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The influence of the abutment stiffness on the design of the new steel double track integral railway bridge in Mechelen

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Summary

In extending the existing railway infrastructure from Brussels to Antwerp, a new double track railway is foreseen in making a by-pass over the station in the city of Mechelen. In crossing a local canal a new railway bridge must be designed in front of historical steel Vierendeel bridges. The paper describes the final design of the new integral railway bridge contrasting in all aspects the Vierendeel bridges with riveted bolt connections. The bridge consists of two lateral main girders with variable rectangular sections and is designed as an integral structure without bearings. The superstructure is fully welded and the main girder in box section near the abutments has a height of 3.65 m. The lower flange remains almost horizontal and is slightly twisted about a horizontal axis as it becomes wider at mid span. The upper flange decreases significantly and becomes smaller as it reaches mid span, obtaining less construction height of 1.65 m. This creates a waving pattern of the structure both in a horizontal plane as in the front view showing a contra bending referring to the arches of the Vierendeel bridges. The deck carrying both tracks consists of steel transverse girders with a concrete deck on top of it. The concept differs from a more classical integral bridge by totally stiff abutments. The paper describes the influence of the abutment stiffness as particular edge conditions in designing the main box sections taking all temperature effects. In addition, these abutments take part of a tunnel construction underneath the bridge. A parametric study of the abutment stiffness was needed. The advantage of the totally fixed portal structure has put into balance with the consequence of taking all temperature effects.

Keywords: Integral steel railway bridge, abutment stiffness, parametric study.

1. Introduction

In extending the existing railway infrastructure from Brussels to Antwerp, a new double track railway is foreseen as a by-pass along the railway station in the city of Mechelen. In combination to this project, a new road connection between the southern and northern part of the city as well as a new railway station will be built. In the southern part, this new road is situated in a tunnel under the by-pass railway. In designing the project, the process in obtaining a building permit in the city centre was very difficult dealing with historical and environmental conditions.

Fig. 1: Air photograph of the existing situation with view to the three Vierendeel bridges

A lot of attention was given in the architectural integration of structures. In this paper, only a particular situation in the southern part of the project is described. In crossing a local canal a new railway bridge must be designed parallel to historical steel Vierendeel bridges. A new bridge is only acceptable if it could be fully integrated into this historical site as can be seen in figure 1. This is an air photograph of the existing situation with 3 steel Vierendeel bridges for railway, build in the early 1930's and having a span of about 60 meter. The railway and road project is situated in front of these bridges.

2. A New double track railway bridge

2.1 Criteria for the new construction [1][2]

In designing and integrating the new structure, an important criterion seems to be keeping the view of the historic Vierendeel bridges. This may be achieved by looking for alternatives which do not imitate the arches nor try finding modern versions of this structure. The following items were felt to be important guidelines in making the new design: contrast of old and new technology, the new structure must not be of imposing character, bearing in mind the special texture and detailing of the Vierendeel bridges and leaving the characteristic view. This list was a help to review different proposals and brought forward a basic idea for further detailing. A fundamental discussion was to make use of the symmetrical situation of the existing bridge construction itself or to accentuate the non-symmetrical situation due to the position of the canal and also a similar Vierendeel bridge located in the northern part of the project crossing a local road and an existing railway. In this case two new railway bridges could be the start and end point of the new railway station infrastructure in between.

2.2 Overview of the different alternatives

During the pre design, different steel and concrete alternatives were considered. The first two alternatives referring to the figures 2 and 3 take into account the symmetrical option in integration of a new construction. A first alternative consists of en steel tied arch bridge with serious attention to the characteristic connection of the arch with the main girder of the deck. Giving extra stiffness to this connection limits the dimensions of the arches and limits the number of hangers so an optimal view to the Vierendeel bridge can be obtained. The particular node connection has a rounded shape of the arches with the main girders of the deck refers to a similar connection in case of the Vierendeel bridge. The geometry of the arch in height as well as in length is larger than the existing arch so that the structure forms a frame over the existing view in front of the bridge. An optimisation in the number and the positions of the hangers was studied. Over several other configurations of straight and radial hangers, the composition as can be seen in the front view of figure 2 on the left was chosen due to structural reasons. The design is considered as an architectural daring solution and has many advantages as the limitation of the amount of material. Referring to the design criteria in the previous paragraph, the concept is totally welded and has a smooth character which is in contrast with the existing structure. The bridge is fully integrated in the historical situation. An opposite alternative is given in figure 2 on the right.

Fig. 2: Alternative with steel arch and Low profile concrete viaduct

It consists of a concrete viaduct with limited construction height. The superstructure is a concrete deck plate bridge having a height of 1 meter of which the edges are rounded forming a larger cross section than strictly necessary. This solution is only possible when concrete piers near the borders of the canal limiting the spans to about 25 meter are provided. The superstructure is a continuous pre-stressed construction by post-tensioning cables. This alternative is considered as a low profile solution, the full attention is left to the existing structure. The presence of the piers is only acceptable if the sections remain limited. Several designs of the intermediate piers were considered. Over piers in V-shape and piers consisting of triangular plates, simply round columns with limited diameter were chosen. As a railway structure dealing with severe design criteria as horizontal deformations due to braking and acceleration forces, the limitations remains restricted to 1.3m at the minimum. Nevertheless, as for such railway structures, the chance of collision of the columns by road traffic under the bridge is an imported risk. Figure 3 gives a simulation of the low profile solution. In this situation, the viaduct continues till the station situated on the right some 100 meters from this location.

Fig. 3: Alternative with cable-stayed bridge and cable-stayed bridge at the northern part

A third alternative consists of a totally different construction. The accent is given to a non-symmetrical situation referring to the total site. A similar Vierendeel bridge is located some 500 meters from this location crossing an existing local road and a railway. At this location, the very slope crossing of the latter railway dominates in the non-symmetrical situation. The station of Mechelen is located between the two identical bridges. In this design, the idea of creating two new identical asymmetrical bridges accentuates the start and end of the station. For the construction, it was chosen for a cable-stayed bridge with limited cables regarding to the view to the original bridges. It would be the first cable-stayed bridge for railway applications in Belgium, as it was at that time the case for the application of a Vierendeel structure. The pylon has limited height and is located at the outer sites of both locations. The figure 3 give a simulation of this particular design at the two locations. On the left photograph the situation over the canal is given, on the right the situation at the second Vierendeel bridge is visualised. Referring to the criteria, the construction has not an imposing character and shows the contrast of old and new technology.

2.3 Final design

Finally, in combining all criteria, a last design was developed in using an integral steel portal bridge. The bridge consists of two lateral main girders having variable rectangular sections and is designed as an integral structure without bearings. The superstructure is fully welded and the main girder of a box section near the abutments has a height of 3.65 m. The lower flange remains almost horizontal and is slightly twisted about a horizontal axis thus becoming wider near the centre. The upper flange decreases significantly and becomes smaller near mid span, thus obtaining less construction depth of 1.65 m. This creates a waving pattern of the structure both in a horizontal plane as in the front view showing a reversed curvature near to the arch springs of the Vierendeel bridges.

The geometry is illustrated in figure 4, showing the particular curvature in front view as can be seen on the photograph on the left and in the 3-dimensional model on the right. Referring to the structural conditions of the bridge, this curvature has only sense if the abutments are fully integrated in the foundations introducing moments. To accentuate the symmetry, at both sides a talus is created.

The span is about 65 meters, which is 5 meters more than the arch Vierendeel bridge. To accentuate the symmetry, at both sides a talus is created.

Fig. 4: View in front of the final design and 3-Dimensional model of the final design

Referring to the criteria in the previous paragraph, the bridge shows contrast in the connection of steel material (riveted bolts in contrast with a fully welded construction) and differs in the structural behaviour due to the integral situation. The smooth modern steel construction contrasts the rough Vierendeel and its several remarkable details. It could be concluded that in respect to the existing structure and in respect to the integration in the situation, the latter option was to be chosen.

Fig. 5: Simulation of the final design with steel portal structure

3. The design of the integral bridge

3.1 Foundations

As already mentioned in the introduction, a road connection between the southern and northern part of the city is foreseen in combination with the new railway project. At this particular site, the road crosses the canal by tunnel as can be seen in the view in front (on the left) as in the cross section (on the right) of figure 6.

Fig. 6: View in front and cross section at mid span of the total project with tunnel and bridge.

This situation makes that the abutments of the bridge are founded on the tunnel. This can be done by a complex concrete structure with internal concrete shells or discs in transferring the forces from the main box girders to the vertical walls of the tunnel (the two outer walls as well as to the inner wall). A fully 3-dimensional view of the structure can be seen in figure 7. Since the bridge is an integral construction, the foundations must resist to the forces due to temperature.

Fig. 7: 3-Dimensional view to the total foundation system of the bridge.

In dealing with the transfer of forces to the tunnel construction, the whole foundation system can be considered as totally fixed. This concept differs from a more classical integral bridge by the large stiffness of the abutments. The transfer of the internal steel forces to the concrete is realized by placing a large number of post-tensioning tendon bars in the inner part of the steel main box girders. This connection can be seen in the 3-dimensional model in figure 8 on the right.

3.2 Steel superstructure with variable hollow section

The steel superstructure is a fully welded construction consisting of two main box girders and steel transverse beams in between. At the highest point, the main girder section near the abutments has a height of 3.65 m. The lower flange remains almost horizontal and is slightly twisted about a horizontal axis thus becoming wider near the centre. The upper flange decreases significantly and becomes smaller near mid span, thus obtaining less construction depth of 1.65 m. This creates a waving pattern of the structure both in a horizontal plane as in the front view. Figure 8 gives the

cross-sections of the superstructure at 4 locations: at mid span, at a fourth of the span, at the highest construction height and just before the anchorages into the foundations. Special attention is given to the variation of the main girder section. As can be seen in the cross sections on the left, the outer web plate of the steel superstructure shows torsion. During construction, this outer plate will be pre-deformed. On the right of figure 11, a 3-dimensional model gives a view of the inner parts of the superstructure. Due to the restricted construction height, the slender cross-section at mid span has limited stiffness. This brings concerns about the transverse distortion, such as the twist of the deck which must be strictly limited for railway bridges. To raise the torsion stiffness of the main box girders, internal stiffening is used. In the final design, the use of longitudinal stiffening as well as the use of diaphragms on very short distances in relation to the transverse beams has been foreseen.

Fig. 8: Cross sections at different locations and a view of the inner parts in a 3-D model.

3.3 Design considerations [3] [4]

3.3.1 Vertical deformations for railway bridges

The style, grammar and phrasing should be edited by a person with an excellent command of As already mentioned, the design of the new superstructure is only acceptable if the total construction height remains limited in order to guaranty a full front view on the existing structure. Evidently, this restriction is not unlimited dealing with the strict serviceability criteria and dynamic analysis for railway bridges according to the Eurocode (ENV 1991-3). In the further design, these criteria are decisive comparing with the criteria of strength. It concerns not only the restrictions in vertical deformations for safety purposes, but also the transverse deflections and the twist of the deck. In this configuration, the restriction of the vertical deflection δ/L to a maximum value of $1/1090$ for a train speed of 160 km/h and the restriction of the rotations at the end of the deck to $6.5 \cdot 10^{-3}$ radians for ballasted track can be fulfilled.

Fig. 9: Vertical deformation due to temperature and to mobile loads

The vertical deformations are illustrated in figure 9 on the right showing maximum deformations of about 90 mm in the centre of the deck by mobile. These deformations are too large referring to the restrictions, so a solution is found in using a concrete deck on top of the steel transverse beams. Due to the higher stiffness, the deformation drops to a value of about 70 mm which is acceptable. Since the structure is made integral, also temperature effects are important. The deformation due to temperature inclination is illustrated in figure 12, being at mid span about a third of the vertical deformation.

3.3.2 Parametric study of the abutment stiffness

A particular concern in the design of the bridge is the abutment stiffness. Therefore, a parametric study has been carried out in taking account the estimated abutment stiffness by finite element modelling of the integral construction of the abutment and tunnel structure consisting of slurry walls as shown in the 3-dimensional model of figure 7. The horizontal longitudinal deformation and rotation stiffness was found by taking into account the deformations and rotations which would occur at the level of the fixing points of the steel superstructure. Since this is difficult to simulate, a range of different edge conditions in the finite element model of the foundation and tunnel structures was taken into account. In the final design, the steel construction is fixed by post-tensioning bars as well as by steel dowels on the outer steel webs which are fading into the concrete abutments.

Fig. 10: Fixations of the steel structure simulating the dowels and post-tensioning bars

In figure 10, both fixations are showed, on the left picture the outer dowels are modelled as fixed points. In the picture on the right as indicated in red, post-tensioning fixations are simulated as fixed points at the level of horizontal steel plates. The post-tensioning bars are needed avoiding rotations and deformations at these fixation points. In replacing the edge conditions by horizontal and rotation springs taking into account a flexible foundation, the influence on the structure is calculated. As for the spring stiffness, the spring stiffness in horizontal longitudinal direction k_x is $8,62 \cdot 10^6$ N/mm. As for the individual spring stiffness is vertical direction k_z , a range of $0,99 \cdot 10^8$ N/mm² till $1,25 \cdot 10^9$ N/mm² has been taken into account. These values have been derived of the results of the finite element model of the foundation and abutment model and are indicated as “MOG1” as for the lowest value till “MOG3” for the highest value of k_z . With these parameters, calculations have been carried out. It can be seen that a small deformation in the edge conditions has a negative influence on the bridge at mid span. This can be seen in the graphs of figure 11. In both graphs, the evolutions of the normal stresses are given over the total length of the main girder of the bridge. On the left, it consists of the stresses in the lower flange of the main girder at the side of the transverse girders. This point is indicated as B1 of the main girder HL1. On the right, the normal stresses in the upper flange at the inner side or the side of the transverse girders of the same main girder is given. This point is indicated as B2 of the main girder HL1. The evolutions in red in both graphs are the normal stresses in the load combination taking into account the temperature, the dead and fixed load and the mobile load. The evolutions in blue and green are the stresses in the case of modelling with vertical and horizontal springs. It could be noticed that the range of values hardly influences the results. However, the differences regarding to 100% fixed edge conditions are remarkable for the mid span section but not for the edge sections. In the particular bridge, a steel quality of S460 has

been used.

Fig. 11: Evolutions of normal stress (N/mm^2) in the upper and lower flanges of the main girder

4. Summary

In extending the existing railway infrastructure from Brussels to Antwerp, a new double track railway is foreseen as a by-pass along the station in the city of Mechelen. In crossing a local canal a new railway bridge must be designed parallel to historical steel *Vierendeel* bridges. A new bridge is only acceptable if it could be fully integrated into the historical site. The paper describes the final design of the new railway bridge contrasting in all its aspects to the *Vierendeel* bridges with riveted bolt connections. The bridge consists of two lateral main girders having variable rectangular sections and is designed as an integral structure without bearings. The superstructure is fully welded and the main girder of a box section near the abutments has a height of 3.65 m. The lower flange remains almost horizontal and is slightly twisted about a horizontal axis thus becoming wider near the centre. The upper flange decreases significantly and becomes smaller near mid span, thus obtaining lesser construction depth of 1.65 m. This creates a waving pattern of the structure both in a horizontal plane as in the front view showing a reversed curvature near to the arch springs of the *Vierendeel* bridges. The deck carrying both tracks consists of steel transverse girders with a concrete deck on top of it. The concept differs from a more classical integral bridge by the large stiffness of the abutments. The paper describes the consequences of this particular edge conditions in the design of the main box sections and the internal stiffening avoiding local instability and creating stiffness respecting the severe deformation criteria for railway bridges.

5. References

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