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THE EFFECT OF JOINT GAP SIZE ON THE SEISMIC PERFORMANCE OF RAILWAY BRIDGES

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Abstract

Boundary conditions play an important role in the response of bridges to different actions, particularly dynamic loads. Gap closure at end joints, resulting in activation of the abutment-backfill-embankment system, considerably affects the dynamic characteristics and, hence, the seismic response of the bridge. In particular, consideration of abutment-backfill flexibility may often result in substantial reduction of the contribution of piers to the bridge response under earthquake loading. Moreover, gap size and closure are related to various damage stages including backfill deformation/damage and deck unseating, while the varying boundary conditions during an earthquake affect the inelastic behaviour of critical bridge components (i.e. piers, piles), as well as the damage sequence.

The use of gap sizes larger than the ones resulting from Eurocode 8 provisions is a common practice in seismic design of bridges in Greece; this is apparently considered to be on the safe side and conveniently relieves the designer from the difficulty of accounting for gap closure effects in the analysis. However, this means over-dimensioning of bridge joints, with subsequent increase in both initial and maintenance costs, while it is not certain that preventing activation of the abutment-backfill system under seismic actions exceeding the design ones increases the safety of the bridge.

In this context, the aim of this paper is to study the effect of gap size on the seismic performance of concrete bridges, providing insight into the distribution of seismic action effects among the key components of the bridge i.e. piers and abutments, accounting for varying gap sizes and hence boundary conditions. The behaviour of an existing railway bridge with a passive ssytem is evaluated using inelastic response history analysis for a set of design spectrum compatible artificial accelerograms, considering different gap sizes for the end joints, i.e. those resulting from Eurocode 8, as well as higher and lower values. Analyses are carried out for different levels of seismic action, up to twice the design one.

Keywords: Bridges, Boundary conditions, Joint gap size, Seismic performance.

1 INTRODUCTION

Joints are required to accommodate movements of the deck due to thermal expansion and contraction, shrinkage, creep and prestressing of concrete, and earthquake-induced horizontal movements. The use of gap sizes larger than the ones prescribed by Eurocode 8 is a common practice (particularly in Greece) in order to ensure that the gap remains open during the design earthquake and avoid verification checks to account for gap closure effects. Dual analysis is recommended by Caltrans [1], i.e. the bridge is analysed assuming either free movement or full restraint at the "compression end" of the bridge. The most unfavourable response quantities from either set of analyses are taken into consideration, rendering this practice conservative and cost ineffective. Since the boundary conditions are different depending on whether joints are open or closed, the necessity for joint modelling during assessment of the seismic behaviour of bridges emerges. When either of the abutment joints closes during the earthquake, substantial forces are transferred to the abutment-backfill system.

Kappos & Sextos [2] have studied the importance of boundary conditions on the seismic response of bridges, with a view to highlighting the necessity of capturing the effect of gap closure on the seismic behaviour. In the studied bridge, failure was expected for a displacement twice the gap size and was attributed to unrecoverable damage to the backfill soil, while the piers remained well within their rotational capacity. However, a different failure mechanism, i.e. exceedance of available pier ductility, would have been predicted if the end supports were modelled as longitudinal restraint (as per the Caltrans simplified approach).

The main goal of this paper is to investigate the optimum design of critical bridge components, based on a proper gap size selection. In this context, the effect of joint gap size on the seismic performance of an existing bridge is investigated. The bridge studied is a seismically isolated railway bridge in Northern Greece. Different scenarios regarding the gap sizes for the end joints are studied, considering values calculated according to the provisions of Eurocode 8 [3], as well as half and twice the code values. Inelastic response history analysis is performed, using a set of 10 artificial accelerograms compatible with the design spectrum. Two different levels of seismic intensity are considered, corresponding to 1.0 and 2.0 times the design level. The results clearly show that the response of the bridge is significantly affected by the gap size. An important increase in the shear forces carried by the abutments is observed for smaller gap sizes, still well within the capacity of the abutments. Conversely, the relevant seismic forces in the bridge piers are reduced. Overall, it appears feasible to optimize the design by a proper selection of the gap size; this means that gap closure should be accounted for in the analysis, which is feasible when advanced software packages are used.

2 CASE STUDY RAILWAY BRIDGE

2.1 Overview of the bridge

The T4 railway bridge is part of the new High-Speed Railway Network of Northern Greece, connecting Polykastro and Eidomeni. The bridge has four spans (39m, 45m, 45m and 39m respectively), and the deck consists of a bearing-supported continuous box girder with constant height of 3.6m and width at the top 13.90m (Fig. 1b). The longitudinal slope is 2% and the maximum height above ground level, 24 m. The bridge piers have a hollow rectangular section with outside dimensions 3x5.5m and wall thickness 0.45m (Fig. 1d). The seat-type abutments have longitudinal joints but not transverse ones, as required in railway bridges.

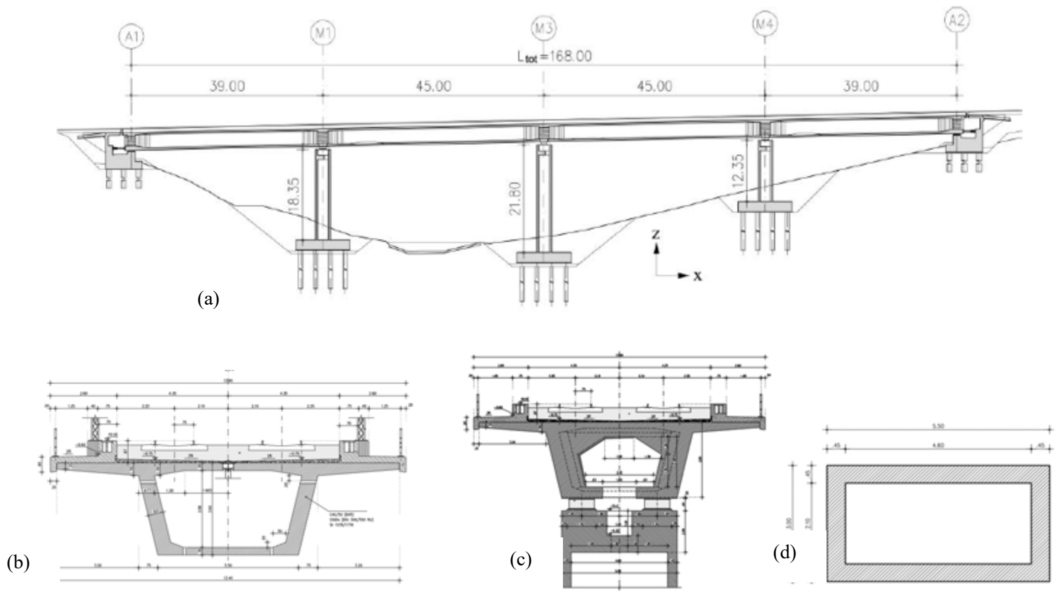


Figure 1: (a) Longitudinal section of the bridge (b) Typical Cross Section (span), (c) Cross section close to Pier (d) Pier Section

The bridge was designed according to the Greek Standards for Seismic design of Bridges ([4], [5]) which are similar to Eurocode 8-2 [3], using the seismic isolation concept. Lead rubber bearings were used at both piers and abutments (with dimensions (mm) equal to 900×900/231-200 and 1200×1200/286-250, respectively), while shear keys and fluid viscous dampers were provided at each abutment. The shear keys prevent end displacement of the bridge in the transverse direction (to prevent derailment), hence the bridge is not fully isolated in that direction. Two fluid viscous dampers are provided at each abutment, in the longitudinal direction of the bridge, to achieve the required amount of damping. The selected damping coefficient C of the nonlinear dampers ($F=Cv^{\alpha}$) is 2350 kN·s/m and the velocity exponent α=0.15. Finally, pile foundation was adopted (Fig. 1a) for both piers and abutments.

2.2 Finite element modelling of the bridge

The finite element model of the bridge was set up in OpenSees v.2.5.0. [6] (Fig. 2). The focus of this study was on the effect of joints on the seismic response of the bridge; response history analyses were performed to this purpose for different 'scenarios' of joint gaps. It is noted that in the analyses reported herein expansion joints were assumed along both the longitudinal and the transverse directions, to fully study the effect of gap size on the seismic performance.

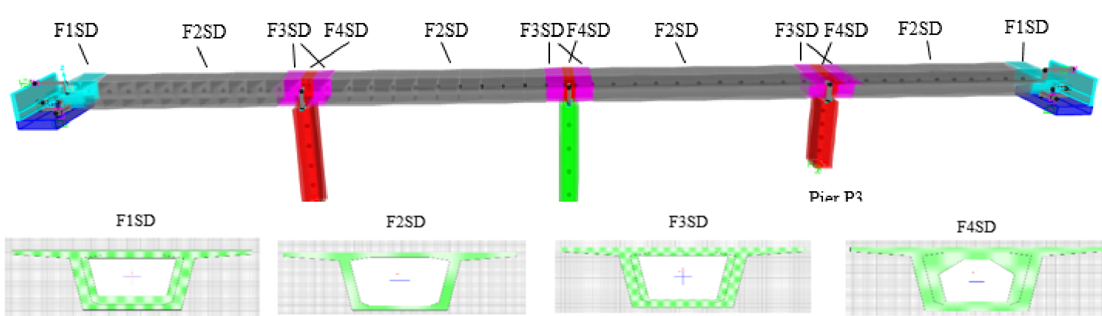


Figure 2: Finite element model of the bridge.

Parameter	F1SD	F2SD	F3SD	F4SD
A (m^2)	15.4	10.2	14.1	17.7
J (m^4)	23.9	16.5	22.3	26.9
I_z (m^4)	25.4	17.8	22.8	25.9
I_y (m^4)	122.1	106	120.9	131.8

Table 1: Geometric characteristics of the deck.

The bridge deck, which is intended to remain elastic during the design earthquake was modelled with elastic beam-column elements with gross section properties given in Table 1 and Figure 2. Bridge piers are expected to develop inelastic behaviour; hence, a lumped plasticity model was used, accounting for the plastic hinge length given in equation (1), where L is the length of the contraflexure point under seismic action, f_{yk} is the characteristic yield stress of steel reinforcement and d_{bl} the bar diameter.

$$L_p = 0.1 \cdot L + 0.015 \cdot f_{yk} \cdot d_{bl} \tag{1}$$

Bilinearised moment-curvature (M-φ) curves were obtained from section analyses for the axial load of the seismic combination $N_{G+0.3Q}$, using the AnySection software [7]. Regarding confined concrete of hollow rectangular sections, the stress-strain model by Kappos [8] was used (Figure 3). Pier properties were based on secant values at yield.

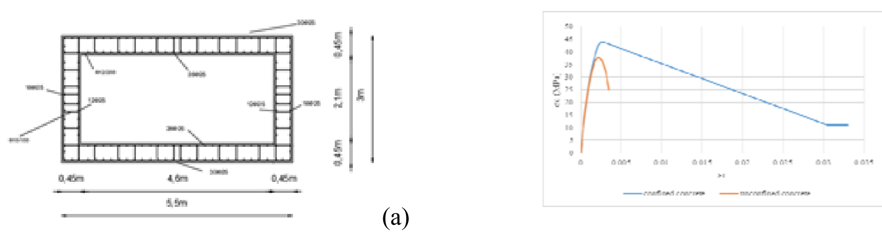


Figure 3: (a) Pier reinforcement (b) Stress-strain curves for the confined and unconfined concrete of the pier

Regarding lead rubber bearings, the horizontal shear stiffness (K_h), as well as the flexural (K_b) and axial stiffness (K_v) were calculated according to [9]. The hysteretic model for lead-rubber bearings is depicted in Figure 4(a), while the effective stiffness was calculated using an iterative procedure. Viscous dampers were modelled using a two-node link element (Figure 4(b)), while the stiffness and damping parameters were taken from manufacturer data.

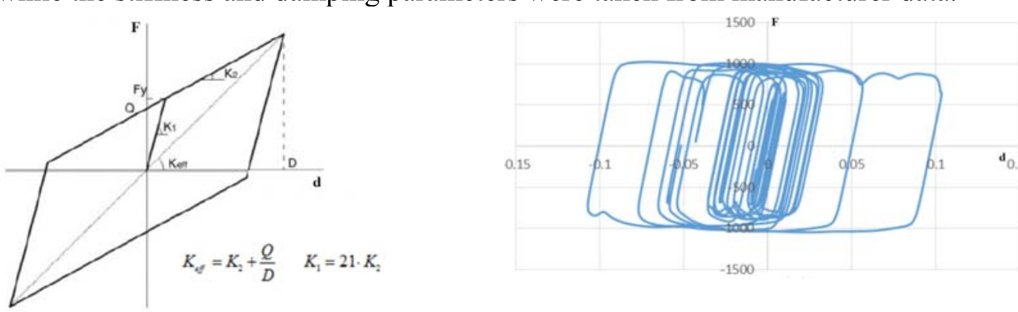
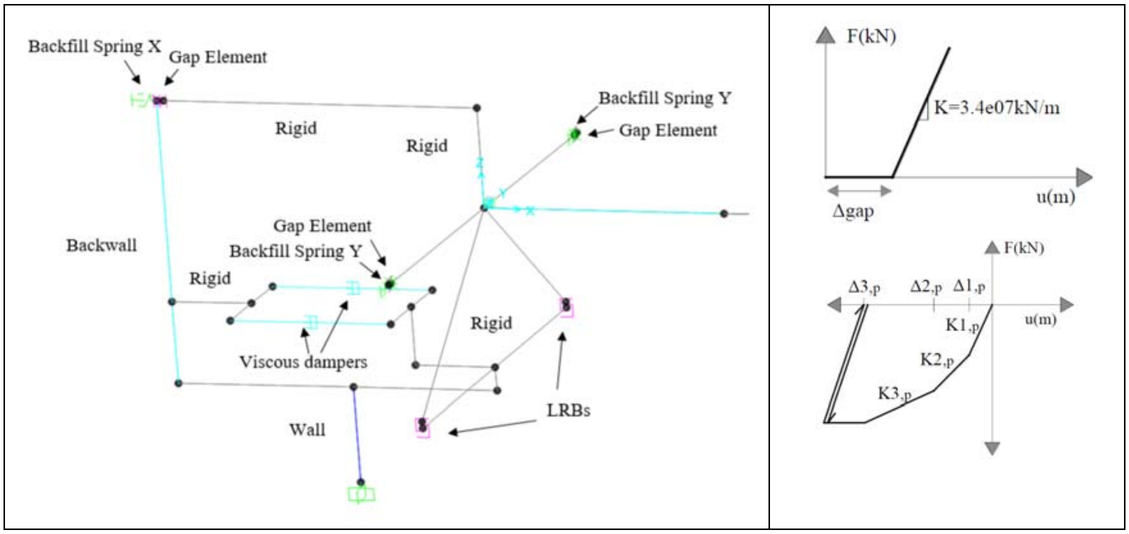


Figure 4: (a) Hysteretic model for lead rubber bearings, (b) Viscous Damper

Detailed modelling of abutments should account for all resistance mechanisms and components, including an accurate estimation of mass, stiffness and nonlinear hysteretic behaviour [10]. The resistance of the abutment-embankment system was modelled through springs, based on Caltrans recommendations [1] and simplifying assumptions.

Regarding the case-study bridge, the detailed model of the abutments is depicted in Figure 5(a). The springs for lead rubber bearings and viscous dampers are shown, along with gap elements and abutment-embankment springs in both directions (Figure 5(b)). The detailed, trilinear, inelastic model proposed by Nielson [11] was adopted for the resistance of the abutment-backfill system subsequent to gap closure.



(a) (b)

Figure 5: Abutment modelling (a) Opensees model; (b) Constitutive laws

3 JOINT GAP SIZE ACCORDING TO EC8-2

According to Eurocode 8-Part 2 [3], adequate gap sizes according to equation (2) should be provided for protection of critical or major structural bridge members

$$d_{Ed} = d_E + d_G + \psi_2 d_T \tag{2}$$

where:

d_E is the design seismic displacement

d_G is the displacement due to the permanent and quasi-permanent actions measured in long term (e.g. post-tensioning, shrinkage and creep for concrete decks)

d_T is the displacement due to thermal movements

ψ_2 is the combination factor for the quasi-permanent value of thermal action

The detailing of non-critical structural components, such as deck movement joints but also abutments with ‘sacrificial’ backwalls, should be related to controlled and repairable damage, additionally accounting for creep and shrinkage effects. According to EC8-2, clearances should accommodate appropriate fractions of the seismic design displacement and thermal movement (p_E=0.4 and p_T=0.5, respectively), allowing for any long-term creep and shrinkage effects, so that damage under frequent earthquakes is avoided.

To study the effect of joint gap in both directions, in addition to the existing longitudinal joints, a case with joints in the transverse direction was also studied. The required value of design displacement (joint gap) is determined for both bridge directions, according to Eurocode 8; the resulting values for each action are given in Table 2.

Actions	**Abutment**			
	A1		A2	
	Ux (m)	Uy (m)	Ux (m)	Uy (m)
Thermal Movements:	0.016	0.0172	0.016	0.0029
Permanent and Quasi-Permanent Actions:				
Prestressing	0.011	0	0.009	0
Shrinkage and Creep	0.044	0	0.044	0
Seismic Displacements:				
|±Ex|	0.102	0	0.102	0
|±Ey|	0	0.28	0	0.26

Table 2: Design displacements at abutments.

COMBINATION	**Abutment**			
	A1		**A2**	
	X-X (m)	Y-Y (m)	X-X (m)	Y-Y (m)
d_{Ed}=+0.4d_E+d_G+0.5d_T	0.104	0.121	0.102	0.105
d_{Ed}=+0.4d_E+d_G-0.5d_T	0.088	0.103	0.086	0.103
d_{Ed}=-0.4d_E+d_G+0.5d_T	0.006	-0.131	0.004	-0.105
d_{Ed}=-0.4d_E+d_G-0.5d_T	0.006	-0.131	0.004	-0.105
Critical Combination	0.104	0.131	0.102	0.105
Design Value of the Gap Size	**X-X (m)**	**0.104**		
	Y-Y (m)	**0.131**		

Table 3: Required joint gap size: Case of acceptable damage (d_{Ed}=±0.4d_E+d_G±0.5d_T)

COMBINATION	**Abutment**			
	A1		**A2**	
	X-X (m)	Y-Y (m)	X-X (m)	Y-Y (m)
d_{Ed}=+d_E+d_G+0.5d_T	0.165	0.289	0.163	0.261
d_{Ed}=+d_E+d_G-0.5d_T	0.149	0.271	0.147	0.259
d_{Ed}=-d_E+d_G+0.5d_T	-0.055	-0.289	-0.057	-0.261
d_{Ed}=-d_E+d_G-0.5d_T	-0.055	-0.289	-0.057	-0.261
Critical Combination	0.165	0.289	0.163	0.261
Design Value of the Gap Size	**X-X (m)**	**0.165**		
	Y-Y (m)	**0.289**		

Table 4: Required joint gap size: Case that no damage is allowed **(**d_{Ed}=±d_E+d_G±0.5d_T)

The required gap size according to Eurocode 8-2 provisions for the cases that acceptable or no damage is anticipated, are presented in Tables 3 and 4, respectively, for the longitudinal and transverse directions. For the case that damage (under the design earthquake) is acceptable, gap sizes equal to 105mm and 130mm (for the longitudinal and the transverse direction respectively) are calculated. When no damage is sought, the longitudinal joint gap increases to 165mm and the transverse one to 290mm. However, in the actual bridge, the gap size at end joints is equal to 500mm, much higher value than the required based on EC8-2 provisions. As discussed in the Introduction, the use of gap sizes larger than the ones calculated according to Eurocode 8 is common practice in modern bridges in Greece, resulting in over-dimensioning of bridge joints and increase in both initial and maintenance costs. Furthermore, critical bridge components (i.e. bridge piers) attract significant earthquake loading and deformation during an earthquake, whereas the abutments are not contributing to the seismic energy dissipation.

4 NON-LINEAR RESPONSE-HISTORY ANALYSIS

The case study bridge described in section 2 was assessed considering various gap sizes, namely 0.5, 1.0 (related to acceptable damage) and 2.0 times the calculated EC8-2 design gap size (*d*E) for each direction. Nonlinear dynamic response history analyses were performed in the longitudinal and transverse direction, using 10 spectrum compatible artificial accelerograms scaled to two different intensities that correspond to the design, and twice the design, earthquake intensity.

Non-linear response history analyses were performed using the OpenSees software [6]. The mean spectrum of the ten artificial, spectrum compatible, accelerograms used in the analyses is depicted in Figure 6; the average value of response quantities is considered in the following, since the number of accelerograms is greater than 7.

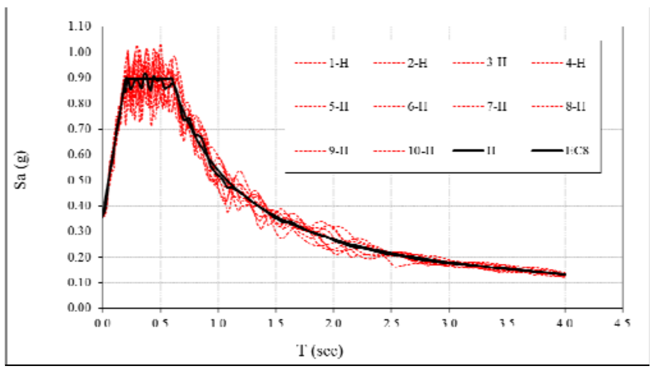


Figure 6: Spectra of artificial records, Mean Spectrum and Eurocode 8 Spectrum

The different gap size scenarios for both directions and earthquake intensities are summarised in Table 5. The key results used to compare and assess the seismic performance for varying gap sizes are section forces of critical components, namely bridge piers and abutments, and the corresponding horizontal displacements.

Earthquake Intensity	*Longitudinal Direction*			*Transverse Direction*		
	Scenario	×d_{ed}	Gap size (mm)	Scenario	×d_{ed}	Gap size (mm)
0.24g	1X	1/2	**50**	1Y	1/2	**65**
	2X	1	**100**	2Y	1	**130**
	3X	2	**200**	3Y	2	**260**
0.48g	4X	1/2	**50**	4Y	1/2	**65**
	5X	1	**100**	5Y	1	**130**
	6X	2	**200**	6Y	2	**260**

Table 5: Gap size ‘scenarios’ for the longitudinal and transverse direction of the bridge.

5 ANALYSIS RESULTS

Nonlinear response history analyses were performed considering the 6 scenarios described in Table 5 for ten spectrum-compatible artificial accelerograms (scaled to two intensities), resulting in a total of 60 analyses for each direction (longitudinal and transverse). Shear forces of piers and abutments were obtained and discussed with a view to highlighting the effect of gap size on bridge performance and the feasibility of design optimization by a proper selection of gap size.

5.1 Longitudinal direction of the bridge

Regarding the longitudinal direction of the bridge, the design seismic level (0.24g) and the gap size of 10 cm (corresponding to the design values), closure of joints at both abutments (A1 and A2) occurs (although for some of the accelerograms). When a gap size equal to 20cm (twice the design value for the case of acceptable damage) is considered, no gap closure at the end joints for the design earthquake is recorded; however, when twice the design earthquake is considered, gap closure is observed. Furthermore, for the case that an earthquake equal to twice the design level is considered, gap closure at both ends is observed for a gap size equal to 5 cm (half the design value).

The results considering shear forces are provided, for the case of excitation along the longitudinal direction, and various gap sizes at the end joints (Figures 7,8,10).

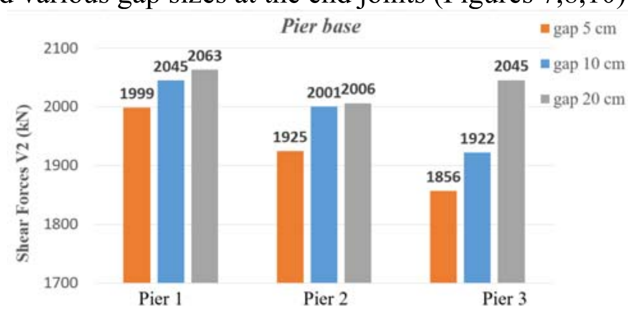


Figure 7: Shear forces at the top and base of the piers for bridge subjected to **1**× the design earthquake intensity

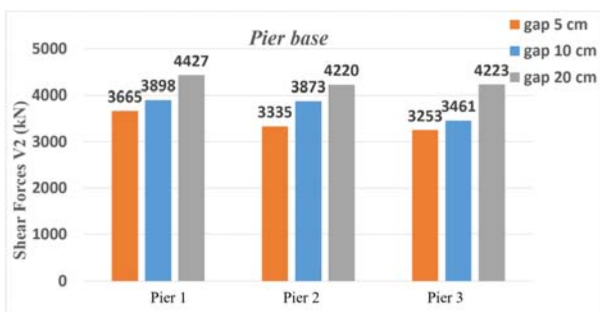


Figure 8: Shear forces at the top and base of the piers for bridge subjected to **2**× the design earthquake intensity

Tables 6 and 7 show the (percentage) changes in pier shears for reduction of the gap size from the design value (10 cm) to half the design value (5 cm) and from twice the design value (20 cm) to the design value (10 cm).

It can be observed that in the case of the reduced gap size, there is a significant reduction in the pier shear forces. In the case of twice the design earthquake intensity, this reduction is, as expected, more significant. Varying the gap size from 20 cm to 10 cm, there is no significant reduction in the key results, as the end joints do not close for the gap size of 10 cm.

PIER		Shear Forces	
		from 10 to 5 cm	from 20 to 10 cm
P1	**Base**	-2.31%	-0.87%
P2	**Base**	-3.93%	-0.27%
P3	**Base**	-12.45%	-0.37%

Table 6: Changes in pier response for different gap sizes – **1**× Design Earthquake

PIER		Shear Forces	
		from 10 to 5 cm	from 20 to 10 cm
P1	**Base**	-6.37%	-13.56%
P2	**Base**	-16.12%	-8.96%
P3	**Base**	-6.40%	-22.01%

Table 7: Changes in pier response for different gap sizes – **2**× the Design Earthquake

The forces resisted by the abutment – backfill system for the different gap size scenarios are shown in Figure 9, along with the capacity of the abutment – embankment system, estimated according to Nielson [11]. It can be concluded that even for twice the design earthquake the forces at the abutments are well within their capacity and, hence, no failure of the abutments is expected when they are activated subsequent to joint gap closure.

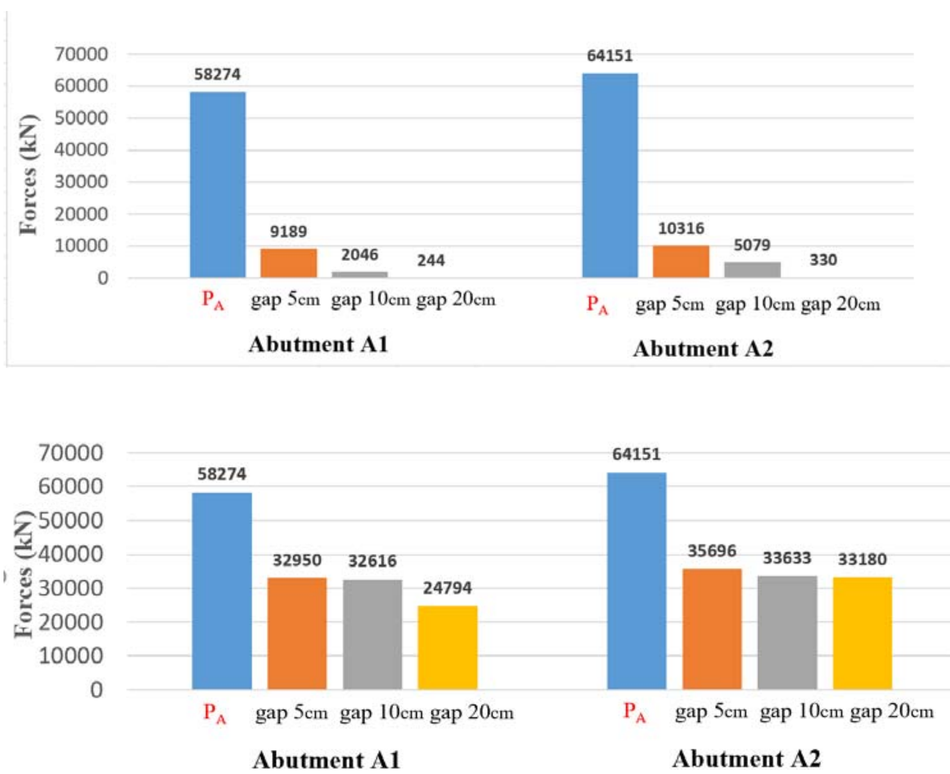


Figure 9: Abutment ultimate capacity and abutment forces in relation to the gap size for **1**× the design earthquake (up) and **2**× the design earthquake (down)

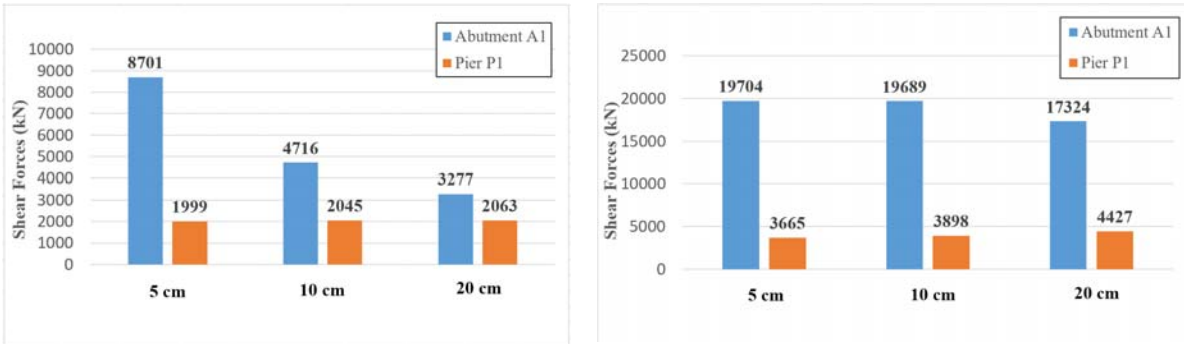


Figure 10: Shear forces of the critical abutment and critical pier in relation to the gap size for **1**× the design earthquake (left) and **2**× the design earthquake (right)

5.2 Transverse direction of the bridge

Regarding the transverse direction of the bridge and the 13 cm gap size, calculated according to Eurocode 8 provisions (case of acceptable damage, 'sacrificial' abutment), abutment joints are expected to close at the design earthquake level. For twice the gap value (26 cm gap), there is no joint closure. However, for twice the design earthquake intensity (0.48g), end joints are expected to close, even for the largest gap size.

Shear forces at pier top and bottom, considering excitation along the transverse direction of the bridge are shown in Figures 11 and 12, while tables 8 and 9 summarise the changes in these quantities for various gap size scenarios. Reduction in shear forces is observed, as anticipated, for decreasing gap sizes. This reduction is more significant for the case of twice the design earthquake. It is clear from Fig. 12 that the forces developing at the abutment – embankment system (in the transverse direction) are much lower than the corresponding capacity in all cases studied.

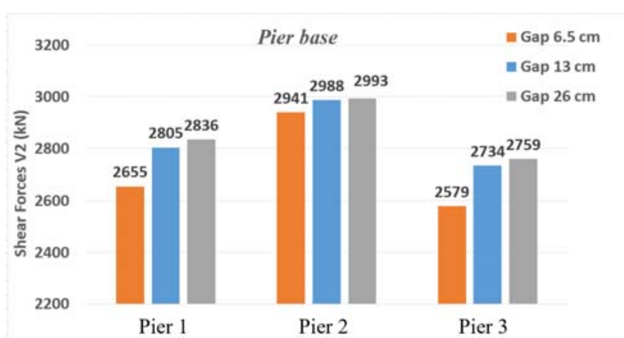


Figure 11: Shear forces at pier base (max shear) for bridge subjected to **1**× the design earthquake intensity

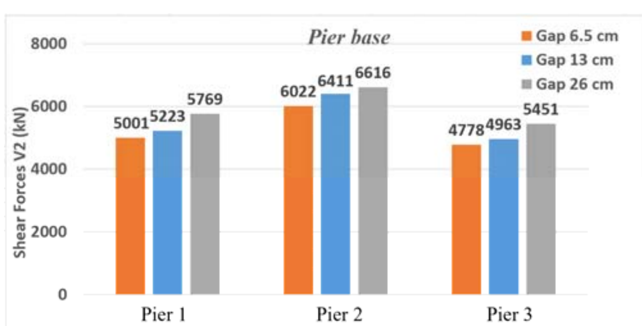


Figure 12: Shear forces at pier base (max shear) for bridge subjected to **2**× the design earthquake intensity

PIER		Shear Forces	
		from 13 to 6.5 cm	from 26 to 13 cm
P1	**Base**	-5.31%	-1.11%
P2	**Base**	-1.59%	-0.16%
P3	**Base**	-5.68%	-0.90%

Table 8: Changes in pier response for different gap sizes – **1×** Design Earthquake (transverse)

PIER		Shear Forces	
		from 13 to 6.5 cm	from 26 to 13 cm
P1	**Base**	-4.23%	-9.48%
P2	**Base**	-6.07%	-3.10%
P3	**Base**	-3.73%	-8.95%

Table 9: Changes in pier response for different gap sizes – **2×** the Design Earthquake (transverse)

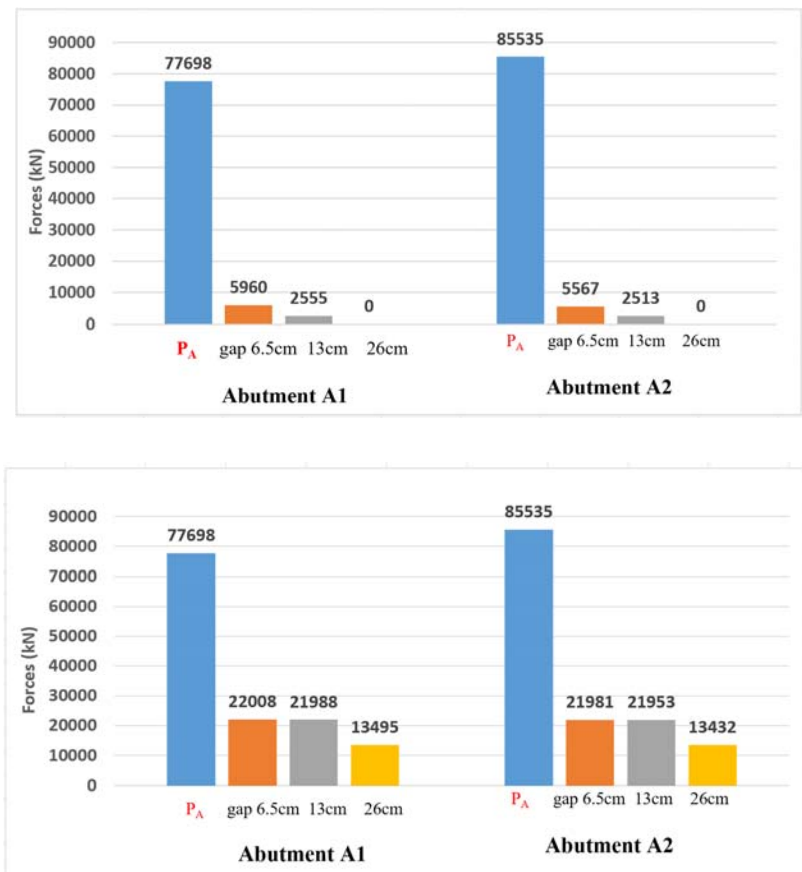
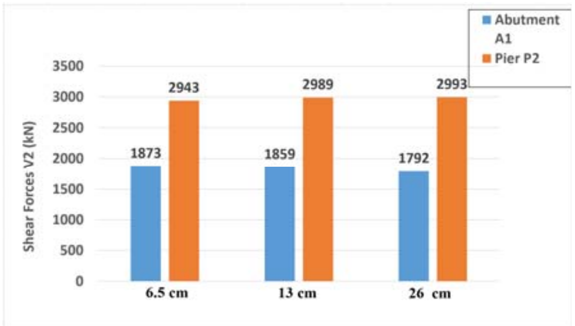


Figure 13: Abutment ultimate capacity and abutment forces in relation to the gap size for (a) 1× the design earthquake (up) and (b) 2× the design earthquake (down)

Finally, Figure 14 depicts the shear forces of the critical abutment and critical pier for the different gap size scenarios. Pier shear forces decrease as the gap size becomes smaller, while shear forces at the abutments are increasing. In the case of twice the design earthquake this behaviour becomes more noticeable (note the different scale in each figure).



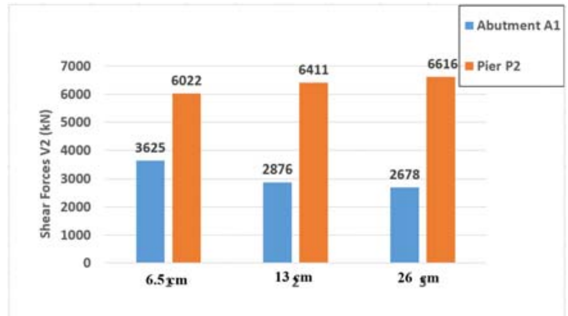


Figure 14: Shear forces of the critical abutment and critical pier in relation to the gap size for **1**× the design earthquake (left) and **2**× the design earthquake (right)

6 CONCLUSIONS

The effect of the joint gap size on the seismic performance of bridges was studied, focussing on an existing railway bridge that was assessed using inelastic response history analysis for a set of artificial accelerograms. Different gap size scenarios were considered for the end joints, i.e. gap sizes equal to the ones resulting from Eurocode 8, as well as twice and half these values. The analyses were conducted for the design and twice the design seismic level for the longitudinal and transverse direction of the bridge. From the results obtained for both directions of the bridge, several conclusions were drawn.

- Considering the response of the abutments for the different gap size scenarios, it was concluded that for open joints, the participation of the (seat-type) abutments in seismic energy dissipation is low.
- On the contrary, when the end joints close, further activation of the abutment – embankment system was obtained, particularly for small gap sizes. In general, the forces carried by the abutments do not exceed the capacity values and, thus, are considered to be acceptable.
- At joint closure, the shear forces in the piers decrease. This reduction was more noticeable for smaller gap sizes and was attributed to the consideration of the abutment – backfill flexibility in the seismic response of the bridge. For twice the design earthquake intensity, the reduction in shear values was even higher. Therefore, the distribution of seismic energy across the members of the bridge was found to be more uniform when gap closure was taken into account in the analysis.
- Finally, the aforementioned decrease in pier response quantities and increase in the forces carried by the abutments was found to be well within the capacity of the abutment-backfill system. Therefore, it seems feasible to optimize the design by a proper selection of the gap size.

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