International Journal of Bridge Engineering (IJBE), Vol. 10, No. 3, (2022), pp. 63-71

SUSTAINABLE BEHAVIOUR OF BRIDGE COLUMN SUBJECTED TO THREE-DIMENSIONAL GROUND EXCITATION

Raghda Adel Gad[1], Ahmed Farghal Maree[2] and Bahaa Sharaf Tork[3]

[1,3] Faculty of Engineering, Dept. of Structural and Geotechnical Engineering, Ain Shams Univ., Cairo, Egypt.
[2] Faculty of Engineering, Dept. of Structural and Geotechnical Engineering, Ain Shams Univ., Cairo, Egypt; Innova Technologies, Inc., Las Vegas, NV.
e-mail: Raghda.adel@eng.asu.edu.eg, afmaree@innovanv.com, ahfarghal@nevada.unr.edu, bahaa_tork@eng.asu.edu.eg

ABSTRACT: Infrastructure is the core of smart cities. Maintaining longevity and sustainable performance is essential in the planning and design of new cities. This cannot be achieved without confident design of infrastructures to resist hazard loads like earthquakes. Numerous cases of substantial damages have been reported in bridge columns affected by the three-dimensional (3D) ground motion excitation. Horizontal ground motion excitations have been studied extensively and considered in the design process whereas the vertical component of earthquake excitation has generally been neglected or underestimated in analysis and design. This paper presents analytical study using ABAQUS finite element analysis software for investigation of vertical motion effects on reinforced concrete (RC) bridge column. In this study, nonlinear time history analysis was performed for two cases of loading: horizontal ground motion as well as horizontal and vertical ground motions. The vertical component of the ground motion will increase the level of response and the amount of damage sustained by a highway/railway bridge. Vertical motion generates fluctuating axial forces compression and tension in the columns, which cause magnification of the hysteresis loops.

KEYWORDS: 3D ground excitation; Vertical ground motion; Bridge columns; Spectral matching Cyclic loading; Time history analysis.

1 INTRODUCTION

Several studies identified the lack of engineering attention to the vertical seismic excitation. In 1990, Saadeghvaziri and Foutch [1] had reported that the variable forces induced by the vertical motion on the abutments are not included in seismic codes. For major earthquakes, the intensity of these forces could be so high that the compressive forces were as large as three times of the dead load. Also, a great tensile axial load was generated. In 1995, Broderick and Elnashai [2] performed a 3D nonlinear analysis of a highway bridge to evaluate the critical response parameters. The vertical ground motion was found to cause fluctuation of pier axial load, failure in shear and flexure, and the moment capacity and ductility of RC columns was reduced.

In 2008, Kunnath et al [3] examined a two-span highway bridge with a double-column bent for six different structural configurations. The vertical component of ground motion was found to cause amplification in axial force demands in columns, and failure would be unavoidable. In 2011, Kim et al [4] conducted a study consisting of two hybrid simulations with and without vertical seismic excitation, The results indicated that the presence of vertical ground motion increased the variation in axial force of the test specimen up to 100%, and at times caused axial tension forces that did not exist under horizontal motion only. In 2013, Wang et al [5] conducted an analytical study on a multi-span continuous (MSC) highway bridge, to investigate the effect of vertical ground motion on the axial force in the columns, bending moments of deck and normal force of bearings, as well as its indirect effect on the shear and flexural capacities of the columns. All these serious matters could not be sensible if we eliminate the vertical component of earthquake during analysis.

2 GROUND MOTION SELECTION

The selected ground motions were chosen from Pacific Earthquake Engineering Research Center (PEER) [6]. Then ground motion scaling was performed using SeismoMatch software [7] to obtain representative ground motions.

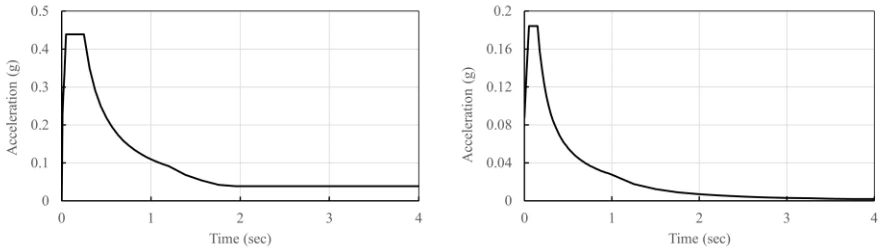
2.1 ECP (Egyption code of practice)

The hypothetical location for the investigated cases is in Cairo Egypt, therefore, the defining parameters for the horizontal and vertical elastic response spectrum are considered according Egyptian code of Practice (ECP 207-2015) for bridges [8] as illustrated in Table 1.

Table 1. Response spectrum defining parameters

Response spectrum curve	Type 1
Building location (zone)	3
Designed earthquake acceleration	0.15g
Soil type under the building	B

The developed vertical and horizontal response spectra as per ECP207-2015 are shown in Figure 1.



(a) Horizontal (b) Vertical

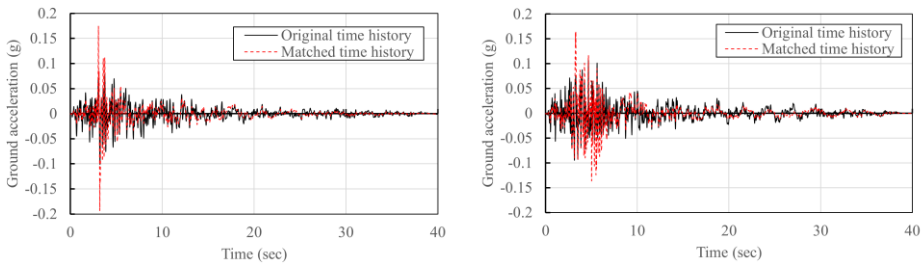
Figure 1. Horizontal and vertical response spectra according to (ECP207-2015) for bridges

2.2 Spectral matching

Enhanced matching for the obtained ground motion was performed using SeismoMatch [9]. SeismoMatch is an application capable of adjusting earthquake accelerograms to match a specific target response spectrum, using the wavelets algorithm proposed by Abrahamson 1992 [10] and Hancock et al. 2006 [11].

In this study, San Fernando 1993 ground motion was scaled by 1.5, which is the ratio of the area under spectrum curve between the matched and target spectrum along 0.2Tto 1.5T. This scale factor provided better matching correlation with the target response spectra.

Figure 2 (a) and (b) show the matched time history compared to the original ground motion for both horizontal and vertical directions, respectively.



(a) Horizontal (b) Vertical

Figure 2. Matched time history of San Fernando (1993) HZ direction

3 MODEL VERIFICATION

A finite element was developed using ABAQUS V.6.14. ABAQUS [12] is a finite element software to simulate behavior of different types of structures and materials. Two experimental output data for reinforced concrete (RC) column using cyclic loading analysis were used to check the reliability and validity of the nonlinear finite element model based on the work presented by Matsuzaki et al (2012) [13].

Experimental work done by Matsuzaki et al included two reinforced concrete specimens with the same section and material properties as shown in Figure 3.

The test specimens had a 400 mm × 400 mm square section, and the total height and effective height of 1,750 mm and 1,350 mm, respectively. The effective height represents the distance from the column base to the loading point. The specimens were supported by 400 mm thick footings, and rigidly anchored to the loading floor by PT rods. The swivel head of the vertical actuator was fixed at the column top using anchor bolts to impose varying axial force including tensile force to the columns. Twenty 13mm diameter deformed bars with a nominal strength of 295N/mm^2 were used for longitudinal reinforcements, and 6mm diameter deformed bars were provided at 50mm interval for ties. The tie bars were anchored using 135^o bent hooks with a development length of 100 mm. The longitudinal reinforcement ratio was 1.58% while, the volumetric ratio of tie reinforcement was 0.79 %. Yield strength of longitudinal bars and tie bars based on the coupon tests were 374N/mm^2 and 375N/mm^2, respectively as summaries in Table 2. Flexural capacity and shear capacity under the axial stress of 1.0N/mm^2 in compression was 119kN and 215kN respectively, so that the columns failed in flexure.

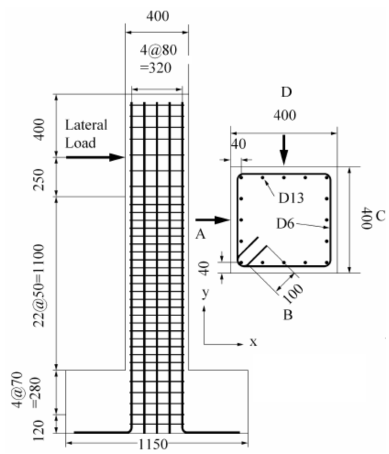


Figure 3. Cross-Section of the tested RC column and its dimensions [12]

Tested RC columns were subjected to a combination of axial force variation developed by a vertical ground motion and lateral response displacement as shown in Figure 5. The number of cycles of varying axial force per cycle of lateral cyclic loading is controlled by the combination of natural period in the lateral direction and the vertical direction.

As shown in Table 2, experimental results of the two columns by Matsuzaki et al (2012) [13] were used for comparison; one was a column subjected to a constant compressive axial stress of 3N/mm^2 (denoted as Case 1) and the other was a column subjected to a cycle of varying axial force which had the peak axial stress of 1N/mm^2 in tension and 3N/mm^2 in compression per cycle of lateral displacement.

Table 2. Loading conditions and material properties of model columns

Loading condition		Case 1	Case 2
Number of cycles of varying axial force per cycle of lateral displacement		-	1
Peak axial stress induced by varying axial force (N/mm^2)	Tension	-	1
	Compression	3	3
Concrete compressive strength (N/mm^2)		23	
Yield strength of longitudinal reinforcements (N/mm^2)		374	
Longitudinal reinforcement ratio (%)		1.58	
Yield strength of ties (N/mm^2)		375	
Volumetric ratio of tie reinforcement (%)		0.79	

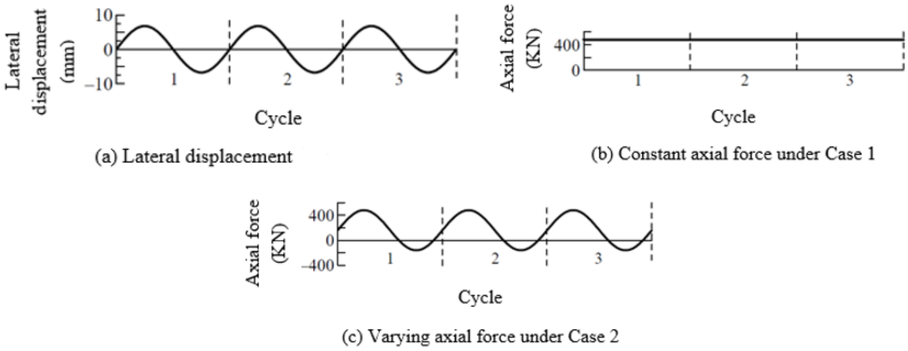


Figure 4. Lateral displacement and varying axial force imposed to tested specimens

3.1 Evaluation of the numerical results

A finite element mode was developed with the same dimensions and material properties of the tested RC columns. The finite element model showed good agreement between the experimental results by Matsuzaki et al (2012) [13] and the corresponding results from the nonlinear analysis for tested RC bridge column as shown in Figure 5.

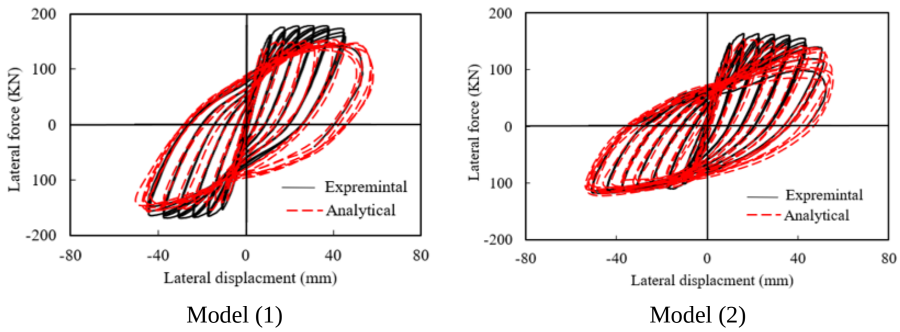


Figure 5. ABAQUS model verification results for the reinforced concrete (RC) column specimens

A comparison between analytical and experimental results is presented in Table 3 and the error in results as shown is taken as the ratio between the difference of analytical and experimental result to the experimental value.

Table 3. Comparison between experimental and analytical results for the two reinforced concrete (RC) column specimens

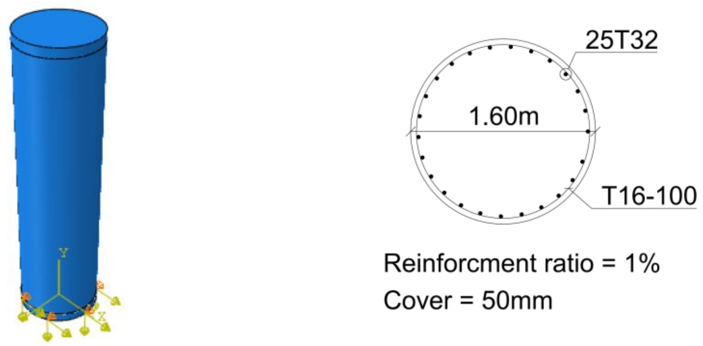
Model	Experimental (force)	Analytical (force)	%Error*	Experimental (displacement)	Analytical (displacement)	%Error*
	F_{ult} (kN)	F_{ult} (kN)		Δ_{ult} (mm)	Δ_{ult} (mm)	
1	190	178	6.30%	55	60	9.09%
2	180	165	8.33%	51	55	7.84%

(*) $\%Error = \left(\frac{\text{Analytical mean value} - \text{Experimental mean value}}{\text{Experimental mean value}}\right) \times 100$

4 PARAMETRIC STUDY

4.1 Numerical simulation

Based on the model verification illustrated in the above section a new finite model was developed considering two cases: 2D ground motion (horizontal excitation only) and 3D ground motion (horizontal and vertical excitations). The column used in the analysis was designed according to ECP 207-2015 for bridges. The model dimensions and material properties considered as shown in Table 4. Finite element model boundary conditions and column cross section are shown in Figure 6. Ground Motion Excitation: San Fernando (1993) matched to target spectrum developed according to ECP 207-2015



a. Boundary conditions. *b. Cross section of RC column*

Figure 6. Column geometry

Table 4. Model dimensions and material properties

Diameter of concrete column	1600 mm
Column height	6 m
Reinforcement ratio	1 %
Stirrup's ratio by volume	0.5%
Concrete compressive strength (cube) (fcu)	40 MPa
Concrete Strain at maximum compressive stress	0.002 mm
Steel yield strength (fy) for vertical reinforcement and stirrups.	400 MPa
Steel young's modulus (Es)	200 GPa
Poisson's ratio	0.2

4.2 Nonlinear time history analyses

The axial force time history for the column under horizontal and horizontal and vertical excitation is presented in Figure 7, it is observed that vertical excitation increases axial force, in case of horizontal excitation the maximum value of axial load equal to 4108.5 ton, while maximum value in case of horizontal and vertical excitation equal to 9691.3 ton.

Figure 8 and Figure 9 indicate that effect of vertical motion on shear response and horizontal displacement of column is negligible.

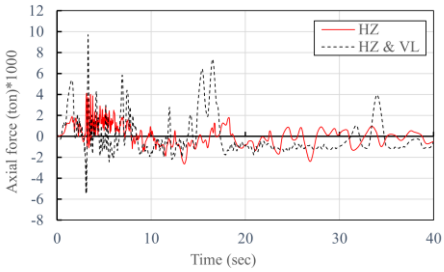


Figure 7. Time history of column axial load

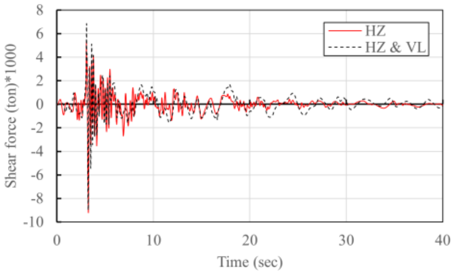


Figure 8. Time history of column shear load

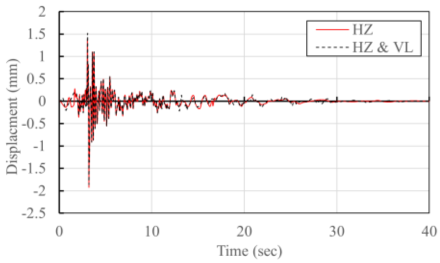


Figure 9. Time history of column horizontal displacement

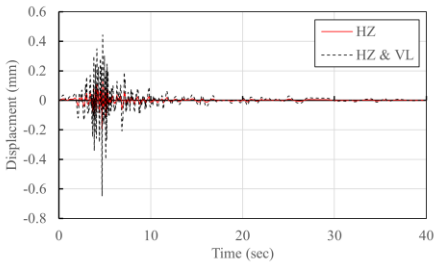


Figure 10. Time history of column vertical displacement

Vertical displacement time history is shown in Figure 10, which illustrates the effect of vertical motion on vertical displacement for RC column. Vertical displacement increases due to vertical component of ground motion.

The effect of vertical motion on axial strain response for RC column is presented in Figure 11, which indicates that maximum axial strain under horizontal excitation is only 0.0163 mm/mm contrary to the effect of vertical component of ground motion, where the maximum axial strain reaches 0.0498 mm/mm. Both tensile and compressive strain increase due to vertical component of ground motion.

Shear strain time history is shown in Figure 12, the combined vertical and horizontal excitation significantly affects the shear strain due to vertical component of ground motion.

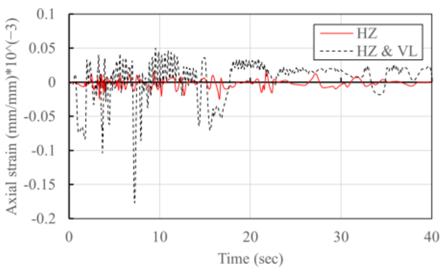


Figure 11. Time history of axial strain

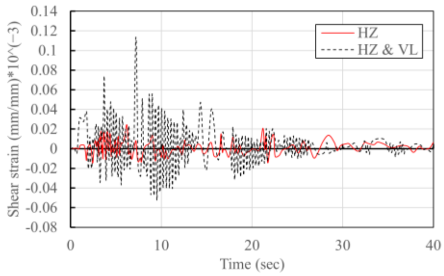


Figure 12. Time history of shear strain

5 CONCLUSION

Vertical component has significant influence on the inelastic response of RC column and should be included in the seismic design of such structural elements. The vertical component of the ground motion has remarkable effect on the following:

- Increase in fluctuating axial force and corresponding axial strains.
- Increase in vertical displacement and base deformations.
- Combined shear strains due to the fluctuating axial forces.

On the other side, the vertical component of the ground motion excitation has negligible effect on the horizontal displacement and base shear forces.

6 REFERENCES

[1] M. A. Saadeghvaziri and D. A. Foutch, “Behavior of RC Columns under Nonproportionally Varying Axial Load” *J. Struct. Eng.*, vol. 116, no. 7, pp. 1835–1856, Jul. 1990.

[2] E. Broderick, B. M., “Analysis of the failure of Interstate 10 freeway ramp during the Northridge earthquake of 17 January 1994” *Earthq. Eng. Struct. Dyn*, vol. 24, no. 2, pp. 189–208, 1995.

[3] Y. H. and Y. Kunnath, S. K., Erduran, E., Chai, “Effect of Near-Fault Vertical Ground Motions on Seismic Response of Highway Overcrossings” *ASCE*, vol. 13, no. 7, pp. 282–290, 2008.

[4] S. J. Kim, C. J. Holub, and A. S. Elnashai, “Experimental investigation of the behavior of RC bridge piers subjected to horizontal and vertical earthquake motion” *Eng. Struct.*, vol. 33, no. 7, pp. 2221–2235, Jul. 2011.

[5] Z. Wang, L. Dueñas-Osorio, and J. E. Padgett, "Seismic response of a bridge–soil–foundation system under the combined effect of vertical and horizontal ground motions" *Earthq. Eng. Struct. Dyn.*, vol. 42, no. 4, pp. 545–564, Apr. 2013.
[6] "Users Manual for the PEER Ground Motion Database" 2010.
[7] "SEISMOMATCH Software Help."
[8] "ECP (Egyptian Code of Practice for bridges), 2015."
[9] N. Jayaram, T. Lin, and J. W. Baker, "A Computationally Efficient Ground-Motion Selection Algorithm for Matching a Target Response Spectrum Mean and Variance" *Earthq. Spectra*, vol. 27, no. 3, pp. 797–815, Aug. 2011.
[10] N. A. Abrahamson, "Non-stationary spectral matching. Seismological Research Letters 63:1, 30-30" 1992.
[11] J. Hancock *et al.*, "An improved method of matching response spectra of recorded earthquake ground motion using wavelets" *J. Earthq. Eng.*, vol. 10, pp. 67–89, 2006.
[12] ABAQUS/Standard Analysis User's Manual, Version 6.14.
[13] K. K. Matsuzaki, H., Y. Kumagai, "Effect of Strong Vertical Excitation on the Seismic Performance of RC Bridge Columns" 2012.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Declaration

Competing interest

The authors declare that they have no competing interests.