Seismic retrofit of bridges through the external installation of a new type restraining system

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SUMMARY:
A smart mechanism for restraining seismic loads is presented. The mechanism retrofits the structural system and decreases the loads to the level of its capability. It consists of steel bars that behave as struts-ties. Their one edge is anchored on the bridge deck, resulting in minor works. The other edge is anchored behind the abutments' wing walls through pile-diaphragms without harming the stability of backfill soil. This retrofit method belongs to indirect methods, which are considered more reliable regarding safety than the direct, since they rely on assumptions and uncertainties, i.e. samplings of member's strength. The proposed indirect method has minor intervention cost compared to that of a direct method. The presented system is applied in an existing bridge that was designed according to EC8 for seismicity zone I. The mechanism's application resulted in upgrading the bridge's seismic response to meet the requirements of Eurocode 8 for seismicity zone II.

Keywords: Concrete Bridge, Earthquake, Retrofit, Struts-Ties, Steel Bars

1. INTRODUCTION

Earthquake events cause major or minor damages on structures (Moehle and Eberhard 2000). Each structure is designed to maintain a certain level of performance depending on several factors such as the seismicity of the area or their importance (EC8-Part1 2003), (EC8-Part2 2003). Bridges, as key parts of the areal infrastructure, are expected not only to avoid collapse but also to remain functional even after a major earthquake event. The bridge traffic is expected to continue undisrupted under extreme conditions. Bridges designed according to current Specifications (i.e. EC8, AASHTO) conform to these requirements. However, worldwide there are bridges that were constructed formerly and their performance does not meet the contemporary requirements. For these bridges seismic retrofit is necessary for upgrading their seismic resistance. In addition, retrofit is essential even for properly designed bridges in cases that these bridges had been constructed in areas where due to changes in the geological data the design seismicity zone was increased. The larger seismicity of the area leads to higher seismic forces. Thus, the capacity of the existing bridge structural system shall be increased through retrofit methods.

Worldwide extensive research has brought up several retrofit techniques for bridges (FHWA 2006).For the purposes of this study the retrofit techniques are presented in two main categories. The first category includes the "conventional" direct strengthening methods. They are widely used and they include the strengthening of the deficient structural members of the system generally. The "unconventional" indirect methods constitute the second category. The issues that rise regarding the safety, economy and constructability of direct strengthening methods lead to the utilization of the "unconventional" indirect. The proposed method of struts-ties in the present paper belongs to the indirect methods.

The herein division could be justified considering the following. The fundamental safety inequality (EC2-Part2 2001), which requires everywhere and at all times the resistance to predominate the applied load, indicates the selection of one of the following two ways: 1) The increase of the member's structural resistance (direct strengthening methods) (Gergely et al. 1998). This action increases the first part of the inequality actually. For the application of this strategy it is necessary to rely on sampling for determining the condition of the members that will be strengthened leading to major assumptions and uncertainties. The application also includes major works, interventions and disturbances to the bridge functionality. These issues could be minimized with the second strategy. 2) The incorporation in the system of new members that change the structural system leads to a reduction of the existing members' applied forces, resulting in a lower magnitude than that of the available members' capacity (indirect methods). This action aims to decrease the second part of the fundamental code inequality. The indirect strategy is preferable since it corresponds more effectively against the concealed, in the sense that are not always traceable, structural flaws. These flaws could be "fatal" for the earthquake resistance of bridges by overruling the most diligently performed "diagnosis" and by-passing the heaviest direct strengthening. Regarding the cost, which includes not only the actual construction cost but also the economic losses caused by the interruptions to the operation of the bridge during the works, they can be characterized more economic since they include minor interventions.

In the last decades there are valuable efforts from the scientific community for the implementation of indirect retrofit methods for structures. The present approach proposes the implementation of an indirect method, the struts-ties method. The authors have presented a similar method for buildings (Markogiannaki and Tegos 2011),too. The overall goal is to develop a reliable and effective mechanism that reduces the total cost, maintenance and construction, of a retrofit method in bridges. The struts-ties can be characterized as similar to seismic isolation method, like the isolating dampers that absorb the seismic energy (Constantinou et al. 1998), but the seismic forces on the bridge structural system are reduced in a different manner. It includes the application of bundles of steel bars in bridges, as a struts-ties system, for limiting the seismic displacements of bridges. This system is based on an already proposed system for new bridges design (Tegos and Markogiannaki 2011), (Tegos et al. 2011). The method presented in this paper is advantageous regarding the necessity of maintenance and replacement especially. The members utilized in the proposed method do not need any maintenance and their life-time is the same with that of a reinforced concrete bridge. The proposed mechanism is applicable in integral bridges. Herein, the method proposed for the design of new bridges is adjusted to the requirements and conditions for the improved performance of existing bridges which is more demanding than the development of the restraining system in a completely new bridge. The application of struts-ties in existing bridges raises issues regarding their installation in the structural system of the bridge. The key objective of the present paper is to provide an efficient description and an analytical study of the proposed system and its efficiency.

2. STRUTS-TIES RETROFIT METHOD

The proposed mechanism, the struts-ties system, includes the application of bundles of longitudinal steel bars in the bridge superstructure. The steel bars are installed in four bundles towards the longitudinal direction of the bridge and each two bundles are placed in the outer spans of the bridge. The bars are placed in plastic ducts, which is the same method that is used in superstructures that are prestressed before the cast of concrete (un-bonded prestressing), in order to keep them unbonded from the deck's and abutment's concrete. They are bonded only at their ends through the anchorage length. A medium steel bar diameter, D14mm or D16mm, is assumed. These steel bar diameters are the largest ones available in the contemporary steel market in lengths up to 200m. The bars, due to anchorage needs, are grouped in teams of four vertically. The steel bars that are in the same group are anchored in positions that vary by 1m from the anchorage position of the steel bars of the next group. In new bridges the struts-ties system is installed in the cross section of the deck. (Figure 1, Tegos and Markogiannaki 2011). They are anchored in their ends; the one end is installed on the deck and the other in the four wing walls of the bridge's abutments.

The aforementioned mechanism is altered in its key parts for the application of the system in existing bridges as a seismic retrofit method. The issues that rise regarding the application of the restraining system are: a) The struts-ties of the restraining system shall be in a member of the bridge deck out of the structural system, since they cannot be installed in the existing structural system, i.e. in the cross section of the deck. b) The anchorage of the struts-ties on the deck of the bridge so that the seismic restraining forces will be transferred safely. c) The anchorage of the other end of the struts-ties in a position outside the existing structural system in a manner that the existing "status quo" will not be harmed and the restraining forces will be transferred in new reliable structural members.

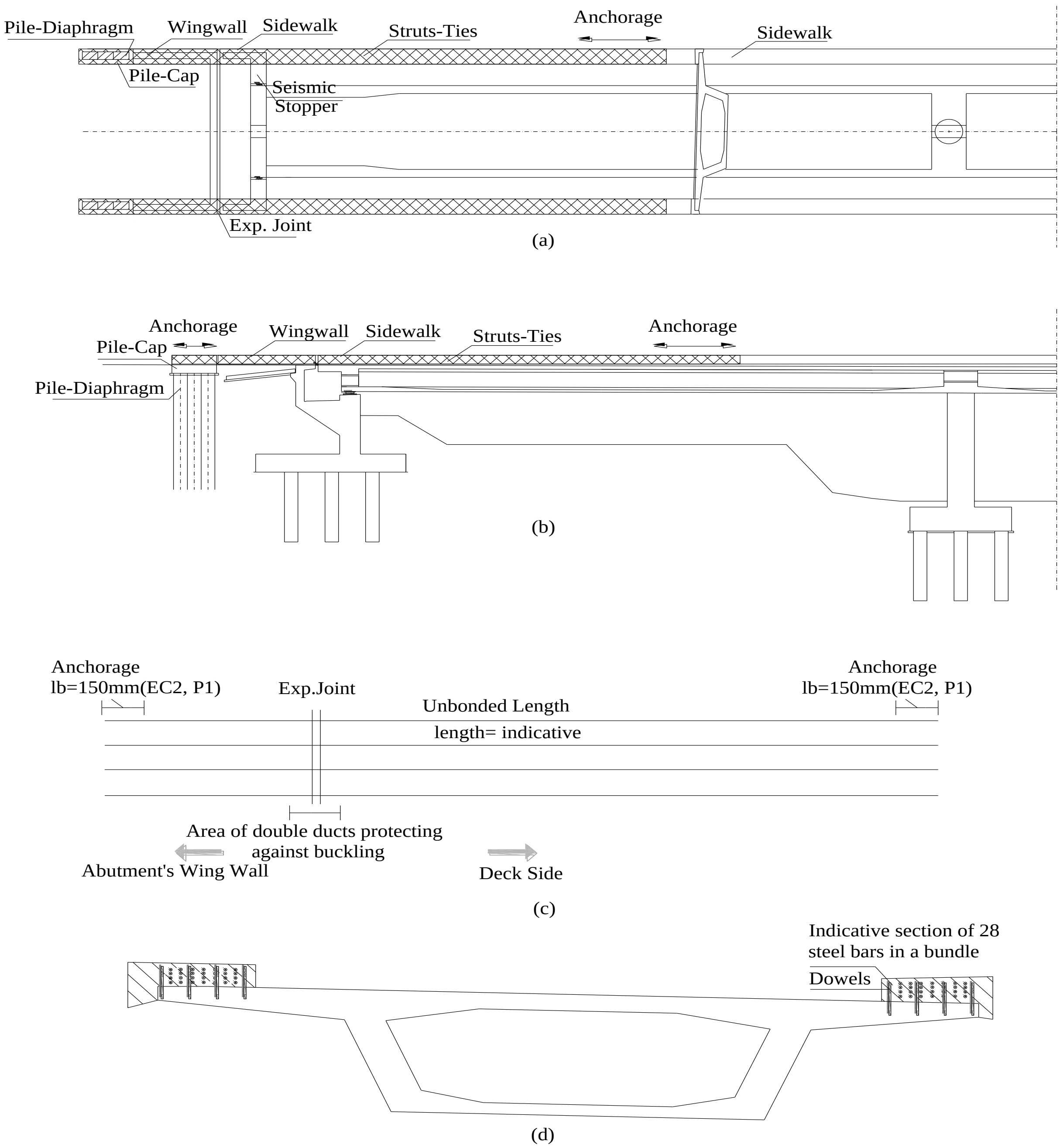

Figure 1. a) Plan of the bridge, b) Longitudinal cut of the bridge, c) Longitudinal Detail (indicative) of the steel bars, d) Detail of sidewalks on the cross section of the deck (indicative)

The proposed system is described schematically in Fig. 1. For paper space economy an indicative symmetric part of a bridge is presented (Fig. 1a, Fig. 1b). The mechanism of the struts-ties cannot be installed inside the cross section of the deck in existing bridges, since the bridge deck construction is already completed. Thus, a member out of the structural system of the bridge shall be found for the installation of the bundles of steel bars. The sidewalks that are constructed at the outer edges of the cross section of the deck and serve the needs of the transportation system are the non-structural system member where the steel bundles can be installed. The steel bars that constitute the struts-ties mechanism extent from the outer span of the bridge through the area beyond the wing walls of the abutments. For the proper application of the steel bars, the existing sidewalks, in the area where the steel bars of the mechanism are applied, shall be reconstructed. New sidewalks with the same width as the initial and length equal to the necessary for the installation of the struts-ties are planted with high strength concrete (i.e C35/45Mpa) which is stronger than the concrete of the sidewalks in the initial construction phase of the bridge.

For the safe anchorage of the new sidewalks to the cross section of the deck, dowels are utilized and installed in the whole length and width of the new sidewalks. The dowels are concrete type and are installed creating a mesh in the whole area of the replaced sidewalks. The dowels provide adequate corporation between the two connected elements (Choi et al. 1999). Additional measures for the safer anchorage of the sidewalks can be taken through the transverse wavy configuration of the interface between the sidewalk and the upper part of the deck and through the utilization of industrial non-shrinking high performance mortars. The roughness of the interface affects its shear resistance (Jilio et al. 2004; Tegou and Tegos 2009). The anchorage of the steel bars of the struts-ties mechanism is achieved through the necessary length extension of the steel bars in the sidewalks. The forces of the struts-ties either from the service or the seismic loading are transferred to the structural system by this anchorage.

The issue rising regarding the safe anchorage of the struts-ties in the part out of the bridge deck, which in the case of new bridges is handled by extending-anchoring the steel bars in the wing walls, is discuused below. In existing bridges the wing walls are not safe structural members to undertake the additional forces transferred from the restraining system, since they are not adequately designed. In existing bridges the steel bars of the proposed mechanism shall be anchored outside of the structural system of the bridge in a new reliable structure. The new structure utilized for the anchorage of the mechanism is a concrete pile-diaphragm in the extension of the wing walls of the abutments. The pile diaphragm consists of three rectangular concrete piles. These piles are connected through a pile cap which has the same width as the sidewalks. The steel bars are anchored inside the pile cap of the pile diaphragm system. In this manner the forces from the struts-ties mechanism are safely transferred and do not affect the structural system of the bridge.

The bundles of the steel bars are not used only as tension ties but also as members that receive compression since their installation in the sidewalks of the deck protects them from buckling. A critical part against buckling is at the outer expansion joint between the abutment and the deck. However, it is possible to take appropriate measures at that position in order to avoid buckling. The steel bars are activated by the in service loading of the bridge. They are in tension during contraction of the deck and are compressed during the expansion of the deck. Serviceability constraint movements induce additional stress that although it is of small magnitude, they shall be accommodated by a proper design of the abutments and the deck. The steel bars are subjected to fatigue due to daily and seasonal cyclic movements. This effect is not possible to be ignored despite the late improvements concerning steel ductility. Hence, the required lengths of the bars are estimated considering the requirements against fatigue (Eurocode 2-Part 2 2004).

The seismic response is improved mainly in longitudinal earthquake direction. The transverse system is widely accepted that is more advantageous than the longitudinal, since it usually has the advantage of the strong resistance of the longest direction or the rectangular cross section of the piers. The induced forces from the struts-ties mechanism develop moments due to the eccentricity of the anchorage points which, however, affect only the longitudinal direction and not the transverse due to the symmetrical application of the bars.

3. SEISMIC RETROFIT OF AN INTEGRAL CONCRETE BRIDGE

3.1. Description of the Bridge

The bridge that was utilized for the application of the proposed retrofit system is a monolithic prestressed bridge of Egnatia Motorway, located in Veroia territory in north Greece, in the Thessaloniki-Veroia route (Fig. 2). The bridge is skewed in plan by 51,84 degrees. It has three spans. The end spans are 45,10m and the middle span is 45,60m long. The total length of the bridge is 135,80m. The deck of the bridge consists of a concrete box cross section and is 13,5m wide and 2,20 m high. The deck is supported on the abutments by elastomeric bearings and is connected to the piers monolithically. The piers are circular with 2m diameter. They are founded on 3x3 pile groups. The piles have circular cross section of 1m diameter. The pile-caps of the foundations have dimensions 7,5x7,5m and cross-sections' height equal to 2,0m. The bridge's abutments are conventional seat-type abutments that provide the appropriate clearance (EC8-Part2, 2003) between the deck and the backwall. The abutments restrain the transverse movements of the deck, since there are capacity design stoppers installed on them.

The bridge is founded on ground type B and the design ground acceleration is equal to 0,16g (EC8-Part1, 2003) according to seismicity zone 1. The importance factor is taken equal to γ_I=1,3. The behavior factors are equal to 3 for the longitudinal, to 3,5 for the transverse and 1,0 for the vertical seismic action (EC8-Part1, 2003).

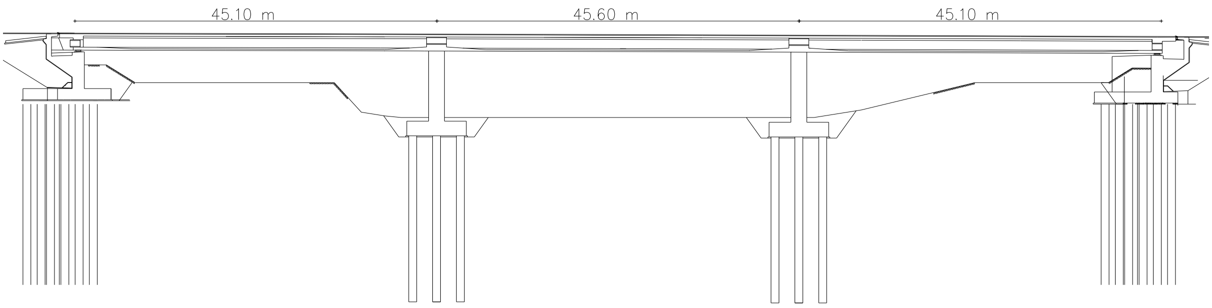

Figure 2. Longitudinal view of the bridge

3.2 Description of the Retrofitted Bridge (Preliminary Design of the proposed system)

The key objective of this study is to upgrade the seismic response of the existing bridge, herein the Veroia Bridge. For the purposes of the study it is recognized that there is a necessity for retrofitting the bridge in order to have a reliable performance for seismic forces of an increased seismicity zone, zone II. The proposed retrofit method, the struts-ties system, is applied on the bridge. The so-called Retrofitted Bridge has the same geometry namely, the same deck and pier height and total length as the existing Bridge. The difference between the existing Bridge and the Retrofitted Bridge is the introduction of the proposed seismic restraining system, which is described in section 2, in the Retrofitted Bridge. In the Retrofitted Bridge 28 steel bars of 14mm diameter, in 4 bundles in the sidewalks of bridge system as it is described in section 2, are introduced. The minimum design length of the steel bars was determined assuming that the steel bars are elastic for the serviceability needs. The required steel bar length, *l*, is calculated by equating the maximum strain of the steel bars, first part of Eqn. 1, to the maximum allowable strain, second part of Eqn. 1, which is the elastic response for the in service limit state. Generally, the maximum allowable strain is derived by the deviation of the yielding stress of the steel bars (taking into account a safety factor 1,15), in this case 435 MPa, with the modulus of Elasticity *E*, 200 GPa. In this particular case fatigue shall be taken into account, too. This leads to a decrease in the maximum allowable strain. It should be noted that although the stress is cyclic annually, the number of cycles is minor regarding fatigue and is equal to the estimated life time of the bridge, 100 years. Consequently, a minor decrease to 85% of the calculated yielding stress is preferable. The 85% corresponds to the case of the serviceability criterion of prestressed tendons that can be taken as a relevant precursor. Hence, the maximum allowable strain is 0,185%.

$$\frac{\Delta l}{l-2l_b}=0{,}185\% \quad (1) \qquad\qquad \Delta l = a\cdot\Delta T_{N,tot}\cdot\left[\frac{L_{tot}}{2}-l_{eff}\right]+a\cdot\Delta T_{N,con}\cdot\left(l-2l_b\right) \quad (2)$$

The term Δl is the maximum in-service change in the bar's length. It includes the unknown length l and is derived by Eqn. 2. The first term of the second part of Eqn. 2 corresponds to the maximum in-service movement of the bridge. The deck is contracted due to the maximum thermal contraction, $\Delta T_{N,con}$ (25^{o}C), (EC1-Part 5, 2003) and the simultaneous influence of creep, prestressing and shrinkage effects, $\Delta T_{N,per}$ (25^{o}C) (PCI 2010), $\Delta T_{N,tot}$ is equal to 50^{o}C. The second term of the second part of Eqn. 2 corresponds to the change in the bar's length due to the thermal contraction. α is the coefficient of thermal expansion, equal to 10^{-5} $m/^oC$, L_{tot} is the total length of the continuous deck of the bridge., l_{eff} is the effective length of the bar from the expansion joint to the anchorage point in the bridge sidewalk. It is noted that, l_{eff}=l-2l_b-l_w, where l_b is the anchorage length and l_w is the length of the bar into the wing wall. Based on the assumptions that lb=1m and lw=8 m, the minimum design length was calculated 20.0 m.

3.3 Model And Analysis

The existing and the Retrofitted Bridge system were modeled with stick models using SAP2000 (Computers and Structures Inc. 2007).

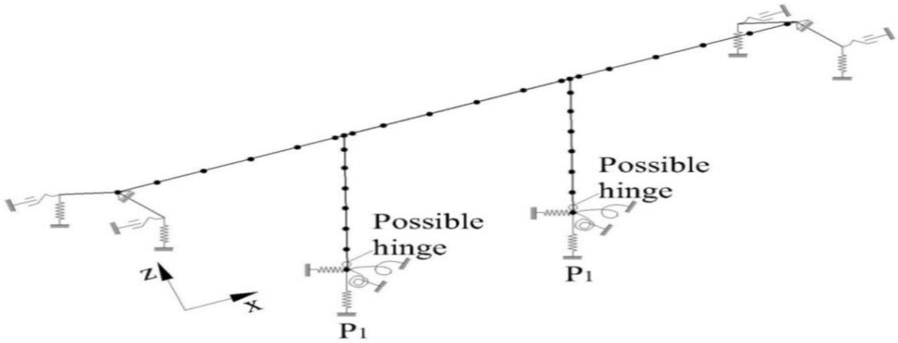

Figure 3. Stick Model of Retrofitted Bridge

In Fig. 3 the stick model of the Retrofitted Bridge is represented. The deck of the bridge was modeled with beam elements having the geometrical properties of the box cross section of the deck. The piers were modeled as beam elements, too, and had possible plastic hinges at the bottom. The plastic hinge zone was assigned a lumped plasticity model, fiber hinge model SAP2000, while the rest of the element outside the plastic hinge was assigned an elastic frame element with a solid cross section, according to its geometry, using effective section properties (PEER 2008). The flexibility of the foundation was also taken into account by assigning spring elements according to the geotechnical report. The steel bundles were modeled by link elements with the corresponding stiffness, k, derived by the Eqn. 3, where A is the steel bar area of each of the four bundles, l is the length of steel bars and E is the Young's Modulus of Elasticity. The link elements were introduced in the model, as it is shown in Fig. 3, symmetrically in both sides of the outer spans.

$$k=\frac{EA}{l} \quad (3)$$

The bridge seismic performance was assessed by applying both linear modal response spectrum analysis (Chopra 1995) and non-linear dynamic time history analysis. It should be noted that an advantage of the proposed method is the applicability of the simple linear dynamic analysis which is convenient to all structural designers. Two sets of time history analysis were utilized. For each set of non-linear dynamic time history analysis five artificial records were utilized; the records were compatible to EC8-Part 1 elastic spectrum of soil type B and corresponding to 0.16g and 0.24g respectively. The maximum response values (displacement and forces) were then calculated. The Newmark $\gamma=1/2$, $\beta=1/4$ integration method was used, with time step Δt =0,01 s and a total of 2000 steps (20sec of input).

3.4 Seismic Performance and Discussion

The analysis was conducted in SAP2000 structural analysis program. The results derived from the analysis focus on the longitudinal response of the bridge, as this direction of the bridge is known as more demanding than the transverse one. In Fig. 4 the maximum longitudinal displacements for the Existing and the Retrofitted Bridge are presented and the corresponding reduction in percentage, too, regarding the seismic zone I. The longitudinal movements of the Retrofitted Bridge system are reduced up to 45%. The application on the bridge of the seismic loads of seismic zone II on the Existing and the Retrofitted Bridge, shown in Fig. 5, indicates that even for higher seismicity the longitudinal movements of the bridge are still greatly reduced. In fact the corresponding maximum movement of the bridge deck for seismicity zone II for the retrofitted bridge is much lower than the expected maximum movement of the Existing Bridge for the current seismic zone I. The low values of the maximum displacement of the bridge deck that are developed in the case where the proposed system is applied (Retrofitted Bridge) are shown in the following figure.

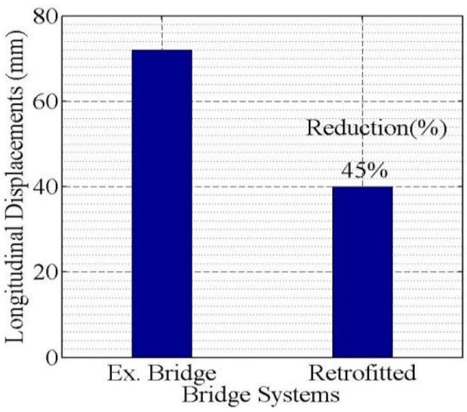

Figure 4. Max Longitudinal displacements (zone I)

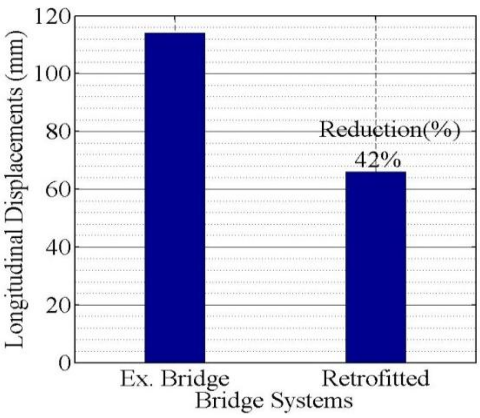

Figure 5. Max. Longitudinal displacements (zone II)

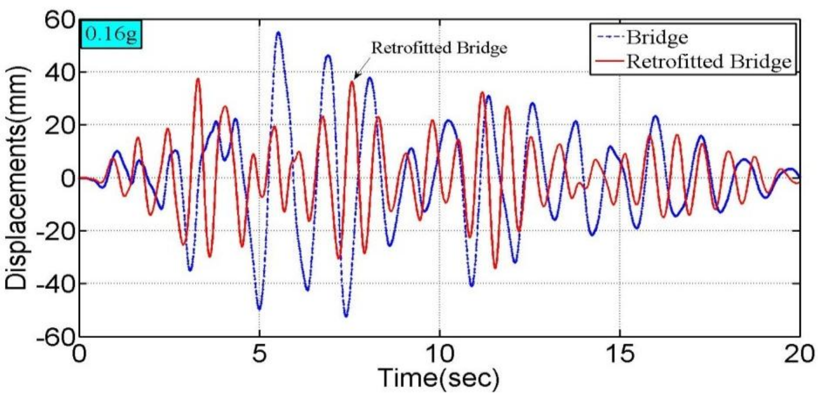

Figure 6. Deck's longitudinal displacement, Retrofitted Bridge for zone I

In Fig. 6 two displacement-time history functions are plotted for the Bridge, with and without the proposed retrofit System resulting from the analysis of the structural model with artificial records compatible to Eurocode 8 for 0.16g peak design ground acceleration. In Fig. 7, similarly, two displacement-time history functions are plotted for the Bridge, with and without the proposed retrofit System resulting from the analysis of the structural model with artificial records compatible to Eurocode 8 for 0.24g peak design ground acceleration. One response from each record set was selected. The functions that are presented lead to the maximum system displacements for the aforementioned ground accelerations. The time histories indicate that the overall structural system with the struts-ties becomes stiffer.

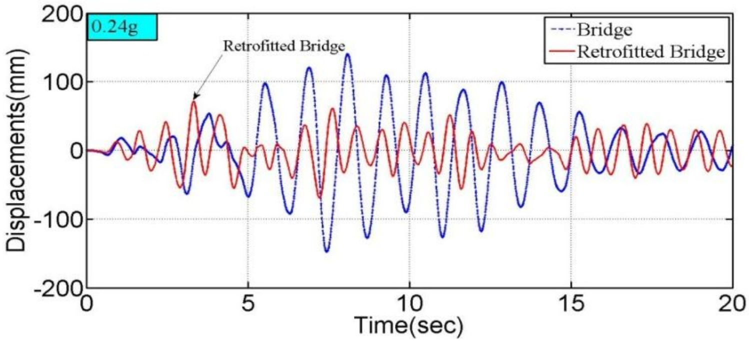

Figure 7. Deck's longitudinal displacement, Retrofitted Bridge for zone II

The evaluation of the proposed system was also implemented by calculating the percentage reductions in the seismic actions at the piers' base. In Fig. 8 the percentage reductions in the bending moment actions and the shear forces at the pier's base are presented depending on the different sets of time history analysis, 0.16g and 0.24g. In the Retrofitted Bridge, which is how the bridge system with the struts-ties system is called, the $M_{y,x}$ bending moments and the V_y shear forces are more than 40% smaller than the $M_{y,x}$ bending moments and V_y shear forces of the Bridge without any retrofit respectively. It can be concluded, that the struts-ties mechanism responses as an effective restraining retrofit system.

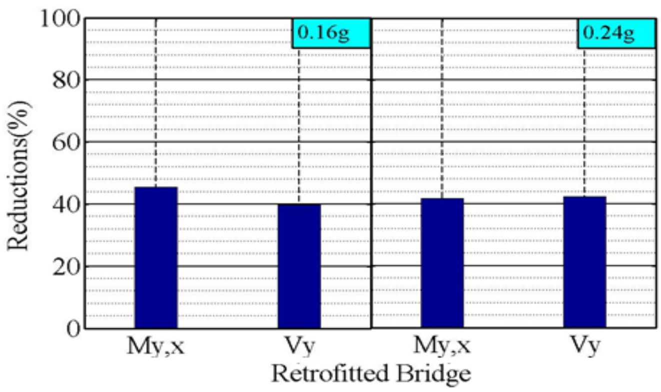

Figure 8. Reduction of pier base moments for retrofitted bridge (seismic zone I, II)

This is proved also by the change in the fundamental periods of the system, Fig 9. There is a reduction in the longitudinal fundamental period of the structural system of the bridge when the proposed retrofit system is applied. In Fig. 10 the forces developed in the proposed restraining system for the longitudinal earthquake (time history analysis for seismic zone I, II) are presented. One response from each record set was selected leading to the maximum forces transferred to the structural system of the Bridge. For seismicity zone I the maximum values of the forces developed in each bundle are close to 1500 KN. Considering that two bundles are installed in each outer span of the deck symmetrically in the sidewalks and anchored in the pile diaphragm, the total maximum force that is transferred is not more than 3000KN. For seismicity zone II the maximum values of the forces developed in each bundle are close to 1900 KN. In this case the system shall be able to accommodate no more than 3800kN. The magnitude of the horizontal forces developed by the application of the restraining system can be undertaken by the deck safely.

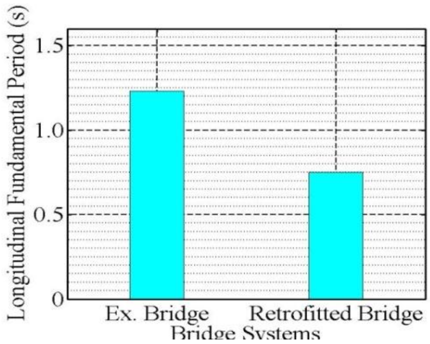

Figure 9. Fundamental periods

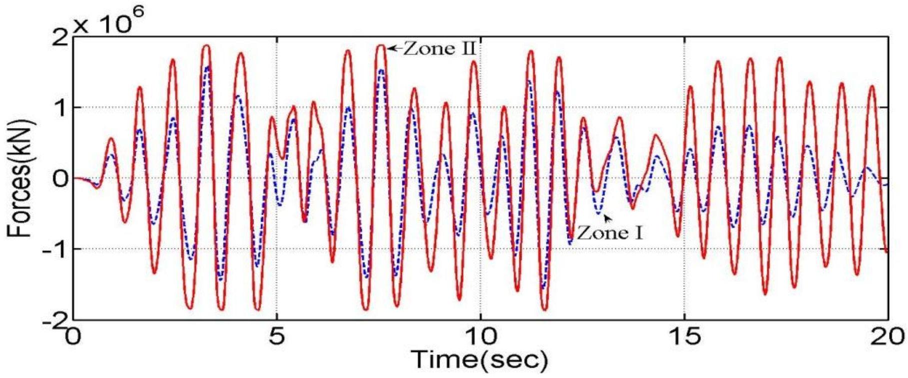

Figure 10. Forces on each bundle for the retrofitted system

4. CONCLUSIONS

An indirect intervention method for the seismic response upgrade of an existing bridge is presented in this study. This retrofit method includes the installation of a struts-ties mechanism in the outer parts of the two sidewalks after the demolition of the necessary length of the existing ones. The aforementioned struts-ties are anchored in a special wall-like pile-diaphragm that constitutes the extension of the existing wing-walls of the abutments. The main results derived from the study and the application of the mechanism on an existing bridge of Egnatia Motorway can be indicated as the following:

1) The seismic performance upgrade of bridges resulting from the application of the mechanism includes mainly the difficult longitudinal earthquake direction. Actually, the mechanism is applied in the longitudinal direction.
2) The analysis on a three span concrete bridge showed the high efficiency of the method is remarkable. The resulting longitudinal maximum displacements and the bending moments and shear forces of the piers are reduced greatly for the seismic forces of zone I and II. The analysis of the structural system with the response spectrum of seismic zone II and the record sets compatible to Eurocode 8 - (0.24g) showed that the developed seismic values could be adequately sustained by the bridge’s structural members. The seismic upgrade of the bridge was achieved.
3) The safety provided to the bridge structure can be characterized as more reliable than that of a respective conventional method, since it is created by the introduction of new structural members in the bridge system and is not dependent on the existing bridge members capacity, as it is usually when conventional methods are utilized.
4) The resulting cost of the retrofit method, construction and maintenance, is lower than that of a conventional retrofit method. The steel bars have minor cost compared to any other retrofit

method and the pile diaphragms are of low cost, too. The proposed restraining retrofit system has no maintenance cost since it does not require any replacement through the lifetime of the bridge.

5) The disruptions caused to the bridge's traffic during the application of the struts-ties method are nearly negligible considering that the construction works in the sidewalks can be performed without stopping the traffic of the bridge at all times.
6) The bridge aesthetics is reserved intact, since there is no change in the geometry of the bridge system. This is due to the fact that the struts-ties mechanism is fully incorporated in the sidewalks of the bridge.
7) Includes the advantage of flexibility, since it can be adapted in all levels of seismic requirements. The amount of steel bars used in the struts-ties mechanism can be increased for reaching high performance level of seismic response. Even the requirements of seismicity zone III could be accommodated with the appropriate steel bar area.

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