0368

PERFORMANCE OF STRUCTURES DURING NEAR-SOURCE EARTHQUAKES

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SUMMARY

The dynamic response behaviour of two steel frame-structures due to the Kobe earthquake is considered. Since structures experience horizontal and vertical ground motions simultaneously, the response of structures is therefore defined by the interaction between the excited natural vibrations in these two directions. If only one of these ground motions is taken into account in the analysis different structural responses will be obtained. In the considered case the development of plastic hinges does not cause significant response behaviour changes. A consideration of horizontal ground motions alone may underestimate the structural responses, hence a simultaneous ground excitation should be taken into account.

INTRODUCTION

Some recent earthquakes show that ground motions near the fault have different dynamic characteristic than that far from the source. Vertical ground accelerations, which are associated with propagating compressive waves, can have larger amplitude and higher frequency content than horizontal ground accelerations. Figure 1(a) shows the ratio of the greatest peak of the vertical ground motion PGA_v to the greatest peak of the horizontal one PGA_h with an increasing epicentral distance for the case of 1994 Northridge earthquake. Up to the distance of 60km the vertical ground motion can still have the size of the horizontal ground acceleration. However, a large PGA-ratio does not mean that a structure will suffer strong damages, since PGA_h can be small. The greatest ratio of 3.64 at the epicentral distance of 31km for example has a small PGA_h. In the case of the Northridge earthquake most of the vertical and horizontal PGA at the distance larger than 40km were below 0.2g. However, near the source the ground motion can be really strong as the 1979 Imperial Valley earthquake with the magnitude of 6.4. The PGA_v at the epicentral distance of 27.12km is about 1.6g. It is 4.8 times larger than the PGA_h (figure 1(b)).

The belief that structures are over-designed by a large factor of safety to resist gravity loads, hence will invariably withstand additional forces from vertical ground motion, causes limited works on the structural behaviour during near-source earthquakes [Chouw, 1999, Christopoulus et al., 1999, Elnashai et al., 1997 and Xie et al., 1999]. This belief, however, ignores the dynamic nature of the fact. Strong vertical ground motion acts in the vertical direction. It acts indeed in both vertical directions. Vertical natural vibration modes of structures will experience strong excitations, which can not be observed, if only the horizontal ground motion is considered. In this work the induced vibrations, the activated forces and the effect of a plastic hinge formation in the steel frame-structure due to the 1995 Kobe earthquake are considered.

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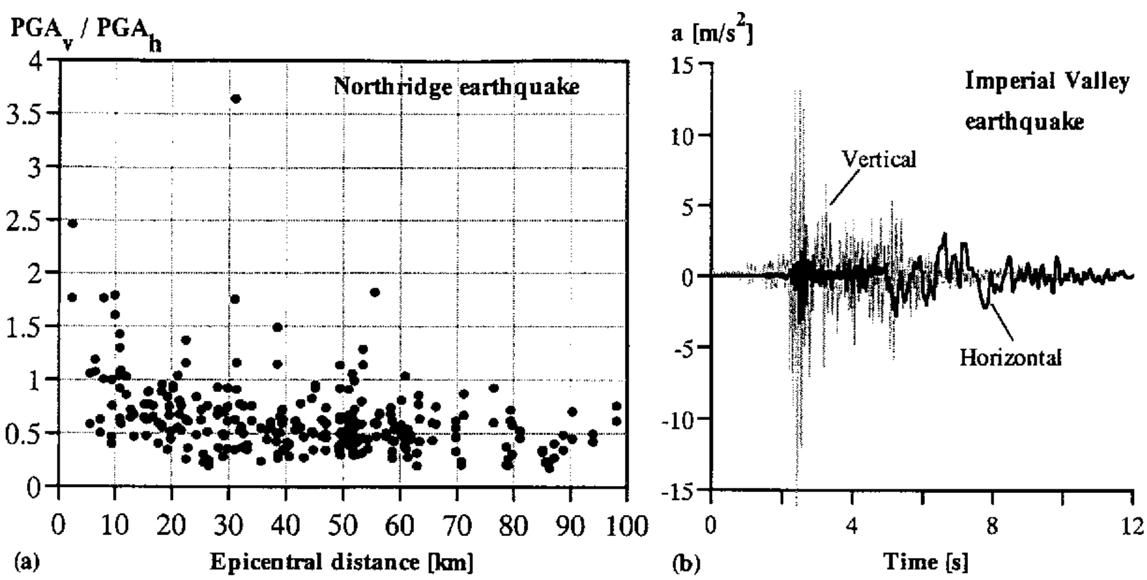

Figure 1(a) and (b): Characteristics of near-source earthquakes.
(a) Ratio of the maximum peak ground accelerations, and (b) strong vertical ground motions.

2. INDUCED VIBRATIONS AND ACTIVATED FORCES IN STRUCTURES

Two steel structures are considered (figure 2). Table 1 displays their material data. The numbers of the structural members are given in figure 2. The mass of the girder in table 1 includes the corresponding mass of the dead load. The effect of the gravity load, represented by the compressive forces in the columns, is taken into account in the analysis of the response of the structures. The column forces of the 1st, 2nd and 3rd storey due to the dead load are 255.35kN, 150.70kN and 50.23kN, respectively. Both columns of the one-storey frame-structure experience a compressive force of 104.22kN. Since vertical ground motions have high frequency content, in order to describe high frequency behaviour of the structures correctly a continuous mass model is used. The calculation is performed in the Laplace domain. The material damping of the structures is described by a Kelvin chain. It is characterized by the parameters E_1 and E_n. By using the Kelvin chain a causal and almost frequency independent damping is obtained. For the chosen parameters E_1 and E_n all structural members have a damping of about 1%. The first horizontal and vertical vibration modes of the three-storey structure have the natural frequencies of 1.24Hz and 6.25Hz, respectively. The frequencies of the first natural horizontal and vertical vibration modes of the one-storey structure are 2.32Hz and 6.16Hz, respectively.

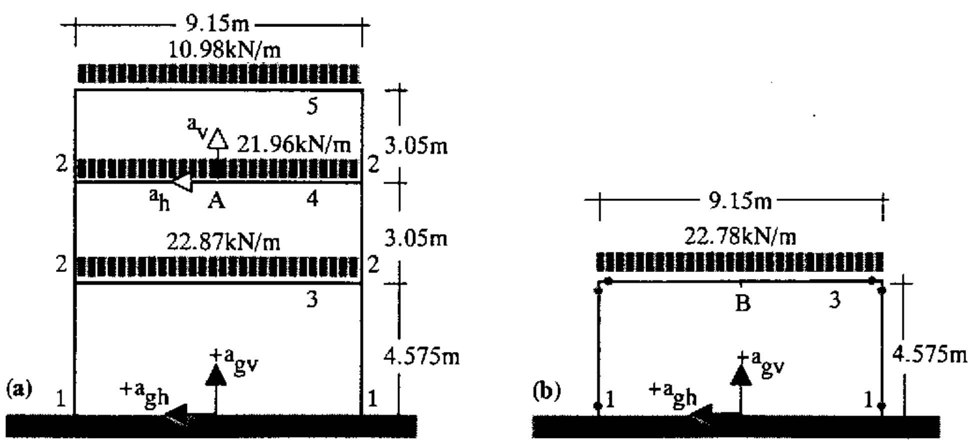

Figure 2(a) and (b): Frame structures. (a) Three-storey structure, and (b) one-storey structure.

Table 1: Data of the frame structure

	Number of the structural member				
	1	2	3	4	5
Length [m]	4.575	3.05	9.15	9.15	9.15
Mass [kg/m]	67	33	2447	2358	1209
EA [kN]	$1.72*10^6$	$8.37*10^5$	$3.19*10^6$	$3.19*10^6$	$2.36*10^6$
EI [kNm^2]	$2.10*10^4$	$9.80*10^3$	$2.00*10^5$	$2.00*10^5$	$1.00*10^5$

Kelvin-chain parameters: E_1=1.0 and E_n=$1.0*10^{29}$

The considered ground excitation is the ground motion at the surface of Kobe Port Island during the 1995 Kobe earthquake (figure 3(a)). The PGA_v of 5.6m/s^2 occurs at 4.29s, and the PGA_h of 3.4kN appears at 6.21s. The PGA-ratio is 1.64. The response spectra in figure 3(b) show that both the fundamental horizontal and vertical vibration modes will be excited strongly by the ground motions. Figure 3(c) shows the axial force F in the uppermost right column due to the vertical ground excitation a_{gv} or due to the horizontal ground motion a_{gh}. Each of these ground motions causes different axial forces not only in amplitude but also in frequency content. The reason for this is that due to the difference in the excitation direction of the vertical and horizontal ground motions different natural vibration modes are excited. The axial force due to the vertical ground motion occurs earlier corresponding to the excitation, since all columns are excited directly. The maximum axial force also appears almost at the maximum excitation. In the case of the horizontal ground excitation the activated forces are determined by the fundamental horizontal vibration mode. While the frame-structure is swinging in the horizontal direction, axial forces occur in the columns. Therefore there is a larger delay between structural response and excitation than in the case of the vertical ground excitation. The axial forces decrease also faster with the height than those in the case of a vertical excitation. In the considered case the greatest axial force in the uppermost column is 20.7% of that in the bottom column for the vertical ground excitation, and is 7.6% for the horizontal ground excitation. This result shows that a consideration of the horizontal ground motion alone can underestimate the activated forces in structures, since in near-field region vertical ground motions can be much larger than the horizontal one. The difference in frequency content of the column responses indicates also the difference in column ductility in the axial direction, since the ductility demand depends strongly on the excitation frequencies. An analysis of structural responses due to the horizontal ground motion will not give the proper information on the column ductility demand [Xie et al., 1999].

Interaction between the excited vertical and horizontal natural vibration modes occurs when a simultaneous ground excitation is considered. Figure 3(d) shows this effect. Generally the PGA_v which is associated with propagating compressive waves arrives earlier, since compressive waves have higher propagation velocity than the shear waves. Although PGA_v and PGA_h do not coincide in time the other peak coincidences at 6.33s, 7.4s or 7.73s for example produce larger axial forces than that due to the horizontal ground excitation alone. Since at 10.83s each of the two ground excitations alone will already induce tensile forces, the simultaneous excitation amplifies the tensile force to 22.59kN. It is 1.35 times the tension due to the vertical ground motion, and is 3.82 times the force due to the horizontal ground motion.

The frequencies of the first natural vibrations in the horizontal and vertical directions can be clearly seen in the induced vibration in the middle of the middle girder of the three-storey frame-structure (figure 4(a) and (b)). While the induced horizontal vibrations are determined by the fundamental horizontal vibration mode, the induced vertical vibration is define by the first vertical vibration mode, which is characterized by the vertical vibration of the middle girder. At the location A the vertical ground motion induces therefore no horizontal vibrations. No vertical vibrations will also be produced by the horizontal ground motion. Since induced vibrations is important for the design of secondary structures, correct prediction of induced vibrations can not be obtained, if we only consider one of these ground motions [Chouw, 1999].

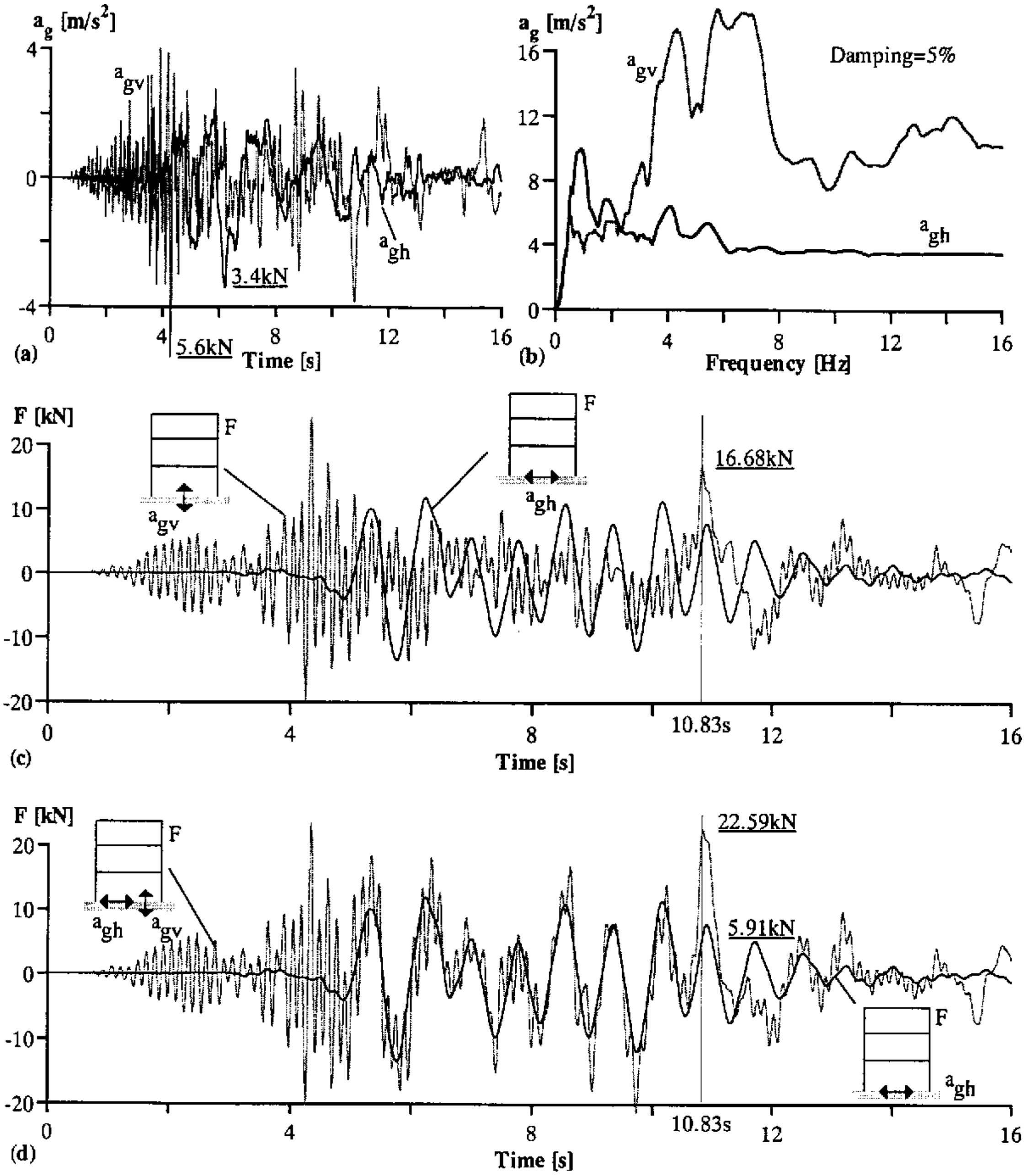

Figure 3(a)-(d): Effect of strong vertical ground motion and the time coincidence of the horizontal and vertical peak ground motions on structural responses. (a) Vertical and horizontal ground accelerations a_{gv} and a_{gh} at the Kobe Port Island, (b) response spectra of the ground accelerations, (c) development of axial force F due to vertical and horizontal ground excitation a_{gv} and a_{gh}, and (d) development of axial force F due to a simultaneous ground excitation.

Figure 5 shows the bending moment M in the middle of the girder of the one-storey frame-structure. A total different result occurs when the horizontal or the vertical ground motion is considered. While the vertical ground excitation produces the maximum bending moment the horizontal ground motion produces no bending moment at all. The vertical ground motion excites the girder. The girder vibrates in the vertical direction with the maximum amplitude in the middle of the girder span and vibration nodes at both ends of the girder. The horizontal ground motion excites the girder, and produces the maximum inertial force at the top of the frame-structure which acts in the horizontal direction. This force causes bending moment at the supports and corners of the frame, but no bending in the middle of the columns and in the middle of the girder span.

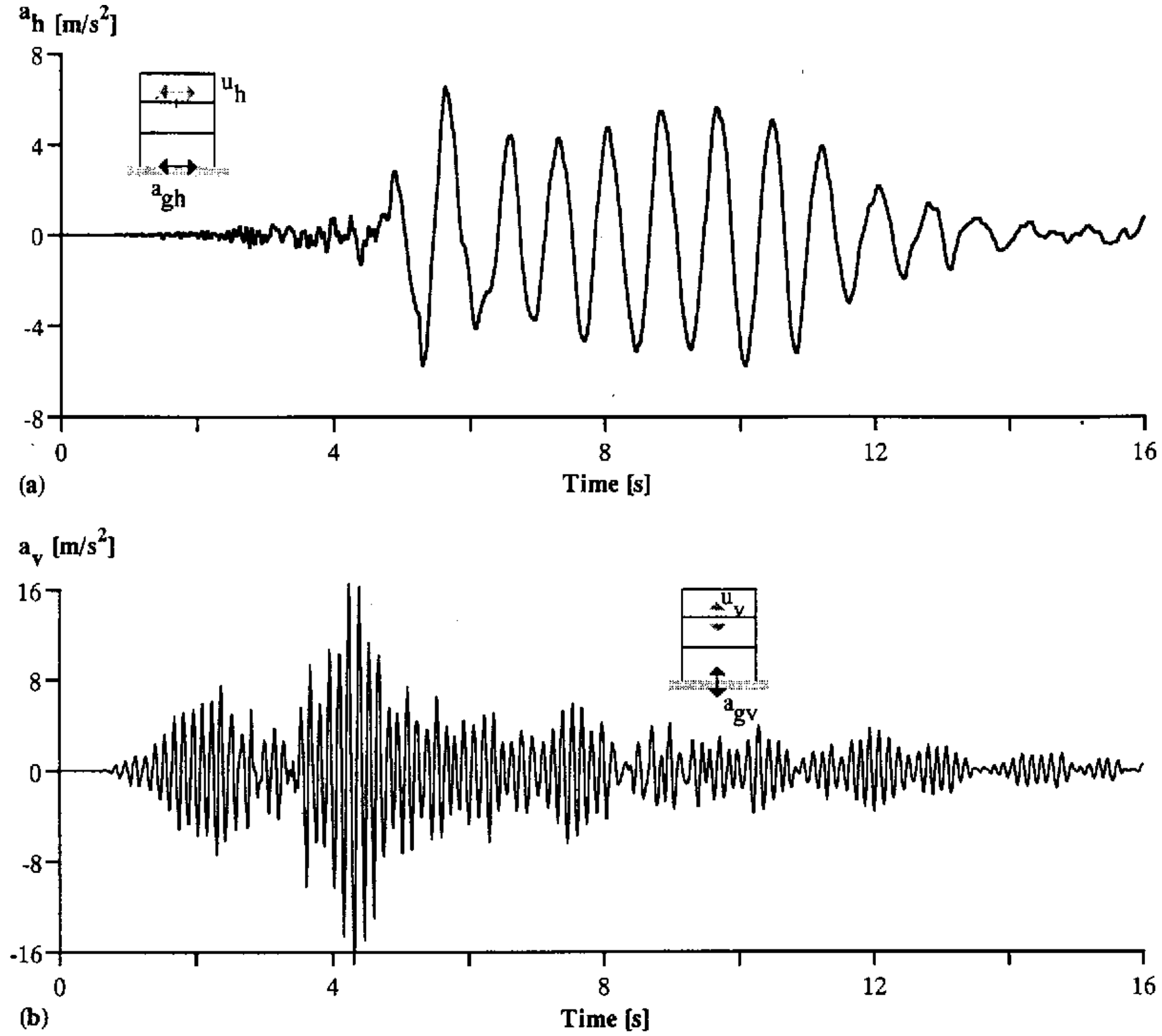

Figure 4(a) and (b): Induced vibrations in the three-storey frame-structure at the location A.
(a) Horizontal accelerations due to the horizontal ground motion a_{gh}, and
(b) vertical accelerations due to the vertical ground motion a_{gv}.

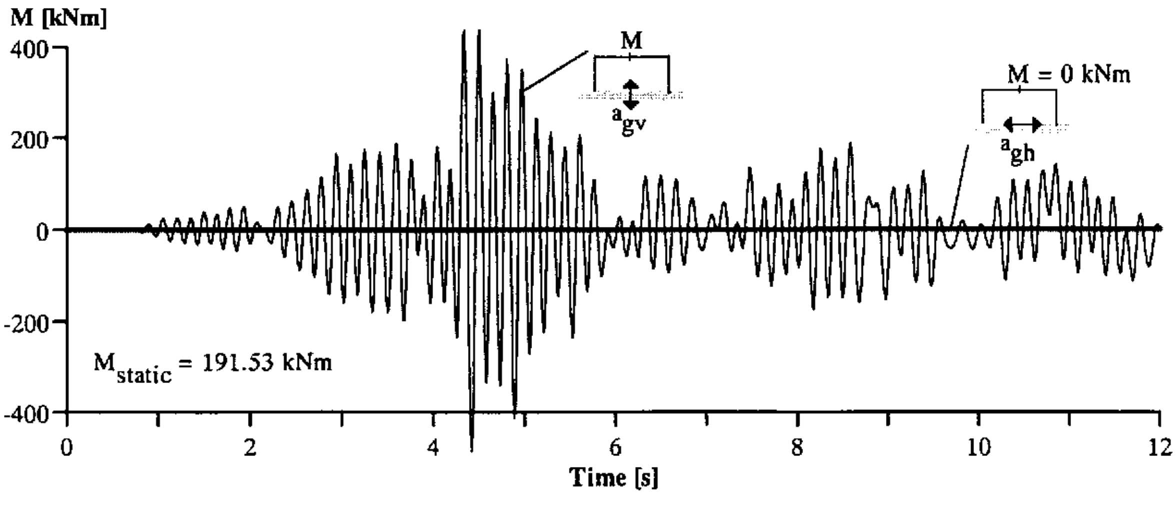

Figure 5: Bending moment M at the location B.

3. EFFECT OF PLASTIC HINGE DEVELOPMENT

In order to investigate the effect of plastic hinge development on structural responses only, no material damping and no compressive forces in the columns are taken into account. The considered structure is the one-storey frame-structure. For the description of the formation of plastic hinges the non-linear structural behaviour is formulated in an incremental way and in each of the increments the structure behaves linearly. The time, when the structure changes its linear characteristics, can be determined in the time domain. By alternatively performing the calculations in the Laplace and time domain, the development of plastic hinges will be considered. In the investigation an elasto-plastic model is used. The maximum and minimum bending moment M_{pl+} and M_{pl-} at the lower and upper end of the left column are 200.6kNm, –247.2kNm, 176.8kNm and –270.6kNm, respectively. M_{pl+} and M_{pl-} at the left and right end of the girder are 957.9kNm, –864.2kNm, 864.2kNm and –957.9kNm, respectively. M_{pl+} and M_{pl-} at the lower and upper end of the right column are 247.2kNm, –200.6kNm, 270.6kNm and –176.8kNm, respectively. The locations of a possible plastic hinge formation are indicated by grey dots in figure 2b.

Figure 6(a) shows the bending moment M at the upper end of the left column (grey dot). At 11.04s the linear response (bold grey line) exceeds the plastic level. Due to the plastic hinge formation the equilibrium location of the bending moment shifts to the lower level. The vertical ground motion alone does not cause any plastic behaviour in the structure. Figure 6(b) shows the non-linear responses due to the horizontal ground motion alone (black thin line) and due to a simultaneous excitation (bold grey line). The interaction between the excited structural vibration modes causes larger bending moment, hence the plastic hinge occurs already at 5.07s. The contribution of the vertical ground motion can be clearly seen in the higher frequency content of the response.

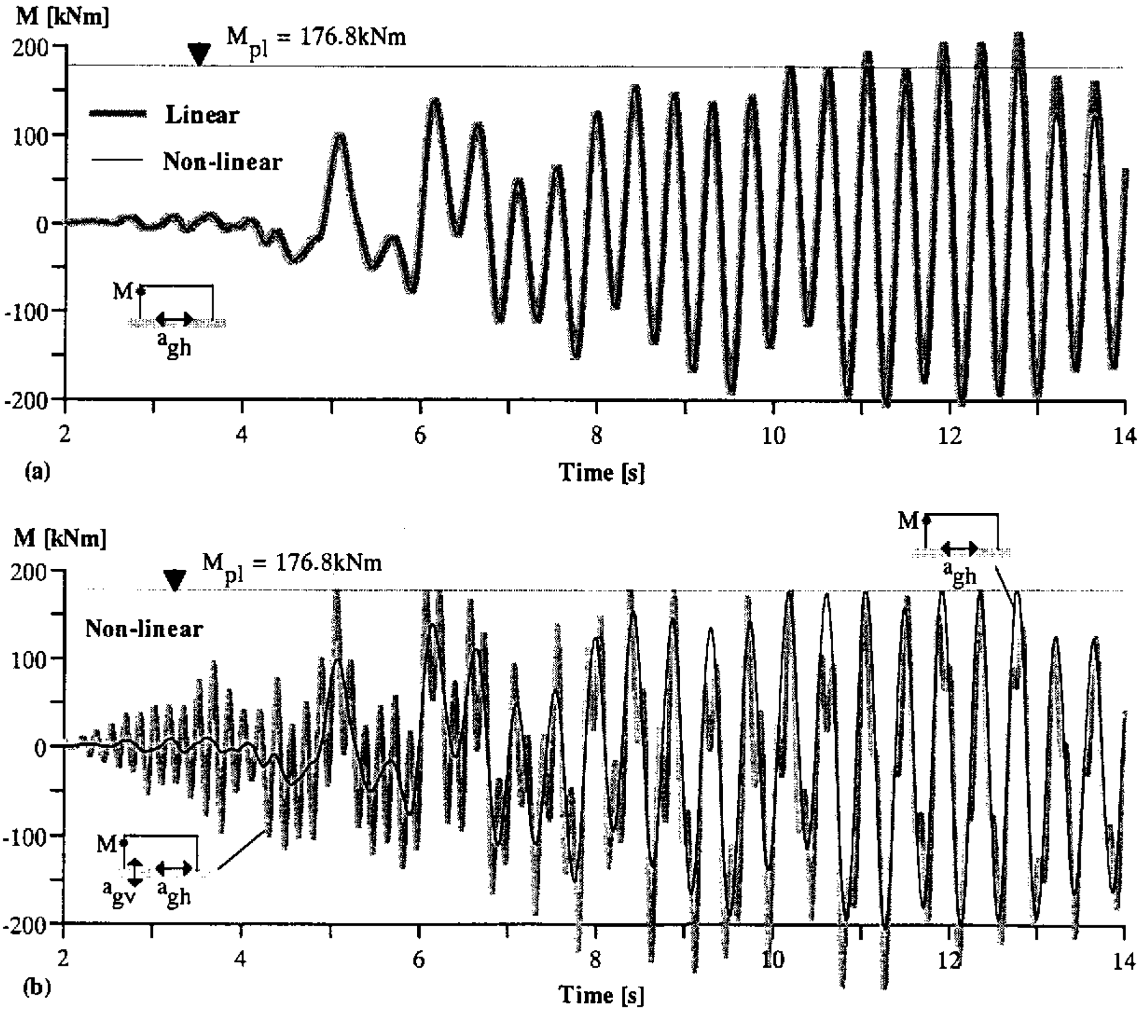

Figure 6(a) and (b): Plastic hinge effect on the bending moment M at the left corner of the one-storey structure. (a) Non-linear behaviour due to the horizontal ground motion a_{gh}, and (b) due to the simultaneous ground excitation a_{gh} and a_{gv}.

The effect of plastic hinge formation on the horizontal displacement of the girder is shown in figure 7. The equilibrium position of the non-linear response due to the horizontal ground motion shifts to the upper level (thin black line). A simultaneous ground excitation causes reduction of the horizontal displacement (bold grey line in figure 7(b)).

Figure 8 displays the development of the axial force F in the left column including the plastic hinge effect. The result shows that the occurrence of plastic hinges does not change the linear response drastically. The statement, given in [Christopoulos et al., 1999] that in some cases after the occurrence of the major yielding the effect of vertical excitation becomes insignificant, can not be observed here. The reason given by Christopoulos et al. was the shift of the structural frequencies of the vertical modes to the lower frequency range due to the damage. They give the vibration of beams as the cause of the axial force development. The author is of the opinion that the cause of the axial force development is the compressive waves due to the ground excitation, which propagate along the columns in the axial direction, and the excited fundamental vertical vibration mode. In this considered case the fundamental vertical vibration mode of the one-storey frame-structure is characterized by vertical vibrations of the girder in the vertical direction and by horizontal vibrations of the columns. The horizontal vibrations of the columns with the maximum amplitude in the middle of the columns alone will not produce large axial forces. In figure 8 the axial force due to a simultaneous excitation is determined by the natural frequency of the fundamental vertical vibration mode, since no damping is considered. However, when the damping is taken into account, the frequency content of the vertical ground motion can then be clearly seen (figure 3(c) or 3(d)), because the free vibrations of the structure will no longer dominate the structural response.

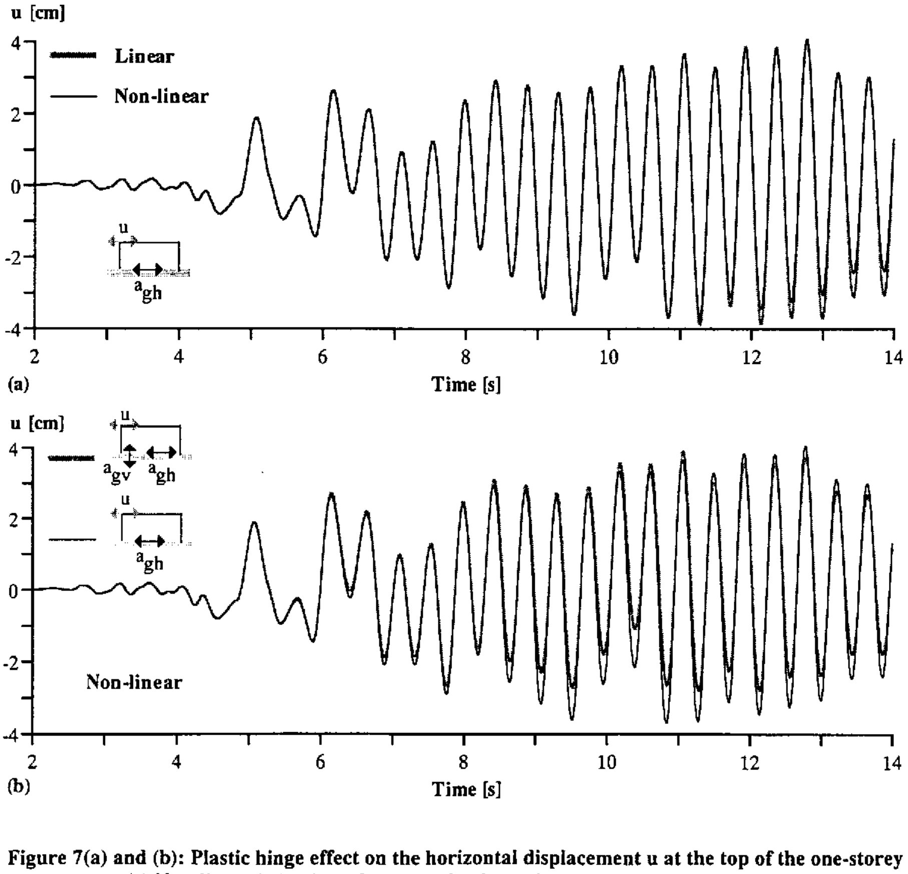

Figure 7(a) and (b): Plastic hinge effect on the horizontal displacement u at the top of the one-storey structure. (a) Non-linear behaviour due to the horizontal ground motion a_{gh}, and (b) due to the simultaneous ground excitation a_{gh} and a_{gv}.

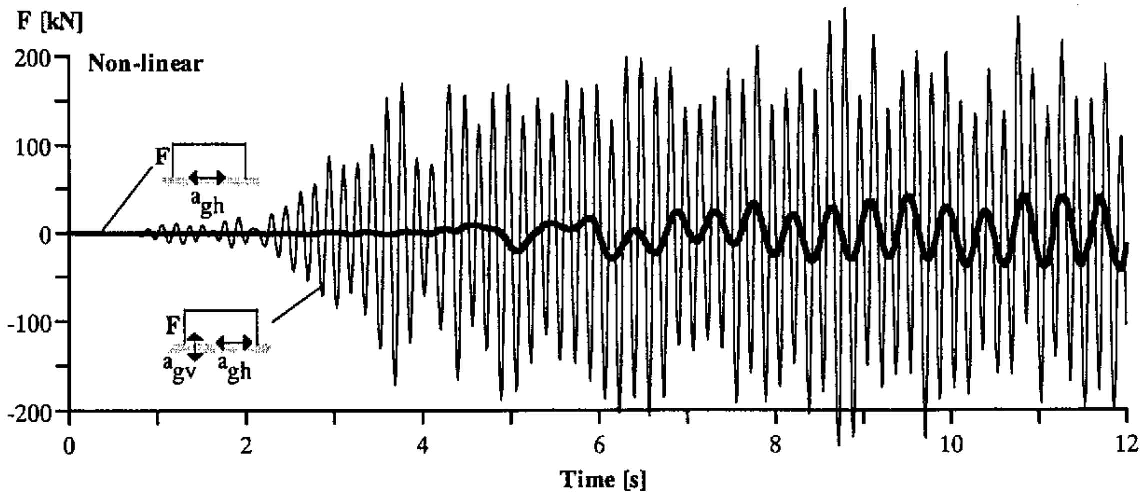

Figure 8: Plastic hinge effect on the development of the axial force F in the left column.

4. CONCLUSION

In case of strong vertical ground motions a consideration of horizontal ground motions alone may lead to an unrealistic structural response. Since horizontal and vertical ground motions have a different direction, different natural vibration modes of the structure will be excited. A consequence of this is that different forces will be activated in the structure. In case of a horizontal ground excitation the axial force in the columns is determined mainly by the fundamental horizontal vibration mode of the structure. In case of a vertical excitation the axial force is defined by the characteristics of the excitation and the natural vibrations of the structure in the vertical direction. At certain structural locations a horizontal ground excitation will produce no response, while a vertical ground excitation causes the maximum response. Induced structural vibrations, which are significant for the design of secondary structures, can not be obtained correctly, if only one of these ground motions is considered. Since a simultaneous ground excitation can amplify the structural responses, the formation of plastic hinges can differ from the development, which occurs if only horizontal ground motion is considered. The current investigation shows that the plastic hinges due to the horizontal ground motion or due to the simultaneous excitation does not change the response behaviour significantly.

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