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BRIDGES WITH FIXITIES AND BEARINGS VS ISOLATED SYSTEMS

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Abstract. *Seismic isolation exhibits a breakthrough in contemporary bridge engineering. The principal of isolation is to protect the bridge piers, by either reducing their seismic actions or through the increase in the damping of the structure. However, there are bridges in which the seismic loading of piers is not effectively reduced when using seismic isolation, and hence the use of expensive and expendable isolators can be avoided. The ineffectiveness of seismic isolation with typical elastomeric bearings was observed in bridges with tall piers. As such the piers can be connected with the deck through rotation-free connections, such as fixed bearings or stoppers, while their seismic loading is not significantly increased. A parametric study is conducted with alternative isolated bridge-models to identify the necessity of piers' isolation against longitudinal seismic actions. Bridge-models with bents of variable heights ranging from 5m to 30m and cross sections ranging from flexible to stiff bent-types were analyzed. All bridge-models were re-analyzed considering that shear keys placed on the piers restrict the longitudinal deck displacements. The adequacy of the piers was checked against longitudinal and transverse seismic actions. The analyses for two levels of the seismic action indicated specific bridge design cases that can utilize both rotation-free pier-to-deck fixities and bearings, while the bridge remains essentially elastic.*

1 INTRODUCTION

A breakthrough of seismic isolation in bridge engineering is established during the last decades. To date there are several hundred bridges in New Zealand, Japan, Italy and the United States using seismic isolation principles and technology for their seismic design. [1]. An isolation system placed between the bridge superstructure and its supporting substructure lengthens the fundamental period of the bridge structure such that the bridge does not respond to the most damaging energy content of the earthquake input [2], while offering damping to the bridge. During the bridge service, bearings accommodate the constraint movements of the deck that are the changes in the length of the bridge due to thermal effects, creep, shrinkage and prestressing. There are bridge construction methods, such as the precast and the incremental launching method, which lead to the compulsory use of bearings, because the deck is not connected rigidly to the piers. According to Calvi et al. [3] seismic isolation practice and technology went farther than research and codes. At the same time, conceptual design of bridges, which is strongly related to the selection of an appropriate earthquake resisting system (ERS) for the bridge, has been disregarded or is given far too little attention by bridge engineers [4] [5]. Conceptual design is fundamental to achieving adequate seismic performance and low, as possible, structural costs [6]. The correct identification of the lateral-force-resisting concept and the selection of the necessary elements to facilitate the concept are essential, while earthquake resistance is enhanced by systems with regular configurations and evenly distributed stiffness and strength according to MCEER/ATC-49 [7] and Imbsen [8].

Isolation bearings and dampers were proved to perform well even during the tremendous seismic loading of the late Tohoku 2011 earthquake according to Kawashima [9]. However, seismic isolation is not always efficient. Liao et al. [10] compared the response of regular and LRB isolated 3-span continuous RC box girder bridges subjected to the near and far records of the Chi Chi Taiwan earthquake and concluded that the PGA is the most important factor in determining the response of isolated bridges, and that during near-field earthquakes the base shear reduction from the use of bridge isolation is limited. Nearly two hundred highway bridges and numerous rail bridges were damaged during earthquake by effects including span unseating and ruptured bearings [11]. Damaged bearings, following severe earthquakes, is a quite frequent bridge failure mode as observed by Chang et al. [12]. According to Lin et al. [13] the lift-off failure of the bearings was one of the significant reasons for the collapse of Baihwa bridge. Similarly, the Dong Feng bridge girders were dislodged and fallen due to the failure of the supporting bearings, while Ji-lu bridge suffered similar span unseating (Chang et al. 2000). Ruptures of bearings were also observed in the last Tohoku earthquake. On the other side, isolated bridges are expected to remain essentially elastic during an earthquake that is reflected by the use of a q-factor of Eurocode 8-2 [14] and R-factors as prescribed by AASHTO's Tables 3.10.7.1-1 and section 3.10.9.5 [15] and also stated by Constantinou et al. [16]. This implies that the ductility based portion of the R-factor is unity or close to unity [17], while bearings burden significantly bridge's initial and final costs. Isolation devices should be inspected and replaced every 5 to 20 years according to the Chinese [18] and the Australian [19] code respectively, as the reliability of the ERS of the bridge relies heavily on the integrity and the response of the bearings. Large seismic displacements of flexible isolated bridge systems increase the requirements of the expansion joints movement capacities and their cost, induce P-D effects and increase the likelihood of span unseating. To reduce these effects, supplementary damping with dampers is attempted to reduce deck's movements, expansion joints are designed with limited gap clearances, i.e. 80% of the seismic design action according to AASHTO's section 9 [17] and 40% according to Eurocode 8-2 (2005), or no consideration for seismic displacements [20] [21] and bridges are equipped with cable restrainers, span unseating devices, shear keys and a vast of new innovative and emerging technology devices. It is questionable though whether these devices will respond as prescribed or if bridges will require retrofitting in the near future.

During the last years many bridge engineers and academics have shed light on alternative bridge ERS. Rigid pier to deck connections have been achieved through accelerated bridge construction (ABC) methods [22] [23] as means to reduce maintenance costs supporting the philosophy of “get in, get out, stay out”. An experimental study of a highway bridge with shape memory alloy restrainers have been conducting by Anxin [24] to enhance the seismic performance of isolated bridges. Xu et al [25] have studied different earthquake resisting systems for high-pier continuous bridges to decide on the most appropriate and efficient system to receive lateral seismic actions. A partial bridge isolation scheme is proposed, which is a combination of fixed and sliding supports. Their analytical results showed that the correct selection of fixed and isolated bents can significantly reduce the force of piers the displacements of the bridge. The need for a technically sound selection of the bearings, expansion joints and shock transmission units (STU) for an effective control of the seismic loading of the substructures was studied by Bandyopadhyay [26]. Monzon et al. [27] have also studied hybrid isolation schemes to reduce deck displacements, while their research concluded that both full isolation and partial isolation are successful at protecting the columns, even during the maximum considered earthquake that is 150% the design earthquake. In particular, an efficient structural concept was demonstrated by the so-called “hybrid system”, which combined the self-centering properties of unbonded posttensioning together with energy dissipation characteristics being provided by internal mild steel or other means of energy dissipaters [28]. Hybrid seismic isolation has been found to offer lower levels of damage and negligible residual deformations. The development of alternative solutions for precast concrete buildings based on jointed ductile connections has introduced innovative concepts in the design of lateral-load resisting frame and wall systems [29]. Palermo [30] compared hybrid bridge isolation schemes with traditional monolithic solutions and found that hybrid is a viable and efficient solution for an improved seismic performance of bridge systems. Concept of hybrid system offers self-centering and energy dissipation capacity are adequately combined [31]. Dicleli [32] found that the hybrid seismic isolation system provided a structure with a fundamental period long enough to attract smaller seismic forces, while controlling the magnitude of bearings’ displacements. It also resulted in a more uniform distribution of seismic forces among substructure elements, while the piers may provide a restoring force to re-center the structure in such circumstances. The aim of the new design configuration was to allow the designer to pre-assign, to some extent, the seismic characteristics of the bridge, as done in the study of Saiidi et al. [33]. This is related to the even distribution of seismic actions that is based on the regularity criteria set in codes for bridges that are expected to dissipate energy through hysteretic behavior. The resulting configuration is in contrast to the case that existing topography dictates the bridge geometry. Eurocode 8-2 allows the design of the isolation system without taking into account the flexibility of the piers. However, the abutment bearing displacements may be underestimated if the flexibility of the piers is ignored [2] [34].

A viable and efficient solution for an improved seismic performance of bridges is the use of shear keys that restrict longitudinal deck displacements at piers. Use of shear keys is a mature and reliable technology covered extensively by both the current state-of-the-art and codes. External shear keys have been proposed in bridges to minimize longitudinal movements [35]. Hindi and Dicleli [36], studied the modification of the seismic response of bridges when modifying the fixity conditions of bearings. Bridge systems were modified to obtain different configurations of bridge earthquake resisting systems. Their research yielded that changing the fixities of the bearings may be an effective response modification technique to mitigate the effect of seismic forces on vulnerable substructures of the bridge under consideration. AASHTO and Caltrans [37] require the use of shear keys to minimize the possibility of span unseating. Accordingly, Eurocode 8-2 [14] requires the use of seismically inactive shear keys that reduce the deck dislodgment potential, while additional to this the Japanese code [38] [39] requires that stoppers should provide means to dissipate the seismic energy. The Chinese code specifies that, except for displacement limiting and dissipation, shear keys can be used for two levels of resistance [18].

Toward this end an extended parametric study is performed in this paper. The study aims to identify which piers can be connected through rotation-free connections to the deck, under the criterion that the piers remain elastic, while being reinforced with the minimum flexural and shear reinforcements. The study included eight different pier heights, six different pier sections and two levels of the seismic action. More than one hundred realistic bridge-models were analyzed and the study illustrates conclusions that can be useful for future design of hybrid bridge systems that combine shear keys and bearings as means to enhance both seismic resistance and cost-effectiveness. Alternative bridge models were compared on the basis of the aforementioned parameters. Maximum piers' capacity against bending moments was designed to be the same to all the models, while piers were considered to have the same reinforcement ratios, i.e. equal to 1% that is the minimum requirements for columns according to Eurocode 2-1 and Eurocode 2-2 [40] [41]. An extended parametric study was performed to identify whether the seismic isolation with elastomeric bearings is more efficient and cost effective or if bridge systems with fixed connections of the piers to the deck result in a more economical bridge designs**.**

2 THE BENCHMARK BRIDGE

A simplified version of a real bridge was used as a benchmark. The bridge is described in detail by Manos et al. [34]. The simplified bridge system consists of four spans as opposed to the six spans of the real structure, and a total length equal to 154.0 m. Figure 1 shows the longitudinal section of the bridge, as well as the deck and pier cross sections. The finite element model of the isolated bridge system is given in Figure 2.

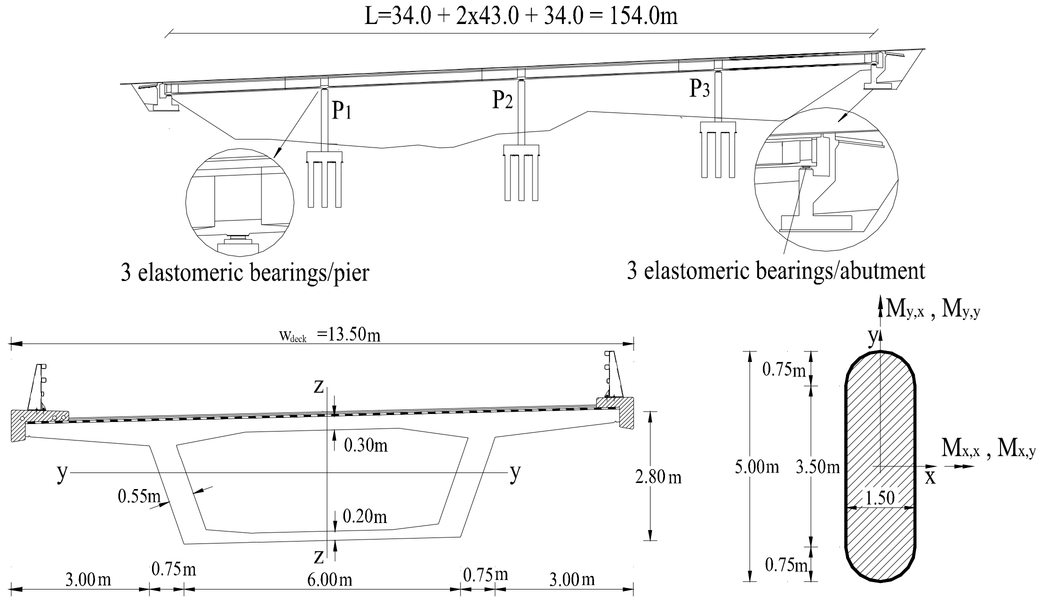

Figure 1: Geometry of the benchmark bridge.

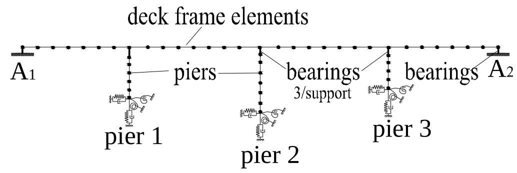

Figure 2: Simplified model of the benchmark bridge with frame elements.

Three bearings were selected for supporting the deck on each abutment and pier in order. The length of the central spans is 43m, the lengths of the end spans are 34m, the shape of the bearings is rectangular, soil type was taken corresponding to class B according to the Eurocode 8, the design ground acceleration was taken equal to 0.16g, the importance factor was assumed to be γ_I=1.30. The bearings were considered to have shear modulus G=1MPa for all the alternative bridge models that were generated based on the benchmark bridge. The deck mass was estimated equal to 308.4kN/m and took into account the dead, the additional permanent and 20% of the live vertical load of the bridge according to Eurocodes.

3 PARAMETRIC STUDY ON ARAHTHOS-PERISTERI BENCHMARK BRIDGE

The bridge of Arachthos-Peristeri that belongs to Egnatia Odos was used to generate realistic bridge-models that were parameterised to account for the following different seismic input motions corresponding to EC8-2 elastic spectrums and to two different Eurocode's 8-1 [14] ground types i.e. ground type B ($v_{s,30}$≈580m/s, N_{SPT}>50 and c_u>250kPa) and C ($v_{s,30}$≈270m/s, N_{SPT}≈32 and c_u≈160kPa) were used. Elastic spectra were calculated by considering the critical damping equal to 5% of the critical one, as the isolators are low damping bearings. Potential different designs that may by adopted by the bridge engineer during the conceptual design process were examined as follows: (a) different pier heights, all bridge models were considered to have variable pier heights ranging from 5m to 30m, (b) different pier cross sections, the piers were considered to be either wall-type columns, circular square, hollow circular, hollow rectangular or multi-column bents, (c) fully isolated bridge-models, i.e. bridges whose deck rests on the piers through low damping elastomeric bearings and bridge models with pier-to-deck connections through shear keys, namely through rotation-free connections that allow for the free relative rotations of adjacent spans and accommodate the constraint movements of the deck during the bridge service (creep, shrinkage, thermal movements). Table 1 illustrates the parameters of the study.

The efficiency of seismic isolation was assessed in all bridge-models. Seismic isolation is considered to be efficient in case the piers actions are effectively reduced by the seismic isolation. The following ratios were considered to be significant in assessing the efficiency of the seismic isolation: (a) the longitudinal pier cap displacement versus the deck's displacement, (b) the bearings' shear displacement versus the deck's displacement, (c) the piers' bending moments versus the piers' bending capacity at yielding (elastic capacity) and (d) the shear displacement of the bearings versus the total thickness of their elastomer that reflects the bearings' shear strain, which is the most important check against failures.

Parameter	pier heights (m)	pier cross section	seismic action PGA (g)	Soil type (Eurocode 8-1)	direction of the bridge	pier-to-deck connection
range of parameter or description	5,10,15,20, 25,30,35,40	wall-type (3.0x5.0m) circular (d=2.5m) square (2.0x2.0m) hollow circular (d_{ex}=3.0m, d_{in}=2.0m, t=0.5m) hollow rectangular (5.0mx3.0m, t=0.5m) multi column (5 columns with diameter 1.0m transverse distance between columns: 2.0m)	0.16 or 0.24	**B** ($v_{s,30}$≈580m/s, N_{SPT}>50 and c_u>250kPa) or **C** ($v_{s,30}$≈270m/s, N_{SPT}≈32 and c_u≈160kPa)	longitudinal (x) or transverse (y)	through bearings or through shear keys (rotation-free)

Table 1: The parameters of the study.

pier type \ pier height:	5m	10m	15m	20m	25m	30m
	bearing used					
multi-column	B1*	B2**	B2	B2	B2	B2
wall-type	B1	B1	B1	B2	B2	B2
square	B1	B1	B1	B2	B2	B2
circular	B1	B1	B1	B2	B2	B2
hollow circular	B1	B1	B1	B1	B2	B2
hollow rectangular	B1	B1	B1	B1	B2	B2

*B1: 800x700x70(50) 3 layers of 16.67mm each

**B2: 800x800x79(59) 3 layers of 19.67mm each

Table 2: The bearings used at the isolated bridge-models for a_g=0.16g.

pier type \ pier height	5m	10m	15m	20m	25m	30m
	bearing used					
multi-column	B5	B6	B4	B4	B4	B4
wall-type	B2	B5	B6	B3	B4	B4
square	B2	B5	B6	B3	B4	B4
circular	B2	B5	B6	B6	B7	B4
hollow circular	B2	B5	B5	B6	B3	B4
hollow rectangular	B2	B2	B5	B5	B6	B6

B3: 800x700x150(110) 7 layers of 15.7mm

B4:800x700x270(200) 13 layers of 15.4mm

B5: 800x800x102(77) 4 layers of 19.3mm

B6: 800x800x125(95) 5 layers of 19mm

B7: 800x800x148(113) 6 layers of 18.8mm

Table 3: The bearings used at the isolated bridge-models for a_g=0.24g.

4 RESULTS

4.1 Comparison of isolated and hybrid solutions

It was considered to be essential to choose pier-deck fixed-hinged connections to piers that are not subjected to significant constraint movements during the bridge service, i.e. due to creep, shrinkage and thermal effects. The displacements of the bearings and the bending moments of the piers under the longitudinal seismic action were considered to be the significant design parameters. Based on the study of Manos et al. the isolation schemes of all isolated bridge-cases were re-designed. Tables 2 and 3 show the dimensions of the elastomeric bearings used at alternative bridge-models under different levels of the seismic action. It is stressed that the area of the isolators was not significantly changed due to the fact that the vertical compressive load of the bearings is not altered significantly, as vertical loading of the isolators is mostly dependent on the dead load plus the live load of the deck [14].

Based on Figures 3 and 4 (continuous black lines indicated by letter b) it is evident that the shear capacity of the bearings, in terms of maximum allowable shear strain of the bearings, is not fully developed in any case. Hence, the displacements that are received by the isolators is lower than the Eurocode's 8-2 [14] maximum allowable shear strain that equals ε_s=200%. The bearings shear deflection is maximum when the stiff piers (i.e. hollow circular and rectangular) were used and when the height of the piers was the minimum, namely when the bridge's ERS is quite stiff. The opposite was found to be valid when the flexible pier was considered (i.e. the multi column bent) and when the heights of the pier was increased. Bearings were found to receive relatively small shear displacements, corresponding to less than ε_s=100% of the maximum allowable shear strain, when the bridge models with multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were used with heights greater than 6m, 10m, 11m, 12m, 14m and 19m respectively (as shown by the black discontinuous lines). Correspondingly, the multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were found to receive 40%, 40%, 45%, 40%, 45% and 43% of the maximum deck's longitudinal displacement. The piers were found to develop 76%, 40%, 72% 62%, 75% and 25% of their bending moment at yielding (elastic capacity), that was estimated based on the minimum longitudinal reinforcement ratio of ρ=1% [40] [41]. Hence, piers' elastic capacity redundancy is not developed, while the role of the bearings is reduced effectively when the bridge systems became more flexible, i.e. when more flexible bents were used and when taller piers were used. Figures 3 and 4 show that the piers' elastic capacity was not developed in any bridge-case under the transverse seismic action (figures on the right). It is stressed that transverse seismic displacements of the deck were restricted by shear keys placed on the bents.

When the higher seismic action 0.24g was considered, the bearings were found to receive relatively small shear displacements, corresponding to less than 50% of the the maximum allowable shear strain (i.e. ε_s=100%), when the bridge models with multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were used with heights greater than 8m, 12m, 14m, 15m, 17m and 23m respectively, as shown by the black discontinuous lines of Figure 4. Correspondingly, the multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were found to receive 50%, 50%, 55%, 44%, 50% and 47% of the maximum deck's longitudinal displacement. The multi-column, the square, and the hollow-circular cross sections of the piers were found to receive bending moments greater than their elastic capacity, when considering a longitudinal reinforcement ratio ρ=1%, while the wall-type, the circular and the hollow rectangular bents were found to develop 57%, 92% and 37% of their elastic capacity. The multi-column, the square, and the hollow-circular piers

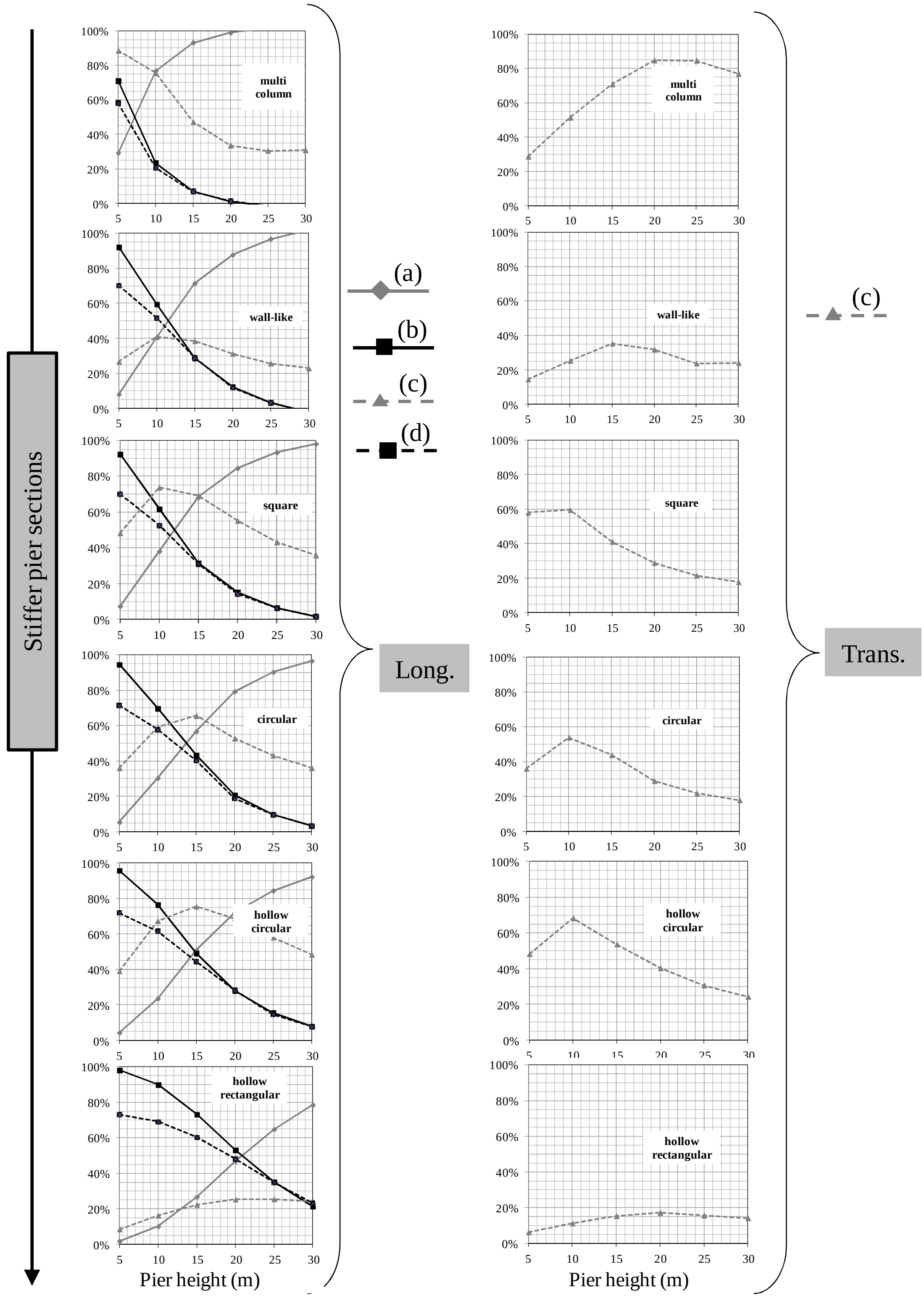

Figure 3: The ratios of (a) the longitudinal pier cap displacement versus the deck displacement (continuous gray line), (b) the bearings' shear displacement versus the deck displacement (continuous black line), (c) the piers' flexural loading versus the piers' bending moment at yielding (elastic capacity) (discontinuous gray line) and (d) the shear displacement of the bearings versus the total thickness of their elastomer (discontinuous black line) (a_g=0.16g).

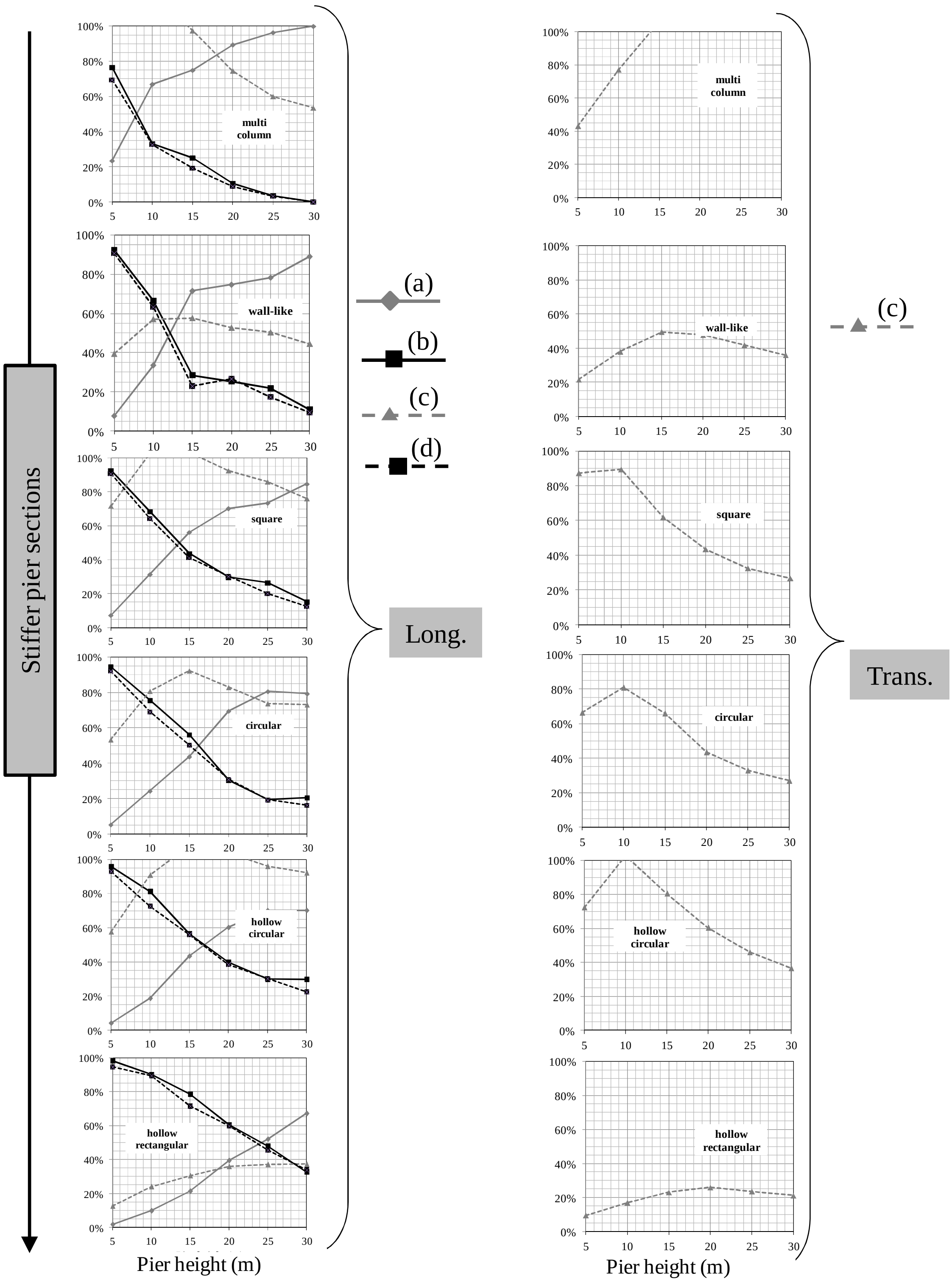

Figure 4: The ratios of (a) the longitudinal pier cap displacement versus the deck displacement (continuous gray line), (b) the bearings' shear displacement versus the deck displacement (continuous black line), (c) the piers' flexural loading versus the piers' bending moment at yielding (elastic capacity) (discontinuous gray line) and (d) the shear displacement of the bearings versus the total thickness of their elastomer (discontinuous black line) (a_g=0.24g).

were found to remain within the elastic range in case their heights were greater than 14m, 16m and 23m correspondingly. The check of the piers, when the bridge-models were subjected to the transverse seismic action, showed that the multi column pier yield, i.e. the bending moment action is greater than the elastic capacity. For the other bent types, the elastic capacity was greater than the one developed during an earthquake with a PGA equal to 0.24g.

Hence, it seems that there are bridge-designs in which seismic isolation may not be used to safeguard the piers against seismic actions, due to the fact that on the one hand the bearings receive small part of the deck's displacements, while on the other hand the piers can receive safely the seismic actions without exhibiting yielding, while using only the minimum longitudinal reinforcements, i.e. 1%. Hence, the piers can be connected to the deck through rotation free connections, such as shear keys, to provide a cost-effective bridge design, while the seismic safety of the bridge can be relied on both isolation devices, namely on the bearings, and on the resistance of the piers. The selection of the piers, which can be connected to the deck through rotation-free connections, have been studied in a previous paper [42]. Table 4 summarizes the results of this parametric study showing what the minimum required height of the piers is in case a rotation-free connection is used for the design of the ERS of the bridge. The results are based on the parametric study that was conducted on isolated bridge-models.

All the analyses were repeated considering that all the piers are connected to the deck through rotation-free connections, i.e. shear keys that restrict both the relative pier-deck displacements in the longitudinal and the transverse direction of the structure. This case was considered to be the "stiff" version of the bridge-model, while the bridge-models with seismic isolation that was studied above were considered to be the "flexible" versions of the bridge-models. Table 5 shows the minimum pier heights that can utilize rotation-free connection, under the assumption that the piers will not require additional reinforcements than the ones required in the benchmark bridge-model (i.e. 1%).

	pier section					
pier type:	multi-column	wall-type	square	circular	hollow circular	hollow rectangular
seismic action						
0.16g	6	10	11	12	14	19
0.24g	-	12	16	15	23	23

Table 4: The minimum pier heights in isolated bridge-models that were found to have ineffective isolation (flexural reinforcement of the piers 1%).

	pier section					
pier type:	multi-column	wall-type	square	circular	hollow circular	hollow rectangular
seismic action						
0.16g	10	all heights	14	15	19	all heights
0.24g	-	12	20	20	25	20

Table 5: The minimum pier height that can utilize rotation-free connection (flexural reinforcement of the piers 1%).

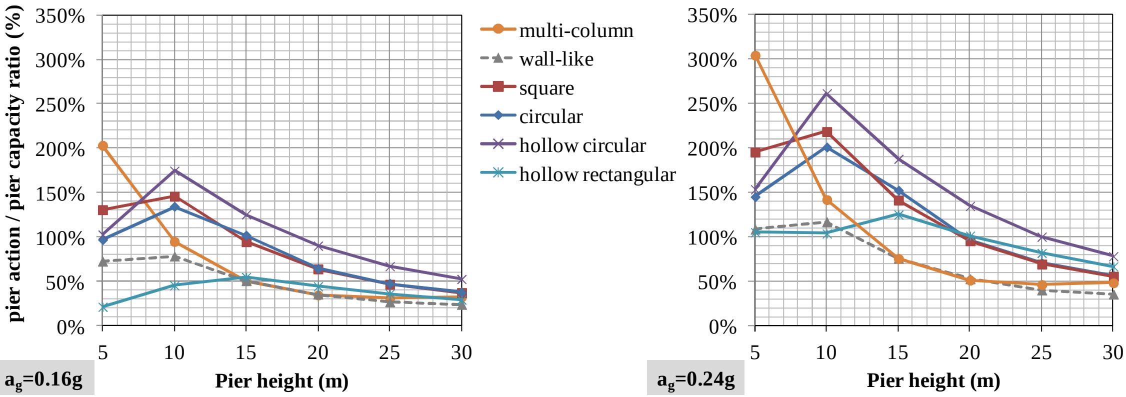

Figure 5: The pier action (bending moment) vs the pier elastic capacity ratio when all the piers of the bridge models are connected to the deck with rotation-free connections (figure's results summarized in Table 5).

The two tables reveal that there are bridge-models that can combine both seismic isolation and rotation-free pier-to-deck connections. The pier heights given in Table 4 show what is the maximum pier height after which the benefits of seismic isolation are fading, while the pier heights shown in Table 5 are the minimum pier heights that are required in case all the piers are connected to the deck through rotation-free connections. Intermediate values of piers' heights indicate the bridge design case in which some piers may be connected to the deck, whereas the rest of the bents may be isolated.

4.2 Modification of the dynamic system of the bridge

The parametric study that was conducted for this paper emphasized on the modification of the dynamic response of bridges that is strongly related to the period of the bridge-models in both the longitudinal and the transverse direction of the bridge. For this reason the fundamental periods in both the longitudinal and the transverse directions of the bridge-models were estimated. The analyses of the bridge-models with and without pier-to-deck rotation-free connections revealed that the modal periods are only slightly altered when the piers are connected to the deck under the condition that the piers have heights greater than the ones shown in Table 4. More specifically, the bridge-models with the 10m long multi-column, the 15m long wall-type, the 15m long square, the 15m long circular, the 25m long hollow circular and the 25m long hollow rectangular bents revealed a decrease in their longitudinal periods of the order of 4%, 5%, 7%, 12%, 2% and 7% when the piers were connected to the deck instead of isolating them. The above period reductions corresponded to the following increases in the seismic action: 4%, 5%, 6%, 12%, 2% and 8%. It follows that no significant increase in the induced seismic action took place in case the piers were connected to the deck through shear keys. At the same time, the piers remained elastic despite the use of minimum flexural reinforcements (1%), while the initial and final cost of the bridge is effectively reduced, due to the use of smaller bearing sections and smaller expansion clearances.

5 CONCLUSIONS

An extended parametric study was conducted to compare the seismic response of conventional seismically isolated bridge-models to the hybrid bridge alternative, which combines the use of isolation and rotation-free connections, i.e. shear keys. Towards this comparison the minimum required piers' flexural reinforcement ratio of 1% was considered, while the piers were considered to remain essentially elastic. The parametric study included different pier heights, pier sections and different levels of the seismic action. The study came to the following conclusions:

There are bridge designs, with flexible pier sections that is either bents with relatively small sections or tall piers, in which seismic isolation benefits fading. This is due to the fact that the piers receive a large portion of the deck's longitudinal and transverse seismic displacements. Hence, bearings are considered to be superfluous in that case and as such can be avoided by utilizing common shear keys.

The study showed that isolation became ineffective in bridges having flexible piers. The analyses indicated what were the maximum pier heights for the different pier sections that isolation is effective in reducing their loading. Isolation was considered to be ineffective when the bearings' movement capacity is not developed, namely when the shear strains εs are smaller than 100% and when the piers loading is smaller than their elastic flexural capacity. The above consideration was found to be valid when the bridge-models with the multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were used with heights greater than 6m, 10m, 11m, 12m, 14m and 19m respectively. The results refer to the case that a seismic action equal to 0.16g was considered, while in case a PGA equal to 0.24g was considered the corresponding pier heights of the bridge-models with multi-column, wall-type, square, circular, hollow circular and hollow rectangular bents were used with heights greater than 8m, 12m, 14m, 15m, 17m and 23m respectively. However, when 0.24g was considered the transverse seismic action required additional flexural reinforcements for the piers (i.e. a ratio greater than 1%). This was found to affect the multi-column bents which required an increase in their reinforcements in all cases. In case the square and the hollow-circular piers were considered the piers' loading was found to be smaller than their elastic capacity if the piers have heights greater than 16m and 23m.

Re-analyses of all bridge-models considering that all the piers are connected to the deck through rotation-free connections were conducted to indicate what are the minimum piers' heights for different bent sections that can be connected to the deck. The analyses yielded that the multi-column, square, circular, and hollow circular piers can be connected to the deck when their heights are greater than 10m, 14m, 15m, 19m correspondingly. If the pier have a wall-type or a hollow rectangular section then all the piers may be connected to the deck independently from their heights. The former results refers to the case that the bridge-models were subjected to a seismic action of 0.16g, while in case a PGA equal to 0.24g was considered then the wall-type, square, circular, hollow circular and hollow rectangular piers should have at least heights 12m, 20m, 20m, 25m and 20m respectively. The multi-column piers having a flexural reinforcement ratio 1% were found to be inadequate to receive the 0.24g seismic action.

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