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ANALYTICAL AND EXPERIMENTAL INVESTIGATION ON THE SEISMIC EFFICIENCY OF A NEW RESTRAINING SYSTEM FOR LIMITING THE SEISMIC MOVEMENTS OF THE BRIDGE DECK

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Abstract. *The aim of this study is the analytical and experimental investigation on the seismic efficiency of an innovative restraining system. This system consists of transversely directed R/C walls, which behave as seismic stoppers. The aforementioned walls constitute part of the abutment and they are transversely directed to the longitudinal direction of the bridge. The available height of the abutment and the thickness of the walls are the main parameters affecting the serviceability level and seismic resistance of the aforementioned system. These parameters are strongly correlated, as they both influence the shear ratio of concrete walls and consequently, the seismic efficiency of the abutment. It is noted that the restraining walls of the abutment contribute not only by their own stiffness but also by dissipating energy through hysteretic behavior. In the first part of the study the investigation on the applicability of the proposed restraining system in all bridge types, independently of their length and the abutment's available height is presented. In the second part of the study the experimental investigation on the seismic efficiency of the proposed restraining system under monotonic and cyclic loading is presented. The experimental program involves three specimens. The results of the investigation showed that the proposed restraining system improves the safety, durability, serviceability, aesthetics and cost-effectiveness of bridges. Specifically, the exploitation of the proposed abutment in monolithic and floating deck bridge systems showed that, the longitudinal and transverse movements of the deck are effectively reduced. The aforementioned reductions in the seismic movements lead to reduced seismic actions of the piers. It is noted that, the reduction in the seismic actions leads to cost- effective and smaller cross-sections of the piers, which also serve aesthetics. Finally, the experimental investigation verified that the capacity of the system to dissipate energy is significant.*

1 INTRODUCTION

In-service requirements are mainly critical in the longitudinal direction of the bridge and require the free expansion and contraction of the deck due to temperature [1], creep, shrinkage [2] and prestressing effects. These requirements are in contrary to the bridge earthquake resistance requirements, as they are usually enhanced by rigid, as possible, connections. In these cases, the increase of the capacity of the structure to avoid structural damage is usually the most common solution in order to meet the ultimate lime state requirements. However it is not practical to continuously increase the strength of the structure as this also increase the structural cost. For this reason the conceptual concept of ductility is introduced by Codes [3]. According to this concept the structural elements are deformed beyond the elastic limit in a controlled manner.

An alternative to the aforementioned approach which is based on the reduction of the seismic demand is represented by seismic isolation practice. In many bridges, deck is supported on piers and abutments through bearings aiming at the shift of the vibrational period of the structure so as to avoid resonance with the excitations. These devices constitute the most used isolation system. In long bridges dampers are also used to increase the in-structure damping and to reduce the lateral movements of the bridge due to the seismic loading. The support of the deck on the piers and abutments through bearings also accommodates the in-service bridge requirements.

The use of bearings for the deck support on the piers is inevitable, especially in precast bridges and bridges constructed with the incremental launching method, as the deck construction method does not allow the monolithic connection of the deck to the piers. Bridges whose deck consist of beams or boxes, cast in place or precast, lifted or launched into place are usually protected against earthquakes by using seismic isolation devices. As a result these bridges are considered as structures with limited ductile behaviour and analyzed for values of the behaviour factor less or equal to 1.5 [3]. A recent study proposes a method based on the Code's provisions, for the conversion of these bridges to ductile systems [4-5].

It is obvious from the previous analysis that the treatment of problem of seismic safety aims at the satisfaction of the well-known inequality of safety, which includes, in its first member, resistances of critical cross-sections and in the second the loads, as these arise from the familiar loads of design earthquake. In the second case of seismic isolation, intervention in the second member of inequality is sought through the deliberate reduction of seismic action having as a final objective the alleviation of the cross-sections of load-bearing members of the system. However doubts arise about the time-related performance of seismic isolation devices. Concerns are also formulated regarding the future of these devices and questions arise if their future is going to be similar with that of bearings and expansion joints, which although they gave the perfect solution against the in-service induced movements of the deck, however the current bridge engineering seeks their expulsion.

Recent studies [6-7] showed that the reduction in the demand can also be achieved by the abutment and backfill soil participation which contribute to the enhancement of the earthquake resistance of bridges. The advantages of this seismic participation are reflected on the construction cost of the bridge [8], as smaller pier cross-sections meet Code's requirements as well as bridge aesthetics. The authors of this study have proposed an innovative seismic restraining system consisting of concrete walls which behave as seismic stoppers [9]. These walls constitute part of the abutment and they are transversely directed to the longitudinal direction of the bridge. This study presents the analytical investigation on the applicability in different bridge types, serviceability performance and seismic efficiency of the unconventional abutment. The experimental investigation on the seismic efficiency of the abutment under monotonic and cyclic loading is also presented in this study.

2 PRESENTATION OF THE PROPOSED ABUTMENT-ANALYTICAL INVESTIGATION

2.1 Description and serviceability performance of the proposed abutment

The proposed restraining system consists of transversely directed R/C walls, which behave as seismic stoppers. The aforementioned walls constitute part of the abutment and they are transversely directed to the longitudinal direction of the bridge, Figure 1. In cases that the serviceability requirements of the bridge are not critical the concrete walls are rigidly connected to the extension of the deck slab. Alternatively, the R/C walls are arranged in pairs between extrusions of the extension of the deck's slab. Each pair of concrete walls is in contact with the extrusion of the slab toward the abutment's web while a clearance of some centimeters depending on the serviceability requirements of the bridge separates it from the extrusion constructed toward the embankment. The distance between the walls is achieved by the interjection of an expanded polystyrene (EPS) layer, with a small thickness, i.e. 20mm. The walls are constructed in a concrete box-shaped substructure, which replaces the conventional wing walls and retains the backfill material. The longitudinal clearance between the box-shaped wall and the transversely directed R/C walls is designed to absorb the total seismic movement of the deck. The longitudinal walls of the concrete box are used to increase the foundation's stiffness, as the abutment is designed to transmit not only the soil pressures of the backfill, but also the seismic loads of the R/C walls. The earth pressures affect only the stability of the concrete box-shaped substructure and the abutment's foundation, but not the earthquake resistance of the restraining walls.

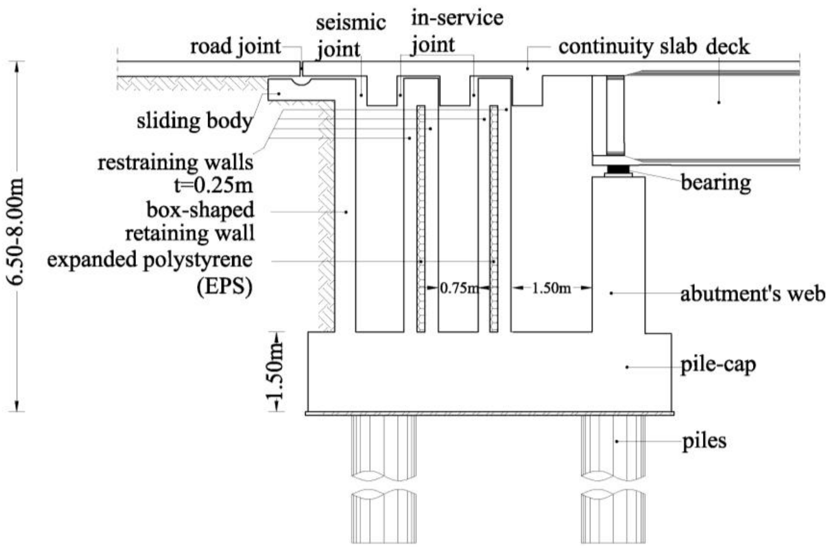

Figure 1: Longitudinal section of the proposed abutment.

In cases that the walls are rigidly connected to the extension of the deck slab the constrained-type movements of the deck due to the serviceability requirements of the bridge are restrained. The complete control the deformation of the deck due to creep, shrinkage effects, prestressing and thermal movements is quite difficult. However, additional structural measures can be taken to minimize their influence. Specifically, the extension of the deck slab can be constructed during the final stage of the bridge construction. This measure ensures that creep and shrinkage effects have been partially or fully developed and consequently their influence is controllable and may be effectively reduced.

The selection of the height and thickness of the walls is mainly depended on the serviceability requirements of the bridge. The in-service bridge loading is increased as the length of the bridge is also increased. Figure 2 shows the minimum required height of the walls for bridges whose length is from 100m to 400m, considering that the thickness is from 25mm to 40mm and the longitudinal reinforcement D16@100mm or D16@50mm. The horizontal axis of the figure shows the equivalent total uniform bridge temperature $\Delta T_{N,tot}$ due to creep, shrinkage and thermal effects. The figure shows that for a given longitudinal reinforcement of the walls, (e.g. D16@100mm or D16@50mm) the increase of the walls' thickness also increases the minimum required height. The increase of the total bridge's length, also increases the minimum required height of the walls. The figure shows that for bridges whose total length is 400m and for $\Delta T_{N,tot}$.=40^{o}C, which is an acceptable temperature value, the minimum required height of the walls is 8.9m or 6.5m, when the longitudinal reinforcement of the walls is D16@100mm or D16@50mm respectively. However, it is well-known that the use of high walls would lead to a lower seismic efficiency of the restraining system, as the stiffness of the walls would be effectively reduced [9]. Hence, their seismic loading would not lead to the development of plastic hinges at the walls. For this reason, in long bridges, the non-rigid connection between the R/C walls-stoppers and the extension of the deck's slab is proposed. The clearances between the slab's extrusions and the wall pairs allow the partial contraction of the deck without the activation of the resistance of the walls.

2.2 Comparative analytical investigation on the seismic efficiency of the proposed abutment in different bridge types

The analytical investigation on the seismic efficiency of the proposed abutment showed that it can be implemented in all bridge types (monolithic, precast I-beam bridges, incrementally launched bridges), independently of their length by applying proper modifications imposed by serviceability requirements. It is noted that the restraining walls of the abutment contribute not only by their own stiffness but also by dissipating energy through hysteretic behavior. As a result, the proposed abutment should mainly be exploited in ductile bridge systems. In this respect, the authors of this study have proposed in previous studies a methodology for the modification of floating deck bridges to ductile systems[4-5]. It is noted that, floating deck bridges are the ones constructed using the method of segmental erection with precast prestressed I-beams and the incremental launching method.

The aim of the investigation is the comparative presentation of the seismic efficiency of the proposed abutment in different bridge types (monolithic, precast I-beam bridges, incrementally launched bridges). Three representative bridges of the major motorways in Greece are used as the "reference" cases of the investigation: The monolithic bridge of Aracthos- Peristeri (B1) with total length 240m [9], a precast I-beam bridge of P.A.TH.E Motorway (B2) with total length of 177.5m [9] and an incrementally launched bridge of Egnatia Odos Motorway (B3) with total length of 481.7m [4]. The analytical description, of the "reference" bridges is presented in detail in previous studies [4] [9] . Table 1 summarizes the main characteristics of the bridges. The "reference" bridges were analyzed for the purposes of the present study. These bridges were also re-analyzed considering the abutment proposed in the paper. Table 2 summarizes the main properties of the walls-stoppers as they are prescribed by the serviceability requirements of each bridge system.

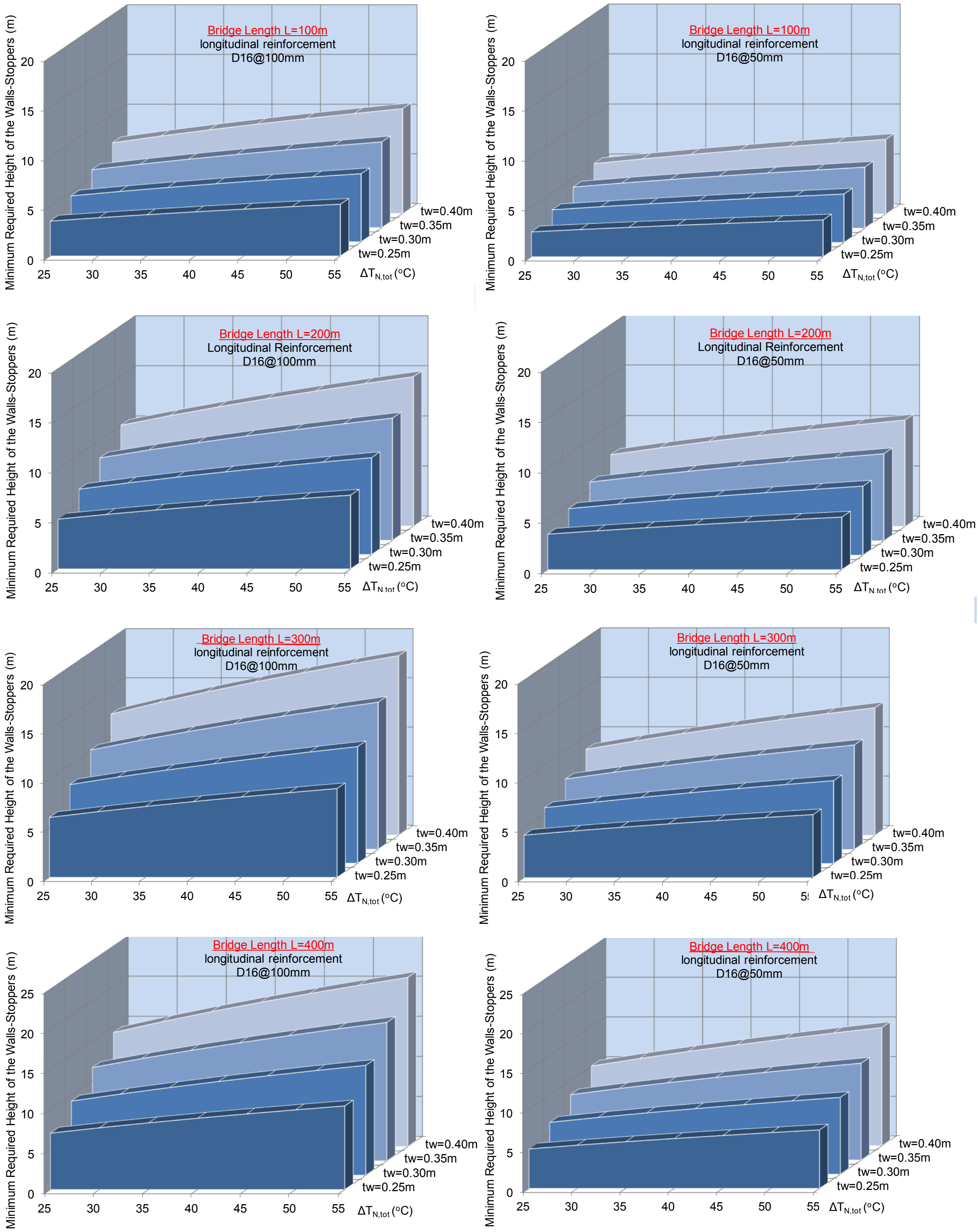

Figure 2: The minimum height of the walls required by serviceability loading for bridges whose length is 100m, 200m, 300m, 400m and for two different longitudinal reinforcement patterns, D16@100mm and D16@50mm.

The selection of the total number of walls per abutment is mainly based on economic criteria. In cases that the walls are rigidly connected to the continuity slab the use of five walls per restraining abutment seems to be a rational selection as this accommodates both cost-effectiveness and earthquake resistance of the bridge [9]. Each unconventional abutment of bridges B1 and B2 consist of 5 walls-stoppers rigidly connected to the extension of the deck's slab. In the case of bridge B3, the walls are arranged in pairs between extrusions of the deck's slab and as a result the abutment should consist of an even number of walls (e.g. four).

Bridge	Type	Length	Cross- sections	Soil Class	Design ground acceleration
B1	Monolithic Bridge	240m (6 spans)	Deck: Single cell box girder Piers: Wall-type columns	B	0.16g
B2	Precast I-beam Bridge	177.5m (5 spans)	Deck: Precast prestressed beams Piers: Hollow circular sections	B	0.24g
B3	Incrementally Launched Bridge	481.7m (11 spans)	Deck: Single cell box girder Piers: Hollow rectangular section	B	0.16g

Table 1: The main characteristics of the "reference" bridges.

Bridge	Height/ Thickness	Number of walls per abutment	Type of connection between walls and deck's slab	Longitudinal Reinforcement pattern
Monolithic Bridge (B1)	4.5m/0.25m	5	rigid	D16@50mm
Precast I-beam Bridge (B2)	4.5m/0.25m	5	rigid	D16@50mm
Incrementally Launched Bridge (B3)	4.5m/0.25m	4	Isolated head of the pair of walls (clearance s=70mm)	D16@100mm

Table 2: The main characteristics of the abutments of the unconventional bridges.

The seismic performance of the analyzed bridge systems was assessed using nonlinear time history analysis. Analysis was carried out by using the SAP 2000 program [10]. The models and the analysis procedure are described in detail in previous studies [4] [9].

The calculation of the percentage reductions in the longitudinal movements of the bridge deck was used for the comparative assessment of the restraining effect of the proposed walls-stoppers. Figure 3 shows the percentage reductions in the average longitudinal movements of the three bridge decks for design accelerations 0.16g, 0.24g and 0.36g. It is noted that the longitudinal movement of the different joints of the deck over the piers is about constant and the calculated percentage reductions correspond to the average value of the movements of these joints. The figure shows that the abutment is more efficient in monolithic and precast I-beam bridges whose length is of the order of 200m, as the longitudinal movements are reduced from 50 to 65%. The corresponding reduction in the longitudinal movements of the long bridge constructed with the incremental launching method varies from 18% to 38%. The figure also shows that the abutment is more efficient in higher design accelerations (e.g. 0.24g and 036g) which is attributed to the inelastic response of the concrete walls.

The aforementioned results show that the proposed abutment is quite efficient even in the case that the walls are not rigidly connected to the extension of the deck's slab. The proposed configuration at the walls heads gives the opportunity to reduce the longitudinal reinforcement ratio, which is mainly determined by the serviceability and not the seismic bridge requirements. Considering that the unconventional bridge is designed as a ductile system and hence the formation of plastic hinges is allowable, this leads to the yielding of the walls' longitudinal reinforcement.

Although the longitudinal earthquake is more demanding than the transverse one, the investigation showed that the restraining effect of the abutment is also significant in the transverse direction. Analytical results concerning this direction are available in previous study [9].

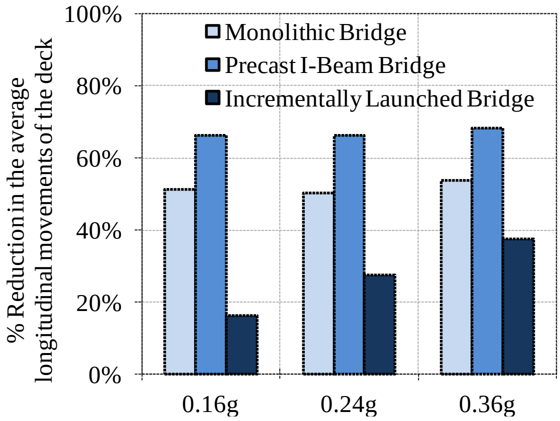

Figure 3: The percentage reduction in the average longitudinal movements of the bridge deck.

3 EXPERIMENTAL INVESTIGATION

The scope of the experimental investigation is the verification of the analytical results concerning the strength, stiffness and ductility of the walls-stoppers of the proposed abutment, Figure 1. The experimental investigation of the above properties is accomplished under monotonic and cyclic loading. The accuracy of the consideration of the complete restrain at the ends of the walls is also examined under monotonic loading.

3.1 Description of specimens

The experimental program presented in this work involves 3 specimens, denoted as SPEC1 SPEC2 and SPEC3. SPEC1 was subjected under monotonic loading while SPEC2 and SPEC3 were subjected under cycling loading. All specimens were constructed under a scale 1:2. The difficulty on the experimental investigation of members whose ends are completely restrained under monotonic loading, motivated the authors of this investigation to study a substitute symmetrical simple supported member. This member consists of three rows of walls arranged along its height. The walls are rigidly connected at their ends. Figure 4 shows the geometry and steel reinforcements of specimen 1 (SPEC1). The longitudinal reinforcement ratio of SPEC1 is 1.6% and corresponds to walls with longitudinal reinforcement D16@100mm. Steel reinforcement (longitudinal and transverse) was instrumented using strain gages.

Each of specimens 2 and 3 (SPEC2, SPEC3) consists of two walls. Figures 5 and 6 show the geometry and steel reinforcements of specimens 2 and 3 (SPEC2 and SPEC3) respectively. SPEC2 has a longitudinal reinforcement ratio equal to 1.6% (D16@100mm in the real scale) while the longitudinal reinforcement ratio of SPEC3 is 2.9% (D16@50mm in the real scale). In all specimens, the diameter of the transverse reinforcement is 4.2mm while its spacing along the length of the walls is 25mm at the possible plastic hinges regions (20cm from the ends of the walls) and 50mm at the other regions.

3.2 Overview of experimental setup

Test specimen 1 (SPEC1) was subjected to loading coming from a single load at the middle, Figure 7. A deflection measuring system was attached at the midspan of the specimen. Figure 7 also illustrates the positions of the strain gages used for the instrumentation of the reinforcement (longitudinal and transverse).

Figure 8(a) illustrates the experimental setup used for the cyclic loading of specimens 2 and 3. The setup consists of the two steel beams HEB 320, which substitute the bridge deck and pile-cap respectively. The double-acting hydraulic actuator is connected to the one steel beam, which has the ability to slip through two steel bars fixed at the laboratory's floor. It is noted that the connection between this steel beam and the specimen allows the partial rotation of the specimen's head. In cases that the serviceability requirements impose the construction of abutments' web with height greater than 4.5m (this height corresponds to the 1:2 scale of the experiment), but it is not possible, due to other parameters' limitations (i.e. construction cost, seismic efficiency etc.), these rotations accommodate part of the in-service induced movements (see Section 2). The second steel beam is fixed at the laboratory's floor. The aforementioned specimens were subjected to a number of cycles of quasi-static cyclic loading, Figure 8(b).

3.3 Discussion of Results

Figure 9 displays the variation of the deflection in the middle of SPEC1 with the increment of the load. The theoretically calculated effective stiffness of the specimen which is also displayed (red line) in the figure is very close to the experiment one. This stiffness is calculated according to Codes provisions [3] and is equal to 8043 kN/m while the experimental one is 9879 kN/m. The figure also shows that the specimen developed a displacement ductility factor equal to 11.7 which is attributed to the well –confined ends of the walls. The theoretical displacement ductility factor of the specimen is calculated according to the methodology proposed in Caltrans Seismic Design Criteria [11] and is equal to 7.2. Figure 10 displays the P-ε diagrams of steel strain gages. Specifically, Figures 10(a) and 10(b) correspond to the strain gages placed at the longitudinal bars of the external and the middle walls of SPEC1 (according to Figure 7), while Figure 10(c) corresponds to the strain gages placed at the stirrups. The figures show that the longitudinal bars of the middle walls yield and consequently they are activated more than the corresponding of the external ones. A plumb line was used at the end of the experiment as a simple but accurate tool, for determining that the edges of the specimen is perfectly vertical, Figure 11.

Hysteresis loops for the two specimens (SPEC2 and SPEC3) subjected to cycling loading are shown in Figure 12. Regardless of the large relevant displacements between the specimen's head and foot, the failure of the specimens was not reached. The noticed plastic branch has short length in both cases and consequently, a conclusion about the ductility of the specimens it is not possible to be extracted. However, the observation of the last loop indicates that, both specimens have available ductility, as the three last loops corresponding to the maximum displacement are coincided. The intended non-full impaction of the specimens' head caused rotations, which affect the results.

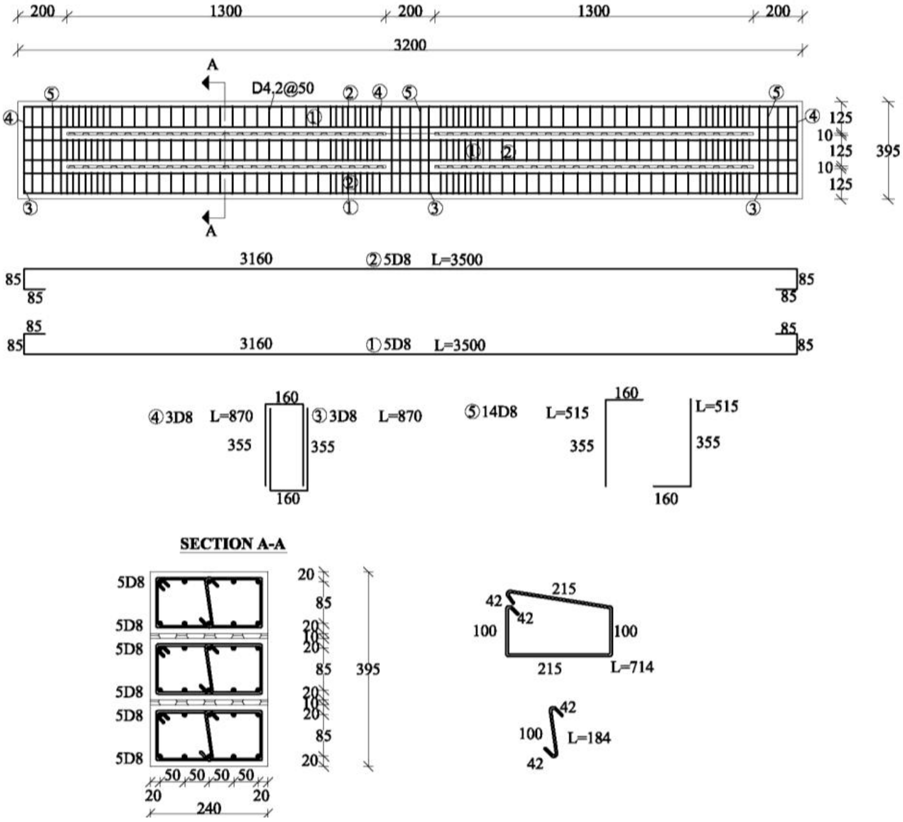

Figure 4: Geometry and steel reinforcement of specimen 1 (SPEC1).

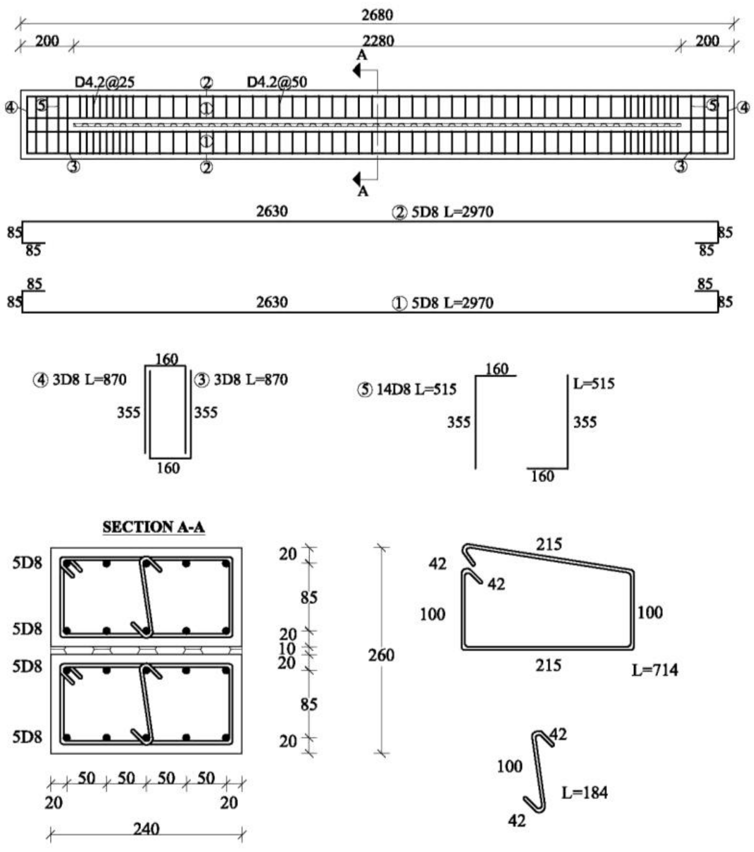

Figure 5: Geometry and steel reinforcement of specimen 2 (SPEC2).

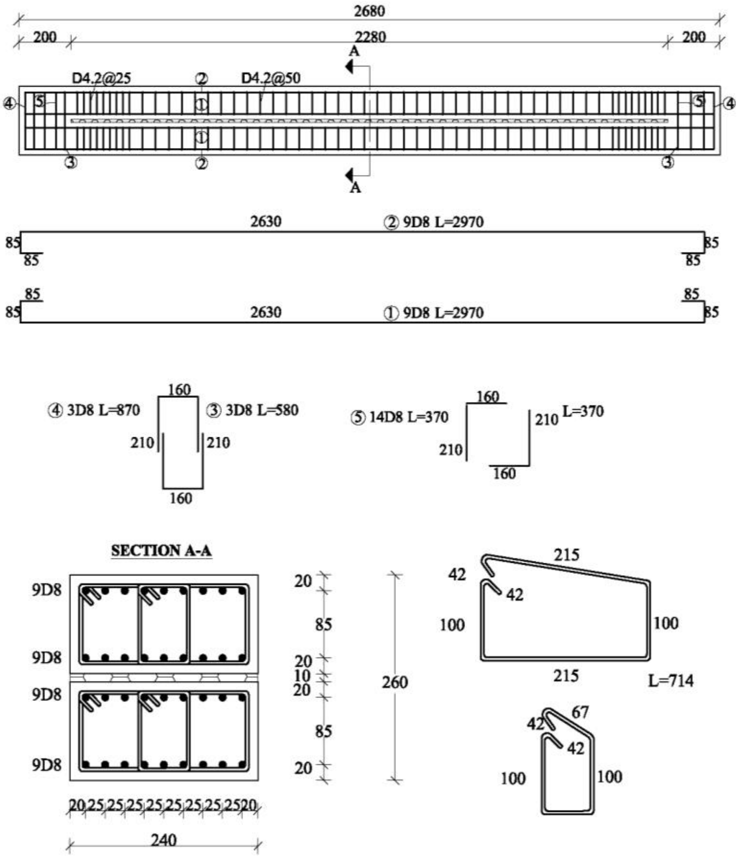

Figure 6: Geometry and steel reinforcement of specimen 3 (SPEC3).

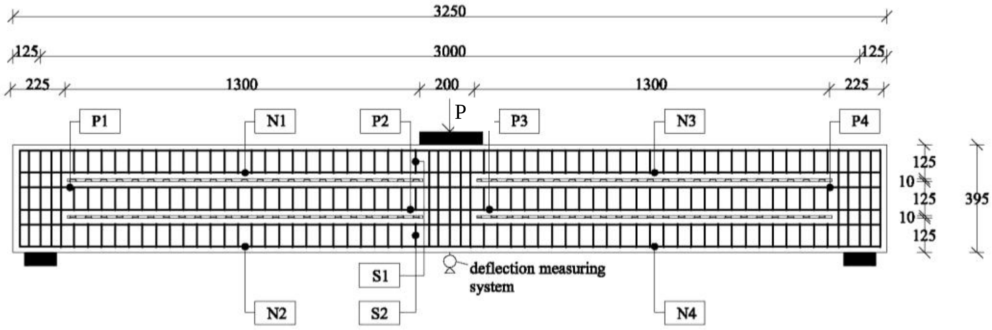

Figure 7: Experimental loading of specimen 1 (SPEC1) and positions of steel strain gages and deflection measuring system.

Any relevant movement between the specimen's head and base causes (a) linear variant bending moments along the height of the walls, (b) tension and compression axial forces corresponding to the direction of the head's movement (the presence of the tensile axial loading is confirmed by the appearance of flexural cracks in the middle of the tensile wall of the specimen during the loading) and (c) second-order effects. The described above parameters affect the loops' shape and cause the loops' pinching. In any case, the area enclosed by the envelope, which is quite large, indicates that the energy dissipation is significant in both specimens. Figure 13 shows that the energy dissipated by SPEC3 (SPEC3, ρ=2.9%) is greater than the corresponding dissipated by SPEC2 (SPEC2, ρ=1.6%). According to this figure the energy dissipation presents normal, gradually increasing progress. Finally, the experimental values of the stiffness are smaller than the theoretical ones due to the partial restrain of the specimens' ends.

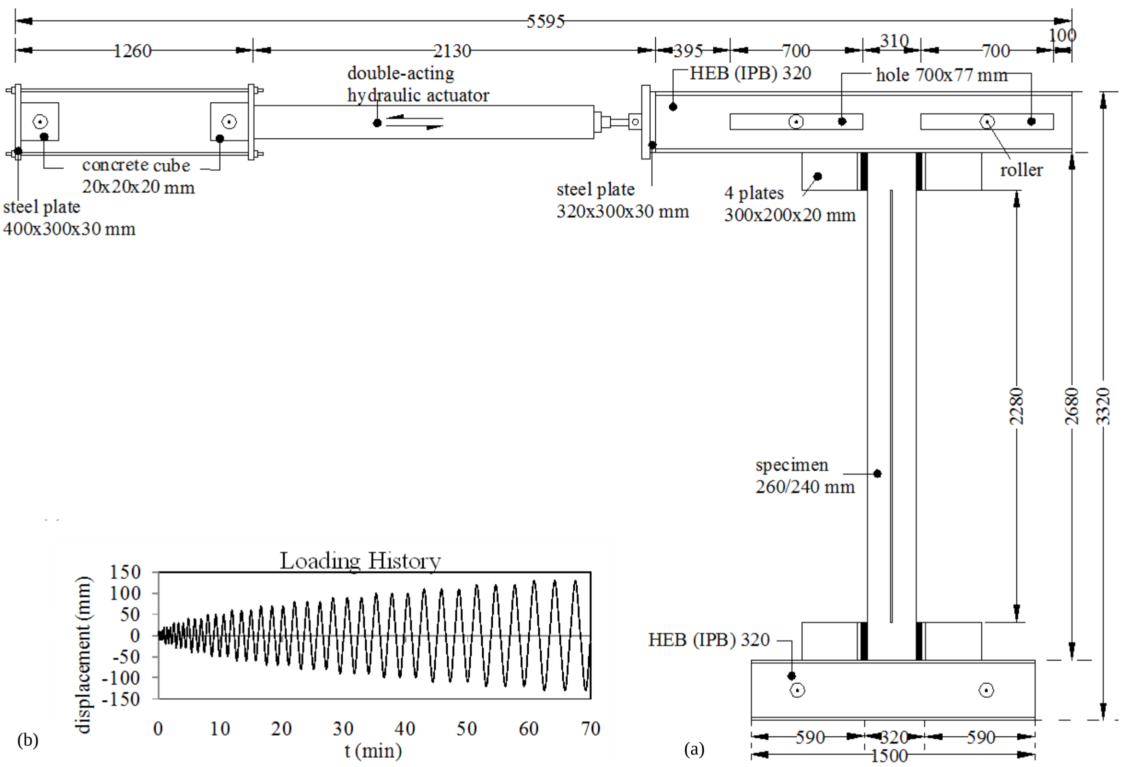

Figure 8: (a) Experimental setup for cycling loading and (b) loading history.

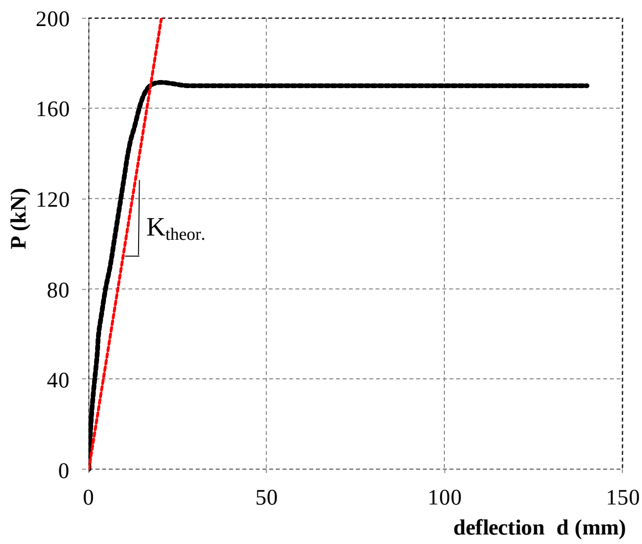

Figure 9: P-d diagram of specimen 1 (SPEC1) under monotonic loading P.

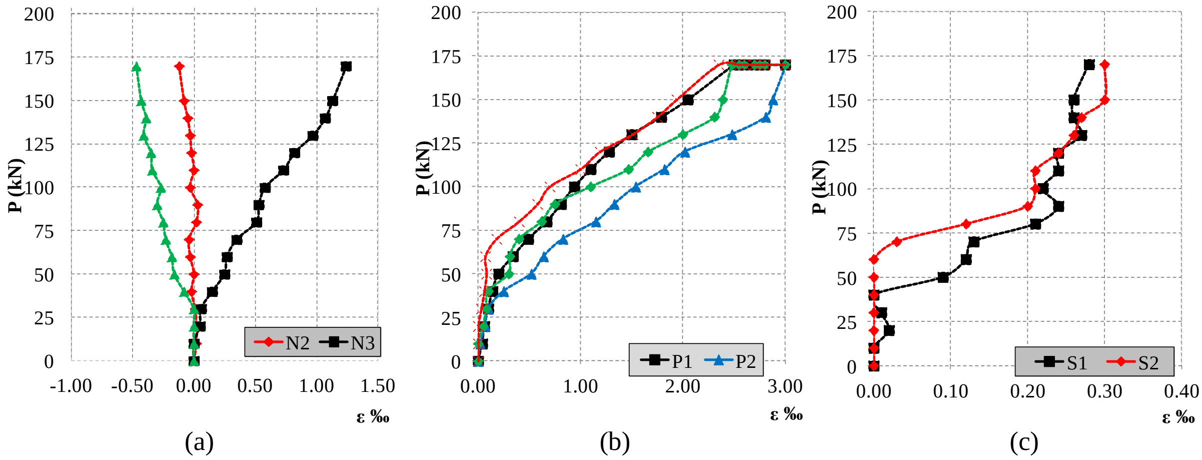

Figure 10: P-ε diagrams of strain gages placed at (a) longitudinal bars of the external walls, (b) longitudinal bars of the middle walls and (c) stirrups of specimen 1 (SPEC1).

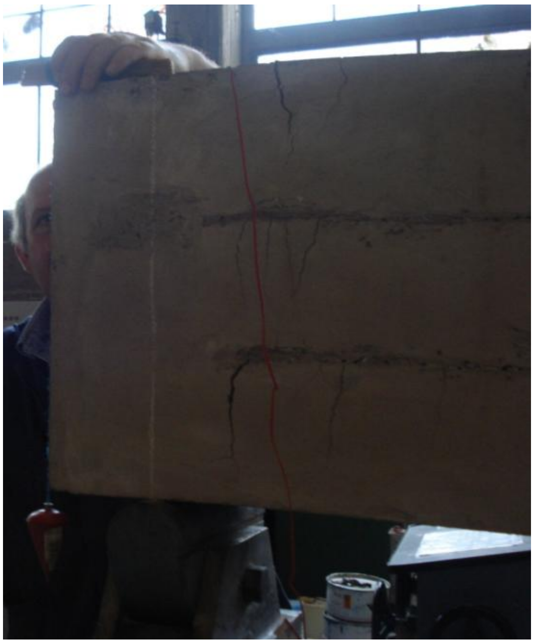

Figure 11: Using of plumb line for determining that the edges of the specimen are perfectly vertical.

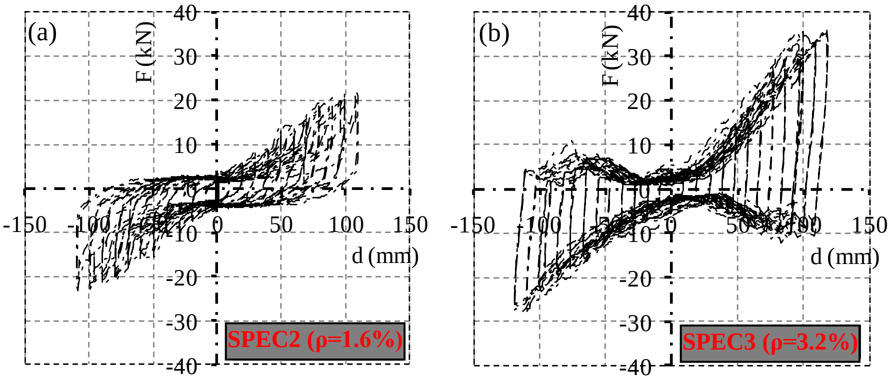

Figure 12: Hysteresis loops for (a) specimen 2 (SPEC2) and (b) specimen 3 (SPEC3).

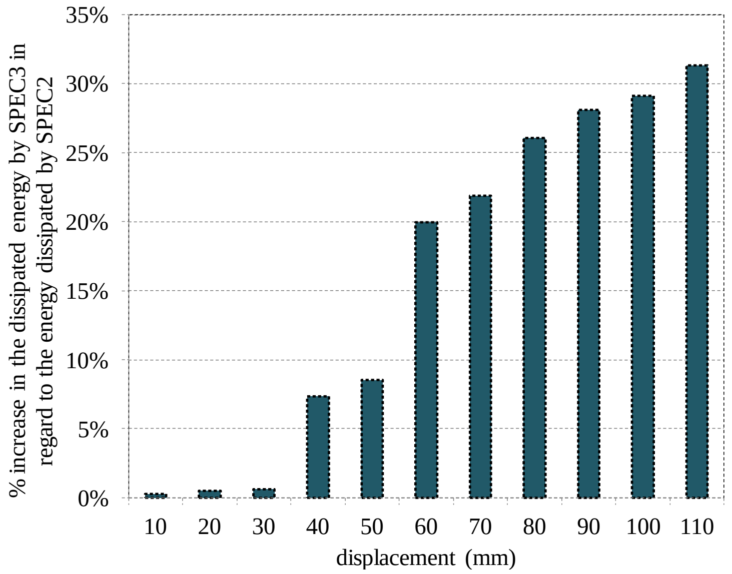

Figure 13: % Increase in the dissipated energy by SPEC3 in regard to the energy dissipated by SPEC2.

4 CONCLUSIONS

In this study the analytical and experimental investigation on the seismic efficiency of an unconventional abutment was presented. This system consists of transversely directed R/C walls, which behave as seismic stoppers. The main conclusions of the investigation are the following:

- The proposed restraining system consisting of walls-stoppers is quite efficient in both long and short bridges. The longitudinal and transverse movements of the deck are effectively reduced.
- Proper structural configuration at the walls' heads accommodates a part of the in-service constraint bridge movements. The aforementioned accommodation reduces the longitudinal reinforcement requirement of the walls as it is mainly determined by the serviceability and not the seismic bridge requirements. Considering that the unconventional bridges are designed as ductile systems and hence the formation of plastic hinges is allowable, the longitudinal reinforcement of the walls yields and consequently a great part of the induced seismic energy is dissipated through the hysteretic behaviour of the restraining walls.
- The experimental study of members whose ends are completely restrained under monotonic loading was accomplished. The plump line used at the end of the experiment determined that the edges of the specimen were perfectly vertical.
- The well-confined possible plastic hinge regions at the ends of the walls improved the ductility of the specimens under monotonic and cyclic loading.
- The experimental effective stiffness of the specimen (monotonic loading) is quite close to the theoretical one. The ductility of the specimen under monotonic loading is about two times the theoretically calculated according to Code's provisions.
- The failure of the specimens under cycling loading was not reached despite the large relevant movements between their ends. The observation of the last loop indicates that, both specimens have available ductility, as the three last loops corresponding to the maximum

displacement are coincided. The intended non-full impaction of the specimens' head caused rotations, which affect the results.

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