Roof structure for the new Zaragoza Delicias station. Concept and design

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Summary

One of the main infrastructures on the new high-speed railway from Madrid to Barcelona is the Zaragoza Delicias station with its outstanding roof. The paper describes the basic ideas for the conceptual design of the roof structure, bearing in mind the complex interactions between geometry, functionality, construction materials, manufacturing, erection, structural overall-concept and detailing. The adopted solution is described and the importance of a consistent conceptual design is emphasised in order to obtaining a reliable, functional and economic structure. Some hints concerning the construction are also given. The example shows that the success of a structural design strongly depends on a good co-operation between the owner, the architect and the structural engineer. It further shows that an architectural design may be improved through structural considerations.

Keywords: Building structure; architectural requirements; reliability; functionality; economy; structural idea; conceptual design; interaction; co-operation.

1. Introduction

The project of the new Zaragoza Delicias station has been developed as a result of an architectural contest. The outstanding part of the winning proposal is the roof needed to cover the whole station of 480 m overall-length and 110 m width. From the outside, the spectator becomes aware of a prism-like building. In plan, its shape is very roughly a rhomb. One of the longitudinal façades is constituted by a slender concrete wall, whereas the opposite longitudinal side of the prism is closed by a volume containing a hotel, conceived as a concrete structure (*Fig. 1*). The remaining façades, oblique to the rails, are constituted by 5 boxes each, also built in structural concrete (*Fig. 2*).

The main elements of the roof structure are constituted by 9 steel arches of the bow string type at 43.64 m centres (*Fig. 3*), supported at both ends by the aforementioned longitudinal concrete wall and the hotel, respectively (*Fig. 1*). In plan, the angle between the axis of the arches and these concrete elements is 45º, corresponding to the rhomboid shape of the station in plan (*Fig. 1*). Each arch is therefore spanning 154.29 m and the separation between each pair of the 4 studs, connecting the tension member (tie) with the compression member, is 30.858 m (*Fig. 2, 3*). The ties of adjacent arches are connected by transverse beams, situated at their intersections with the studs. In plan, the ties of the arches and these beams are therefore constituting a series of squares with 30.858 m side length. The secondary structure supporting the roof panels is fitted into these squares dividing each of them in two triangles, one of which constitutes a flat roof whereas the other is forming a semi-pyramid limited by a vertical skylight (*Fig. 1, 2a, 3*).

Two main levels can be distinguished in the interior of the station. The upper level is intended for the access for the passengers, as well as for commercial activities. From this level, inclined mechanical stairways give access to the lower level where the platforms and the railway tracks are situated.

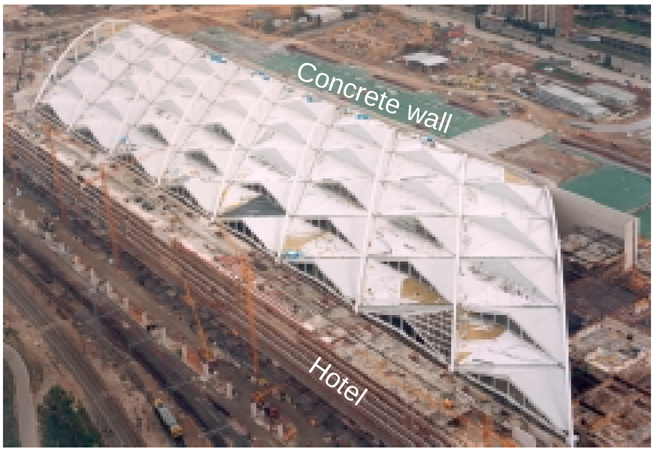

Fig. 1 General view of the Zaragoza Delicias station under construction (overall length: 480 m; width: 110 m)

Fig. 2 Zaragoza Delicias station; a) Elevation; b) Façade oblique to the rails, constituted by 5 concrete boxes (Photos by courtesy of C. Ferrater)

2. Boundary conditions for the structure

In the case of most buildings, the main difficulty for an engineer arises from the need to translate the architectural and functional requirements into a geometrically consistent structure. Architectural requirements include those due to the geometry of the architectural design itself, the planned concept for insulation and sealing of the building, the solutions for ceilings, as well as the requirements due to general aesthetic concepts and preferences of the architect and of the owner. In the present case, the following conditions required very careful consideration:

- The architect wished to fasten as well the inner ceiling as the outer sandwich panels directly to the roof structure, thus avoiding the need of any additional substructure.
- The ceiling should partly be made from translucent elements, suggesting a very neat layout and detailing for the roof structure.

Concerning the functional requirements, those related to the draining system for this roof with a surface of 40000 m^2 required also detailed consideration. The same is valid for the maintenance of all installations that, according to the wishes of the owner, must be possible at any time without interference with the use of the railway station.

In general, difficult boundary conditions are firstly perceived as an inconvenience. Nevertheless, very often they reveal as being a catalyst for a consistent or an innovative structural design. The success of the translation of the original architectural idea into a reliable, functional, economic and aesthetically attractive structure depends on a good co-operation between the owner and the project team including both, structural engineers and architects. Sometimes, the architectural design may be improved through structural considerations. In the present case, for example, the architect originally planned a cable system for the stabilisation of the arches. By means of the adopted structural concept (section 3), stability was achieved without these cables, obtaining a very neat solution for the roof structure.

3. Conceptual design

3.1 General remarks

The geometrical translation of the architectural and the functional requirements into a consistent solution is only one of the objectives of the conceptual design of a structure. Indeed, the reliability, the functionality and the economy of a structure directly depend on its conceptual design. For this reason, and although structural analysis is important with a view of verification or optimisation of any adopted solution, the conceptual design is possibly the most important step in the whole process of structural design. Going out from a structural “idea”, the solution is to be developed in terms of schematic drawings including structural detailing. The viability is to be demonstrated by means of simplified calculations. The outcome of this step also includes the definition of the main dimensions for the members of the adopted solution. The basic ideas for the conceptual design of the roof structure of the Zaragoza station are directly deduced from the boundary conditions as mentioned in section 2. The most important of these basic ideas are treated in section 3.2.

3.2 Basic ideas

Conceptual criteria

For the planned architectural design, only the use of structural steel can lead to an efficient and economic solution. The separation between structural members as well as the span lengths of these members should be rather large. Additionally, the geometry of the prefabricated structural members is unified as far as possible. In this way, the number of different structural members and the number of connections to be carried out on site are relatively small.

Although the structure is entirely prefabricated, the use of simply supported members is avoided. The robustness of structural members and of the structure as a whole is increased by means of rigid or semi-rigid joints. In this way, all the structural members contribute to the overall stability of the structure and the use of a cable system for stabilisation of the arches, originally planned by the architect, is no longer required. Furthermore, the stability of the continuously changing statical system during erection is also improved.

Cross-sections of structural members

The cross-sections are to be chosen in a way that their characteristics are in accordance with the structural function of the member. In other words, when choosing cross-sections the geometrical dimensions are to be minimised and the resistance and stiffness, related to the structural function of the member, are to be maximised. Compatibility between the profiles and their connections is also an important parameter for the choice of cross-sections. Furthermore, in the case of visible structures, aesthetical aspects can not be neglected. Indeed, the choice of cross-sections decisively influences the perception of the structure by the user. Another parameter to be taken into account refers to the interaction between the structure, the roof panels, the ceilings and the installations. Finally, the specific surface to be protected (corrosion, fire) can also influence the choice of cross-sections.

Considering all the aforementioned parameters, structural members with hollow cross-sections are chosen in the present case, since their characteristics comply with the structural function of most members, as well during erection as at the final stage:

- Box sections are advised for the arches in order to achieve in-plane and out-of-plane stability.
- Also for reasons of stability, the introduction of vertical loads in the arches is made by means of rigid studs with box sections instead of hangers constituted by cables (section 3.5).
- The beams supporting the inclined surfaces of the semi-pyramids are subjected to skewed bending. Consequently, hollow sections are advised also in this case.
- By using hollow sections lateral torsional buckling of the beams supporting both, the flat and the inclined roofs can be avoided. In this way, no additional bracing systems are needed.

Other important reasons for the choice of hollow sections are related to their compatibility with the chosen type of connections (see below) and to the aesthetics of the structure. Indeed, a conceptual design with relatively few structural members, with welded connections and without any additional bracing system leads to a very neat and aesthetically attractive solution.

Connections

In the case of the roof structure of the Delicias station, welded connections are chosen that are compatible with the structural members with hollow sections:

- They allow to transmit the internal forces and moments assuring at the same time the assumed structural behaviour (rigid or semi-rigid joints) with a view to obtaining a robust solution.
- Welded connections between members with hollow sections do not normally require any stiffeners nor gusset plates.
- Structural efficiency is therefore combined with a satisfactory aesthetical aspect.

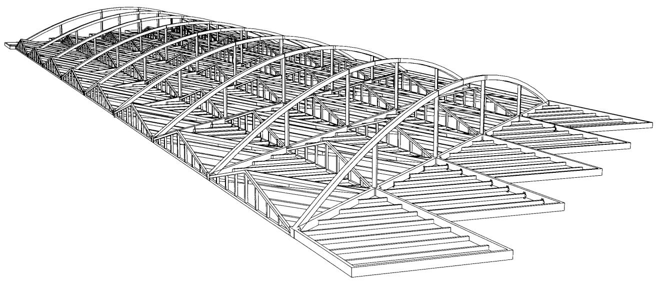

Fig. 3 Schematic representation of the roof structure

Fig. 4 Anchorage of prestressing cables in the tie of one of the arches

3.3 Flow of forces

According to the geometry of the secondary structure (*Fig. 3*), the major part of the vertical loads are transmitted respectively by the Vierendeel and the transverse beams to the studs of the arches at the level of their intersections with the tie of the corresponding arch. Only a small part of the loads is directly introduced into the tie of each arch and from them into the arch itself by means of the corresponding studs. The arches finally transmit the loads to the concrete structure mentioned in 1.2. Since the thrust of each arch is equilibrated by the corresponding tie, the horizontal reactions to be transmitted to the concrete structure –e.g. due to wind or temperature– are small. Therefore, fixed supports are introduced on the side of the relatively rigid structure of the hotel. At the opposite end, the supports only transmit vertical loads from the arches to the flexible concrete wall.

3.4 Structural members

The relationship of arch to span is of 1/11, approximately. The steel box-sections of the arches are 1200 mm high and 1000 mm wide. The thickness of the steel plates (structural steel S 355) is variable between 30 mm and 45 mm, depending on the action effects, particularly the in-plane bending moments interacting with the compression forces. For the height and the width of the tie, the same dimensions are chosen as for the arch. In order to reduce the quantity of structural steel, part of the tensile forces acting on this element are resisted by prestressing cables (*Fig. 4*). The side length of the square cross-section of the vertical studs is of 1000 mm.

As mentioned earlier, box sections are also used for all other structural members. Standard profiles with hollow sections are used for the fabrication of the Vierendeel beams. All other beams are to be fabricated from welded box sections.

3.5 Overall stability

Out of plane

The out of plane stability of the arches is achieved through the combination of different measures:

- The rigidity of the arch itself.
- The use of rigid studs instead of flexible hangers for the introduction of the vertical loads from the level of the roof into the arches. These studs provide elastic lateral supports to the arches.
- The torsional stiffness of the tie with a box section leads to an increase of the stiffness of the aforementioned lateral supports. A similar positive effect is achieved through the rigid connections between the tie and, respectively, the transverse beams and the secondary structure supporting the roof panels.

In plane

The rigid studs connecting the tension member with the compression member of the arch lead to a structural behaviour similar to the one of a Vierendeel beam. In this way, the in plane capacity of the arch is also improved [1]. Assuming a failure mechanism with two plastic hinges in the compression member, it appears that the virtual displacement of the loads is larger in the case where flexible hangers are used instead of a rigid element connecting the tension with the compression member. On the other hand, if the same plastic deformations are assumed and the ultimate bending moment of the compression member is the same in both cases, the work of the internal forces is also the same. Since according to the theory of plasticity (principle of virtual displacement) the sum of the external and the internal work is zero, the load bearing capacity of the arch with rigid studs is larger.

3.6 Assembly

In a first step, the ties of the first four arches are assembled and connected by the corresponding transverse beams. To this end, temporary supports are situated below the future vertical studs (*Fig. 5*). In the next step, the vertical studs are erected and each of these arches is assembled in four pieces. Simultaneously, the Vierendeel beams between these arches are put into place whereas the secondary beams are erected at a later stage. The temporary supports of the first two arches are then removed and reused for the assembly of the following two arches. The aforementioned process is repeated until completing the whole structure.

4. Construction

For different circumstances, partly related to the tight construction programme, it was decided to introduce some changes to the architectural design. Particularly, the ceiling was no longer to be fixed directly to the structural elements, but should be suspended from the roof-structure conforming a horizontal plan. Due to this change, one of the main difficulties from the point of view of a consistent geometrical definition of the structure disappears.

According to the preferences of the subcontractor for the steel structure, the main contractor introduced some changes to the conceptual design of the secondary structure:

- A new layout was chosen for the secondary beams, reducing considerably their separation.
- For the fabrication of the Vierendeel beams as well as for the secondary beams laminated profiles with open cross-sections were used.
- Bolted connections were used for the assembly of the secondary structure.

Through these changes, many of the advantages of the conceptual design according to the original project are lost. Particularly:

- By using simply supported beams for the constitution of the secondary structure, the robustness of the solution decreases.
- Additional bracing systems are required in order to provide lateral stability of beams with open cross-sections.

- The combined effect of the different changes (increase in the number of structural members, additional bracing systems, open cross-sections, bolted connections) leads to a considerable decrease in the aesthetic quality of the structure compared to the solution from the project (*Fig. 6*). This is particularly regrettable since the structure is visible through the ceiling.

However, the main structure was built according to the project. Only a few minor changes were introduced to some of the details, again according to the preferences of the contractor. For the erection of the structure, the procedure described in 3.6 was maintained (*Fig. 5*).

Fig. 5 Erection of the main structure

Fig. 6 Roof with changes to the original project of the secondary structure (Photo by courtesy of C. Ferrater)

5. Concluding remarks

Difficult geometrical and functional requirements were the dominant conditions for the conceptual design of the roof structure of the new Zaragoza Delicias station. Very careful planning was required, bearing in mind the complex interactions between the geometry, the functionality, the structural concept and the aesthetic aspect of the structure. Using a consistent structural concept, in which all the elements contribute to the stability of the system and in which the mechanisms of resistance are unequivocal, a very neat structure of great robustness has been designed.

The example shows the importance of the conceptual design since the functionality, the reliability and the economy of a structure depend on the solutions adopted at that stage. During the subsequent design stages, a careful conceptual design will undergo minor changes only. The success of a structural design depends very strongly on a good co-operation between the owner, the architects and the structural engineers during the different design stages. This co-operation also is of primary importance during execution in order to build what has been designed. Indeed, the changes introduced during execution very often respond to the preferences of the contractor or to other demands of the moment rather than to real practical needs. Finally, the example of the Zaragoza station also shows that an architectural design may be improved through structural considerations.

References

[1] MUTTONI, A., “Brücken mit einem innovativen statischen System”, *Schweizer Ingenieur und Architekt*, Zürich, No. 26, 1997, pp. 28-31.