A Proposal for the Seismic Strengthening of Existing Bridges

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SUMMARY:
The present study proposes a reliable and cost-effective method for the seismic strengthening of existing bridges. The proposed method utilizes the end parts of the sidewalks of the bridge, which are removed and reconstructed. The new sidewalks are of the same geometry with the initial ones and have the ability to slip on the bridge deck. One end of the reconstructed part of the sidewalk is anchored to the deck through high strength dowels, while the other is anchored to the top of the wing-wall which is extended toward the approach embankment through a barrette wall. The aforementioned barrette wall has adequate length to resist the in-service and seismic loading of the bridge. In this way, the bridge obtains four restraints (one per wing-wall), which behave as tension ties during the deck contraction. During the longitudinal earthquake, the sidewalks also behave as tension ties which restrain the movements of the deck. The efficiency of the proposed method is investigated by utilizing an existing bridge of Egnatia Odos Motorway in Greece.

Keywords: Bridge, seismic, strengthening, sidewalks, restrainer

1. INTRODUCTION

The aim of the seismic strengthening of structures, buildings and bridges, is the accomplishment of the basic Code's requirement which imposes that the capacity of the structure should be greater than the demand for a specific selected limit state. There are two ways to accomplish the aforementioned code requirement: 1) by increasing of the element structural resistance where it is required, 2) by incorporating in the system of new elements that leads to a reduction of the old members' stress, so that it will be less than the available resistance. Considering the above retrofitting strategies, the second one, which is an "indirect" approach, seems to be more attractive, as it nearly eliminates the disturbances to the structure's operation through the application in specific restricted parts of it.

Regarding the cost of a strengthening technique, we should note that it is complex and includes the economic losses caused by the interruptions in the operation of the structure during the strengthening interventions. Thus, the indirect method can be considered more interesting from the economic point of view, since the cost is reduced by avoiding major interventions. The indirect technique is more preferable since it corresponds more effectively against the structural drawbacks which are not always traceable. These could be critical for the earthquake resistance of the structures by overruling the most diligently performed "diagnosis" and by-passing the most effective strengthening strategy.

Regarding the seismic strengthening of bridges, which is the subject of this study, the conventional retrofit strategies include the use of new materials and mainly aim at the strengthening of members aiming at a higher level of the seismic performance of bridges, (Cheng et al. 2003; Li and Sung 2003; Pantelides and Gergely 2002; Sieble 1994). The seismic strengthening of bridges also includes additional measures to reduce the likelihood of collapse due to unseating at the supports. The use of restrainer cables (Saiidi et al. 2001; Des Roches et al. 2003) to limit the relative hinge displacement became popular especially in the United States the last 40 years. These elements do not dissipate any significant amount of energy, since they are generally designed to remain elastic while studies showed that a very large number of restrainers are often required to limit joint movement to acceptable levels, particularly for high seismic loads (DesRoches and Fenves 2000). An advanced type of cable restrainers constitute the Shape Memory Alloys (SMA) (DesRoches and Delemont 2002), which act as both restrainers and dampers as they have the ability to dissipate energy.

The present study proposes a reliable and cost-effective indirect method for the seismic strengthening of existing bridges aiming to restrain of the development of the free longitudinal deck's movement and, by extension, to reduce the seismic actions. The proposed method utilizes the end parts of the sidewalks of the bridge, which are removed and reconstructed. This indirect bridge seismic strengthening method is described and analytically investigated below. An existing precast I-beam bridge is used as the reference case of the study.

2. DESCRIPTION OF THE PROPOSED INDIRECT SEISMIC STRENGTHENING TECHNIQUE

2.1 General

The bridge sidewalks are non-structural elements that are included in the additional permanent loads of the bridge. In the present study the sidewalks are developed and considered to participate in the earthquake resisting system of the bridge.

The end parts of the existing bridge sidewalks are removed and reconstructed so as to be converted to seismic restrainers which behave as tension ties and restrain the longitudinal movements of the bridge. The so-called seismic active length of the sidewalks is mainly determined by the serviceability requirements of the bridge. The configuration of the proposed restraining system is given in Fig. 2.1. The new sidewalks-restrainers constitute the extension of the existing sidewalks of the bridge and are not connected to the deck so as to allow the expansion and contraction of the bridge deck due to the in-service loading (see Fig. 2.2).

The implementation of the proposed technique requires the proper anchoring of the sidewalks ends. More specifically, the inner end of the sidewalks (toward the centre of the bridge) is anchored to the bridge deck through dowels arranged in a grid of 150x150mm (see Fig. 2.3). The anchorage length is about 2.0m. The outer end of the sidewalks (toward the embankment) is anchored to the top of the wing-wall which is extended toward the approach embankment through a barrette wall. In this way the existent "status quo" of the system is not be deteriorated and the seismic actions are transmitted to new and reliable structural members.

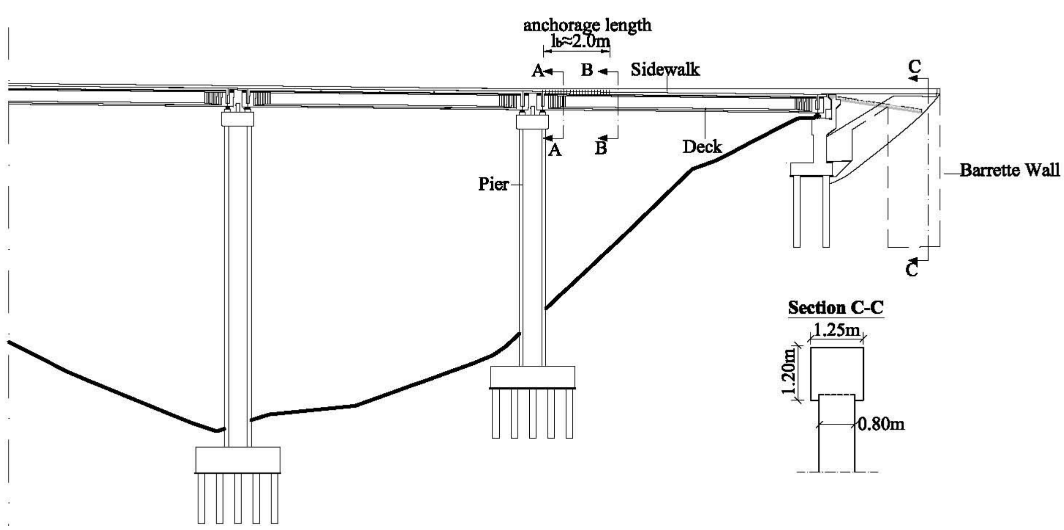

Figure 2.1. Longitudinal section of a precast I-beam bridge in which the proposed sidewalks-restrainers are implemented

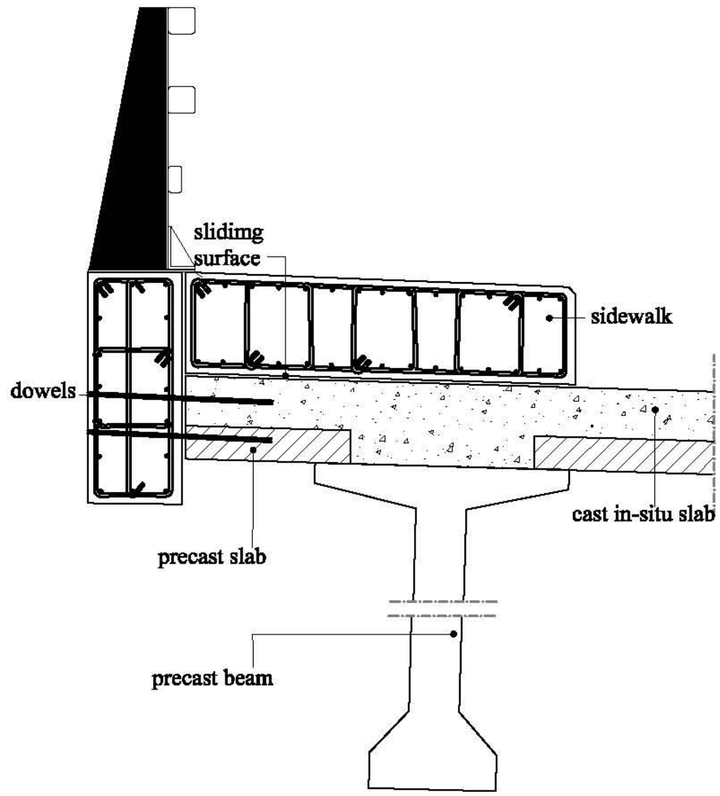

Figure 2.2. Cross-section of the sidewalks-restrainers (section B-B in Fig.2.1)

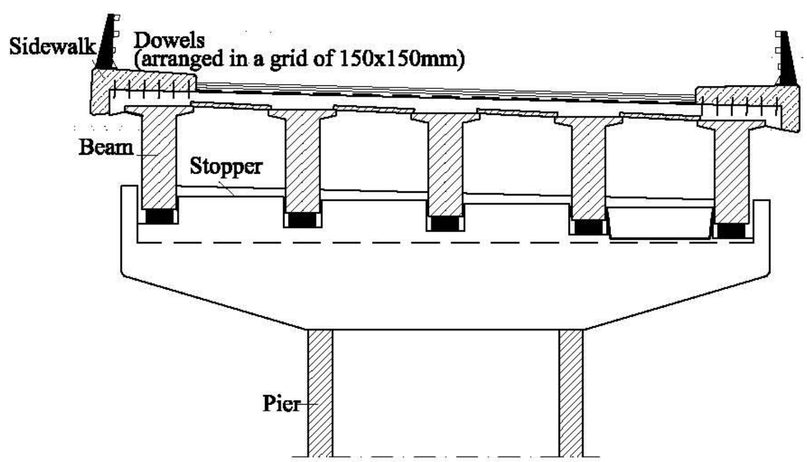

Figure 2.3. Cross-section of the sidewalk-restrainers at the anchorage length (Section A-A in Fig. 2.1)

2.2 Serviceability performance of the sidewalks-restrainers

During the contraction of the bridge deck the sidewalks behave as tension ties. The developed tensile forces are balanced by the longitudinal reinforcement of the sidewalks. In Fig. 2.4 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 minimum design length of the seismically active parts of the sidewalks is determined by the serviceability requirements of the bridge. More specifically its calculation is based on the crack control according to the Code's requirements (Eurocode 2-Part 1 2003). In this calculation the modulus of elasticity of the sidewalk-tie is taken 20% greater than the modulus of elasticity of the steel according to Fig. 2.4. At this point it is also necessary to note that, there is a difference between the requirements of the serviceability and seismicity needs regarding the longitudinal reinforcement ratio of the sidewalks. This happens because an increase in the number of bars, although it definitely improves the seismic resistance, it leads to additional secondary moments for the service limit state.

The maximum in-service change in the sidewalk's length Δl is derived by Eqn. 2.1. The first part of Eqn. 2.1 corresponds to the maximum in-service movement of the bridge. The deck is contracted due to the maximum thermal contraction (Eurocode 1- Part 1-5 2003). The second part of Eqn. 2.1 corresponds to the change in the sidewalk's length due to the thermal contraction, creep and shrinkage. $\Delta T_{N,tot}$ is the sum of the maximum variation of the uniform bridge temperature contraction component $\Delta T_{N,con}$ and the equivalent uniform contraction temperature $\Delta T_{N,per}$ due to creep and shrinkage (PCI 2012). The first part of $\Delta T_{N,tot}$ was considered to be equal to 25°C (Eurocode 1- Part 1-5 2003) while the second part was also considered equal to 25°C. a is the coefficient of thermal expansion, assumed to be equal to 10^{-5} m/°C (Eurocode 2-Part 1 2003), L_{tot} is the total length of the continuous deck of the bridge and l_{eff} is the effective length of the sidewalk- restrainer.

$$\Delta l = \alpha \cdot \Delta T_{N,con} \cdot \left(\frac{L_{tot}}{2} - l_{eff} \right) + \alpha \cdot \Delta T_{N,tot} \cdot l_{eff} \tag{2.1}$$

The minimum length, l_{eff}, is derived by Eqn. 2.2 as it is the only unknown factor. The first part of the equality corresponds to the deformation of the sidewalk. Δl is the maximum in-service change in the sidewalk's length and includes the unknown length l_{eff}.

$$\frac{\Delta l}{l_{eff}} \simeq 0.15\% \tag{2.2}$$

The deck's contraction due to creep, shrinkage and thermal effects causes tension of the sidewalks-restrainers. The developed axial force acting at the centre of the sidewalk's cross section at the anchorage joint causes a bending moment which compresses the bottom surface and has favourable effect on the distress of the deck due to the dead and traffic loads. On the other hand, the thermal expansion of the deck does not cause additional forces as the implied buckling of the sidewalk contribute to the elimination of the negative effects. The maximum lift of the sidewalks-restrainers due to the aforementioned inappreciable bend is of the order of some millimetres.

2.3 Seismic performance of the sidewalks-restrainers

During the longitudinal earthquake the sidewalks-restrainers behave as tension-ties which restrain the longitudinal movements of the bridge deck. The forces of the sidewalks-restrainers are transferred to the wing-walls which are extended toward the approach embankment through barrette walls, see Fig. 2.1. Eqn. 2.3 gives the maximum tensile resistance F_{yd} of the sidewalks. In this equation A_s is the longitudinal reinforcement area and f_{yd} is the design yielding stress of the steel bars (taking into account a safety factor 1.15) (Eurocode 2-Part 1 2004).

$$F_{yd} = A_s \cdot f_{yd} \tag{2.3}$$

The longitudinal reinforcement of the sidewalks-restrainers consists of bars of 14mm or 16mm diameter corresponding to a ratio equal to 2-4% while dense transverse reinforcements of diameter 8-10mm are used for the confinement of the cross-section.

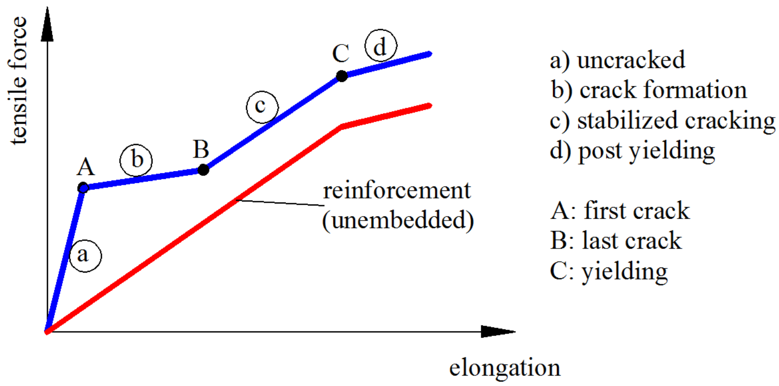

Figure 2.4. Idealized behaviour of a reinforced concrete tie

3. IMPLEMENTATION OF THE PROPOSED TECHNIQUE FOR THE SEISMIC STRENGTHENING OF A PRECAST I- BEAM BRIDGE

3.1 Description of the Bridge

The efficiency of the proposed seismic strengthening technique was assessed by applying it on a precast I-beam bridge, which is located at Asprovalta territory of Egnatia Odos Motorway and is given in Fig. 3.1(a). This bridge has four spans and a total length equal to 137.6m. The deck, Fig. 3.1(b), consists of five simply supported precast and prestressed I-beams, precast deck slabs and a cast in-situ part of the slab. The deck is supported on both abutments and on the piers through low damping rubber bearings. The piers, Fig. 3.1(c), are hollow rectangular sections with external dimensions 3.1x5.1m and a web thickness equal to 0.45m. The bridge is founded on a ground type B according to the Greek seismic design code (Ministry of public works of Greece 2000). The design ground acceleration was equal to 0.16g. The importance factor adopted was equal to γ_I=1.3 (Ministry of public works of Greece 2007), while the behaviour factors were equal to 1.0 for the three directions.

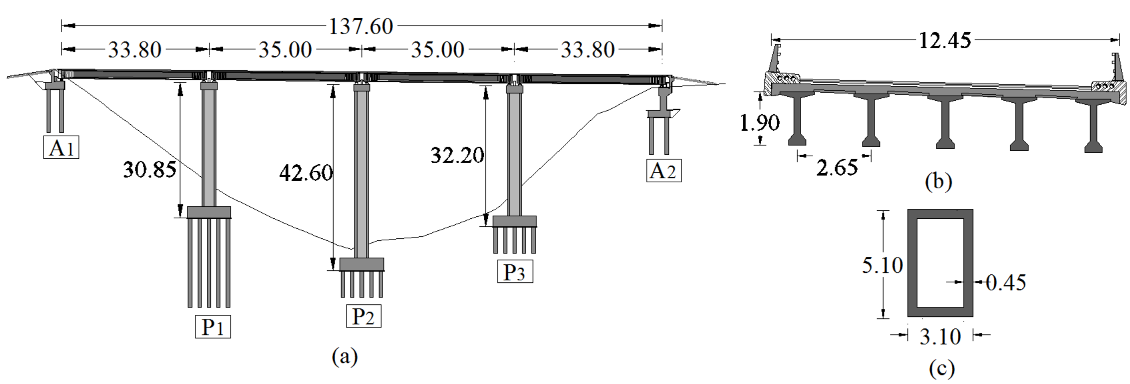

Figure 3.1. The "reference" bridge (a) Longitudinal section, (b) Cross –section of the deck and (c) Cross –section of the piers

This bridge which is considered to be the "reference" bridge of the study is strengthened so as to resist seismic actions corresponding to reference ground accelerations 0.24g and 0.36g.

The longitudinal reinforcement of the sidewalks corresponds to a ratio equal to 2%. The minimum design length of the seismically active parts of the sidewalks was determined according to the serviceability requirements of the bridge (see Section 2.2). This length is equal to 13.8m. The seismic active length of the sidewalks-restrainers must be greater or equal than the aforementioned minimum length. In this study the seismically active parts of the sidewalks is selected to be anchored at the first and third pier. Considering that the length of the end spans of the bridge is 33.8m the total length of each sidewalk-tie is 36.8m. This length is the span's length plus the anchorage length of the sidewalk into the wing-wall (5m) minus the anchorage length of the sidewalk on the deck (2m).

As mentioned in the previous section, the forces of the sidewalks-restrainers are transferred to the wing-walls which are extended toward the approach embankment through barrette walls. Fig. 3.2 shows the dimensions and the reinforcement detailing of the barrette walls, which are designed to resist forces corresponding to the upper limit of 5000kN. The resistance of these members against the transmitted forces is ensured by applying capacity design according to current Code's provisions (Eurocode 8- Part 1 2003).

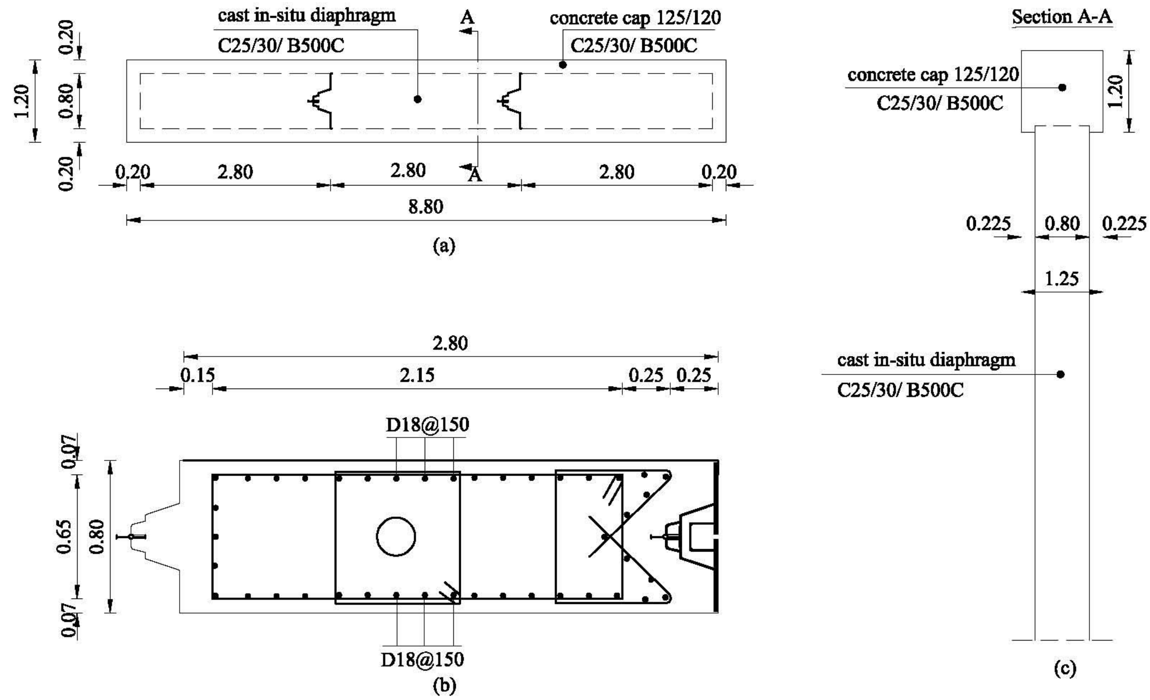

Figure 3.2. (a) Plan view of the barrette wall (b) reinforcement detailing and (c) Section A-A

3.2 Evaluation on the seismic performance of the upgraded bridge

The seismic performance of the upgraded precast I-beam bridge was assessed using nonlinear time history analysis. Five artificial records compatible with the Eurocode 8- Part 1 (2003) elastic spectrum and corresponded to 0.16g, 0.24g and 0.36g ground accelerations were used. The Newmark integration method was used, with time step $\Delta t = 0.01$ s and a total of 2000 steps (20 s of input).

Fig. 3.3 illustrates the model of the upgraded bridge, in which the sidewalks are used as seismic restrainers. The superstructure was modelled by frame elements and the existing bearings by springs. The sidewalks-restrainers were modelled by springs, which act only in tension. Analysis was carried out by using the SAP 2000 program (Computers and structures 2007). The plastic hinging in the piers was modelled by considering nonlinear rotational spring elements at the ends of the piers. The input parameters of the moment-rotation (M-θ) relationship were determined by fibre analysis performed in the computer program RCCOLA-90 (Kappos 2002) for each pier cross-section.

The analysis presented in the following paragraphs focuses on the longitudinal response of the bridge, as the seismic strengthening technique presented in this study deals with this direction of the bridge, which, as it is known, is more demanding than the transverse one. The response of the bridge to the transverse earthquake is more easily treated due to the presence of seismically active stoppers at the head of the piers.

The moment capacity of the piers to resist the increased seismic actions was mainly checked as well as the adequacy of the existing elastomeric bearings. Fig. 3.4 illustrates the bending moments at the base of the piers of the initial bridge for ground accelerations 0.16g, 0.24g and 0.36g and the bending moments of the upgraded bridge for ground accelerations 0.24g and 0.36g for the longitudinal design earthquake. It is observed that for design ground acceleration 0.24g the moment actions of the upgraded bridge system are significantly smaller than the corresponding of the initial bridge due to the beneficial participation of the proposed restraining system. This means that the bridge has the ability to resist earthquakes greater than the one corresponding to ground acceleration 0.24g. The investigation showed that even for ground acceleration 0.36g the bridge piers of the upgraded bridge remain elastic.

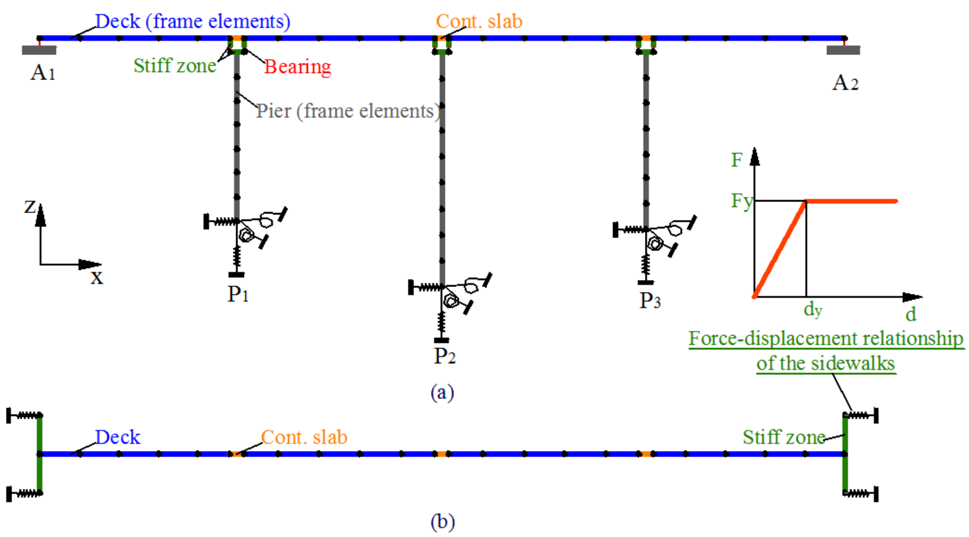

Figure 3.3. The model of the upgraded bridge: (a) Longitudinal section and (b) Plan view

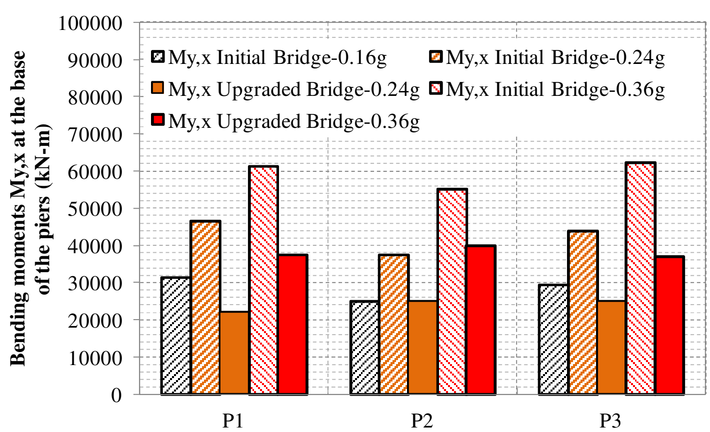

Figure 3.4. The moment actions ($M_{y,x}$) at the base of the piers for the longitudinal design earthquake (ground acceleration 0.16g, 0.24g and 0.36)

The efficiency of the seismic strengthening technique was also assessed by comparing the longitudinal movements of the upgraded bridge deck with the movements of the initial one. The adequacy of the existing elastomeric bearings was also checked. Fig. 3.5 shows the longitudinal movements of the initial and the upgraded bridge systems for two ground accelerations 0.24g and 0.36g. It is deduced that the longitudinal movements of the upgraded bridge are about 70% smaller than the movements of the initial one. The significant reduction of the deck's longitudinal movement also reduces the demand for voluminous bearings, whose thickness is mainly determined by the seismic displacements. Fig. 3.6 shows the maximum allowable ($\varepsilon_{s,max}$) (Eurocode 8- Part 2 2003) and the developed ($\varepsilon_{s,x}$) shear strain of the bearings due to the longitudinal earthquake for the bridges with and without the proposed restraining system and for a_g=0.24g. It is obvious that the code's requirement is easily satisfied in the case of the upgraded bridge ($\varepsilon_{s,x} < \varepsilon_{s,max}$).

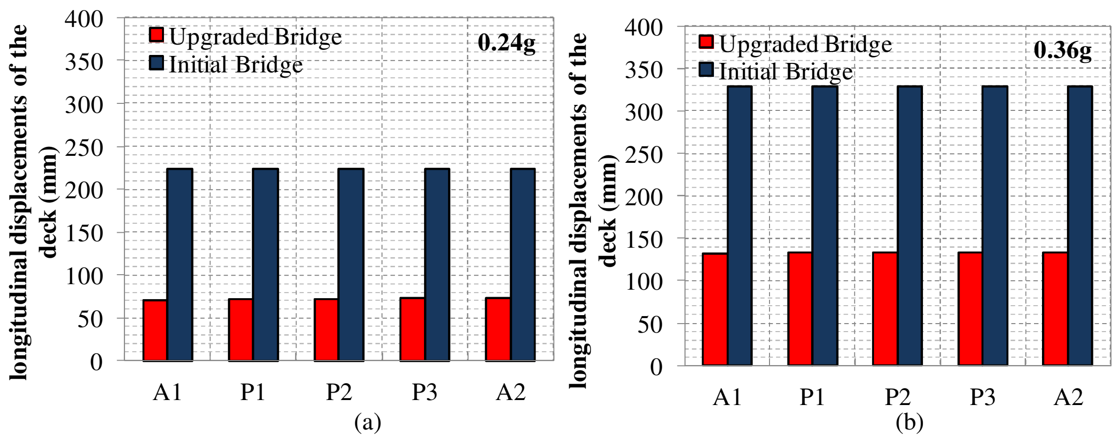

Figure 3.5. The longitudinal displacements of the deck over the piers (a) a_g=0.24g and (b) a_g=0.36g

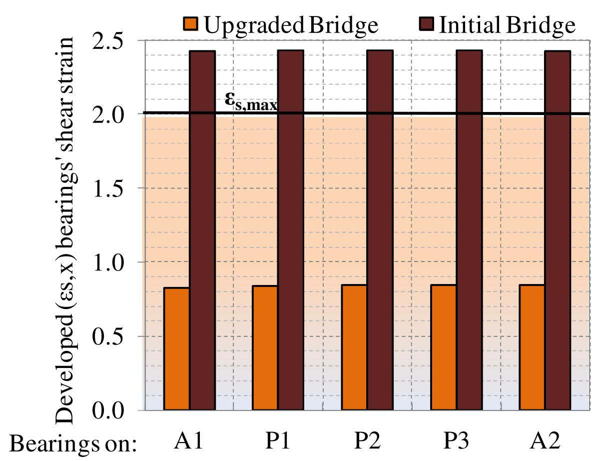

Figure 3.6. The values of the allowable ($\varepsilon_{s,max}$) and the developed ($\varepsilon_{s,x}$) shear strains of the elastomeric bearing for the longitudinal design earthquake (a_g=0.24g)

4. CONCLUSIONS

In this study the efficiency of a proposed technique for the seismic strengthening of existing bridges was presented. The proposed methodology is based on the conversion of the end parts of the bridge sidewalks to seismic restrainers. These sidewalks which are removed and reconstructed are of the same geometry with the initial ones and have the ability to slip on the bridge deck. The one end of the reconstructed part of the sidewalk is anchored at the deck through high strength dowels, while the second is anchored at the top of the wing-wall which is extended toward the approach embankment through a barrette wall. An existing precast I-beam bridge is strengthened so as to resist higher seismic actions than these that had been taken into account during its design (a_g=0.16g). It is desirable to underline the following as the main results of the investigation:

The proposed methodology comprises an indirect seismic strengthening technique in the sense that it does not cause interruptions to the operation of the structure during the strengthening interventions. The proposed seismic strengthening technique neither does affect the aesthetics of the bridge.

Major reduction of the seismic actions is achieved. The bending moments at the base of the piers of the strengthened bridge system are smaller than the bending moments of the initial bridge.

The reduction in the maximum seismic displacements of the strengthened bridge system is also significant. The resulting displacement magnitude is limited to 30% of the displacement magnitude of the initial bridge system. The significant reduction in the deck's longitudinal movement also reduces the demand for voluminous bearings, whose thickness is mainly determined by the seismic displacements.

From the economic point of view, the proposed restraining system has minor cost considering its effectiveness on the longitudinal earthquake, which is generally more difficult to be treated than the transverse one.

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