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ANALYTICAL AND EXPERIMENTAL STUDY ON THE RESPONSE OF A SEISMIC RESTRAINER SYSTEM FOR BRIDGES

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Abstract. *The present study focuses on the description and the application of a seismic restrainer system on a large scale bridge of Egnatia Highway for limiting the longitudinal bridge seismic movements. The investigated mechanism is considered as an alternative solution to the use of dampers that limit the longitudinal movements, as well. The restrainer system consists of a group of struts - ties that are anchored at the one end in the outer span of the bridge and at the other end in the abutments in a manner that the abutments are activated along with their embankment under seismic loading and the piers develop lower seismic forces. The cross section of the struts –ties consists of a group of common steel rebars of medium diameter that are placed in a cold formed tube inside the bridge sidewalks. Regarding the experimental study and, generally, the evaluation of the efficacy of the restrainer system, especially regarding the behavior of the system under compression loading, a series of experimental sets were conducted. The experimental procedure aimed on identifying the mechanical response of the steel rebar-tube system against buckling. After the completion of the experiments, the experimental results were used in the analytical modeling of the bridge with the restraining mechanism. Nonlinear seismic analysis was performed on the benchmark and the modified bridge systems for the evaluation of the effects of the presence of the restrainer system on the bridge response. The results from the analysis showed remarkable changes in the bridge seismic behavior and significant conclusion for the efficiency of the restraining system could be drawn.*

1 INTRODUCTION

In the last decades, there have been several research efforts for developing innovative methods[1] for the seismic design of bridges. In general, seismic isolation [2] which involves devices, such as bearings (i.e. elastomeric, lead) or dampers (i.e. hydraulic, viscous), is the design method that has been used at most. Another common design practice is the design of bridges as ductile structures[3] 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 [4] and researchers [5] suggest the participation in the seismic resistance of other structural members of bridges such as the abutments. The ongoing research has shown that except the traditional seismic links that transfer forces to the abutments there are further effective systems that can activate their participation. The activation of the abutments can be achieved with link slabs [6], [7], friction slabs[8] and other examples that include the design of the approach slab for the connection of bridges with the abutments [9], the design of integral abutments with transversely directed R/C walls [10] and the design of sidewalks connected with the abutments as restrainers [11] that can participate in the seismic resistance of bridges. In addition, improved seismic response of bridges especially against increased seismic longitudinal movements can be achieved with the use of steel or cable restrainers [12]. It is common in practice the cable restrainers to be used in retrofit solutions of existing bridges for limiting the relative longitudinal movements between the abutments and the deck of the bridge and between intermediate joint spans and joints in simply supported bridges while they can be used in bridge design, as well.. A lot of researchers have focused on studying the design of this seismic restraining system [12]–[14] and the seismic response of bridges with steel restrainers [15], [16] or restrainers with enhanced materials like shape memory alloys [16]–[18].Although, the restrainers are considered effective in limiting longitudinal displacements, there are issues related to their response since a) they present the limitation of developing unilateral response, because they are activated only under tension loading, b) they are designed with a slack which can result in their late activation under seismic excitation and c) as it is stated in Caltrans[19] an effective design method hasn't been proposed yet. As a result there are cases were steel restrainers failed under strong earthquakes such as in Loma Prieta 1989 and Northridge 1994.

In the frame of developing alternative methods for anti-seismic design, which are effective and with minor cost, the authors have presented in previous research work, [20] [21][22], a restraining system with bundles of steel rebars, which are installed on R/C bridges between deck and the abutments and can increase the contribution of the abutments to the bridge seismic resistance and limit the longitudinal bridge seismic movements aiming at the decrease of the seismic forces on the main structural members, the piers. Although, the proposed mechanism has some common characteristics with the steel restrainers, it has distinguishing differences regarding the actual response of the system and the goal of the application of this method which is the alteration and improved response of the whole bridge system and not the local limitation of bridge movements. The key part of the behavior of the steel bundles is that they can be activated under tension and compression loading, acting as a struts-ties system. 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 [23]. The aim of the present study is to accommodate mechanic response issues that arise regarding the response of the proposed mechanism under compression loading. The steel bundles are placed inside ducts that prevent the transverse deformation of the steel bundles that could be developed due to buckling. An experimental study was conducted for justifying the effective response of the steel bundles. The density, which is the level of filling of the duct with steel bundles, is considered as the main parameter of the experimental investigation. The specimens tested in the experiment included duct cross sections that had variable densities, filling levels. After the completion of the experiment, the experiment results were used for evaluating the seismic response of a three span R/C bridge with the proposed mechanism.

2 LONGITUDINAL STRUTS - TIES SYSTEM

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, (struts-ties), as well. The mechanism can be applied in different bridge classes. In the present study the mechanism is investigated for its response regarding the application on a bridge wih the piers monolithically connected to the deck. A schematic representation is shown in Fig. 1. The restraining system involves the installation of four bundles of steel bars in the sidewalks of the deck of the bridge. The steel bundles are installed along 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 ducts 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 inside the ducts. The steel bars have common steel strength (i.e. S500) and medium diameters of 14mm or 16mm.

The proposed system under seismic excitation receives seismic forces and limits the longitudinal seismic displacements. The steel bundles transfer part of the seismic action to the abutments and the piers receive the rest. In this manner, the abutments that are usually designed not to contribute to the seismic response participate in the seismic resistance, while the piers continue to have the major role in the seismic response as the main structural members. It shall be noted that balance between the contribution of the piers and the abutments is necessary for ensuring an effective bridge seismic behavior with the creation of plastic hinges at the piers and the capacity of the abutments , [22]. Furthermore, the proposed mechanism is activated by in service loading, as well. The steel bundles are in tension during deck contraction and are compressed during deck expansion. Regarding the design of the system the elastic response of the steel rebars under in-service loading is considered as a prerequisite, [22].

Regarding the aforementioned seismic and in-service response, it is assumed that the bundles of the steel bars are not only activated as tension members but also as members that receive compression. This assumption is based on the fact that the installation of the steel bars inside the bridge concrete protects them from any buckling issues. However, the area at the outer joint is the most sensitive regarding the response of the steel bars under compression because of the gap between the decks ad abutments concrete and may induce concerns regarding buckling failures. The following experimental study was conducted in order to eliminate any concerns regarding the development of an effective response without any bucking occurring.

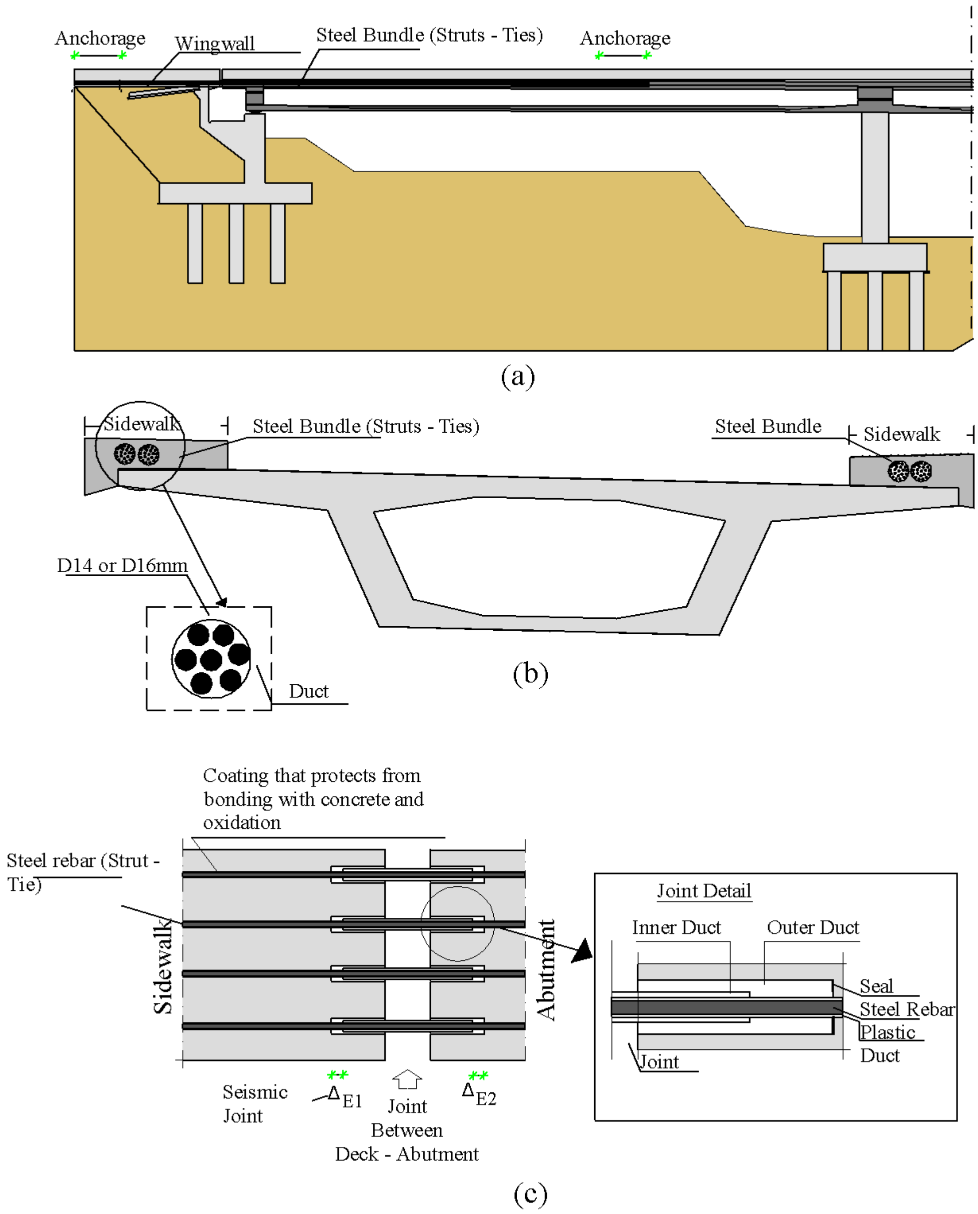


Figure 1: Restraining System. a. Longitudinal view of the bridge, b. Detail 1: cross section of the deck of the bridge, c. Detail at the Expansion Joint between Deck and Abutment

3 EXPERIMENTAL STUDY

3.1 Aim of the study

The target of the experimental investigation is to study the mechanical behaviour of the steel bundles under compression loading. For this purpose several steel bundle specimens were tested. By evaluating the experimental results the goal is to indicate whether the use of the steel bundles in plastic ducts as struts is can be assumed, in other words if the reception of compression loading without buckling is feasible. In addition to the compression tests, a tension loading test on a steel rebar was conducted for identifying the expected stress-strain response of the steel rebars.

3.2 Parameters

The proposed mechanism suggests that the steel bundles are placed inside ducts that prevent the transverse deformation of the steel bundles that could be developed due to buckling. The parameters that were studied are the following:

- One main parameter is the presence or not of concrete around the steel bundles. The presence of concrete corresponds to the position of the steel bundles inside the bridge concrete and the absence of concrete corresponds to the area of the expansion joint where the steel bundles are exposed to the environment.
- Another significant parameter of the experimental investigation is the level of filling of the duct with steel rebars. The specimens tested in the experiment included duct cross sections that had variable filling levels.

3.3 Specimens

In Table 1 the specimens that were used in the experimental tests are presented. The specimen scale is 1:2. The *Table 2* includes the name of each specimen, the characteristics, rebar diameter, number of rebars and surrounded by concrete or not, and the filling level. A total number of 10 specimens were studied. Common steel rebars were used for the research with a diameter of 8mm. The filling level of 76% is the highest feasible for the available diameters. The two large classes of specimens are steel bundles that are inside concrete and bare steel ducts. The ducts used were steel type, 30cm log and had 30mm outer diameter (26mm inner + 4mm wall thickness). High strength concrete (emaco) with spiral 4mm transverse reinforcement was used in order to simulate the presence of the massive bridge concrete. A square steel plate with a steel dowel welded on it was used to all specimens for accommodating the requirement for a smooth surface in order to transfer the compression loading to the steel bars inside the ducts uniformly. The two arrangements are shown in Fig. 2 and Photo 1.

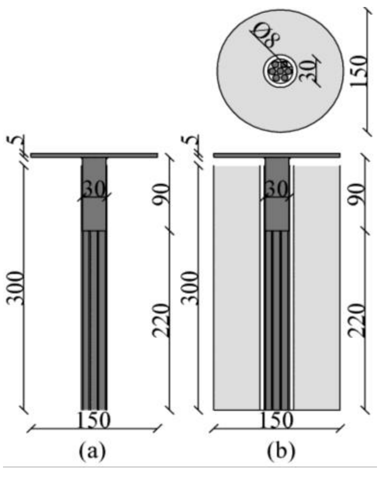


Figure 2:. a) Specimen S-NC b) Specim. S-C

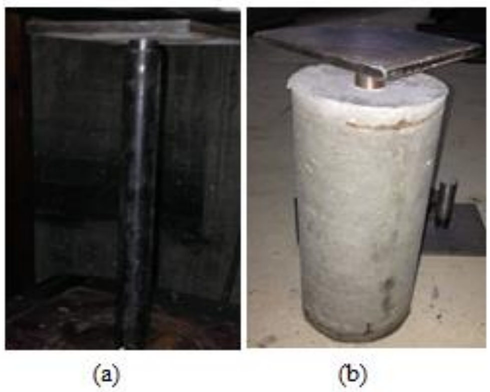


Photo 1:. a) Specimen S-NC b) Specimen S-C

Concrete			No Concrete		
Name	Characteristics	Density (%)	Name	Characteristics	Density (%)
S-C-1	4D8mm	38%	S-NC-1	4D8mm	38%
S-C-2	5D8mm	47%	S-NC-2	5D8mm	47%
S-C-3	6D8mm	57%	S-NC-3	6D8mm	57%
S-C-4	7D8mm	66%	S-NC-4	7D8mm	66%

S-C-5	8D8mm	76%	S-NC-5	8D8mm	76%

Table 1 :Specimen Properties

3.4 Test Set-up and Results

The experiment was conducted in Aristotle University of Thessaloniki. The preparation of the specimens took place at the Laboratory of Masonry and Concrete Structures and the tests were performed with the Compression Machine at the Laboratory of Experimental Strength of Materials and Structures in Aristotle University of Thessaloniki. The specimens were centred on the table of the machine and the steel smooth plates were placed at the top of the specimens so that the loading part of the machine could rest on them. The target of the process was to induce clear compression loading to the steel bars without any bending or lateral additional forces.

Photo 2: Test set-up

(α) (b)

Photo 3: a) Tension Test, b) Rebar Failure

Photo 2 shows the test set up for the compression of the specimens. The deformation of the specimens was measured during the experiments, as well. The machine used for these tests had a capacity of 20 tonnes in the vertical direction and only static loading could be applied. The compression tests were performed until the failure of the steel bars and returned the machine back to zero loading. After the completion of the compression tests, a tension loading test was performed on a single steel bar, Photo 3.

As it has been described in the previous sections the purpose of the experimental study was to determine whether or not buckling occurs. Regarding buckling the critical buckling load is calculated from the well-known Euler Equation, where E is the Modulus of Elasticity, I is the

Moment of Inertia, L is the Length and K is the effective length coefficient depending on the support conditions. Figure 3 presents the K factor values depending on the support conditions.

$$P_{cr} = \frac{\pi^2 * E * I}{(K * L)^2} \quad (1)$$

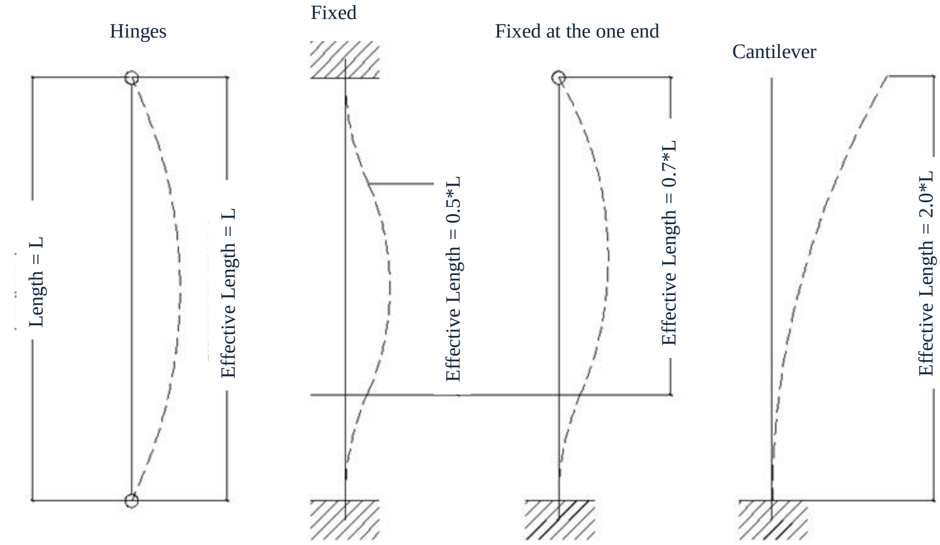


Figure 3 :. Buckling modes and k effective length coefficient

In Table 2, the critical load and stress due to Euler buckling is presented for all different support conditions.

Δοκίμιο		$P_{euler\ (hinges)}$ [kN]	σ_{euler} (hinges) [MPa]	$P_{euler\ (fixed\ at\ one\ end)}$ [kN]	σ_{euler} (fixed at one end) [MPa]	$P_{euler\ (fixed)}$ [kN]	σ_{euler} (fixed) [MPa]
S-C-1	S-NC-1	65.6	326.26	66.94	332.93	131.20	652.54
S-C-2	S-NC-2	82.	326.26	83.67	332.93	164.00	652.54
S-C-3	S-NC-3	98.4	326.26	100.41	332.93	196.80	652.54
S-C-4	S-NC-4	114.8	326.26	117.14	332.93	229.60	652.54
S-C-5	S-NC-5	131.2	326.26	133.88	332.93	262.40	652.54

Table 2 : Specimen critical buckling loading

Photo 4 shows the specimens after the completion of the compression tests. The force-displacement and stress-strain curves derived from the experimental study are shown in Fig. 4 and 5 respectively. Regarding the S-C specimens, that are surrounded by concrete, the observation of the experimental results and the comparison of the results to the buckling loading shows that the specimens failed without any buckling occurring before their failure. In fact, the stress-strain curves follow the stress-strain curve that was derived by the tension test. Regarding the N-SC specimens, the response is differentiated depending on the filling level of the ducts. There are cases where buckling occurs before yielding. Characteristic examples of such failures are specimens S-NC-1 and S-NC-2. From the experimental results, it can be concluded that the sparse (<50%) application of steel bars in a duct has negative effects on their response under compression loading. In the case of high densities the performance is gradually improved and is similar to that of the tension loading behavior. Especially, in the case of the highest filling level the walls of the steel duct were engaged in the response of the steel bundle due to the development of friction forces resulting in higher forces than the failure of the steel bars.


(a) (b)


(c) (d)

Photo 4 : (a) Specimen Failure S-NC-1, (b) Specimen Failure S-NC-2, (c) S-NC Specimens, (d) Spesimen S-C after test completion

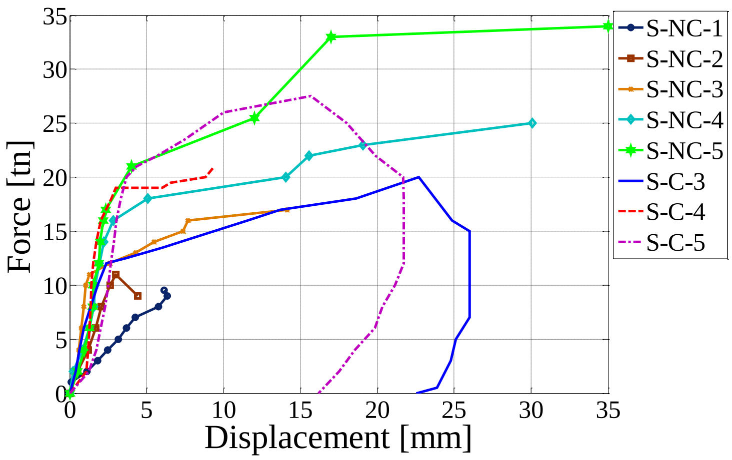


Figure 4 : Force - Displacement Curves

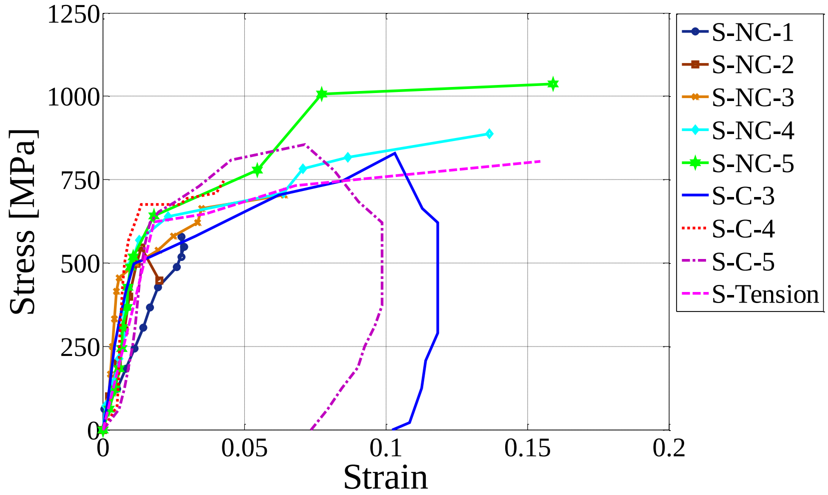


Figure 5 : Stress - Strain Curves

The high activation of the proposed system has two side effects. The one refers to the fact the friction forces that appear between the steel rebars and walls of the steel duct lead to the early damage of the steel duct, which is not a preferable response for the system. In addition, the amount of forces that would be transferred by the mechanism to the abutment would be higher than the expected and could induce capacity issues to the abutments. As a result a level of 67-72% of filling or in other words 7 bars in a duct is a solution that shall be acquired for the analytical investigation of the effectiveness of the proposed mechanism.

4 ANALYTICAL STUDY

The results from the experimental study were used in an analytical case study that evaluates the effectiveness of the proposed mechanism on the seismic response of bridges.

4.1 Description of the Reference Bridge

The Reference Bridge that was used foe the analytical study is a monolithic three span prestressed R/C bridge. The end spans are 45.10m, the middle is 45.60m and the total length is 135.80m. The deck is a concrete box section, connected to the piers monolithically, and is supported on the abutments by low friction sliding bearings. The piers are circular and are founded on 3x3 pile groups. The bridge's abutments are seat-type and have transverse seismic links-stoppers. The bridge is founded on ground type B and the area is in seismic zone I, [24]. A 3-D finite element bridge model, Fig. 6, was generated in the analysis software OpenSees, [25], accounting for abutment-embankment interaction.

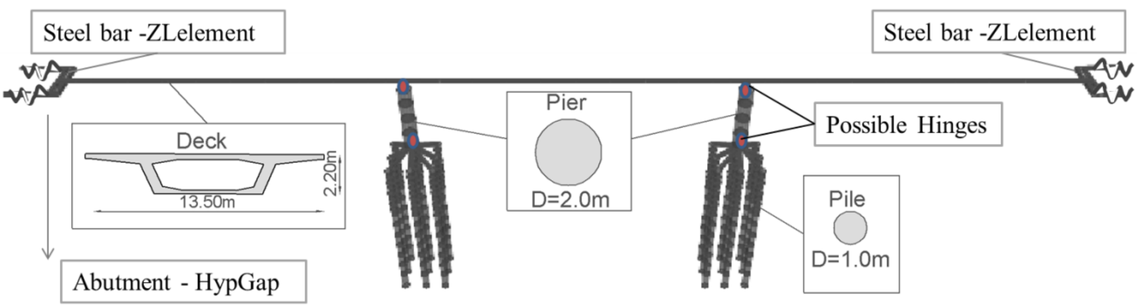
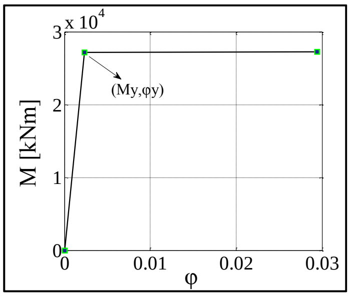


Figure 6 : 3-D Reference Model

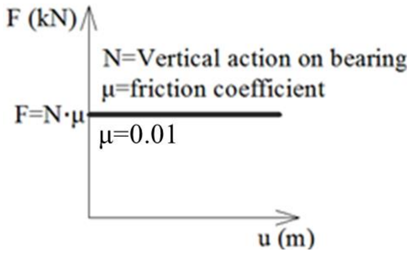


(a)

$$F_{(X)} = \frac{X}{\frac{1}{K_{max}} + R_f \frac{X}{F_{ult}}}$$

Kmax [Kn/m]	81000
Rf	0.7
Fult [kN]	-2739
Gap [m]	-0.07

(b)



(c)

Figure 7 : a)M-φ curve, b) Abutment P-Y curve, c) Sliding Bearing

Bridge members are modeled with frame elements with material nonlinearities. The section analysis, Fig 7(a), for the assignment of concentrated plasticity (hinges) at the top and bottom of piers was performed with AnySection v4.0.6,[26]. The foundation springs were provided by the geotechnical report. The passive resistance of the abutments due to embankment mobilization was simulated according to Shamsabadi guidelines [12],[13] and the HyperbolicGap compression material was used in OpenSees, Fig 7(b). The sliding Bearing were modeled as shown in Fig 7(c).

The proposed mechanism is modeled as nonlinear springs as shown in Fig. 6. The nonlinear response of the steel bars was derived from the stress-strain experimental results. The stress – strain curves for tension and compression were bi-linearized. Respectively to the experiment 7 rebars of a 16mm diameter were used in a steel duct of 52mm inner diameter, as the initial size of the mechanism. In the parametric investigation there were used 1-7 steel ducts in each steel bundle. The bi-linearization of the two stress-strain curves showed almost symmetrical response under tension and compression which is the initial assumption for the proposed mechanism. In the finite element model the response of the mechanism is modeled as a force-displacement response including the cross section of one steel bundle based on the stress - strain curves. The steel bundle yielding force and yielding displacement is calculated by equation (2), where σ_y is the yielding stress, A the cross section of the steel bundle, L is the length of the steel rebars without accounting for the anchorage lengths and ε_y is the yielding strain. The resulting curves are shown in Fig. 8.

$$F_y = \sigma_y * \mathrm{A}, \quad \delta_y = \varepsilon_y * \mathrm{L} \tag{2}$$

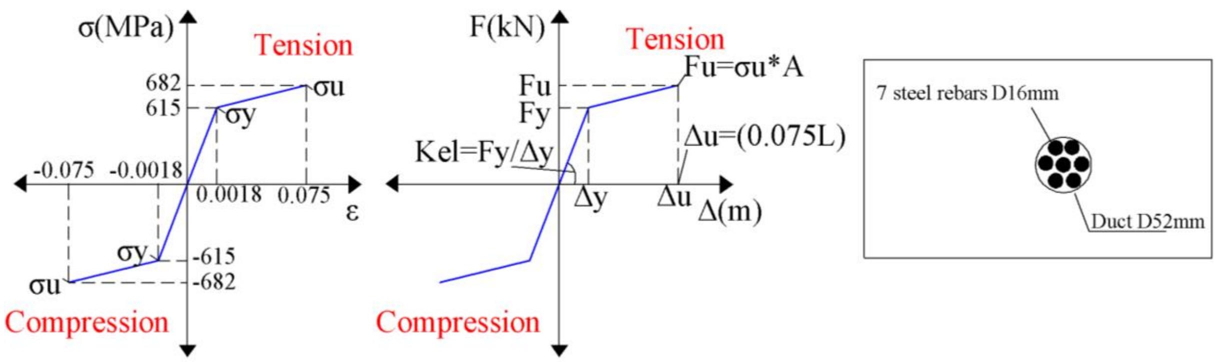


Figure 8 : Steel bundle nonlinear spring response

The proposed mechanism was studied for various characteristics regarding the cross section and length of the steel bundles, in order to indicate the efficiency of the system in limiting seismic movements and seismic actions on the piers. The properties of the system used for the analytical study are presented in Table 3 sorted by initial stiffness. The minimum length of the longitudinal bars is determined based on the condition that the steel bars remain elastic under serviceability loading,[23]. The seismic analyses were conducted using five artificial accelerograms complying with seismic design zone I. Table 4 shows the analysis results for the Reference Bridge. In Figure 9 the displacement, shear and moment reductions and the response of the steel bundles are shown for the two earthquake intensities respectively.

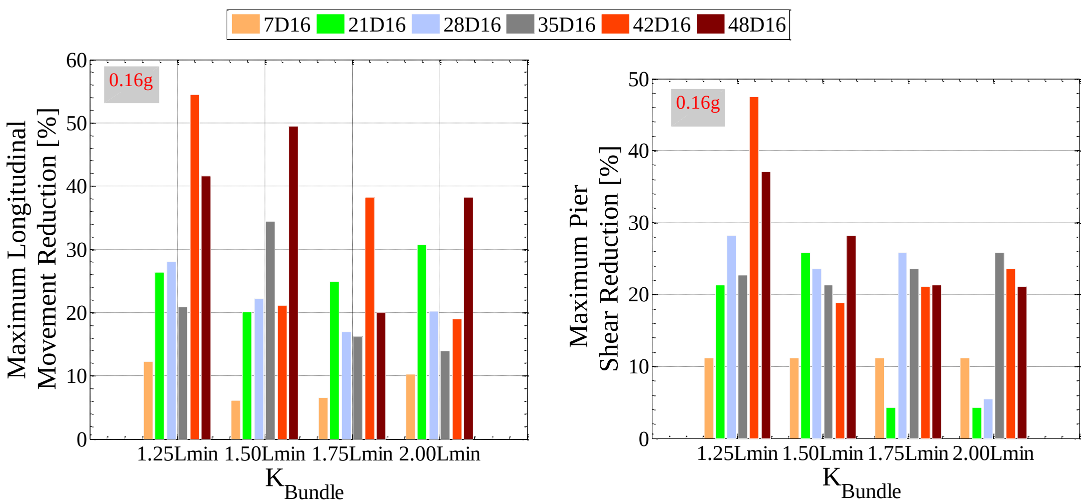
Steel Bundle		K_{el} [kN/m], L_{min}=17.7m			
Steel Duct (D52mm)	No. of Bars	L=1.25L_{min}	L=1.5L_{min}	L=1.75L_{min}	L=2.0L_{min}
1	7D16	12722.56	10602.14	9087.545	7951.602
2	14D16	25445.13	21204.27	18175.09	15903.2
3	21D16	38167.69	31806.41	27262.63	23854.81
4	28D16	50890.25	42408.54	36350.18	31806.41
5	35D16	63612.81	53010.68	45437.72	39758.01
6	42D16	76335.38	63612.81	54525.27	47709.61
7	49D16	87240.43	72700.36	62314.59	54525.27

Table 3 : Steel Bundle Properties

	max U1 [m]	max V2 [KN]	max M3[KNm]
0.16g	0.08	4826	18968

Table 4 : Reference Bridge Analysis Results

The analyses results indicate remarkable reduction, up to 50% in the longitudinal bridge movements and moment and shear force at the piers, as well, especially when large steel bundle cross sections and small steel bar lengths are used. The efficiency of the mechanism is reduced when the length of the steel bundles is increased or the cross section of the steel bundles is low. Regarding the steel bundles, they have inelastic response for small steel bar lengths and a length increase leads to less stresses on the steel bars.



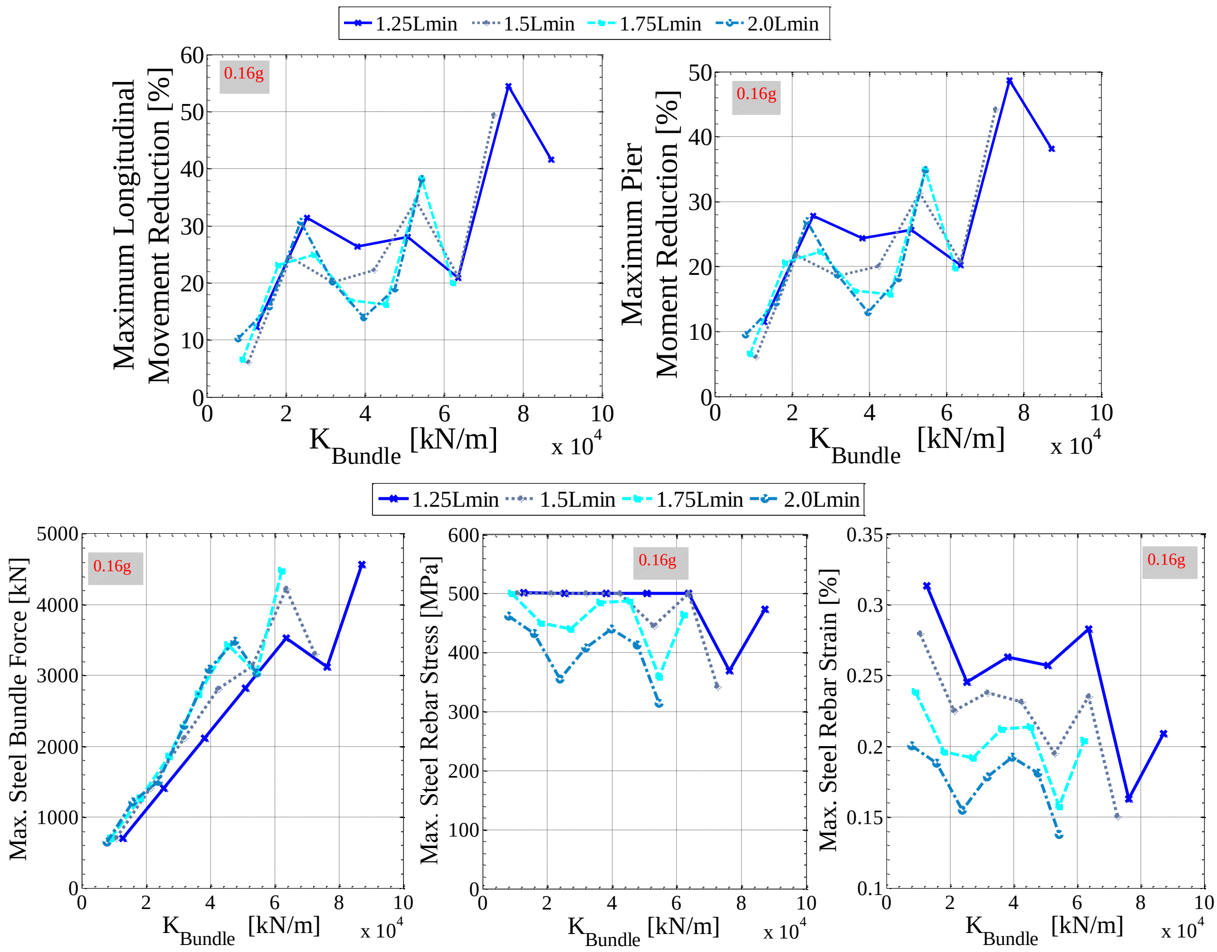


Figure 9 : Analysis Results, 0.16g

The forces that are developed at the proposed mechanism are transferred to the abutments. It is noted that the level of the aforementioned forces is acceptable for the capacity of the abutments, which indicates another aspect of the efficiency and applicability of the proposed system.

5 CONCLUSIONS

The present study focuses on the experimental study of a proposed seismic restrainer system and the use of the experimental results for evaluating the efficiency of the proposed system with an analytical study on an R/C bridge of Egnatia Highway. The following conclusions were derived:

- The experimental results have shown that the cross section of the steel bundles shall be in accordance with the cross section of the steel duct used. A medium to high filling lower than to 76% is preferable for the proposed mechanism. In fact, in the analytical study 7 steel bars of 16mm were used inside a D52mm duct.
- An extremely sparse installation of steel bars in the steel duct indicated that it will cause side effects on the response of the bars as struts, under compression loading. Extreme high filling level of the steel ducts can develop side effects, as well. The side effects developed for the highest density achieved are related to the fact that friction forces are developed and activated which increase the efficiency of the struts. Howev-

er, wear phenomena of the walls of the steel ducts and premature degradation arise that are not acceptable for the use of the ducts as part of the restraining system.

- It has to be noted that as tension members, ties, the steel bars are not affected by the more or less density of the filling level of the steel bars in the steel duct.
- The analytical study that took into account the experimental results for the proposed mechanism response showed high efficiency of the system in limiting longitudinal bridge movements, moment and shear force at the piers.

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