STRENGTHENING OF EXISTING ROAD BRIDGES WITH EXTERNAL POST – TENSIONING

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ABSTRACT

Assessment and rehabilitation of existing bridges, and concrete structures in general, has become an important issue for civil engineers nowadays. There are several factors causing structural deterioration of bridges. Along with aggressive environment and ageing of material, bridges are exposed to increasing traffic loads, due to rapid growth in volume and weight of heavy vehicles. Furthermore, more than fifty percent of bridges in the region are more than forty years old and designed with previous design standards, which increases the need for strengthening. Among the various methods for increasing capacity of existing bridges available today, external post-tensioning provides very efficient solutions for small and medium span bridges, because of the speed of construction and minimal disruption to traffic flow. Scope of this paper is to give an insight on external PT technique and its application in retrofitting and strengthening of existing bridges. Case studies of assessment and repairing of two bridges in the region using external PT will be presented. There are several design, detailing, durability and construction issues that need to be considered with special care when designing an external PT system. Anchorage zones and deviators should be carefully designed and detailed to ensure transfer of forces to concrete. Furthermore, effects of the new forces introduced to the system must be carefully evaluated, as they depend on condition of existing bridge.

Keywords: external post – tensioning, existing bridges, strengthening, traffic assessment, deviators

1. Introduction

Rehabilitation of existing structures presents an important figure in the field of civil engineering nowadays. As integral parts of road and infrastructure systems, bridges must be safe for their users and economic in terms of maintenance and repair. More than fifty percent of existing road bridges in the region are forty or more years old, designed with old codes and guidelines accordingly. Introduction of the new traffic load models, along with the steady increase in weight and the volume of traffic on the road systems in the region over last few years, has caused many existing bridges to carry traffic loads much higher than the ones in their original design. Furthermore, exposure to aggressive environment and ageing of materials, additionally contributes to deterioration of the bridge structure. As imposing a traffic weight restriction on these bridges is not economical solution, various methods of strengthening and rehabilitation are available (Xanthakos 1996) in order to increase structural capacity of the system or to resolve an existing deficiency. Two methods, proved to be very useful applied to short and medium span bridges, are plate bonding (either fibre reinforced plastic (FRP) laminates or steel plates) and external post - tensioning (Daly & Witarnawan 2000). Purpose of this paper is to provide an insight on application of external post - tensioning in bridge strengthening, demonstrated through a case study for two existing road bridges in the region. Detailed assessment of the bridge is required to determine its condition in order to estimate the need for structural repair or strengthening, as there is no formal design code or guidelines in Croatia. Number of factors must be considered in evaluation, including type of structure, required amount of strengthening and the associated costs. Also, the importance of the bridges as a part of international road systems must be taken into account, as closing the traffic always causes additional expenses. These aspects highlighted the need for quick, simple and economically convenient strengthening technique.

External post – tensioning for bridges has been used since the 1950s, at the beginning only for designing new bridges, but over time, it became considered as one of most powerful techniques for structural strengthening and rehabilitation. (Suntharavadivel & Aravinthan 2005)

2. External post – tensioning as a strengthening technique

Strengthening systems can be divided into two categories: *passive* and *active systems.* Passive systems do not introduce forces to the structure or its components, such as are addition of the structural elements or enlargement of the cross sections. Active systems, on the other hand, involve the introduction of external forces to the structural elements in order to increase structure capacity (Alkhrdaji & Thomas 2009). Strengthening by external post – tensioning is simply the application of an axial load combined with a hogging bending moment, using high strength cables, to improve the flexural and/or shear capacity of a structural beam. It also can be used to improve serviceability, reducing deflections and vibrations by increasing the stiffness of the structure. Changing of the structural behavior can also be achieved with external PT, for example, to provide continuity across a support and to change series of simply supported spans into continuous one. This technique is mainly used for strengthening in longitudinal direction to increase flexural capacity of a structure, and its application has been studied in detail by researches and used in many bridges around the world. It is also possible to use external PT for strengthening in transverse and vertical directions (Daly & Witarnawan 2000), shown in Figure 1. However, studies and application of external PT on shear strengthening have been limited, and future research is required in this area, mainly because shear capacity of element with external tendons is difficult to determine. Additional experimental studies revealed significant effect of shear cracks, where strengthening is only effective if existing cracks are properly repaired by a suitable technique prior to post - tensioning. (Aravinthan 2006)

Principal characteristics of external post-tensioning are:

- Prestressing tendons are located outside of the concrete cross section
- Prestressing force is transferred to concrete by means of end anchorages, deviators and saddles.

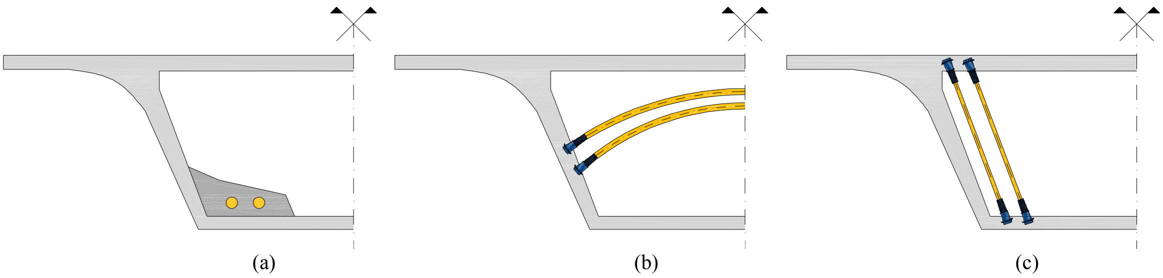

Fig. 1. External Prestressing of a box girder bridge: a) Longitudinal; b) Transverse; c) Vertical

Main advantages of external PT over other strengthening techniques are:

- It can be used on a wide range of bridges – short and medium, even long span bridges, not depending on a material (concrete steel, timber etc.), and it can be applied on different systems, mainly on a beam and truss bridge types.
- Economical construction – tendons can be applied on a bridge without severe traffic restrictions; equipment is light and easy to use.
- Increasing of dead load of a structure can be neglected.
- Monitoring and maintenance – as tendons are placed outside of concrete section, inspections, additional tensioning and eventual replacement are easily conducted.
- Easy and short installation, simple tendon layout, does not affect existing bridge aesthetics.

3. Design and detailing of externally post – tensioned system

There are several design, detailing, durability and construction issues that need to be considered with special care when designing an external PT system. Tendons, being external, are more subjected to corrosion and other impacts, so they are often placed inside ducts filled with grouting for protection. Prestressing force is transferred into structures trough end-anchorages and deviators, causing high stress distribution in these sections. These sections are also critical because proposed tendon lay-out, determined from design criteria, is achieved through them, so they must be carefully inspected and evaluated. Furthermore, deviators and anchorages must be designed to ensure corrosion protection for tendons, and to enable visual inspections, additional prestressing or even replacement of tendons. Tendons can be anchored at different parts of structure, in end blocks, diaphragms, on webs or on flanges, depending on the tendon lay-out, amount of prestressing force, material and structural system of the bridge. Reinforced concrete blocks, or custom steel anchorages are most commonly used when strengthening the existing bridges. Drilling trough or welding existing structural components to steel webs or concrete webs or flanges is required, causing high stresses on already under – strength bridges, so local stiffeners may be required at anchorages and deviators zones. (Daly & Woodward 2004). Deviators and anchorages are generally made of reinforced concrete or steel. Concrete deviators are used mainly in box girder bridges (Figure 2), and due to concrete characteristics are more commonly used in design of new externally prestressed bridges, than strengthening of existing ones.

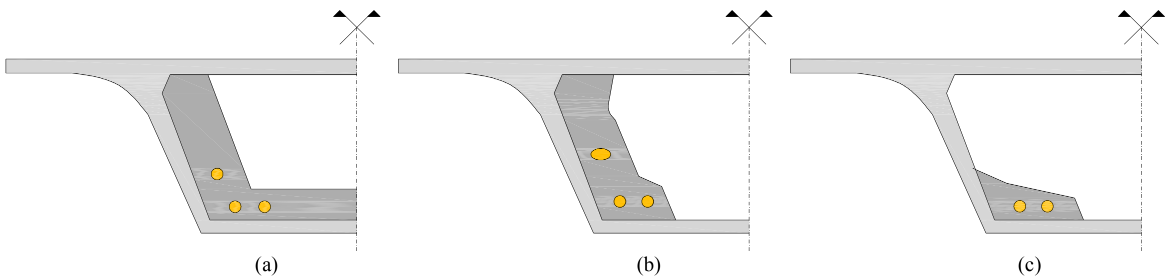

Fig. 2. Types of reinforced concrete deviators: a) Diaphragm; b) Rib or stiffener; c) Saddle or block

Steel deviators are more often used in strengthening, due to easier attachment to existing structure, lower selfweight, and simpler inspection. Design of steel deviators depends on specific bridge, but they generally consist of steel plates welded or bolted to the structure, depending on bridge material. Steel tube is welded to the plate, with piece of polyethylene pipe placed inside the tube to protect the tendon from damaging. Generally, three types of anchoring techniques are used in existing bridges: End – anchor blocks, bonded anchor blocks and diaphragm anchoring. End anchor blocks are reinforced or prestressed concrete blocks or cross beams constructed at the end of the beam (Figure 3a). If there is already cross beam it is possible to thicken it with additional concrete in order to transfer prestressing force to structure. Bonded anchor blocks are attached to webs or flanges of existing bridge and can be made with cast in place concrete, or wit steel elements attached with bolts or welding. Depending on the materials, friction between two surfaces must be carefully calculated to take into accounts prestressing losses.

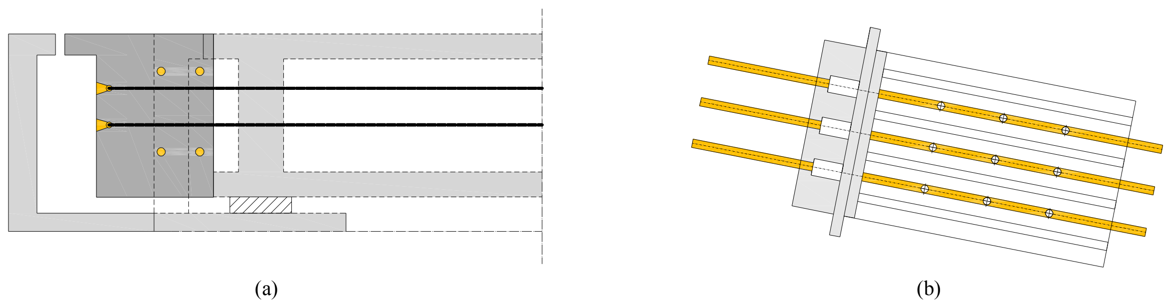

Fig. 3. Types of anchor blocks: a) End prestressed concrete block; b) Bonded steel block

If existing structure web or flanges are not sufficient to transfer external force, they can be strengthened with local stiffeners or transverse prestressing. Steel bonded anchor block, attached to web with bolts is shown on Figure 3b (Daly & Woodward 2004). If there are existing diaphragms on a bridge, tendons can be anchored directly to them. Special evaluation of diaphragms is necessary to determine their strength and effect of drilling and prestressing force introduced in the structure. Finite element method analysis of local model is proposed for diaphragm evaluation, along with inspection of connection between diaphragm and bridge deck. Critical diaphragms can be additionally strengthened by vertical or transverse prestressing, or with local stiffeners. If there are no existing diaphragms, new ones can be constructed.

4. Case study 1 – Obod Bridge

4.1 Geometry and materials

Obod Bridge (Šavor 1963) is a reinforced concrete road bridge, constructed monolithically on wooden scaffolding more than fifty years ago. It is located on a road between Dubrovnik and Kotor, and follows a complex road axis geometry comprising of horizontal and vertical curves. Total width of the superstructure is 8.4 m, with two way lane 7 m wide and sidewalks of 0.5 m. Road cross fall at bridge amounts 3.1 %.

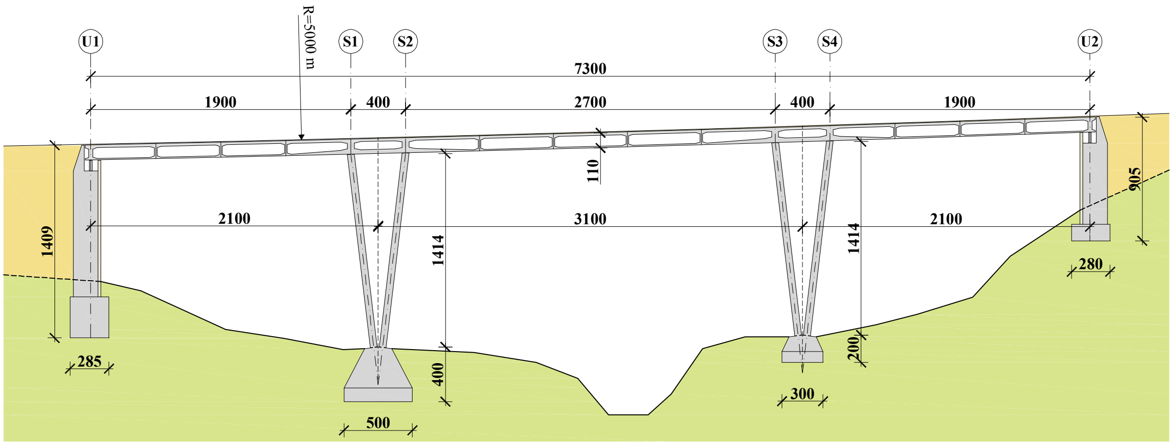

Fig. 4. Longitudinal section of Obod Bridge

The bridge deck is a reinforced concrete voided slab 1.1 m deep with 8 voids (80/80cm) in cross section and variable bottom slab depth. Cross beams in spans are 20 cm thick, at abutments 30 cm and at piers 50 cm thick. Distance between cross beams in end spans amounts 4.75 m and in middle span 5.40 m. This type of cross section has a great torsional stiffness. Bridge deck is supported by V-shaped pier bents and concrete hinge bearings at abutments which altogether form a hinged strut frame bridge with spans of 19+4+27+4+19=75 m (Figures 4 and 5).

Fig. 5. View of Obod Bridge

Reinforced concrete V-shaped pier bents consists 4 piers of a constant depth (50 cm) and variable width (1 m at the bottom and 2 m at the top of the pier), supported with a single foundation. The bridge was designed according to the 1960's design codes based on the static analysis performed by the classical elasticity theory. Bridge dead loads, live traffic loads, shrinkage and temperature effects and wind loads with no seismic actions were taken into the account. The concrete quality used in the calculation is equal to C 20/25 based on Eurocode, and reinforcing steel quality was S220 B.

4.2 Assessment due to traffic demands

The numerical model of the bridge, developed in *Sofistik* software, is made of beam elements of the deck and piers, concrete hinged bearings at abutments, hinged top and fixed support points of piers as the bridge is founded on a sound rock. Cross sections of the bridge were defined with their actual built-in reinforcement (Figure 6) and using materials according to characteristics defined in Eurocode.

Only permanent actions (self-weight, fixed equipment and road – surfacing) and traffic loads were taken into account. Although based on the research of the realistic traffic simulation of the todays' heaviest Croatian road traffic, adjustment factors α_{Q1}=0.8 and α_{Q2} = α_{q1} =0.78 of the European traffic load Model 1 may be used (Mandić et al. 2009), it was decided to assess this bridge additionally using pure European Model 1 without adjustment factors based on National Annex of a Croatian code HRN EN 1991-2: 2012/NA which attends to predict the future traffic demands on Croatian roads.

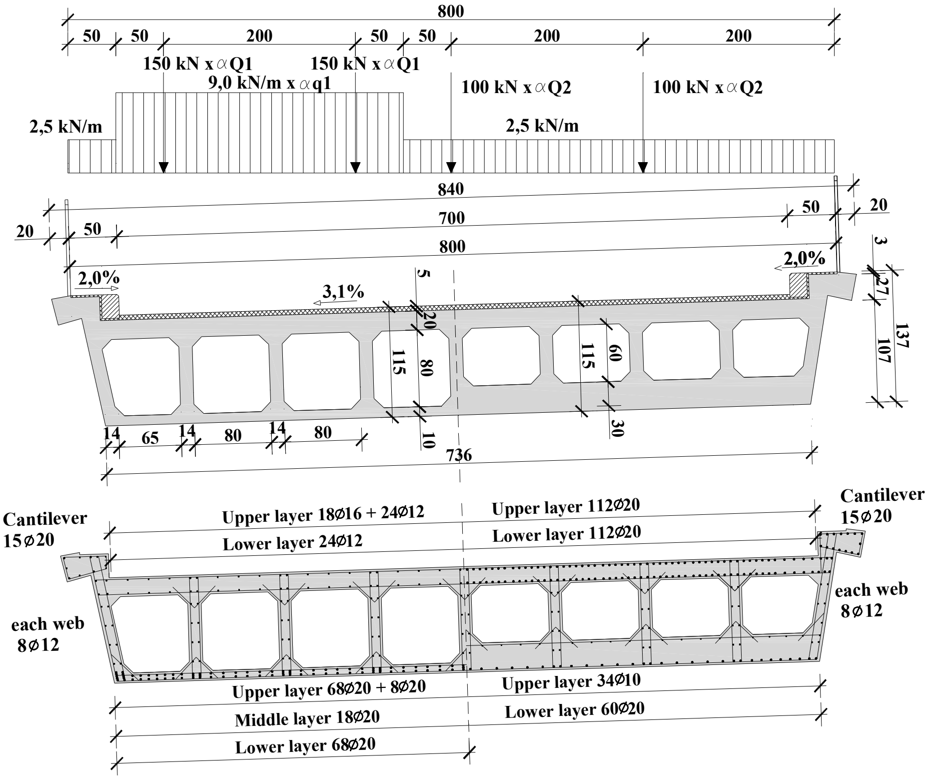

Fig. 6. Cross sections of Obod Bridge with built in reinforcement (left: in a middle span and right: over the piers) and the applied traffic load scheme.

Values of internal forces and moments are calculated in *Sofistik* software package and compared (Table 1) with resistances due to bending, shear and torsional effects calculated based on available reinforcement (Figure 6).

Table 1. Results of traffic load assessment – Obod Bridge

Bending resistance			Shear resistance		Torsional resistance		
$M_{Rd,s1,3}$	$M_{Rd,s2}$	$M_{Rd,sup2}$	$V_{Rd,sup1}$	$V_{Rd,sup2}$	$T_{Rd,1}$	$T_{Rd,2}$	$T_{Rd,3}$
Edge span	Middle span	Middle support	Edge support	Middle support	Concrete resistance	Transversal reinforcement	Longitudinal reinforcement
8853	9823	14668	2885	3352	10005	4395	15768
Bending moments			Shear forces		Maximal torsional moment		
$M_{Ed,s1,3}$	$M_{Ed,s2}$	$M_{Ed,sup2}$	$V_{Ed,sup1}$	$V_{Ed,sup2}$	T_{Ed}		
Realistic traffic simulation demands							
9666	10895	14398	2617	3918	1728		
HRN EN 1991-2 + National Application Document demands							
11052	12286	15940	2799	4080	2295		
Strengthening necessary							
YES	**YES**	**YES**	**NO**	**YES**	**NO**		

It is clear that the torsional stiffness of the bridge is adequate but bending and shear resistance are below required level and that the bridge would need strengthening in order to satisfy the current and future traffic requirements.

4.3 Strengthening overview

Strengthening with external prestressing using *Dywidag system* cables is proposed(Mandić - Ivanković et al. 2014; Radak 2013). After preliminary calculation where required number of cables was determined based on differences in bending moments and shear forces from Table 1, the complete calculation and design of strengthened bridge is conducted, including:

- Numbers of cables from the decompression condition at the section edges;
- Cables layout and losses of prestressing force due to friction, at anchorage and time dependent losses due to relaxation of steel;
- Design for ultimate limit states (design value of prestressing force, design for failure without announcement, design for bending with axial force, check of tensile stresses in concrete at the time of transfer, design for shear);
- Design for serviceability limit states (stresses range for rare load combination, limit state of decompression, limitation of concrete stress to $0.6f_{ck}$ for characteristic load combination and to $0.45f_{ck}$ for quasi-permanent load combination, crack control for frequent load combination, limitation of stress in prestressing cables to $0.65f_{pk}$ for characteristic load combination. (Mandić - Ivanković et al. 2014)

Figure 7 shows a schematic layout of the strengthening scheme (Radak 2013). Two Dywidag 6819 cables, composed of 19 strands are chosen, one on each side of the bridge deck. Additionally, two extra cables are proposed on top of every pier, in order to satisfy both ULS and SLS conditions. Layout of the cable (Figure 7) is defined based on bending moment diagram, to provide sufficient eccentricity in critical sections of the bridge. Anchorage zones and deviators are defined, made of steel plates and ducts, and connected to bridge deck with steel bolts. Partial reconstruction of abutment wall and wingwalls are necessary, in order to place hydraulic jacks and apply tensile force in cables.

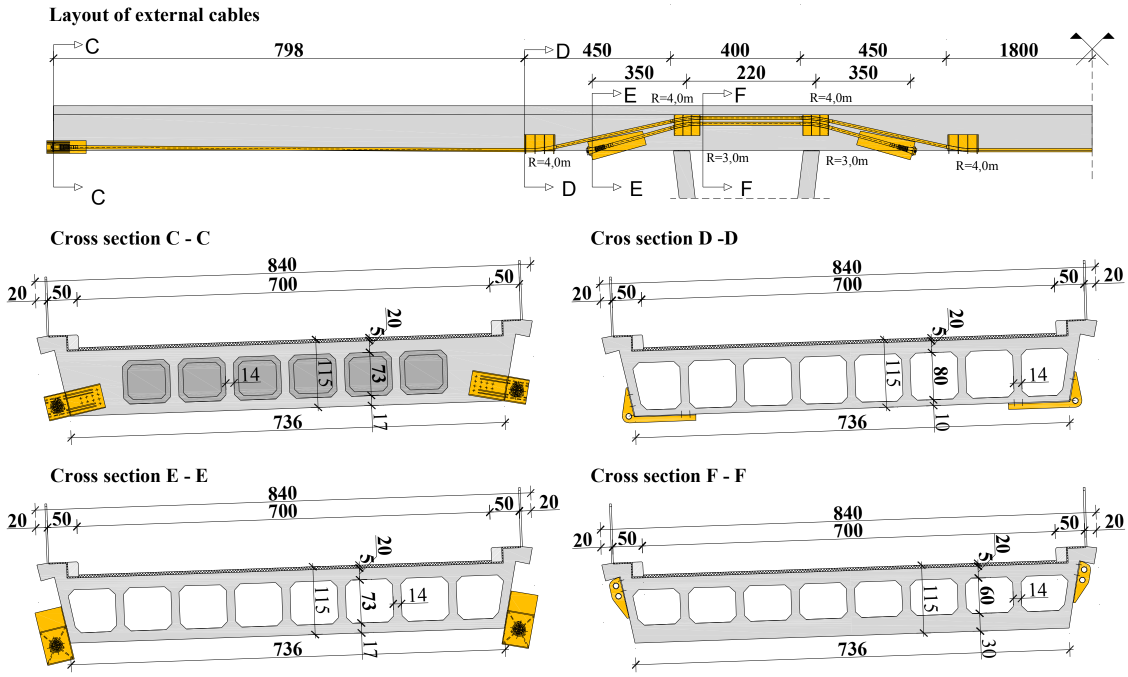

Fig. 7. Layout of external cables in longitudinal and cross sections of Obod Bridge

5. Case study 2 –Bridge over Morača River

5.1 Geometry and materials

Second bridge (Šram 2002) is located in Montenegro, on a road between cities of Podgorica and Kolašin, above Grlo canyon and Morača river. It is prestressed batter - post rigid frame bridge (Figure 8) consisting of three spans: 21.5+ 49.0 + 24.5 m. It was opened in 1963, constructed in two phases, combining monolithic and prefabricated methods. In the first phase cantilevers and angled piers on every side of the canyon were built monolithically on wooden scaffolding. Then, prefabricated prestressed girders, assembled on left bank, were placed in the middle span, using temporary portal cranes. Girders and cantilevers are connected with half–joints introduced into bridge deck, and continuity over supports is provided with additional tendons.

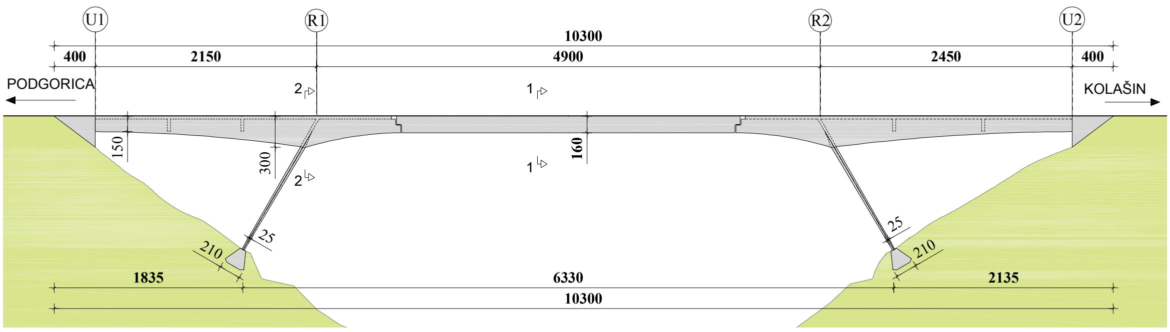

Fig. 8. Longitudinal section of "Morača" Bridge

Superstructure consists of four longitudinal prestressed girders, with height varying from 1.50 at abutments to 3.0 m above piers (Figure 9). Girders are supporting a reinforced concrete slab, 0.16 m thick, with total superstructure width of 8.8 m, consisting of two traffic lanes 7.0 m wide and sidewalks of 0.75

m on every side. Cross section of angled piers is varying from 0.25/0.5 at the bottom and 0.75/1.25 on the top. Bridge was post-tensioned in two phases, in the first one, four central span girders were post tensioned on a left bank of the river, with 28 tendons placed in a bottom, and 4 in the top flange of each girder. Each tendon was composed of 6 wires with a diameter of 7 mm. Additionally, girders were reinforced with 14 mm bars in the flanges and 10 mm bars in the web. In the second phase, concrete deck was post – tensioned with 50 tendons to provide continuity over supports. Tendons are same as in the flanges described above, and additional reinforcing bars with 14 mm diameter are added in both zones of the deck (Figure 9). Concrete quality is equal to C30/37 based on HRN EN 206-1:2006. Reinforcing steel quality is GA 220/340, while quality of steel used for post-tensioning is 1520/1352 N/mm^2.

5.2 Assessment due to traffic demands

Numerical model of the bridge is made in *Sofistik* software package, using the same methods as in the first case study bridge described above. Only permanent and traffic loads are assessed using European traffic load Model 1 with adjustment factor 0.8 for axle loads.

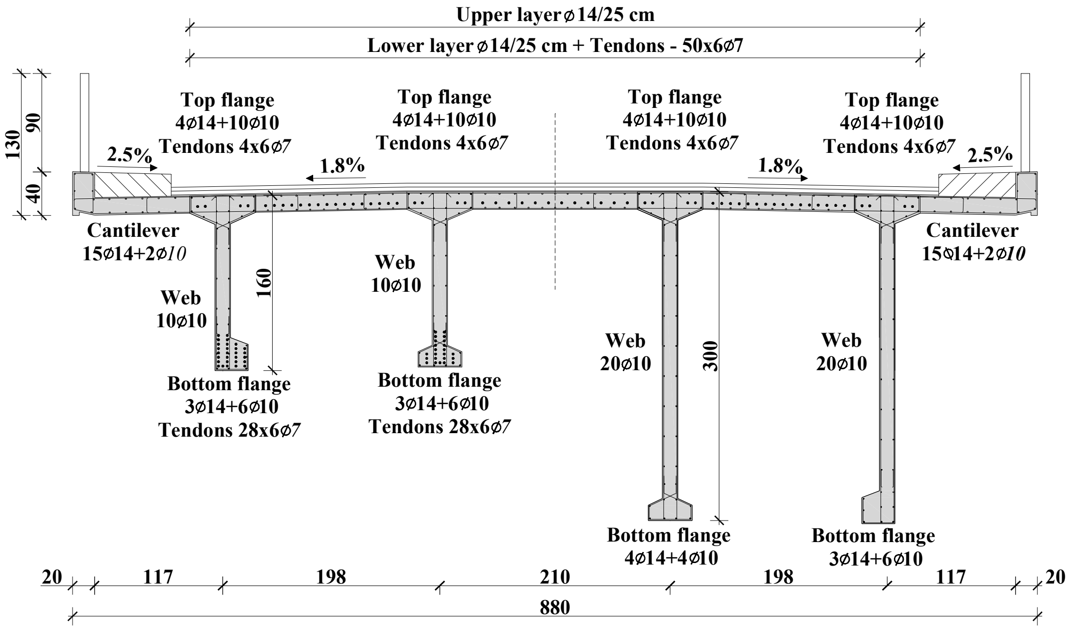

Fig. 9. Cross sections with built in reinforcement and tendons (left: middle span; right: above pier R1)

Table 2. Results of traffic load assessment – “Morača” Bridge

Bending resistance						Shear resistance					
Middle span			Support above pier R1			Support above pier R2			End support		
Edge girder	Middle girder	Cross section	Edge girder	Middle girder	Cross section	Edge girder	Middle girder	Cross section	Edge girder	Middle girder	Cross section
$M_{Rd,m,1}$	$M_{Rd,m,2}$	$M_{Rd,m,3}$	$M_{Rd,s,1}$	$M_{Rd,s,2}$	$M_{Rd,s,3}$	$V_{Rd,s,1}$	$V_{Rd,s,2}$	$V_{Rd,s,3}$	$V_{Rd,e,1}$	$V_{Rd,e,2}$	$V_{Rd,e,3}$
11610	9635	42491	10329	15221	51101	1115	1115	4460	466	466	1866
$M_{Ed,m,1}$	$M_{Ed,m,2}$	$M_{Ed,m,2}$	$M_{Ed,s,1}$	$M_{Ed,s,2}$	$M_{Ed,s,3}$	$V_{Ed,sup1}$	$V_{Ed,sup2}$	$V_{Ed,sup3}$	$V_{Ed,end,1}$	$V_{Ed,end,2}$	$V_{Ed,end,3}$
9072	6778	25368	17520	13649	49584	1966	1529	5567	942	614	2501
Strengthening necessary											
NO	**NO**	**NO**	**YES**	**NO**	**NO**	**YES**	**YES**	**YES**	**YES**	**YES**	**YES**

Results of traffic assessment, considering bending and shear, are shown in Table 2. It is clear that bending and shear resistances of a bridge are not sufficient for present and future load demands. Strengthening of bridge deck is required over supports, as middle span has adequate resistance due to bending moment.

5.3 Strengthening overview

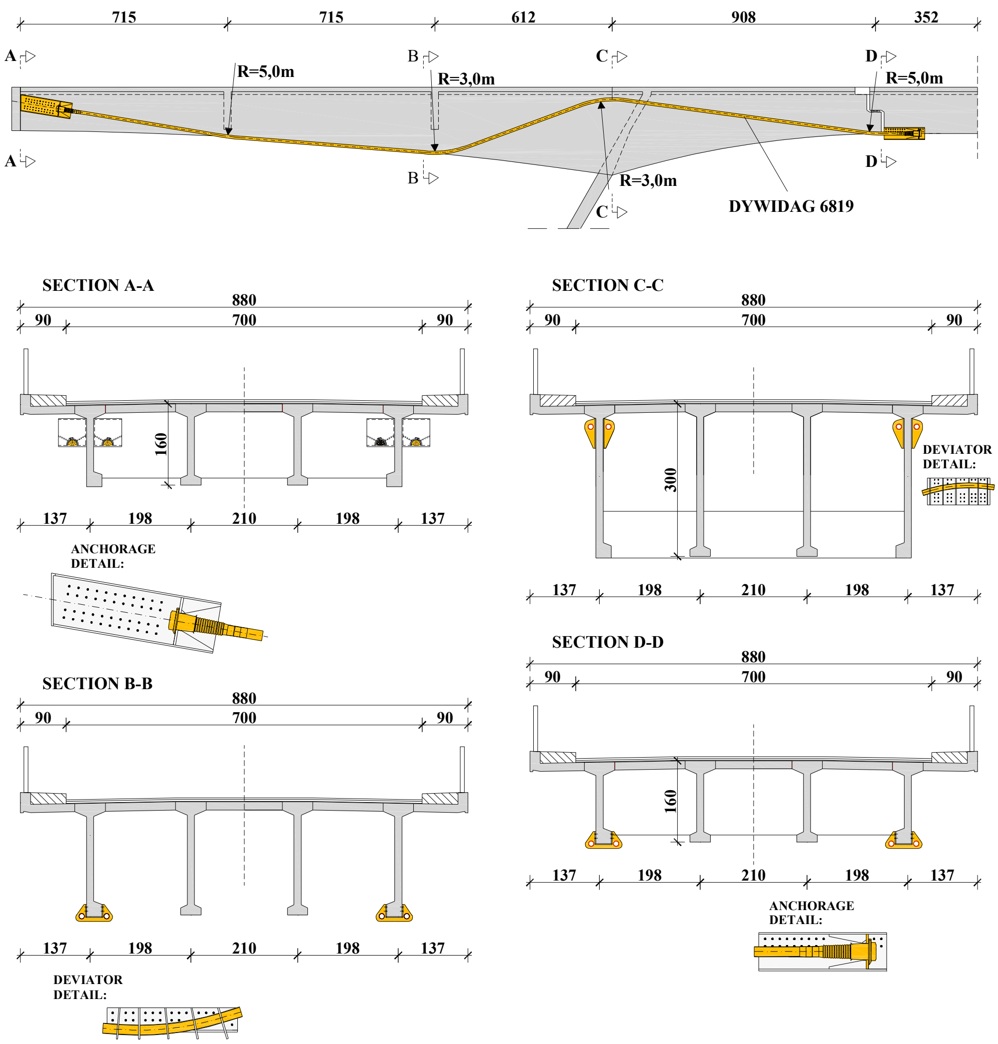

Fig. 10. - Layout of external cables in longitudinal and cross sections of "Morača" Bridge

Based on a preliminary calculation (Debelec 2015), two *Dywidag* tendons 6819 were chosen. Each is comprised of 19 strands, where area of every strand is 150 mm^2. Calculation process with same design considerations to those used for *Obod* Bridge is performed. Figure 10 shows schematic layout of the strengthening scheme, only for one edge span of the bridge, as other one is symmetrical. Four cables are proposed, two on each side of bridge deck. Additional calculations showed that prefabricated girders in the middle span are not able to withstand compressive stresses on bottom edge caused by external cables. As those girders have sufficient bending resistance (Table 2) and thus no need for strengthening, except to provide continuity over supports, cables are placed only in edge spans of the bridge. Dead end anchorages are located on the end of cantilever (Figure 10 – section D-D), with live anchorages on beginning of a bridge (Figure 10 – section A-A) where the force is applied on external cables. Layout of cables is defined with anchorages and deviators, made of steel plates and bolts adjusted to geometry and materials of a bridge. Calculation and details design for both bridges are not presented, due to its complexity and length.

6. Conclusions

Overview of existing bridge strengthening with external post - tensioning and its application on two case study bridges is presented in this paper. This technique can be used on wide range of bridges and is proved to be very efficient due to minimal traffic interruption, easier tendon layout and negligible self – weight. Assessment of two bridges in the region, due to current local and/or European traffic demands is presented. Obod Bridge, fifty years old reinforced concrete hinged strut frame bridge (with spans of 19+4+27+4+19=75 m) has adequate torsional stiffness, but strengthening is required to resist bending along the bridge length and shear at the pier support. Morača Bridge, prestressed batter - post rigid frame (with spans of 21.5+ 49.0 + 24.5 m) requires strengthening to resist bending at the pier support and shear at the end and the pier support. To compensate the differences in bending moments and shear forces the strengthening with external post-tensioning technique is proposed for both bridges. Transfer of the prestressing force in structure trough anchorages and deviators requires future research and development due to high stress distribution in these areas.

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