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PARAMETRIC INVESTIGATION FOR THE OPTIMIZATION OF A LONGITUDINAL SEISMIC RESTRAINING SYSTEM CONSISTING OF STRUTS-TIES FOR CONCRETE BRIDGES

Olga G. Markogiannaki[1], Ioannis A. Tegos[2]

[1] Department of Civil Engineering, Aristotle University of Thessaloniki
e-mail: omarkogiannaki@civil.auth.gr

[2] Department of Civil Engineering, Aristotle University of Thessaloniki
e-mail: itegos@civil.auth.gr

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Abstract. *Seismic response of R/C bridges is an issue that has been investigated thoroughly the last decades. Many efforts have been conducted towards the enhancement of bridges seismic response and two categories of seismic design practices can be identified; seismic isolated systems and ductile systems. This paper focuses on a seismic restraining system, consisting of steel bundles, that aims on improving R/C bridges seismic response. The restraining system limits the longitudinal displacements of continuous integral concrete bridges under lateral earthquake loading. The targeted reduction of the longitudinal seismic displacements is achieved with four bundles of steel bars that act in tension and compression, as well. The steel bars of the four bundles are installed in post-tension ducts, in the superstructure of the bridge longitudinally, without bonding with the bridge's deck concrete. The forces of the steel bundles are transferred to properly designed abutments. The study includes a parametric investigation on the area, the number and length of the steel bars for optimum results in the seismic response of a concrete bridge. A six-span concrete bridge was used as the benchmark bridge and a corresponding nonlinear finite element model was developed according to the analyses' demands. Nonlinear analyses were performed for variable parameters, i.e. material and geometrical properties, number of spans, ground motion etc., after proper sampling. The analyses results have shown how the seismic performance of bridges varies when the area, number and length of steel bars (as restrainers) applied in each analysis case change and how the optimization for the dimensioning of the proposed system can be achieved. The parametric investigation can be the basis for a more general guideline for the design of the system. An optimized selection is found to reduce the longitudinal displacements efficiently and improve the seismic performance of bridges without introducing any structural capacity issues to the rest of the structural members of the bridge.*

1 INTRODUCTION

Concrete bridges in seismic regions are designed for lateral forces induced by strong earthquake motions. Bridge's seismic resistance can be achieved through several design practices that can be divided into two main categories. The first corresponds to the design of bridges as seismic isolated structures. In seismic isolation the means of seismic resistance consist of devices, such as bearings (i.e. elastomeric, lead) or dampers (i.e. hydraulic, viscous), that are installed on the bridge. Another common design practice is the design of bridges as ductile structures that aim on the contribution of the post-elastic behavior of the structural components of the bridge, i.e. more often the piers. Except from the contribution of piers, international seismic design codes, i.e. Eurocode [1] and researchers suggest the participation of other structural members of bridges such as the abutments that can participate in the seismic resistance of bridges. More specifically, integral abutments, [2][3], or abutments equipped with seismic links, such as shear key arrangements, buffers, can receive the seismic forces of the bridge according to Eurocode [1].

The ongoing research has shown that except the traditional seismic links there are further effective systems that can activate the participation of abutments. Such examples include the design of the approach slab for the connection of the bridge with the abutment [4], the design of integral abutments with transversely directed R/C walls [5] and the design of sidewalks connected with the abutments as restrainers [6]. Furthermore, steel or cables restrainers [7] can be used for limiting the longitudinal displacements between the abutments and the deck of the bridge. Recently, shape memory alloys [8] that are introduced as a more effective restrainer system for bridges than the steel restrainer have been suggested for limiting the longitudinal drift as well. Nevertheless, steel cable systems are applied more often for retrofit purposes and mainly on simply supported bridges, [9].

The authors have presented in previous research work, [10] [11], a restraining system with steel bundles that can be installed on R/C bridges and can increase the contribution of the abutments to the seismic resistance of bridges. The steel bundles act as a struts-ties system, applied longitudinally in the outer spans of the deck of the bridge through the abutments. The restraining system limits the longitudinal movements of the bridge and transfers part of the seismic forces to the abutments. It is noted that the restraining system of struts-ties can be applied with some modifications, regarding its installation, in the superstructure of the bridge for the seismic retrofit of concrete bridges, as well [12]. The key objective of this paper is to investigate the performance of the struts-ties restraining system through a comprehensive parametric analysis and to derive some guidelines that can be applied on the design of in multi-span continuous R/C bridges.

2 RESTRAINING SYSTEM OF STRUTS-TIES

The restraining system can be described as a mechanism that reduces bridge seismic displacements through the activation of its components that act in tension and compression, as well (act like struts-ties). The mechanism can be applied in different bridge classes. This paper focuses on the application of the mechanism in multi-span continuous concrete box girder bridges that is shown in an indicative representation in Figure 1. The restraining system involves the installation of four bundles of steel bars 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 bars are placed in plastic ducts, similar to prestressed concrete practices,in order to avoid bonding between the steel bars and the concrete of the bridge. The steel bars are only bonded with the concrete at their ends to ensure sufficient anchorages. Each of the four bundles consists of groups of steel bars that are anchored at different points so that the anchorage forces are not developed in the same positions. The bundles of the steel bars are not only activated as tension members but also as members that receive compression, since the installation of the steel bars inside the deck protects them from buckling issues. The steel bars 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.

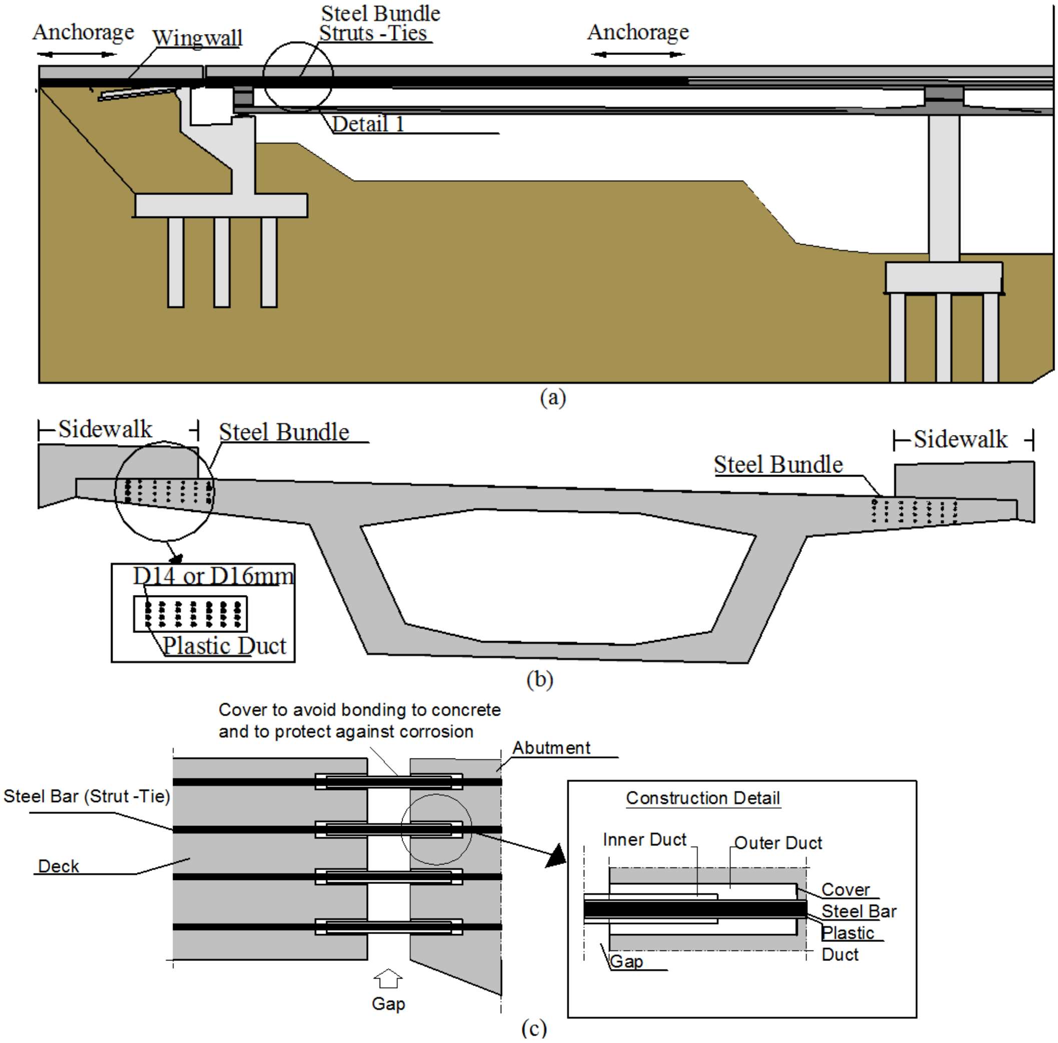


Figure 1: Restraining System. a. Longitudinal view of the bridge, b. Detail 1: cross section of the deck of the bridge, c. Detail at the Expansion Joint between Deck and Abutment

3 DESIGN OBJECTIVES IDENTIFICATION AND SEISMIC COMPLIANCE CRITERIA

The identification of the design objectives and the criteria that shall be fulfilled in a bridge seismic design is necessary for the investigation of the performance of the seismic restraining system. Structural design focuses on reaching a solution at which the bridge components satisfy the design criteria, defined as the design constraints, and is the optimum one that minimizes the cost of the bridge, which is defined generally as the design objective.

For a better understanding of the compliance criteria for the design of R/C Bridges that are equipped with the restraining system, it is necessary to take into consideration the distribution of forces in the structural system of the bridge. The service loads as defined by Eurocode, [1], activate the struts-ties system. The steel bundles are in tension during deck contraction and are compressed during deck expansion. One design compliance criterion for the steel bundles regarding the in-service loads is to have elastic behavior in the serviceability limit state. This criterion corresponds to a minimum acceptable steel bar length that can be calculated by Equation (1) and Equation(2), [11]. The term Δl is the deformation of a steel bar of the struts-ties system, a is the coefficient of thermal expansion, $\Delta T_{N,tot}$ is the sum of the maximum variation of the uniform bridge temperature contraction component $\Delta T_{N,con}$ and the equivalent uniform bridge contraction temperature $\Delta T_{N,per}$ due to prestressing, creep and shrinkage [13]. L_{tot} is the total length of the superstructure, l is the length of the steel bar., l_{eff} is the effective length of the bar from the expansion joint to the anchorage point in the deck; $l_{eff}=l-2l_b-l_w$, where l_b is the anchorage length and l_w is the length of the bar in the wingwall. ε_{smax} is the maximum allowable deformation for steel bars corresponding to 85% of the maximum steel deformation *esy*=0.001 due to low cycle fatigue.

$$\Delta l = a \cdot \Delta T_{N,tot} \cdot \left\lfloor \frac{L_{tot}}{2} - l_{eff} \right\rfloor + a \cdot \Delta T_{N,per} \cdot \left(l - 2l_b \right) \quad (1) \qquad \frac{\Delta l}{l-2l_b} = \varepsilon_{s\max} \quad (2)$$

Earthquake loads induce lateral forces in bridges that are accommodated by the structural components of the bridge. Continuous box girder R/C bridges are designed as ductile systems. The bridge components that are highly activated under seismic loading in common design practice are the piers that are designed to respond in an inelastic manner. With the presence of the restraining system the longitudinal seismic displacements of the bridge are reduced [11] and the seismic forces are redistributed to the structural members of the bridge. A part of the seismic forces is transferred through the steel bundles to the abutments and 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. The compliance criteria regarding the abutments induced in the design of bridges with the restraining mechanism include: the fulfillment of increased seismic resistance requirements of the abutments and the accommodation of stability issues. Although part of the seismic forces is transferred to the abutments, the piers continue to play a significant role in the seismic resistance. The compliance criterion regarding the design of piers in bridges that have the restraining system of struts-ties is to ensure that the piers continue to high contribute highly to the seismic resistance. In this manner, the ductility of the system can be utilized. The criterion is determined according to the concept of the formation of plastic hinges at the bottom and top of the piers. More specifically, it is preferable that the seismic demand pier moments approach or exceed the piers' yielding moments.

The transverse seismic resistance is addressed with the use of rectangular cross-sections of the piers (the long side in the transverse direction) and with shear keys at the abutments.

Optimum Solution	Cost Minimization (Piers & Abutments Dimensions)	
Compliance Criteria	Service Loads:	Steel bundles Elastic Behavior
	Seismic Loads	Abutment Capacity
		Abutment Stability
		Creation of Plastic hinges in Piers

Table1: Design Objective and Compliance Criteria for bridges with the restraining system

Except from the determination of the compliance criteria, the design objective shall be determined, as well, in order to reach optimum design solutions. In design practice the minimization of the bridge cost is defined as the design objective. The design of bridges equipped with the restraining mechanism follows the same concept. The selection of minimum cross-sections and reinforcement ratios of the piers and the abutments that fulfill the compliance criteria is crucial for the minimization of the total bridge cost. The cost of steel bundles, which includes four bundles of steel bars, has minor contribution to the total cost. Hence, the minimization of the cross-section of the steel bars in the bundles is not included in the design objective. The size and length of steel bundles can be derived from the evaluation seismic performance of the bridge and the compliance with the aforementioned criteria. In Table 1 the design objective and compliance criteria are summarized.

For the configuration of a more general guideline that could be incorporated in the design of R/C bridges with the suggested steel bundles requires an extensive parametric analysis in order to observe the influence of various parameters on the response of the mechanism. The present study investigates various bridge and restraining system properties in combination with different earthquake intensities in order to screen the effect of each parameter on the seismic performance of the bridge.

4 BRIDGE 3-D ANALYTICAL MODEL

The parametric analysis was performed on 3-D bridge models. The models were generated in the finite element analysis software *O*penSees, [14].

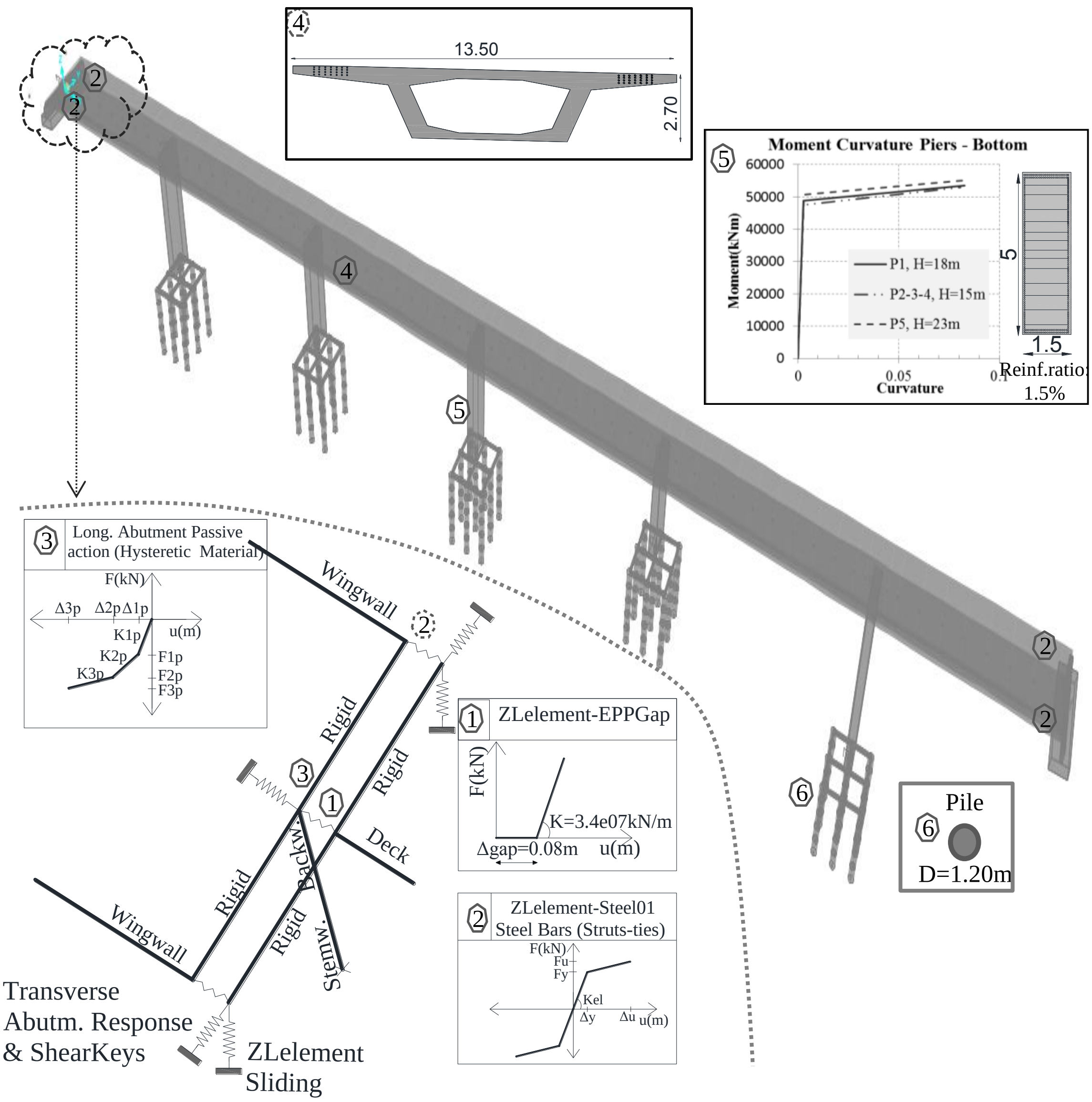


Figure 2: 3-D Bridge Model

Figure 2 demonstrates the properties of one of the models created for a typical six span concrete box girder bridge, based on the characteristics of an Egnatia Highway bridge, T5. The total length of the bridge is 240m and the deck is monolithically connected to the piers, while sliding bearings on the abutments support the two outer spans of the deck. The bridge components are modeled with frame elements taking into consideration material nonlinearities. The section analysis for the assignment of concentrated plasticity at the top and bottom of piers was performed with Bomber Biaxial v3.8.2,[15]. The foundation springs were provided by the geotechnical report of the bridge. For the passive resistance of the abutments, the stiffness values from Caltrans, [16], and the procedure demonstrated by Nielson, [17], were used. The derived values are shown in Table 2. The steel bars of the restraining system (in 4 bundles) were modeled as nonlinear springs, as shown in Figure 2 and Table 3 (*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 analyses were 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 [18] and they are compatible, their average spectra, to Eurocode design spectra for 0.16g, 0.24g and 0.36g and for soil type B.

Habtm (mm)	3200	Ae(m2)	10.24
	Longitudinal		Longitudinal
K1p (kN/m)	91840.00	F1p (kN)	2351.10
Δ3p (m)	0.26	F2p (kN)	4980.52
Δ2p (m)	0.09	F3p (kN)	7131.86
Δ1p (m)	0.03		

Table 2: Abutment Passive Action

STEEL BUNDLE PROPERTIES			
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

Table 3: Steel bundle properties (applicable to each of the 4 steel bundles applied in deck

5 PARAMETRIC ANALYSIS AND RESULTS

5.1 Variation of Parameters

A number of parameters are utilized to screen the effects of the application of the proposed mechanism on the seismic response of continuous concrete box girder bridges. The parameters considered involve the structural system of the bridge, the mechanism characteristics and the earthquake intensity.

Starting from the geometry, the first parameter considered is the number of spans. It is determined by local site conditions and defines the nature of the bridge. The various resulting bridge configurations (1 span, 2 spans, 6spans etc.) are characterized by heterogeneity and, the overall bridge length differentiation plays significant role in the determination of the appropriate restraining mechanism characteristics. Hence, in the analysis bridges with different number of spans are treated separately and the rest of the parameters are screened for each bridge configuration. The second parameter is the height of the piers which depends on the topography of the bridge site. Because of the participation of the piers in the seismic response of continuous concrete bridges it is necessary to study the influence of the mechanism and the redistribution of forces on the response of bridges with variable pier heights. A subsequent pair of parameters includes the dimensioning of the piers, the width of the cross-section and the longitudinal reinforcement of the piers. The investigation of the performance of various pier dimensions and reinforcement ratios is crucial for the implementation of optimized solutions for bridge design with the restraining system of steel bundles.

PARAMETERS	VALUES
No. of Spans	1-6
Height of piers (m)	13 18 23
Width of piers (m)	1.2 1.5
Long. Steel Reinforcement (%)	0.1 0.15 0.2 0.3
Length of Restrain. Bars ('factor'xLmin)	1.25 1.5 1.75 2
Diameter of Restrain. Bars (mm)	D14 D16
No. of Restrain.Bars/Bundle	7 14 21 28 35
Seismicity	0.16g 0.24g 0.36g

Table 4: Parameter Values

Another set of parameters consists of the mechanism characteristics. In particular, the effect of the *length* and *cross-section of the steel bars* of each bundle that are installed in the outer spans of the bridge is screened for different bridge configurations and pier geometries. The variable characteristics correspond to various effective stiffness values of the mechanism that influence the seismic response and the distribution of forces of the bridge. Regarding seismicity, all parameters are screened for the three seismic design intensity levels according to Eurocode 8, [1]. The parameter values used in the study are presented in Table 4. The selection of the geometrical parameter values is based on typical values of R/C bridges in Greece.

5.2 Results Discussion

In the paper the authors have selected to include a part of the total investigation in order to highlight the important results of the study and to satisfy clarity purposes. The analysis discussion for the effect of each parameter is sorted by the various bridge configurations that were created based on the number of spans.

a. Analysis Results for Single-Span Continuous Concrete Bridge

The main characteristic of single-span bridges is the absence of piers. Generally these bridges have elastomeric bearings. The restraining system of struts-ties aims on limiting the longitudinal displacements which leads to the use of sliding bearings, as a more preferable solution.

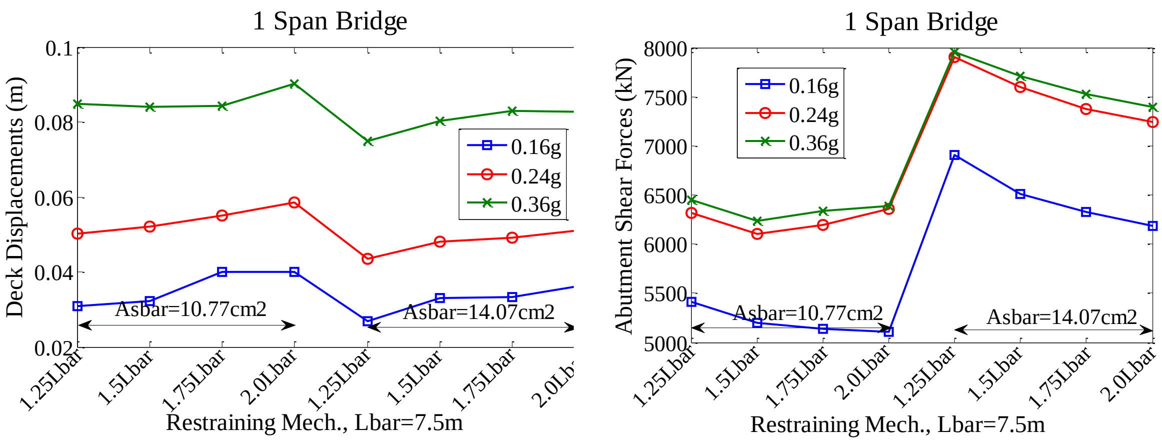


Figure 3: Analysis results for a Single - Span Bridge – varying restraining system characteristics

In Figure 3, a 34m long single-span bridge was investigated with two different sizes of steel bundles (Asbar/bundle, 4 bundles-one bundle at each wingwall) and various lengths. The lengths are determined by applying variable factors to the minimum required steel bar length (Lbar) derived by Eq(1) and Eq(2), Lbar=7.5m. The movements of the bridge are lower for the larger bundle cross-section while the total abutment (values for both the abutments) shear forces are increased respectively. Additionally, it appears that the various lengths affect more the value of the abutment forces with the larger lengths leading to lower abutment shear forces.

b. Analysis of Multi-span Bridges

The bridge configurations presented in the following figures include: a. 2-span bridge 64m long b. 6-span bridge 240m long. The piers in both bridges have 1.5mx5m rectangular cross section and longitudinal reinforcement of 1.5%. Although the reference bridge had variable pier heights, the authors selected three different height values that were applied to total number of piers in the six and two spans bridges in each case study.

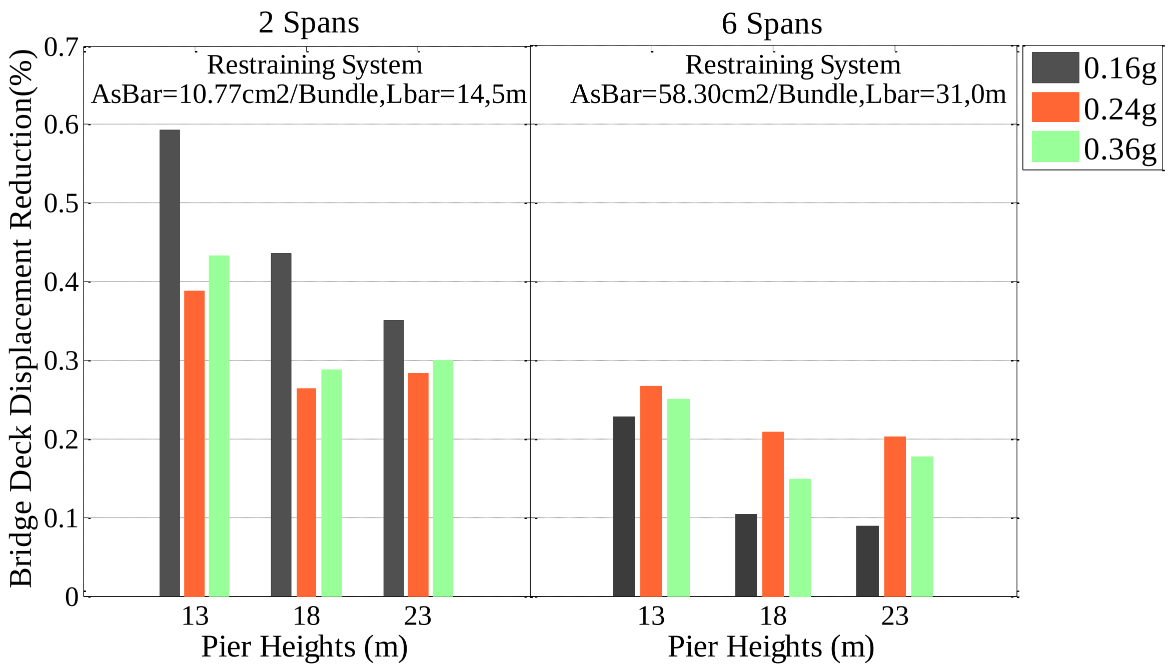


Figure 4: Reduction of Bridge Displacements for variable pier heights

Figures 4 and 5, demonstrate the effect of the pier height variation. The length for the steel bundle bars is determined by the minimum required length (Eq.(1),Eq.(2)) increased with a 1.25 factor. Since the minimum length requirement depends on the total length of the bridge the required lengths derived for the bridges of two and six spans vary significantly. The selection of the size of the steel bars in each bundle is based on the size of the bridge, as well. The short bridge requires smaller steel bundle sizes, i.e. 7 bars of 14mm diameter = 10.77cm2/Bundle, in contrast to the longer six spans bridge that requires for instance 28 bars of 16mm = 58.30cm2/Bundle. It can be noted that bridge deck movement reduction is higher for bridges with shorter piers. In bridges with six spans the contribution of piers to the seismic resistance is higher (considering the number and higher stiffness of piers). As a result the redistribution of shear forces with the presence of the restraining mechanism increases largely the abutment participation. The higher contribution of the abutments is more evident in bridges with shorter piers.

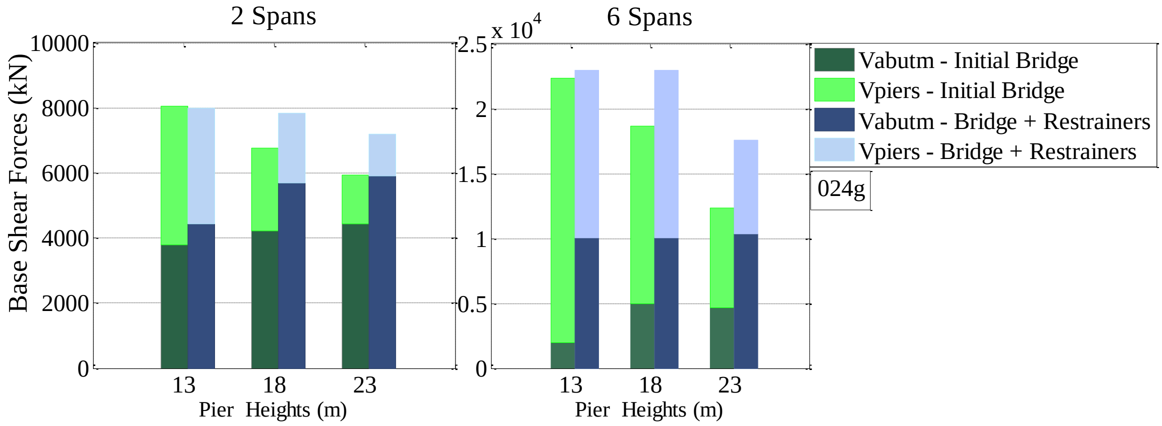


Figure 5: Distribution of Bridge Shear Forces for variable pier heights

Regarding the effect of the mechanisms' characteristics on the seismic response of bridges, the data shown in Figure 6 indicates the trend of the response. In Figure 6, it is observed that the increase in the reduction of bridge displacements follows the increase of the size of steel bundles. This trend has been also observed for bridges with a single-span (Figure 3).

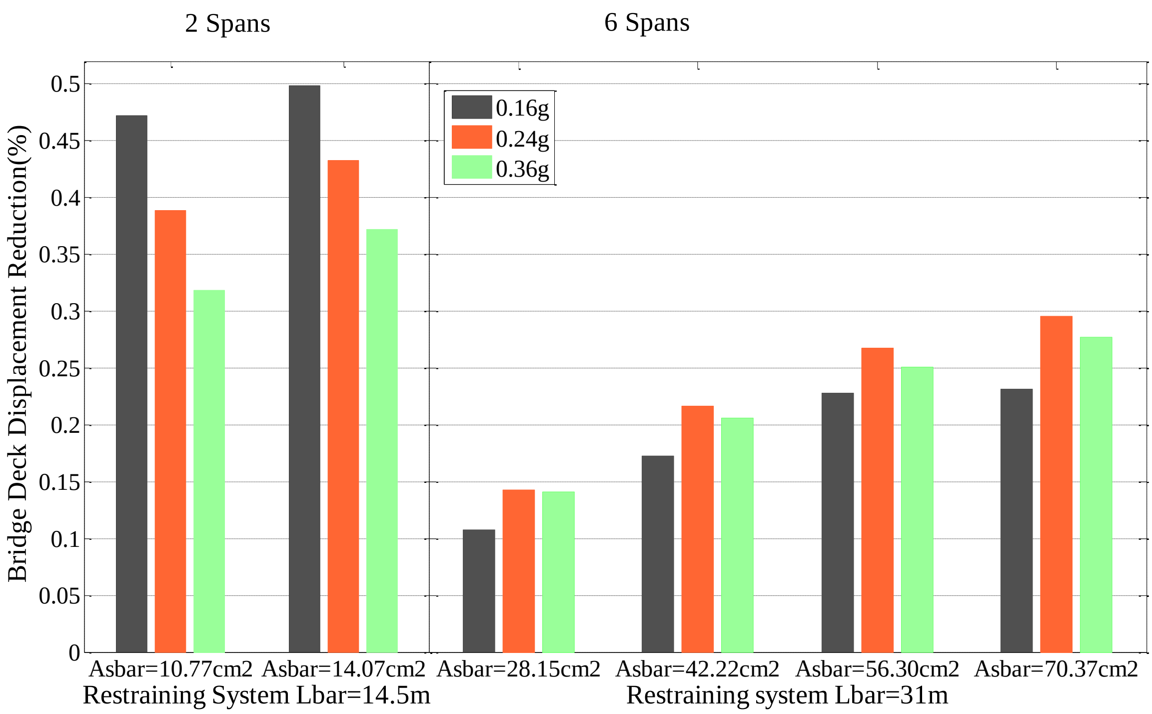


Figure 6: Reduction of Bridge Displacements for variable bundle cross section, Asbar/bundle

Similar plots are presented in Figures 7-8, for the effect of the length variability on the seismic response of the bridge. The increase of the steel bundle length results in a reduction in the effectiveness of the struts-ties system, as shown in Figure 7, which can be characterized as minor (~10%). However, the increase in the steel bundle length is advantageous for the abutments, since it reduces the seismic forces received by the abutments, Figure 8. This reduction can compromise the reduction in the efficiency of the restraining system in limiting the seismic displacements.

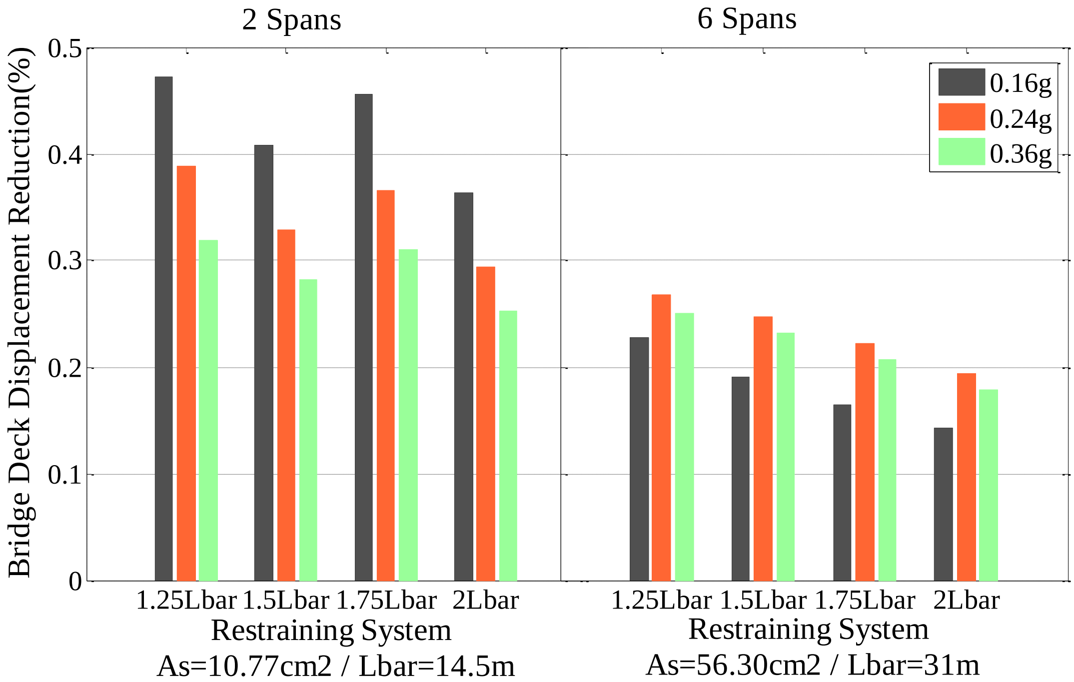


Figure 7: Reduction of Bridge Displacements for variable steel bundle lengths

The influence of the steel bar length on both the abutment seismic contribution and the seismic displacements allows for length modifications of the steel bundles that can lead to lower seismic forces to the abutments capacity level.

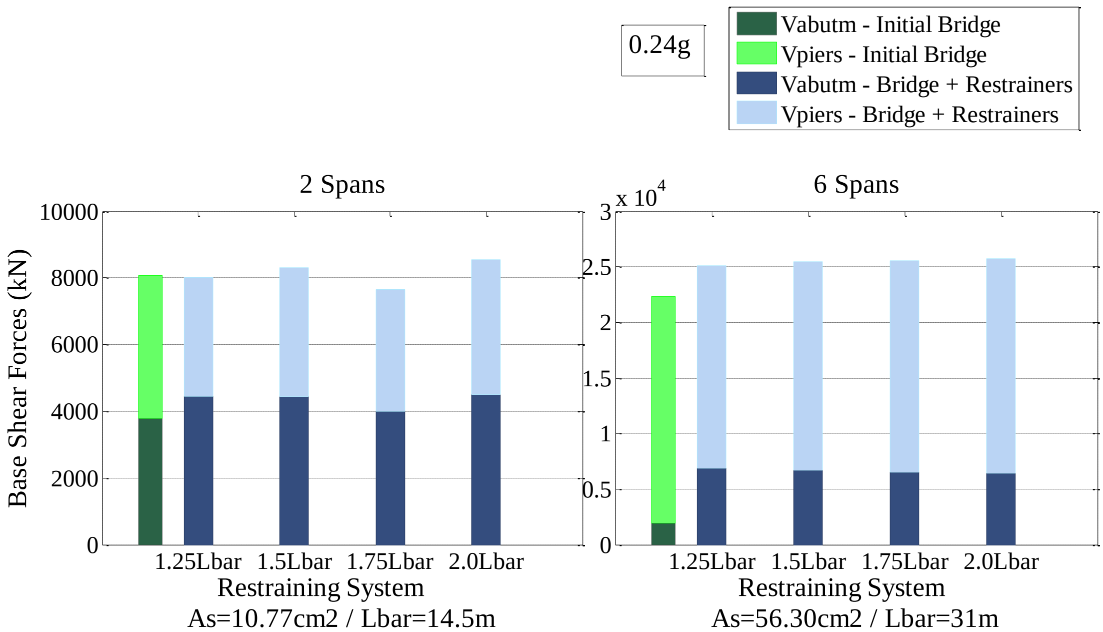
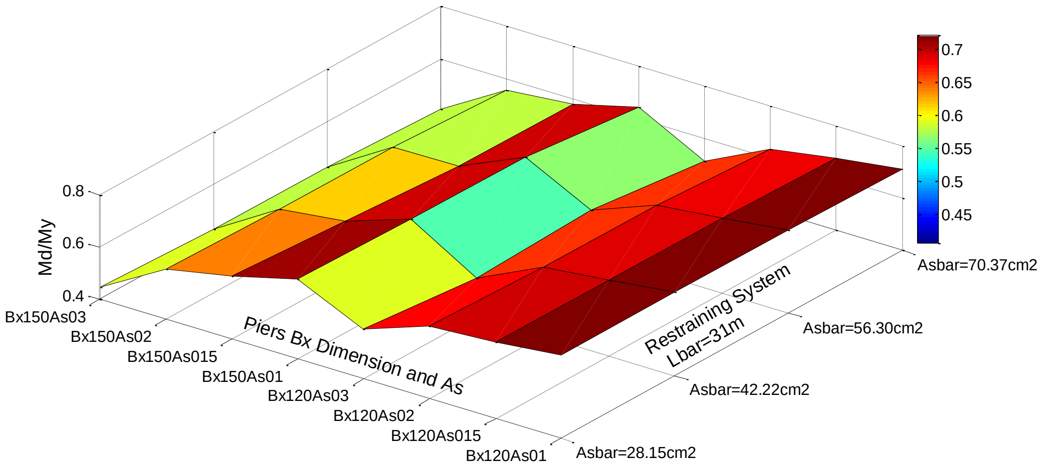
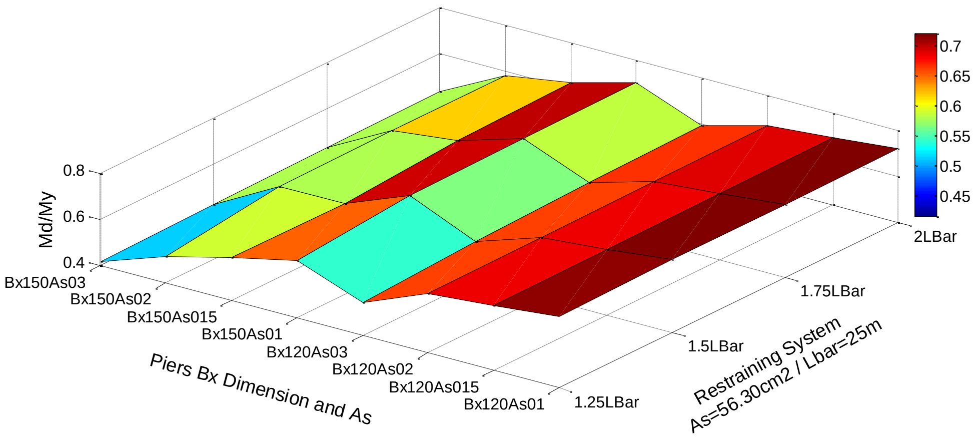


Figure 8: Distribution of Bridge Shear Forces for variable bundle lengths

The effect of the variation of piers' cross-sections and the reinforcement ratios has been analyzed in combination with the variation of the steel bundle size and length. Regarding the cross-section of the piers the variation refers to the width (short side) of the rectangular cross section, since the long side addresses the transverse seismic requirements.

In Figure 9 it is worth highlighting that with the presence of the restraining system design seismic demand moments that reach pier yielding moments (higher pier contribution) are developed in the case of shorter piers (Bx120) with higher reinforcement ratios in comparison to larger piers (Bx150) with the minimum reinforcement ratio of 1%. Figure 10 indicates that larger sizes of piers lower the participation of the abutments-mechanism. Hence, the use of the restraining system is more preferable to be combined with small pier dimensions that have higher longitudinal reinforcement ratios.





(b)

Figure 9:a. Piers & Length of Bars b. Piers & Length of Bars – ratio of M/My on Middle Pier (6-span, 024g).

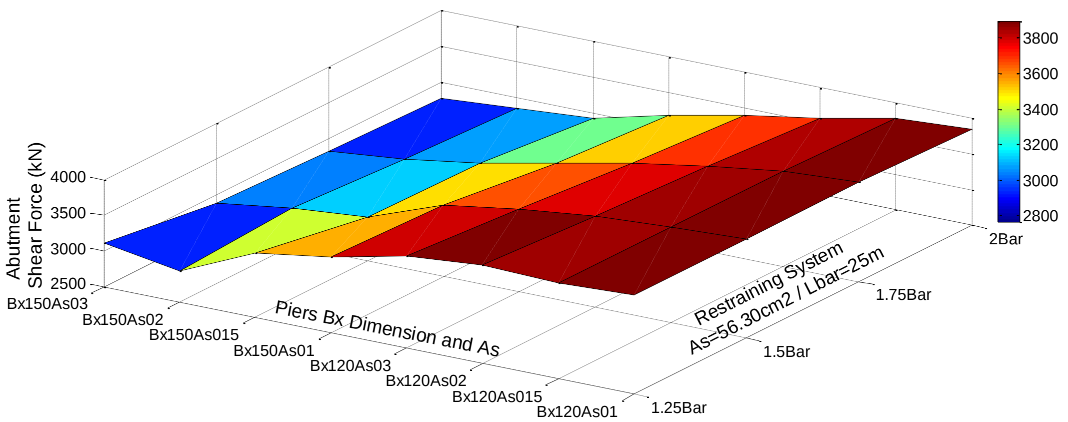


Figure 10: Piers & Length of Bars Forces developed at the abutments (6-span, 024g)

6 GUIDELINES FOR OPTIMUM DESIGN SOLUTIONS FOR BRIDGES WITH THE RESTRAINING SYSTEM

Useful concepts for the design of bridges with the restraining system can be derived from the observations and conclusions from the parametric analysis. Herein these concepts are presented in a guideline form in order to address the issue of optimum design solutions for bridge structural systems - restraining system properties. These concepts can be incorporated in the design process of a bridge under Eurocode Provisions and the guideline form includes an iterative design procedure, Figure 13.

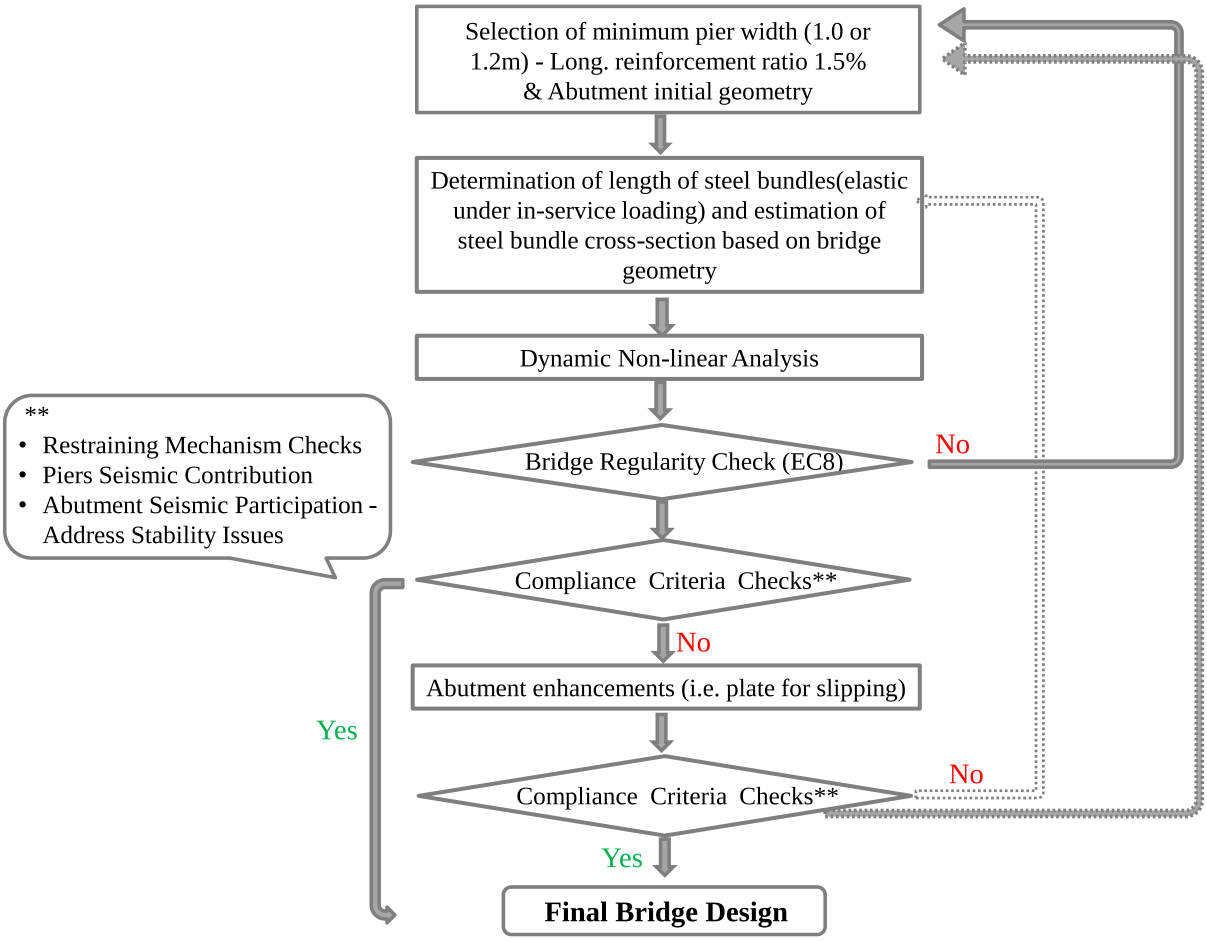


Figure 13: Guideline for optimum design solutions for bridges with the restraining system of struts-ties

The key points are described in the following paragraphs.

- The procedure starts with the selection of piers cross-section and reinforcement ratio. The piers are the most crucial bridge component regarding the minimization of the design objective (cost of bridge) and the response of the bridge; as shown in Figures 9-11 the cross-section of piers determines the range of seismic forces distributed to the structural components.
- After the determination of the restraining systems' properties and the seismic analysis of the bridge, the first check that shall be performed corresponds to the check of regularity of the bridge, [1]. It is expected that the design will result in regular bridge

solutions. Thus, if a bridge is found irregular the cross section of the pier is revised before continuing to the next design steps.

- The compliance criteria to be checked include: a. the response of the mechanism; forces on the steel bundles shall be lower than the ultimate values, b. the distribution of the seismic forces between the abutment and the piers. The piers shall contribute highly to the seismic resistance. The abutments are designed for the additional forces transferred from the steel bundles that may cause stability problems as well. If stability issues are not accommodated with the geometry determined in the initial design, abutment enhancement solutions are investigated,[19]. Indicative examples are slabs that protrude towards the embankment, under the weight of which the slipping of abutment is prevented by developing friction or the use of piles for the overturning moments. If the criteria requirements are not fulfilled a revised deisgn solution is saught.
- After the iterative design procedure has established the optimum dimensions for piers and abutments, the bridge design is continued with the remaining comprehensive design checks.

7 CONCLUSIONS

The influence of various parameters on the seismic response of continuous integral concrete box girder bridges with the struts-ties restraining system (bundles of steel bars in the superstructure of the bridge) has been investigated. The objective of the parametric analysis has been to present the observations acquired and to configure a suggestion for the optimization of the bridge design for the struts-ties mechanism. The main conclusions derived are:

- It has been identified that compliance criteria for R/C bridges designed with the restraining mechanism related to the ratio of the distribution of seismic forces between the piers and the abutments of the bridge are necessary. The criteria refer to a balanced participation of the bridge components in the seismic response so that the compliance criteria of stability, regarding the abutments and the criteria of regularity, economy and aesthetics, regarding the piers are satisfied.
- Because of the minor cost of steel bundles, the economy criterion regarding the size of the steel bars is not included in the optimum design selection.
- The abutments have higher contribution to the seismic resistance of bridges with the presence of struts-ties system. It is noted that before revising their dimensions, the designer can use low cost design solutions, like a friction slab, in order to address the increased seismic demand.
- The parametric analysis has shown the influence of different bridge geometries and steel bundle properties on the effectiveness of the mechanism and the response of bridges
- The guidelines presented include a simple iterative procedure for the optimum design of bridges with the struts-ties that could be incorporated in the bridge design process

Future research work has already been initiated for the poly-parametric investigation of other bridge classes (i.e. cantilever bridges) aiming on highlighting the effectiveness of the struts-ties restraining system in a wide range of bridges.

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