Effect of Ground Motion Spatial Variations on Seismic Responses of a Long Span Steel Trussed Arch

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Abstract

This paper presents numerical results from a case study of a long span steel trussed arch structure to multiple support earthquake excitations. Intensive numerical simulations of the responses of the trussed arch subjected to the combined horizontal and vertical ground excitations are carried out. In numerical calculations, the simulated multiple support ground motions are individually compatible with response spectrum defined in Chinese Seismic Design Code, and are compatible with an empirical coherency loss function between each other. Compared with structural responses calculated using uniform excitations, numerical results have highlighted that seismic response is amplified when considering multiple support excitations. Numerical results also indicate that considering simultaneous vertical and horizontal ground motions will lead to more accurate response predictions of the trussed arch as compared with those obtained by considering horizontal excitations only. Therefore, to have an accurate structural response assessment and a better design of long span steel trussed arch structure, a reliable ground motion spatial variation model is required.

Keywords: trussed arch, seismic response, multiple support excitations, response spectrum, coherency loss function

1. INTRODUCTION

There are many long span arch structures in the real world such as arch bridges and arch roofs of long span workshops. It is known that nonuniform support movements may cause more severe damage to arch structures than to the straight beams. Some authors performed seismic response analysis of arch structures subjected to spatially varying ground motions. Hao (1993) carried out response analysis of incompressible circular arches to spatially correlated horizontal multiple excitations and concluded that the responses may be underestimated by neglecting the ground motion spatial variations. Hao (1994) extended the work to analyse the responses of circular arches subjected to simultaneous horizontal and vertical excitations subsequently, in which the multiple input effects on arches having different properties are studied by varying the arch span length and material properties, and demonstrated the significant effect of vertical ground motions on arch responses. Zanardo *et al*. (2004) investigated the seismic responses of some reinforced concrete arch bridges to multiple support excitations and compared the responses with conventionally used uniform input and partially correlated multiple inputs with phase shifts. Su *et al*. (2007) studied the behaviour of steel arch to horizontal and vertical multiple support excitations separately. These studies indicated the significance of ground motion spatial variations on large arch structures. However, there is no study of large dimension spatial trussed arch structure to simultaneous horizontal and vertical spatially varying ground motions. The previous studies did not consider the local site effect on ground motion spatial variations either. In reality, multiple supports of many large dimensional structures may rest on sites of different conditions. Irregular local site conditions will result in different site amplifications and hence affect the structural responses, as observed in the 1995 Kobe earthquake (Kawashima *et al*. 1996) and the 1999 Chi-Chi earthquake (EERI 1999). Response analysis of long span spatial steel arch structures subjected to simultaneous spatially varying horizontal and vertical ground excitations including local site effect can not be found in the literature.

The objective of this paper is to investigate the effect of simultaneous spatially varying horizontal and vertical ground excitations on responses of a large steel trussed arch structure. Comprehensive numerical simulations are carried out. Spatially varying ground motion time histories are stochastically simulated as inputs in the numerical calculations. The simulated spatial ground motions are individually compatible with the design response spectrum with 2% damping for specific site conditions defined in the Chinese Seismic Code (GB 50011 2001), and are compatible with an empirical coherency loss function between each other (Hao *et al*. 1989). Discussions on the ground motion spatial variation and simultaneous horizontal and vertical inputs on structural responses are made.

2. STRUCTURAL MODEL

The structural model considered in this study is shown in Figure 1. It is a two-side supported long span steel trussed arch structure, which is a common structural type for hangers and workshops. Because of its long span, it is difficult to provide a tie-beam between the distantly separated supporting points therefore it makes these kinds of structures very sensitive to the input differences (Kato and Su 2002). The configuration of the steel trussed arch is a double layered cylindrical structure with a 100 meters span, 120 meters long and 25 meters high, the corresponding central angle of the arch is 106°. The arch structure consists of 7200 members and 1861 nodes. The truss members are made of steel pipes with the elastic modulus of 206 GPa. Table 1 gives the properties of all the structural elements. The structure is pin connected to the foundation as shown in Figure 1.

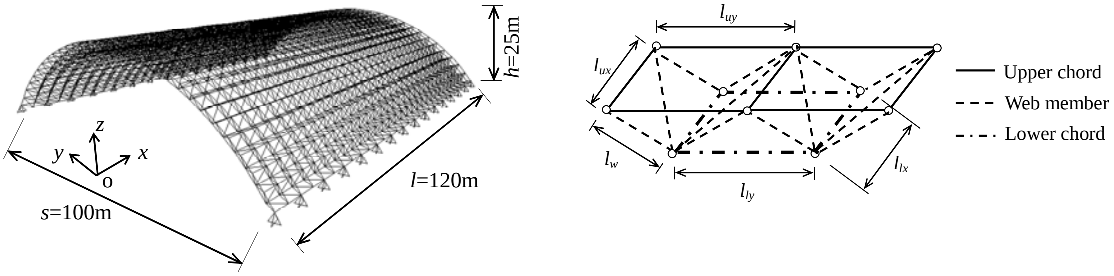


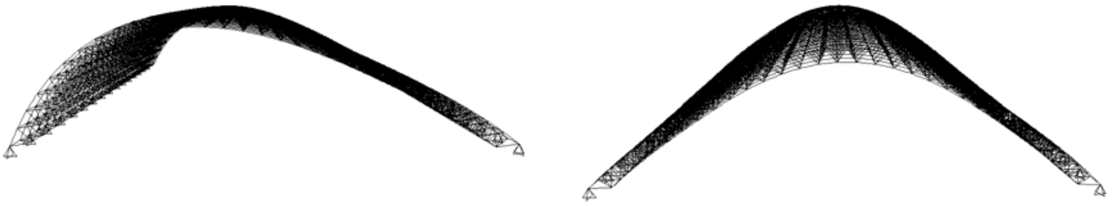
Figure 1. Steel trussed arch structure

Table 1. Properties of structural elements

Type of element	Properties
Upper chord	$\phi 127\times 8mm,\ l_{ux}=4m,\ l_{uy}=3.863m,\ A=29.91cm^2$
Web member	$\phi 89\times 6mm,\ l_w=4.069m,\ A=15.65cm^2$
Lower chord	$\phi 127\times 6mm,\ l_{lx}=4m,\ l_{ly}=3.678m,\ A=22.81cm^2$

Table 2. First 8 natural vibration frequencies

Mode	1st	2nd	3rd	4th	5th	6th	7th	8th
Frequency (Hz)	1.52	1.81	2.92	3.32	3.66	3.82	4.03	4.24
Type	Antisym	Sym	Antisym	Sym	Antisym	Antisym	Sym	Antisym



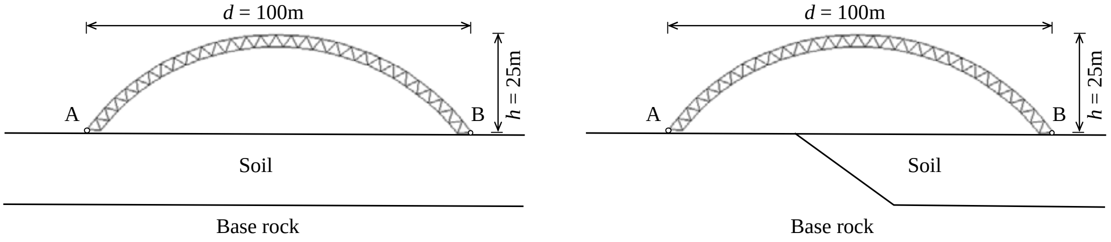
(a) First mode

(b) Second mode

Figure 2. The first two vibration-mode shapes

Computer software SAP2000 is used in the study. A detailed computer model is created. In numerical modelling, all the masses are lumped to the respective node joints. Table 2 gives the first 8 vibration frequencies of the structure. The first two vibration mode shapes are illustrated in Figure 2. Since there are a large number of supports in the x direction of the trussed arch structure, the structure is a lot stiffer in the x direction than in the y and z directions. Therefore, only the earthquake excitations in the y and z directions are considered in this study.

Figure 3(a) and 3(b) show the schematic view of the steel trussed arch structure located on a uniform and a nonuniform site, respectively. In practice, it is not uncommon for multiple supports of a large dimensional structure sit on site of different conditions. For example, according to the Japanese Design Standard (RTRI 1999), the typical irregular terrain shown in Figure 3(b) can often be found at an alluvial valley site. In Figure 3, points A and B represent the first column and the second column of structural supports on ground surface, while d and h represent the span length and the height of the arch structure. Only linear elastic responses are considered in this study, and a 2% modal damping of the arch is adopted in the response calculations. Because the primary objective is to investigate the effects of ground motion spatial variations on the trussed arch structure, soil-structure interaction is not considered in the study.



(a) (b)

Figure 3. Steel trussed arch structure on sites with
(a) Uniform site conditions; (b) Nonuniform site conditions

3. GROUND MOTION SIMULATION

Standard stochastic ground motion simulation method is used to simulate response spectrum compatible spatially varying ground motions (Hao et al. 1989). In this study, individual simulated ground motion time history is iterated to be compatible with response spectrum defined in Chinese Seismic Code (GB 50011- 2001) for respective site conditions. The ground motion spatial variation is modelled by an empirical coherency loss function derived from recorded strong ground motions at the SMART-1 array (Hao et al. 1989). The coherency loss function between ground motions at two points i and j on ground surface is

$$\left|\gamma_{ij}(i\omega, d_{ij})\right| = \exp(-\beta d_{ij})\exp[-\alpha(\omega)\sqrt{d_{ij}}(\omega/2\pi)^2] \qquad (1)$$

in which d_{ij} is the projected distance between points i and j on ground surface in the wave propagation direction, β is a constant and $\alpha(\omega)$ is a function. The constants of the coherency loss function applied here are derived from the recorded strong ground motions during Event 45 at the SMART-1 array (Hao 1989), and it represents highly correlated ground motions.

The trussed arch structure is assumed to locate in the Chinese Seismic Intensity Zone 8 with peak horizontal ground acceleration 4m/s^2. The intensity of the vertical component, as stated in the code, is 0.65 times of the horizontal component. Figure 4 shows the corresponding 2% damped horizontal and vertical code response spectrums for the firm site and the medium site defined in the Chinese Code. In this study, the ground motion duration is assumed to be 20 sec, the simulation is carried out with a time increment of

Δt =0.02 sec and the upper cut-off frequency is set to be 25Hz . To improve the computational efficiency, the ground motions are generated in the frequency domain by using the FFT technique, with the total number of points N=1024 for each simulated time history.

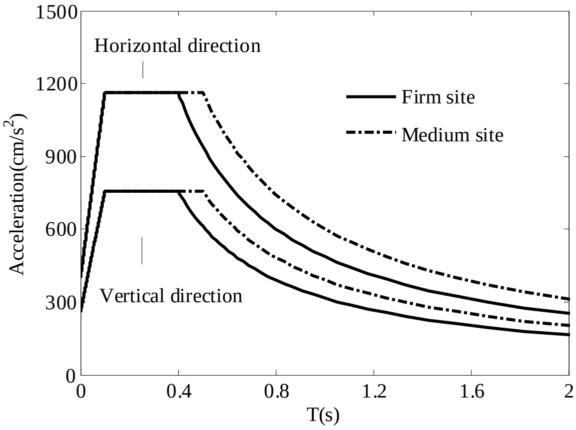


Figure 4. Code spectrum with 2% damping for Chinese Seismic Intensity Zone 8

A total of 5 cases, representing different spatial variations, of spatial ground motions are simulated in this study:

(1) Uniform ground motion on firm site.

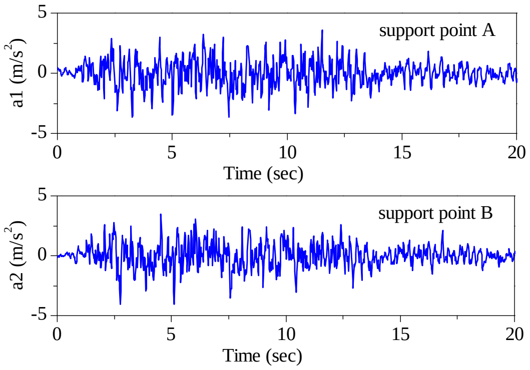
(2) Spatial ground motions on firm site with wave passage effect only, (V_{app} =1000 m/s).

(3) Spatial ground motions on firm site with coherency loss effect only, (highly correlated).

(4) Spatial ground motions on firm site with both wave passage effect and coherency loss effect, (V_{app} =1000 m/s, highly correlated).

(5) Spatial ground motions on firm-medium site with both wave passage effect and coherency loss effect, (V_{app} =1000 m/s, highly correlated).

In each case, 10 sets of ground motion time histories are simulated with different random phase angles. Each set consists of four time histories, two horizontal and two vertical components of spatial motions at the left and right structural supports. Figures 5 and 6 show one typical set of simulated highly correlated spatial horizontal and vertical acceleration and displacement time histories on uniform site with apparent velocity 1000 m/s. Figure 7 shows the comparison of the coherency loss between the typical simulated ground accelerations and the corresponding empirical coherency loss. The response spectrum of a typical set of horizontal and vertical simulated ground motions on firm site conditions and the corresponding response spectrum specified in the design code (GB 50011-2001) are shown in Figure 8. As can be seen from these figures, the simulated ground motions are compatible with the target response spectrum and the empirical coherency loss function.



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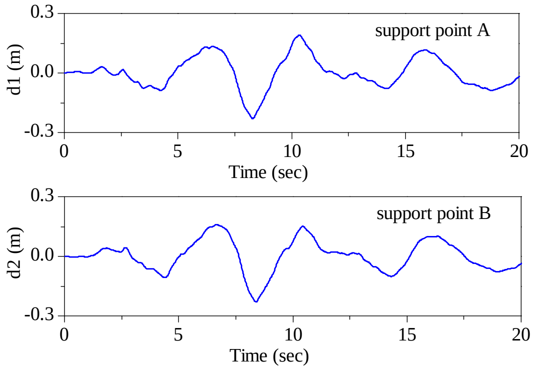
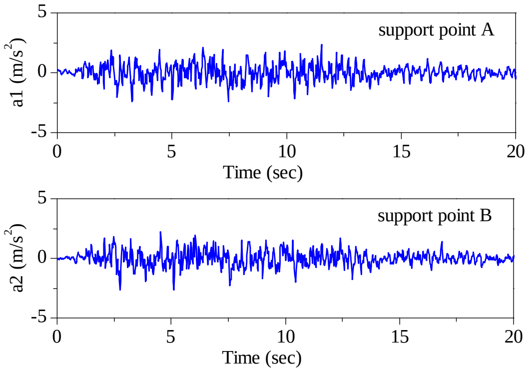
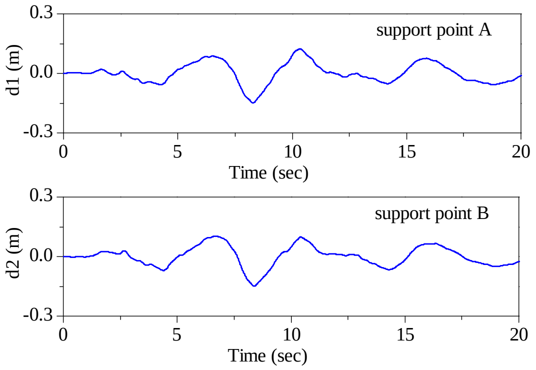


(a)



(b)

Figure 5. Generated spatially correlated ground accelerations on firm site (case 4) (a) Horizontal; (b) Vertical



(b)

Figure 6. Generated spatially correlated ground displacements on firm site (case 4) (a) Horizontal; (b) Vertical

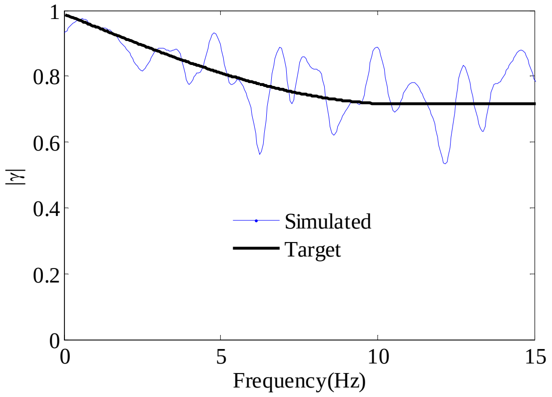


Figure 7. Model coherency loss function and typical coherency loss function of simulated ground motions

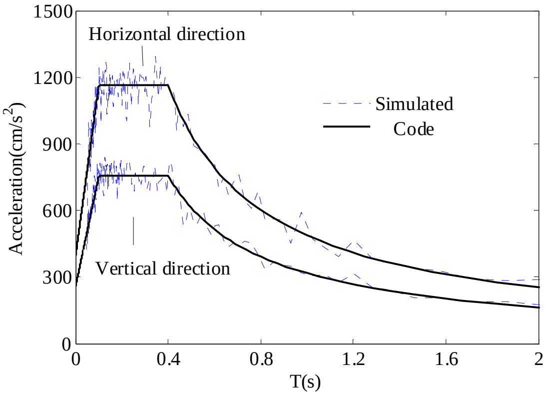


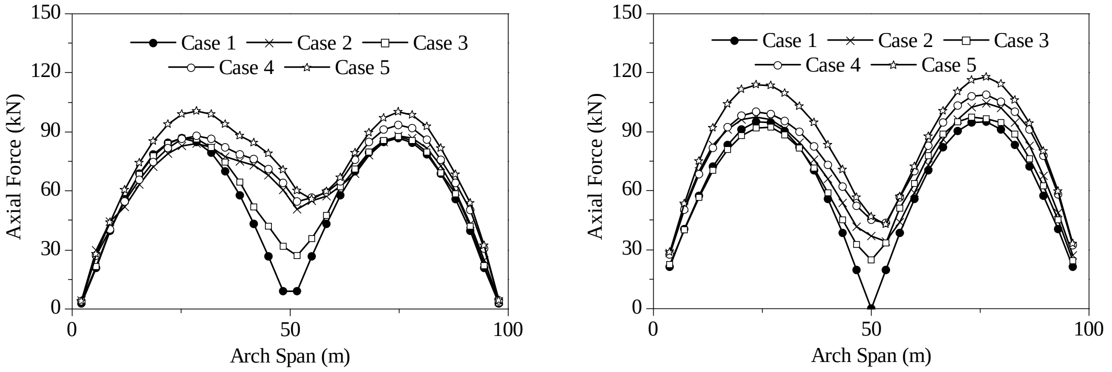
Figure 8. Code response spectrum and the response spectrum of typical simulated ground motions

4. NUMERICAL ANALYSIS

Responses of the long span steel trussed arch structure shown in Figure 1 subjected to the above simulated spatially varying ground motions are calculated. The damping ratio of the structure is assumed to be 0.02 for all the modes. The Newmark-β method is applied in the numerical integration, in which β is set to 0.25. For each ground motion case listed, 10 independent numerical calculations are carried out using the 10 sets of independently simulated spatial ground motions as input. The mean values of the structural responses obtained from the 10 numerical calculation results are presented and discussed in this study.

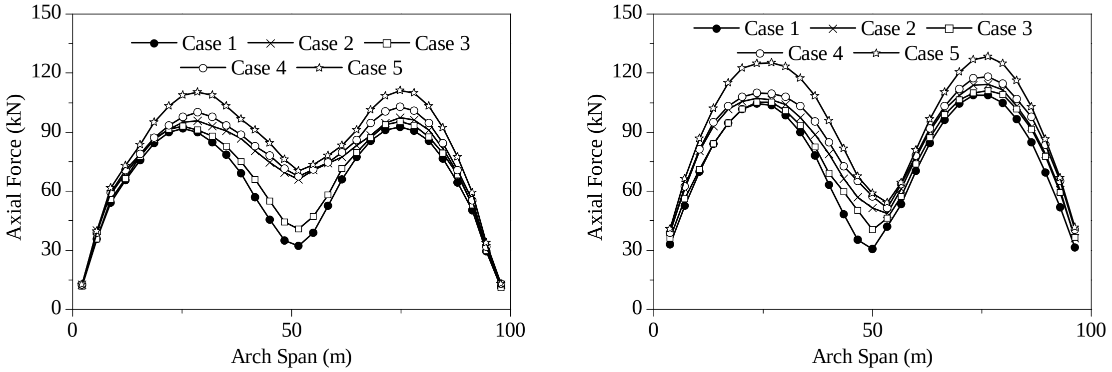
4.1 Effect of ground motion spatial variations

In this section, the effects of seismic ground motion spatial variations on responses of the trussed arch structure are examined. Because the seismic forces are mainly resisted by the chord members, and the web members are used only to connect the upper and lower chords of the arch structure for stability purpose, they are not meant in the design to resist seismic forces. Therefore only the responses of the chord members are presented and discussed for brevity purpose.



(a) (b)

Figure 9. Mean maximum axial force of structural members induced by spatial horizontal ground excitations (a) Upper chord member; (b) Lower chord member



(a) (b)

Figure 10. Mean maximum axial force of structural members induced by simultaneous spatial horizontal and vertical ground excitations
(a) Upper chord member; (b) Lower chord member

Figure 9 shows the mean maximum axial force of structural members along the span length of the arch subjected to the simulated spatial horizontal ground motions. Those subjected to the simultaneous spatially varying horizontal and vertical motions are shown in Figure 10. As shown the member force distributions follow closely the symmetric second vibration mode of the arch. This is because the first vibration mode of the arch is antisymmetric and is not excited by uniform ground motion. Nonetheless, the contributions from the antisymmetric modes is prominent when nonuniform ground motion is considered as the responses corresponding to the ground motions of Cases 2 to 5 are not exactly symmetric. It can also be observed that the more significant is the ground motion spatial variation, the larger is the arch structure responses. Case 5 ground motions, which have most significant spatial variations, produce the largest axial forces in the truss members, followed by Case 4 motions. Considering spatial ground motion wave passage effect only (Case 2) results in slightly larger responses than considering only the spatial ground motion coherency loss effect (Case 3), indicating the ground motion wave passage effect is more significant than the coherency loss effect for this structure. A previous study (Hao 1993) revealed that spatial ground motion wave passage effect is more significant if the structure is relatively flexible as compared to the dominant ground motion frequency. The trussed arch structure under consideration has its first and second model frequency about 1.5 Hz and 1.8 Hz, which is a relatively flexible structure. Therefore the ground motion wave passage effect is more significant than the coherency loss effect.

As can be noticed, neglecting the ground motion spatial variations could substantially underestimate the axial forces in the trussed arch structure members, especially in those members near the symmetric mid span, where the axial forces could be underestimated by more than 80%. These observations indicate the importance of considering the ground motion spatial variations in analyses and design of large dimensional trussed arch structures to seismic loadings.

4.2 Effect of simultaneous horizontal and vertical excitations

In most structural response analyses and design to resist earthquake ground motions, vertical ground motion component is usually neglected because vertical ground motion component often has a relatively small intensity as compared to the horizontal components, and because most structures are stiffer and stronger in the vertical direction. For an arch structure, however, its vertical direction is not necessarily stiffer and stronger than the horizontal direction. Although the vertical ground motion component is smaller than the horizontal ones, neglecting vertical ground excitation may substantially underestimate arch structure responses. Comparing the results shown in Figures 9 and 10, it is obvious that neglecting the vertical ground motion component may result in underestimation of the trussed arch structure responses. In this section, the effect of neglecting the vertical ground motion component on the response of chord members is examined.

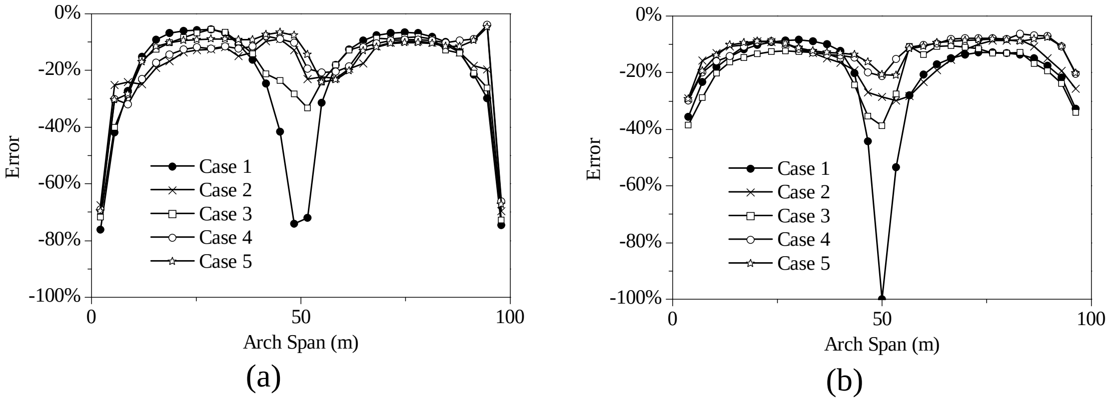


Figure 11. Relative error induced by neglecting the vertical ground motion component
(a) Upper chord member; (b) Lower chord member

Figure 11 shows the relative errors induced by neglecting the vertical ground motion component. It is defined as

$$Error = \frac{F_h - F_{h+v}}{F_{h+v}} \times 100\% \qquad (2)$$

where F_h and F_{h+v} are member forces obtained by considering horizontal excitations only, and by considering simultaneous horizontal and vertical ground motion components, respectively. As shown, neglecting vertical ground motion component always results in an underestimation of the structural responses for all the five ground motion input cases. The most significant underestimation occurs near the two support lines and the mid span. At the two support lines, the axial forces in the upper chord members could be underestimated by about 70%, irrespective of the ground motion spatial variation assumptions. It is interesting to note that the uniform horizontal ground motion assumption substantially underestimates the member axial forces near the mid span of the arch structure. This is because uniform horizontal ground motion excites only the symmetric modes which results in zero or small axial forces in the lower and upper chord members at the mid span; whereas the uniform vertical ground motion excites both the symmetric and antisymmetric modes. Therefore the axial forces in structural members near the mid span corresponding to the simultaneous horizontal and vertical excitations are not small. It can also be noticed that in general the more significant is the ground motion spatial variation, the slightly less is the underestimation of the structural responses by neglecting the vertical ground motion component. This is again because the spatially varying ground motions excite both symmetric and antisymmetric vibration modes of structures. These observations are consistent with those reported in (Hao 1994) based on theoretical analysis of an idealized incompressible arch structure, which demonstrate the importance of including the vertical ground motion component in arch structure response analysis to earthquake ground excitations.

5. CONCLUSIONS

This paper investigates the seismic response of a long span steel trussed arch structure subjected to spatially varying ground motions. The following conclusions are drawn:

(1) Ground motion spatial variations have significant effect on trussed arch structure responses. Neglecting ground motion spatial variations in analysis may lead to incorrect predictions of structural responses.
(2) Ground motion spatial variations induced by wave propagation (phase delay) and loss of coherency are both important to structural responses. Neither of them should be neglected.
(3) Ground motion spatial variations induced by heterogeneous site conditions also have significant influences on structural responses, an accurate estimation of the site conditions on ground motions where the arch structure sited is essential.
(4) Neglecting vertical component of spatial ground motions in analysis may lead to substantial underestimation of structural responses.

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