An Experimental Investigation of the Seismic Response of a Bridge due to Simultaneous Horizontal and Vertical Excitations

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Abstract

Investigations of the effects of strong vertical ground motions on structures have been gaining more attention in recent years. Many researchers have found that the assumptions in current design codes underestimate the significance of vertical excitations, especially in near-source earthquake events. Several numerical analyses have been conducted to investigate these effects. However, not many experimental works have been done. In this paper, a bridge model was excited simultaneously in the horizontal and vertical directions through a series of shake table tests. The bridge model was fixed to the base of the shake table. The seismic responses of the bridge structure in the longitudinal direction are discussed. It was found that the inclusion of vertical excitation can significantly increase the bending moment demand of the bridge deck and the development of axial force and plastic hinging in the bridge piers. However, the bending moment demand in the bridge piers have not been greatly affected by the vertical excitations.

Keywords: vertical excitation, bridge, bending moment, plastic hinge, shake table test

1. INTRODUCTION

In recent years, the significance of vertical ground excitation has been gaining more attention. Papazoglou and Elnashai (1995) were the pioneers who investigated the devastating effects of strong vertical ground excitation, especially in near-source earthquakes, on structures. Most of the current design standards assume the vertical component of an earthquake to be a fraction, normally less than 70 per cent, of the horizontal ones. An example of this is the New Zealand design standard, NZS 1170.5:2004 (Standards New Zealand, 2004).

However, in many of the past and more recent earthquakes, such as the 1994 Northridge Earthquake, 1995 Kobe Earthquake (Papazoglou and Elnashai, 1996), as well as the September 2010 Darfield and February 2011 Christchurch earthquakes (Kaiser et al., 2012, Chouw and Hao, 2012), the effects of strong vertical ground excitations have been observed.

Several numerical investigations have been conducted to investigate the effects of concurrent horizontal and vertical ground excitations on structures, e.g. by Chouw (2002a, 2002b), Kodama and Chouw (2002) and Kunnath et al. (2008). They found that vertical ground excitation can affect structural responses differently than horizontal excitation and also increase the loadings on structures.

Not many researchers, however, have carried out experimental analyses to better understand these effects. Kim et al. (2011) and Sakai and Kawashima (2002) were amongst the few who have done experimental work in this area. Their results further reinforced the findings from the numerical studies. The lack of experimental studies on these effects have thus led to this research.

In this paper, the investigation of these effects was done by subjecting a bridge model to simultaneous horizontal and vertical excitations through a series of shake table tests. The discussion will be focused on structural performance in the longitudinal direction.

2. METHODOLOGY

2.1 Prototype and scaled model

The bridge prototype used was a single span bridge spanning 15 m with a height of 5 m. The bridge deck was a concrete-steel composite element, consisting of a 6 m wide by 0.2 m thick concrete slab supported by six 900WB218 mild steel beams. The prototype and scaled parameters are given in Tables 1 and 2, respectively.

Table 1: Parameters of prototype

Span	14100 mm	$I_{x\text{-beam}}$ (each)	4.06×10^9 mm^4
Column height	5000 mm	$I_{y\text{-concrete deck}}$	4.0×10^9 mm^4
Column width	400 mm	$I_{x\text{-column}}$	1.067×10^9 mm^4
Column thickness	200 mm	$I_{y\text{-column}}$	2.667×10^8 mm^4
Number of columns per support	2	E_{steel}	200 GPa
	Fundamental frequencies	$E_{concrete}$	25 GPa
Longitudinal	1.6 Hz	Seismic mass	69850 kg
Transversal	5.44 Hz		
Vertical	10 Hz		

The prototype was then scaled down using principles of similitude outlined by Dove and Bennett (1986).

Table 2: Parameters of scaled model

Bridge Deck	Dimension (mm)	Column	Dimension (mm)
Span length	500	Effective length	107
Width	80	Width	15
Thickness	17.5	Thickness	2.7

2.2 Setup

A 25 kg capacity vertical shaker was fixed onto a 1 tonne capacity horizontal shaker to simulate the simultaneous horizontal and vertical excitations. The bridge model was fixed onto a rigid wooden platform, which was then bolted onto the platform of the vertical shaker.

The x-axis of the bridge model was aligned with the loading direction of the horizontal shaker. Both the elastic and plastic responses of the bridge model were investigated. To simulate the plastic damage in the bridge piers, artificial plastic hinges have been introduced. The elastic case was done by applying a 6 Nm torque on the plastic hinge, while plastic hinge development was achieved by reducing the hinge capacity to about 1.5 Nm.

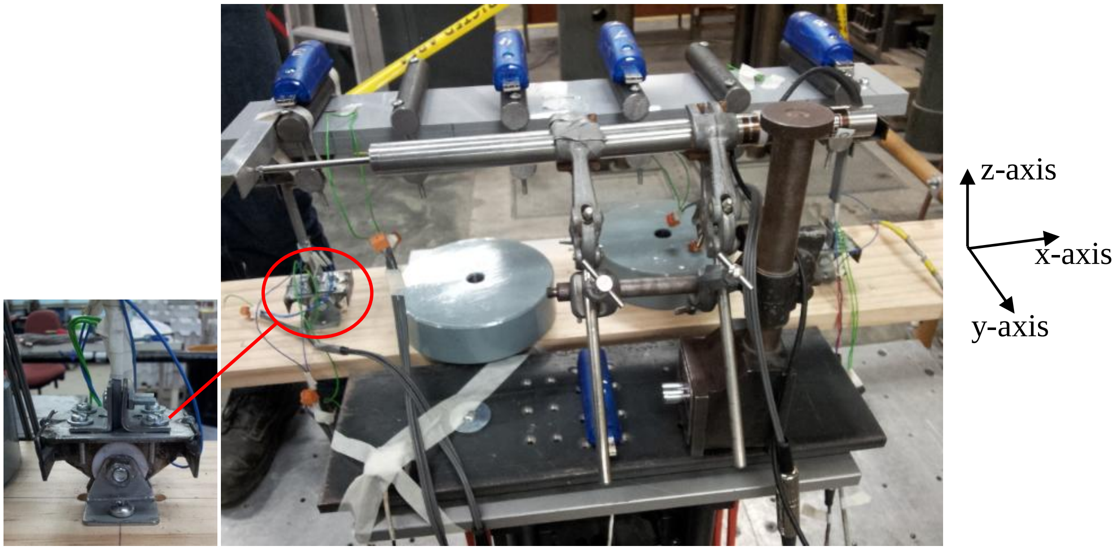

Figure 1: Artificial plastic hinge (left) and bridge model setup (right)

The displacement of the bridge deck relative to the ground was measured using an LVDT. Figure 1 shows the setup of the artificial plastic hinge (left) and the bridge model (right). Strain gauges were also placed on the bridge deck and piers to measure the induced bending moments. Figure 2 shows the position of the strain gauges on the bridge deck to measure the vertical vibrations.

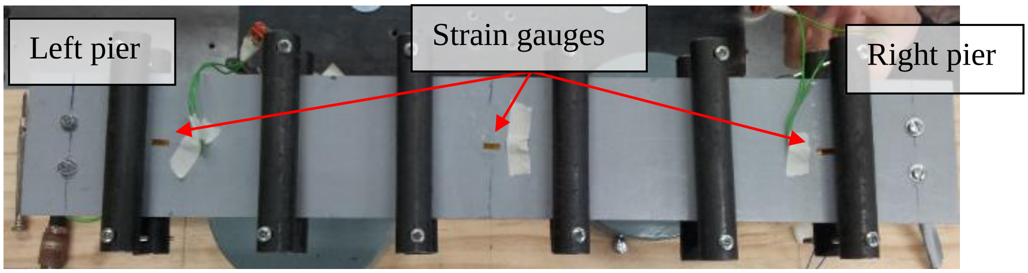

Figure 2: Position of strain gauges on bridge deck

2.3 *Ground motions*

The ground motions used were selected from the February 2011 Christchurch earthquake. These records were adopted from the GeoNet online database, GeoNet (2011). In this paper, the results from the Christchurch North New Brighton School (NNBS) station records will be discussed. This ground motion was selected because of the high ratio of vertical spectral acceleration (SPA_V) to horizontal spectral acceleration (SPA_H) at the vertical fundamental frequency of the bridge. The response spectrum for the scaled NNBS station ground motion is shown in Figure 3.

To investigate the effects of vertical ground motion on structural response, the bridge model was subjected to both pure horizontal ground motion as well as simultaneous horizontal and vertical excitations in the longitudinal direction (x-axis).

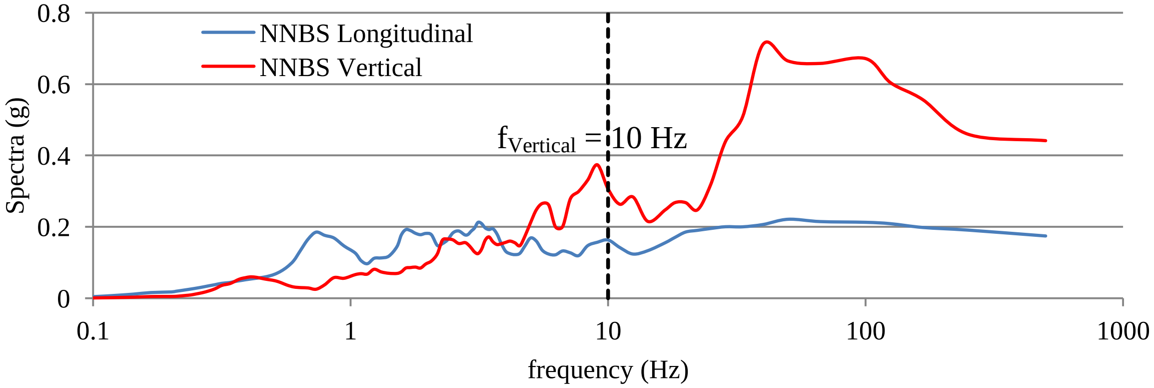

Figure 3: Response spectrum for the scaled NNBS ground motion

3. RESULTS AND DISCUSSION

3.1 *Bending moment in bridge deck*

A comparison of the induced bending moments at the mid-span of the bridge deck can be seen in Figure 4. The results shown were from the 6 Nm bolt pressure (elastic) case. It can be clearly seen that the bending moment demand induced by the simultaneous loadings is much greater than that of the pure horizontal excitation. The maximum bending moment induced at mid-span of the bridge when excited purely in the horizontal direction is 0.015 Nm and 0.25 Nm when excited simultaneously in both horizontal and vertical directions. The significant increase in bending moment is most likely due to the activation of the vertical modes of the bridge when vertical excitations are introduced. This means that the bending moment demand in the bridge deck will be significantly underestimated if vertical excitations are not taken into account in the design of structures.

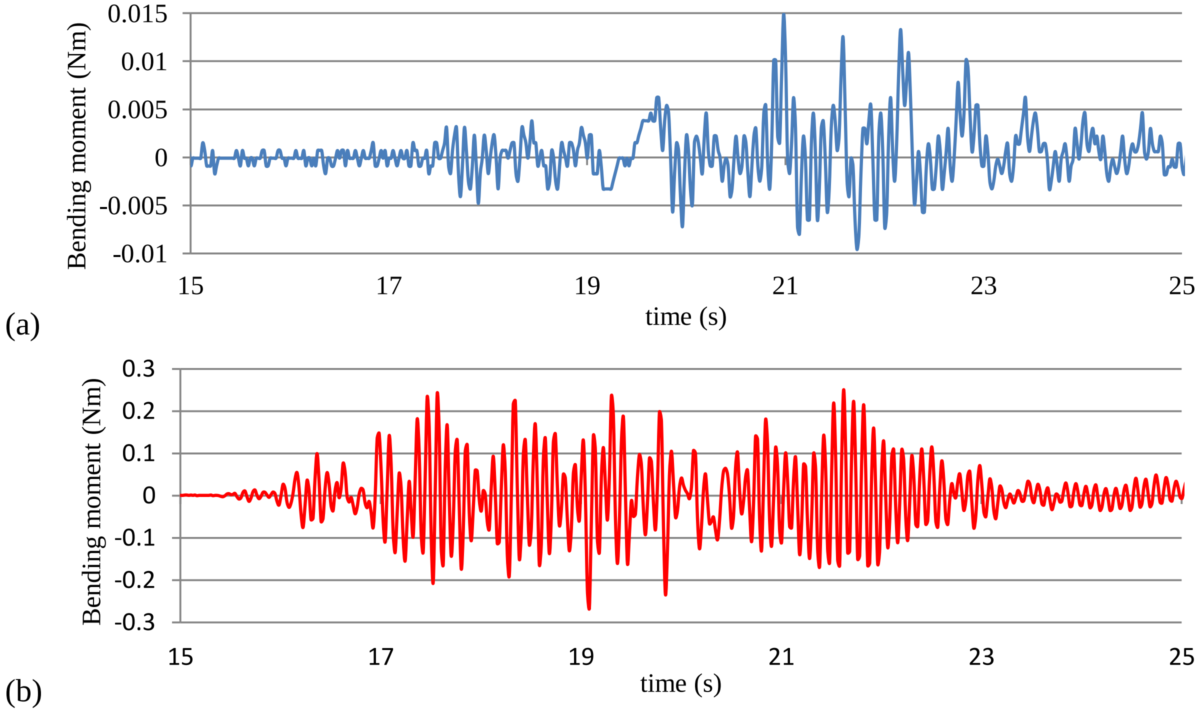

Figure 4: Bending moment at mid-span of bridge deck when subjected to (a) pure horizontal excitation and (b) simultaneous horizontal and vertical excitations

3.2 Bending moment in bridge piers

The differences of bending moments in the bridge piers due to the vertical excitation have also been investigated. Figure 5 shows that the bending moment measured in the pure horizontal excitation case was 7.964 Nm while in the concurrent horizontal and vertical excitation case the bending moment measured was 7.955 Nm. These results show that vertical ground excitation has little or no effect on the bending moment induced in the bridge piers. As anticipated the vertical excitation does not increase the contribution of horizontal modes and thus no significant increase in the structural response is observed.

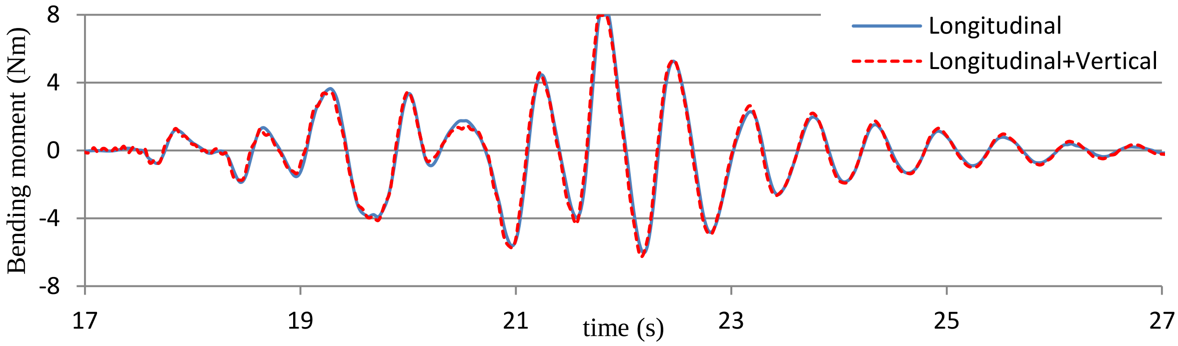

Figure 5: Bending moment in bridge left pier when subjected to pure horizontal and simultaneous horizontal and vertical excitations

3.3 Axial force in bridge piers

The axial forces generated in the bridge piers when subjected to pure horizontal and simultaneous horizontal and vertical excitations have been plotted in Figure 6. It can be seen that without considering vertical ground excitation, the maximum axial force generated was 36.8 N, whereas when vertical ground excitation was included, the maximum axial force was substantially increased to 39.4 N.

Although the artificial plastic hinge developed has no significant effect on the induced axial force since the axial force in this study was controlled mainly by the activated horizontal mode. A possible significant increase in generated axial force means, however, that rebar buckling and crushing of the concrete at the base of the piers are likely to occur.

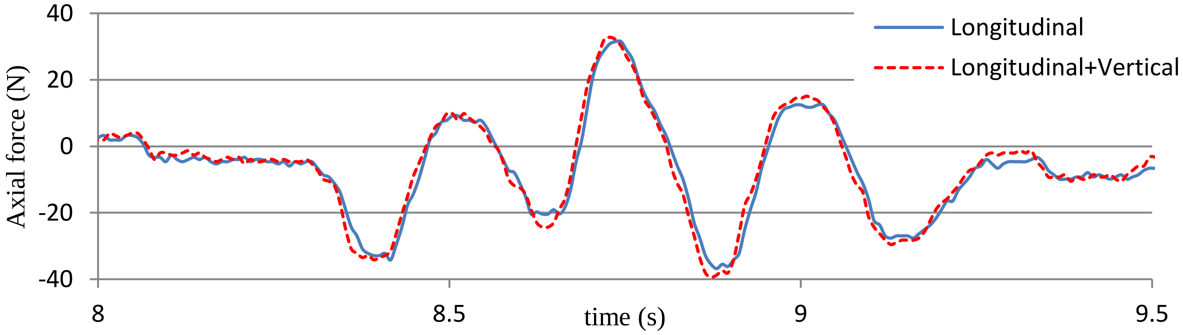

Figure 6 : Axial force development in bridge pier when subjected to pure horizontal and simultaneous horizontal and vertical excitations

3.4 Plastic hinge development

Figure 7 shows the effects of vertical ground motions on plastic hinge development in the bridge piers. In the pure horizontal case the amount of horizontal permanent deformation developed in the bridge pier is about 0.75 mm and for the combined horizontal and vertical ground excitation, a permanent deformation was about 1.59 mm. The increase in permanent deformation could be due to the added effects of the activated inertial forces in the vertical direction, causing more rotation in the piers, when vertical excitation is present. This shows that the consideration of vertical ground excitation is vital in the seismic design of structures.

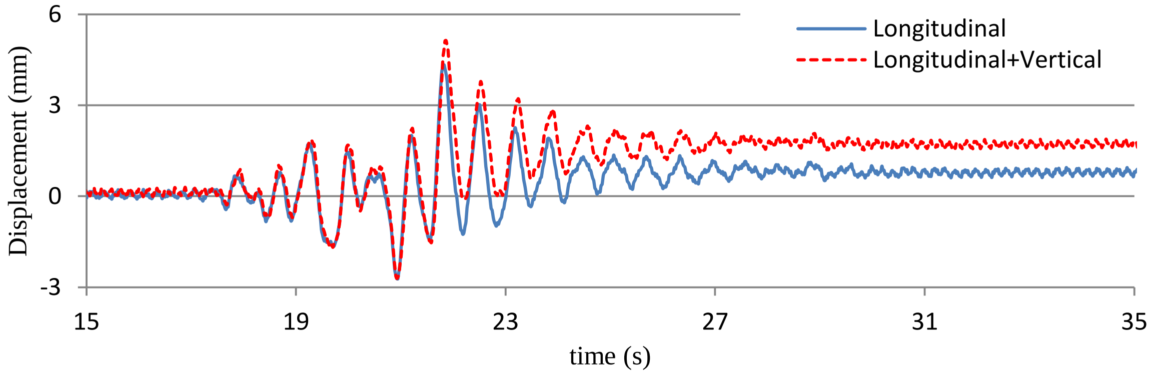

Figure 7: Plastic hinge deformation of bridge column when subjected to pure horizontal and simultaneous horizontal and vertical excitations

It is suggested that numerical analyses of the tests discussed in this paper be conducted in the future to better understand the effects of vertical ground excitation on structural response and to compare with the experimental results obtained.

4. CONCLUSIONS

This paper discusses the effects of vertical ground excitations on the seismic response of a bridge structure. The bending moments in the bridge deck, piers and the damage in the piers were investigated. The following conclusions can be drawn:

- Vertical excitation prompts the activation of vertical modes of a structure that cannot otherwise be achieved by considering pure horizontal excitation
- Subsequently, the bending moment induced in the bridge deck is increased
- The introduction of vertical excitation however, does not greatly affect the contribution of horizontal modes to the bending moment development in the bridge piers, but increases the axial forces generated.
- Despite having no increase in bending moment, the bridge piers showed more plastic deformations due to the increased rotation induced by simultaneous excitation.

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