

Improving user comfort in metro stations through a structural dome

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Abstract

This paper explores the challenges encountered during the design and execution of the new Toots Thielemans metro station in Brussels.

Key requirements included accommodating full-size trees on the surface and maintaining traffic operational in a densely urbanized area, enhancing user comfort, and improving fire safety. These needs led to the selection of a robust yet elegant arch-based structure. The development of different structural models is also discussed.

Additional complexities arose from the typical constraints of underground construction, such as work phasing, top-to-bottom construction and soil-structure interaction.

Keywords: Fire safety; soil-structure interaction; architecture; sustainability; Finite Element Method.

1 Introduction

The Toots Thielemans metro station is the first new station to be built as part of the Brussels Metro 3 project which consists of developing the capital's North-South metro axis.

The first phase of the project essentially involves adapting the existing tramway network along ten existing stations to make it compatible with metro traffic.

In addition to the larger dimensions of metros, their turning radius is also more restrictive. The existing tunnel (light blue in

Figure 1) linking the Gare du Midi to downtown Brussels takes a bend that is too sharp for metros, making it necessary to build a new tunnel alignment (light green in

Figure 1). A new station, the Toots Thielemans station (dark green in

Figure 1), is built along this tunnel. It is integrated under the Avenue de Stalingrad, in the heart of a dense urban district.



Figure 1. Project location

2 Project requirements

Prior to the works, the Avenue de Stalingrad, planted with tall trees, was a green lung in the heart of the area (Figure 2).



Figure 2. Avenue de Stalingrad before works
(photo credit: Google Maps)

The integration of new high-growing trees after the works quickly became an essential challenge for the project.

This meant burying the station deep enough to leave enough soil for the tree roots to develop. The load of 2 meters of soil, coupled with road traffic, is equivalent to a 6-storey building. We had to build a structure capable of taking such a load over a span of 20m, the width of the station.

As the load-bearing structures were placed at approximately 7m intervals, each of them absorbed a bending moment of the order of 30 000 kNm.

The needs within the structure are contradictory to this heavily-loaded structure. Indeed, a common problem with underground structures, particularly metro stations, is the feeling of oppression generated by structures that are often dark and low-ceilinged. The second key challenge was to create a bright, spacious station that would encourage the use of public transport.

The final major challenge in designing the station was fire safety. In the event of a fire in a metro station, it is essential to evacuate the smoke to prevent it from accumulating to allow passengers to evacuate safely and the fire department to intervene quickly and effectively. This problem is traditionally dealt with by equipment such as boosters, which channel the smoke to evacuation points.

3 Selected design



Figure 3. 3D rendering of the metro station interior

To meet the project's three main challenges, we designed a structure composed of four transverse elements (two large beams and two arches) and one longitudinal arch forming a dome taking advantage of the full height of the intermediate level usually reserved for technical rooms (Figure 3). There are three identical domes along the length of the station.

The arches enable the structure to take up very high loads, working in compression and limiting the amount of reinforcement required. To work properly, the arch needs to be able to apply pressure at the foot of the arch. This thrust can be compensated for by the earth pressure and balanced through the intermediate slab.

Pre-stressed concrete solutions were considered, but these had the disadvantage of placing the cables under stress in an underground structure. The heads of the pre-stressed cables are theoretically buried and therefore not easily accessible.

The arches appear as if the material has been hollowed out by a giant invisible sphere. Not only is this an aesthetic choice, but the arches also contribute to the comfort felt in the station by creating a significant sense of openness. The hollowing out of the curve is carried right through to the station's platform wall, where the benches are integrated. The space thus created becomes a luminous, comfortable bubble of calm.

Finally, the shape created by the arches also offers major advantages in terms of fire safety.

In the event of fire, smoke rises naturally and becomes lodged in the space between the arches, acting as “smoke traps” that act as buffers, keeping smoke away from passenger areas and allowing for safe evacuation and efficient firefighting. Smoke is then quickly extracted by an integrated ventilation system (Figure 4).

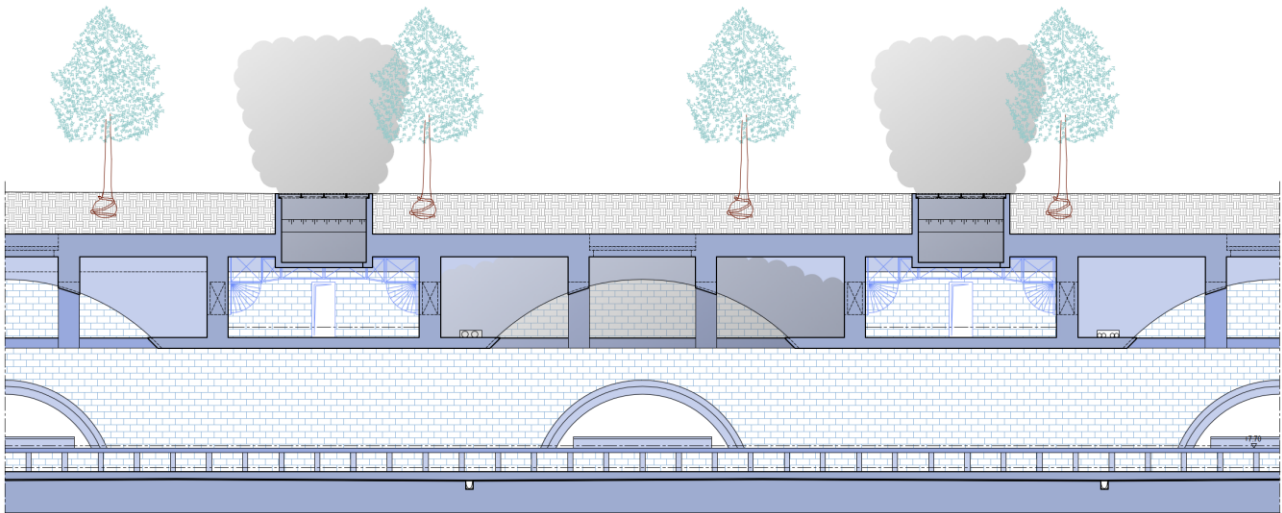


Figure 4. Longitudinal section of the station illustrating the main functions of the arch beams

4 Phasing

Given the dense urban character of the avenue under which the station will be built, it was imperative not to block traffic during the 5-year construction period. The station was therefore built with a top-down phasing.

The first step was to make the diaphragm walls from the surface (Figure 5).

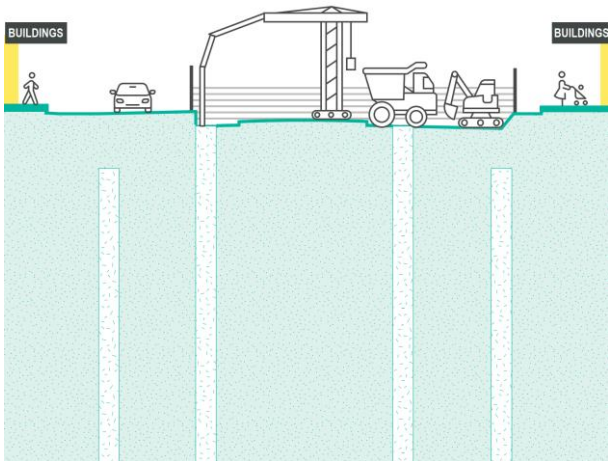


Figure 5. Phase 1: diaphragm walls (photo credit: STIB-MIVB)

Next, the roof slab was poured (Figure 6).

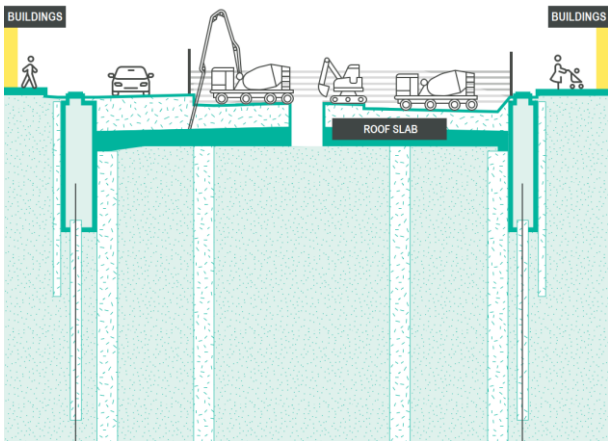


Figure 6. Phase 2: roof slab (photo credit: STIB-MIVB)

Due to the presence of a very high water table, it was not possible to build the arched beams supporting the roof all at once. It was therefore decided to build a first section of the beams, up to the level of the water table (Figure 7). Given that they are not at their full height, and already must bear most of the loads, temporary metal supports had to be pre-founded in the ground. This first beam height also ensures a certain distance between the roof slab and the rest of the concrete structure to be poured.



Figure 7. Concreting of the first height of the arch beams completed

Then came the excavation phase under the roof (Figure 8).

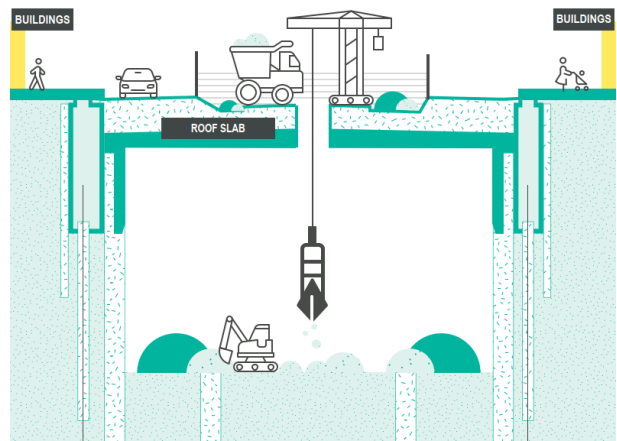


Figure 8. Phase 3: excavation (photo credit: STIB-MIVB)

The load-bearing structures were built as the excavation progressed. The intermediate slab with its large circular hole and the second part of the beams were poured as soon as the excavation to their lower level was completed (Figure 9). Once the concrete had set, the temporary metal supports for the beams could be cut away, and the domed structure assumed its stability function (Figure 10).



Figure 9. Underground construction of the arches

As the earthworks continued, struts were placed at an intermediate level to stabilize the diaphragm walls and the floor slab was poured.

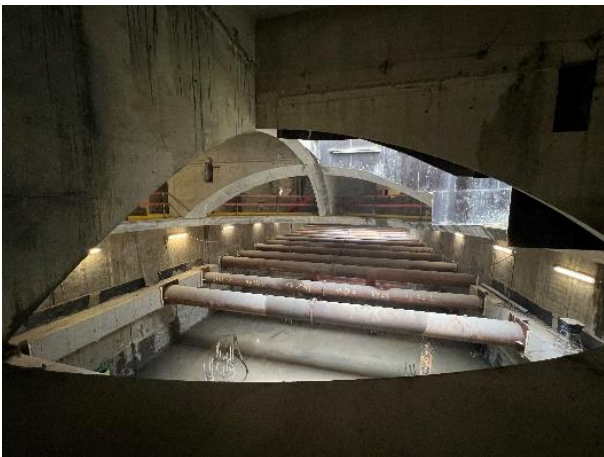


Figure 10. Built structure (from intermediate level)

Once the floor slab has fully set, the struts will be removed, and the interior fittings will be completed, preparing the station to welcome passengers (Figure 11).

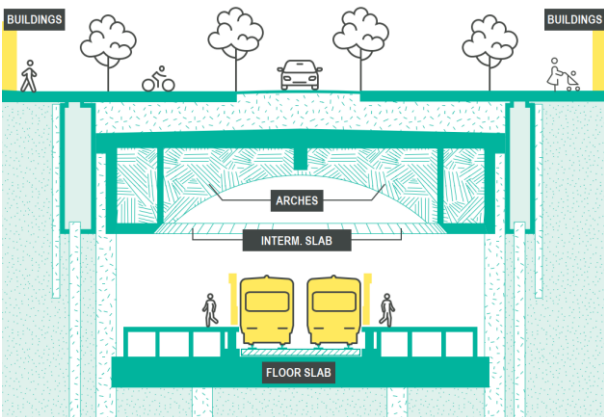


Figure 11. Phase 4: station completed (photo credit: STIB-MIVB)

5 Structural design

The dome structure provides a safe and comfortable environment but presented a challenge in the modelling of the station. The interaction between the different load-bearing elements, i.e. the arches, the phasing of the construction and the soil-structure interaction result in different load distributions and the need for adaptable models.

The station consists of three domes, three repetitions of the same load-bearing structure.

Each dome consists of four transverse elements (two full walls and two arches) and one longitudinal arch element connecting the four (Figure 12).

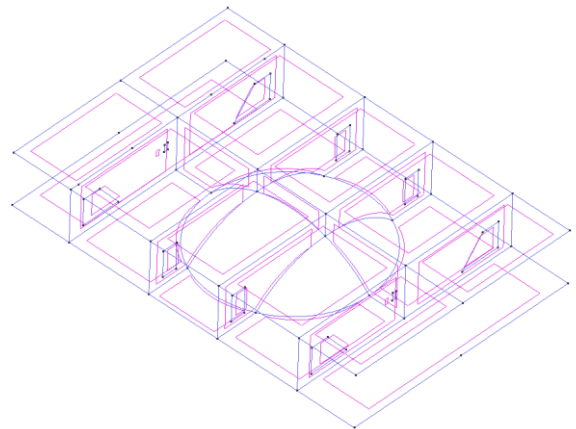


Figure 12. 3D finite element model of an isolated dome structure with FINELG software

The longitudinal arch ensures that loads can be redistributed between the transverse elements. In a phase where the transverse arches don't find enough footing due to lesser earth resistance or less rigidity of the intermediate level slab, the longitudinal arch helps to defer loads towards the full walls. In a situation where the arch finds a stiffer support, less loads are transferred, and each element carries roughly its own portion of the roof.

Due to the complexities of the modelling mentioned above, a single 3D finite element model (Figure 12) would not be sufficient to interpret the different interactions correctly and to know if it would be a correct representation of reality. Therefore, it was decided to revert to a simplified modelling in 2D, allowing a better comprehension of the element's interactions (Figure 13).

The 2D model allows a direct read of the load distribution over the different structural elements, which can then be compared to the load distribution in the 3D model. In line with strut and tie modelling, it also made it easier to determine the internal forces within the elements, facilitating the dimensioning of the reinforcement bars, which would be more difficult starting from the 3D model.

Another advantage of the 2D model was that it made clear how the relative stiffness of the supports of the arches influenced the load distribution. The stiffness of the supports depends greatly on the soil resistance, the relative rigidity of the diaphragm walls and the floor slab of the -1 level and was therefore another difficulty in modelling.

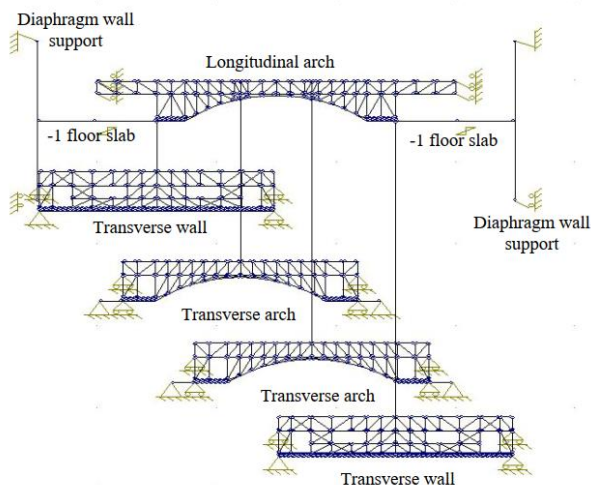


Figure 13. 2D model of a complete dome structure (Flexible arch supports)

The load distributions found within the different models and for different situations represented by alternating the support stiffnesses, are shown in Table 1. Figure 14 clearly shows how a change in supports can make 10% difference in load for an arch or wall. For example, right after the realisation of the -1 level, excavation is continued. At this point soil pressure is still minimal, and the arches have a less rigid support at their footing. The load distribution will thus lean towards the ‘Flexible arch supports’ distribution, which means the transverse walls will carry 65% of the charges. In the final situation, soil pressure increases substantially, raising the portion carried by the arches to 46% of charges.

Table 1. Comparison of the load distribution for different models and support stiffnesses

Approach	Transverse walls [%]	Transverse arches [%]
Geometric	61	39
2D Rigid arch supports	54	46
2D Flexible arch supports	65	35
3D Rigid arch supports	59	41
3D Flexible arch supports	66	34

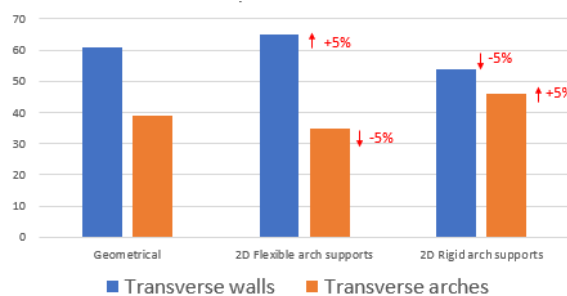


Figure 14. Graph of the comparison between different support stiffnesses for the 2D model

After determining which load distributions might occur, the elements were isolated in the 2D models and reinforcement was determined based on the maximal charges.

Another interesting aspect in the design was the requirement to integrate doorways through each of the transverse load-bearing elements to be able to access the technical rooms. These doorways had to be located along the diaphragm walls and thus are located exactly where the last strut normally leads to the support point. This demanded a different approach of the strut and tie model. As you can see in Figure 15, a large strut arrives right before the hole of the doorway (struts represented in red), where the loads must be pulled upwards by a large bundle of bars (ties represented in blue). Above the doorway, the loads are deposited on the diaphragm wall by a last strut.

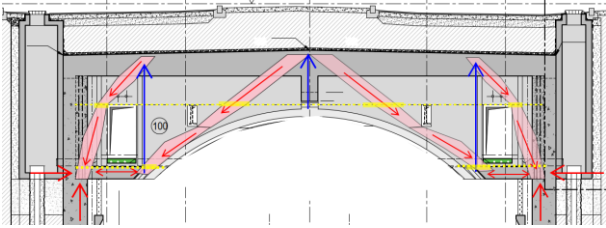


Figure 15. Representation of the strut-and-tie mechanism in the transverse arch

The internal forces in the arch are thus slightly different from a standard arch because the footing is not directly supported on the diaphragm walls. This also implicates the floor slab connected to the arches. The thrust forces of the three arches forming the dome had to be equilibrated in the floor slab. An arrangement of reinforcement bars in the slab around the hole ensures that the forces were balanced out internally in the intermediate slab (Figure 16).

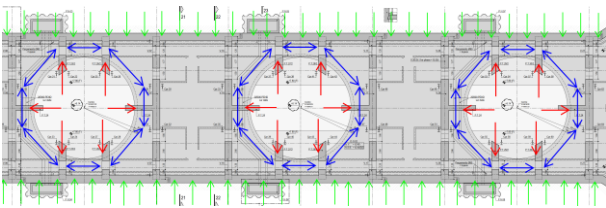


Figure 16. Equilibration of the thrust forces in the intermediate slab

Due to the substantial loads on the roof of the station and the large span, the structural elements are heavily loaded, and despite the compression behaviour of the arch, a significant amount of reinforcement was required in the walls and arches as well as in the intermediate slab.

For architectural purposes the width of the elements is limited and so a large amount of reinforcement needed to be fitted in a small space. On top of that the many connections between the elements demanded a detailed study of the arrangement of the reinforcement bars, in which all crossings, phasing of installation and overlap of the bars were important aspects to be considered.

Due to the complexity 3D models were made of the densest nodes to ensure no conflicts would occur during installation (Figure 17).

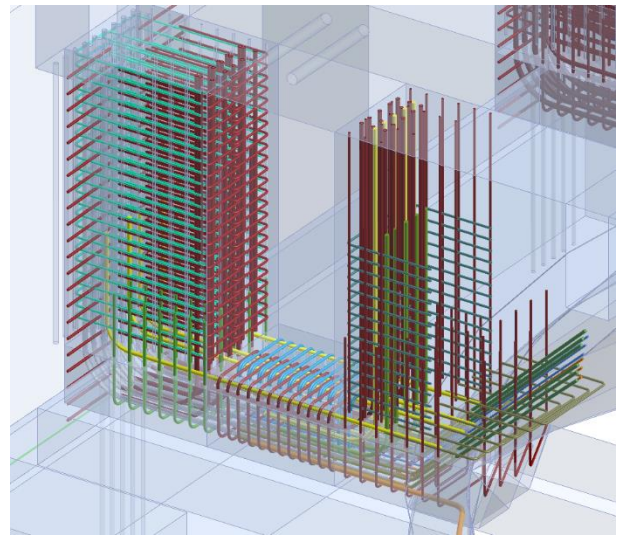


Figure 17. 3D rendering of the reinforcement in the transverse arch

6 Site experience

Given the high density of reinforcement in certain areas of the arch beams and the phased concreting process, the risk of reinforcement conflicts was particularly high during execution. Therefore, beyond careful design and detailed planning, meticulous preparation of the work was essential.

To prevent geometric conflicts between the reinforcement bars in the first and second concreting phases of the beams, the general contractor proposed using a prefabricated formwork plate, which allowed for the precise positioning of the couplers (mechanical splices) (Figure 18). A 3D model of the reinforcement bars was also established by the contractor.

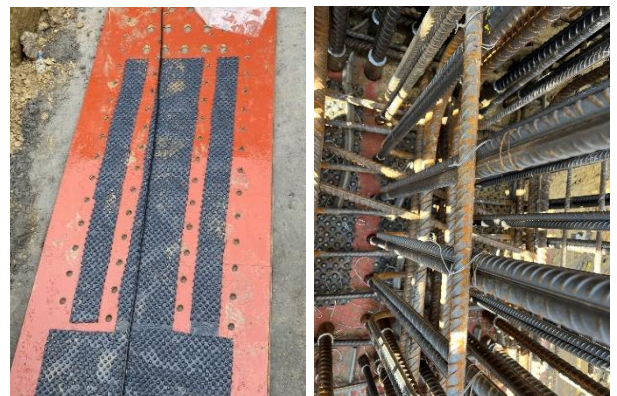


Figure 18. Prefabricated formwork plate used for the first phase of concrete (before and after placing the rebars)

Additionally, the construction joint surface had to transfer significant shear forces. To ensure sufficient shear capacity, it was required to create a rough surface. For this purpose, a bubble-textured membrane was placed between the couplers at the bottom of the first concreting phase (Figure 18).

At first glance, this solution appeared highly effective. The resulting surface was very rough, with visible indentations before the implementation of the second phase (Figure 19).

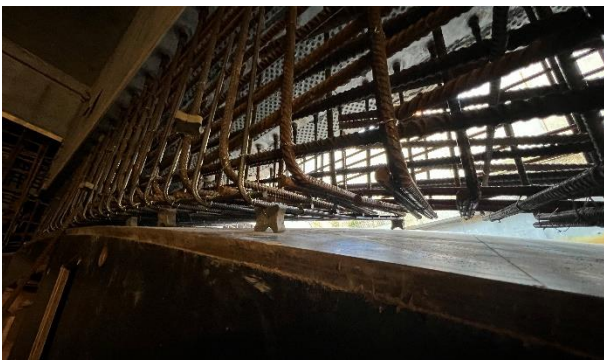


Figure 19. Rough concrete surface and no rebar conflict before concreting of second phase

However, after completing phase 2 and removing the formwork, small voids were detected locally. This led to further investigations, initially using non-destructive tomography and later through targeted core drilling. The analysis revealed significant cavities in the construction joint.

One possible cause of the observed voids is that the bubble-textured membrane, placed with its reliefs facing upward, may have created sealed air pockets where the poured concrete could not penetrate.

Since these elements were subjected to high loads, achieving perfect contact between the two phases was crucial. Consequently, hydrodemolition was required across the entire construction joint surface, with a depth varying between 10 and 20 cm (Figure 20).



Figure 20. Surface between the first concreting phase and the second phase after hydrodemolition

The voids were then filled using a shrinkage-compensating grout, specifically designed to penetrate gaps smaller than 5 mm. Additionally, after verification through a new series of core drills, localized epoxy injections were carried out to ensure full contact across the entire surface.

After solving this problem, several questions arose about how to prevent similar issues in the future while still ensuring adequate surface roughness. Several solutions were considered:

- Using a membrane that produces a surface with convex rather than concave indentations, unlike the bubble-textured membrane used on site
- Designing an inclined construction joint surface, allowing trapped air to escape and facilitating concrete penetration. However, this approach would have required greater precision in formwork and reinforcement placement, which was already a challenge given the complex geometry of the elements.
- Creating roughness manually after concreting phase 1 on a smooth formwork surface, using jackhammers or chiseling.

7 Conclusion

With hindsight, even though the structural behaviour was more difficult to model, and that the realization was sometimes complex, we believe that the dome system was truly the structure best suited to the circumstances of this project.

The problem of the contact surface between the two concreting phases highlighted the importance of clear communication between the design office and the contractor. The distinction between design and execution is sometimes subtle, making close collaboration essential to anticipate and avoid such problems.

The station is scheduled for completion by the end of 2025, after five years of work. Due to difficulties encountered on other tunnel sections, outside the scope of our studies, it will not be ready to receive passengers until 2031. By then, the missing tunnel section under a heritage building (Palais du Midi) linking the station to the existing tunnels will have been completed.

Even if they won't be aware of the difficulties encountered either at the design or execution stage, we hope that travellers will appreciate the striking aesthetics of the dome, making it a daily landmark, punctuating their commute.

8 References

We would like to thank all those involved in this project:

- Client: STIB-MIVB (Operator of public transport in the Brussels-Capital Region)
- General contractor: SM Toots (partnership between Besix, Jan de Nul, Franki)
- Architect: SumProject