Structural design for the Quickway System

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Abstract: Quickway is a stand-alone traffic system – specifically, a flyover network – for use in overpopulated megacities or smart cities whereby people and small goods are automatically moved with electric cars. The flyover network is represented by a grade separated traffic system made up of single-span beams, which are supported by columns and covered by a multi-functional roof. Current research activities include environmental impact studies and the development of efficient traffic control solutions, modular precast construction and preliminary structural design and construction methods.

The flyover network is realized by a grade separated traffic system of single-span beams, sub-classified in straight-, curved-, ramp- and merger elements. In general, the construction is chosen to be realized with a modular construction kit out of slender components made of Ultra High Performance Concrete (UHPC), which are assembled with dry joints and external tendons. When it comes to curved elements, however, eccentricities introduce high torsion stressing which require further considerations. This contribution presents the result of preliminary studies on the static behavior of a standard curved element. By using FEM and the consideration of the post cracking behavior of fibre-reinforced UHPC (UHPFRC) a suitable cross section without the need for conventional reinforcement could be designed.

Keywords: Modular construction, UHPFRC, smart city traffic system, flyover constructions

1. Introduction to the Quickway system

Quickway is an automated people and small goods traffic system for overburdened megacities and smart cities. The system is a new elevated roadway network along existing road networks. Quickway includes the existing infrastructure and is very efficient due to grade separated traffic as well as centrally navigated vehicles.
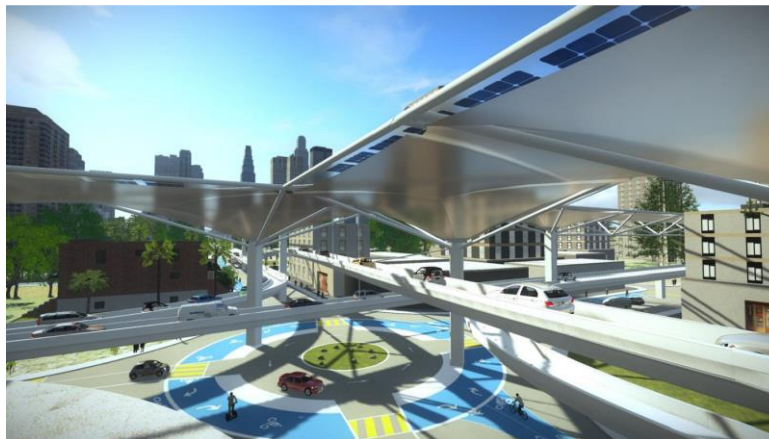

Figure 1: QUICKWAY

To minimize the pollution in the city, the vehicles are operating electrically. Next to this, Quickway is covered by a multifunctional roof allowing the installation of solar energy systems and/ or systems for rain water collection, which is a good of increasing importance for such cities.

The Quicknet can be separated into three different network types, which are connected among each other. The primary and secondary network consists of new Quickways above the existing road network and organizes the main traffic. In detail, the primary network enables efficient superior traffic on Quicknet with access to the secondary network, which is much more subdivided, see Figure 2. The tertiary network, which is directly connected to secondary network, is installed on the existing road network and provides short distance connections in the destination area.
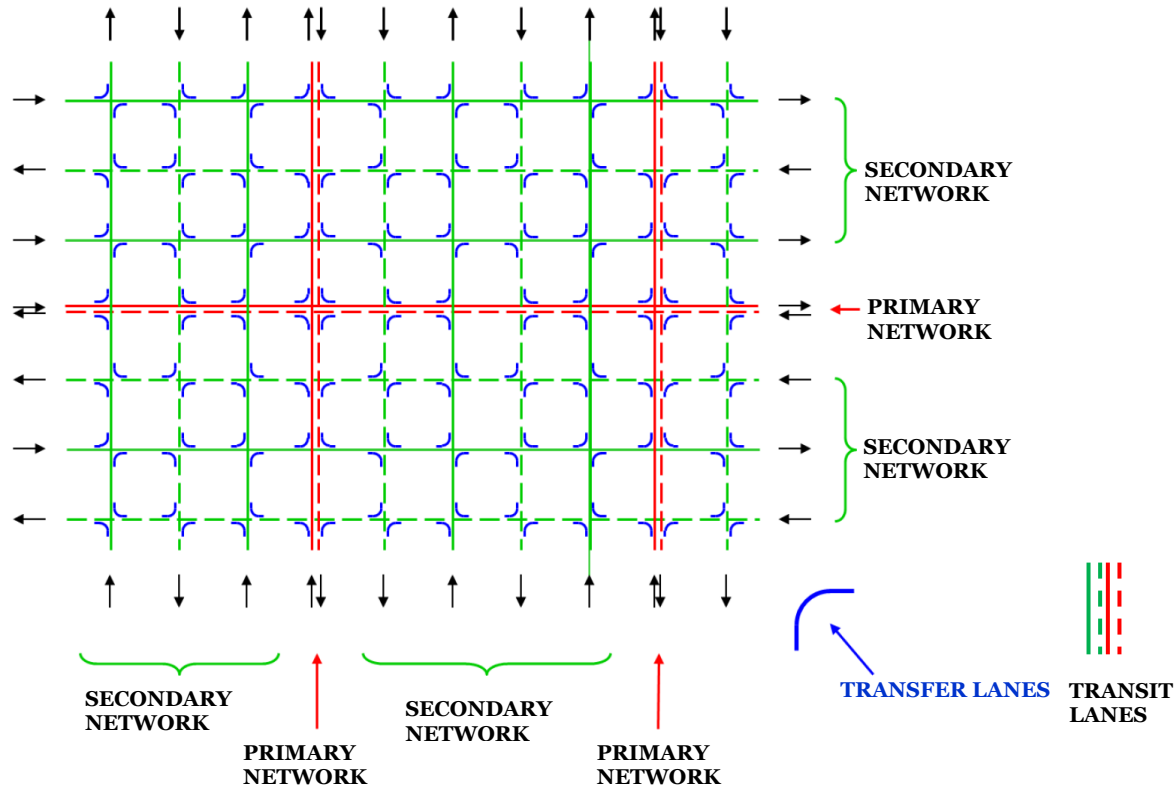

Figure 2: QUICKNET, consisting of QUICKWAYs (schematic)

The primary and secondary network are located on the same level at a minimum height of 5.5 m above the existing road network. To ensure fluent traffic on both networks, direct junctions are strictly avoided in the Quickways. Therefore, crossing lanes are led over each other by introducing a second level on a height of approximately 10 m, as visualized in Figure 1**Fehler! Verweisquelle konnte nicht gefunden werden.**.The connection to crossing lanes will be provided by transfer lanes and merger zones. Within this connection concept, left-hand turns are conducted as a clockwise loop on a Quickway square.

The Quicknet is planned to consist almost entirely of a row of straight and slightly curved single spanned girders for transit lanes as well as girders for curves, ramps and merging zones for transfer lanes (see Figure 3). The girders are supported on a crossbar, which transfers the load over the column to the foundation (see Figure 4).

The flyover character of Quickway requires a construction with less columns on the existing road network and without columns on the existing junctions. With regard to the static and dynamic behaviour of the transit lane girder a length-to-height ratio of 22.5 is assumed to be suitable, which leads to the standard length of 40.5 m with a height of 1.80 m of the cross-section. As shown in Figure 4, the standard transit girder consists of five elements (three middle elements and one end element on each side). For a simplified assembling on site a transit girder is supposed to be delivered by three segments. The elements connect with external straight tendons inside the hollow box pre-stressing dry joints. The design parameters of the cross section are explained in section 2.
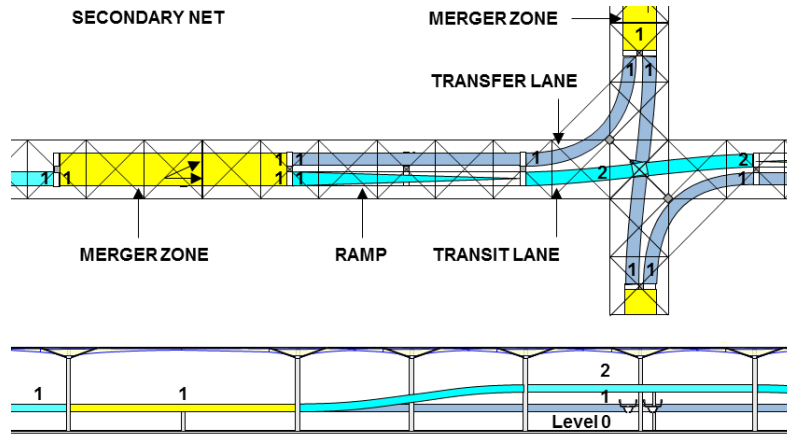

Figure 3: Standard modules of transfer lane and merger zone of QUICKWAY

Transfer lanes require various curve radiuses from 15, 30, 50 and 80 m. This will be realized by curved middle elements while the end elements and the cross bars at the end remain straight (same as transit lane). Further geometric requirements to enable a comfortable and safe performance of the vehicles (tractrix curve, clothoidical drive lane of the carriageway, limits for the lateral acceleration and lateral jerk) are considered by a variable set of curved elements. In order to avoid formwork difficulties for the production of the curved elements, the requirements are fulfilled by wider cross-sections and a basked arch. Next to this, the merger zones (connection between transit and transfer lane) will be realized by three transversal connected elements (Figure 4).
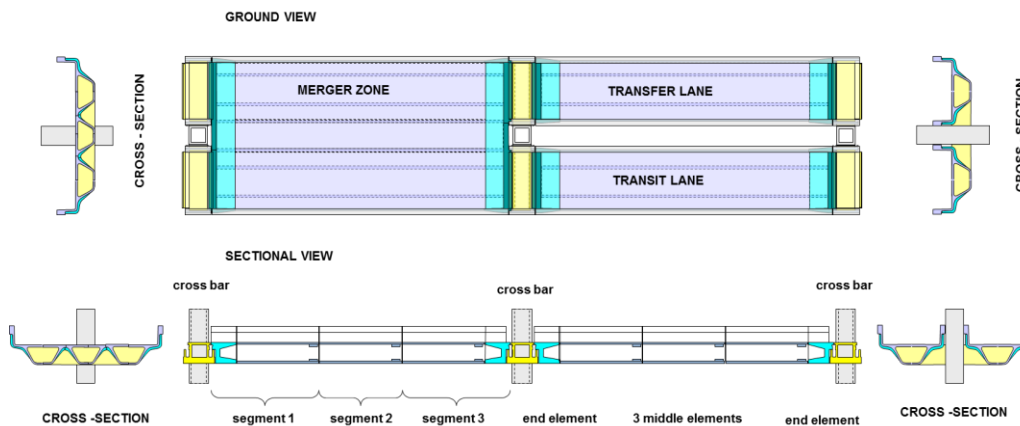

Figure 4: Standard modules for transit lane of QUICKWAY

For efficiency reasons Quickway is to be realized by a modular construction kit. The benefits are mainly in the short assembling process. The prefabricated elements will be delivered in preassembled segments, connected on site and positioned by lifting the whole member. Additionally, an extendible and exchangeable modular construction system allows for Quickway to be installed in different cities and to be adaptable on individual requirements.

A fundamental design task is the dimensioning of curved transfer lanes with special regard to the significant curve radius. General design assumptions of Quickway as well as detailed studies on the design of the curved element are presented in the research below.

2. Design Concept

Main principle of Quickway is to implement a slender but robust roadway network over existing road networks. The single elements are pre-fabricated and assembled on site by external tendons pre-stressing dry joints without any further measures of joint connection. For efficient and fast construction, Quickway is to be based on a modular construction kit.

The major girder elements are determined to be produced with UHPC to enable slender cross sections and lightweight elements. For simplification of the production ordinary reinforcement should generally be avoided by using fibers (UHPFRC). Exceptions are parts with high loads, e.g. anchoring of tendons, support areas or regions with high torsional forces.

2.1. Material & safety factors

The used UHPFRC mixture according to the challenging requirements of all components of Quickway is developed at Graz University of Technology. By using 1.5 % by volume of fibers with a diameter of 0.2 mm and a length of 20 mm the required hardened concrete properties could be achieved without any restriction on the self-compacting behaviour, namely slump flow 800 mm as well as $E_c = 52000$ MN/m² and $f_{ck} = 180$ MN/m², both after 28 days without heat treatment.

The stress strain behaviour under tension is derived from the measurements on 6 four-point bending tests. The tensile strength for a design of uncracked UHPC is determined from the point of the first load drop in the experiment and a safety factor independent of fibre content and orientation. However, the post peak behavior under tension will be described according to Gröger (2012). Beginning from the first load drop a constant stress level is assumed up to 5 ‰, which decreases linearly to zero until a crack opening of $w = l_f / 4$. In that case, the safety factor has to take into account fibre content and orientation. Further details on this procedure are given in Hadl (2016).
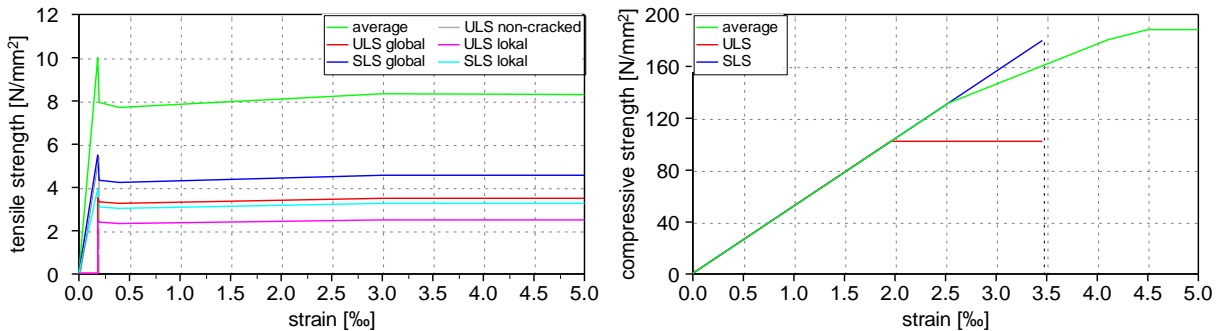

Figure 5: stress- strain behaviour under tension (left) and under compression (right)

The design values are calculated with equation (1), (2) and (3) with a scattering KGlobal = 1.25 and Klocal = 1.75 as well as safety factors of γct = 1.0 in SLS; γct = 1.3 in ULS; γc = 1.5; αcc= αct=0.85.

$$\text{tension, uncracked state:} \quad f_{ct,el,d} = \alpha_{ct} \cdot \frac{f_{ctk,el}}{\gamma_{ct}} \qquad (1)$$

$$\text{tension, cracked state:} \quad f_{ctd} = \alpha_{ct} \cdot \frac{f_{ctk}}{\gamma_{ct} \cdot K} \qquad (2)$$

$$\text{compression:} \quad f_{cd} = \alpha_{cc} \cdot \frac{f_{ck}}{\gamma_c} \qquad (3)$$

2.2. Loadings

The dead load (29.6 kN/m) is given by the cross section of the girder and the density γ = 26 kN/m³ of the UHPFRC. Loads in case of a surface layer on the carriageway or other additional loads are set at 11 kN/m.

Due to the 3500 kg max. weight limitation for a vehicle on the Quickway, the max. vertical service load is chosen by reference to a full utilization of the carriageway by the vehicles. The maximum horizontal service load is calculated with the horizontal acceleration of 2.5 m/s². Winds loads, earthquakes, accidents or construction works are not considered in the preliminary study.

2.3. Modular construction kit

All girders consist of standard or curved middle elements between two end elements. The cross section is in all cases a hollow box with a monolithic connected parapet (in total h = 1.80 m). The max. section thickness is 14 cm, however the webs of the box girder are arranged with haunches taking into account the vehicle wheel positions. In case of the curved element with R = 30 m, the carriageway has a width of 2.75 m yielding a cross-sectional area of 1.14m², as shown in Figure 6.
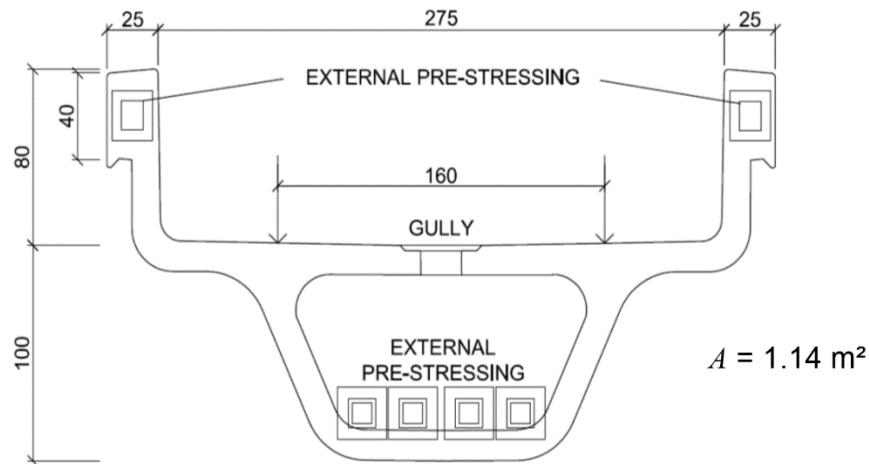

Figure 6: Curved cross section.

The bending behaviour of the single span girder is determined by a compression zone in the upper sections of the parapets and eccentric pre-stressing at the bottom of the hollow box. Besides, additional pre-stressing in the upper sections of the parapets is needed to control the prestressing moment in the edge regions.The cross section of the end element is comparable but has an increased section thickness to enable the bearing of localized stressing at the support area and the anchoring of the prestressing of the girder.

At this point it should be mentioned, that the monolithic parapet has also benefits for the service state in terms of providing a guardrail against defects or accidents as well as noise reducing effects.

In longitudinal direction the girder is assembled by the external tendons prestressing a dry joint without any further measures, as illustrated in Figure 7. The shear resistance of the joint will be provided by friction in the cross section area. The requirements on the accuracy of such joints will be complied by the formwork, further details on related studies are given in Theiler (2015).
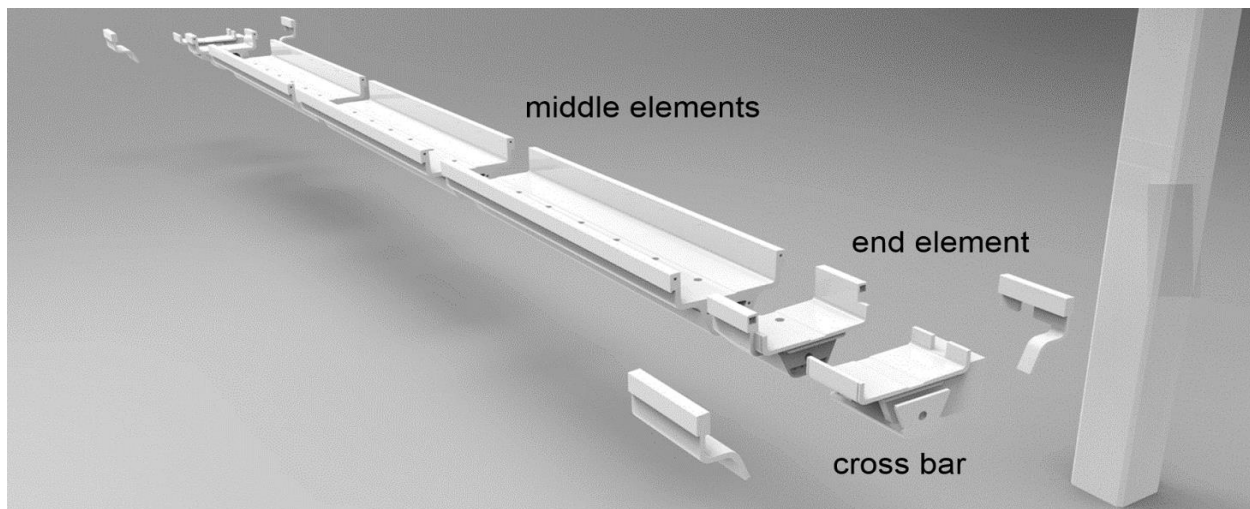

Figure 7: Overview of the precast beam elements

The preliminary studies indicated decompression as the decisive design situation for bending in longitudinal direction, however, the shear resistance has to be provided only by steel fibers.

In case of curved transfer girders additional torsional stressing has to be considered. On the one hand this is caused by load eccentricities. On the other hand, the prestressing in the box is along the curve polygonal (according to the length of the single elements) and this introduces local deflection forces causing further torsional stressing. Besides, this torsional stressing introduces tensile forces in the support which requires further considerations.

3. Detailed studies on the bearing behaviour of a curved element

The following chapter presents the preliminary design study of a curved girder with R = 30 m, which is indicated as the decisive case. The analysis is conducted with FEM using SOFiSTiK. In a first step, only linear-elastic calculations are carried out, however, result interpretation and design assumptions to consider the post peak behaviour of the specifically developed UHPFRC are taken from Reichl (2010) and relevant international guidelines of France AFGC (2013) and Germany DAfStb (2008).

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3.1. FEM model

The curved girder is idealized with 2D-elements in length direction representing the cross section along the girder length with respect to the varying sectional thickness between middle and end elements. Besides, the diaphragms of the end elements are represented by transversal oriented 2D-elements. The support is modelled with tangential oriented point beddings of the diaphragms so that the model is not constrained in longitudinal direction.

The joints between the different elements are simulated monolithically, which is suitable for SLS verifications under decompression as well as the determination of internal forces for ULS verifications by post-processing.

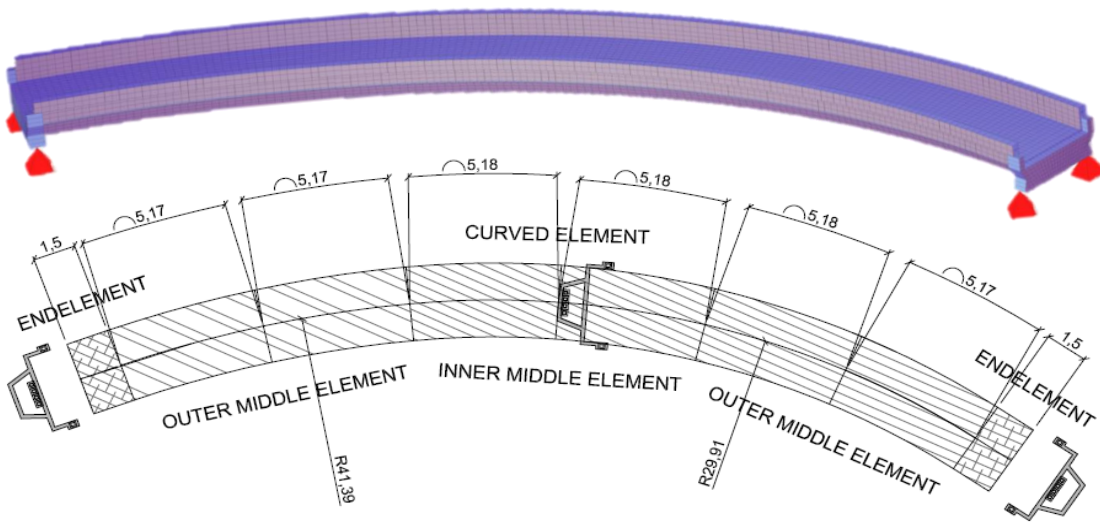The service load is introduced at the road surface. Figure 8 illustrates the model.

Figure 8: FEM idealization of a curved Segment with R = 30 m

The external prestressing is modelled with cable elements. In the hollow box, the cable elements are solely deviated at the end of each single element and have therefore a polygonal course introducing local deflection forces in horizontal directions. In the inner middle elements this prestressing is fixed to the hollow box bottom, however, in both outer middle element the prestressing is deflected to the point of gravity and anchoraged in the diaphragm. In contrast to this, the external prestressing in the parapet is continuously deflected along the curve radius.

3.2. General bearing behaviour

In general, the investigated girder is a statically determined single span beam. However, the eccentricities due to the curve radius introduce torsion. In the model, the support of both ends allow free deformation in longitudinal direction, while the torsion is fully constrained. In the case of R = 30 m the latter condition is required for stability reasons.

This bearing behaviour always leads to tensile forces in the inner supports in combination with high torsional moments in both the outer middle elements and the end elements. In the presented study, this fixing condition is idealistically modelled without any consideration of further support point deformations. The structural design of this fixing is subject to further research, however, its beneficial effect on the deflection verification has to be kept in mind.

The stresses are analysed in radial cross sections. In detail, bending is analysed in the middle of the girder length and shear at both the outer middle elements and the end elements. Thus, the considered bending stresses result only from local My and Mz, however, shear stresses result from local shear forces Vy and Vz as well as the torsional moment Mt.

The parapet has a significant beneficial effect on the bending capacity and bending stiffness. Although, the shear flow due to torsion is restricted to the hollow box section.

3.3. Preliminary SLS verifications

The design criteria of decompression under characteristic load combination requires a prestressing of 17.84 MN (5.30 MN in the parapet and 12.53 MN in the box girder). The related stress distribution in the critical cross section is shown in Figure 9. Visibly, there is a reserve of around 2 MN/m² compressive stress at the bottom and the upper edge.

Hereby, the requirements of a limited utilization of the compressive strength (0.6 fck under quasi-permanent load and 0.45 fck under characteristic load combination) are fulfilled.
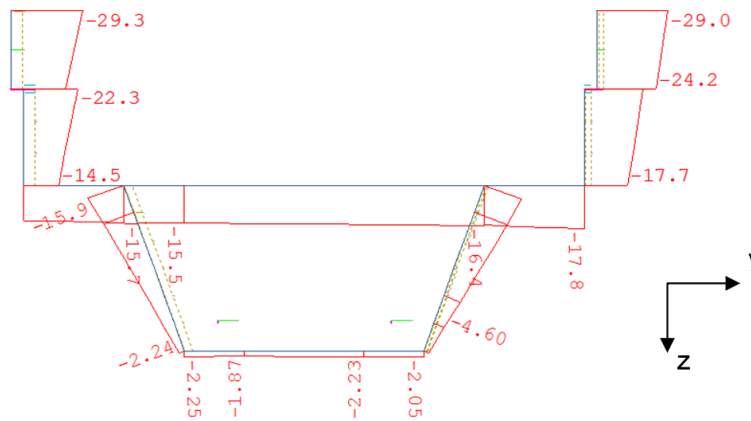

Figure 9: A-A characteristic combination SLS stress σx.

Figure 9 shows the deformation of the girder under characteristic load combination. The maximum deflection occurs at the outer parapet with a value of 81 mm which is within the design criteria of l / 250 = 136 mm.
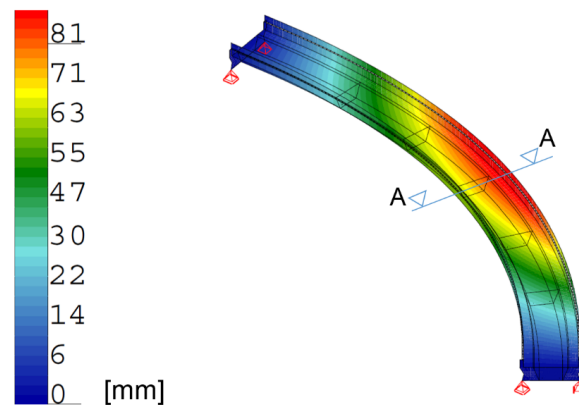

Figure 10: A-A characteristic combination deflection.

3.4. Preliminary ULS verifications

The internal forces are determined by integration of the element stresses in the control cross sections. The bending resistance due to a high inner lever arm (including the parapet) and the considerable amount of prestressing steel at the hollow box exceeds the design moment by a factor around two.

The shear resistance depends on the cracked state of the section. According to ÖNORM EN 1992-1-1 (2015), an uncracked state is assumed as long as the main tensile stresses are smaller or equal to the tensile strength according to Eq. (1). It can be written:

$$f_{ct,el,d} \geq \sigma_I = \frac{\sigma_x}{2} \pm \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau^2} \quad (4)$$

In a situation of higher tensile stresses, which result not only from shear forces but also from the torsional moment, the shear resistance is calculated with Eq. (5) according to AFGC (2013) & ÖNORM EN 1992-1-1 (2015). Hereby, the resistance of the prestressing (Eq. (6)), a part of the post peak resistance of the fibers (Eq. (7)) and an additional reinforcement (Eq. (9)) is considered.

$$V_{Rd,c} = V_{Rd,p.} + V_{Rd,f} + V_{Rd,s} \geq V_{ED,i} + \frac{T_{Ed}}{2A_k} z_i \quad (5)$$

$$V_{Rd,p.} = 0{,}12 \cdot \sigma_{cp} \cdot b_w \cdot z \quad (6)$$

$$V_{Rd,f} = \sigma_{cf} \cdot b_w \cdot \cot\theta \quad (7)$$

$$\sigma_{cf} = \frac{1}{w_u} \int_0^{w_u} \sigma(w)dw \quad (8)$$

$$V_{Rd,s} = a_{sw} \cdot f_{ywd} \cdot z \cdot \cot\theta \quad (9)$$

Altogether, in the extreme case of wide span and curve radius of 30 m the shear resistance of both the outer middle elements and the end elements require the arrangement of ordinary shear reinforcement. In all other cases (long span but less curve shape or more curve shape but shorter span) the shear resistance can be verified for the outer middle elements by means of the fibers, however, the end elements always require conventional shear reinforcement.

4. Conclusions

This paper gives an overview of the Quickway project with special regard to preliminary design studies on a curved girder for the Quickway structure. The girder consists of different prestressed UHPFRC elements. The developed cross section considered both: structural and serviceability requirements. A key point is the monolithic combination of a hollow box with a stiff parapet which provides bending stiffness as well as a guardrail and noise protection. The elements are produced with a specifically designed UHPFRC, presented in Hadl (2016). For preliminary structural design

studies, a simplified FEM model is generated. Besides the determination of required prestressing for decompression, the model is used to quantify the internal forces for SLS and ULS verifications. Next to this, the model give a rough estimate on the deflection to be expected, however, a reliable quantification has to take into account the real stiffness of the support.

5. References

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6. Acknowledgements