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Behaviour of a frame structure during near-source earthquakes

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In many of the current earthquake design codes the effect of the distance between the structures and the source of an earthquake is not considered. Since most of the earthquakes in the past had a far source, the design codes are based on the knowledge of far-source earthquakes. However, some recent earthquakes like the Kobe earthquake and Northridge earthquake show clearly that a near-source earthquake has a different characteristic. It is not uncommon that the vertical acceleration is much higher than the horizontal one. This fact can not be observed during a far-source earthquake, where the vertical component rapidly descreases with the distance and is smaller than the horizontal one, so that the vertical excitation may be neglected in the design of buildings. The other reason for ignoring it is the belief that structures are over-designed by a large factor of safety to resist gravity loads, hence will invariably resist additional forces from vertical excitation. This notion does not take into account the dynamic nature of the fact. Since water and even poorly-compacted soil are able to transmit compressive waves nonlinear soil behaviour like liquefaction does not dampen vertical soil shaking. Vertical accelerations which is associated with propagating compressive waves are amplified towards the soil surface where horizontal accelerations decrease as indicated by the Kobe port island stong-motion array. Since surface layers have generally higher natural frequencies vertically than horizontally the soil prefers to transmit compressive waves with high frequencies and shear waves with low frequencies.
The high frequencies in the vertical ground motions at the surface of port island can be seen in figure 1a. The greatest peak is 5.56m/s^2. The peak ground acceleration in the north-south direction of 3.41m/s^2 arrives 1.92s later. The difference in the predominant frequency range is indicated in figure 1b. Due to different excitation directions structural response is defined by the excited natural modes of vibration in the corresponding direction. Since buildings experience the excitation in vertical and horizontal directions simultaneously, the combined effect of vibration modes in both directions and the coincidence in time of the vertical and horizontal peak ground accelerations can be significant for structural response. The other influence on vibration of structural members comes from the gravity loads. It has different effect if a building is excited in horizontal or in vertical direction, e.g. a column is affected differently by a gravity load if it vibrates in transversal direction or if it oscillates in axial direction.

In the numerical investigation presented, steel frame structures are considered. In order to describe the structural behaviour correctly, the continuous mass model is used. The calculation is performed in the Laplace domain. The damping of the structures is described by a Kelvin chain, so that a causal and almost frequency independent damping is obtained. The effect of the gravity load is taken into account.

Figure 2 shows the axial forces in the top right column of a three-storeys frame with a total high of 10.7m and a span of 9.15m. The first three natural horizontal frequencies are 1.24Hz, 3.72Hz and 5.55Hz, respectively. The first three natural vertical frequencies are 6.25Hz, 6.50Hz and 6.74Hz, respectively. The axial force in figure 2a is caused by the vertical excitation or by the horizontal excitation alone. Corresponding to the excitation the column responses in the case of vertical excitation appears earlier and with higher frequencies than in the case of horizontal excitation since all columns are excited directly.
In the case of horizontal excitation the fundamental horizontal mode is dominant. While the building is swinging in the horizontal direction, axial forces occur in the columns. The axial forces therefore decrease faster with the height than those in the case of a vertical excitation. In the considered case the greatest axial force at the top column is 20.7% of that at the bottom column for the vertical excitation, and is 7.6% for the horizontal excitation. At 4.34s the column experiences a maximum tension of 24.45kN due to the vertical ground motions, while it is under compression if the structure is excited by the horizontal ground motions alone.
The difference in the responses is also reflected in its freqeuncy content. While the axial forces due to the vertical excitation is defined by the excitation frequencies, the one due to the horizontal excitation is determined by the frequency of the fundamental horizontal vibration of the structure. The consequence of this is the material of the structural members will suffer differently.
Another difference in the structural responses is indicated by the responses of the girders. While the responses due to the horizontal ground motions are negligible, all of the girders vibrate significantly due to the vertical ground motions. The maximum bending moment in the middle of the top girder for example is even 2.5 times the moment due to the existing static load.

A nonstructural component, which is anchored at the structural members, will therefore experience an excitation with a different dynamic characteristic.

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The effect of a simultaneous excitation on the structural response can be seen in figure 2b. Since the greatest peak of the acceleration in the vertical and horizontal directions do not coincide in time, the maximum tension force in the column is therefore, as expected, determined by the vertical excitation. Compared to that due to the vertical excitation alone it is 3.7% smaller, because at that moment the horizontal excitation causes a small compressive force. The interaction effect between the two excitations is clearly seen in the response for example at time of 6.3s, 7.4s or 9s. The tension force at 10.8s shows the effect of the time coincidence of the peak vertical and horizontal accelerations (see also Fig. 1a). Since each of the two excitations alone will already induce tension forces a simultaneous excitation amplifies the tension force to 22.59kN. It is 32% bigger than the tension force caused by the vertical excitation alone, and is 188% larger than that produced by the horizontal excitation alone.

In regions with expected near-source earthquakes a more realistic response of structures which are relatively flexible in the vertical direction can only be obtained if the vertical strong ground motions and the effect of the time coincidence of the peak ground vertical and horizontal accelerations are taken into account.

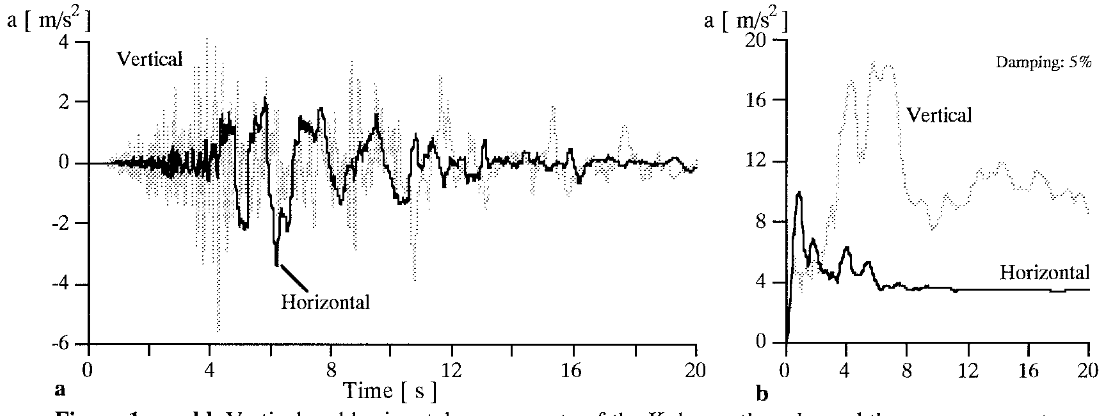

Figure 1a and b. Vertical and horizontal components of the Kobe earthquake and the response spectra

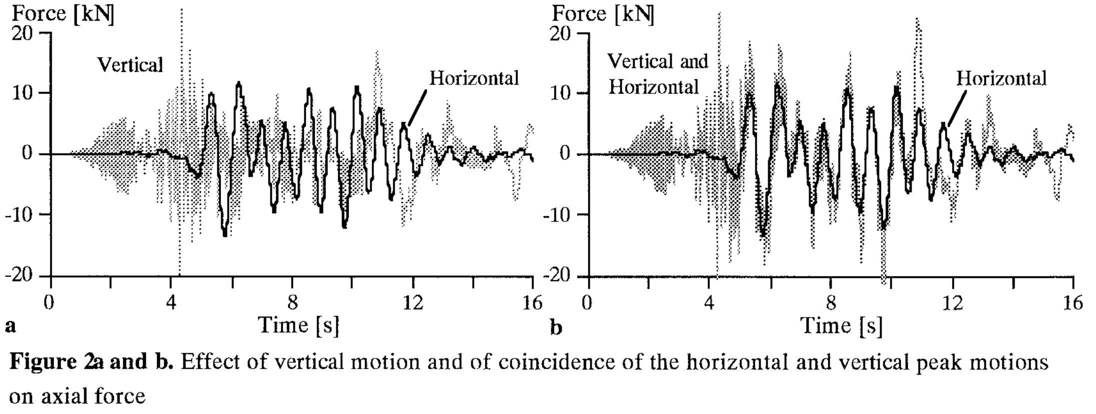

Figure 2a and b. Effect of vertical motion and of coincidence of the horizontal and vertical peak motions on axial force