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SEISMIC RETROFITTING OF R/C BRIDGES WITH THE USE OF UNBONDED TENDONS

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Abstract. *It is widely known that retrofit processes are based on two different retrofit approaches that depend on the treatment of the general safety inequality which requires the capacity to always exceed the demand. The first retrofit approach, direct, includes strengthening of specific bridge members which refers to an increase in capacity that shows focus on the first term of the safety inequality. The second retrofit approach, indirect, includes force limitation or response modification that lowers the demand (second term of the safety inequality) to the level of the existing member's capacity. Characteristic examples of indirect retrofit approaches are seismic isolation and, in general, methods that include the addition of new structural members in the bridge system and/or the activation of non-seismic members. It can be claimed that the advantage of indirect retrofit approaches when compared to direct ones is that they do not depend on the existing member's capacity, while they transfer the seismic forces to new structural members that are highly reliable. In view of the above, the key objective of this paper is to present an alternative retrofit system that follows the indirect retrofit approach that involves the use of unbonded tendons. In this study the tendons are used innovatively for restraining the longitudinal seismic direction. The proposed system is based on previous studies on the use of common steel rebars, which are placed in the bridge superstructure and activated as struts - ties under longitudinal earthquake. Regarding the proposed system, the tendons are placed in the bridge sidewalks at the outer spans through the abutments and the struts - ties response is achieved with appropriate prestressing. The research work performed focuses on evaluating the effectiveness of the application of the proposed retrofit system on R/C multi-span bridges while dealing with in-service issues, as well. The retrofitted bridges were properly modeled with nonlinear elements. The demand of the structural systems was computed using time-history analysis. The time history analyses were performed using a suite of representative ground motions and multiple parameters regarding bridge and the proposed system characteristics were studied. The results of the analyses are presented and show the significant restraining response of the proposed system.*

1 INTRODUCTION

In the last decades, there have been several research efforts for developing effective seismic retrofit methods [1]. Generally, retrofit solutions aim on complying with the safety inequality [2], Eq.(1), which requires the structural capacity of bridge members to exceed seismic demand at all times.

$$Capacity \geq Demand \tag{1}$$

According to Rustum (2012), [3], the various retrofit methods can be summarized in two retrofit philosophies depending on the focus of each procedure on the first or second term of Eq.(1). The first retrofit philosophy which is the direct approach involves methods that are applied on the as-built bridge components with the goal to increase their capacity against seismic loads. For instance, these methods include pier retrofit with steel or concrete jackets or FRP materials,[4]. It shall be noted that the structural capacity of the existing bridge members can be determined with a series of tests, but since the capacity estimation depends on sample measurements it is not considered equally reliable to the estimation of the new structural member's capacity and it may result in misidentifying hidden deficiencies that are not apparent and have severe consequences on the effectiveness of a direct approach retrofit method or in overdesigning the retrofit solution. The second retrofit philosophy, indirect approach, involves the addition of new members in the bridge structural system. The new bridge components are intended to reduce the seismic demand on the as-built bridge members at the level of their structural capacity and they are properly designed for contributing to the seismic resistance by receiving the seismic forces. Such common indirect approach retrofit methods include the use of bearings or energy dissipating devices, i.e. dampers[5], or restrainer cables[6]–[8]. It can be claimed that the advantage of indirect retrofit approaches when compared to direct ones is that they do not depend on the existing member's capacity, while they transfer the seismic forces to new structural members that are highly reliable. A key point in the effectiveness of such methods is the timely activation of the mechanism installed on the bridge; otherwise it is possible that the capacity of the existing components will be exceeded before the activation of the seismic contribution of the retrofit system. In the case of continuous monolithic concrete bridges appropriate indirect retrofit methods are devices like dampers, whilst bearings and restrainer cables are more often used for simply supported bridges, [9],[10].

The key objective of the present study is to study an alternative indirect retrofit approach method which aims on upgrading bridge seismic response by restraining the longitudinal seismic movements. The proposed method involves unbonded tendons and is based on other restraining systems that have been proposed by the authors for limiting longitudinal bridge movements that use steel rebars ,[11], [12] and FRP strips [13] that are applied longitudinally in the bridge superstructure receiving tension and compression loading. The mechanism involving the unbonded tendons has already been proposed by the authors for the design of new bridges[14]. The system can be applied in common monolithic bridges, mainly, and the expected tendons response that reduces their longitudinal movements can be characterized similar to that of seismic links,[15], and dampers which dissipate seismic energy in seismically isolated bridges,[16].

Prestressing in bridges is mostly used for providing necessary resistance to the superstructure's vertical loading and to ensure that concrete stays within its tensile and compressive capacity under the range of the loads applied, [17]. It can be applied with tendons (wires, strands, bars) that are of high strength steel. They can be either internal or external,[18], to the concrete member and can be bonded or unbonded to the structure's concrete. External prestressing can be a rational strategy for strengthening existing bridge superstructures against increased traffic loading demands, as well,[19].Some research efforts have been conducted for utilizing prestressing for upgrading bridge's seismic response, as well. These methods belong to the direct retrofit approach, focus on increasing the pier's capacity against seismic demand and take several forms, such as enhancing pier's flexural resistance with prestressed tendons and rebars [20],[21], introducing prestressed confinement systems for piers, i.e. prestressed FRP strips [22] or prestressing pile and pier caps [1]. Some researchers have investigated the use of unbonded prestressing tendons for limiting the horizontal displacements but their applications are limited to beams in building frame and wall systems [23],[24].

In view of the above, the proposed method can be an alternative approach of the use of unbonded tendons in seismic retrofitting.

2 UNBONDED TENDONS PROPOSED MECHANISM

The restraining system can be described as a mechanism that reduces bridge seismic movements through the activation of its components for both earthquake signs in the longitudinal direction. The restraining system involves the installation of four symmetric groups of unbonded tendons in the sidewalks of the deck of the bridge. The tendons are of high strength steel (i.e. S1570). They are installed along the longitudinal direction of the bridge and each two groups are placed in the outer spans of the bridge extending beyond the abutments' wing walls. The unbonded tendons avoid bonding with the concrete of the bridge. At the positions where the unbonded tendons are installed the sidewalks are replaced with new ones of high strength concrete and the new sidewalks are connected with the deck with dowels. The tendons are anchored at a new pile-diaphragm structure behind the wingwalls, where the seismic forces can be transferred safely without increasing seismic demand on the abutments. The pile diaphragm consists of concrete members which have equal width to that of the wingwalls.

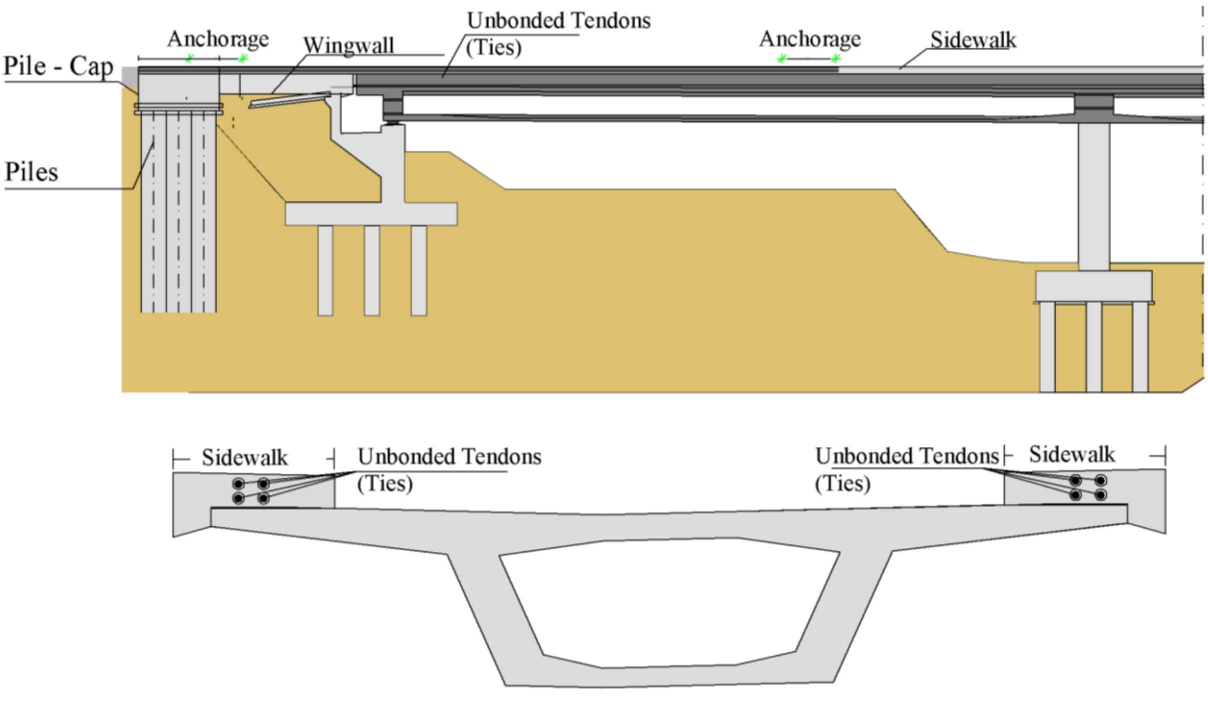


Figure 1: Restraining System. a. Longitudinal view of the bridge, b. Detail 1: cross section of the deck of the bridge

The unbonded tendons receive seismic forces under seismic excitation and limit the longitudinal seismic displacements. The proposed restraining system is an evolution of the struts-ties system that has been proposed by the authors, which uses common steel rebars placed in the superstructure instead of tendons. Although the steel rebars are a reliable solution, as well, they require special care for buckling protection at the positions of the outer expansion joints in order to respond as a struts-ties system. Prestress allows the tendons to receive "compression" loading in terms of lower tensile stresses. Therefore, the prestressed tendons are considered as an efficient alternative system that can develop a "strut" behavior by decreasing their initial prestress (tensile stress). Since the tendons cannot receive compression stresses, the design of the system shall ensure that the seismic demand in the "compression direction will not exceed the tension region. Figure 2 shows the tendon's response

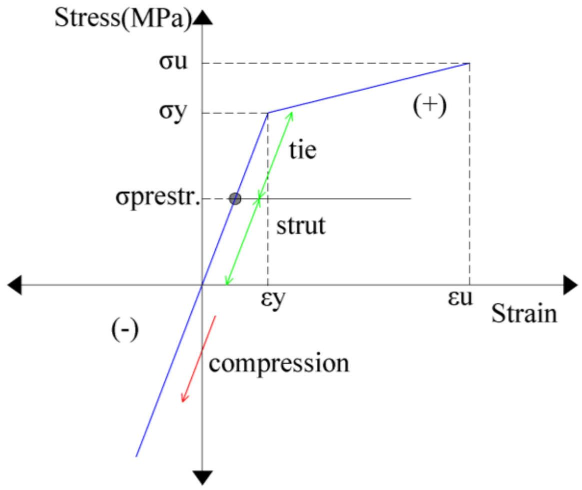


Figure 2: Unbonded tendon response

Furthermore, the proposed mechanism is activated by in service loading, as well. The tendons are in tension during deck contraction and are "compressed" during deck expansion. It is ensured that with in-service loading the proposed mechanism does not arise any issues related to the response of the deck (early cracking) due to the imposed eccentric moments by the mechanism. Analytical investigation shows that an exaggerate size of the mechanism would be required in order to increase the in-service demand on the deck.

In view of the above the determination of the initial prestress shall take into account both seismic and service loads. The initial prestress shall be equal to half of the yielding stress plus a stress caused by in service loads, which is decreased by a factor of 0.5 according to Eurocode 8 provision that service loads are accounted with low values during earthquake events, as shown in Equation 2. In Equation 2 σ_{yd} is yielding stress, E_s is the modulus of elasticity, ΔT is uniform load temperature which corresponds to the critical in service load, L_{tot} is the length of the bridge, l_{eff} is the length of the tendons inside the bridge, l is the total tendon length.

$$\sigma_{prestr.} = \frac{\sigma_{max}}{2} = \frac{1}{2}\sigma_{yd} + \sigma_{\Delta T_{AV}} = \frac{1}{2}\sigma_{yd} + (E_s * \frac{0.5*\alpha*\Delta T*(\frac{L_{tot}}{2} - leff + l)}{l}) \tag{2}$$

Regarding the design of the system the elastic response of the tendons under in-service loading is considered as a prerequisite. More specifically, the maximum allowable strain(or stress) for service loading is determined equal to 70% of the yielding strain(or stress). The minimum tendon length can be determined by equations 3 and 4, based on similar equations for the previous systems ([11], [12]), where $\Delta T_{,con}$ is the contraction temperature which corresponds to the critical in service load and ε_{smax} is the yielding stress.

$$\Delta l = a * \Delta T_{N,con} * \left[\frac{L_{tot}}{2} - l_{eff} \right] + a * \Delta T_{N,con} * \left(l - 2l_b \right) \quad (3)$$

$$\frac{\Delta l + \Delta l_{prestr}}{l - 2l_b} = 0.7 * \varepsilon_{s\max} \quad (4)$$

Regarding the seismic design of mechanism, the size of the tendons is determined according to the seismic demand in order to avoid excess seismic loads beyond the capacity of the prestressed tendons.

3 DESCRIPTION OF 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, [25]. A 3-D finite element bridge model, Fig. 3, was generated in the analysis software OpenSees, [26], accounting for abutment-embankment interaction.

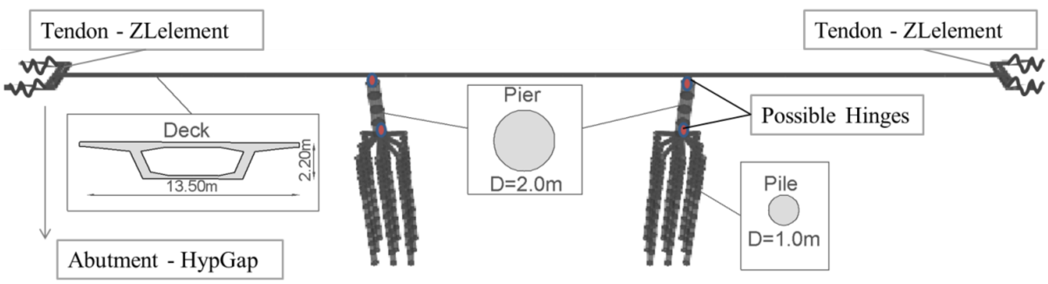
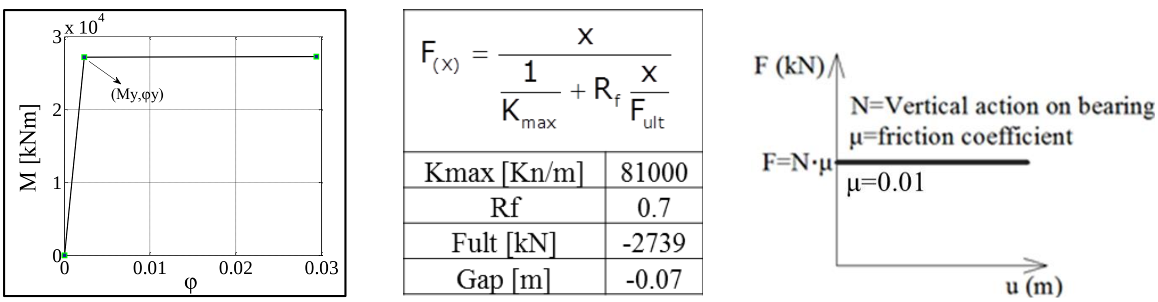


Figure 3 : 3-D Reference Model



(a) (b) (c)

Figure 4 : 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 4(a), for the assignment of concentrated plasticity (hinges) at the top and bottom of piers was performed with AnySection v4.0.6,[26,27]. 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 4(b). The sliding Bearings were modeled as shown in Fig 4(c).

The proposed mechanism is modeled as nonlinear springs as shown in Fig. 5, where K s the initial stiffness of the group of tendons equal to EA/L, (E is the modulus of Elasticity, A cross section of tendons, L length of tendons

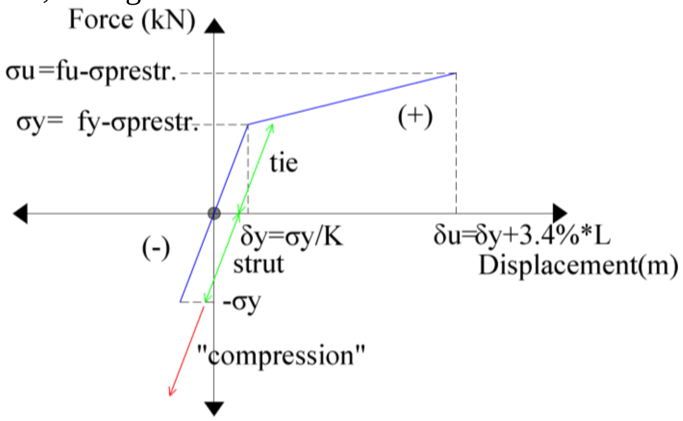


Figure 5 : Tendon nonlinear model

4 ANALYTICAL STUDY

4.1 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 mechanism characteristics and the earthquake intensity.

The first set of parameters consists of the mechanism characteristics. In particular, the effect of the cross-section and the number of tendons each bundle that are installed in the outer spans of the bridge is screened. The variable characteristics correspond to various effective stiffness values of the mechanism that influence the seismic response and the distribution of forces on the bridge. Regarding seismicity, all parameters are screened for the three seismic design intensity levels (I, II and III) according to Eurocode 8, [1]. Seismic zone I is the design intensity level, while the other two levels are used for upgrading the bridge with the same pier dimensions to higher seismic levels by installing in the bridge system the proposed mechanism. For each seismic design level, five artificial accelerograms were used that were compatible to the respective spectrum of Eurocode 8. The parameter values used in the study are presented in Table 1. In Table 2 the specific tendon characteristics are shown. The minimum length of the longitudinal tendons is determined based on equations (3) and (4).

PARAMETERS	VALUES
Diameter of Tendons (mm)	7T15 15T15
No. of Tendons/Bundle	1 2 3 4
Seismicity	0.16g 0.24g 0.36g

Table 1: Parameter Values

5.2 Results Discussion

Table 3 includes the analysis results for the Reference Bridge for the three intensity levels and maximum longitudinal movements, moments and shear forces on piers.

E=190 GPa Fy=1570 MPa										
Tendons	L [m]	A [cm2]	K [kN/M]	σprestr[Mpa]	σy [Mpa]	σu [Mpa]	Fy [kN]	δy [m]	Fu [kN]	δu [m]
1*7T15	41.00	12.37	5732.45	701.56	663.44	776.70	820.68	0.14	960.78	1.54
2*7T15	41.00	24.74	11464.90	701.56	663.44	776.70	1641.36	0.14	1921.57	1.54
3*7T15	41.00	37.11	17197.35	701.56	663.44	776.70	2462.04	0.14	2882.35	1.54
4*7T15	41.00	49.48	22929.80	701.56	663.44	776.70	3282.72	0.14	3843.13	1.54
1*15T15	41.00	26.51	12283.82	701.56	663.44	776.70	1758.60	0.14	2058.82	1.54
2*15T15	41.00	53.01	24567.64	701.56	663.44	776.70	3517.20	0.14	4117.64	1.54
3*15T15	41.00	79.52	36851.46	701.56	663.44	776.70	5275.80	0.14	6176.46	1.54
4*15T15	41.00	106.03	49135.28	701.56	663.44	776.70	7034.39	0.14	8235.28	1.54

Table 2 : Tendon Properties

0.16g	max U1 [m]	max V2 [KN]	max M3[KNm]
	0.08	4826	18968
0.24g	max U1 [m]	max V2 [KN]	max M3[KNm]
	0.12	6143	27193
0.36g	max U1 [m]	max V2 [KN]	max M3[KNm]
	0.14		>M_u(27268)

Table 3 : Reference Bridge Analysis Results

Figure 6 demonstrates the effect of the tendon mechanism on the seismic response of the three span concrete bridge for seismic level I. The significant reductions close to 30% on the longitudinal seismic movements the pier moment and shear forces are the first indicators of the effectiveness of the proposed mechanism. The amount forces that are developed on the tendons under seismic level I earthquake, show that a pile diaphragm of 3x0.3x0.7m dimensions has the capability to receive them safely and the stress and strain plots demonstrate the elastic response of the tendons for both earthquake signs, a behavior which is expected for the proposed system.

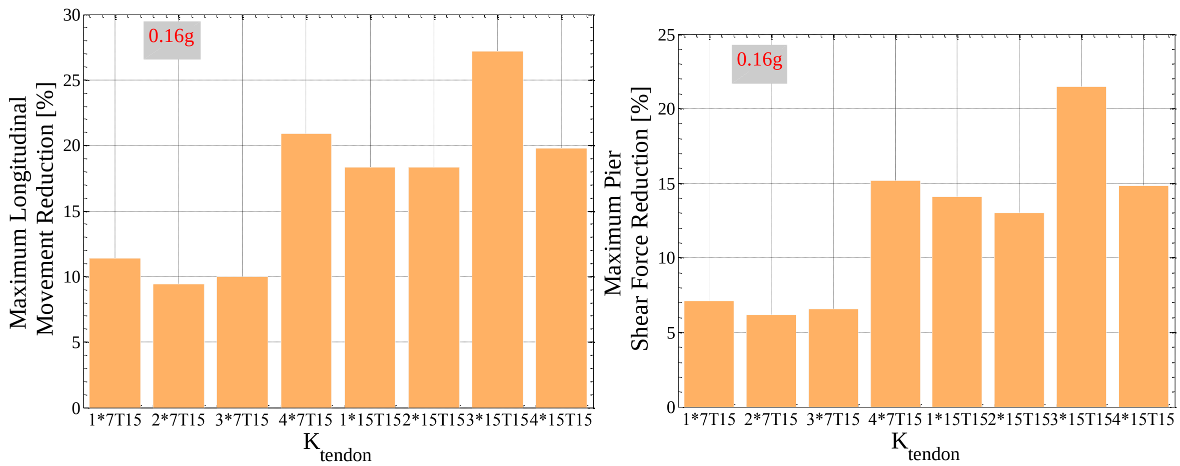


Figure 6: Analysis Results, 0.16g

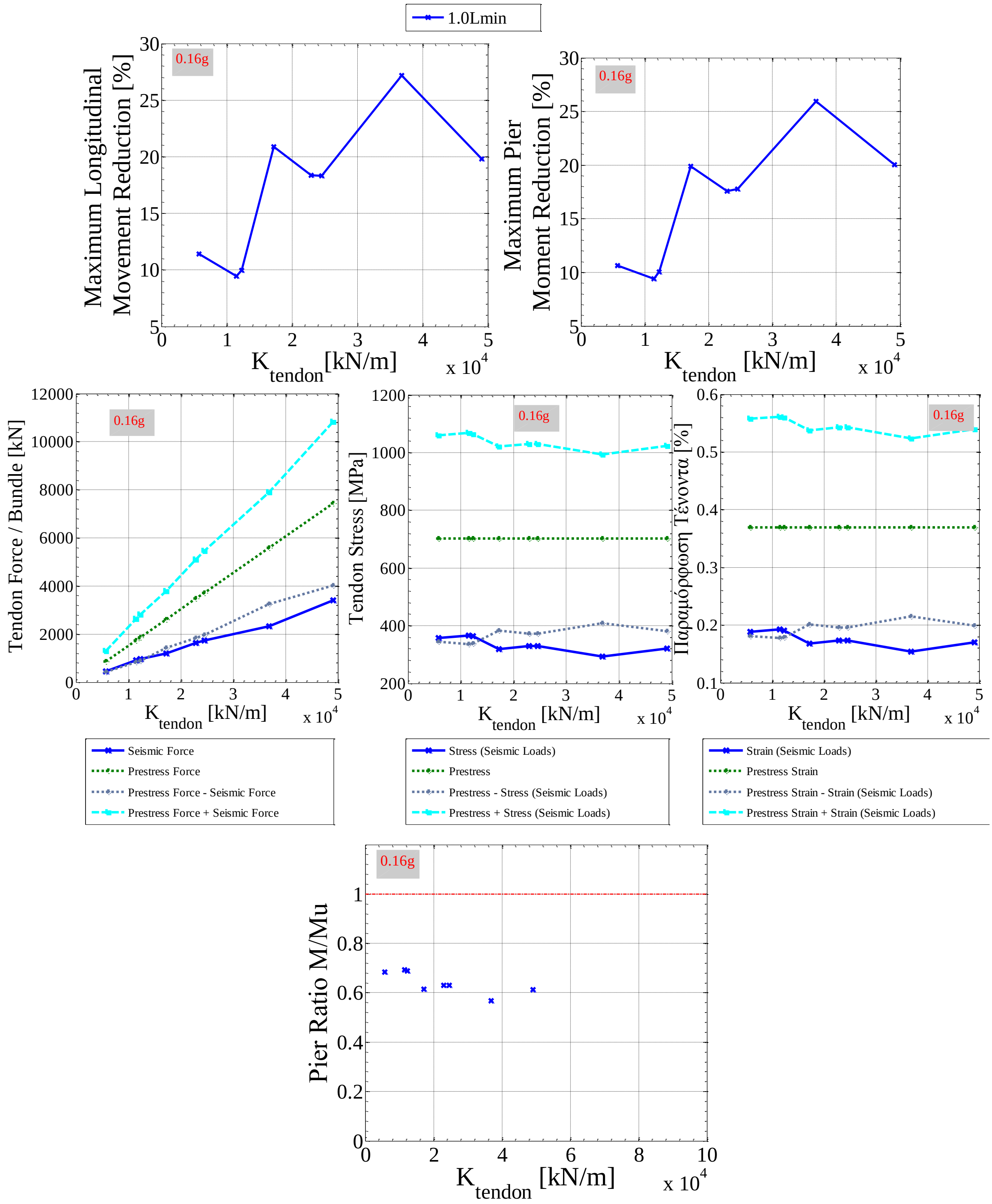


Figure 6 (continued) : Analysis Results, 0.16g

Regarding the capacity of the piers it is observed that since the bridge is designed for this seismic level the initial moment is lower than the Mu. However, the ratio of M/Mu for the bridge systems with the mechanism can be an indicator of the effectiveness of the restraining system on reducing seismic actions, as well. In the results of the two next seismic intensity levels the upgrade of the bridge can be even more obvious.

In Figure 7 the displacement reduction results for seismic levels I and II are shown, while in Figure 8 the ratios or pier moments M/Mu, respectively for the two levels. From the displacement reduction plots, it can be derived that the efficiency of the proposed mechanism is decreased as the earthquake intensity increases, especially for 0.36g when the tendons of small cross section have even negative effect on the seismic movements. However, it can be claimed that the proposed mechanism can upgrade the seismic resistance of the bridge to the higher than the design level seismic intensities. The pier moment ratios in Figure 8 show that, firstly, regarding 0.24g the maximum pier moments are reduced below the yield moment(ratios<0.9) and, secondly, regarding 0.36g the maximum pier moments are reduced below the ultimate moment(ratios<1), which demonstrates the capability of the piers to receive the increased seismic forces in comparison the piers in the Reference Bridge that fail for this specific seismic level.

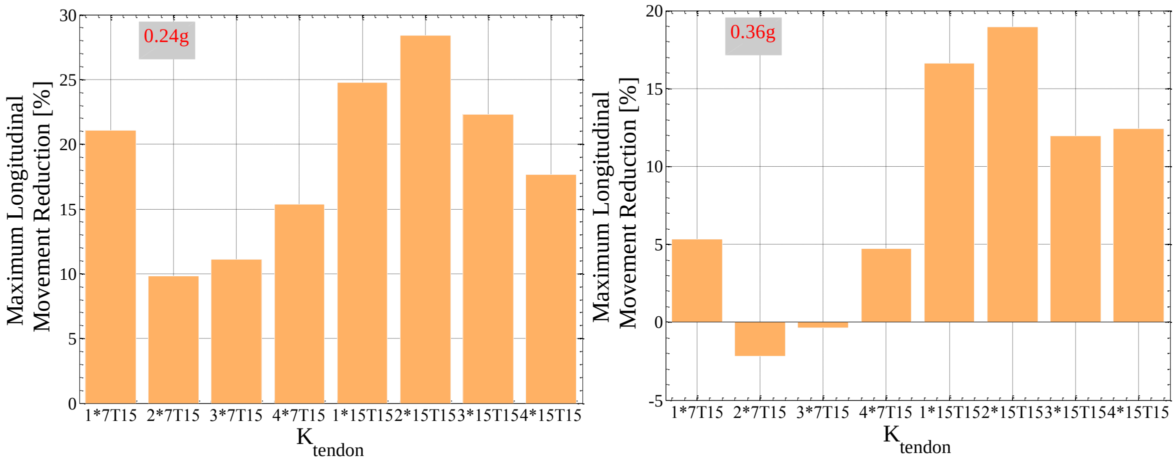


Figure 7 : Long. Movement Reduction, 0.24g and 0.36g

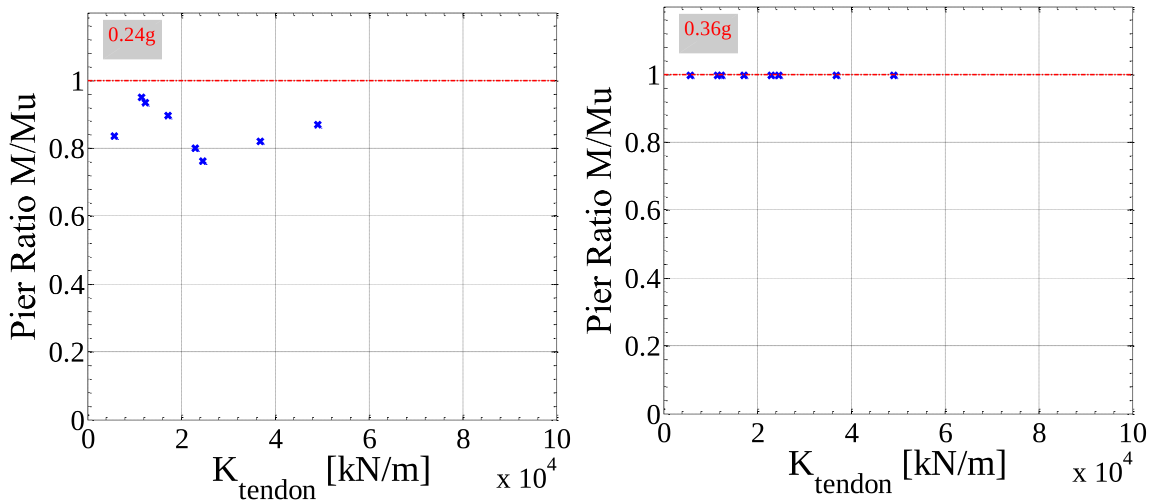


Figure 8 : Pier M/Mu, 0.24g and 0.36g

For selecting an optimum tendon size for the two retrofit cases of 0.24g and 0.36g the level of forces developed at the mechanism is taken into account, as well. Figure 9 presents the response of the tendons for both seismic intensities, where it is apparent that the response of the proposed mechanism is elastic for both earthquake signs. The combination of low seismic forces and significant reduction results in movements and pier moments is required for selecting the appropriate size of the tendons. From the observation of the Figures 7-9 it can be concluded that the cross section of 1*7T15 is sufficient for the seismic retrofit-upgrade of the reference bridge to seismic level II, while a larger cross section with increased stiffness equal to 2*15T15 is required for the seismic retrofit-upgrade of the reference bridge to seismic level III. The maximum forces developed at the selected tendon sizes are included in Table 4 which indicates that they can be transferred to the pile diaphragm without raising any capacity issues.

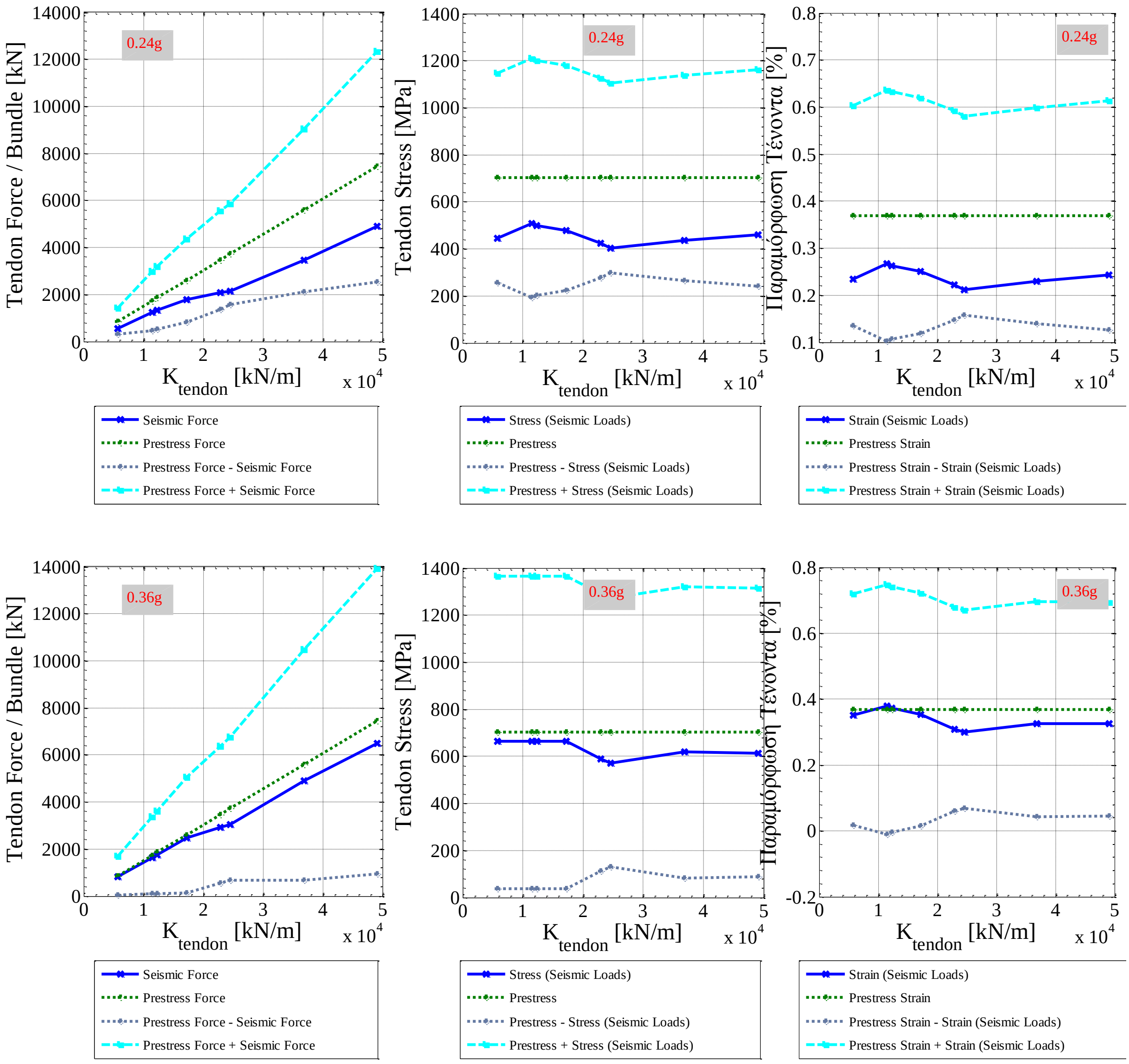


Figure 9 : Tendon Response, 0.24g and 0.36g

Tendons	Forces	
	0.24g	0.36g
1*7T15	1750kN	1900kN
2*15T15	5900 kN	6100 kN

Table 4 : Tendon forces, 0.24g and 0.36g

5 CONCLUSIONS

The key objective of the present study was to investigate the efficiency of a system consisting of prestressed unbonded tendons that is proposed for seismic retrofit of bridges by limiting longitudinal seismic movements. The investigated system belongs to indirect approach retrofit methods due to the addition of new members to the bridge system. The main conclusions derived are the following:

- The indirect accommodation of the increased seismic demand is, in general, the safest way to perform retrofit solutions. Therefore, regarding the longitudinal requirements, the surplus of the seismic actions was driven through the use of the proposed restraining system of tendons to new structures behind the abutments. More specifically, the high seismic demand in combination with the low available additional bearing capacity of the abutments was accommodated with the introduction of tendons in the bridge structural system.
- The proposed system presented high efficiency in limiting longitudinal bridge movements and pier seismic actions for all seismic intensity levels up to 30%. Since the bridge was designed for seismic level I it was taken into account as an indicator of the efficiency of the system. The possible upgrade of the Reference Bridge was more evident for the next two seismic levels. Especially for seismic level III, the seismic demand at the reference bridge exceeded pier capacity, while the installation of the mechanism lowered the seismic demand on the piers to the level of their capacity.
- The tendons are advantageous regarding their response, since they can develop a “strut-tie” behavior with the use of prestress without developing any compression stresses. Analyses for all seismic levels have shown that the proposed system can remain in the elastic region.
- The efficiency in reducing longitudinal movements and in seismic retrofit, the long lifetime of the tendons and the simplicity of the application contribute to the high reliability of the proposed system, as an alternative indirect retrofit method.

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