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Strengthening of bridges by post-tensioning using monostrands in substituted cable ducts

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Abstract. Post-tensioning is suitable, reliable and durable method of strengthening existing engineering structures, especially bridges. The high efficiency of post-tensioning can be seen in many applications throughout the world. In this paper the method is extended by a structural system of substituted cable ducts, which allows for significantly widening application of prestressing so it's convenient mostly for application on beam bridges or slab bridges (built in years 1920 – 1960). The method of substituted cable ducts is based on theoretical knowledge and technical procedures, which were made possible through the development in prestressing systems, particularly the development of prestressing tendons (monostrands) and encased anchorages, as well as progress in drilling technology. This technique is highly recommended due to minimization of interventions into the constructions, unseen method of cable arrangement and hence the absence of impact on appearance, which is appreciated not only in case of valuable historical structures but also in general. It is possible to summarise that post-tensioning by monostrands in substituted cable ducts is a highly effective method of strengthening existing bridges in order to increase their load capacities in terms of current traffic load and to extend their service life.

1. Introduction

When strengthening by post-tensioning, the prestressing tendons must be placed inside a cross section of a bridge structure. It is possible to use the free space between beams in case of monolithic reinforced concrete beam bridges built between 1920 and 1960. U-shaped beam (parapet) bridges do not provide such an option and there is not any free space in case of slab bridges as well. However, there is still a large amount of these structures in the Czech Republic, around 6000 according to databank data.

The possibility of placing prestressing tendons to substituted cable ducts is a construction method based on additional drilling of cable ducts into the concrete of existing bridges. It is then possible to place the prestressing system tendons both into the existing bridge slabs and the existing parapet beam bridges. This construction method is very suitable for beam systems of bridges wherein part of the post-tensioning is placed into concrete beams and part into the free space between them using the substituted cable ducts.

The following article text describes this method in detail and includes examples of successful application.

2. Substituted cable ducts, saddles and anchorage areas

2.1. Implementation of substituted cable ducts

The substituted cable ducts can be applied by construction drilling. It is possible to create very long cavities of relatively small diameters (40–52 mm) and use them for the insertion of prestressing tendons and strands.

When creating the substituted cable ducts in the concrete of existing bridge, it is a drilling of long drilling holes of appropriate diameters suitable for passing the prestressing tendons assembled from either individual strands (separate monostrands) or tendons made of 3, 4 or 6 monostrands. In terms of the existing technology, diamond and hammer drilling using carbide drill bits can be used for such drilling.

Diamond drilling technologies are based on grinding the material by appropriately shaped grinding alloy cutting edges. Industrial diamonds in the form of particles of a few tenths of a millimeter are dispersed in light metal alloy. The drilling segments of a diamond drill are shown in Figure 1. Drills for this technology are made in the shape of hollow metal cylinders; they are fitted with diamond segments on the side intended for drilling in the structure (see Figure 1b). When drilling, a hollow drill is pushed towards a structure with a relatively large force exerted by an auxiliary stand, the segments graze the structure material and the exposed diamond particles grind the drilled material. Drive units are electric or hydraulic. The power consumption of electric drive units are between 1.8 kW up to 4 kW, i.e. small input powers common for small construction site machinery. The drills are supplied in lengths from 300 to 500 mm; the drills of up to 1000 mm can be produced as special order.

Figure 1a. Drilling segments of a diamond drill bit.

Figure 1b. Diamond drill bit.

Hammer drilling technologies with solid carbide drill bits are modifications of classical drilling technology with helix drill bits. Augers are equipped with carbide cutting edges – appropriately shaped and grinded plates from sintered carbides. Figure 2a) shows the drill bit fitted with four cutting edges. Figure 2b) shows a typical carbide spiral drill bit. Small-mechanization machines are designed to drill holes for installations, openings, wall plugs, etc. They are intended for manual handling with no exceptions, which means that workers hold a machine tool – drill in their hands and drill holes without any special demands on the accuracy of drilling trajectory. Hammer drilling technology drive units are mainly electric, exceptionally hydraulic. The power consumption of electric drive units lays between 0.8 kW up to 2.0 kW, i.e. small input powers again, common for small construction site machinery. In terms of power, they are classified by the energy of one impact which is measured in Joules. Impact energy ranges from 4 to 20 J. The augers are supplied in lengths from 150 to 800 mm, in diameters from 8 to 40 mm; it is possible to have drill extension shafts without a spiral of up to 1500 mm produced as a special order.

Figure 2a. Carbide drill bit with four cutting edges.

Figure 2b. Carbide drill bit.

The application of substitute cable ducts requires drilling holes into the concrete of bridge construction in significantly longer lengths than those made by serially supplied equipment and tools. Special positioning drilling equipment – drill support [1] is used for this purpose. Its main parts are rails and drill carriage; see Figure 3. The carriage allows defined fixing of drilling machinery, power transmission for exerting the necessary thrust while drilling. The guide rods along with the carriage allow the extension of drilling shafts. The purpose of the equipment is a guidance of drilling machine, a reduction in drilling machinery operator's fatigue to an acceptable level and a maximum achievable increase in the accuracy of the trajectory of drilled cable ducts with the possibility of setting any trajectory in a space by individually adjustable vertical angle and horizontal angle (usually an angle to the longitudinal axis of supporting structure). The drill support can be coaxially fitted by a diamond and hammer drilling technology which may even be interchanged while applying one cable duct. It can be mounted advantageously to the rehabilitated structure itself or to the auxiliary steel structure. Figure 4 shows deployment of the drill support with diamond drilling technology; Figure 5 shows the location of individual monostrands in the made duct. The cable ducts of 52 mm in diameter and at a length of 6 m, exceptionally even 10 m, can be normally drilled in this way.

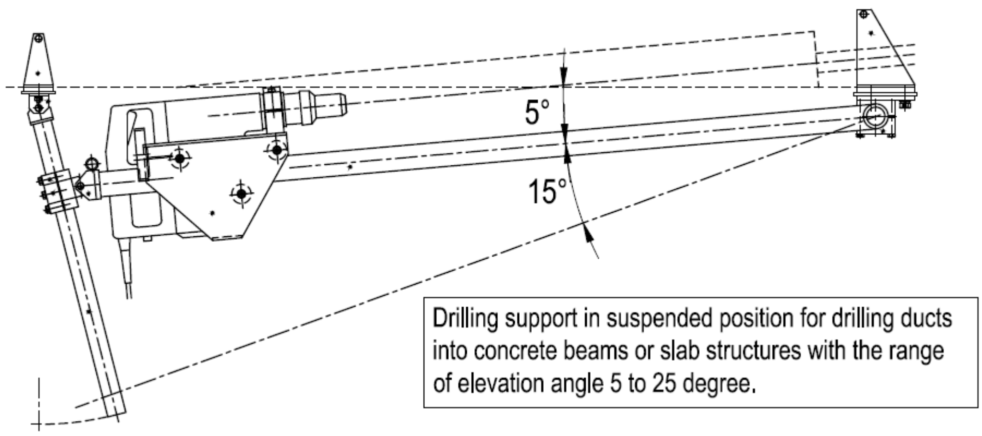

Figure 3. Scheme of the drilling support for drilling substituted cable ducts into concrete or masonry.

When using carbide impact drilling technology for drilling cable ducts, the extension System 6 by Joran is successfully used. HILTI or MILWAUKEE currently uses more precise extension systems. Extension rods have a length of 500 mm or 1000 mm, couplers with patented lock which transfers the impact energy almost without losses from the drill to the drill bit are used for connection. It does not matter how many couplers are used, the system operates with acceptable productivity up to the lengths of about 4 m; the optimal use is for ducts of up to 2.5 m in length. Unit price per 1 m' of drilled duct using the carbide hammer drilling technology is significantly lower than using the diamond technology; it indicatively ranges from 30 to 50% of the diamond technology price. It is due to less wear and lower entry price of impact tools and their much wider application in other construction sectors.

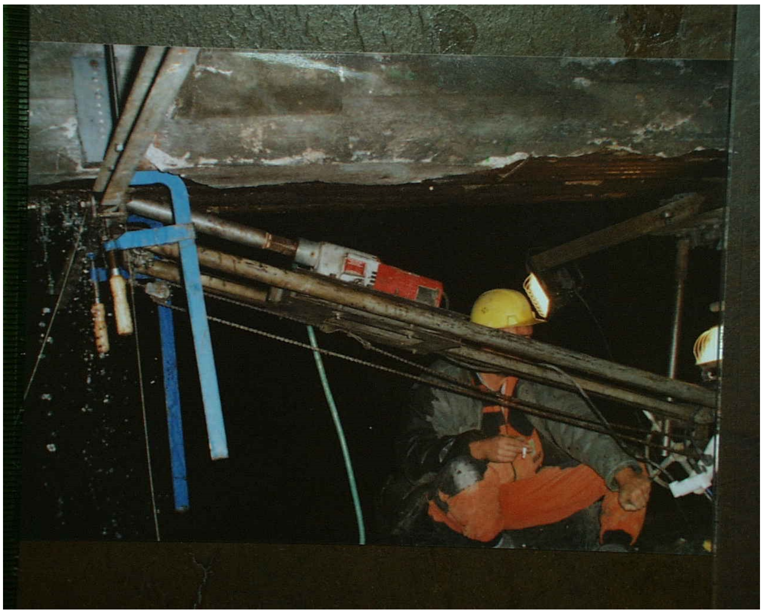

Figure 4. Drilling of substituted cable duct in parapet bridge beam using drilling support.

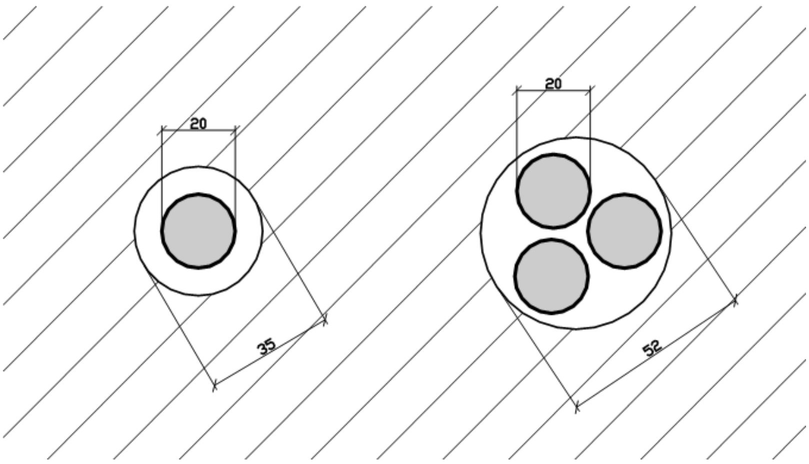

Figure 5. Geometry of substituted cable ducts for single monostrand and tendon with 3 monostrands.

The drill support can be fitted in any position for drilling ducts. The article authors elaborated and verified the preferred method of fitting from the bottom to a structure when drilling cable ducts in reinforced bridge structures – beams and slabs. It is generally possible to perform oblique cable ducts top-down or bottom-up in these structures. The gaps between the existing concrete reinforcement are used to guide the monostrands (Figure 6). During the top-down process, it would be necessary to lead the drilled duct accurately to ‘fit’ into the gap between the reinforcement at the bottom structure surface; particularly in case of the rehabilitated reinforced concrete beams, it is regarded almost an impossible task demanding on the precise geodetic survey of the drilling hole axis due to local irregularities in the structure. In contrast, with the bottom-up process, it is possible to find the suitable gaps in advance, to prepare a drilling start as advantageous as possible, to correct plan projection of the cable axis according to local conditions. Concrete reinforcement is usually placed relatively sparsely near the upper surface (in bridge deck) and the problem of ‘fitting’ into the gap is almost eliminated. A significant advantage associated with the drilling from the bottom approaches this: gravity facilitates ejection of drilled material from the hole which remains permanently clean while drilling. Similarly, flushing water flows away by gravity. However, the decisive advantage of this process is its independence from the traffic restriction on the rehabilitated bridge structure. If the drilling of cable ducts is done from the bottom, most preparatory works for the rehabilitation by tensioning may be carried out with ongoing traffic, thus significantly shortening the necessary time of lockout the bridge. From experience, investors strongly prefer this variant wherever they deal with the strengthening of a bridge with ongoing traffic.

Figure 6. Substituted cable ducts in the gaps between existing reinforcement.
Left – possible variants of the directions for single monostrand.
Middle – cable ducts ϕ 52 mm in suitable gap between reinforcement.
Right – prestressing tendons with 3 monostrands in cable ducts.

2.2. Saddles

The saddles (deviators) are auxiliary parts of the structure designed to alter cable trajectory. Their purpose is to enable the change of cable trajectory and transfer the resulting radial forces into the structure while maintaining the standard conditions prescribed for prestressing reinforcement, its cover and concrete in contact with the reinforcement. Cross-section of the monostrand must not lose its circular shape and a primary protection cannot be broken. One of the sources giving instructions in the Czech Republic was the standard [2] requiring the following, inter alia, in Annexe E:

- Transverse stress of monostrand in the saddle should not exceed 600 kN/m' of the strand (due to bending and lateral compression of the prestressing reinforcement to prevent loss of strand profile circularity, thereby increasing the risk of fatigue);
- Lateral stress of monostrand on protective plastic cover should not exceed 100 kN/m' of the strand (due to denting the cover and losing passivation lubricant);

- Monostrand in the saddle should pass through a bent steel tube which should ensure the position of the strand in the saddle. Its radius should be at least 3 m (requirement ensuring the circularity of strand profile).

These requirements are established primarily to ensure the durability of the prestressing reinforcement at the increased stress during the passage through deviator where the effects of local bending, partial stretching and the tension arising therefrom are added to the overall tension in the reinforcement by prestressing forces. However, these requirements (especially the passage through the tube) are formulated rather for the deviators of new structures with free external prestressing tendons, their application for strengthening existing bridges leads to structural complications.

Saddles made directly in concrete or masonry of the reinforced structure are part of the substituted cable duct method. This modified process of making deviators was verified by numerous applications. It is based on the above requirements, although the saddle construction is more adapted to the nature of work while strengthening. The basic idea is to create a deviator directly in the structure concrete to eliminate complicated transformation of radial forces by auxiliary weldments, for example. The saddle is created using the technology of diamond cutting and partial cutting. When creating it, it is always assumed that the corresponding cable duct has already been made. The saddle is done in the following steps:

1. Lining cuts at the sides of saddle. They are carried out manually in planes parallel with the plane defined by a prestressing tendon polygon. The width between the cuts is equal to the width of cable duct, e.g. 40 mm for monostrands, 60–80 mm for 3strand (4strand) tendons composed of monostrands. This deviator shape ensures that the prestressing tendon (cable) cannot slide to another position. Therefore, it fulfils the function of the tube according to [2] Annexe E.
2. Supporting saddle surface. It is done manually by undemanding cutting; material loosened by lining cuts is collected. It is prepared according to a metal template designed by a designer which defines the saddle shape (the shape of a part of a circular arc). Inequalities up to ± 5 mm can be achieved in the deviator shaped in concrete.
3. Alignment of bearing surface. The bearing surface is aligned – smoothed by high-strength thixotropic anchor mortar. Saddle reinforcement is used to check the shape.

Figure 7. Saddle in the concrete of bridge beam with saddle reinforcement.

4. Fitting saddle reinforcement. The aligned bearing surface of the deviator is reinforced by load distribution reinforcement. It is generally sufficient to use structural steel (e. g. S 235). The strap of steel (see Figure 7) has the same width in the concrete as the diameter of cable duct,

the thickness of 5-8 mm. It also replaces the function of the tube in the deviator according to [2] Annexe E particularly by ensuring the smooth shape of the radial bearing surface and distributing theoretically line load of structure concrete by radial forces to the surface load. This solves the contact problem. Smooth bearing surface without any roughness is necessary for long-term protection of the prestressing tendon plastic cover (to avoid cutting through the plastic cover or tube).

5. Reprofiling the saddle area. After prestressing the structure, the areas of saddle are smoothed out (reprofiled). For this purpose, additionally established concrete covering layer for the cables on the bottom face of the bridge beams is used.

The saddles for monostrand and 3strand tendons were developed and experimentally tested in this manner. Designed and implemented radii r_s = 1200–1500 mm met the requirements, buckling of tendons was avoided and plastic monostrand HDPE covers were not damaged. The radii are therefore feasible smaller than the ones for new buildings with free cables required by the standards [2, 4]. Design of the saddle is done by establishing its radius and testing if the allowable radial stress on strand protecting cover is not exceeded. The overall static solution of the strengthened bridge structure is decisive, which determines the angle of cable trajectory behind the saddle relation to its previous direction.

2.3. Anchorage areas

The latest views on the protection of prestressing tendon passing through anchor require hermetically coated anchors, including bearing plates with leak proof connection of the cover of monostrand and anchor. After prestressing, such an anchor is covered with a plastic sheath and the entire space is injected with the same passivation material as was used in the actual tendon.

Monostrand anchor system by DYWIDAG has a planar bearing surface and is suitable for subsequent installation (Figure 8). It consists of a compact anchor in plastic cover, a sleeve which seals the transition from the monostrand to the anchor, and a cover sheath which ensures closure of the self-locking anchoring three-jaw system after anchoring and cutting the single strand off. It can be underlaid with ordinary locksmith-made bearing plates or weldments according to the particular shape and needs. Figure 8 shows examples of use of this system for anchoring tendons made of several monostrands.

Figure 8. Examples of anchoring tendons using encapsulated system DYWIDAG.
Left – Anchoring of 3strand tendon with tetrahedron load distribution weldment.
Right – Anchoring two 3strand tendons with pentahedron load distribution weldment.

3. Arrangement of prestressing tendons with examples

The substituted cable duct method is especially suitable for slab bridge structures. It can be suitably applied when strengthening in longitudinal direction but also for strengthening in transverse direction. It is very suitable for simple and continuous reinforced concrete slab structures. It can also be adapted to slab structures assembled from lengthwise precast prestressed segments.

Reinforced concrete slabs have a flat surface and there is no suitable structure gap for additional trajectory of prestressing tendons. Therefore, there is no other possibility of lifting cables in the longitudinal direction than using the substituted cable ducts drilled through the slab. At the same time, the original concrete reinforcement of reinforced concrete slabs (longitudinal) with respect to drilling ducts is placed relatively sparsely, usually every 100 to 160 mm in the transverse direction. Sometimes, the single tendons – individual monostrands are sufficient, multiple strand tendons in ducts of larger diameters are used for medium-span slabs, especially for economic reasons (drilling smaller number of ducts is also faster and reduces the extent of preparatory work). The ducts for each monostrand and cables can be appropriately placed between the original concrete reinforcement, without interrupting it, thus eliminating undesirable weakening. The ducts do not need to be at regular intervals. Of course, designing of reconstruction must be preceded by proper structure diagnostics. The tendons can be lead near the lower face of the rehabilitated slab and the structure provided with additional concrete covering layer, or it is possible to cut grooves into the original cover layer using the diamond technology and place the tendons into them. The grooves are then puttied using high-strength cement repair mortar. Figure 9 shows the arrangement of 3strand tendons suitable for strengthening the continuous slab bridges. This arrangement was used when strengthening a continuous slab structure with a span of L = 2 x 22 m.

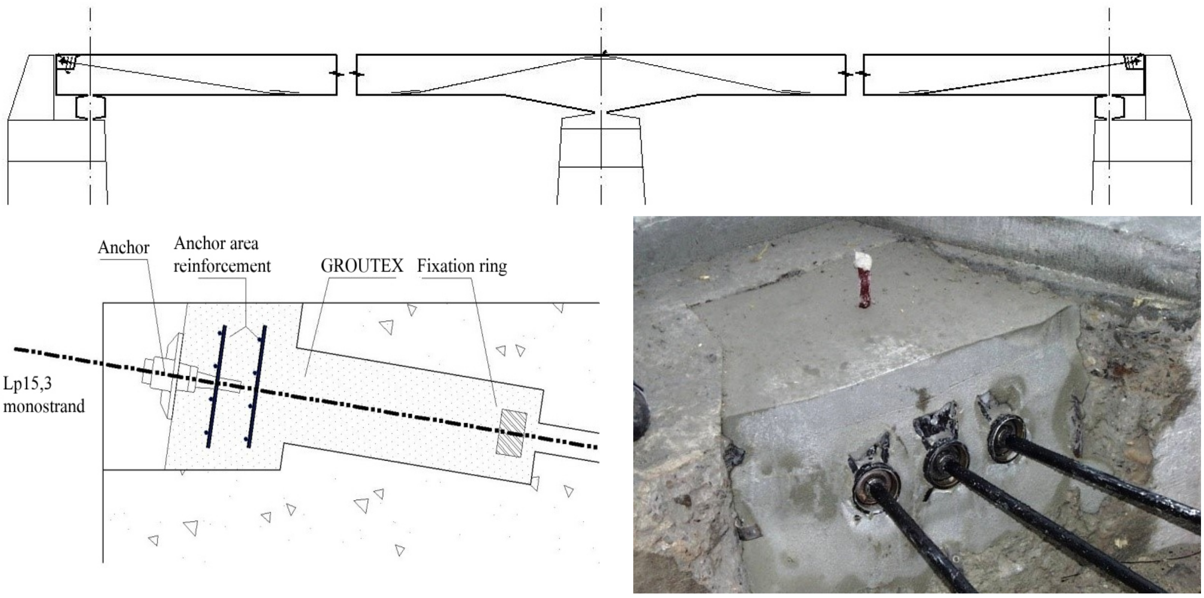

Figure 9. Arrangement of 3strand tendons in continuous slab structure with a span of L = 2 x 22 m.
Top – scheme of the trajectory 3strand tendons in slab structure.
Left bottom – anchoring area in concrete with widening duct outfall.
Right bottom – anchoring area with encapsulated anchors.

When strengthening slab structures, anchorage areas can be done directly into the concrete of the existing slab (this is the most commonly suggested method) or they may also be done (particularly at lower strength of the original slab concrete) in concrete of composite slab, if used. In case of continuous structures, it is necessary to design and implement two-way saddles over internal supports to change direction of additional cables from one (rising) duct to another (decreasing). A necessary condition is the adherence to a prescribed accuracy of drilling ducts (compliance with the deviations of up to ± 30 mm on the duct length is usually prescribed). After making the ducts, the saddles over supports are directionally adjusted to the outfall of ducts. The deviators (over the internal supports) themselves are actually double normal saddles used on the bottom surface of the structure, again with complying radii r_s = 1.2 to 1.5 m.

Parapet beam bridges have two main beams pulled over the road and the bridge deck is supported by cross beams. The cross beams connect the two main beams forming a half-frame in the transverse direction which provides spatial rigidity of the structure. These bridges can be advantageously strengthened by post-tensioning using the substituted cable ducts method in both the longitudinal and transverse direction. The span of these structures is usually between 15 to 25 m.

Figure 10 shows the shape and arrangement of the prestressing system when strengthening the U-shaped beam bridge with variable height of the main beam on a III class road with a span of l = 14.1 m. The main beams were post-tensioned by two tendons with four monostrands, cross beams by one tendon with two monostrands. This created the conditions for carrying up the weight of additionally composite slab. This is also example of anchoring with encapsulated anchoring system DYWIDAG CPS with the primary protection in anchors (already standardly used method of anchoring in bridge structures). Secondary protection was ensured by usual concreting of anchor cellars. Figure 11 shows the details of tendon anchors in the main beam and the cross tendon anchors on the sides of the main beam.

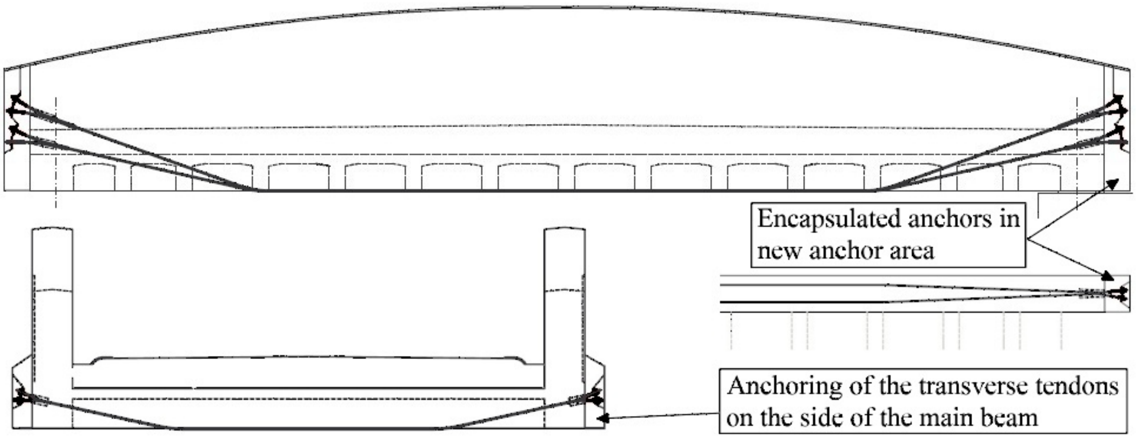

Figure 10. Trajectory and arrangement of prestressing system in parapet beam bridge.
Top – tendons trajectory in the main parapet beams (2 tendons with 4 monostrands).
Left bottom – tendons trajectory in transverse direction (2 tendons with single monostrand).
Right bottom – distribution of monostrands in the main parapet beam (ground plan).

Strengthening the parapet beam bridges by post-tensioning using the substituted cable ducts system generally brings several benefits:

1. Unlike bonded reinforcement, which is activated after being loaded, therefore not participating in the transfer of forces from permanent load, introducing prestressing into a construction balances a significant portion of the internal forces resulting from permanent load; thus, it effectively improves the condition when the structure is not subjected to imposed load and the necessary reserve for the transfer of traffic load effects is created.
2. Increase in load capacity by this method is significant, usually 200 up to 300 %; it is almost several times higher effect than when using bonded reinforcement where, from experience, the improvement by ca. 30 % can be achieved.

3. Cracks caused by static or dynamic loads in strained parts of reinforced concrete beams significantly accelerate the corrosion process of reinforced concrete. Bringing stress forces by prestressing leads to partial or even complete closure of these cracks, thus extending the durability of concrete structures against corrosion.
4. Most of the work associated with this technology can be done without interrupting the traffic on the bridge or with its partial restriction.
5. When strengthening bridges by prestressing, we use the entire width of the prestressing level interval. When strengthening beam bridges, it usually reaches the values of $\lambda = 0.15$ to 0.25.
6. In case of bridges which appear irreparable in terms of structural stability or other methods which cannot achieve the required load capacity and when demolition and construction of a new building occurs, the required parameters can be achieved for a third to half the price of new building using this method of increasing the load capacity.

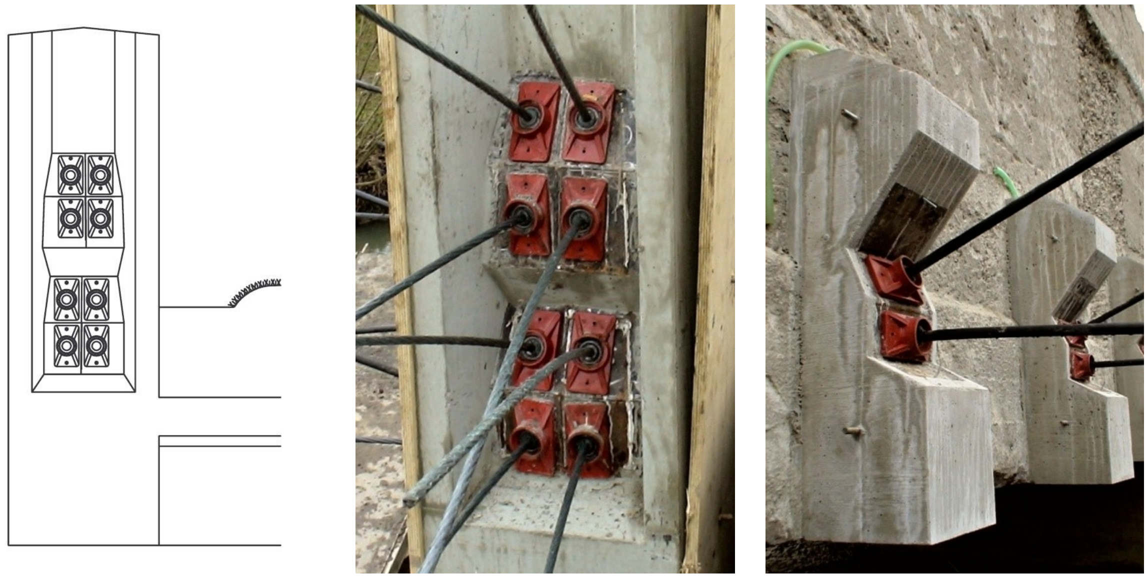

Figure 11. Anchor areas of parapet beam bridge.
Left – disposition of new anchor area on the face of existing parapet beam bridge.
Middle – actual implementation of cast in situ anchor area block on the face of parapet beam bridge.
Right – implementation of cast in situ anchor areas for transverse tendons on the side of parapet beam.

The design and implementation of reinforcement must emphasize the fact that the structural strengthening is part of the overall reconstruction and rehabilitation of the bridge. It must create conditions for the reliability and durability of the chosen design. Therefore, it is necessary to consider and suggest the following measures:

1. Thorough preparation of degraded concrete of the entire bridge (surface layers, including plaster), first mechanically and then using high-pressure waterjet with rotary nozzle.
2. Careful cleaning of the exposed and corroded steel reinforcement in the entire existing bridge structure, first mechanically and then with high-pressure waterjet with a one-nozzle (a point) tool.
3. Carrying out the protection of steel reinforcement by silicate materials.
4. Implementation of own post-tensioning of the bridge construction by both using prestressing and composite slab.

5. Application of adhesive layer in the entire area of rehabilitated bridge concrete components.
6. Performing coarse and fine reprofiling of load bearing bridge structure.
7. Fitting inner and upper surfaces of U-shaped beams by unifying and protective coating.

Using prestressing tendons in substituted cable ducts can strengthen the simple and continuous reinforced concrete beam structures in other way as it was described in [5, 6, 7, 8]. In the case of simple supported constructions (mostly simply placed grids), the ducts and the prestressing tendons are arranged in the appropriate shape which is similar to shape of bending moment diagram resulting from permanent load; in the case of continuous structure as shown in Figure 12. The continuous structures can be effectively prestressed by continuous lifted cables tensioned from both anchors. They may be complemented by not-continuous cables anchored in the composite slab and anchoring blocks (cast in site) which are placed between the original beams.

Figure 12. Strengthening of continuous beam bridge using substituted cable ducts method.
Top – trajectory of tendons of 1. system (in ducts and on the bottom surface of beams) and trajectory of tendons of 2. system (free unbonded tendons in mid span).
Bottom – examples of outlets of substituted cable ducts ф 52 mm in gaps between steel reinforcement of beam.

Friction coefficient when prestressing monostrands which is applied for this arrangement only in the saddles has a value of 0.06 to 0.1. This value was repeatedly verified during the prestressing of thus strengthened structures by comparing the calculated and the achieved sizes of stretching monostrands. Friction is not applied in the straight sections of cable trajectories (the monostrands here are mostly almost in line from saddle to saddle, i.e. in the air and without friction).

The substituted cable ducts can be drilled into the structure very precisely and with minimal damage to the original beam reinforcement. This requires the construction site diagnostics of beam reinforcement, providing data on the most appropriate gap for placing the duct. The designer specifies the position of theoretical points only in the longitudinal direction and accurate outfall of ducts across the width of beams is left for the building process. In many cases, the concrete of reinforced structure in the region of the lower edge of beams is affected by corrosion in the extent that the concrete cover dropped away and the deployment of the reinforcement is obvious. In other cases, it is possible to remove the original cover in the place of future deviators as the cables will be protected by anchored concrete cover after the prestressing and the surfaces of the entire structure are typically rehabilitated by rehabilitation layers. Figure 12 below shows the examples of duct outfalls between the reinforcement of beams of strengthened continuous beam bridge construction. They show that it was always possible to find a suitable gap and to prepare the substituted ducts without or with minimal damage.

4. Summary

The substituted cable ducts method is especially suitable for slab, parapet beam and simple and continuous beam bridge structures. It can be applied when strengthening in longitudinal direction but also for strengthening and structural rehabilitation in transverse direction. It enables efficient life extension of existing bridges which do not meet the current requirements without reconstruction.

Acknowledgements

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