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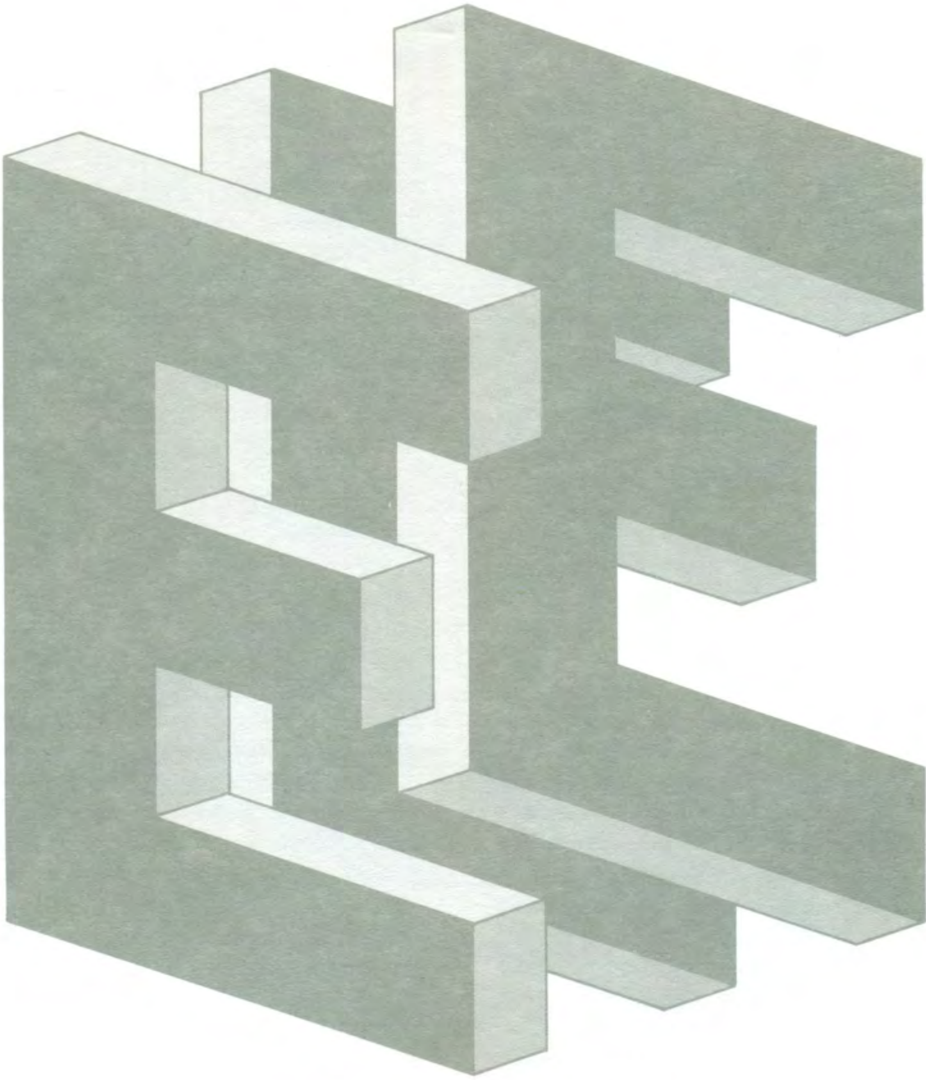

PÀTRON EDITORE

Influence of the vertical component on damage during shallow-nearfield earthquakes

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SUMMARY – The paper considers the effect of the vertical component of earthquakes on damage produced by shallow-nearfield motions. Some typical damages, recorded during recent European earthquakes of this type, are presented and commented. Hints derived from shaking table tests and from simple numerical analysis suggest that the effects may be of two kinds: (a) deterioration of mechanical properties of concrete add of mortar due to high frequencies of the vertical accelerations; (b) a significant increase of vertical normal stresses even for moderate excitations.

KEY WORDS: *Vertical component, Athens earthquake, high frequencies.*

1. Introduction

The development of technologies for strong motion recording allowed a great progress in the domain of earthquake engineering to be made: it was a bright light coming to clarify several items not fully understood yet. But the light was so strong as to reduce, in many instances, our insight into real observation of damage after earthquakes. We think that this is the case of the effect of the vertical component of ground motion on the seismic behaviour of structures during severe shocks. Many important advances of earthquake engineering were mainly based on the analysis of horizontal recorded signals and of their effects. This is reflected on the structure of seismic codes, which consider these components of ground motion as the principal earthquake actions to be taken into account for a safe design. The basic underlying idea is as follows: «Buildings are designed primarily to withstand vertical forces (permanent and accidental loads), ordinary safety coefficients used in traditional design easily account for possible increases of forces due to vertical base excitation». It is noteworthy that the assumption that damage and collapses due to earthquakes have to be attributed essentially to horizontal actions is relatively recent. Before the 50's in seismological books, earthquakes were grouped in two distinct categories according to their effects on structures: the first one comprised the «tectonic» earthquakes, which were considered as the most dangerous because in many instances shaked down the buildings with vertical actions; the second category included the «wavy» earthquakes, which were considered less dangerous, basing on the observed damage.

The above «old» distinction between the two types of earthquakes was mainly originated by the observation of seismic effects of European nearfield shallow earthquakes, hitting rather densely inhabitated regions. It was overcome, after the 40's, by the increasing availability of acceleration records of medium and long-distance strong American earthquakes, whose high frequency content is filtered off with the distance from the epicentral area. This feature is quite different from what occurs in most nearfield shallow European earthquakes, which show a rather important high frequency content in many locations where they produce damage.

Recent shallow nearfield European earthquakes caused damage and collapses that may be rather easily explained by considering the effect of vertical ground motion and, on the other hand, can be hardly interpreted according to the traditional mode, i.e. by means of only the horizontal one.

In what follows we will show some examples of such damage. Then, we will discuss some effects of the vertical component on the horizontal resisting mechanism, which have been put to evidence by the results of shaking table tests on masonry buildings. Finally, we will comment the response of a simple r.c. system subjected to high frequency vertical ground movement, provided by f.e. analyses.

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We do not have absolute certainties to share. However, we feel that the subject deserves to be more investigated than it was in the past, with attention to the interpretation of damage. If the effect of vertical components is found to be crucial for the survival of structures during strong nearfield shallow earthquakes, design procedures and seismic codes will be affected. This will also influence the choice of repair and strengthening interventions of structures that have been damaged by earthquakes of this type, as it is the case for recent strong European earthquakes.

2. Damage from recent earthquakes

This section shows some examples of damage suffered by buildings during recent shallow nearfield earthquakes that point out the effect of the vertical component of ground motion. Most examples refer to the 1999 Athens earthquake. The figures that will now be shown are only few examples out of the hundreds of similar cases that were observed and documented during surveys in damaged areas of Greece and Turkey after the 1999 earthquakes.

a) During the Eagio earthquake (1996) one modern and well designed r.c. structure suffered damage beyond the limit of repair in columns at the ground level. Damage occurred mainly at the top of these columns (Figs. 1a and 1b). It may be explained by considering the effect of the vertical component, due to which the vertically travelling P-waves in the columns are encaged under the rather massive slab at their top. Note that in the figure glasses appear undamaged, thus suggesting rather low horizontal actions on the building, while the buckling of the reinforcement indicates significant vertical actions.

b) The type of damage above mentioned was observed very frequently after the 1999 Athens earthquake. A typical situation is depicted in figs. 2a and 2b. The first one shows damage at interior ground floor columns of a modern r.c. buildings, whose reinforcement buckled. There is a very modest evidence of lateral displacement and the important vertical actions on them cannot be attributed, due to the internal plan locations of the columns, to the effect of the overturning moment. Again, a reasonable interpretation of the damage calls for the effect of the vertical motion. To this respect, fig. 2b shows unbroken glasses at the entrance of the building, what suggest limited horizontal actions. The same damage pattern holds for other 5 buildings of

1a – Eagio (1996) earthquake. The crushing of concrete and the symmetrical buckling of bars are apparent. The vertical edges of columns are still aligned.

1b – Eagio (1996) earthquake. Glasses are unbroken.

2a – Athens (1999) earthquake. Interior columns of a modern r.c. building. There is a poor evidence of lateral motion.

2b – Athens (1999) earthquake. Damage at the ground floor. Glasses are intact.

3a – Athens (1999) earthquake. Damage at midheight of columns.

3b – Athens (1999) earthquake. Details of damage at midheight of columns, bars buckled.

the same type located in the neighbourhood of the one referred to in the figures.

c) Another typical damage that was observed after the same earthquake is shown in figs. 3a and 3b. Damage occurred at midheight of the columns, while no cracks are detected at their top and bottom, as it would be the case for significant horizontal actions. Fig. 3b shows that stirrups are loosened and that the longitudinal bars are buckled. Windows and glasses of the building were undamaged.

4 – Athens (1999) earthquake. Compression damage to short columns. Note the symmetrical buckling of window frames.

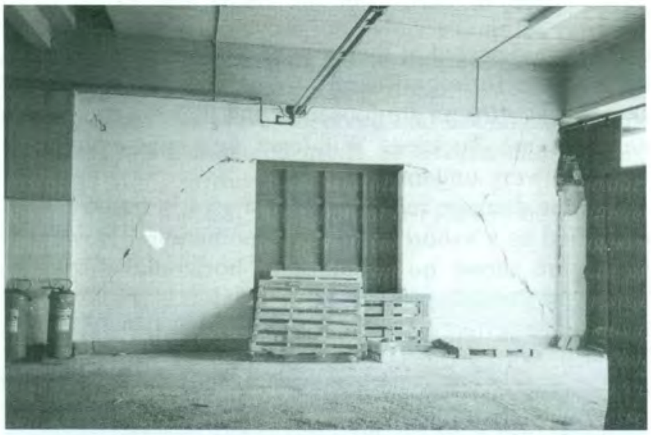
d) The damage represented in fig. 4 is traditionally classified as a «short column phenomenon». However, the figure shows no evidence of horizontal displacement and the interpretation leads again to consider the determinant effect of vertical actions. To this respect, it is worth noting the symmetrical buckling of the windows frames.

e) A similar «short column» effect was observed, after the 1999 Athens earthquake, in three blocks of two storeys industrial buildings (see fig. 5a, showing the east view of one block). Plan dimensions of each block were 31 × 35 m, column sections at the ground level were 50 × 80 cm, while at the upper level were 50 × 50 cm, only columns at this level were damaged. At the ground floor the buildings have several brick-masonry partitions. None of the hundreds of windows glasses of the three blocks was broken during the earthquake (see figs. 5b-5c), with no evidence of important horizontal motion. Recorded damages can only be attributed to vertical action. As a matter of example, consider fig 5b, showing three short columns at the upper storey, fig. 5c, showing damage to a brickwall partition at the ground level and figs. 5d and 5e showing typical compression failures recorded in brick-masonry columns at the ground level.

f) Figure 6a shows the heavy damage to the partitions at the ground floor of a five storeys apartment building in Athens. The load bearing system is a r.c. frame. The portion of wall above the lintel (part B of the figure) was thrown a few meters away the building, as if it were blown out by an explosion. There is a very poor evidence of lateral displacement; to this respect it should be noted that the damaged pattern in a masonry pier due to lateral actions is very similar to the one due to vertical actions, as depicted in fig. 6b. Here, damage may be reasonably attributed to the effect of vertical actions, given to the lack of significant horizontal displacements.

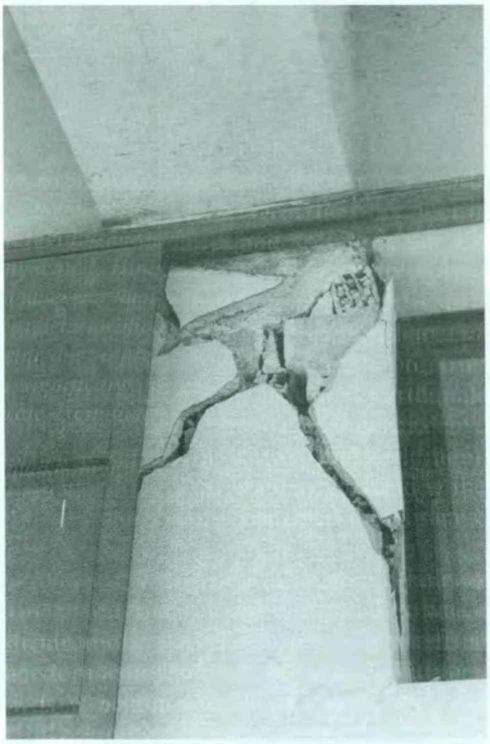
5a – Athens (1999) earthquake. Compression damage to short columns. Glasses are intact. There is no evidence of lateral displacements.

5b – Athens (1999) earthquake. Details of damage to short columns.



5c – Athens (1999) earthquake. Symmetrical compression damage to partitions. There is no evidence of lateral displacements.

5e – Compression damage to brick masonry column. Note the unbroken window.



5d – Compression damage to brick masonry column. No lateral displacements.

g) The vertical component is likely to be the cause of the collapse of a three storeys building, shown in fig 7. The ground floor was open and used for car parking. Its columns penetrated the floor of the first storey almost symmetrically, as seen from details A and B of the figure, and very poor evidence of lateral motion is given.

h) Figure 8a shows the quasi-symmetrical damage suffered at the ground floor of an Athens warehouse while fig. 8b shows details of the damage to the A column. The buckling of bars and the orientation of the cracks in concrete again suggest the predominant effect of the vertical component. Similar phenomena were observed in several other columns of the building, with very limited evidence of lateral motion.

i) The same symmetrical distribution of damage

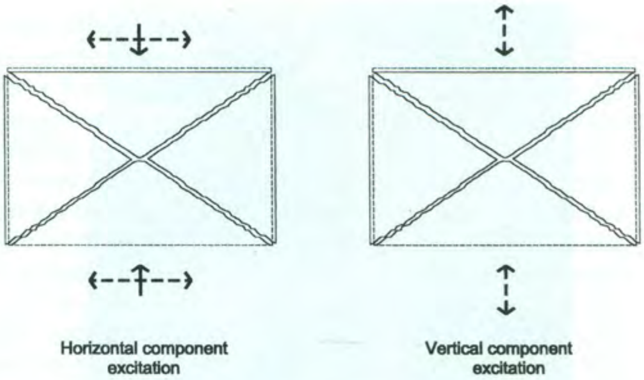
6a – Athens (1999) earthquake. Damage to partitions at ground level. There is a very poor evidence of lateral displacements.

7 – Athens (1999) earthquake. Columns of the collapsed open ground floor penetrated almost symmetrically the slab of the first storey.

8a – Athens (1999) earthquake. Compression damage at the base columns of a warehouse. Note the symmetrical buckling of bars and of window frames.

around a vertical axis, which is typical of the effects of the vertical component, was observed in many traditional masonry buildings. As an example, figure 9 shows one of such buildings, where major damage was suffered at the corners.

j) In several instances situations like the ones represented in figs. 10 and 11 occurred: part of a building



6b – Damage patterns to masonry piers due to horizontal and vertical actions.

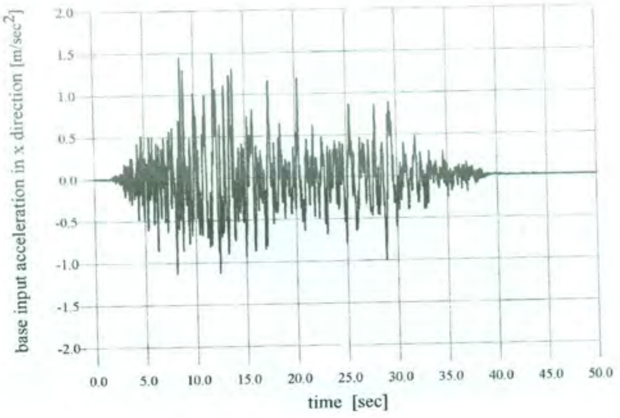
8b – Athens (1999) earthquake. Details of damage of fig. 8a.

9 – Athens (1999) earthquake. Symmetrical compression damage to a masonry building.

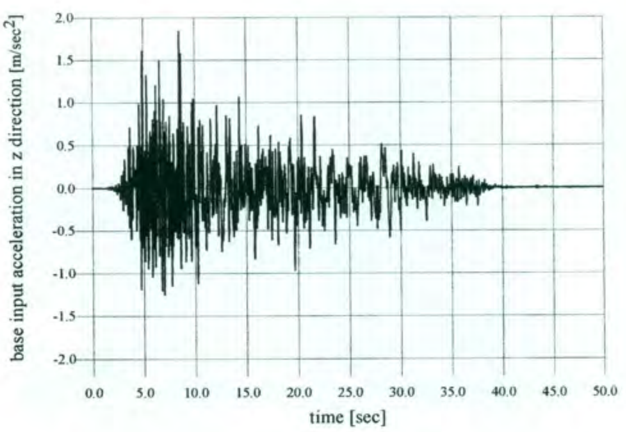
10 – Athens (1999) earthquake. Upper storey compression failure. No evidence of lateral displacements.

11 – Athens (1999) earthquake. Collapse of a part of a r.c. building. Note unbroken glasses of the intact portion of the building.

collapsed partially (fig. 10) or totally (fig. 11), while the remaining parts of the structure were practically undamaged. Although significant changes in the quality of construction between the collapsed and the intact portions of the buildings cannot be excluded, thus explaining their significantly different behaviour, a reasonable interpretation leads again to consider the effect of the vertical component. The intact parts of the buildings prove that they had a quite satisfactory lateral behaviour and the unbroken windows show modest horizontal actions.



12 – Horizontal component used in tests.

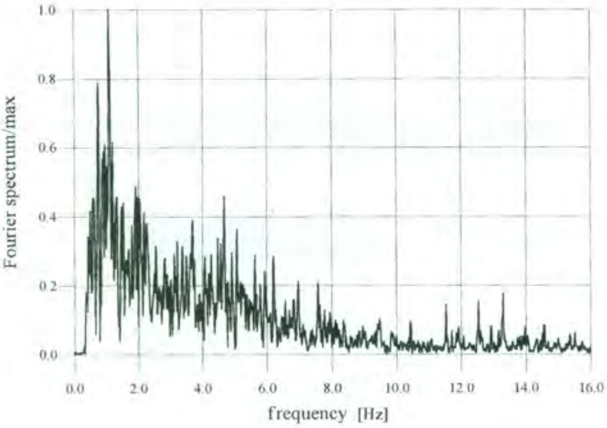


13 – Vertical component used in tests.

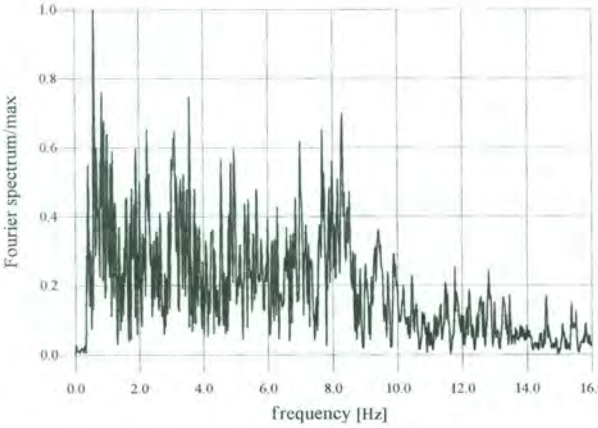
3. Experimental and analytical hints

We think that the effects produced by vertical excitations on a structure are of two kinds: (a) for r.c. and masonry systems, a significant deterioration of mechanical properties of concrete and mortar, (b) for all types of structures, a significant increase of vertical forces, even for relatively moderate excitations, with respect to their static design values. Both effects need to be adequately investigated, however some hints may be derived from available results of shaking table tests and from numerical analysis of simple systems.

In nearfield shallow earthquakes, recorded vertical accelerations show the following characteristics: (a) the high-frequency content of the signals is much more significant than the one of horizontal accelerations; (b) the larger acceleration values occur at the beginning of the excitation, when horizontal accelerations are still rather far from their peak values. As an example, consider figs 12 and 13, which report records derived from Irpinia (Calitri, 1980) earthquake and used for the shaking table tests referred to hereafter. The anticipation of the main vertical shock (up to about t = 8 sec.) with respect to the main horizontal one is apparent. Figures 14 and 15 show the power spectra, normalised to their maximum values, of the



14 – Fourier spectrum, normalized to the peak value, of the horizontal component used in tests.

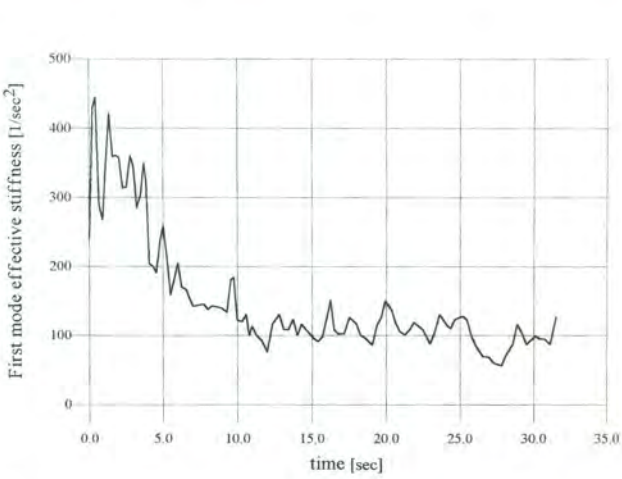


15 – Fourier spectrum, normalized to the peak value, of the vertical component used in tests.

two excitations. The richer high-frequency content of the vertical signal with respect to the one of the concurrent horizontal record is apparent. It should be noted that the frequency content of the vertical excitation shown above, is not fully representative of the real properties of the vertical motion during shallow near-field earthquakes due to the fact that the real recorded signal (1980) has been filtered due to operational needs of the shaking table control. Moreover, field recording of ground accelerations is generally performed with devices with low-pass filters with cut-off frequency starting from 33Hz. This is a consequence of the basic assumption of modern earthquake engineering that traditionally considers lateral actions much more significant than the vertical ones, thus measuring relevant signals in the realm of low and medium frequencies. The high frequencies content in vertical components for the type of earthquakes considered herein may be much higher than what it is now believed to be, basing on available records.

a) Shaking table tests

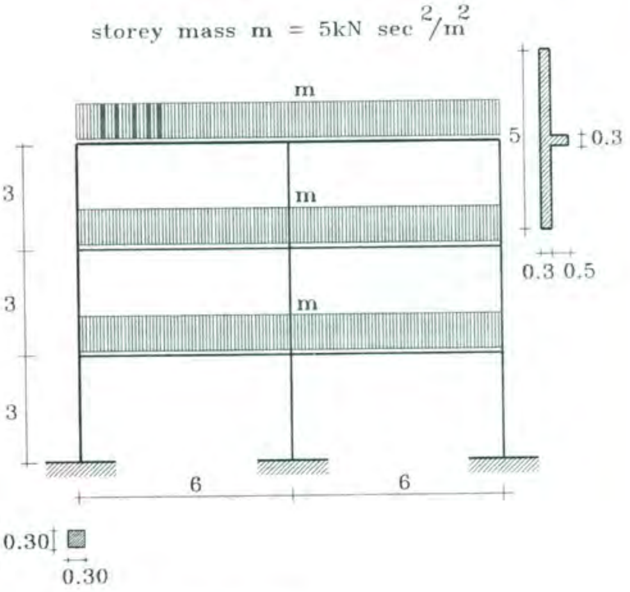
Few years ago the Commission of the European Community (CEC) funded a large experimental program carried out in Italy and Greece in order to improve the knowledge on the seismic behaviour of masonry buildings and the efficiency of several repair and strengthening techniques. Shaking table tests were carried out by using three components ground motions of increasing severity. Excitations were derived from the Irpinia records. Figure 12 shows, as said, a typical horizontal base input applied in *x* direction. The acceleration time history acting along the orthogonal direction *y* is very similar to it and is not shown here. The typical vertical excitation is shown in fig 13. The main results of the tests may be found in ref. 1. Accelerometric responses were recorded at 20 locations, basing on them several elaborations and interpretations of the responses were carried out (see refs. 2-3).The effect of the vertical component was not presented in the above references; this is shortly made now. Tests were carried out up to severe damage both on original buildings and on damaged buildings after repair. Repair and strengthening did not involve any intervention on the mortar, which was strongly deteriorated during the severe base inputs acting on the original structures. For repaired buildings the effect that will be now described could not be observed by the interpretation of recorded responses. On the contrary, for all original buildings a significant decay of lateral stiffness occurred during the base excitation producing some visible damage. In all instances this decay happened at the beginning of the earthquake, during the main part of the vertical shock, but before the main part of the horizontal one. As an example of this phenomenon, consider fig. 16 which reports the variation with time of the first-mode effective stiffness in *x*-direction for the building H1, a stone masonry 2-storeys structure. The tests showed that major damage was recorded in *x*-walls. Moreover, system identification showed that the response was dominated by the first mode during the event under consideration. Peak accelerations, both of the vertical and of the two horizontal ones, were about 0.16g. Inspection of figures 12, 13 and 16 shows that up to t = 8.1 sec. horizontal accelerations are about 30% their peak values, while vertical ones already achieved their maxima. Correspondingly the effective stiffness shows a de-



16 – Variation of the first-mode effective stiffness for building H1.

crease of about 50% the initial value (which is very close to the final stiffness value determined at the end of the previous test). This decrease cannot be attributed to lateral actions, which become significant only after t = 8.1 sec. We think that it is an important effect of high frequency vertical accelerations. This effect may be greater than the one detected here, if harmonics with higher frequencies were included in the vertical input, what is likely to occur during real earthquakes. Note that this decay of stiffness occurred during a moderate earthquake. After t = 8.1 sec. vertical input tends to decrease and the horizontal one to increase, thus producing a further loss of stiffness. What it is important to note is that the main part of the horizontal shock acted upon a structure whose mechanical properties were already deteriorated by the vertical action acting on the repaired systems.

The fact that in repaired system these items were not observed is a confirmation of our hypothesis: there the mortar was already deteriorated by the tests which severely damaged the original system, hence could not suffer additional deteriorating effects due to vertical actions.

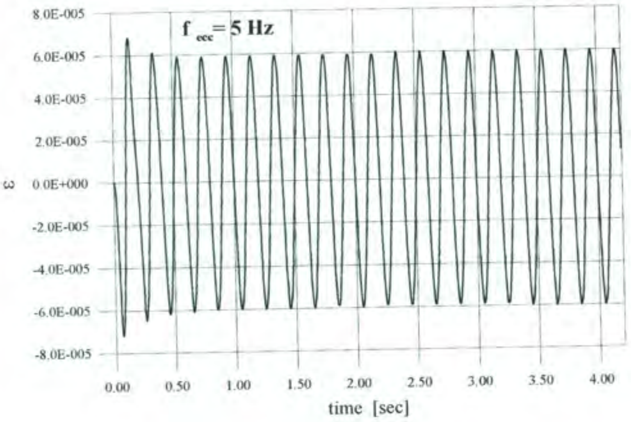


17 – Frame used for f.e. analyses.

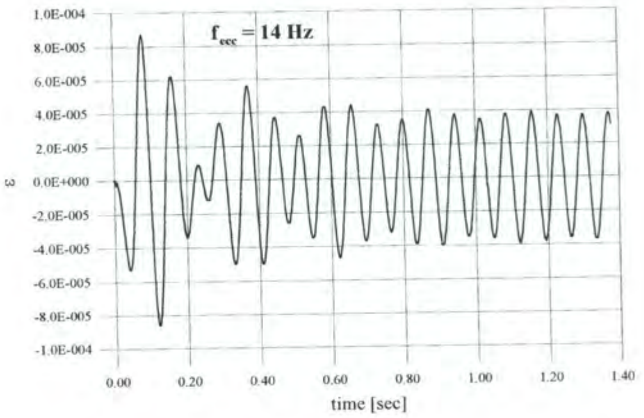
b) Hints from numerical models

A very simple r.c. symmetrical frame, subjected to vertical base inputs, has been analysed by a linear f.e. code. We realise that linear analysis is an intrinsic limitation of the obtained results. However, the aim of the analysis is to acquire some elements to describe another effect of vertical ground motion, in terms of the order of magnitude of the increase of vertical compression forces in columns. Additionally, concrete has a poor ductility in compression, hence information derived from linear analysis may describe, although not precisely, the nature of the phenomena involved in the response. The simple system taken into account is shown in fig. 17. Column sections are 30 × 30 cm. At all storeys, the vertical static load is 600 kN per storey. It turns out that the central column of the frame is loaded at the base by a static compression force equal to 900 kN.; in what follows attention will be focused on this column. Frequencies of the first vertical modes are respectively at 10.1, 16, 16.7, 20.3 and 38.5 Hz. The frame was excited by a signal derived from the one of fig. 13, whose sampling rate was doubled in order to include higher frequencies than the ones shown in fig 15. The peak acceleration was $0.3g$, damping was assumed 5% to critical for all modes. The maximum compressive forces arising from the seismic excitation in the columns taken into account was 770 kN. Similar values were obtained by considering different base inputs, all with a peak acceleration of $0.3g$ and different column sections in the frame, in order to have a non-symmetrical configuration. It turns out that the effect of a vertical component containing high frequencies is such as to almost double the amount of compression normal stresses due to the static vertical load. A quite similar trend resulted by using different base inputs and considering frames with column sections 60 × 60 cm., provided the frequency content of the excitation was able to include the frequencies of the main vertical modes, or at least of the first one. We think that this is quite the case for real vertical components, although we frequently are led to neglect them due to the cut-off of higher frequencies operated by traditional recording equipment.

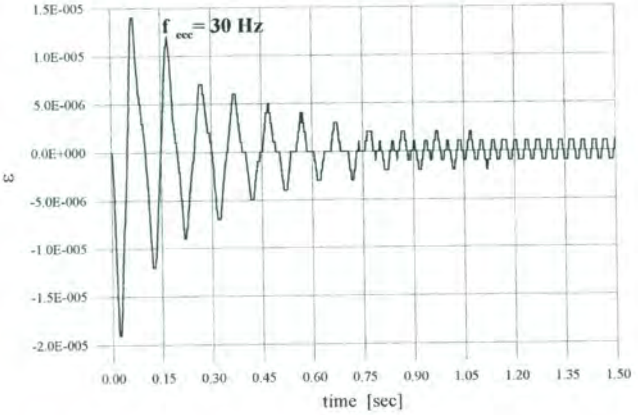
The frame was also excited by separate sinusoidal base accelerations of increasing frequency in order to assess the importance of the contribution of higher vertical modes to the response during an earthquake. To this respect it is noteworthy to observe that Fourier spectra of vertical excitations show a relatively uniform contribution of higher frequency components. As an example, consider fig. 15: it can be seen that up to about 10 Hz the amplitudes of the harmonics are of the same order. Remember that the signal was filtered for the reasons previously stated: for recorded accelerations this relative uniformity extends up to about 20 Hz. Four sinusoidal inputs, all with an amplitude $0.1g$ and with frequencies 5, 10, 14, 15 and 30 Hz respectively, were used. These frequencies were selected in order to be lower than (the first one), equal to (the second one), relatively far from (the other ones) the natural frequencies of the frame. Vertical forces arising at the base of the central column were 161, 960, 190, 150 and 45 kN respectively, that is 18%, 106%, 21%, 17% and 5% of the nominal static vertical load. Of course the increase occurring during an earthquake depends on the actual Fourier spectrum of the latter, on the frequencies and on the partecipation factors of the structure, but the elementary above results show the significant potential contributions connected with high frequencies of the excitation. Of particular interest is the response to the harmonic base excitation with $f_{ecc} = 10$ Hz., practically coincident with the first vertical mode frequency. Here, forces are a little higher than the applied static load. This is not surprising and is typical of resonant condi-



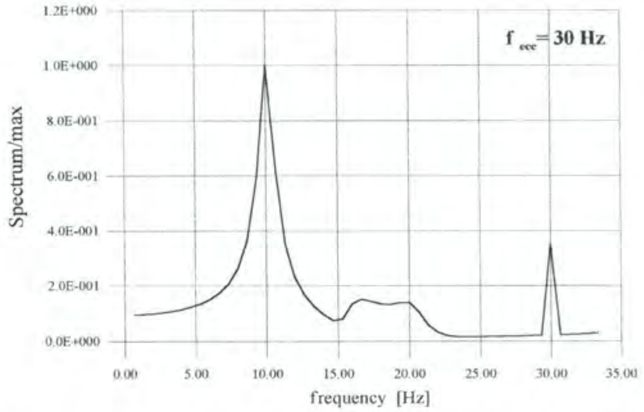
18 – Axial deformations in the central column.



19 – Axial deformations in the central column.



20 – Axial deformations in the central column.



21 – Fourier spectrum, normalized to peak value, of the response to sinusoidal excitation with $f = 30$ Hz.

tions but points out the danger related to the possible excitation of the first vertical mode due to the rich high frequency content of the vertical component of real earthquakes. Figures 18, 19 and 20 show the variations with time of the axial deformations determined at the section of the central column facing the first storey slab by the harmonic base inputs of frequency 5, 14 and 30 Hz ($a_{max} = 0.1g$). These excitations have frequencies far from the modal ones. The graphical representation of the results concerning the 30 Hz harmonic is disturbed by the very low values of ε. In all cases it is apparent the influence of the transient response. Spectral analysis shows that the frequency content of the responses has frequencies respectively of 5 and 10 Hz in the first case ($f_{ecc} = 10$ Hz), 10 and 14 Hz in the second case ($f_{ecc} = 14$ Hz) and 10, 16.7, 20 and 30 Hz in the third case ($f_{ecc} = 30$ Hz). Figure 21 shows the Fourier spectrum of the response, normalized to its peak value, for the latter case. In all instances the steady state response is dominated by the frequency of the base motion but its transient part is dominated by the vertical natural modes, being the first mode predominant even when its frequency is considerably far from the one of the excitation, as it happens in the last case. Peak compression deformations occur during the first or the second period of the transient response and turn out to be respectively 1.23, 2.38 and 14.9 times the steady state values. High frequency harmonics included in a seismic input may hence excite the main vertical modes giving a contribution to the response which may be considerably higher than what expected from their actual amplitudes.

To this respect it is noteworthy to observe that in the experimental case, shortly discussed above, the frequency of the first vertical mode of building H1 was found to be 14.7 Hz in the original state and 13.9 Hz during the last excitation. This mode was excited by the applied ground motion, which shows a relatively significant harmonic content up to $f = 14$ Hz, although it is not fully representative of real vertical signals, as said. The material deterioration, which resulted from the detected decrease of the lateral stiffness, may be explained by the above comments.

4. Conclusions

Observation of damage suffered by buildings during strong nearfield shallow earthquakes in many cases suggests an important influence of the vertical component of ground motion. Basing on previous comments the said influence is mainly connected with the high frequencies content of these motions. They produce two effects, one is the deterioration of the mechanical properties of the concrete (or the mortar), the second is the significant increase of vertical forces that, even for moderately strong shocks, may reach the order of magnitude of the static vertical loads, thus doubling compression stresses in the vertical resisting elements with respect to their design values.

Note that these high forces, and the relevant stresses, act in connection with the decay of material properties and may cause the types of damage previously discussed or even the collapse. The material deterioration anticipates the main portion of the horizontal shocks, as seen. Maximum lateral forces act hence on a damaged structure and this may be a further step towards collapse or very severe damage.

The (neglected) effects of vertical acceleration need to be further investigated, possibly examining the encagements and reflections of travelling vertical waves between vertical elements and massive horizontal structural elements. If these effects are of the type and of the importance suggested by the hints presented here, their inclusion in seismic design procedures will involve some consequences. Few examples: slender columns should be avoided and column sections should be 2-3 times larger than what derived from static traditional design. Strengthening of damaged r.c. framed buildings should include the addition of new walls, particularly at the ground level, in order to significantly increase the vertical load-bearing capacity of the building far beyond the requirements of static vertical loads. Moreover, in strengthening or repairing masonry buildings, particular attention should be paid to the improvement of the quality of mortar, e.g. by cement grouting of walls. This intervention is now less frequently adopted than in past, due to its cost, to architectural reasons and to the fact that, although it considerably increases the lateral strength, it shows limited dissipation capacity and ductility in the lateral response mechanism. The need to protect such buildings from vertical actions may involve a re-evaluation of its use.

Finally, we wish to point out again the purpose of this paper: to call the attention of the research community on an aspect of the seismic response of buildings which we think is very important, although almost neglected during the recent decades.

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