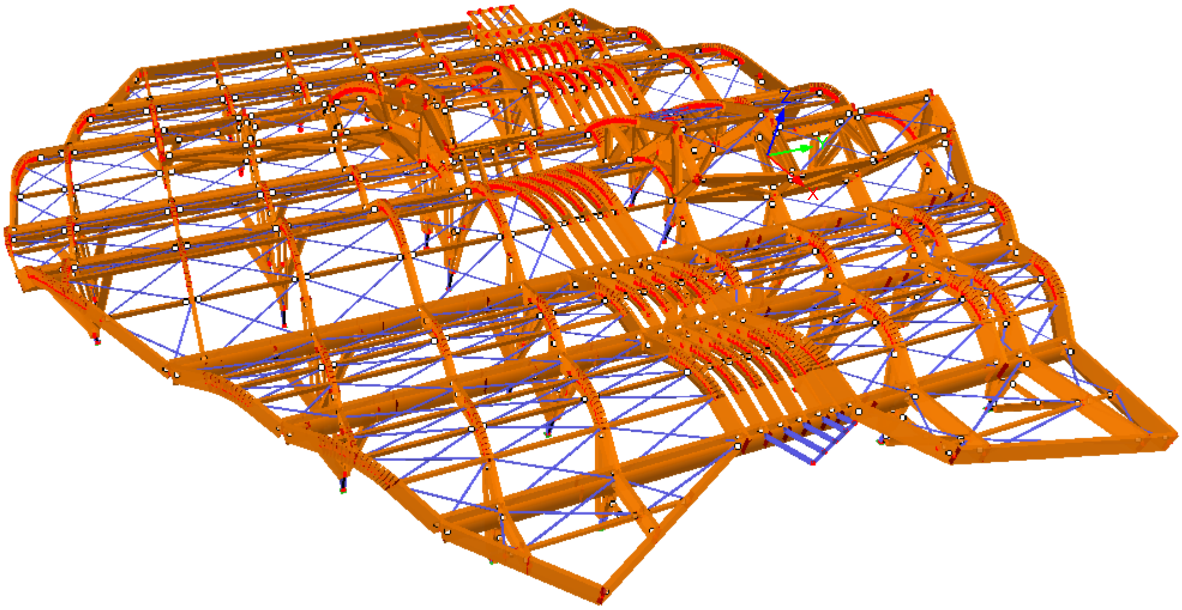

Figure 16: Calculation 3D model, perspective view from above

5. Bibliography and main reference codes

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