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Spatial plates structures behavior: the case study of the Control Tower of Swiss Railways in Pollegio – CH

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Abstract.
The proposed case study is the control tower of Swiss Railways in Pollegio - the railway sector with the 50 km long Gotthardtunnel through the Alps. The structure is the result of a competition held in 2006, the construction has been completed in 2014 and it is until now under deformation control.
The control tower's periscope shape, with an asymmetrical upper box and a solid lower shaft, is the direct result of the load-bearing structure being made of prestressed reinforced concrete plates. The shape resulted from specific choices made in the early design stages together with the architects.
The structure is a complex spatial system that works three-dimensionally and required many different and detailed studies.
In this paper, we will present the overall design process. That process began with the traditional analysis methods based on graphic statics and tension fields refined with finite element analysis that confirmed the important interactions between the multiple structural elements. Those interactions were ultimately validated by the results obtained from continuously monitoring the structure from the construction phase to the present day.

Keywords: spatial plate structure, graphic static, tension fields, monitoring, correlation of testing/analysis.

1 Introduction and context

To understand the design method proposed in this paper, contextualizing it within Switzerland's architectural and engineering culture [1] is essential. The Swiss approach to design has traditionally been a dialogue between architecture and structure [2]. This approach emerged from a historical and academic context that fostered numerous infrastructure projects in the country since the 19th century.

The establishment of the ETH Zurich in 1855 aimed to train professionals capable of designing the infrastructure needed to connect different parts of the country. Karl Culmann's "Die Graphische Statik" [3] in 1864 promoted a geometric and graphic method for analyzing structures, distinct from other European schools' analytical and mechanical approaches. The Swiss school's focus on drawing-led analysis emphasized the formal and aesthetic aspects of artifacts [4].

Another significant aspect of the design process in this paper is the role of materials, particularly concrete. Switzerland's abundant quarries of crushed stone, gravel, and limestone have fostered a strong tradition of concrete construction. Engineer R. Maillart's work on concrete bridges between the two world wars revolutionized the use of the material [5] [6]. His work facilitated the design later by engineers, trained at ETH in the wake of its innovative experiences. More recently, architect Flora Ruchat [7] issued the architectural guidelines for AlpTransit railway line, which is part of Swiss Federal Railways systems including base tunnel and plain lines from Lugano to Flüelen, where the Pollegio control tower is located.

This contextual background sets the stage for the conception of the "Periscope," a control tower at the southern portal of the Gotthard Base Tunnel, resulting from a design competition held in 2006, that encouraged collaboration between architects and engineers.

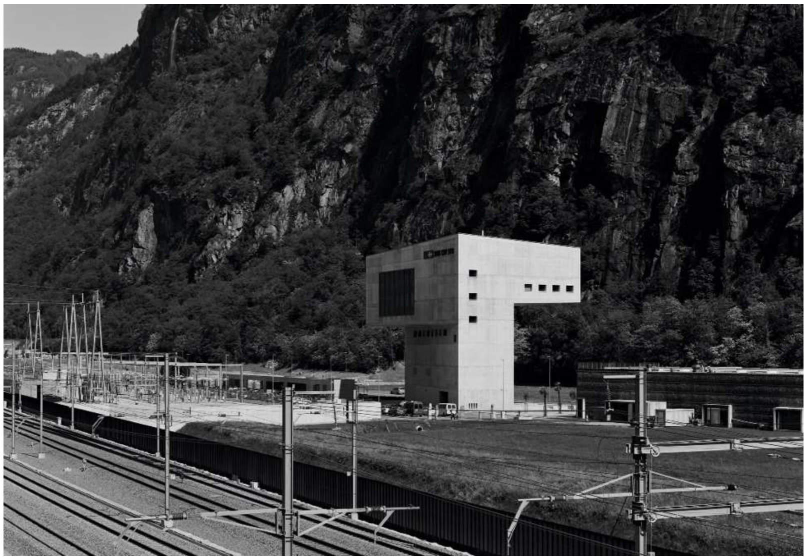

Fig. 1. Landscape insertion of the structure, photographer Hélène Binet

2 Case study

The Berlin-based architecture firm, Bruno Fioretti Marquez Architekten, proposed a sculptural entrance to a tunnel inspired by the Basque artist Chillida. The structure resembles an ever-changing object depending on the perspective of passing train passengers. It also serves as an observant eye for the landscape and infrastructure. Initially conceived as a periscope shape, it evolved into a box rotated on a slanted stem with asymmetrical overhangs and a west-facing window [8] [9]. The structural language comes from different reference buildings that were the products of intense collaborations between an architect and an engineer: the Voltastrasse school in Basel (2000, architect Miller Maranta and engineer Conzett Bronzini) [10] and the Forsterstrasse residential building in Zurich (2003, architect C. Kerez and engineer J. Schwarz) [11].

The 33 m high building combines architectural aesthetics and static requirements with a lower massive shaft and an upper box-like section box with asymmetrical overhangs of 16 m and 9 m. Overall stability is ensured by the balance given by two jutting bodies of different sizes but similar mass and the resultant vertical loads of the building act on the barycenter of the shaft. Reinforced concrete with internal insulation is used as the primary material for the load-bearing structure. The lower floors handle technical activities with loads evenly distributed along the perimeter walls. At the upper floors' transverse wall beams, special steel flag profiles with connectors are inserted to ensure the passage of the large, concentrated forces from the upper box to the shaft.

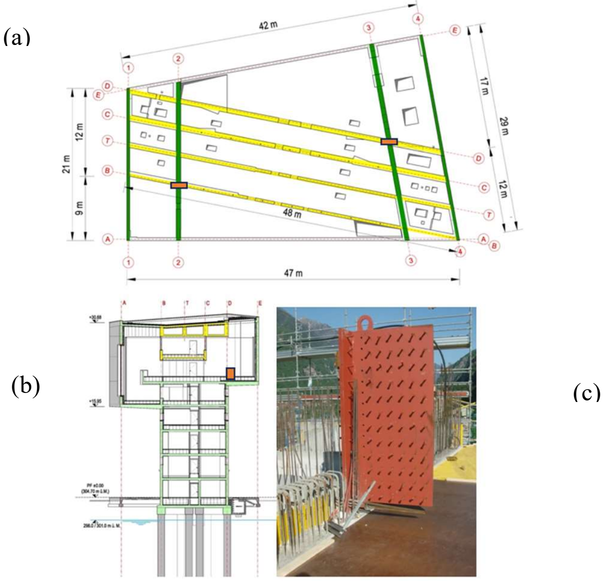

Fig. 2. Upper box structural scheme (a), structure vertical section (b) showing steel connection flag positions and picture (c)

The control room's roof, spanning approximately 33 m, resembles bridge-like box girders, supported by four prestressed longitudinal beams of varying height (1.80m to 3.30m). The design features a two-pitch structure with a compluvium, aiding rainwater drainage. The 6th-floor office slab is suspended from the roof, ensuring the 5th-floor room, where railway traffic is controlled, remains column-free and transparent. The cantilever part's loads are borne by four reinforced transverse wall beams with prestressing cables, and the arrangement of openings is carefully designed to meet plant engineering requirements.

3 Spatial structures design

The analysis method proposed in this paper has its origins in Switzerland's academic environment. In 1899, Karl Wilhelm Ritter developed the concept of truss models embedded in concrete, with tension elements made of reinforcement and compression elements of concrete [12]. This theory was further extended and studied by Emil Mörsch [13], Leonhardt and Walther [14], leading to the definition of design basis in the CB FIB Model code in 1978 [15].

Later, Schlaich and others [16] applied the theory of plasticity to the strut-and-tie model, and ETHZ's research on plastic failure analysis, led by Prof. Bruno Thürlimann [17], was introduced in the Swiss SIA codes in 1989 [18]. These approaches were further developed, including the stress field method by Muttoni [19], whose research at ETHZ culminated in the book "Design of Concrete Structures with Stress Fields" published in 1997 [20].

The authors of this paper, inspired by renowned bridgebuilder Prof. Christian Menn [21,22], extended the tension fields method from 2D to 3D, decomposing monolithic structures into 2D elements. The case study in this paper applies these fundamental concepts and academic references in its design process.

4 Method

The calculation method applied took place in successive steps accordingly to the project phases.

a. Competition phase

From the early stage, the concept of carrying on the cantilever loads with full-height wall beams reinforced with horizontal and vertical prestressing cables was elaborated. The analysis was performed with manual calculations and simple conceptual drawings showing the stress fields in the wall beam.

Foundations were immediately planned with deep bored piles of large diameter, starting from the tensile and compression forces resulting from the balance of forces in the plane of the individual wall beams.

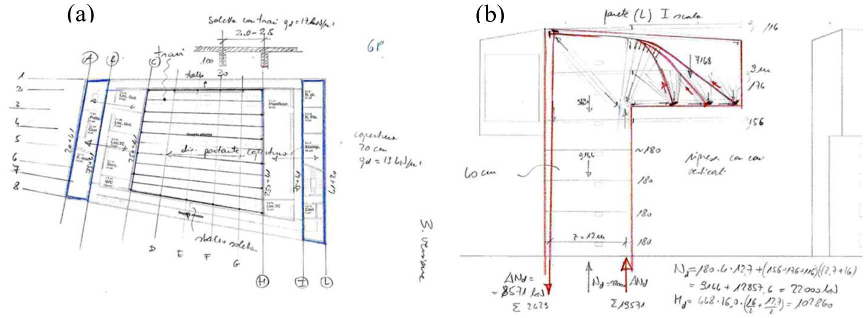

Fig. 3. Loads pattern analysis for competition, in plan (a) and in section (b).

b. Final design

b1 Refinement of competition design

A detailed analysis of the load transmission and decomposition of horizontal (slab-plates) and vertical (wall slabs and beams-wall) elements was carried out. Then, a comparison with two-dimensional calculations FEM program (software Cedrus) was conducted to calibrate the position of the openings and set the concept of prestressing and introduction of loads concentrated on the underlying walls of the massive shaft.

b2 Quickly moved to the three-dimensional calculation.

At the same time, it has been investigated the interaction between the different elements of the building, using a 3D model (software AXIS).Since that:

- the connections are monolithic and,
- horizontal plates can be activated against the in-plane horizontal loads as slabs.

This analysis shows that the internal wall beams (n.2 and n.3), theoretically more loaded, bear only 60% of the vertical loads foreseen during the competition design refinement (b1 phase). This is explained because the two pairs of wall beams interact with the slabs and behave like bent tubes with a compressed flange below and a tensioned flange above.

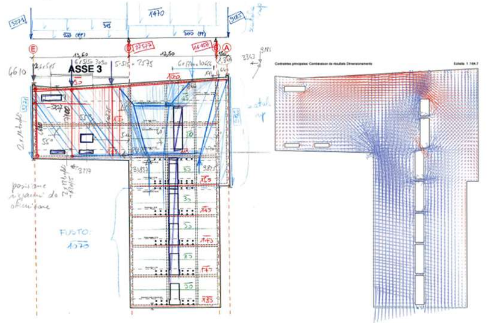

Fig. 4. Comparison of bidimensional analysis with software Cedrus stress-fields

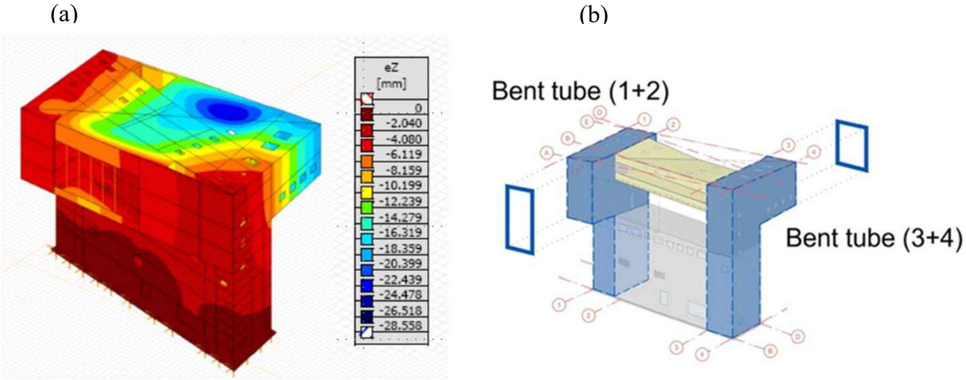

Fig. 5. 3D Model with software AXIS: vertical displacements (a) and bent tubes, stem and roof structure (without façades A and E) (b)

c. Executive project

In the executive project, we deepened how the different structural elements interact to bear the torsion between the two cantilever parts in an asymmetrical way.

Numerous 3D models have been elaborated, simulating different stiffness conditions considering fissured or not fissured behavior for individual elements. In addition, a simplified model has been developed to make it easier to compare the results.

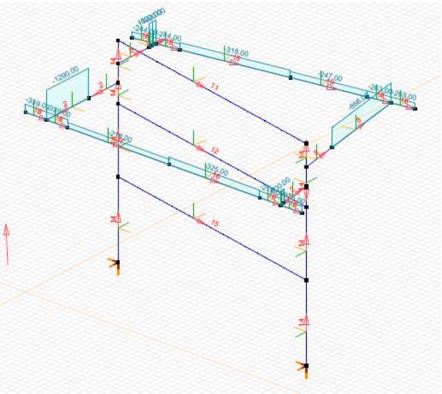

Fig. 6. Simplified structural model for the comparison of different stiffness.

With these analyses and comparisons, the following main equilibria of torsion recovery due to the antimetry of the structure were deduced:

- the two antimetric tubes activate antimetric bending on the longer façades (n.A and n.E), and tubular torsion (Bredt) in the box girders of the roof.

- the roof slab is activated as a shear slab and transmits tubular torsion (Bredt) in the two vertical cores at the ends of the building, which are continuous over the entire height. The torsion is then distributed throughout the perimeter of the stem.

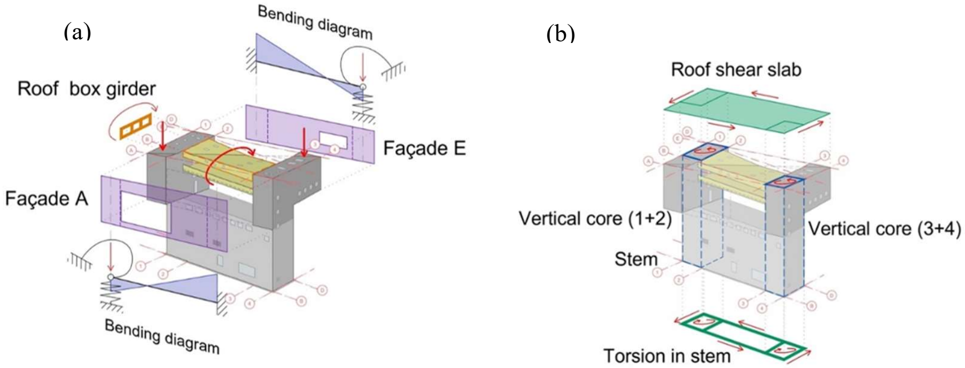

Fig. 7. Façade bending diagram and roof box girder (a), roof shear slab diagram and torsion in the cores and stem (b).

This overlaying of equilibriums ensures that the centre of gravity of the vertical loads, despite the different geometric shapes of the two cantilevered parts, corresponds to the centre of mass of the building: the stem helps to distribute the stresses and loads uniformly on the piles, making the foundation system efficient.
Prestress concept allows the mobilization of these different equilibrium systems, through the creation of ties along the connections of the elements to activate the maximum forces transmission in the plane of the various elements (bent plates).
Dimensioning was then made considering different possible equilibriums and load patterns, to have a certain redundancy as well as robustness.It must be noted that, in this project, in advance of international codes and regulations, robustness concepts have been included and can be related to monitoring results.

5 The importance of monitoring

Because of uncertainties involved in modeling, construction, and measurement systems, the assessment of the FE model validation must be conducted based on stochastic measurements to provide designers with confidence for further applications [23]. The objective of model validation is to refine and confirm the analysis model of structure by using reference data obtained from experimental tests and monitoring can thus be used for design optimization.The complexity of the analyzed structure as well as the difficulty to model in a uniquely precise and exhaustive model the overall structural behavior induced the engineer to perform a monitoring concept.The following monitoring has therefore been planned:

- Control of deformations and building overhangs, in directions x y and z

- Control of foundation displacements.
- Crack openings in concrete.
- Post tensioning efficiency (electrical control from cable heads, as in bridges, but not usual in construction)

The deformations have therefore been measured during and after the construction site until today. The monitoring allowed us to verify the plausibility of the static calculation and to ascertain that the real behavior is strongly influenced by the torsional resistance of the structure. The deflections measured at the worst point are approx. 6 mm horizontally and approx. 12 mm vertically, which is significantly lower than our calculation forecast of approx. 40 mm. It must be noted that in this context a test–analysis correlation applying uncertainty quantification and propagation to monitored values has not applied at the design time. This approach, coming from structural model testing tradition, was only recently extended to civil engineering structures analysis. During the design period, Atamturktur et al. [24] focused firstly on the verification and validation (V&V) of numerical models for establishing confidence in model predictions and demonstrated the complete process through a case study application completed on the Washington National Cathedral masonry vaults.This offers an interesting starting point to continue the research and evaluate the degree of uncertainty of monitoring to have greater certainty on the reliability of the calculation model and extend any considerations to future applications.

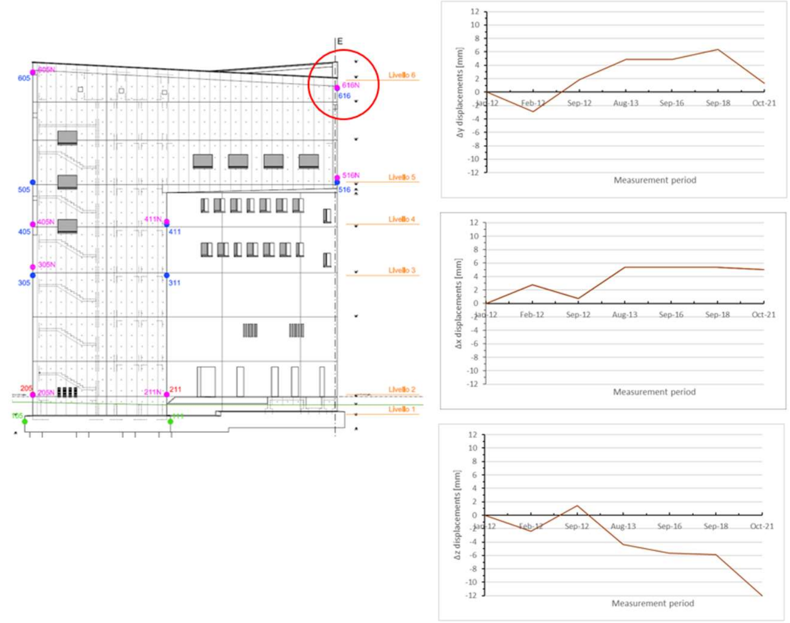

Fig. 8. Monitored points on façade East and displacements evolution of most sensitive point 616.

The first measurements of the monitoring have allowed to confirm that the building has an important torsional behavior, so much so that the displacements are more accentuated as the rotation of the upper box than box cantilever displacements, which were initially imagined as a greater risk.

The detailed survey of the trend of the cracks on the facades, of imperceptible openings, confirms the important effect of the torsion of the entire lower shaft.

6 Conclusions

In this paper, the design process of a spatial plate structure is discussed, emphasizing the significance of cultural and technical context in the approach. Collaboration between engineer and architect from the early design stages, along with the use of materials and technical knowledge, is crucial in proposing and implementing structural solutions. The main conclusions are as follows:

1. An efficient structural system should be defined from the early stages of design.
2. The statical solution raise from the specific cultural context in which the engineer operates (see chapt. 3)
3. The spatial systems can be simplified in bidimensional problems using manual analysis performed with strut-and-tie and stress fields methods that are very efficient for concrete plate design.
4. 3D models can be used to validate the first assumptions and analysis and to estimate overall behavior.
5. The different proposed analysis models can be used according to the different project stages.

The importance of refining the method through iterative steps to deepen the understanding of structural behavior is evident. The presented case study evolves from geometric and visual methods to analytical approaches using FEM models.

Complex structures require merging different methods and simplifying the system into manageable sub-parts to comprehend overall behavior and ensure redundancy and robustness. Monitoring plays a vital role and including it in the early design stages is crucial as fundamental design requirements.

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