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EFFICIENCY OF THE COMPOSITE BRIDGE SECTIONS WITH OPEN AND BOX-SHAPED THIN-WALLED STEEL GIRDERS

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Abstract

Composite girders are commonly used as load-bearing elements in new bridges. This superstructure, which combines materials, most often steel girders with a reinforced concrete deck, is suitable for short to medium spans when used in continuous girder statical system. In a twin or multi girder cross sections, box-shaped thin-walled girders are significantly more efficient than open "I"-section girders in resisting torsional moments and are generally preferred for longer, wider, and horizontally curved bridges. Open sections are simpler and often more cost-effective for straight, shorter spans. The efficiency of these girders can be assessed through various parameters, including weight-to-strength ratio, stiffness, and resistance to bending and torsion. In this study, composite bridge sections with closed and open girders are analyzed using EN 1991-2 Load Model 1 traffic load. Two models of composite bridges with the same span and width but different girders were studied. The paper consists of three parts. The first part, theoretical in nature, discusses the characteristics of open section composite bridges. In the second part, two alternative composite bridges are analyzed, and a composite girder design is conducted. The final part compares the results and efficiency of each girder. The work concludes with recommendations on which type of girder to choose for the given input parameters.

Keywords: composite bridge, box-shaped girder, open section girder, steel design, steel consumption

1 Introduction

Composite bridges are load-bearing structures that combine different materials, most commonly steel and concrete. Steel is primarily used for the main girder, while the deck slab is made of reinforced concrete [1]. Due to their numerous advantages over prestressed concrete girders, these load-bearing systems are frequently used on highways. Advantages include a higher span-to-height ratio, lower dead weight, smaller substructure elements, simpler foundations, improved performance in seismically active areas due to reduced weight, aesthetically acceptable structures, and faster construction compared to bridges with prestressed concrete girders [1]. Compared to steel girders, composite bridges require less steel, offer greater stiffness for the same girder height, exhibit lower deflection under load, and allow for simpler fabrication. This type of superstructure is used for spans up to 130 m. The typical design range for composite bridges is 40 to 90 m for open cross-sections and 70 to 120 m for closed cross-sections [2, 3]. From this, it can be concluded that open-section girders are generally used for shorter spans, while closed cross-sections are preferred for longer spans. This is due to better transverse load distribution and a larger web surface area. The bridge span is also influenced by the construction method.

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The longitudinal launching method is suitable for spans up to 65 m, while for longer spans, the free cantilever method is generally used. This paper presents a comparison of two continuous composite bridges with closed and open cross-sections of the main girder, as shown in figure 1. The analyzed bridges are suitable for construction by longitudinal launching, a method that has recently proven to be the most suitable for these types of bridges.

Figure 1 Composite bridges with open (left) and closed (right) cross-sections of the main girder

All the dominant actions on the bridges were analyzed. Design guides for composite bridges have been produced by various authors [4-7]. The selected main span (60 m) is close to the limiting span for this type of structure and construction method. The different stress states of the girders during the construction phases, problems with cracking of the reinforced concrete slab, and the introduction of as much permanent load as possible into the composite section require detailed calculations of these bridges during the construction phases. The aim of this research is to determine the most appropriate cross-sectional shape for this type of structure, as well as the corresponding span length and construction method. Conclusions will be drawn through the observation of transverse load redistribution, the thickness of the girder plates, the stress distribution across the girder, and the deflection.

2 Layout and static analysis of bridges

2.1 Layout of the bridge

Two continuous composite bridges over four spans, with a total length of 230 m, were analyzed. The two middle spans are 60 m long. To equalize the moments in all the spans, the edge spans were made shorter, at 47 m (ratio 0.78). This layout is supported by three columns and two abutments, as shown in figure 2.

First, the layout with closed main girders was analyzed. The cross-section with a total width of 12.0 m consists of two closed main girders with constant height 2.750 m, connected by a deck slab. The main girders of the closed section are composed of the upper and lower flanges and two webs. These parts form an open cross-section for the before deck slab construction phase, while for additional dead and subsequent variable loads, a closed composite section is activated. It is possible to design the girders with the same (rectangular shape) or different (trapezoidal shape) widths of the upper and lower flanges. For this analysis, a trapezoidal cross-section with a narrower lower flange was selected (figure 3).

The second layout consists of two open “I” girders with a constant height of 2.75 m. For spans greater than 50 m, a layout with more than two spans is not economical [2]. The girders consist of an upper and lower flange and a web. The distance between the main girders is 6.5 m. The girders are connected with 0.8-1.45 m high transverse girders, spaced at 5 m intervals. At the point of connection between the transverse and main girders, vertical stiffening of the web is provided. This connection forms a transverse frame. The horizontal stiffening of the web (web higher than 2.0 m) is placed above the support in the compression (lower) area of the web.

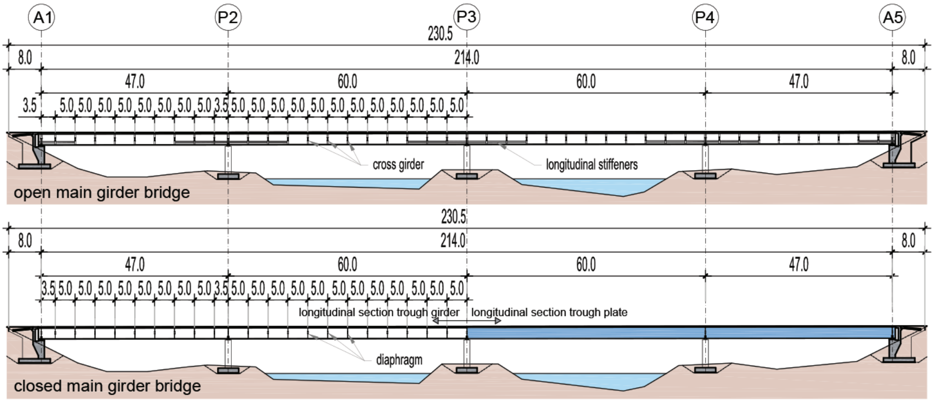

Figure 2 Longitudinal layouts of bridges

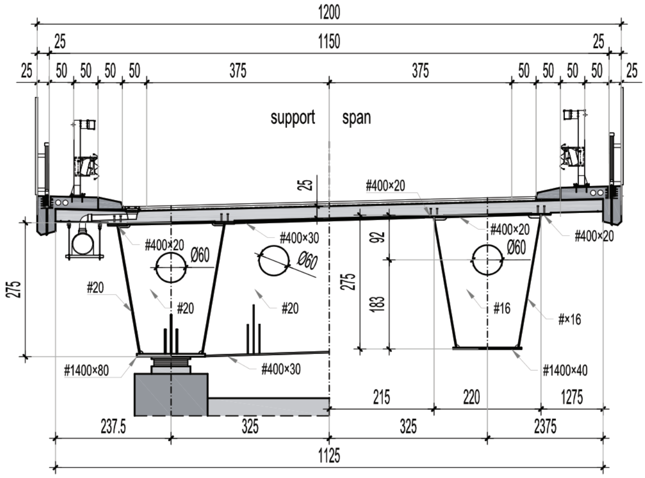

Figure 3 Cross-section of a bridge with a closed girder section

The adopted lower flange thickness of the main girder in the midspan is 40 mm, and 115 mm above the support (two flanges 60+55 mm). The thickness of the upper flange of the girder in the midspan is 20 mm, and 80 mm above the support. The web is 16 mm thick in the midspan and 25 mm above the support. The deck slab is shaped as haunched, the thickness of the slab at the center of the section and at the cantilevers edge is 0.25 m, while the thickness above the main girders is 0.375 m.

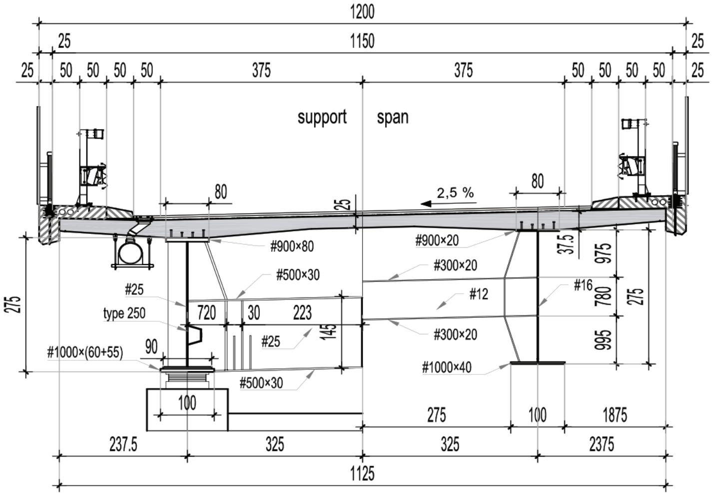

Figure 4 Cross-section of a bridge with an open girder section

2.2 Static analysis of bridges

A numerical model with 3D finite elements was analyzed. A hybrid model was used, in which the longitudinal girders were modelled as beams with equivalent static characteristics, and the deck slab as area elements with reduced longitudinal stiffness. Deck slab longitudinal stiffness was provided by the cross-sectional characteristics of the main girder, with effective widths for the upper flange of the reinforced concrete slab. Transverse stiffness and traffic load distribution was achieved by the transverse deck slab stiffness and by the elements of the transverse girders. The bearings were modelled with high-stiffness springs in the reaction direction. Longitudinally fixed bearings were placed on the two inner piers, while all other bearings are longitudinally movable. The bearings on the right side, viewed in the direction of stationing, are fixed for transverse reactions.

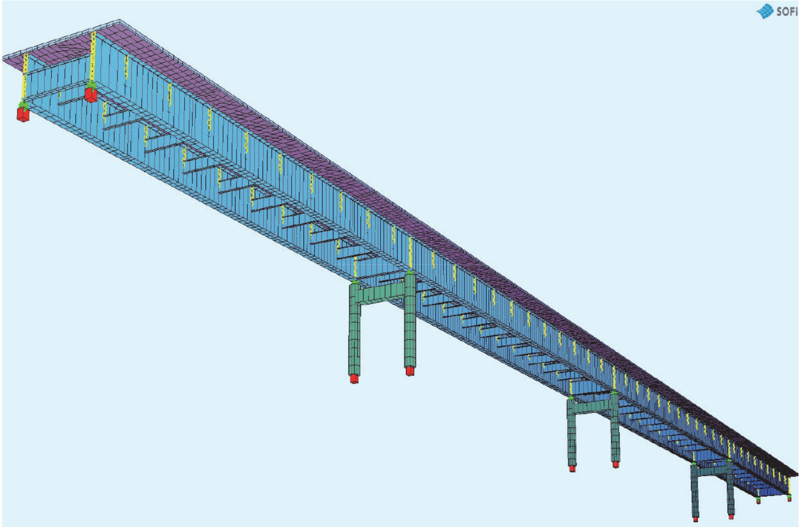

Figure 5 Static model of the bridge with an open girder cross section

All dominant actions on the bridge superstructure were analyzed: self-weight, additional dead load, concrete rheology, traffic load, temperature, and wind. Traffic was analyzed according to EN 1991-2 [8]. The pavement surface consists of two lanes, each 3.75 m wide. Two positions of the main traffic lane were considered. In the first position, the main traffic lane is placed next to the roadway curb. This loading position provides the relevant values of the design forces on the main girder. In the second position, the main traffic lane is located in the middle of the cross-section. This loading position provides the relevant design forces on the pavement slab. The values of temperature and wind actions were analyzed according to the relevant EN standard. The combinations of actions required for the design of the ultimate and serviceability limit states were analyzed according to EN 1991-1.

3 Comparison of results

The sections were designed according to the Eurocode limit state stress design. Limit stresses were reduced according to EN 1993-1-5 [9]. Concrete cracking was considered according to EN 1994-2 [10] (concrete grade C35/45), reducing the section to only steel and reinforcement once the double concrete tensile strength was reached in rare combination. The results for the closed cross-section are presented below. For the highest negative bending moment, the lower flange is in pure compression, and cross-section classification according to EN 1993-1-1 [11] determined that it is class 3. The utilization of the lower flange above the support is 63%, while the utilization at midspan is 53%. Longitudinal normal stresses occur in the web as a result of the bending moment and change sign from compression to tension. In addition to longitudinal stresses, significant shear stresses also occur in the web. The interaction between these stress states – namely, the highest compressive stress with the associated shear stresses, and the highest shear stresses with the associated compressive stress – was assessed according to the expression in EN 1993-1-1 [11]:

$$\left(\frac{\sigma_{1x,Ed}}{\rho_x \cdot ff_y / \gamma_{M1}}\right)^2 + 3 \cdot \left(\frac{\tau_{Ed}}{\chi_w \cdot {}_y / \gamma_{M1}}\right)^2 \leq 1{,}00 \qquad (1)$$

Design of stiffened and unstiffened section plates was carried out. The results showed web utilization above the support of 80% and 62% in the span. The utilization of the upper flange above the support is 73%, while in the span it is 53%. The analyzed thicknesses of the flange and web, along with the given results, indicate potential for optimization of the thicknesses of all elements of this type of cross-section. By analyzing the limit state stress design of the bridge with open girders, the results showed higher utilization of the section plates. The utilization of the lower flange in the span is 76% and at the support is 80%. With buckling verification, the web has a utilization of 97% above the support and 50% in the span. The utilization of the upper flange in the span is 47% and above the support is 76%. With this type of cross-section, there is also potential for optimization.

If we observe the utilization of critical sections of designed bridges, we can conclude that in the case of an open-section bridge with box girders, there is equal utilization of the section above the supports and in the span. Both observed elements, the webs and flanges, have significant reserves of load-bearing capacity, which is desirable for safety and the increasing trend of traffic loads on bridges. The thicknesses of the elements are gradually changed, and there are no large deviations from section to section. On the other hand, in the case of an open-section bridge with I-girders, the section above the supports is highly utilized, while the sections in the midspan are less utilized. The dimensions of the elements, especially the lower flange above the supports, are significantly larger than other elements in the section.

Due to the high compressive stresses in open-section bridges with I-girders, an additional flange plate is added at the support sections to keep the stresses within the limit state. This results in a more complicated and more expensive design. Differences in girder design affect the design of the deck slab in composite sections. In bridges with open girders, the distance between the girders is such that a deck slab with a haunch is required. Such a deck slab increases the dead weight of the superstructure by 18.5% compared to a slab with constant thickness of 25 cm, as is the case of a closed girder layout.

Significant differences in material consumption occur in the girder elements. First, let us consider the cross girders and additional stiffening elements of these bridges. For the bridge with I-girders, 28.3 t of steel is used for all transverse girders in the midspans and all associated stiffening elements, while 21.3 t of steel is used for these elements above the supports, giving a total of 49.6 t of steel. For the bridge with box girders, 26.0 t of steel is used for all diaphragms in the spans and all associated stiffening elements, while 21, 0 t of steel is used for transverse elements above the supports, giving a total of 47.0 t of steel. The total amount of steel for the cross elements and stiffeners shows that almost the same amount of steel is used for them. The largest differences in steel consumption occurs in the flanges and webs of main girders. For the bridge with open I-girders, larger element thicknesses were used, but the number of elements was smaller. A total of 308 t of steel was used for the open I-girders. In contrast, the open-section bridge with box girders has thinner elements but a higher number of them. These girders have two webs and three flanges (one wide at the bottom, and two top flanges). The total steel consumption for these girders is 450 t. The following graph shows the steel consumption for individual elements of the analyzed bridges.

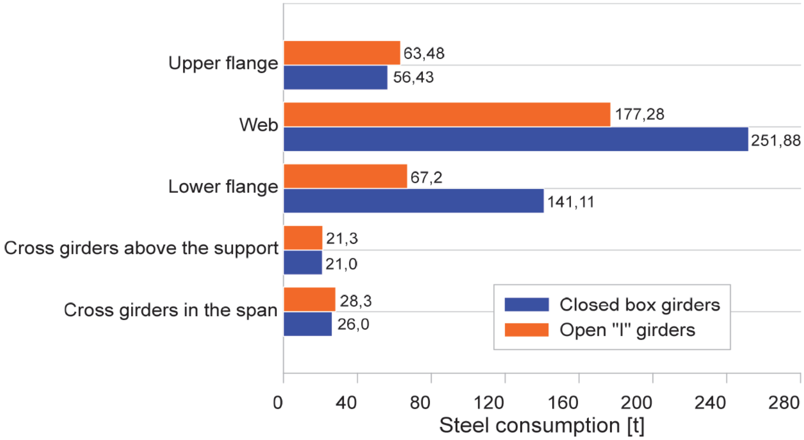

Figure 6 Steel quantities per bridge element

From the above, 26.89% more steel in total was used in bridges with closed girder cross-sections. This information should be taken with the comment that in the limit state design of closed girder cross-sections, lower element utilization was observed compared to bridges with open cross-sections. This is due to the nature of such girders, which have wide bottom flanges for which a minimum 20 mm thickness was adopted. Also, number of webs is double then in the section with I-girders, so naturally their utilization is lower as well. The expected difference could potentially be somewhat smaller, but it can still be concluded that a larger amount of steel is required for the construction of bridges with closed girders.

4 Conclusion

In this paper, two bridges were analyzed, differing in the type of main girder. The goal was to determine which girder is more optimal for a given obstacle. Using a numerical model, the thicknesses of the steel elements for the observed types of cross-sections were determined. Ultimately, considering that the main parameter for the comparison was steel consumption, it was found that the bridge section with open I girders is more cost-effective than the bridge with closed main girders. In terms of load-bearing capacity, stability and robustness, the advantage lies with bridges with closed sections. It is evident that they have larger load-bearing reserves and better resistance to analyzed actions.

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