An Innovative Earthquake Resistant System with Concrete Walls for Bridges

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SUMMARY:
The authors of this study have proposed in the recent past an innovative seismic restraining system consisting of concrete walls which behave as seismic stoppers. These walls constitute part of the abutment and are transversely directed to the longitudinal direction of the bridge. The available abutment's height and the walls' thickness are the main parameters affecting the design of the aforementioned system and are mainly prescribed by the serviceability requirements of the bridge. These parameters are strongly related between themselves, as they both influence the shear ratio of the concrete walls and consequently, the seismic efficiency of the restraining system. In this study, the research is extended so that, the proposed restraining system can be implemented in all bridge systems independently of their length. A long seismic isolated bridge with rubber bearings and viscous dampers, is used as the reference case in this study. The seismic efficiency of the proposed restraining system, which is properly exploited in the reference bridge after its conversion to a ductile system, is investigated. The results of the investigation showed that the new bridge system is advantageous against the initial seismic isolated bridge as far as concerns safety, durability, serviceability, aesthetics and cost-effectiveness.

Keywords: Bridge, ductile, wall, restrainer, seismic

1. INTRODUCTION

In high seismicity regions, bridge design has to accommodate both serviceability and earthquake resistance requirements. Serviceability is mainly critical for the longitudinal direction of the bridge and imposes opposite –to the bridge earthquake resistance- requirements, as it requires the free expansion and contraction of the deck, due to the annual thermal cycle (Eurocode 1- Part 5, 2003), shrinkage, creep (Arockiasamy and Sivakumar 2005) and prestress. On the other hand, the earthquake resistance of bridges is usually enhanced by monolithical, as possible, piers to deck connections. In these cases, the most common solution to meet the ultimate limit state requirements of the bridge is the increase of the capacity of the structure so as to avoid structural damage. However it is not practical to continuously increase the strength of the structure as this also increase the structural cost. So the Codes (Eurocode 8-Part 2 2003) allow engineers to use conceptual concept of ductility to achieve the capacity. According to this concept the structural elements are deformed beyond the elastic limit in a controlled manner. Beyond this limit, the displacements increase with only a small increase in force.

Seismic isolation represents an opposite, to the aforementioned, approach, as it attempts to reduce the demand rather than to increase the capacity of a structure (Kelly 2001; Eurocode 8-Part 1 2003) In this case, the effort on protection of bridges against earthquakes is mainly focused on minimizing the forces to be carried by the piers. Isolation systems are basically typified into bearings and energy dissipation devices. Rubber bearings with high lateral flexibility are meant to shift the vibrational periods of the structures so as to avoid resonance with the excitations. In long bridges fluid 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 induced movements of the deck due to shrinkage, creep and thermal effects. However, although seismic isolation is considered one of the most promising practices worldwide, the high purchase cost of the devices, which increases the total construction cost of the bridge constitutes a major disadvantage of this practice.

In many cases, depending on the method used for the deck construction the use of bearings for the deck support is inevitable. 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. Particularly, in incrementally launched bridges the use of bearings for the support of the deck on the piers is the only solution as the deck construction method does not allow the monolithic connection of the deck to the piers. 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 (Eurocode 8-Part 2 2003). A recent study proposes a method based on the Code's provisions, for the conversion of these bridges to ductile systems (Tegou and Tegos 2012). This method is implemented in the present study.

In regard to the reduction on the demand rather than the increase on the capacity of a structure, the seismic performance of bridges can also be enhanced by the abutment and backfill soil participation. Recent studies (Mikami et al. 2008; Mitoulis and Tegos 2010) investigate the case of abutment- bridge interaction which can contribute to the enhancement of the seismic response of bridge structures. Furthermore the seismic participation of the abutment leads to cost- effective bridge design (Nutt and Mayes 2000). The authors of this study have proposed in the recent past an innovative seismic restraining system consisting of concrete walls which behave as seismic stoppers (Tegou et al. 2010). These walls constitute part of the abutment and are transversely directed to the longitudinal direction of the bridge. In this study, the research is extended so that, the proposed restraining system can be implemented in all bridges independently of their length. The efficiency of the proposed restraining system is examined by analyzing the seismic response of an incrementally launched bridge in Greece which is considered to be the "reference" bridge.

2. DESCRIPTION OF THE PROPOSED ABUTMENT

In this study the investigation on the seismic efficiency and serviceability performance of an unconventional earthquake resistant abutment, presented in previous studies (Tegou et al. 2010), is extended so that it can be implemented in all bridges independently of their length.

This abutment, Fig. 2.1, consists of two discrete parts. The first part is the extension of the deck slab of the bridge, the so-called continuity slab. The second part of the abutment are transversely directed R/C walls, characterized as restraining walls, as they enhance the bridge earthquake resistance by limiting the seismic movements of the deck. In cases that the serviceability requirements of the bridge are not critical and more specifically in bridges whose length is less than 300m, the concrete walls are rigidly connected to the extension of the deck slab. The applicability of the proposed abutment in these bridges was extensively investigated in previous studies (Tegou et al. 2010; Tegou and al. 2011). These studies analytically present the implementation of the proposed abutment in monolithic bridges, precast I-beam bridges and seismic isolated bridges.

The concrete walls are arranged in pairs between projections of the continuity slab. Each pair of concrete walls is in contact with the projection of the slab toward the abutment's web while a clearance of some centimetres depending on the serviceability requirements of the bridge separates it from the projection 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 in order 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. These longitudinal walls of the box also improve aesthetics, as it visually overlaps the multi-wall restraining system. 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.

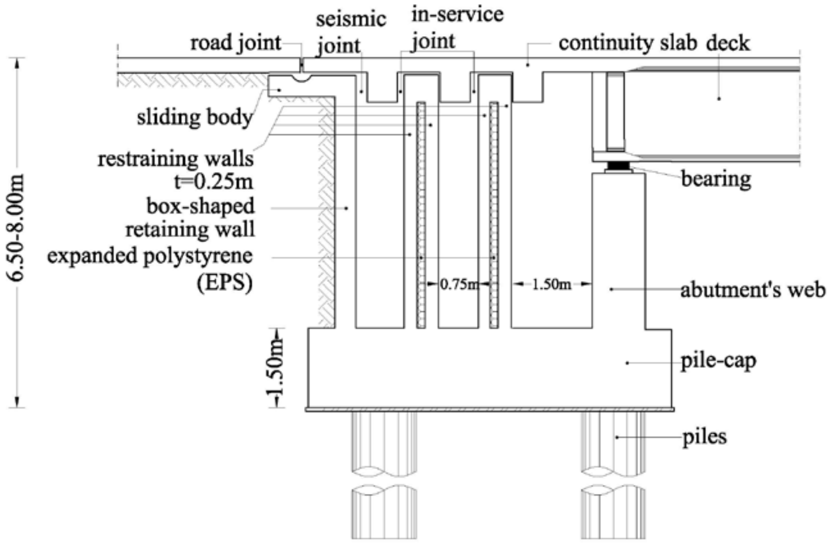

Figure 2.1. Longitudinal section of the proposed abutment

3. INVESTIGATION ON THE SEISMIC EFFICIENCY OF THE PROPOSED ABUTMENT

3.1. "Reference" bridge layout

A seismic isolated bridge of Egnatia Odos Motorway in Greece, Fig. 3.1, erected by the incremental launched method was used as the reference case in this study. This bridge is curved in plan with a radius R=1175m while the deck section is laterally inclined (in the transverse direction) by 4.5%. The end spans Fig. 3.1(a) are 36.7m and 35.5m long respectively and the intermediate nine spans are 45.5m long. Hence the length of this bridge that has eleven spans in total is 481.7m. The deck is a single-cell box girder, Fig. 3.1(b), with 9 different sections along its length. The piers are hollow-rectangular sections, Fig. 3.1(c). All piers are connected to the deck through low damping elastomeric or PTFE bearings. Two fluid dampers in each direction (longitudinal and transverse) are used at the abutments, where the only joints of the bridge deck are located. The dampers have practically hysteretic behaviour, since they realize a velocity exponent a ($F=C\cdot v^a$) as low as 0.05. The maximum strength they provide is 750 kN and 450 kN per damper, in the longitudinal and transverse direction, respectively. According to the Greek seismic design code (Ministry of public works of Greece 2000), the bridge is founded on a ground type B. It is noted that the corner periods of the spectrum used are 0.15s and 0.60s for ground type B, and this corresponds to a ground type between B and C according to Eurocode 8 (Eurocode 8- Part 1 2003). The design ground acceleration is equal to 0.16g. The adopted importance factor is equal to γ_I=1.3 (Ministry of public works of Greece 2007), while the behaviour factors are equal to 1.0 for both horizontal directions and also 1.0 for the vertical seismic action.

3.2. Design and optimization of the abutment

The abutment described in Section 2 replaces the conventional abutment of the "reference" bridge which is converted to a ductile system by implemented innovative seismic links at the head of the piers. The applicability of this proposal is based on the provisions of Eurocode 8-Part 2 (2003) referring to the use of seismic links in the longitudinal direction of the bridge and was analytically investigated by the Authors (Tegou and Tegos 2012).
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. It is well known that it is quite difficult to completely control the deformation of the deck due to creep, shrinkage effects, prestressing and thermal movements. Nevertheless, additional structural measures can be taken in order 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.

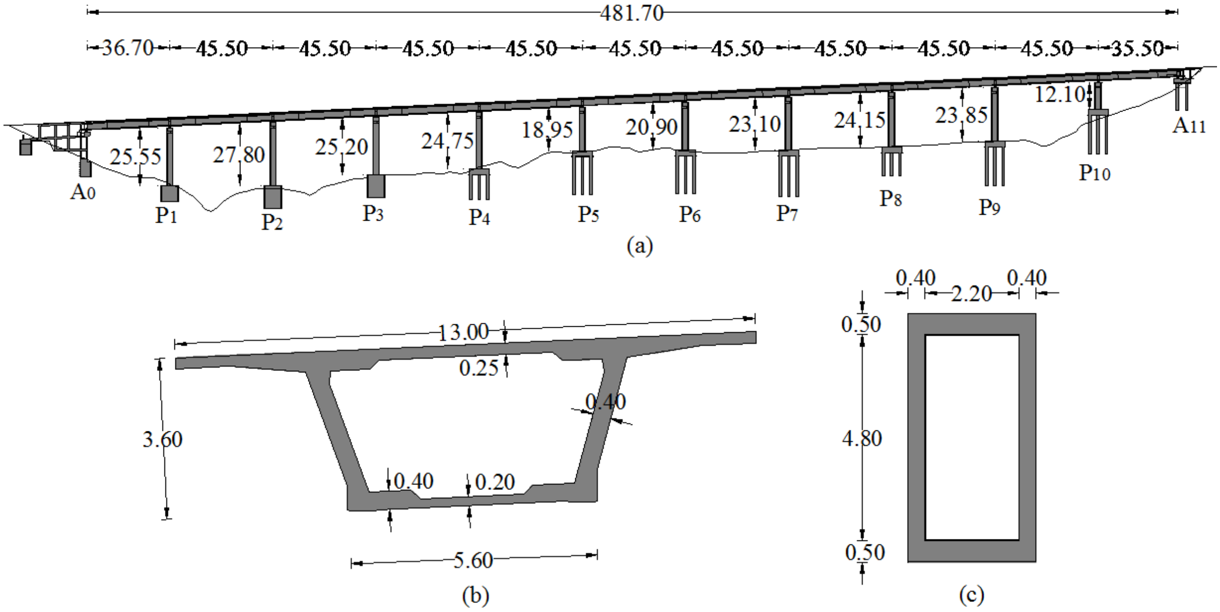

Figure 3.1. (a) Longitudinal section of the "reference" bridge, (b) The deck's cross-section at the mid-span and (c) The pier's cross-section

The critical point, as far as the serviceability requirements of the bridge are concerned, is the selection of the height and thickness of the walls. The investigation on this issue showed that the a thickness of the restraining walls equal to 0.25m and a height equal to 4.50m is the optimum selection for bridges whose length is about 200m. This calculation is based on the assumption that the longitudinal reinforcement of the walls consists of D16@50mm which corresponds to a longitudinal reinforcement ratio equal to 3.2%. The in-service loading of the walls is adequately controlled, through its reinforcements and, on the other hand, they offer a significant earthquake restraining effect. However in the example presented in this study, the clearances between the slab's projections and the wall pairs whose width is 70mm, allow the partial contraction of the deck without the activation of the resistance of the walls. The aforementioned observation leads to the conclusion that the walls' longitudinal reinforcement ratio, which is mainly determined by the serviceability requirements of the bridge can be reduced. The extension of the aforementioned calculation to the field of the long bridges showed that the increase in the bridge length also increases the required height of the walls. Fig. 3.2 shows the minimum required height of the walls for bridges whose length is from 100m to 500m, considering that the thickness is 25mm and the longitudinal reinforcement D16@100mm (ρ=1.6%). 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 show that for bridges whose total length is 500m as the bridge used as the reference case, and for $\Delta T_{N,tot}$.=40°C, which is an acceptable temperature value, the minimum required height of the walls is 9.0m. 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 (Tegou et al. 2010). Hence, their seismic loading would not lead to the development of plastic hinges at the walls.

The main objective of the study is to accommodate serviceability, while keeping a considerable resistance for the walls. The walls' top moves towards the bridge with a maximum movement equal to 96mm, during the maximum deck contraction caused by creep, shrinkage and thermal effects (Eurocode 1-Part 5 2003). This movement is calculated by Eqn. 3.1. In this equation $u_{x,serv}$ is the total in-service maximum constraint movement of the top of the walls, α is the coefficient of thermal contraction of concrete, which was considered to be equal to $10^{-5}/^{o}C$ (Eurocode 2-Part 1 2003) and L_{tot} is the total length of the bridge, Fig. 3.1(a).

$$u_{x,serv} = \frac{\alpha \cdot \Delta T_{N,tot} \cdot L_{tot}}{2} \tag{3.1}$$

The clearances of 70mm between the slab's projections and the wall pairs allow the partial contraction of the deck without the activation of the resistance of the walls. The rest 26mm of the constraint movement of the deck can be adequately controlled, through the flexibility and reinforcements of the walls. The investigation on this issue showed that for walls with the thickness of 25mm and longitudinal reinforcement D16@100, a height equal to 4.5m is adequate in order for the aforementioned requirement to be fulfilled.

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 5 walls per restraining abutment seems to be a rational selection as this accommodates both cost-effectiveness and earthquake resistance of the bridge (Tegou et al. 2010). However in this case that, the walls are arranged in pairs and are not rigidly connected to the slab, the abutment should consist of an even number of walls (e.g. four). However in long bridges the use of more walls is probably required in order for the earthquake resistance of the bridge to be improved. As a result in the example presented in this study the seismic efficiency of abutments consisting of 4 and 10 walls is investigated.

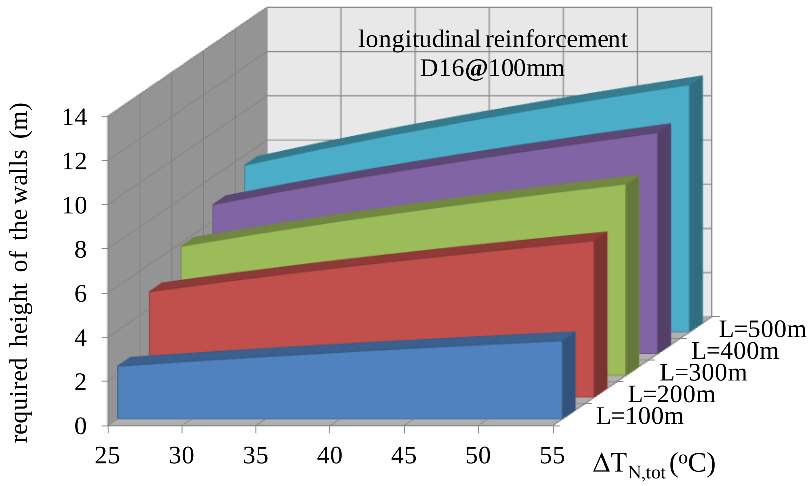

Figure 3.2. The minimum height of the walls required by serviceability loading for bridges whose length is 100m, 200m, 300m, 400m and 500m

The issue of the seismic efficiency of the proposed restraining abutment consisting of pairs of walls whose heads are not rigidly connected to the extension of the deck slab, was experimentally investigated in a previous study (Tegou et al. 2011). The experimental program involved 2 specimens (denoted as SPEC1 and SPEC2). Each of the specimens represents a 1:2 scale pair of walls of the proposed abutment. SPEC1 has a longitudinal reinforcement ratio equal to 1.6% while the longitudinal reinforcement ratio of SPEC2 is 2.9%. The specimens were subjected to a number of cycles of quasi-static cyclic loading. Hysteresis loops for the two specimens are shown in Fig. 3.3. The investigation showed that the area enclosed by the envelope, which is quite large, indicates that the energy dissipation is significant in both specimens.

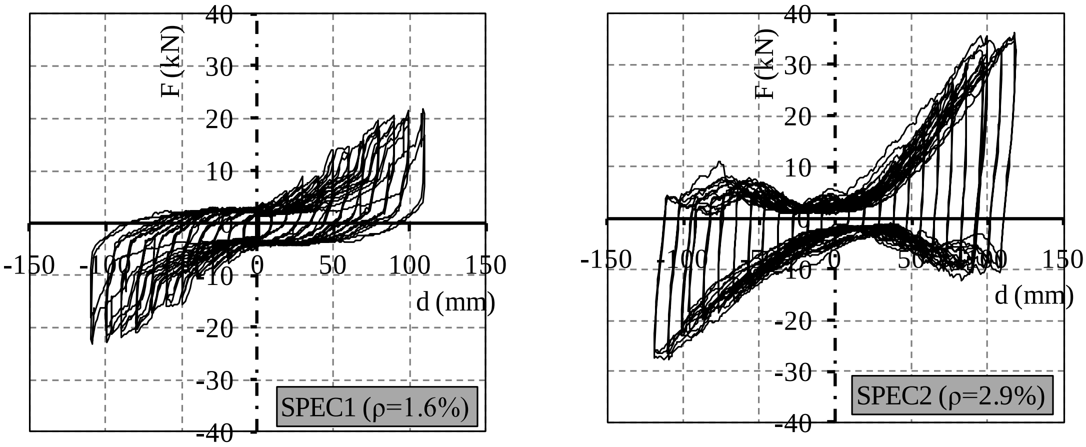

Figure 3.3. Hysteresis loops for the two specimens representing an 1:2 scale pair of walls

3.3. Modelling and analysis of the bridge systems

The as-built bridge system given in Fig. 3.1 and the unconventional, which exploits the proposed abutment were modelled and analyzed for the purposes of the present study. An indicative stick model of the analyzed bridge systems is given in Fig. 3.4. A finer mesh was used close to the deck-pier connections, to accurately capture stress concentrations, as well as the deformation of the deck.

Both bearings and dampers were modelled using inelastic spring elements, with 6 degrees of freedom, which, in the case of elastic analysis, remain elastic. Bearings were modelled using their actual height and effective properties for their five significant degrees of freedom, (their rotational stiffness around the vertical axis was considered negligible), according to Naeim and Kelly (1999). Stiff zones were used in order to take into account the distance of the centre of gravity of the deck's cross-section from the head of the bearings and also the width of the pier's head, see Detail 2 in Fig. 3.4. In the case of the elastic analysis, the dampers were modelled through an equivalent viscous damping ratio and their secant stiffness at the maximum displacement, instead of directly modelling their hysteretic behaviour that is not feasible in this case. The flexibility of the piers' foundations was also taken into account by assigning spring elements. These spring values were obtained by the in-situ geotechnical tests conducted for the design of the as-built bridge of Fig. 3.1.

The "reference" bridge model was exploited for the modelling of the modified bridge system. Both models -initial and modified- had the same length and the same deck and pier cross-section while the dampers were removed from the new model. Seismic links were considered to restrain the movements of all piers' head as the serviceability requirements are properly accommodated through their flexibility. The deck is supported on the abutments by sliding bearings. The seismic links are continuously activated during earthquake, restrain the bearings' deformations and allow the rotation of the supported nodes. Thus these elements were modelled by considering that the deck is connected to the piers' head through moment hinge connections, Detail 2 in Fig. 3.4. The bearings were modelled by link elements as in the case of the initial bridge. The foundation was modelled as in the "reference" bridge model with spring elements. The restraining walls were modelled by frame elements, Detail 1 in Fig. 3.4.

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 (Computers and structures 2007). Appropriate nonlinear links were utilized for time-history analysis, too. A compatible lumped plasticity model was used. The input parameters of the moment-rotation (M-θ) relationship were determined by fibre analysis performed in the computer program RCCOLA-90 (Kappos 2002) for each particular cross-section. Five artificial records compatible with the Eurocode 8 elastic spectrum and corresponded to 0.16g, 0.24g and 0.36g ground accelerations accordingly were used. The Newmark $\gamma=1/2$, $\beta=1/4$ integration method was used, with time step $\Delta t = 0.01$ s and a total of 2000 steps (20 s of input). The plastic hinging in the piers was modelled by considering nonlinear rotational spring elements at the ends of the piers.

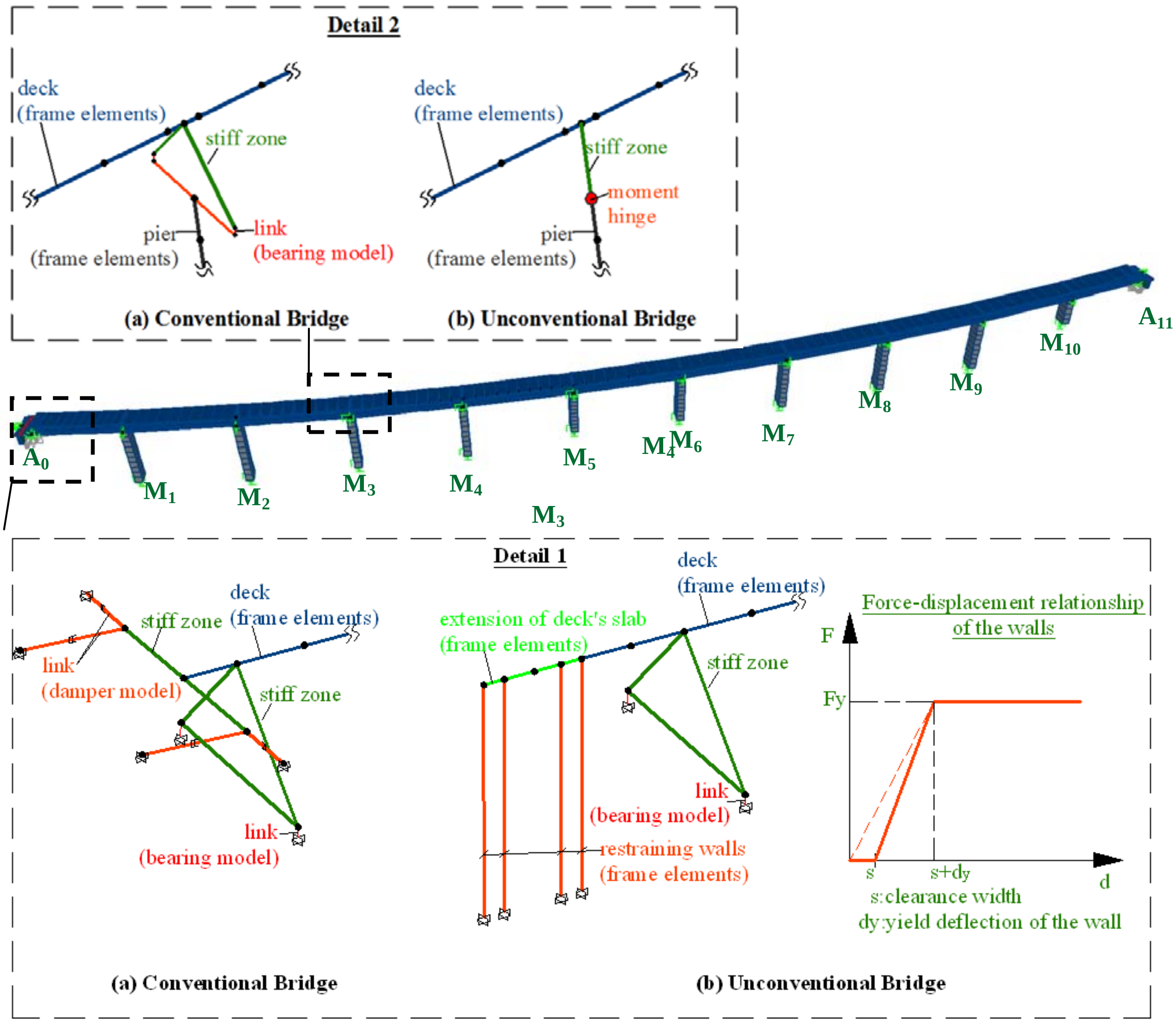

Figure 3.4. The model of the analysed bridge systems

3.4. Results

The restraining effect of the abutment, Fig. 2.1, consisting of concrete walls whose heads are not rigidly connected to the extension of the deck's slab, was mainly assessed by calculating the percentage reductions in the longitudinal and transverse movements of the bridge deck. The ratio of this percentage reduction Δ_{uE} (%) is calculated according to Eqn. 3.2, where $u_{E,CONV.}$ are the maximum seismic displacements of the deck of the conventional bridge and $u_{E,UNCONV.}$ are the maximum seismic displacements of the deck of the unconventional bridge.

$$\Delta u_E(\%) = \left[1 - \left|\frac{u_{E,UNCONV.}}{u_{E,CONV.}}\right|\right] \cdot 100 \tag{3.2}$$

In Fig. 3.5 the percentage reductions in the longitudinal movements of the deck for design accelerations 0.16g, 0.24g and 0.36g are illustrated. Fig. 3.5(a) which corresponds to abutments consisting of 4 restraining walls, shows that the longitudinal movements are reduced by up to 18% when the design acceleration is 0.16g. This percentage is increased to 40% when the design acceleration is 0.36g. This can be attributed to the inelastic response of the concrete walls. Similar conclusions can be extracted by the observation of Fig. 3.5(b) which corresponds to abutments consisting of 10 restraining walls. In this case, the increase of the number of the restraining walls leads to a more efficient reduction in the longitudinal deck movements from 36% up to 56% in proportion to the design seismic action.

Fig. 3.6 illustrates the percentage alterations in the transverse movements of the deck for design accelerations 0.16g, 0.24g and 0.36g. Fig. 3.6(a) corresponds to abutments consisting of 4 restraining walls while Fig. 3.6(b) corresponds to abutments consisting of 10 restraining walls. The figure shows that the seismic contribution of the abutment in this direction is more effective in the second case, namely in the case that the abutment consists of 10 walls. The displacements are mainly restrained over the abutments where the movements are up to 92% reduced. However, we should note here that, the response of the bridge to the transverse earthquake is more easily treated due to the presence of seismically active links (Tegou and Tegos 2012) at the head of the piers without limitations imposed by serviceability requirements.

The aforementioned results lead to the conclusion 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. Fig. 3.7 illustrates the hysteresis loops of a restraining wall for design accelerations 0.16g, 0.24g and 0.36g. All hysteresis loops correspond to artificial earthquake motion that is compatible to soil-dependent B Eurocode 8 elastic spectra. The figure shows that even in the case that the design acceleration is 0.16g the restraining walls respond in an inelastic manner. Consequently, the walls not only resist with their stiffness, but they also dissipate energy through their hysteretic behaviour. This is a desirable effect as it was commented in the description of the proposed abutment.

4. CONCLUSIONS

The extension of the investigation on the seismic efficiency of an innovative restraining abutment aiming at the reduction in the bridge movements was presented. In this case, the system is properly modified so that it can be implemented in all bridges, independently of their length. The concrete walls are arranged in pairs between projections of the continuity slab while clearances of some centimetres accommodate the serviceability requirements of the bridge. The study initiated with the optimization and the design of the abutment, aiming at the accommodation of both in-service and seismic resistance requirements of the bridge. A parametric study was also conducted aiming at the identification of the abutment's seismic efficiency. The main conclusions derived from the analysis are the following:

The proposed restraining system can be implemented in all bridges, independently of their length, as the provided structural configuration at the walls' heads properly accommodates a part of the in-service constraint bridge movements.

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 accommodation of a part of the induced constraint movements of the deck through the construction of the clearances at the walls' heads reduces the longitudinal reinforcement requirement as it 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. As a result a great part of the induced seismic energy is dissipated through the hysteretic behaviour of the restraining walls.

The proposed seismic restrainer effectively reduces the movements of the deck. In the case that the

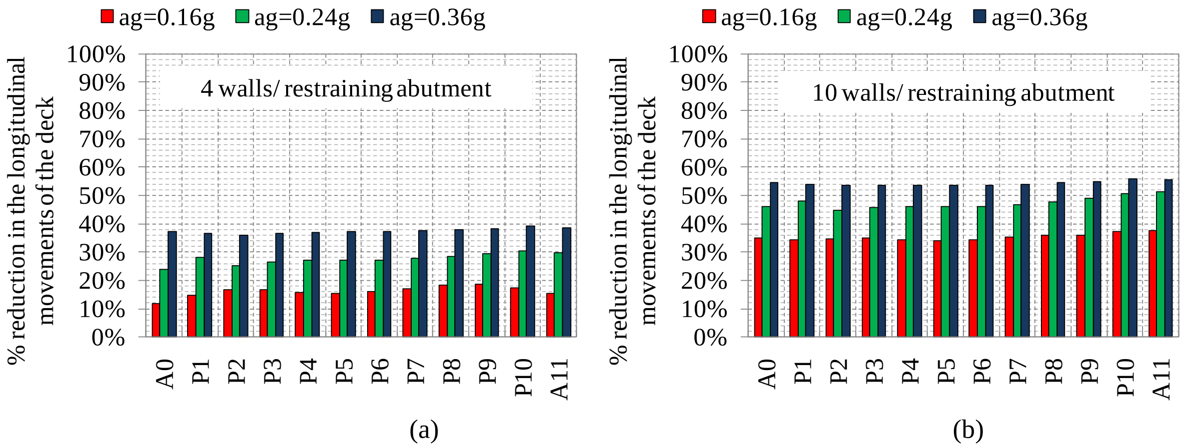

Figure 3.5. The percentage reductions in the longitudinal movements of the deck for design ground acceleration 0.16g, 0.24g and 0.36g for abutments consisting of (a) 4 and (b) 10 restraining walls

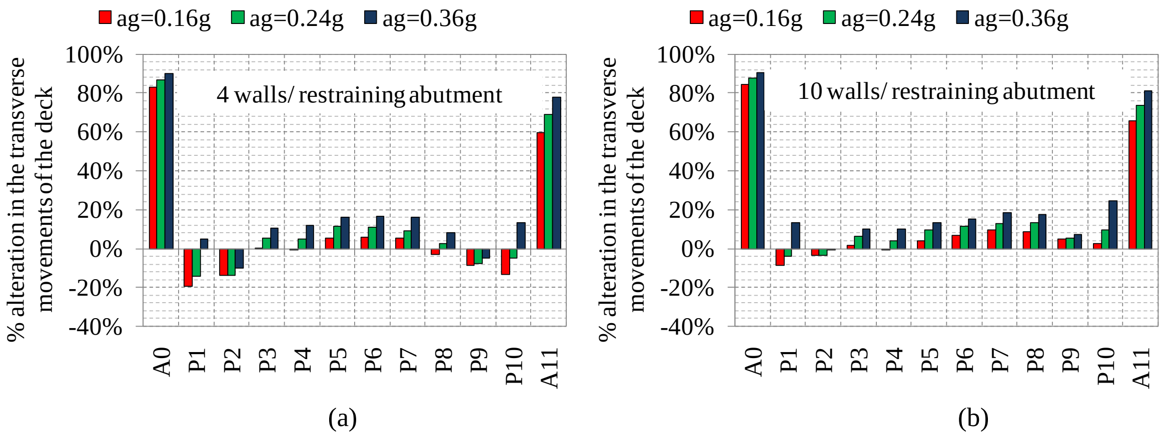

Figure 3.6. The percentage alteration in the transverse movements of the deck for design ground acceleration 0.16g, 0.24g and 0.36g for abutments consisting of (a) 4 and (b) 10 restraining walls

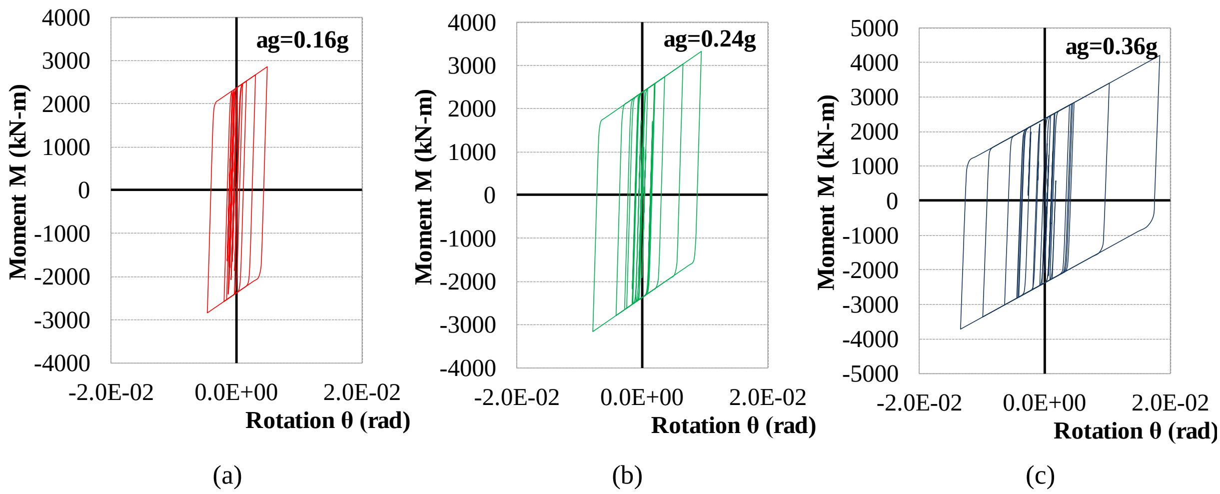

Figure 3.7. The hysteresis loops of a wall for design ground acceleration (a) 0.16g, (b) 0.24g and (c) 0.36g

abutment consists of 4 walls, the reduction in the longitudinal movements of the bridge is of the order of 18% (a_g=0.16g). The ground acceleration influences the efficiency of the proposed restraining system as the restraining walls dissipate greater part of the induced seismic energy through their hysteretic behaviour. The aforementioned reduction is increased to the 40% in the case that the ground acceleration is 0.36g. The efficiency of the proposed abutment is also affected by the number of the restraining walls.

Although the proposed restraining system increases the overall bridge stiffness and consequently the induced seismic load, the energy dissipation mechanism of the system reduces the seismic actions of the piers (shear actions and bending moments). Considering that the construction cost of the abutment is negligible in comparison to the cost of the seismic isolation devices (bearings and dampers), even in the case that the restraining system consists of 10 walls per abutment, a more cost-effective bridge design is accomplished, especially in long bridges, as the higher total cost absorbs possible increases in the cost of the structural members (e.g. pier foundations).

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