Practical experiences with the strengthening prestressed bridges using prestressed CFRP strips

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Summary

Many bridges in Europe were built after World War II (WWII) in the 1950s till 1970s. The condition of these bridges is quite bad. The biggest problem with bridges is the actual state of prestressing - whether the ducts are injected or not and whether prestressing steels corrode or not. Some of these bridges, if are in an emergency state, must be demolished and replaced with new ones. However, if the ducts are injected and the prestressing steel does not corrode, it can mostly be repaired or strengthened to meet the currently valid standards. The paper deals with the diagnosis and strengthening four similar railway bridges using reinforcement with prestressed CFRP strips. The use of only glued strips for the structure is already a relatively common method of strengthening the elements of structures and bridges, but the use of prestressed CFRP strips is still considered a relatively new method of strengthening bridges, which is not yet widespread.

1 INTRODUCTION

Bridges are an essential and important part of the transport infrastructure (road and railway network). Therefore, it is necessary to keep them in operation. It is important not only to build new bridge structures as part of the new transport infrastructure, but also to maintain the existing infrastructure, including existing bridges.

In the northern part of Slovakia, in central Europe, within the Carpathian Mountains, the High Tatras are relatively well-known. They are known for tourism in the summer and skiing in the winter. For this reason, the construction of a narrow-gauge railway began at the end of the 19th century.

The High Tatras have been connected by ecological transport since 1908, when the Tatra Electric Railways (TER) began to be used. TER is single-track narrow-gauge electrified railway. In 1970, the transport was also added by the cogwheel railway, which became one of the three main attractions in the High Tatras. During its existence, it transported more than 16 million passengers. Its modernization, together with the Tatra Electric Railway (TER), creates a solid foundation for an integrated transport system and is crucial in terms of sustainability and the environment in such an important region of Slovakia as the High Tatras.

The paper deals with the reconstruction of 4 bridge structures within the Tatra Electric Railway. Due to the reconstruction of the line, it was necessary to diagnose and recalculate these structures.

2 DESCRIPTION OF BRIDGES AND SITUATION

In November 2020, diagnostics of 3 bridges on the Štrba - Štrbské Pleso cogwheel railway line were carried out. The railway line is 4.75 km long. Mentioned bridges at km 0.435 (bridge n. 1), 1.674 km (bridge n. 2), and 3.282 km (bridge n. 3) (see Fig. 1) were built approximately in 1968-1969 as part of the reconstruction of the railway line. So these are approximately 56-year-old bridges. In 2020, the railway line was renovated and the type of trains was also changed [1-2].

A year later, in November 2021, the inspection and diagnostics of the fourth (last presented) bridge structure was carried out. This bridge object is located on the Štrbské Pleso - Starý Smokovec - Poprad-

Tatry railway line (see Fig. 1(d)). Its age is the same as the three previous bridges. It is located on a railway line that has not been reconstructed, but the need for diagnostics and recalculation of load-carrying capacity arose because it will be loaded with the same new, larger load as the previous bridges.

A visual inspection was carried out and the material and geometric characteristics were verified as part of the diagnostics. Subsequently, calculations of the objects were carried out - determination of the load-carrying capacity of the bridges [3-8]. Due to the new load (new and heavier type of train and a new railway roadway), the reusing of the existing bridges was verified.

a) b) c) d)

Fig. 1 A view on bridges – bridge n. 1 (a), bridge n. 2 (b), bridge n. 3 (c), and bridge n. 4 (d)

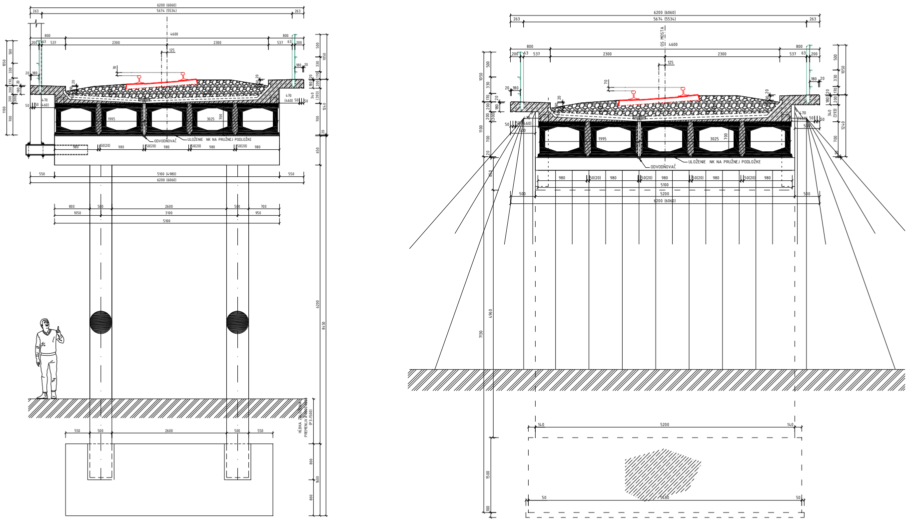
All 4 bridges were made in a similar way and from precast prestressed post-tensioned beams with denotation (type) KA 61 [9]. The first three bridges are of three single spans, the last bridge n. 4 is a 6-span bridge. In the ground plan view, the first and fourth bridges are in an arc, the second and third bridges are straight. The first three bridges are in a longitudinal slope, the fourth bridge is approximately horizontal. In the transverse direction, the beams are not coupled by a composite slab, but static perform as a “curtain slab” – there are longitudinal hinge connections between beams. The peculiarity is that these are the prefabricated beams intended for road bridges, they were not typically used for railway bridges.

In cross-section, each bridge structure consists of five KA 61 beams. The length of the beams and thus the spans of the individual bridge spans are different. Bridge n. 1 has a girders length of 19.6 m in each span, which means the theoretical lenght of each span is 19.0 m. Bridge n. 2 has beams of 10.6 m in the first span (theoretical lenght is 10.0 m) and then two spans of beams of 13.6 m (theoretical lenghts are 13.0 m). Bridge n. 3 has three different girder lengths of 13.6 m + 19. 6 m + 16 .6 m, which represents the theoretical lenghts of the individual spans of 13.0 m + 19.0 m +16.0 m. The last fourth bridge has 6 identical spans with a beams length of 16.6 m with theoretical lengths of 16.0 m.

The KA 61 beams have a box-girder cross-section and were additionally prestressed. The heights of the beams are different for each length.

A typical cross-section of a bridge structures is shown in Fig. 2 - in this case it is bridge n. 4.

The bridges are supported perpendicular to the track (line) axis on the outer two abutments and intermediate pillars. The pillars are made up of two or three vertical columns and a bridge cap in the upper part - they are frame structures.The bridge objects overpasses roads.



a) b)

Fig. 2 The typical cross-section - e.g. bridge n. 4 - in the place of a pillar (a), in the place of an abutment (b)

3 DIAGNOSTICS OF EXISTING BRIDGES

During the diagnostics of all bridges, the non-destructive tests (NDT) and the semi-destructive tests (SDT) of concrete, the depth of carbonization and identification of type of used reinforcement and prestressing steel, were performed [10,11]. The geometric characteristics (dimensions) were verified. The content of chloride ions was also verified since it is the railway bridge over the roads.

The precast prestressed beams KA 61 were made of concrete of class C35/45 according to the NDT using the Schmidt hammer - NDT confirmed the assumption of the concrete class given in [9]. Only a Schmidt hammer tester (NDT) was used to determine the concrete class of the beams, because it was not possible to make the core bores (drilling) in the concrete of the beams due to the small dimensions of the beams' walls and slabs (cross section). According to the original documentation [9], the pre-tensioning was additionally made of cables composed of smooth wires ϕ 4.5 mm (in numbers 6 to 12) – that fact was also confirmed by diagnostics. The injection of cable ducts was also verified - in all cases, the cable ducts were injected, which was good and heartening news.

The pillars' bridge caps and columns were made of concrete of class C25/30. The abutments' caps and basic blocks were made of concrete only of class C12/15. The quality of pillars' and abutments' concrete classes were determined on cylindrical bores and verified by the Schmidt hammer. All the members were reinforced by reinforcement type 10 400 (A III, fyk = 400 MPa) - designation according to new Eurocodes is B 400B. The reinforcement position and their axial distances were scanned. The concrete cover was in the range of 25 - 30 mm. The depth of concrete carbonation was measured and reached a value of 2 to 5 mm on the beams. In the case of piers' caps and columns, the measured value was 10 - 15 mm. After recalculating the content of chloride ions Cl^- to the expected amount of cement mass used in the production of concrete, it emerged that the content of chloride ions Cl^-/mc was for all the samples below the critical value for reinforced concrete (RC) structures (C_{crit} = 0.4.Cl^-/ m_c) and prestressed concrete (PC) structures (C_{crit} = 0.2.Cl^-/ m_c – additionally prestressed concrete) [12].

The diagnostics was focused on both the superstructure and substructure of all bridges. The condition of the bridge structures was very similar, which was to be expected given the same construction period, the same structural design and the same environment to which they were exposed. For this reason, the same identified shortcomings can be formulated for all bridges:

- Superstructure (Fig. 3 a - d):

- water leakage between beams,
- the surface treatment that has been done recently has locally fallen off,
- locally fallen off concrete cover layer at the stirrups,

- the load-bearing structure is only slightly twisted at the edges of the bridge structure at the places of damage to the ledge,

- cracks were visible in the places of the cable ducts from the lower side of the beams, from where the water also flowed locally (wet places),

- concrete leaches from some cracks (local formation of drops and incrustation),

- the reinforcement (stirrups) shows a slight corrosion, the prestressing steel was detected in three places, but no corrosion of the prestressing reinforcement was detected and there was found that the cable ducts were injected,

- the cement mortar between the beams was damaged, the joints were leaking, the joints fall out in places,

- the girders in span no. 4 were (bridge n. 4) slightly damaged (edges) from road vehicles due to the low ground clearance,

- the joint between girders and cornices - longitudinal cracks were detected between the edge girders and cornices in the longitudinal direction in each field, some of which were leaking water and leaching.

a) b) c) d)

Fig. 3 The deterioration of the bridges – leakage between beams and leakage through the expansion joints on the abutment cap (a), leakage through the expansion joints on the pier cap and corrosion of the beams´ stirrups (b), the girders in span no. 4 of bridge n. 4 were slightly damaged (edges) from road vehicles (c), and detail of pillar bridge cup with cracks and with spalled of surface treatment and concrete cover layer (d).

- Substructure - abutments (Fig. 3 a):

- the abutments were in a relatively good condition,

- there is considerable leakage through the expansion joints, and the cover layer was damaged locally,

- there were nets of vertical and horizontal surface cracks on the abutments,

- no corrosion of the reinforcement of the abutments´ bridge cups, or the wing wall has been detected.

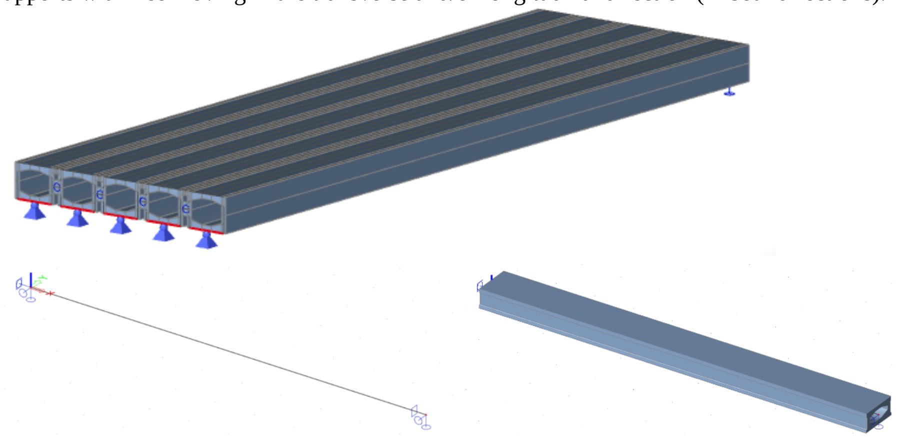
- Substructure - pillars (Fig. 3 b,d):

- the bridge cups of the pillars were leaked,
- the joints in supporting of girders were slightly crumbled,
- locally, the concrete cover and surface treatment fell off, corrosion of the reinforcement was detected in those places,
- a significant number of horizontal and vertical cracks in the bridge cups were found (mainly horizontal),
- there were no surface cracks in the vertical columns of the pillars, no corrosion of the reinforcement was found.

4 LOAD-CARRYING CAPACITY CALCULATION

After the diagnostics, the bridge structures were recalculated to verify the load-carrying capacity of all bridges. The recalculation was necessary due to the use of the new Stadler GTW 2/6 train sets, which have greater axle forces and their shorter distance than the original load that previously provided traffic (EMU series 425.95).

In the case of bridges n. 1, n. 3 and n. 4, the 3D numerical models created in the Scia Engineer software [13] were used. The cross-section was modeled as a whole and individual box-girder cross-section beams were modeled using a slab-wall model. This means that the cross-sections of the individual beams of the type KA 61 were modeled using the two slabs simulating the upper and lower slab of the cross-section of the beam (slabs with hunches) th. 0.10 m and two vertical edge walls th. 0.10 m, which together form the box-girder cross-section of the precast prestressed beams (see Fig. 4 (a)). In the transverse direction, the beams (box-girders) were connected in the middle of their height using hinges (curtain slab) by means of a horizontal plate simulating a concrete grout between the beams. The supporting of the beams respects the assumptions of the static scheme - in the longitudinal direction a simple beam, in the transverse direction the joints were released by a combination of one hinge support and supports with free moving in the transverse and/or longitudinal direction (in both directions).



a)

b)

Fig. 4 The numerical models of the bridges - 3D FEM model of the bridge superstructure of bridges n. 1, 3, and 4 (a), simplified model of one beam for bridge n. 2 (b)

A simple model based on the assumption of uniform distribution of all the loads on all the beams was used in the case of bridge n. 2 (see Fig. 4 (b)) - then it was enough to model only one beam as a member. This simplified model was used to compare both types of models. Of course, in this case we got more conservative (larger) values of internal forces, which were less representative of the real behaviour. The input data about the materials and geometries were taken from [9]. Since these are 3-single span bridges (bridges n. 1-3) or 6-single (separate) span bridge (bridge n. 4), only one independent span had to be modeled (see Fig. 4). However, due to the different lengths of the beams, it was necessary to model and investigate a total of 4 independent spans of theoretical lengths 10.0m, 13.0 m, 16.0 m and 19.0 m. The calculation was performed for the superstructure and the substructure (pillars).

The load-bearing structure was assessed for moment resistance, shear resistance and stresses limitation (concrete in compression, concrete in tension (decompression condition) and steel cables in tension). Since the original superstructure was not designed and verified for the railway load of UIC 71, but was designed and verified directly for a special train (for that reason the prestressed beams for roads were used, which would not be suitable for the load of UIC 71), elements were insufficient and the load-carrying capacity was less than 1.0 in all cases. Therefore, it was necessary to recalculate the passage of the used Stadler GTW 2/6 train. The calculations showed that:

• superstructure:

- beams of a length of 19.6 m and 16.6 m (all spans where they were used) are not suitable for transit (new loads given by the GTW2 / 6 EMU - OŽ 1000 train) due to the tensile stresses in concrete at the bottom edge of the cross-section - those lengths of beams were used in all four bridges,

• substructure:

- piers caps are not suitable for transit (new loads),
- pillar columns are not suitable for transit (new loads).

The results show that in the case of beams, the serviceability limit state (SLS) condition - decompression was not fulfilled. There was a risk of tensile stresses ocuring and subsequent cracking. In the case of substructure (pillars), the ultimate limit state (ULS) was not fulfilled either.

Diagnostics and recalculation have shown that the bridges can be repaired to the level required by current standards (Eurocodes [14]) and regulations, with the necessary funds. The condition of the bridge objects was not so wrong that they had to be replaced with new bridge objects (demolish the existing ones and replace them with new ones). It was shown that it is enough to strengthen the beams and pillars (bridge cups) so that the tensile stresses would not arise in the concrete (the only unsatisfactory condition) [15-20].

5 STRENGTHENING BRIDGES

The design concept of strengthening had to take into account some criteria such as excluding concreting (wet process), speed of application of strengthening and work during the reconstruction of the railway roadway. Replacing the existing bridges with new ones was not possible, since the reconstruction of the entire railway line was already underway - demolishing the existing bridges, designing and subsequently building new bridges would take a lot of time. The reconstruction (strengthening the bridges) also had to respect the investor's request that "wet processes" could not be used - concreting from the upper side of the bridges. So it was not even possible to complete a new layer of concrete that would be composite with the original structure (original beams), thus obtaining a more resistant cross-section. Concreting was allowed only from the lower side of the bridges and on the pillars. Therefore, the only two methods of strengthening appeared to be strengthening with prestressing external cables or using the prestressed CFRP strips.

The use of prestressing cables was problematic in this case, since there were no monolithic transverse beams between the individual fields to which they would be anchored. They would have to be anchored using steel anchor blocks from the lower edge of the beams, which, given the expected dimensions of the steel blocks and cables, would have meant a greater impact on the underpass height, which was limited. Therefore, it seemed best to use prestressed CFRP strips, which were finally designed. This is still a relatively new technology that has not yet been used on bridges in practice. It was the first use of this technology in Central Europe.

The design required the use of two Sika CarboDur Type S626 strips per beam with a force of 140 to 170 kN depending on the beam type (length). The cross-section of the strips is 60x2.6 mm with a characteristic strength of 2800 MPa, modulus of elasticity 165 GPa and limit strains 1.70%. The strips could not be used for the maximum possible force (approx. 240 kN) due to the anchoring, so the prestressing level is approximately 58 to 70%. The prestressing force was applied with a hand-held hydraulic press. Due to the relatively small thickness of the box-girder bottom slab (100-120 mm), it was not possible to use certified anchoring for maximum use, but anchoring using steel bond anchors from Hilty had to be designed. Compressive stresses were inserted to the cross section using prestressed CFRP strips, which eliminated tensile stresses.

In the case of pillars, the strengthening was designed so that the space between the columns and bridge caps was filled with a solid wall (bridges n. 1-3), or a wall with an opening (bridge n. 4) for better light transmission of the space under bridge. The photos after the reconstruction are shown in Fig. 5.

a)

b)

c)

d)

Fig. 5 The bridges after strengthening – side view of bridge n. 2 after reconstruction (a), bottom view of the structure and CFRP strips and anchorage (b), detail of CFRP strips anchoring - bridge n. 2 (c), and view of the strengthened bridge n. 4 (d).

6 CONCLUSIONS

Result of diagnostics and recalculation of four bridges on the railway line between Štrba - Štrbské Pleso and Starý Smokovec in northern part of Slovakia are shown in this paper. The bridge objects were diagnosed as a part of modernization of the railway lines and their possible reusing was verified. The results of diagnostics and calculation have shown that the bridge objects were in a satisfactory state (condition), but it did not satisfy the load-carrying capacity to the new type of train (new load).

In order to be able to continue to use objects, strengthening of all bridges was designed. The best and fastest method of strengthening was shown to be the use of prestressed CFRP strips. This is a relatively still little used method of strengthening bridges. In this case, it was a unique and first use in Central Europe. We believe that in this case it was the best conceptual design considering the speed of application and minimizing the intervention in the cross section.

The first three bridges were strengthened in 2022, the last bridge n. 4 was strengthened in 2023, so the bridges are more than 1.5 to 2.5 years in service after strengthening. No unexpected behavior has been recorded on the bridges yet, so the strengthening method is assumed to be correct for now. The behavior of the bridges was also verified using proof-load tests after reconstruction.

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