Shear Assessment of Existing Prestressed Box Girder Bridge

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Abstract. The paper deals with the shear assessment of existing prestressed concrete box-girder bridges. Mainly focuses on the historical development of technical standards used in the design of prestressed concrete road bridges in the Slovak Republic. The standards for bridge design have been amended several times. A parametric study was performed on a model post-tensioned concrete bridge with a box-girder cross-section, which compares the internal forces along the length of the bridge using various standards and technical regulations. The differences in design principles and shear capacity were investigated while the amount and geometry of the longitudinal prestressing of the bridge were the same for all cases. Case of study is a road three-span post-tensioned concrete bridge with a main span of 50 m and end spans of 40 m. The single box-girder cross section height is constant of 2.5 m. The bridge is straight without any curvature in the horizontal plane. The thickness of the bottom slab is variable near the inner supports. The prestressing is formed by 19-strands tendons with a strand diameter of 15.7 mm with a polygonal cable geometry. The numerical model is considered as a beam element with neglecting of the torsional effects of the load. The parametric study points out the differences in the internal forces with use of different design regulations and standards. It also focuses on the shear resistance of the walls of the box-girder cross-section of the bridge. Differences in design methods are presented by the required area of shear reinforcement in the wall of box cross-section. The aim of the study is to point out the historical development of design from the point of view of shear resistance of prestressed bridges. When assessing existing older bridges and trying to achieve reliability according to the current Eurocodes, there is subsequently a requirement for additional shear reinforcement.

1. Introduction
In practice, we increasingly encounter the assessment of any load-bearing structures, for their repairs or reconstruction. In the case of bridges, we meet with the requirements for their higher carrying capacity due to increasing traffic intensity. It leads to development of new traffic load models, which we use for their assessments. Also, in Slovakia, interesting reconstructions of bridges have been carried out in recent years. These bridges were built according to standards that are no longer valid today. In Krásno nad Kysucou, one of the oldest concrete bridges was reconstructed, which was built in 1892 [1]. The prestressed segmental bridge over the Ružín dam build in 1967 was reconstructed by an additional external prestressing [2].

This work deals with the shear resistance of prestressed structures. In the case of prestressed bridges, the effect of a gradual reduction of the prestressing force due to prestressing losses or corrosion is often investigated. Experimentally, this effect was investigated on concrete beams with naturally corroded prestressing [3]. The analysis of shear resistance, which the article deals with, includes standards for the...
design of prestressed bridges since 1968 used in Czechoslovakia and later in Slovakia. By 2020, a total of 5 changes in standards were processed in this region, which meant a change in load models as well as the principles of designing concrete prestress structures.

2. Case of study
The objective of the work is the concrete three-span prestressed bridge with a box-girder cross-section. The bridge is supported by bearings with one fix, which allows free horizontal movements of the bridge. The length of the superstructure is 131 m. The end spans have a length of 40 m and the main span has a length of 50 m. On the bridge there is a road with two-way traffic with a width of 9.5 m. The road is made of a 90 mm thick asphalt mixture. The cross-section of the bridge deck and accessories are present in figure 1. The total width of the bridge deck, including the kerbs, is 13.6 m. The cross section of the bridge is designed as box-girder with a height of about 2.5 m and a width of the box-girder of about 7.0 m, shown in (Figure 1). The lower slab of the chamber increases its thickness from 250 mm to 500 mm at the supports. The wall thickness is 500 mm. The upper slab has a variable thickness. The minimum thickness of the top plate is 250 mm, in the case of walls 500 mm. The extension of the cantilever is 2.7 m.

![Figure 1. Geometry of box-girder cross section and the bridge accessories](image)

3. Specification of the materials
3.1. Concrete
The superstructure of the bridge is made of concrete C35/45 according to Eurocode 2 (STN EN 1992-2). Material characteristics are given in table 1. For assessment according to the original Slovak national standards (STN) and Czechoslovak technical standard (ČSN) is equivalent class of concrete B500. Material characteristics are given in table 2.

| Characteristic compressive cylinder strength $f_{ck}$ (MPa) | Mean value of concrete tensile axial strength $f_{ctm}$ (MPa) | Modulus of elasticity $E_{cm}$ (GPa) |
|---------------|------------------|------------------|
| C 35/45       | 35               | 3.2              | 34               |
Table 2. Concrete properties according to STN and ČSN standards

|               | Mean compressive cubic strength $f_{cm,\text{cube}}$ (MPa) | Limit tensile stress in concrete $\sigma_{t,\text{max}}$ (MPa) | Modulus of elasticity $E_{cm}$ (GPa) |
|---------------|----------------------------------------------------------|------------------------------------------------------------|----------------------------------|
| B 500         | 50                                                       | 3.1                                                         | 38.5                              |

3.2. Reinforcing steel
The class of used reinforcing steel is B 500B according to Eurocode 2. Material characteristics are given in table 3.

Table 3. Reinforcing steel properties according to Eurocode 2

|               | Characteristic yield strength $f_{yk}$ (MPa) | Design yield strength $f_{ywd}$ (MPa) | Modulus of elasticity $E_s$ (GPa) |
|---------------|---------------------------------------------|---------------------------------------|----------------------------------|
| B 500B        | 500                                         | 434.78                                | 200                              |

3.3. Prestressing strands
The prestress of a bridge is composed by 19-strands tendons with a strand diameter of 15.7 mm. The properties are given in table 4.

Table 4. Prestressing steel properties according to Eurocode 2

| Nominal diameter of strands $\bar{O}LS$ (mm) | Characteristic tensile strength of prestressing steel $f_{pk}$ (MPa) | Maximum stress applied to the tendon $\sigma_{p\text{max}}$ (MPa) | Coefficient of friction $\mu$ | Cross-section area of strand $A_p$ (mm$^2$) |
|---------------------------------------------|-------------------------------------------------|------------------------------------------------------------|-------------------------------|---------------------------------|
| 15.7                                        | 1860                                            | 1488                                                       | 0.2                           | 150                             |

4. Prestressing of the bridge
The bridge is cast in place on a falsework in one working stage. The prestressing of the bridge involves polygonal tendons running along the entire length of the bridge prestressed from both sides. For prestressing were used 2 different basic geometries of tendons. The total number of prestressing tendons is 16. Of which 12 tendons are placed according to geometry A and 4 tendons are placed according to geometry B. The geometry is shown in figure 2, which representing half-length of superstructure.

Figure 2. Geometry of tendons

5. Applied standards
5.1. ČSN 73 6203 (1968)
The technical standard has been used for the design of bridge structures in Czechoslovakia territory since 1968. The assessments of prestressed structures were according to the theory of allowable stresses.
The theory of the degree of safety is used to assess the shear stress and to determine the amount of shear reinforcement. The load model consisted of two loads: uniformly distributed load 5.4 kN/m² in the entire width of the bridge and a three-axle vehicle with weight of 600 kN. Pedestrian load was assumed with a value of 4 kN/m². The scheme of the load model is shown in figure 3.

Figure 3. Traffic load model according to ČSN 73 6203 (1968)

5.2. ČSN 73 6203 - amendment A (1975)
National standard ČSN 73 6203 was changed in 1975 by amendment A. This update brought about a change in traffic load patterns. It contained two load models.

Load model 1 represented a uniformly distributed load 4.0 kN/m² over the entire width and a three-axle vehicle with a weight of 600 kN. Model 2 represented a uniformly distributed load 4.0 kN/m² along the entire width with additional area load of 4.0 kN/m² in line 3.0 m wide. Pedestrian load was assumed with a value of 4kN/m². The load model schemes are shown in figure 4.

Figure 4. Traffic load models according to ČSN 73 6203 - amendment A (1975)

5.3. STN 73 6203 (1994)
After the dividing of Czechoslovakia, in 1994 the standard STN 73 6203 came into force in Slovakia. It brought another change in load models. The standard prescribed traffic loads using three load models. The pedestrian load was assumed at 4kN/m².
The load model 1 represented six three-axle vehicles with a total vehicle weight of 320 kN and a uniformly distributed load of 2.5 kN/m² on rest area. The load model 2 represented an area load of 9.0 kN/m² for a width of 3.0 m supplemented by an area load of 3.5 kN/m² for the rest of the width. Load model 3 represented one four-axle vehicle with a total weight of 800 kN. Schemes of load models are shown in figure 5.

Figure 5. Traffic load models according to STN 73 6203 (1994)

5.4. STN EN 1991-2 (2010)
The currently valid standard on the territory of the Slovak Republic since 2010 are common European standards - Eurocodes. The decisive model of traffic load is load model 1. The load is simulated by a tandem system (TS) and uniformly distributed load (UDL). The pedestrian load is prescribed as 3 kN/m² in combination with the traffic load. Individual loads school be adjusted by adjustment factors α according to national annex.

The load models adjusted according to the national annex are shown in figure 6. The combination of TS and UDL load schemes represents the dividing of the road into four traffic lanes. The first 3 m wide traffic lane contains an area load of 0.9x9.0 kN/m² and a two-axle vehicle with an axle weight of 0.9x300 kN. The second 3 m wide traffic lane contains an area load of 2.5 kN/m² and a two-axle vehicle with an axle weight of 0.9x200 kN. The third 3 m wide line contains an area load of 2.5 kN/m² and a two-axle vehicle with an axle weight of 0.9x100 kN. The fourth traffic lane is spread on the residual area formed only by an area load with an intensity of 2.5 kN/m².
5.5. STN EN 1991-2 (2020)
The national annex was amended in 2020, which also affected the adjustment factors $\alpha$. It brought a change from 0.9 to 1.0 for two-axle vehicles and for the UDL in the first lane. The load values adjusted according to the amended national annex are shown in figure 6 and the comparison of factors $\alpha$ are given in table 5.

| Annex | LANE No.1 | LANE No.2 | LANE No.3 | LANE No.4 |
|-------|-----------|-----------|-----------|-----------|
| UDL   | 2010      | 0.9       | 1         | 1         | 1         |
|       | 2020      | 1         | 1         | 1         | 1         |
| TS    | 2010      | 0.9       | 0.9       | 0.9       | -         |
|       | 2020      | 1         | 1         | 1         | -         |

Figure 6. Traffic load models according to STN EN 1991-2 and Slovak national annex 2010, 2020

6. Results and comparisons
The calculation aims to compare the approaches and the level of reliability of national standards intended for the design of prestressed bridges in Slovakia in the past with the currently valid Eurocodes. It deals with the shear resistance of the prestressed bridge in critical sections. The comparison aims to calculate the required area of shear reinforcement in the webs of the box cross-section. The prestressing of the bridge was determined according to the Eurocode to meet criteria of decompression under a frequent combination of loads. This level of prestressing was used for each compared standard.

6.1. Shear forces
This section compares shear forces of the design standards separately. The graphs show shear forces from traffic loads in combination with pedestrian loads. The horizontal axis represents the distance of the section from the beginning of the bridge and the vertical axis represents the shear forces. The following graphs present half of the total structure length.

The graphs show the influence of load models of individual standards on the magnitude of the shear force. In the case of ČSN 73 6203 shown in figure 7, in the case of ČSN 73 6203 A shown in figure 8, load model LM2 is decisive. In the case of STN 73 1251 shown in figure 9, load model LM1 is decisive. In the case of STN EN 1991-2 (2010,2020) shown in figure 10, standard from 2010 has bigger values. A comparison of all standards shown in figure 11 shows that the maximum shear force is calculated according to STN 73 1251.
Figure 7. Shear forces $V$ according to ČSN 73 6203

Figure 8. Shear forces $V$ according to ČSN 73 6203 amendment A

Figure 9. Shear forces $V$ according to STN 73 6203
6.2. Required shear reinforcement area
The graph in figure 12 represents the required shear reinforcement area per meter along the length of the beam designed by Eurocode 2 (2020) calculated by the equation (1):

\[ A_{sw} = \frac{V_{Ed}}{f_{yd} \cdot z \cdot \cot \theta} \text{ [cm}^2\text{/m]} \] (1)

Where \( V_{Ed} \) is design value of the applied shear force, \( f_{yd} \) is design yield of shear reinforcement, \( z \) is lever arm of internal forces and \( \theta \) is angle of compression strut.

The sections required the largest shear reinforcement area were selected as critical sections in figure 12. Five critical section were selected to compare the required shear reinforcement according to all above mentioned standards. The distance of the section from the beginning of the beam is 8.875 m, 26.875 m, 37.875 m, 42.125 m and 57.125 m. Previous standards STN and ČSN designed shear reinforcement through principal stresses. The principal stresses were quantified at critical section according to equation (2). The required shear reinforcement area was subsequently designed.
\[ \sigma_{1,2} = \frac{\sigma_x}{2} \pm \sqrt{\left(\frac{\sigma_x}{2}\right)^2 + \tau_{xy}^2} \]

(2)

Where \( \sigma_{1,2} \) is principal stress, \( \sigma_x \) is normal stress in longitudinal direction and \( \tau_{xy} \) is shear stress.

Figure 12. Required shear reinforcement area according to Eurocode 2 (2020)

If the principal tensile stress \( \sigma_t \) from the design combination did not exceed value 75 % of the limit tensile stress in concrete 3.1 MPa, according to the design principles of the standards, the shear reinforcement was proposed as a four legged stirrup with a diameter of 10 mm and a spacing of 400 mm (7.86 cm²/m).

If the principal stress from the design combination was in range of 75–100 % of limit tensile stress 3.1 MPa, a four legged stirrup with a diameter of 10 mm and a spacing of 250 mm (12.57 cm²/m) was proposed.

If the principal stress from the design combination exceed the value of 3.1 MPa shear reinforcement were designed according to equation 2 and 3. Evaluated shear reinforcement are presented in table 6. Comparison of shear reinforcement cross-sectional area is provided in figure 13.

\[ A_{sw} = \frac{b_w(\sigma_t-0.2\sigma_{1,max})}{f_{ywk}} \]

(3)

Where \( A_{sw} \) is shear reinforcement area per meter, \( \sigma_t \) is principal tensile stress, \( f_{ywk} \) is characteristic yield strength, \( \sigma_{1,max} \) is limit tensile stress (3.1 MPa) and \( b_w = 0.5 \) m is a web width of the box-girder section.

Table 6. Required shear reinforcement area

| Section | Distance [m] | EC 2020 Asw req [cm²/m] | EC 2010 Asw req [cm²/m] | STN 731251 Asw req [cm²/m] | ČSN 736203 amendment A Asw req [cm²/m] | ČSN 736203 Asw req [cm²/m] |
|---------|-------------|---------------------------|--------------------------|----------------------------|----------------------------------------|----------------------------|
| 1       | 8.875       | 24.3                      | 23.7                     | 7.86                       | 7.86                                   | 7.86                       |
| 2       | 26.875      | 14.1                      | 13.9                     | 7.86                       | 7.86                                   | 7.86                       |
| 3       | 37.875      | 18.6                      | 17.7                     | 7.86                       | 7.86                                   | 7.86                       |
| 4       | 42.415      | 24.5                      | 21.8                     | 33.96                      | 29.67                                  | 29.67                      |
| 5       | 57.125      | 18.0                      | 17.4                     | 7.86                       | 7.86                                   | 7.86                       |
According to STN and ČSN standards, in sections 1, 2, 3, and 5, the shear reinforcement is designed according to the prescribed detailing principles, because principal tensile stress is lower than limit tensile stress. According to Eurocode in all sections, the shear reinforcement is directly proportional to the magnitude of the shear forces. Therefore, in these sections, the ČSN and STN standards do not meet the level of Eurocode reliability significantly. In section 4, according to ČSN and STN, the reinforcement is designed from principal stress. This approach requires in section 4 a larger amount of reinforcement than the Eurocode and meets the requirement of the currently valid standard.

7. Conclusions

The results show that, previous standards considered the interaction and influence of concrete on the shear transfer and resistance. They required a significantly less need for shear reinforcement before reaching the stress limit value of 3.1 MPa for B500 concrete (C35/45). The designed reinforcement represented only the prescribed detailing principles. The change occurs when the tensile principle stress exceeds 3.1 MPa. Here, the calculation method according to STN and ČSN is changed and the reinforcement is designed to principal stresses reduced by 20% of the tensile strength of the concrete. On the contrary, this method exceeds the required shear reinforcement compared to the Eurocode. It can therefore be stated that the reinforcement calculated for the principal stress meets the requirements of the Eurocode 2 or are approximately at a comparable level. If the reinforcement was not evaluated from the principal stress, only the prescribed detailing principles were used. Therefore, there are sections in the structure, where the current reliability of the Eurocode are not met significantly.

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