Reduction in Seismic Actions of Bridges by Utilizing the Sidewalks as Restrainers

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SUMMARY:
In conventional bridge design the sidewalks are functional but non-structural elements, whose weight is included in the permanent loads of the structure. In the present study, the sidewalks are considered to participate in the earthquake resisting structural system of the bridge. This approach aims at enhancing the seismic response of the bridge mainly in the longitudinal direction. The objective is achieved by connecting the sidewalks with the central part of the bridge deck and the abutments while serviceability is appropriately preserved. This proposal can be implemented in bridges of all types and aims at the elimination of displacements and consequently at the reduction of the seismic effects of the longitudinal earthquakes, which are usually more critical than the ones in the transverse direction.

Keywords: Bridge, earthquake, serviceability, sidewalks, abutment

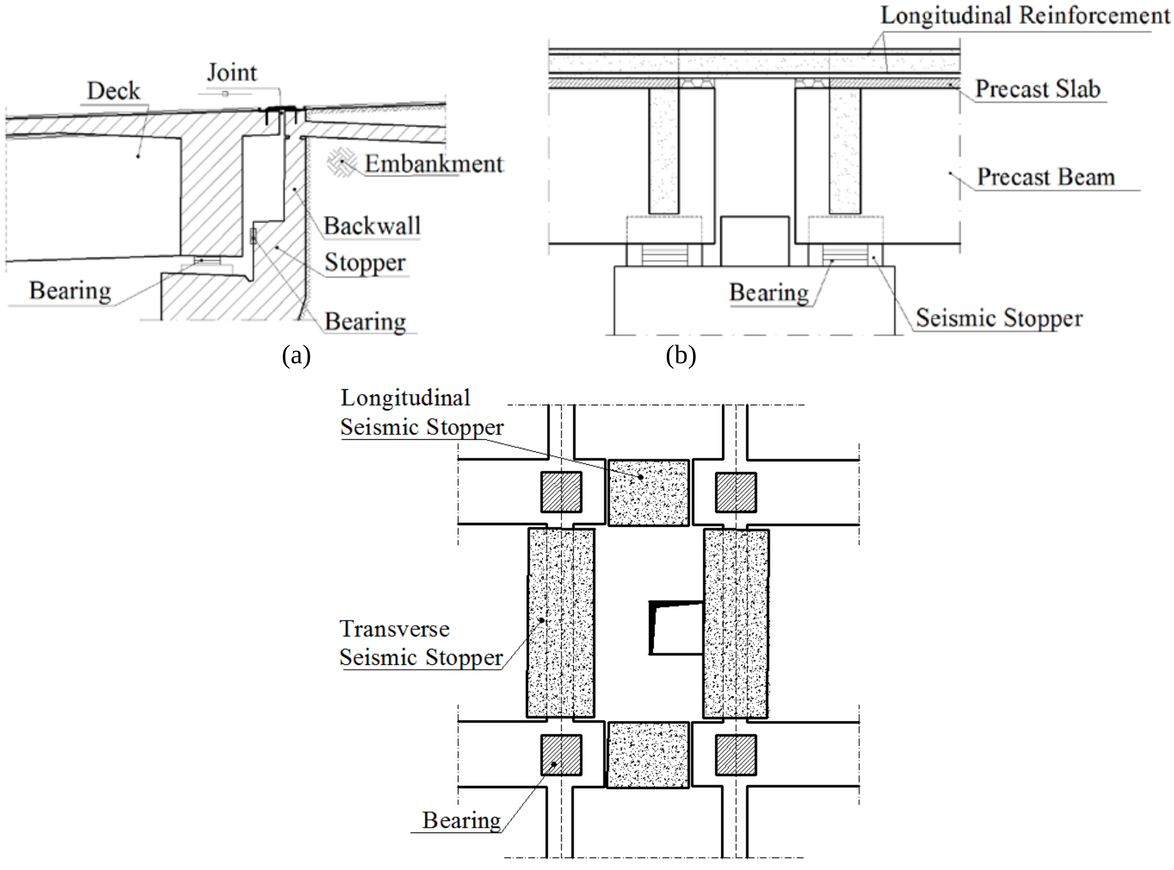
1. INTRODUCTION

The conventionally designed bridges are supported on the abutments through bearings, while expansion (flexible) joints (between the deck of the bridge and the abutment) are provided in order that length changes of the bridge's deck - due to temperature and other effects – take place without inducing additional stress and strain fields. This way, the system abutment-embankment is not a part of bridge's structural system and therefore it does not play an active role in resisting the earthquake action.

However, it is possible to include stoppers between the piers and the deck of the bridge, Fig.1.1, in order to enforce common displacements in these elements. Actually, modern earthquake codes, such as Eurocode 8- Part 1 (2003) include a methodology for designing bridges with stoppers acting as restrainers. Nevertheless, this methodology is followed very rarely, since designers prefer to include expansion joints to address the temperature effects. Another concern that makes designers cautious in including stoppers is the resulting nonlinear stiffness of the piers.

Recently, there have been efforts aiming at reducing the seismic displacements of bridges. In particular, Mikami et al. (2003) studied ways of including the abutments in the bridge's resistance to earthquakes, while Mylonakis et al. (1999) and Zhang and Makris (2001, 2002) included in the bridge's resistance to earthquake action the transitional embankment. Nutt and Mayes (2000) showed that this way the cost of the bridge is reduced. Along these lines there has been recently a lot of activity at the Reinforced Concrete and Masonry Structures Lab of the Aristotle University of Thessaloniki, Greece. In particular, Mitoulis and Tegos (2010) and Tegou et al. (2010) have studied how the transitional embankments as well the abutments could enhance the earthquake resistance capability of the structure with the aid of suitable stoppers.

This work is a first attempt at studying the effects of including the sidewalks in the structural system of the bridge against earthquake action. In particular, in this study is investigated how the sidewalks may work in compression as restrainers. The proposed methodology is reliable and cost-effective, and it is proposed as an alternative to the base isolation one that has started been widely accepted in recent years.



(a) (b)

(c)

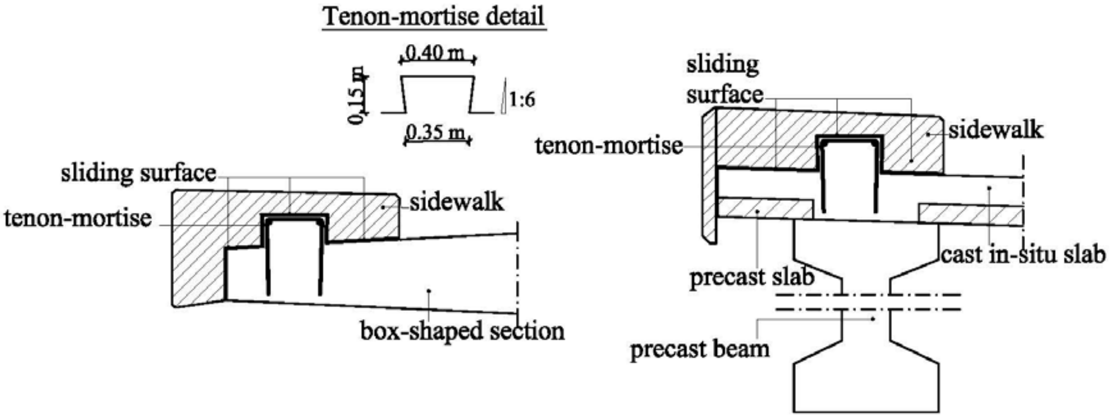
Figure 1.1. (a) Seismic stopper at abutment, (b) Longitudinal seismic stopper at pier of a precast I-beam bridge and (c) Plan view of a pier’s head

2. DESCRIPTION OF THE SIDEWALKS-RESTRAINERS SYSTEM

It is well known that sidewalks are not a part of the structural system of a bridge and they play a functional role; their weight is included in the dead (permanent) weight of the structure. In this work, the way these elements could be included in the structural system of the bridge against earthquake actions is studied.

In this section the serviceability performance and design of the system bridge-sidewalks are discussed. In order that the sidewalks be free to elongate and shrink, according to temperature conditions, these elements should not be connected to the deck of the bridge. On the other hand, these elements should be protected from buckling phenomena, Fig. 2.1. For this purpose, the anchorage of the sidewalks to the deck of the precast bridges is achieved with the aid of transverse reinforcement, that can sustain a surface shear force at the deck’s slab above the central pier, where the bending moment is zero, Fig. 2.2. In the rest of the bridge’s length the sidewalks can slide freely with respect to the structure. In continuous deck bridges, the anchorage takes also place at the zero moment positions, approximately at the 20% of spans’ length. The proposed sidewalks-restrainers are connected rigidly to the immovable wing-walls of the abutments, Fig. 2.3.

In order to design properly this new system the strength capacities of its members should be categorized, in order to make sure that the abutment is fixed (immovable). This may be achieved by extending the foundation slab towards the embankment.



(a) (b)

Figure 2.1. Structural configuration for the avoidance of the buckling (a) bridge with box-shaped deck's section and (b) precast I-beam bridge

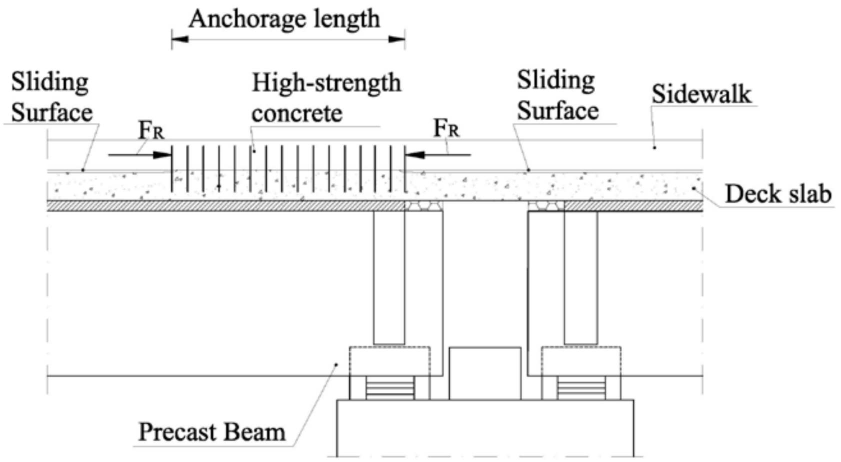


Figure 2.2. Anchoring of the sidewalks at the deck slab over the central pier

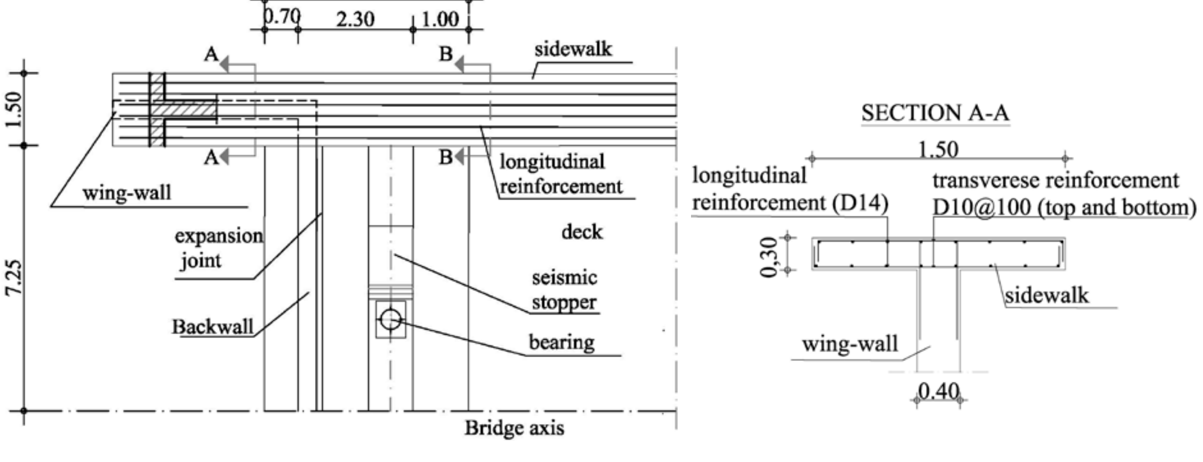


Figure 2.3. The connection of the sidewalks to the wing-walls (indicative dimensions)

2.1. Serviceability performance of sidewalks as struts and ties

As it was already mentioned in the previous section, sidewalks should be free to expand and shorten because of temperature changes, creep and shrinkage. The decrease of temperature during the winter months results to shortening of the deck of the bridge and therefore to a tensile stress state for the sidewalks, since these are constrained at their end boundary points. On the contrary, increase of the temperature during summer months leads to the expansion of bridge's deck and consequently to the compression of the sidewalks. In Fig. 2.4 and Fig. 2.5 the response of sidewalks during winter (tension) and summer (compression), in terms of applied force vs. width of developed cracks is shown. In the sidewalk under tension, the stresses of the longitudinal reinforcement equilibrate the tensile stresses that are developed in the element.

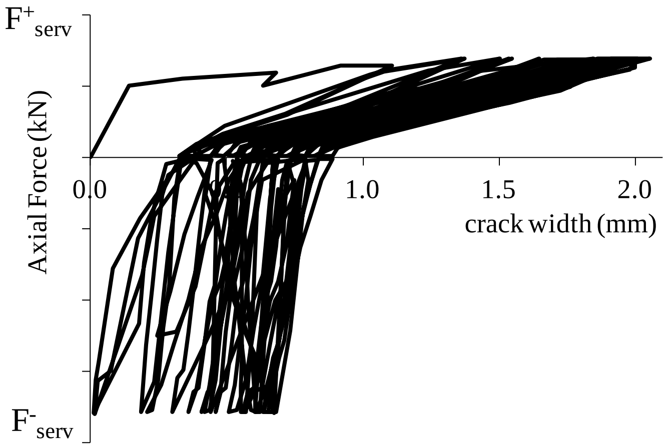


Figure 2.4. The response of the sidewalks during winter (tension)

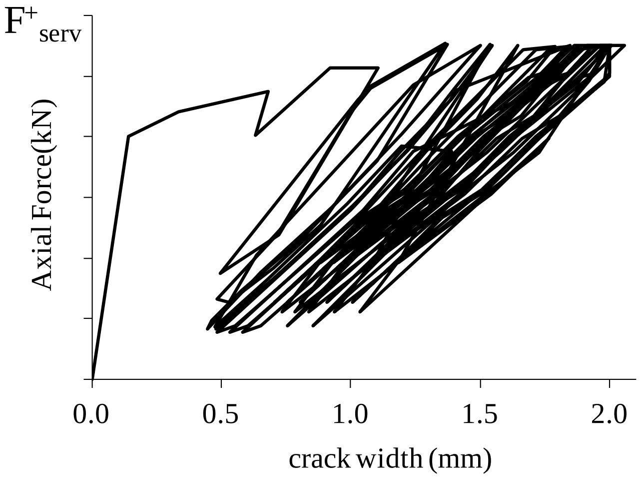


Figure 2.5. The response of the sidewalks during summer (compression)

In Fig. 2.6 the idealized behaviour of a reinforced concrete tie is presented (CEB 1991). According to this figure the contribution of the concrete may be considered to increase the stiffness of the tensile reinforcement (tension stiffening effect).

The formation of the cracks results to the decrease of the axial stiffness of the element. During this phase the region between the cracks remains in stage I ($\varepsilon_c=\varepsilon_s$). The distribution of longitudinal strains (in both steel and concrete) in a reinforced concrete tension element, of cross sectional area A_c, along its length is shown in Fig. 2.7. In Fig. 2.7(a) the distribution of strains after the first crack appeared is shown, while in Fig. 2.7(b) the distribution of strains after the element has been fully cracked is depicted. In the areas between cracks the tensile forces are transferred from steel to concrete by the friction (bonding) forces. Concrete contributes to reinforcement's axial stiffness increase.

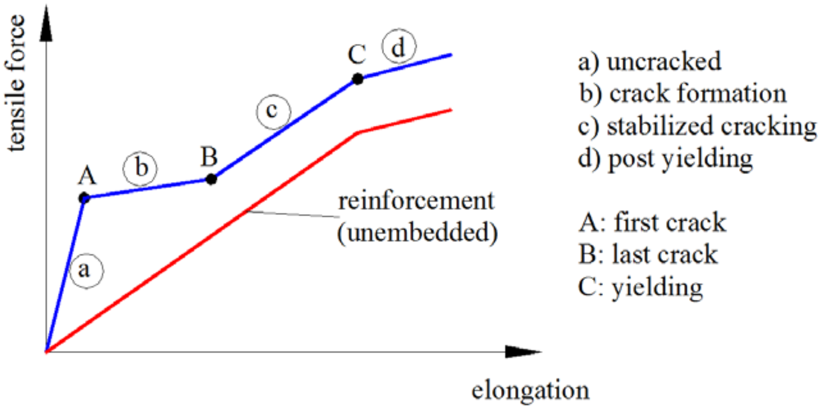


Figure 2.6. The idealized behavior of a concrete tie

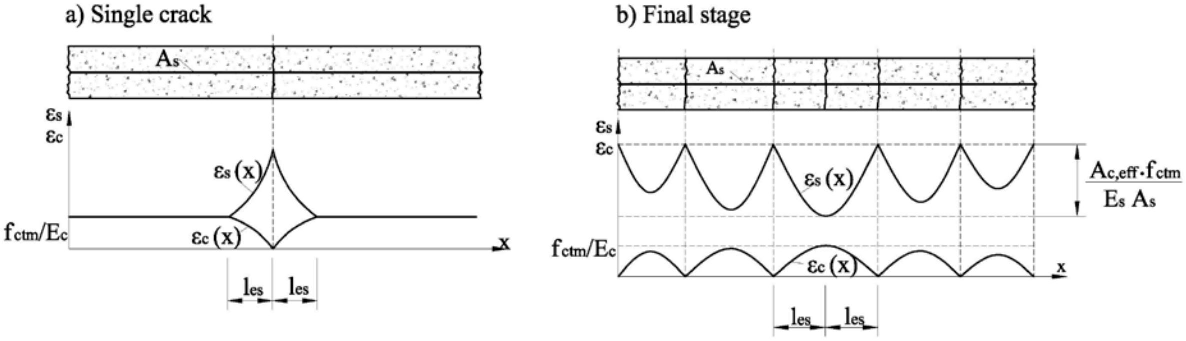


Figure 2.7. (a) The distribution of strains after the first crack appeared and (b) the distribution of strains after the element has been fully cracked

The aim is to reduce the width of the cracks induced and to keep them within acceptable limits according to the Eurocode 2-Part 1 (2004), in order that the length of the sidewalks is adequate. This length is getting reduced because of uniform temperature decrease as well as because of time dependant effects. The uniform temperature decrease is taken equal to 25^{o} C (Eurocode 1- Part 1-5 2003), while creep and drying shrinkage effects are taken into account via an equivalent temperature change of 15^{o}-25^{o} C (PCI 2012). This way, a percentage of the time dependant deformations is calculated, since the connection of the sidewalks to wing-walls is taking place after the major part of the strains has been developed. The displacement $u_{x,serv}$ of the end of the bridge structure, because of these effects is given by Eqn. 2.1. In this equation α is the coefficient of thermal expansion of concrete, which according to the Eurocode 2-Part 1 (2004) is taken equal to $10 \cdot 10^{-6}$ C^{-1} , L_{tot} is the total length of the bridge's deck and ΔT_{equiv} is the equivalent temperature, through which the effects of uniform temperature change, creep and drying shrinkage combined, are taken into account.

$$u_{x,serv} = \frac{\alpha \Delta \mathrm{T}_{equiv} L}{2} \quad . \tag{2.1}$$

2.2. Seismic response of sidewalks as compression elements

During a longitudinal earthquake action, the proposed sidewalks – restrainers act as compression elements in stage I, confining the displacements of the bridge structure. This is accomplished because of the restraint of the sidewalks' motion by the immovable abutment. The maximum compressive resistance of those elements is given by Eqn. 2.2, where F_R is the maximum compressive resistance, f_{cd} is the design compressive strength of concrete, reduced because the confinement has been ignored, A_c is the cross sectional area of the sidewalks and ω is the mechanical percentage of the combined compressive – sidewalk.

$$F_R = A_c f_{cd} + A_s f_{yd} = A_s f_{cd} (1+\omega) \,. \tag{2.2}$$

These forces are transferred to the wing-walls to which they are connected. Taking into account that these walls have small ductility (because of their small shear opening) and because the structure is trapped in the ground, since its vibration is constrained by the sidewalk-restrainers, it shall be designed as a stable abutment according to Eurocode's 8- Part 2 (2003) provisions.

In order that the sidewalks perform as struts during an earthquake, special care must be provided against buckling failure. This is accomplished by suitably shaping the sliding surface, in which a tenon-mortise system with inclined surfaces, is participating, Fig. 2.1.

In this paper, a reinforcement of the sidewalks in the longitudinal direction with bars of 14mm diameter is proposed, in combination with a strong confinement with densely put stirrups of 8-10mm diameter, Fig. 2.8.

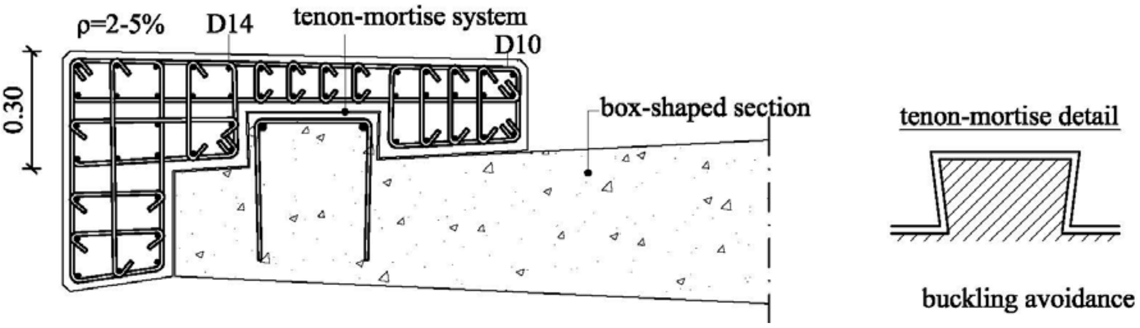


Figure 2.8. Proposing reinforcement detailing of the sidewalks

3. AN EXPAMPLE OF THE APPLICATION OF THE SIDEWALKS-RESTRAINERS

3.1. Description of the bridge

The method is applied to an existing precast I- beam bridge of the highway connecting the city of Patras to the northern border of Greece via Athens and Thessaloniki (the so-called "P.A.TH.E." highway in Greek, i.e. the Patras-Athens-Thessaloniki-Evzonoi highway). The design of this bridge has been conducted by the design firm METE-SYSM and its longitudinal section is shown in Fig. 3.1(a). Its total length is L=177.5m and it consists of 5 spans; the end spans have length 34.75m while the rest three 36.0m. The deck's cross section, Fig. 3.1(c), consists of six prestressed precast double T beams of 2.0m height and from the deck's slab whose depth is 0.25m. The beams' axes have the same distance equal to 2.50m. The deck's slab is shaped from precast slabs of depth 0.10m, which are supported on the upper flange of the beams and from a layer, constructed on site, of depth 0.15m.

The deck is supported on piers through rubber bearings. At the ends the deck is supported on the abutments through rubber bearings, too, as is shown in Fig. 3.1(b). The piers have a hollow circular cross section, Fig. 3.1(d), with interior and exterior diameters equal to 2.0m and 3.0m respectively. Their foundation is taking place by a group of 3x3 piles with diameter equal to 1.0m. The bridge is in a seismic zone II (with acceleration α_g=0.24g) and its foundation soil is in the group B (Ministry of Public Works of Greece 2000). The coefficient of importance is γ_I=1.00, while the behavior factor is considered to be q=1.00 (Ministry of Public Works of Greece 2007), in the longitudinal as well as in the transverse direction.

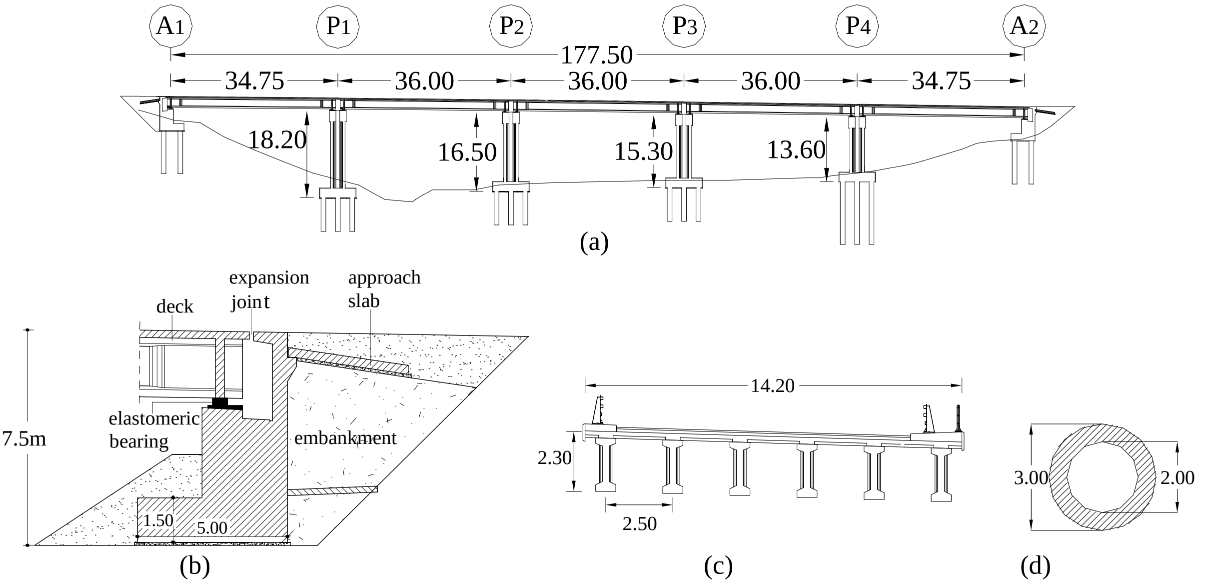


Fig. 3.1. (a) Longitudinal section of the “reference” conventional bridge (b) Longitudinal section of the abutment (c) The cross-section of the deck at the mid-span. (c) The cross-section of the pier

3.2. Application of the sidewalks-restrainers system to the bridge

The morphology and the dimensions of the sidewalks of the particular bridge which is studied and to which the method is applied, are shown in Fig. 3.2. The materials used for the sidewalks are concrete C30/37 and steel B500C. The sidewalks are reinforced longitudinally with bars of diameter 14mm, in the amount of 2% of their total cross section.

One of the most important decisions regarding the design of the proposed innovative configuration concerns the choice of the length of the sidewalks. It should be remembered that the sidewalks can slide freely with respect to the bridge. Their length should have the maximum possible value, in order that the serviceability needs appear with the smallest possible intensity. Therefore, the sidewalks are anchored in the middle of the bridge, which is the optimum place, provided that a pier exists in this position. If the number of the spans is odd, we choose one of the two central piers, at which the moment in the structure is zero. In this case the length of the sidewalks is 34.75m+36.00m=70.75m.

The constraint movement of the end points of the bridge, due to a temperature change, creep and shrinkage can be calculated, by using an equivalent temperature change for the combined effect of these three causes, as it was discussed earlier. For equivalent temperature change equal to $\Delta T=-25-15=-40^{o}C$, the movement is determined with the aid of Eqn. 2.1. This movement is $u_{x,serv}=0.036m$ and corresponds to a relative elongation $\varepsilon_s=0.036/70.75=0.5\ \%_o$. This elongation gives rise to a stress in the reinforcement that is equal to $\sigma_{serv}=0.0005 \cdot 1.2 \cdot 2 \cdot 10^5=120MPa$, where 1.2 is the amplification coefficient of concrete’s Young’s modulus, because of the complex behavior of steel and concrete (CEB 1991). The stress obtained is much smaller from the allowable (by Eurocode 2-Part 1), with respect to the requirement of reducing the cracking. This requirement is satisfied as long as the diameters of the reinforcement bars do not exceed the corresponding values of Table 7.2N of Eurocode 2-Part 1 (2004).

Taking into account that the environmental conditions in this case are at most mildly corrosive and that the diameter of the sidewalks’ reinforcement is 14mm, it is concluded that the maximum stress that may be developed in the reinforcement is $\sigma_{serv,\ max}=260>120$ MPa. This means that bars with much bigger diameter can be used.

In winter conditions, the tensile force in a sidewalk can be obtained from Eqn. 3.1 (see Fig. 2.4):

$$F_{serv}^{+} = \rho A_c \sigma_{serv} \,, \tag{3.1}$$

where F^{+}_{serv} is the tensile force, ρ is the percentage of the longitudinal reinforcement of the sidewalks, A_c is the cross sectional area of the sidewalks and σ_{serv} is the stress that is developed in the reinforcement during the structure's serviceability performance. During this stage, the resultant of the sidewalks' tensile stresses is a tensile force acting at the centroid of the reinforcement of the sidewalks' cross section, in the interior of the bridge. This force in this case is computed to be $F_{serv}=0.02\cdot0.4\cdot120\cdot10^3=960$ kN, where A_c is the cross sectional area of each sidewalk. Since this force causes compression to the lower fiber of the structure's cross section, there is no need for additional prestress reinforcement.

In case of compression, the maximum allowed compression force is given by Eqn. 3.2:

$$F_{serv}^{-} = 0.6 f_{ck} A_c (1 + \alpha\rho) \;. \tag{3.2}$$

In Eqn. 3.2 F^{-}_{serv} is the maximum compressive force during the serviceability performance of the sidewalks, f_c is concrete's compressive strength A_c the sidewalks' cross sectional area, ρ the percentage of the longitudinal reinforcement, $\alpha=E_s/E_{c,eff}=10$, E_s steel's Young modulus, and $E_{c,eff}$ the effective concrete's modulus of elasticity. Then, the compressive force per sidewalk is computed to be: $F^{-}_{serv}=0.6\cdot30\cdot10^{3}\cdot0.4\cdot(1+10\cdot0.02)=8640$ kN.

As it was said earlier, the contribution of the sidewalks in the case of a longitudinal earthquake, is achieved because the sidewalks are behaving as struts, in stage I. From Eqn. 2.2 is computed that $F_R=20\cdot103\cdot0.4\cdot(1+0.02x435/20)=11500$ kN. As it was emphasized earlier, during a longitudinal earthquake the structure is "trapped" to the ground. An earthquake in the transverse direction may be dealt with by enhancing the cross section of the piers in the transverse direction. It should also be noted that an earthquake in the transverse direction is dealt with by using stoppers in the abutments.

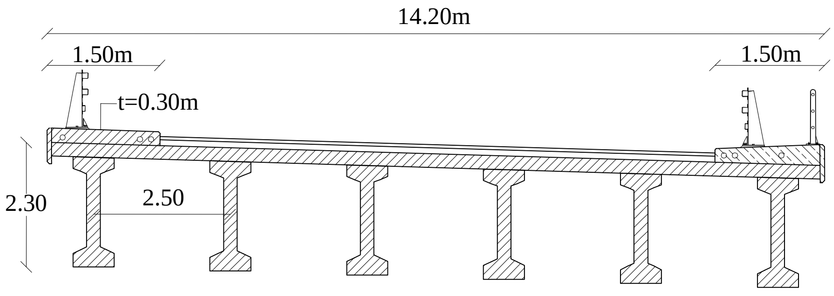


Fig. 3.2. The cross-section of the deck and sidewalks

4. CONCLUSIONS

In this paper the possibility of including the sidewalks in the structural system of the bridge, in particular against longitudinal earthquake actions as restrainers was studied. Particular attention was paid in studying the way the restrainers are reinforced as well as how they are connected to the abutments. The main conclusions of the study are the following:

1. The method can be used in all bridge types and aims at drastically reducing the displacements from a longitudinal earthquake, which is more severe than the one in the transverse direction.

2. During the longitudinal earthquake, because of the action of sidewalks-stoppers, the structure is "trapped" in the ground, with almost no vibrations at all.
3. The proposed earthquake resistance system deals effectively with the bridge's serviceability demands through the free slippage of the sidewalks on the main structure. Therefore, no buckling problems arise.

4. There are advantages from the use of the proposed system in the piers' stress state. The transverse direction of the earthquake can be also effectively dealt with the use of a behavior factor q>1; moreover the piers' cross sections may be geometrically enhanced (wall-type of cross sections).

5. It is remarkable that the proposed earthquake – resistant mechanism can be substituted, in cases damages have occurred.

The authors of this study believe that, in the future, bridge engineering will move away from today's popular systems, such as base isolation and the proposed system in this work, may prove to be one of the successful successors.

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