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EXPERIMENTAL AND ANALYTICAL STUDY ON HOLLOW PRECAST PIERS WITH UNBONDED CONVENTIONAL REINFORCEMENT TO CONTROL SEISMIC AND IN-SERVICE RESPONSE OF BRIDGES (COMPDYN 2017)

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Abstract. *Common construction practice of cast in-place piers in reinforced concrete bridges presents limitations due to high construction and post-earthquake rehabilitation cost. The latter can become extensive due to the potential development of plastic hinges at the top and bottom of the piers. Another issue that arises due to the large pier stiffness in cast in-place piers is the accommodation of in-service deformations without the development of any plastic deformations that require rehabilitation works, as well. Therefore, alternative solutions that avoid permanent deformations on piers, reduce seismic demand and develop elastic seismic and in-service bridge response have been investigated in the last years. The present paper to address this issue studies, experimentally and analytically, the use of precast piers either full-height or segmental and proposes a hybrid precast pier system. In the novel approach the connection of the prefabricated segments with the foundation at the pier's base and the deck at the pier's top is achieved with unbonded conventional steel reinforcement. The piers are not expected to develop cracking except from the top and base interfaces due to rocking response. In this way, precast piers can accommodate bending deformations from seismic and in-service demand. A benchmark three span R/C Bridge was used for the investigation. Three 1/3 scale pier specimens with precast hollow sections were experimentally tested and compared regarding their flexural response and stiffness. The experimental results were then used in an analytical application on a finite element model of the Benchmark Bridge and time history analysis was conducted to evaluate the bridge seismic response. It is evident from the analytical and experimental outcomes that the different methods that were studied control the flexural stiffness of piers, develop improved seismic response and have positive effects on the economy and constructability of R/C bridges.*

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1 INTRODUCTION

Bridge construction practice of cast in place piers is the most common method worldwide for the construction of concrete bridges that have monolithic connections between deck and piers. However, there are some limitations regarding the use of the current construction practice. One concern is the high cost of using scaffolding, in terms of complexity, workman efforts and time-intensiveness, when used in elevating heights. In particular, when the pier height is larger than 10m cast in place piers are not economically feasible [1]. Furthermore, the resulting monolithic connections in the cast in-place practice, arise an issue of high rehabilitation costs due to the potential development of plastic deformations at the top and bottom of the piers, either under in-service or seismic loading according to Eurocode provisions, [2]. The widely used isolation devices between deck and piers, recommended also in Eurocode [2], cannot be a panacea since although they accommodate the latter issue with the development of elastic deformations, are considered quite expensive, especially regarding the required maintenance costs. Therefore, it is essential to investigate novel ways to mitigate the stated problem.

In the last decades, pier prefabrication which is a feasible alternative to cast in place practice, is more and more used in bridge construction, [3]. However, precast of bridge substructures is still not used widely and most precast pier construction is limited to bridges that involve isolation devices for the support of the deck on piers. In most precast pier applications, moment connections between piers and pile caps at the bottom and piers and beam caps at the top are developed, [4]. Recently, there have been, some scientific efforts for creating hybrid precast pier systems, [5] for altering pier top and bottom connections, but they haven't yet been incorporated in practice due to the lack of extensive investigation of these pier types and the lack of any design specifications and design tools. More specifically, in Hieber [3] it is stated that solid circular precast piers can be used in combination with longitudinal unbonded tendons and conventional steel reinforcement. In such cases, the pier rotation caused from relative seismic lateral movements is accommodated through the rocking response of the gap openings at the interfaces near the top and bottom of the pier and the tendons can provide recentering forces to the system. However, important considerations regarding the use of prestress is the increased axial load that is induced in the system and the protection of the prestressing steel from corrosion throughout the structure's design life.

It is noteworthy that rocking piers on foundations have been widely investigated by the scientific community and not limited to prefabricated pier applications. Some researchers have indicated that the rocking itself can act as a form of isolation mechanism. Mander and Cheng [6] introduced rocking frames as an alternative design concept of bridges. Several studies have been conducted based on the response of rocking frames. Makris and Vassiliou [7] and DeJong and Dimitrakopoulos [8] revisited the seismic response of the freestanding rocking frames. Various systems, not limited to prefabricated piers, that combine the use of recentering, such as prestress steel tendons and energy dissipation devices with rocking response have been proposed for both buildings [9] and bridges [10]–[13].

On the light of the above, the present paper proposes a hybrid precast pier rocking system with unbonded conventional reinforcement as a novel approach to pier prefabrication. The steel reinforcement is placed longitudinally in circular hollow cross sections and is not bonded from the concrete except from the areas of the anchorage length. Conventional reinforcement instead of prestress steel was preferred to avoid high axial load values on piers and to overcome corrosion issues with the use of stainless steel rebars. The investigation was held for circular hollow cross sections, while most of the previous precast pier systems [5] used solid. Circular hollow cross sections have the advantage of reduced weight that makes transfer and erection of pier segments easier and more economic and rapid, are common for bridges with large heights and have the same mechanical behavior in all directions. Research studies that have been conducted regarding the structural response of hollow cross sections [14] and issues like confinement [15], were taken into account for the configuration of the reinforcement in the pier cross section. Additionally, the response of bridges with precast full-height or segmental piers was studied, as well, aiming at further enhancing scientific knowledge for prefabricated piers. The investigation was conducted experimentally and analytically and a three-span R/C concrete Bridge was used as Benchmark for both parts of the study. The ultimate target regarding the bridge application was to achieve with the proposed precast piers a significant reduction in the seismic actions in a way similar to seismic isolation. Three 1/3 scale pier specimens with precast hollow sections were experimentally tested and compared regarding their flexural response and stiffness. The experimental results were then used in an analytical application on a finite element model of the Benchmark Bridge and time history analysis was conducted to evaluate the bridge seismic response. From the analytical and experimental outcomes, it became evident that the different types of piers that were studied have improved seismic response and have positive effects on the economy and constructability of R/C bridges.

2 RESEARCH SIGNIFICANCE AND DESCRIPTION OF THE PROPOSED SYSTEM

The proposed herein precast pier system originates from the need to satisfy the following requirements of the compliance criteria of current bridge practice, with an emphasis on constructability, economy, aseismic and serviceability response: a) Construction of piers is a demanding issue, especially for large heights which often require large cross sections, as well. The common cast in place construction practice with a moving scaffolding through the pier height, which is expensive and difficult to apply, tends to result in piers of low quality. By the proposed pier system, constructability issues are eliminated as precast solutions can increase quality and speed the construction of piers. Regarding the arising issue of the transfer of precast piers from production to the site, it is possible to be treated with a piece by piece transfer and an appropriate segment connection during erection process [16]. b) Accordingly, from an economic perspective, the industrial production of pier segments can lower the construction cost drastically. c) Regarding seismic response of bridges, often there is the need to avoid plastic hinges or vary the stiffness of piers to address seismic requirements, while it is essential at all times to keep the same pier dimensions due to aesthetic reasons. The common practice is to lower the flexural stiffness of piers with the use of isolation devices, which, however, are expensive with respect to supply and maintenance. The proposed system aims to alter the flexural stiffness of piers, lengthen the fundamental period of bridges and reduce seismic actions on piers. It is actually a way to introduce in bridge systems seismic isolation characteristics. The intervention can be more evident in the shorter-stiffer piers, especially in long bridges that present large differences in pier heights; piers in the middle are usually higher than those at the end spans due to topographic reasons. In these bridges, variance in pier stiffness affects even the regularity of bridges, which results in the reduction of the behavior factor of bridges according to Eurocode 8- Part 2 [17], while the novel precast pier system can reduce the stiffness of short piers and transform irregular systems to regular. d)Serviceability issues that arise in shorter piers due to their large stiffness can be accommodated, as well. It is noted that in the context of this study the analytical investigation is limited to seismic response.

Therefore, the proposed hybrid precast pier system aims to answer the question of controlling seismic and in-service response in a constructible and economic way. The proposed system includes the use of precast piers. The piers can be either of full height or segmental. The ability to use precast piers and, especially, segments, is based on a former study of the authors [16] and on the experimental study herein. The precast piers are introduced in bridges without creating moment connections at the top and bottom of the pier. At these positions gaps are developed between pier- deck and pier-foundation interfaces. The connections between the precast concrete columns and cap-beam are achieved with longitudinal conventional steel reinforcement that is not bonded to the pier's concrete. In the present study, it is a novel approach to use conventional steel reinforcement instead of prestressed tendons that are used in common practice. The steel reinforcement is anchored with the appropriate length and unbonded through the full pier height with the use of plastic sheets or ducts and located around the external diameter of the pier. The system is applicable for a variety of cast-in-place concrete foundation types and deck cross sections. Herein the investigation is limited to connections with box girder decks and pile-cap foundations. Figure 1 shows a sketch of the hybrid pier supported on a pile-cap foundation and the unbonded conventional longitudinal reinforcement.

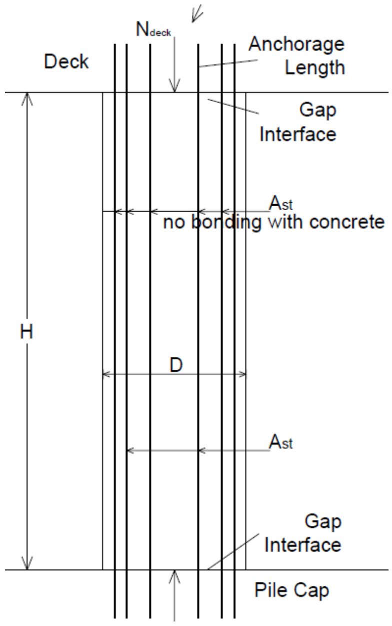


Figure 1: Schematic figure of the proposed hybrid pier system

The precast piers are designed so that, as the pier sways during a seismic event or deforms under in-service temperature loading, the unbonded conventional reinforcement is stretched and the rotation caused from the relative lateral movement between the cap-beam and the foundation is accommodated through one gap opening at the interfaces near the top and bottom of the pier. The piers develop a rocking response and, therefore, the lateral deformations are a result of rigid column rotation, not plastic deformation of materials within the plastic end region at the highest moment demand area and crack growth is avoided in the piers. Since cracks are expected to develop at the contact interfaces at the top and bottom of piers, it is advised to use stainless steel reinforcement to avoid corrosion. The unbonded conventional reinforcement is designed so that the rebars do not yield. By remaining elastic, the bars do not provide any energy dissipation, but they do provide a re-centering ability. The re-centering ability causes the hybrid pier to have small residual displacements after an earthquake. The unbonded reinforcement does not yield because the increase in strain as the frame sways is distributed over the length of the entire bar. In Figure 2, the mechanism that receives the seismic forces is prsented. The seismic shear is received from a diagonal strut from the concrete cross section and from the horizontal forces of the rebars under tension. The equations governing the response are shown in Eq (1)-(3). The flexural stiffness of piers is significantly reduced. Although energy dissipation mechanisms are disabled in this system the reduction in the pier flexural stiffness, elongates the fundamental period of the structure, giving to the system seismic isolation characteristics, which results in a large reduction of the seismic forces. The resulting stiffness will be further investigated in the experimental study.

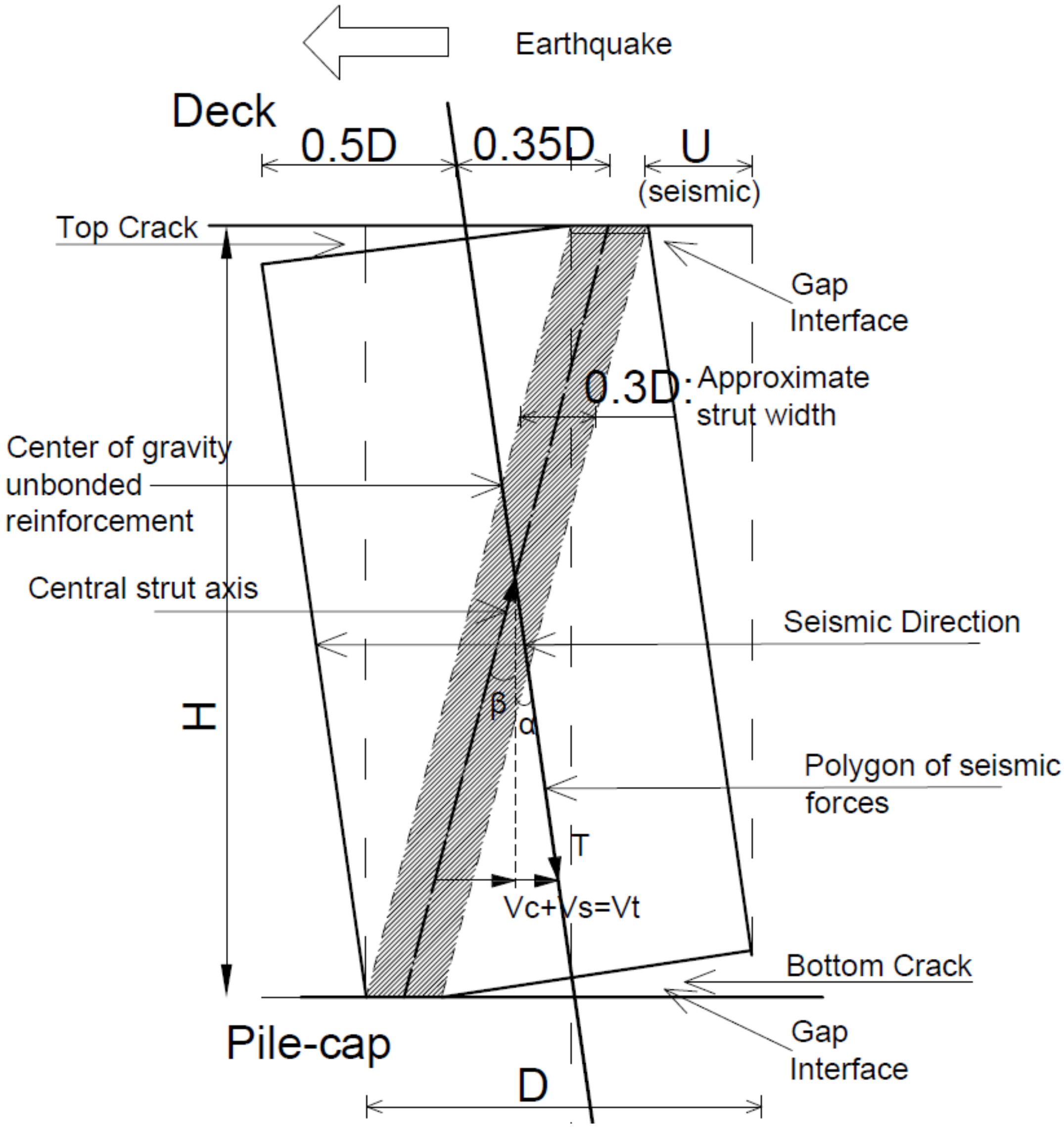


Figure 2: Polygon of seismic forces in the proposed pier

$$T = A_{st}\sigma_s = A_{st}\varepsilon E_s \quad (1)$$

$$\varepsilon = \frac{(u^2 + L^2)^{1/2} - L}{L} = \left(\frac{u^2}{L^2} + 1\right)^{1/2} - 1 \quad (2)$$

$$V = T\tan\alpha + \frac{T}{\cos\beta}\sin\beta = (\tan\alpha + \tan\beta)\mathrm{T} = \left(\frac{u}{L} + 0.70\frac{D}{L}\right)T =$$
$$= \left(u + 0.70D\right)\frac{T}{L} \quad (3)$$
$$= \left(\frac{u}{L} + 0.70\frac{D}{L}\right)A_{st}E_s\left[\left(\frac{u^2}{L^2} + 1\right)^{1/2} - 1\right]$$

Where V: Shear seismic force, Vc: Shear force from concrete strut , Vs: Shear force from the unbounded longitudinal reinforcement, T: tension force, Ast: area of the steel reinforcement cross section, σs: steel stress, Es: steel elastic modulus, ε= steel deformation and L= pier height.

The system allows the proportion of the unbonded reinforcement and the reduction of flexural stiffness of piers to be selected on the basis of the required response for providing an increased re-centering ability and not allowing maximum displacements to reach high values. It is noteworthy that seismic displacements can be further reduced through the use of a steel restrainer mechanism in the deck of the bridge that has been proposed by the authors in previous studies. [18], [19].

3 EXPERIMENTAL STUDY

3.1 Aim of the experimental study

The purpose of the experimental investigation is the response of precast piers in full height, in segments and with the proposed precast pier system. Three types of specimens were tested and the experimental research focused on the evaluation of the resulting stiffness of the precast pier specimens. The experimental study also compared the response of a full height precast pier specimen and a segmental pier specimen, which is considered critical for the pier seismic response.

3.2 Description of specimens

The specimens were developed based on the dimensions of the piers of a three-span monolithic bridge of Egnatia Motorway in a 1/3 scale, which is described in 4.1. The bridge piers have a solid circular cross section of 1.80m diameter and are 9m high. (Fig.8). A hollow cross section of the specimens was selected to lower construction cost with 0.60m external diameter and a height of 3m. The three precast concrete specimens that were investigated are shown in Table 1. The class of the concrete was C30/37. The yield stress of the steel rebars used for the longitudinal and transverse reinforcement was considered equal to 500MPa.

Name	Description	Dimensions	Height
SP1	Precast Pier Segments	Hollow cross section d_{exter}=0.60m, d_{inner}=0.30m	3m
SP2	Precast Pier Full Height	>>	3m
SP3	Precast Pier with unbonded conventional steel rein-	>>	3m

forcement

Table 1: Example of the construction of one table

More specifically, the first specimen represents a pier constructed segmentally and according to a construction method (SP1) that is proposed and described in detail in a previous research work of two of the authors of the paper [16]. SP1 consists of two segments; each segment is a hollow circular column with a thickness of 5 cm. The inner column has a diameter of 30 cm and the outer column 60 cm. Each segment has a height of 1.75 m. The gap between the two columns is casted in-place and has a thickness of 5cm, as well. The second specimen represents a pier constructed according to the current pier precast practice in full-height (SP2). Similarly the construction process is described in detail in [16]. SP2 has a height of 3.5 m and the thickness of the hollow cross-section is equal to 15 cm. The reinforcement of SP2 is placed at the same position as in case of SP1 but its length is equal to 3.5 m, in contrary with SP1, in which the longitudinal reinforcement consists of 1.50 m rebars as shown in Fig. 3. The third specimen was developed as a single segment pier, as SP2, with the same geometry and outer longitudinal reinforcement of 56Ø8 that were anchored at the ends of the specimen with the appropriate anchorage length. Former research on hollow circular cross sections [14], [15] was taken into account and the inner longitudinal reinforcement was not considered to contribute in the pier response. The cross section and elevation of the specimens are shown in Figure 3. The difference of SP3 lies in the absence of the bonding of the steel reinforcement with the concrete in the central part of the specimen which can be avoided during the pour of concrete with the use of pvc sheet protection. The transverse reinforcement in all three cases consists of two coils, an internal coil of Ø8/60 mm and an external coil of Ø8/50 mm.

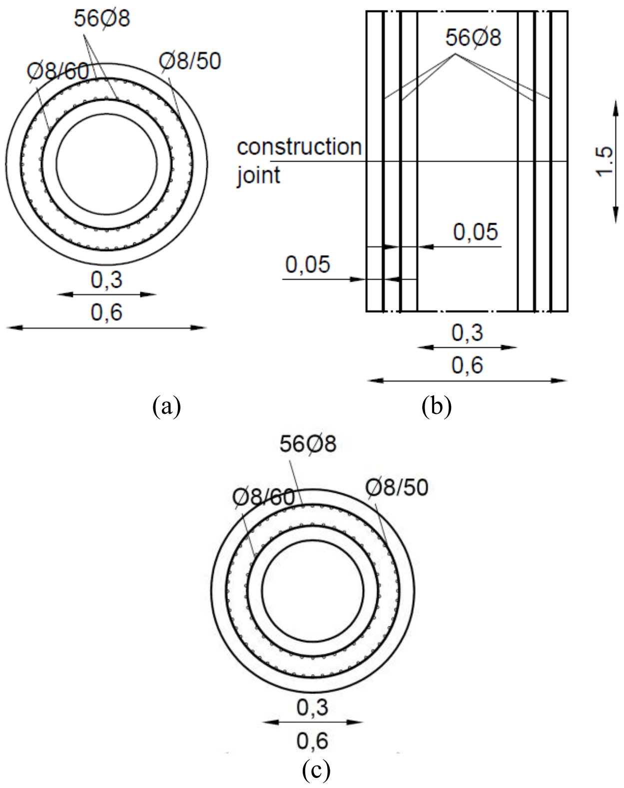


Figure 3: a) Specimen 1- cross section, b) Specimen 1- elevation b) Specimen 3-cross section

3.3 Test Set up and Results

The experiment was conducted in the Laboratory of Experimental Strength of Materials and Structures, Department of Civil Engineering, Aristotle University of Thessaloniki. The preparation of SP1 and SP2 specimens that were tested took place at ARMOS precast factory. Regarding the first two specimens that have moment connections at the pier top and bottom it should be noted that although piers are not simply supported components, fixity is very difficult to achieve in the laboratory. Thus, it was decided to test each specimen as a simply supported beam, which is a common practice, and then convert the results to fixed conditions, which represent reality. Each specimen was supported at their ends and was subjected to an incrementally applied point load in their mid-length (Fig. 4) in two diametrically opposed directions until their yield point, which was circa 500 - 600 kN, as the ultimate load capacity had already been calculated at about 50tn.

Figure 4: Loading of specimen SP1 in Laboratory.

Deflection at mid-length of the specimens was recorded by the use of an analog displacement sensor. The test set up model is presented in Figure 5. The results obtained from the experimental study of the first two experiments are shown in Figure 6. The x-axis represents the deflections at the mid length of the specimen and the y-axis the load applied. It can be observed that the two slopes at the state of Stage II (cracked section) are similar, which means that the specimen of the segmental case (SP1) approaches the behavior of the full-height specimen (SP2) and that the specimens have similar flexural stiffness.

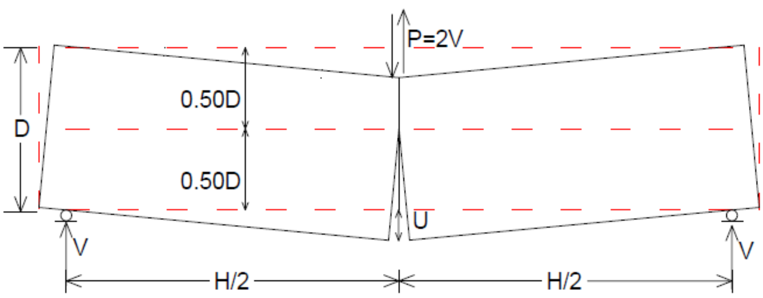


Figure 5: Experimental set up

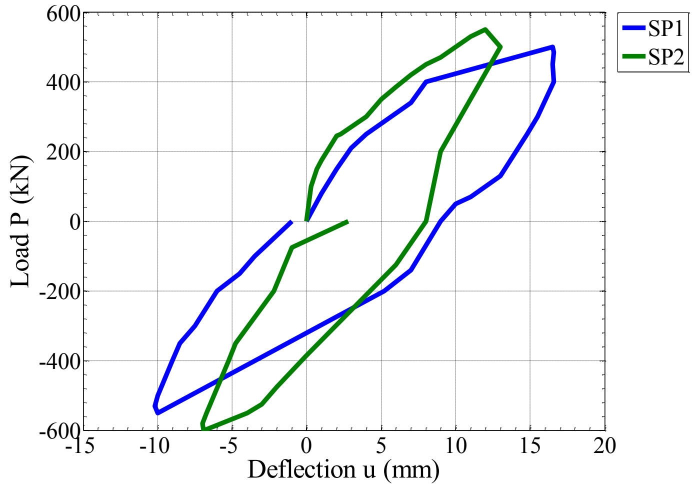


Figure 6: Load – Deflection (at mid-length) experimental results.

The third experiment was conducted analytically “on paper”, a term that was introduced by Professor Tasios of NTUA. The specimen was considered as simply supported at the ends and was subjected, similarly, to an incrementally applied point load at the mid-length of the specimen. No axial load was applied on the specimens. The load deflection relationship was calculated according to Eq. (3) for incrementally applied load to the yield point of the reinforcement. The load P is calculated as a function P(u) of the deflection u at the mid length of the specimen. The proposed hybrid precast pier system is expected to develop elastic response, therefore, the results beyond yield point are out of the scope of the present study. The values of the required parameters for the experiment “on paper” are shown in Table 2.

Parameter	Value
D (m)	0.60
A_{st} (cm^2)	28.20
H (m)	3.00
E_s (GPa)	200
ε_{sy} (%)	2.17
u_y (m)	0.10

Table 2: SP3 parametric values

In Figure 7a the flexural stiffness of the specimens is presented. Since the response of the first two specimens was quite similar, the mean effective flexural stiffness of the first two specimens was calculated and compared with the effective flexural stiffness of the third specimen SP3. The effective stiffness can be calculated as a linear approximation of the force-deflection relationship, a process followed by Eurocode specifications [20], Fig 7b, as well. It is observed that the effective stiffness is tremendously reduced when compared to the stiffness of the first two specimens. The ratio of the effective flexural stiffness of SP1 and the mean of SP1 and SP2 is equal to 0.13. The reduced flexural stiffness can be used as means of transforming structural systems to seismically isolated without introducing any isolation devices. The ratio of the effective flexural stiffness of the specimens to the uncracked pier flexural stiffness is shown in Figure 7c. It is noteworthy the cracked stiffness of State II for a regular pier is analytically calculated equal to 37% of the uncracked stiffness and the stiffness of the specimens SP1 and SP2 presents low difference to that value.

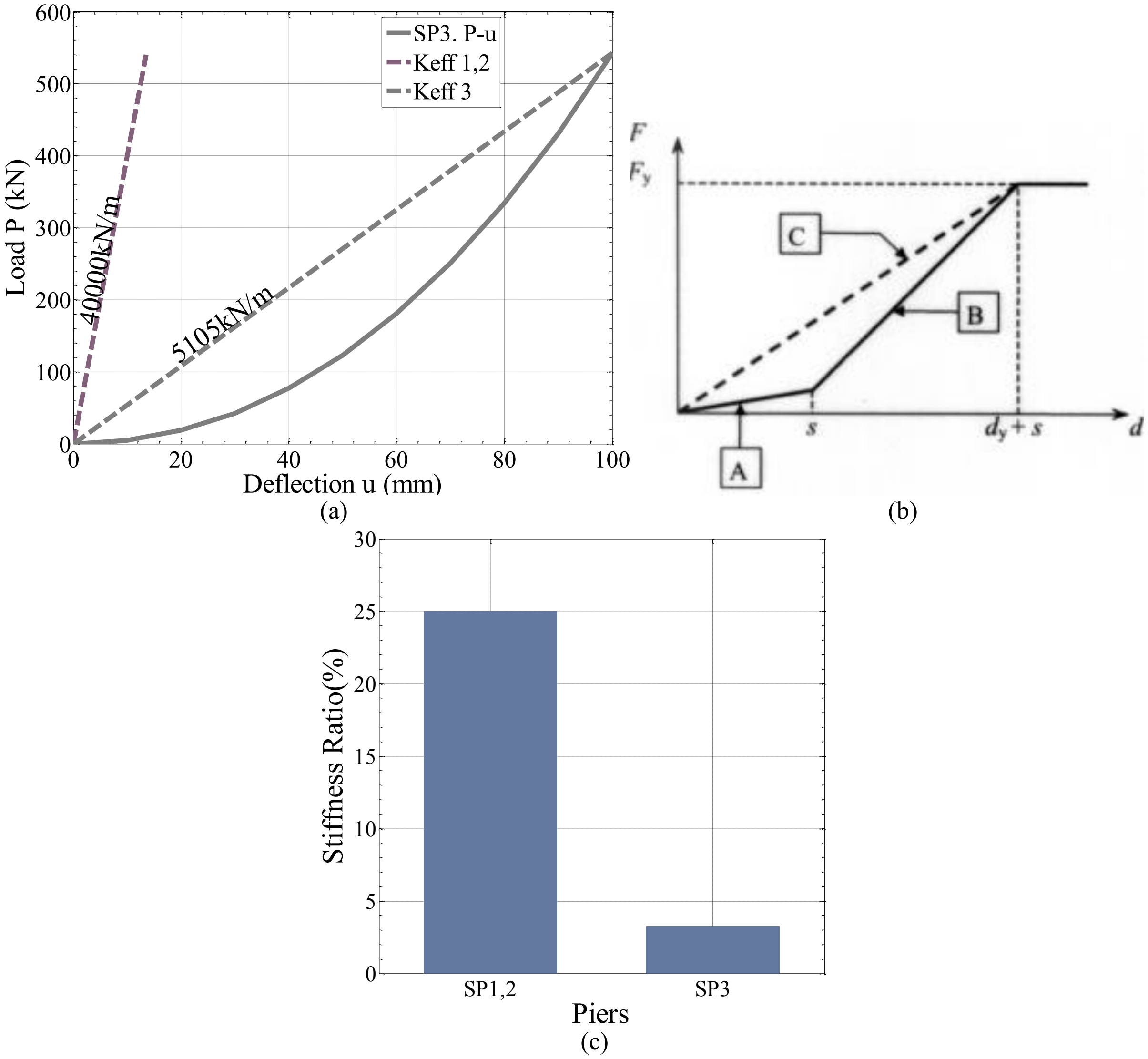


Figure 7: a) Effective stiffness diagrams, P/u at the mid length of the simply-supported specimens, b) Fig.6.2 Eurocode 8-Part2, c) ratio of the calculated flexural stiffness to the uncracked stiffness

4 ANALYTICAL STUDY

The results from the experimental study were used in an analytical case study to evaluate the effectiveness of the proposed precast pier application on the seismic response of bridges.

4.1 Description of the Benchmark Bridge

The Benchmark Bridge that was used in both analytical and experimental study is a monolithic three span pre-stressed 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, [21].

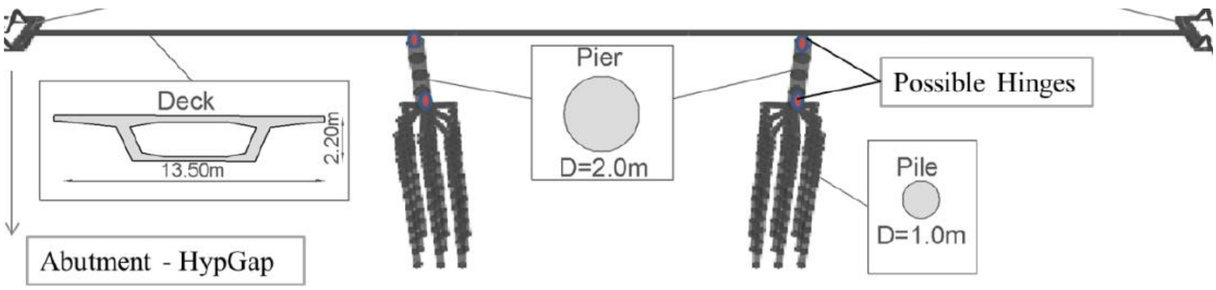
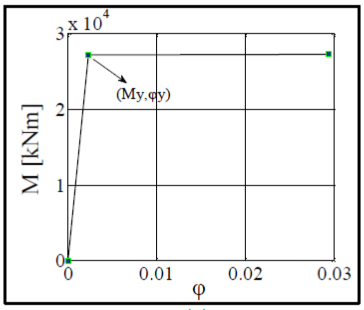


Figure 8: 3-D Benchmark Bridge Model

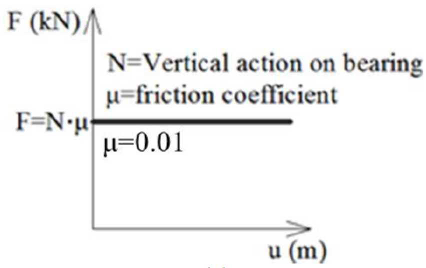


(a)

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

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

(b)



(c)

Figure 9: a) M-φ curve, b) Abutment P-Y curve, c) Sliding Bearing

A 3-D finite element bridge model, Fig. 8, was generated in the analysis software OpenSees,[22] accounting for abutment-embankment interaction. Bridge components were modeled as frame elements with material nonlinearities. The section analysis for the benchmark bridge, Fig 9(a), for the assignment of concentrated plasticity (hinges) at the top and bottom of piers was performed with AnySection v4.0.6, [23]. 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 [24] and the HyperbolicGap compression material was used in OpenSees, Fig 9(b). The sliding bearings were modeled as shown in Fig 9(c).

4.2 Application of the proposed precast piers

The results obtained from the experimental test can be used in the case study, since the specimens were created based on a 1/3 scale to the Benchmark Bridge. Three different bridge pier cases are investigated analytically. The first is the benchmark bridge (B), the second the bridge with precast pier with hollow circular sections and conventional reinforcement, as SP1-SP2,(PR2) and the third with the hybrid precast pier system which has the same cross section and unbonded longitudinal reinforcement through the height of the piers (PR3). The dimensions of the piers in the two latter cases are: 1.8m outer diameter and 0.35m thickness. The concrete class is C30/37. The unbonded reinforcement is introduced in the outer coil of the pier. The advantage of using hollow cross sections lies in the reduction of the weight of concrete cross sections and the reduction of their cost of transfer consecutively. The flexural stiffness of the precast piers derived from the experimental results is used. Eigen analysis of the three structural systems resulted in the following plot, Figure 10a which depicts a significant elongation of the fundamental period of the PR3.

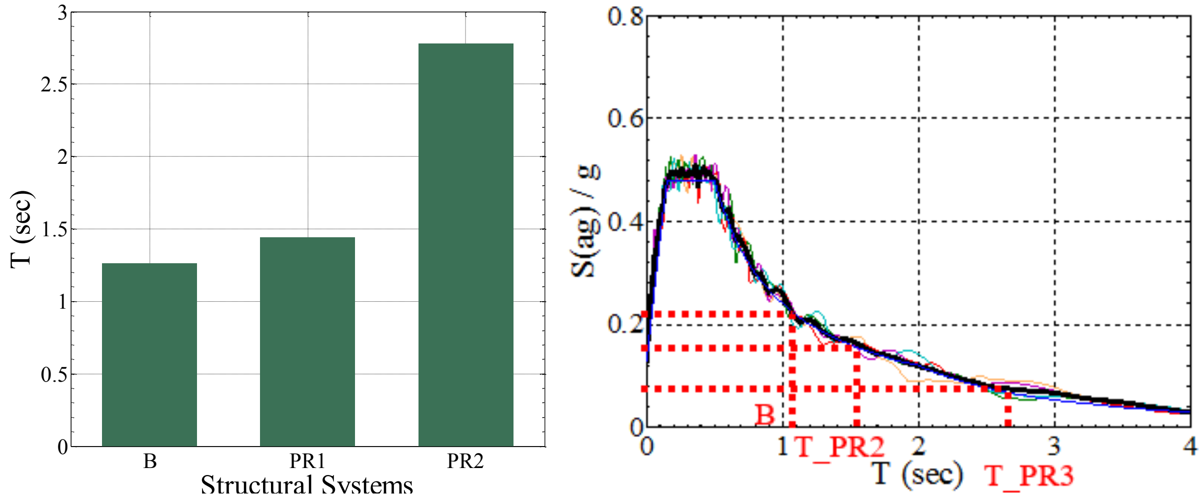


Figure 10: a) Fundamental period of the systems, b) Eurocode spectrum for 0.16g

Figure 10b includes the elastic spectrum according to Eurocode 8 for the bridge. It is even more evident from this plot that the fundamental period of the system increases that much that the proposed system can be characterized as a type of seismic isolation. The structure is shifted to the right of the spectrum which reduces the seismic actions significantly. Time history analysis was performed with seven artificial accelerograms compatible to Eurocode 8 spectrum for 0.16g , Zone I. In Figure 11a the maximum pier top displacements from the time history analysis are presented. It is observed that there is a substantial increase to the maximum seismic displacement, but it is not increased to an extent that it cannot be accommodated by the bearings at the abutments or with a slight increase of the end joints of the bridge. On the other hand, the seismic actions on bridges are remarkably low for the proposed pier system which depicts that the bridge will develop elastic response under the design earthquake loading. The seismic moments are more than 60% lower the yielding pier moment at the pier base.

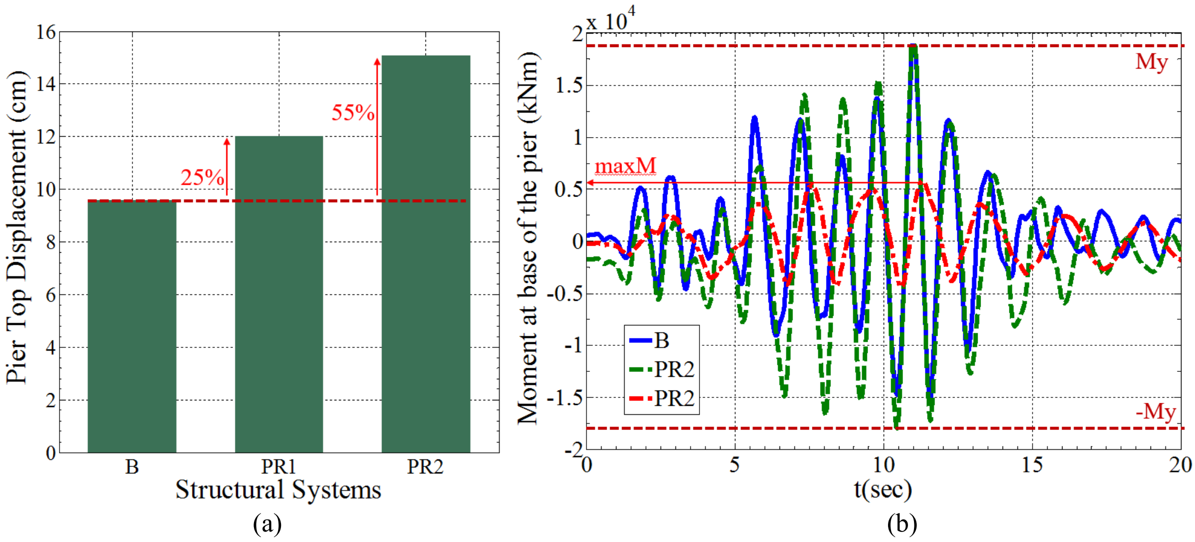


Figure 11: a) Maximum seismic displacements, b) Maximum seismic actions at the piers

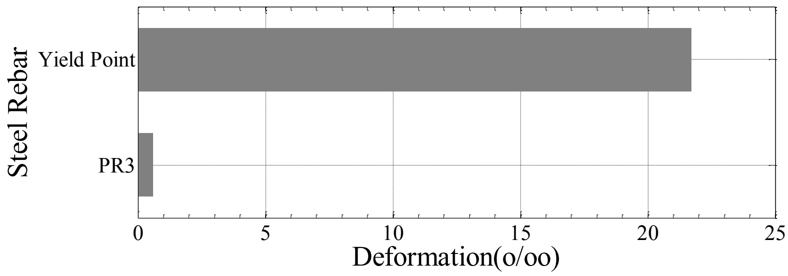


Figure 12: Steel Rebar Seismic Deformation in PR3

Finally, the deformation of the unbonded longitudinal reinforcement is investigated to ensure that the steel reinforcement is elastic and able to provide the bridge with the re-centering forces. In Figure 12, it is shown that the maximum seismic steel bar deformation is significantly lower in comparison to the yielding deformation of the steel bar.

5 CONCLUSIONS

The present study proposes a novel hybrid precast pier system with stiffness control features the addresses most of the various compliance criteria in current bridge practice. Experimental and analytical investigation was conducted to three different types of precast piers to gain further knowledge in the response of precast piers and to validate the proposed method. The conclusions derived by the present study are stated in the following paragraphs:

- The experimental study has shown that precast piers either with single elements in full height or in segments can have a reliable response, as the calculated stiffness from the experiments does not differ significantly from the analytically calculated stiffness of State II (cracked) and the analytical results depicted similar behavior to the cast in place piers.
- The proposed hybrid precast pier system uses conventional steel reinforcement unbonded through the pier height. The investigation showed that the system can be effective without the use of prestressed tendons, which is the current practice. In this way, the large axial load that is induced in the bridge system from the tendons and prestress tendons corrosion issues can be avoided.
- Regarding the analytical study, it is observed that the fundamental period of the structure is lengthened to an extent that the proposed system can be characterized as a seismic isolation mechanism that is achieved without the use of isolation devices. Therefore, it can be characterized as an economic system when considering the construction and maintenance cost of the isolation devices that can be avoided.
- The seismic response of bridges is also improved through the reduction of seismic actions on piers to the level of their capacity. Furthermore, the post-earthquake required rehabilitation works are minor as cracks on pier webs are avoided and re-centering forces are developed to return the system to initial position. The system is expected to develop linear elastic behavior and the seismic actions are reduced around 60%.
- Constructability criteria are highly met, as it is possible to use precast pier cross sections which can be erected without difficulties at the site. Finally, serviceability requirements could be addressed by the controlled reduction of pier stiffness, as well, although analytical investigation was not included in the scope of the present study.

6 ACKNOWLEDGEMENTS

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