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Evaluation of the Seismic Response of High Pier Bridges with Longitudinal Restrainers

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***Abstract*—The presence of high piers in bridges increases the influence of P-δ effects and results in large longitudinal movements regarding the seismic response of bridges. The main target of the present study is to propose and investigate the performance of a longitudinal restraining system for bridge movements that accommodate P-δ effects. A possible solution for addressing large longitudinal displacements is increasing piers' stiffness which can be achieved by enlarging their cross-sections in the bridge design. However, in this manner the total cost of the bridge is largely increased and in case that hollow sections are used the available ductility is reduced. The use of seismic dampers could be another possible way to reduce seismic movements but it is not cost-effective, as well. In the present paper a cost-effective restraining system is presented. The targeted reduction of the longitudinal seismic displacements is achieved with the installation of four bundles of steel rebars, called STR's, in bridge's deck which can receive tension and compression loading, as well. The forces of the steel bundles are transferred to the properly designed abutments. A bridge with high piers was utilized as a case study for the investigation of the contribution of the mechanism to limiting the longitudinal displacements and P-δ effects. Non-linear analyses were performed for a suite of ground motions. The analyses' results have shown the improved seismic behaviour of bridges with high piers when designed with the restraining system of steel bundles.**

Index Terms*— Bridge, High Piers, Seismic Response, Restrainers,

I. Introduction

In bridges with high piers various structural issues arise. More specifically, in cases of large pier heights phenomena as second order effects, P-Delta effects, shall be considered in the design. As described in [1] second order effects are additional action effects caused by the interaction of axial forces and deflections under lateral load. First order deflections lead to additional moments caused by the axial loads and these in turn lead to further increases in deflection. Such effects are also sometimes called P-Delta effects because additional moments are generated by the product of the axial force and element or system deflections. Second order effects can be calculated by second order analysis that takes into account this additional deformation. Eurocode 8, [2], includes provisions that propose the consideration of second order effects in the design.. Second order analysis for reinforced concrete elements is non-linear with respect to both geometry and material behavior. Eurocode 8, [3], proposes even for linear analysis cases approximate methods to estimate the influence of second order effects in critical sections. Except P-delta effects and buckling, designers shall accommodate large seismic movements of the bridge superstructure in high seismicity areas. The increased movements of bridges require the consideration of large expansion and seismic joints that further complicate the structural design and affect the total cost of bridges. Often in bridges of low seismicity regions passive restraining devices are used in order to limit the seismic movements of the deck drastically without aiming on the reduction of the seismic inertial forces.

Regarding serviceability, large pier heights are advantageous since it is possible to arrive to integral bridges without any negative consequences on the piers by bridge's contraction and expansion. However, constructability issues arise regarding purring of concrete because of large heights. The most common solution is the balanced cantilever construction solution which is generally expensive compared to other bridge construction methods. It should be noted that besides the expensive equipment required there is also the need to use hollow pier cross sections in order to satisfy the increased stiffness demand due to large pier heights. Hollow cross sections are considered to have better response for elastic behavior requirements, behavior factor 1or 1.5, rather than for ductile which is required for integral bridges seismic response. On the other hand the substantial increase of seismic pier moments due to P-δ effects results in large reinforcement ratios at the positions of possible plastic hinges which lead to further decrease of the available plasticity.

On the light of the above remarks, the investigation of a mechanism that could control the size of the seismic movements constitutes a research goal that could be applicable to various design cases. In the present study such a restraining system for bridges with high piers is proposed and described in the following paragraphs based on previous research of the authors [4]. The use of restrainers in different formations has been extensively investigated in the last decades. However, it has been based mainly on the use of high strength steel restrainers and advanced materials (i.e. shape memory alloys), [5], [6], [7]. Hollow pier cross sections were avoided along with any resulting consequences on the seismic safety, the aesthetics, the serviceability, the economy and

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durability of the bridge structure.

II. Proposed Seismic Restrainers

The restraining system proposed for limiting the longitudinal movements under earthquake loading is a system of steel bundles that can be activated both under tension and compression loading. Therefore the proposed system can be referred as a struts-ties restrainer mechanism (STR). The restraining system involves the installation of four bundles of steel rebars in the cross section of the deck of the bridge. The bundles are installed towards the longitudinal direction of the bridge and each two bundles are placed in the outer spans of the bridge extending through the abutments' wing walls. The steel rebars are placed in plastic ducts, similar to prestressed concrete tendon practices, in order to avoid bonding between the steel rebars and the concrete of the bridge. The steel rebars are only bonded with the concrete at their ends to ensure sufficient anchorages. Each of the four bundles consists of groups of steel rebars that are anchored at different points so that the anchorage forces are not developed in the same positions. The bundles of the steel rebars are not only activated as tension members but also as members that receive compression, since the installation of the steel rebars inside the deck protects them from buckling issues.The steel rebars have common steel strength (i.e. S500) and medium diameters of 14mm or 16mm that are available in steel market in lengths up to 200m. In Figure 1 the struts-ties system is graphically described.

It is important to underline the key points of the structural behavior of the struts-ties system for a more comprehensive understanding of the investigation discussed in the next sections. Regarding service loading, the steel bundles are in tension during deck contraction and are compressed during deck expansion. The steel bundles are expected to have elastic behavior in serviceability limit state. This goal is achieved through a minimum steel rebar length requirement as described in previous work, [8], [9]. Under earthquake loading, the STRs restrain the longitudinal movements of the bridge and a part of the seismic forces is transferred through the steel bundles to the abutments and embankments. The piers receive the rest of the seismic forces. In this manner, the abutments are activated and contribute to the seismic resistance of the bridge. It is noted that in traditional ductile bridges, the piers receive the major part of the seismic forces and the abutments are not considered as seismic resistant components of the bridge while in bridges with the STRs there is a balanced participation of piers and abutments in the seismic resistance of the bridge.

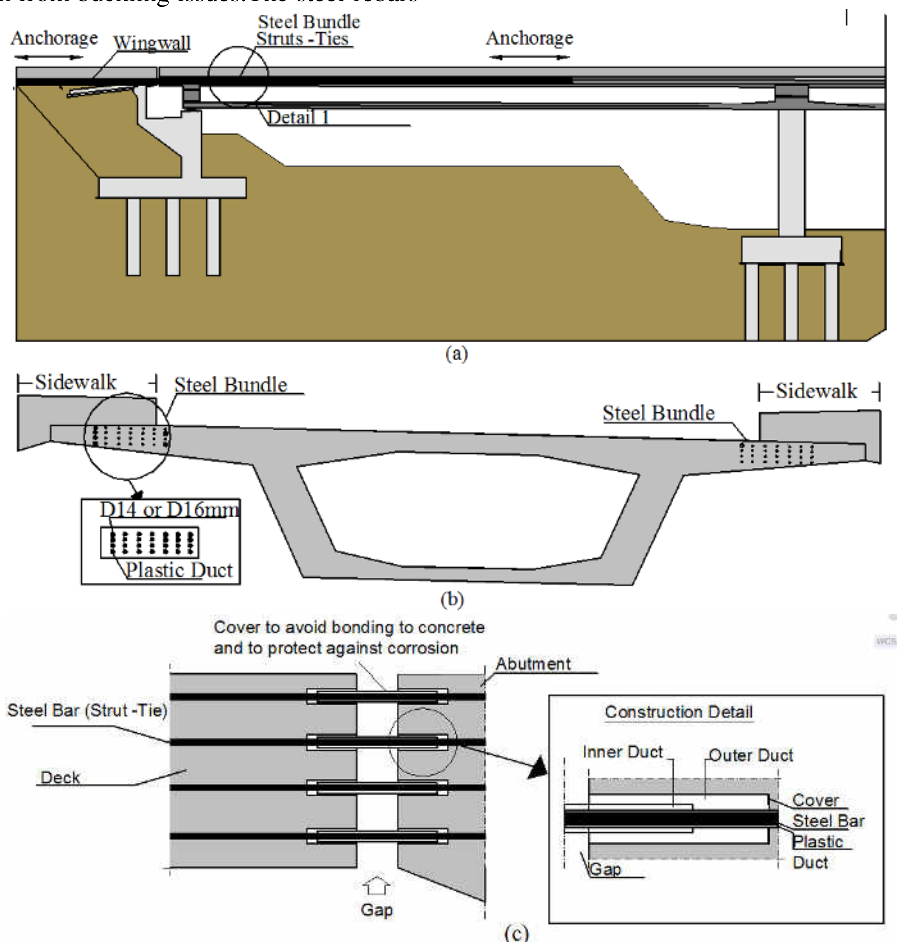

Figure 1. Restraining System. a. Longitudinal view of the bridge, b. Detail 1: cross section of the deck of the bridge, c. Detail at the Expansion Joint between Deck and Abutment

III. CASE STUDY BRIDGE

A. Case study Bridge Description- Bridge Model.

The bridge used as a Reference Bridge for the application of the proposed system is an integral concrete bridge in north Greece, (Fig. 2).

The bridge has five spans with a total length of 240m. The deck has concrete box cross-section, 13.5mx2.7m and is supported on the abutments by sliding bearings. The piers have rectangular cross section, 1.5mx5.0m. In the original bridge the pier heights differ but in the present study for research purposes, they are all considered equal to 23m (as the highest pier). The piers are founded on 3x3 pile groups. The piles have circular cross section of 1.2m diameter. The pile-caps of the foundations have dimensions 7.7x8.9m and cross-sections' height equal to 2.2m. The bridge's abutments are conventional seat-type abutments. The abutments restrain the transverse movements of the deck, since there are capacity design stoppers inshighed on them. The bridge is founded on ground type B, [2]. The bridge model includes nonlinearities and was generated in the finite element analysis software OpenSees, [10]. The section analysis for the assignment of concentrated plasticity at the top and bottom of piers was performed with AnySection developed by [11]. The foundation springs were provided by the geotechnical report of the bridge. For the passive resistance of the abutments, the stiffness values from Caltrans, [12], and the procedure demonstrated by Nielson, [13], were used. The steel rebars of the restraining system (in 4 bundles) were modeled as nonlinear springs, as shown in Figure 2 and Table 1 (AsBars refers to the Steel Area of each of the four bundles and lbar to the length of each steel bar without accounting for the anchorage length). Time-history nonlinear dynamic analysis was carried out with 7 independent pairs of recorded events taking the average of the individual responses as the design seismic demand. The records were selected with REXEL 3.5 Beta [14] and their average spectra is compatible to Eurocode spectra for 0.16g, 0.24g and 0.36g.

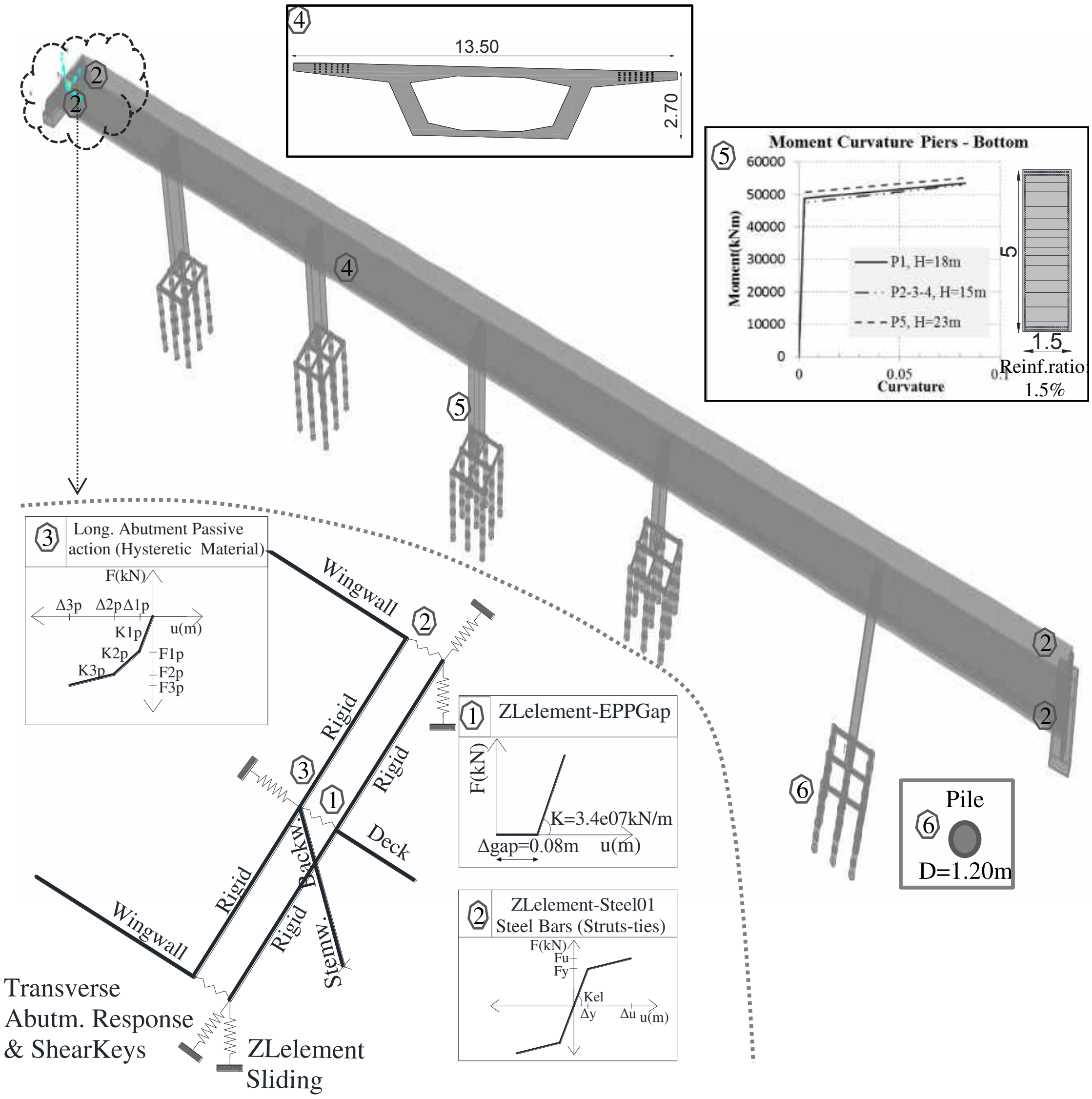

Figure 2. 3-D Bridge Model

Table 1. Steel bundle properties (applicable to each of the 4 steel bundles applied in deck)

Steel Bundle Properties (STR's)			
fy	AsBars x σy (500MPa)	fu	AsBars x σu (600MPa)
Δy	esy(0.001) x lbar	Δu	esu x lbar
Kel	E x Area of Bars / lbar	Kinel	0.8% x Kel

IV. ANALYSES AND RESULTS DISCUSSION

In bridges with high piers P-Delta effects shall be incorporated in the analysis. In Table 2 the increase in the seismic forces is presented for the initial bridge accounting for P-Delta effects. The observed response of the piers is affected by the incorporation of P-Delta effects and avoiding them would lead to underestimation of the seismic demand.

Table 2. Increase of Pier Moments due to P-Delta effects

Bridge Pier Moments	% Increase due to P-Delta effects in the analysis	
	0.16g	0.24g
$M_{pier_{1,5}}$	4.3	7.6
$M_{pier_{2,3,4}}$	4.2	7.5

The initial bridge as formed with five piers of 23m faces large displacements. At first, the bridge seismic response was investigated for the application of STRs, 28 steel rebars of 16mm diameter in each of the four steel bundles, on the initial bridge geometry of piers that have 1.5mx5.0m cross section, Figure 3. The analysis showed reduction in the longitudinal displacements of the bridge, especially for the second seismic design level. Such results indicate that the STR's could be used for limiting displacements instead of high cost damper solutions and that the size of the required seismic joints and bearings at the abutments could be kept in lower levels. For a more comprehensive study different longitudinal reinforcement ratios were applied in combination with an alternative smaller pier width, 1.2m. For both cross-sections buckling criterion is satisfied for this bridge according to Euler's Equation.

In Figure 4 reduction of the longitudinal movements in bridges with STRs in comparison to initial configurations without STR's for different pier cross section widths and longitudinal reinforcement are demonstrated. It is observed that in bridges with high piers the presence of STRs results in substantial reduction of the longitudinal movements ,especially for higher seismicity, seismic design level II and subsequently limits the influence of second order effects while lowering the demand for the expansion joints at the outer spans of the bridge as well. In absolute value terms, the movements of the bridge of Bx1.20m and with 2% reinforcement ratio are lower the initial bridge of 1.5m width without the STRs and the seismic demand forces on piers are within capacity limits. Therefore, the bridge with the STR's could be designed even more economically, with smaller pier cross-section and the smaller sizes of seismic joints and bearings on the abutments. For studying the STR's behaviour regarding their characteristics a parametric investigation regarding the size of the four steel bundles in the initial bridge geometry was conducted. As it can be seen in Figure 5, for low seismicity the size of STRS does not affect significantly the effectiveness of the mechanism , while for 0.24g seismic design level the seismic response of the bridge is highly influenced by the size of the steel bundle of the STRs. It is obvious that for such seismic demand it is preferable to use sizes of28 or 35 steel rebars per bundle.

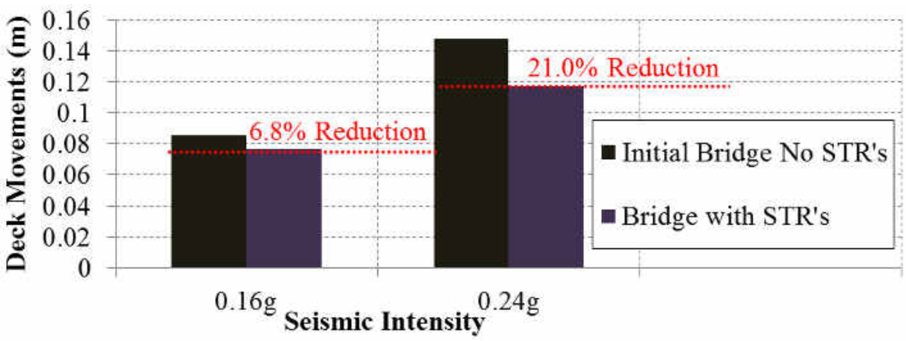

Figure 3. Deck movements for initial bridge with and without STR's

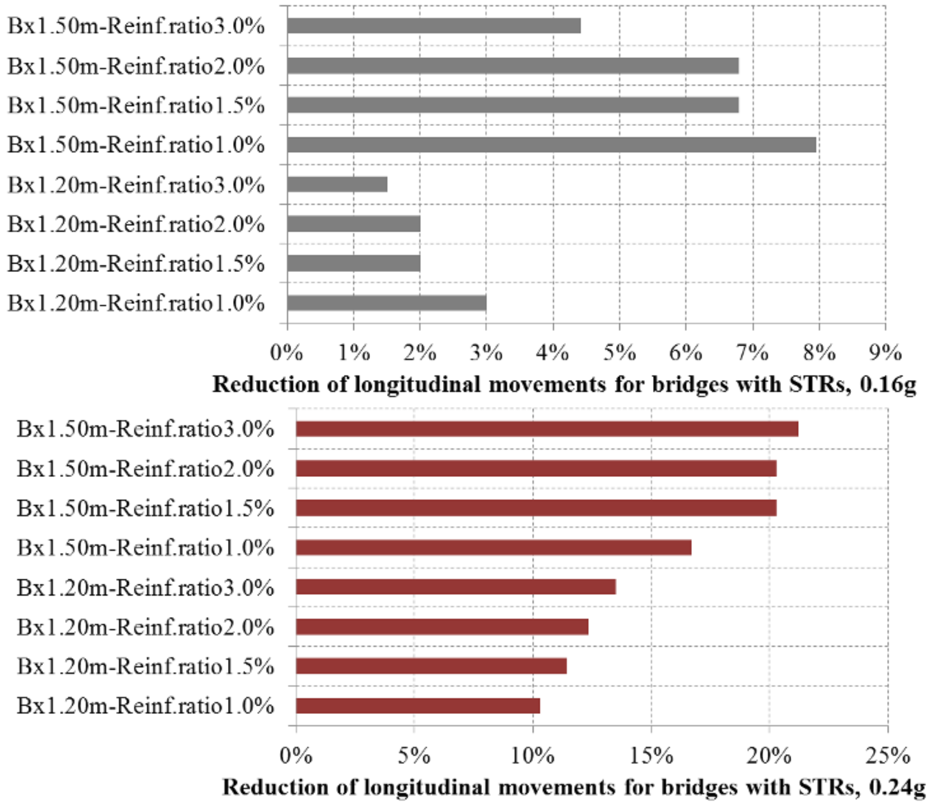

Figure 4. Reduction of Bridge Displacements for different pier widths and long. reinforc. ratios

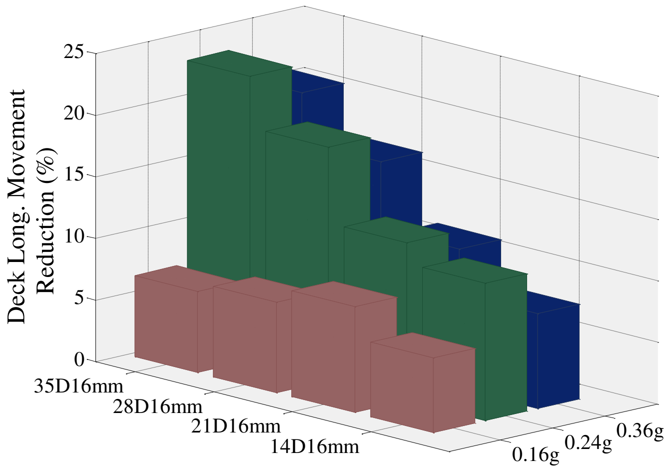

Figure 5. Reduction of Bridge Displacements for different steel bar sizing

V. CONCLUSIONS

The present study focuses on the investigation of the performance of a longitudinal restraining system for bridges with high piers. For this purpose a six span bridge influenced also by second order effects was studied. The main conclusions that can be derived regarding the application of STRs in these bridges are the following.

The application of STRs on the bridge can replace the use of other passive control devices for reducing large displacements of the bridge. In this manner, smaller and solid cross sections of the piers can be used resulting in many advantages in the aesthetics, economy and seismic performance of the bridge in comparison the use of larger hollow cross sections.

A parametric investigation for various pier widths and longitudinal reinforcements was conducted. For the initial condition of the bridge large reductions can be achieved especially for the seismic design level II. However, the STRs are also effective on reducing the longitudinal movements of the deck for smaller cross section of the piers, for seismic design level II in particular, meaning that in the bridge design smaller cross sections could be used with the installation of the STRs. The reduction of the displacement results in reduction of the sizes of the seismic joints and the bearings needed on the abutments, as well.

The cross section of the STR's changes the effectiveness of the system. The largest differences are observed for large seismic intensities.

VI. ACKNOWLEDGEMENTS

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