The effect of the vertical earthquake motion in near field

P. G. Carydis
Laboratory of Earthquake Engineering, National Technical University of Athens, Greece

Abstract

In the present paper a demonstration is given of the catalytic importance of the vertical component of the shaking on the earthquake response of structures in the near field. Since in the earthquake ground motion the two horizontal components are always present, the vertical component must also be considered either acting independently, or in combination. In the epicentral regions of most of the damaging Greek earthquakes of the last decades there is strong evidence of the presence of the vertical seismic component. The paper refers to normal shallow earthquakes which are the majority of Greek and of many European earthquakes. For these earthquakes a model for the initial tectonic motion is proposed. The resulting motion on the surface of the ground is a superposition of the various well-known types of waves and of the response of the ground to an abrupt tectonic subsidence. At the end of this paper some constructional and design measures are proposed for the protection of existing and new structures in order to confront the vertical component.

1 Introduction

The paper has various objectives:

- To prove that the vertical seismic component is the dominant parameter (in combination with the horizontal motions) in the various near field regions, mainly in earthquakes caused by normal faults. This is the case of the most of Greek destructive earthquakes as well as European earthquakes and in various regions around the world.
- To stimulate the interest of seismologists and engineers in order to direct their research towards this subject, both in the analytical and experimental domain.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

- With this action as much as possible evidence from the field will be collected after damaging events, that justify this point of view. Further, to be widely accepted that the vertical component is the dominating parameter in epicentral regions of shallow normal earthquakes and very important when it comes in combination with the horizontal motion in earthquakes due to strike – slip faults.
- To accumulate new knowledge that will enrich the new structural codes, in order to influence the design and calculation of new structures, the way of carrying our experiments, the respective seismic modeling and in analyzing the response of the ground for microzonation studies. The paper will also contribute in designing the seismic passive or active control of structures to resists also the vertical motions that dominate in epicentral regions. It must be mentioned that the vertical component as it is dealt today in the various earthquake design codes is not satisfactorily covered, from both parameters, the nature (it must be treated as an impact) and the magnitude (it is of much higher acceleration).
- To adequately design, calculate and construct the repair and/or strengthening of structures that have been damaged or not after destructive earthquakes. It is sometimes really dangerous to prove that although the repair and strengthening schemes aim mainly against the horizontal seismic motions, the respective damages are mainly due to the dominating vertical component.

The result of the above mentioned goals is to produce safer structures against earthquakes. In the same sense with the same safety level more economic structures will be produced, since it will be proved that the most of the damages we observe in epicentral regions, after strong earthquakes, are not due to the inferior horizontal seismic coefficients but mainly due to the lack of adequate design and calculating provisions against the effect of the vertical seismic component.

2 The seismic motions exciting the structures in epicentral regions

Accelerographs record the X, Y and Z motion at a point on the earth surface or deeper. This motion is the projection along the two horizontal and vertical planes of the convoluted motions at the respective point. In the following list the far or near field effects are also indicated. The wavy only character of these motions is indicated in fig (1).

a. P waves. Vertical motion. Wavy character. Stronger in near field.
b. S waves. Horizontal motion. Wavy character.
c. Rayleigh waves. Horizontal and vertical motion. Wavy character.
d. Love waves. Horizontal motion. Wavy character.
e. Motions due to reflection and refraction of incident waves, mainly in near field.
f. Tectonic and creep motions. One directional and ground vibration in parallel. Mainly in the near field where the respective motions take place. According to the earthquake generation mechanism are the respective

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

motions. The resulting vibration of the ground may overwhelm the P wave motions in near field.

A model for calculating the vertical earthquake response of the ground due to the vertical tectonic drop in normal earthquakes is given in the following according to Carydis [2].

In case of large dimensions of buildings additional torsional and shear motions along its length due to phase lag of the exciting ground motion, the angle of the incident waves and the Love waves may be observed.

3 Documentation of the catalytic presence of the vertical component in near field

The documentation presented in the following pictures are unique cases that appear only in epicentral regions. The types of damages that are observed after strong earthquakes in epicentral regions and which may only be attributed to the additional effect of the vertical component are the following:

a. Toppling or dislodging of structures from their foundation, the framing system is not damaged due to relative deformations between the various stories. This case distinguished from the well known case of liquefaction.
b. Partial collapse of buildings. In the most cases in the ground floor of the collapsed part there are no secondary walls compared to the remaining other part.
c. The beams and/or slabs are penetrated by the vertical load bearing elements.
d. Damages at the center length of beams and slabs.
e. Cantilever beams or slabs are dropped down or collapsed. Also, cantilevers may produce damages to their neighbor region due to vertical motions.
f. Masonry arched lintels are intact.
g. The collapsed buildings remain almost horizontal within their foundation plan and the remaining columns or walls are vertical.
h. The broken columns present an explosive manner of braking either above their foundations or under the slab or beam of the ground floor. In many cases there are lighter damages in the ground floor columns at any distance from its base.
i. In rather symmetrical masonry structures, as these are the most common cases, the damages in the walls are horizontal. There are obvious traces in the roof and floors of the vertical motion and all corner cornices are fallen down. In general, damages are symmetrical to the vertical axis of the building.
k. Picture frames, doors, radiators and other appliances are dismantled from their supports and are fallen down. Cooking stoves, and other kitchen appliances topple over and if it is cooking time they may produce fires that are ignited simultaneously at various places around the city.

In general, the severity of the effects of the vertical component is almost independent of the magnitude of the earthquake. Intensive damages are observed during the Rio, Corinth, Greece, 1974, M = 4.2 earthquake, during the Tbilisi, Georgia, 2002, M = 4.8 earthquake according to Mukhadje and Timchenko [5],

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

during the Parnitha, Greece, 1999, M = 5.9 earthquake etc. The surface of the pleioseismic area depends on the magnitude and other parameters.

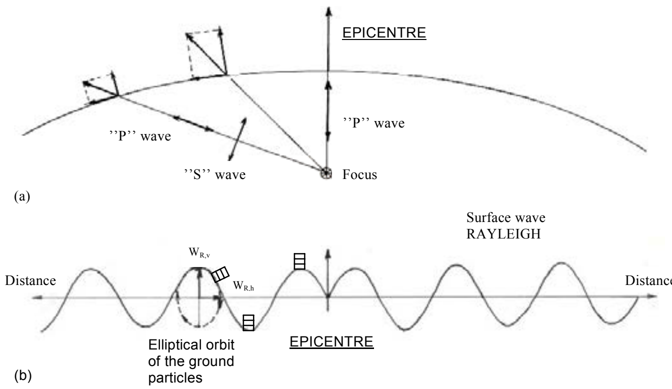


Figure 1: The structures are like vessels traveling on a rough sea, due to Rayleigh surface waves. The contribution of P and S waves should be added.

(a) (b)

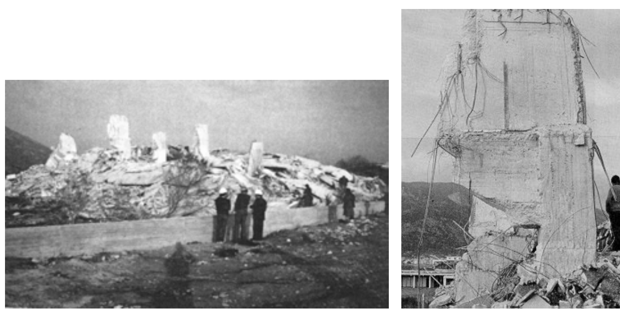
Figure 2: There are no damages justifying important horizontal motion. Notice that the windows are unbroken in both cases. Explosive type of damage. fig (2a): Epicentral region, Parnitha earthquake, 1999, fig (2b): Epicentral region, Aegion earthquake, 1995.

Figure 3: It is evident the vertical action during the Dinar, Turkey 1995 earthquake (no diagonal cracks). Symmetrical damages around a vertical axis of symmetry, horizontal cracks on the first and second levels.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

(a) (b)

Figure 4: The remaining gap is noticeable. Also, note that the glasses are not broken. Epicentral region, Parnitha earthquake, 1999. Explosive type of damage.



(a) (b)

Figure 5: The hotel building collapsed down to the pillars without any evidence of horizontal motion. Alkyonides central Greece earthquakes, 1981.

(a) (b)

Figure 6: Total vertical drop of the whole building of about 8 cm without any permanent horizontal movement or inclination. Explosive type of damage. Epicentral region, Parnitha earthquake, 1999.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

(a) (b)

Figure 7: Two different types of damage in the same building. In the right hand side there are only horizontal damages in the infill brick wall, indicating no horizontal motion. Epicentral region, Parnitha earthquake, 1999.

Figure 8: The cantilever slab dropped. Epicentral region, Parnitha earthquake, 1999.

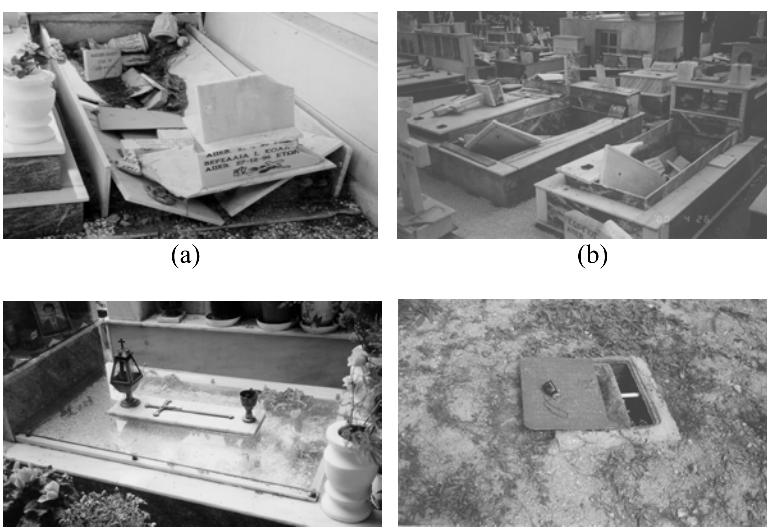
(a) (b) (c)

Figure 9: There are even no minor damages in the brick walls. Not compatible to the observed damages in the structural elements. The bottom support of the central column in fig (9b) is hinged and therefore no moments are created there. Epicentral region, Parnitha earthquake, 1999.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

(a) (b)

Figure 10: Only upward and downward motion could explain this type of observed damage. The unconfined region between the stirrups is obvious in fig (10b). The columns are in the center of the building. Strong like impact, P waves are traveling upward the columns of the building. Epicentral region, Parnitha earthquake, 1999.



(a) (b)

(c) (d)

Figure 11: All tombstones have been broken without any evidence of horizontal motion. Only the one out of glass on elastic bearings in fig (11c) is unbroken. The sewage cover has been dismantled by lifting and horizontal motion in fig (11d). Epicentral region, Parnitha earthquake, 1999.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-706-X

(a) (b)

Figure 12: The books, bottles etc. on the selves have not been dislocated in the remaining part of the building, the other part of which was fully collapsed. The remaining part has brick walls down to the foundation. The collapsed part had no brick walls at the ground floor. Epicentral regions. fig (12a), Parnitha earthquake, 1999. fig (12b), Aegion earthquake, 1995.

(a)

(b) (c)

Figure 13: The staircase is statically independent from the rest of the structure with a gap of 2 - 3 cm. There is extremely small contact damage (due to horizontal motion) as shown in fig (13c). The whole building suffered extensive structural damages, as shown in fig (13b). Epicentral region, Parnitha earthquake, 1999.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-706-X

(a) (b)

Figure 14: The masonry arched lintels behaved very well due to the symmetrical vertical loading of the earthquake ground motion. Epicentral region, Cefalonia earthquake, 1953.

Figure 15: The damaged columns are not due to the 'short column' case. The damages are transverse to the plane of the brick walls. Note that the windows are unbroken. Epicentral region, Aegion earthquake, 1995.

Figure 16: Ground floor collapse. The hypocentre is close to the foundation of the building. Epicentre of the Rio, near Patras earthquake M=4.2, 1974.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-706-X

4 Analytical model for the generation of the vertical P waves in near field, normal faults

According to the above mentioned, in order to calculate the vertical ground motion due to the tectonic fall as mentioned in paragraph 2.f, the following procedure is proposed.

The resulting motion is due to the abrupt fall of the base of the soil deposit – the bedrock over the underlying rock formation. According to Carydis [2], the acceleration of the fall is constant, equal to a_g =1.0 g. As it is shown in fig (17), A is the equilibrium position, B is the point with the maximum velocity in time t1, where starts the contact – impact on the underlying rock. The impact takes place between time instances t_1 and t_2 , in which some failures between the two surfaces of the broken rock occur. The base and together with the soil deposit continue to fall up to the point C. The severity of the whole phenomenon depends on the time duration $\Delta t = t_2 - t_1$ of the impact. The most severe effects take place for purely elastic impact ($\Delta t \rightarrow 0$), while the smoothest effects correspond to plastic impact, leading to longer Δt. The magnitude of the created acceleration at point C is given by:

$$a_c = \frac{\Delta v}{\Delta t} = \frac{v_B}{t_2 - t_1} \qquad (1)$$

It is obvious that the value of the created acceleration, a_c, greatly depends on the characteristics mentioned just before and not so much on the value of v_B, namely the magnitude of the earthquake since,

$v_B = \sqrt{2 \times d \times a_g}$, (d is the tectonic displacement)

In other words, this means, as it has already been observed, that earthquakes even of a rather small magnitude may produce high epicentral accelerations with high damage potential.

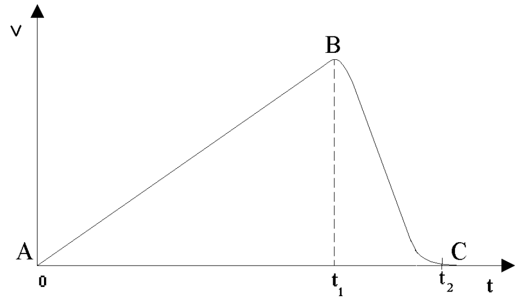


Figure 17: The velocity of the motion at the bottom of the bedrock.

The abrupt fall of the above lying tectonic block due to gravity in normal earthquakes can be simulated with the Brazilian test as it is shown in fig (18). The pressure due to compressional forces F along E – W direction causes an

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-706-X

abrupt breaking of the cylinder that externally gives the same result as if tensional forces F′ were applied along the perpendicular direction N – S. On the other hand it must be noted that internal tensional forces can not be developed primary.

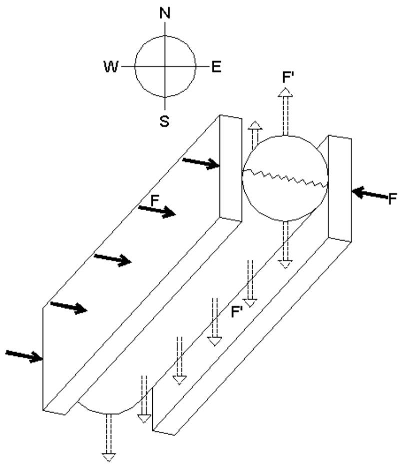


Figure 18: Loading of a cylinder along a generating line (Brazilian test). A simulation of the normal fault mechanism in order to explain the abrupt failure of the tectonic blocks.

The drop model mentioned above is illustrated with an example of the Parnitha earthquake of 1999. According to Kontoes et al [4], the vertical tectonic drop of the southeast tectonic block was about 8 cm from its original position.

The velocity $v_B = a_g \times t_1$ and $t_1 = \sqrt{2 \times \frac{d}{a_g}}$

For $a_g = 9.81\ ms^{-2}$ and $d = 8\times10^{-2}$ m, results $t_1 = 0.128$ sec. The velocity at point B is $v_B = 1.256$ m/sec. The acceleration according to eqn (1) is $a_c = v_B / \Delta t = 1.256\ msec^{-1} / 0.016\ sec = 78.5\ msec^{-2}$. If the soil deposit is hard enough this acceleration is reflected to the surface of the ground. The acceleration can be absorbed in softer grounds, while the vertical displacements will be higher. This is presented in fig (19) which presents the final results based on parametric solutions with the ABACUS computer code. The soil deposit has a depth of 30.0 m and each one of the soil deposits is characterised by the respective shear wave velocity V_s as it is shown in fig (19). In the model tensional stresses can not be created. The mass density of the soil is taken equal to $\rho = 2\ Mg / m^3$ and the Poisson ratio $\nu = 0.3$. The modules G and E are automatically calculated in the code based on V_s , ρ and ν. From the response at the surface of the soil deposit one may observe that the diagrams are unsymmetrical along the zero line. The downwards motion is always with 1.0 g acceleration – free fall. The response at the surface is a strong non – symmetrical vertical P wave, with high frequency content.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

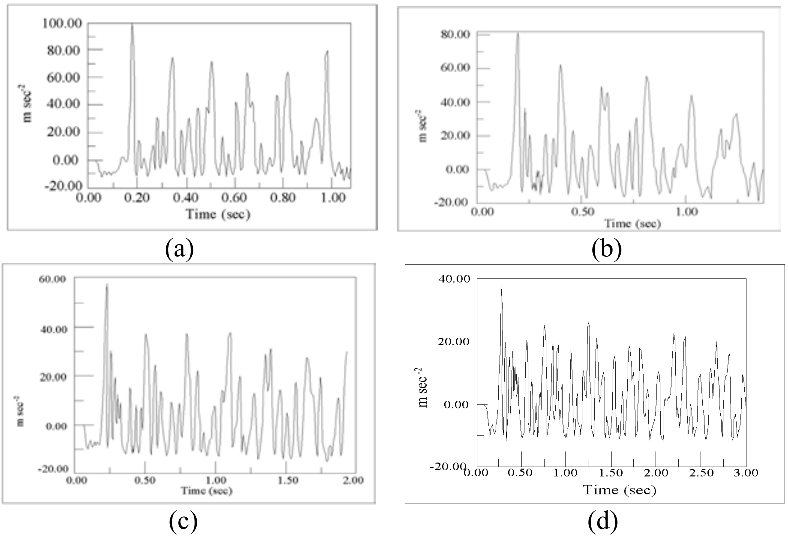


Figure 19: Acceleration time histories calculated at the surface of the deposit for shear wave velocity: deposit (a): V_s = 450msec^{-1}, deposit (b): V_s = 350msec^{-1}, deposit (c): V_s = 250msec^{-1}, deposit (d): V_s = 150msec^{-1}.

5 New codes. A trend to increase the design accelerations

The only important parameter that structures distinguish is the input motion along the three main coordinates of the structure (x, y, z) and their phase difference along each direction, due to the size of the structure.
It is a fact that a very important progress has been carried out in the domain of Earthquake Engineering, mainly with the installation of large number of strong motion instruments and the recording of the seismic motion in the ground and structures. The respective seismic analysis of structures as well as the respective codes at the present is almost absolutely based on the obtained records. In fact, as a contemporary engineer could say, the relevant knowledge came as a strong light into the scientific darkness that dominated the domain of Earthquake Engineering until few decades ago. This light was so strong that made faint the technical knowledge at this domain. It limited us to be satisfied with the recordings of the instruments. Enforced us not to proceed in very detailed evaluations of the real observations after destructive earthquakes. The importance is to analyze both the damaged and the non-damaged structures, which may be adjacent one to the other and even more to be very similar, and the soil conditions are also similar.

Following this practice we do not consider our all important obligation to get the clearest possible idea of the motion of the ground before drawing any conclusions about the response of the structure. On the other hand, the evaluation of the response of structures and mainly of the simplest ones may result in very important conclusions about the response of the ground. For example, the

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-706-X

maximum gap between the frame and the brittle wall may give the displacement response spectrum value at the respective period of the frame.

It must be mentioned here that traditional analogue strong motion instruments do not record monotonic motions of the ground but only the resulting wavy motions. They record motions of low frequencies due to their low pass filters up to no more than 20-25 Hz. Now, with the use of more sophisticated digital strong motion instruments it is certain that very high accelerations will be registered.

A logical result of all these observations is that during the recent years the design accelerations are continuously increased for civil engineering structures as well as for electromechanical installations. This may be called "instrumental" increase of the design accelerations rather than natural, since earthquakes occurred, certainly, since the formation of the earth. According to various observations and analytical calculations, the maximum vertical accelerations at the epicentral regions are of the order of 1.0 g or much greater, and as already mentioned they are equally high almost independently of the magnitudes of the shallow shocks. With the lapse of time, higher accelerations will be recorded which refer to a single point on the ground.

It has also been proven that the vertical accelerations are more quickly absorbed with the epicentral distance compared to the horizontal ones. This fact enhances what has been stated just above, that with the increase of the number and areal distribution of strong motion instruments the "instrumental" design accelerations will be increased in the coming years, and the vertical accelerations will be more drastically increased rather than the horizontal ones. The magnitude of the earthquake has a loose correlation mainly for the maximum accelerations of the vertical component in epicentral regions.

Therefore, with the lapse of years a general opinion is formed that for the horizontal direction the seismic coefficients used in the past are inadequate and they are much smaller than what they should be. Besides the recordings this opinion is also supported by observational data, on damages in structures after destructive earthquakes during the last decades. Following this logic one comes to the conclusion that the design base accelerations should be increased as well as the required ductilities. The increase of these parameters is at such a level that a problem may appear as far as the possibility of the realization of structures with such characteristics is concerned. Perhaps the inclusion into the structures of various systems for passive or active control and damping mechanisms might proved to be indispensable even for simple structures.

The trend for increasing the design ground motion seismic parameters should be hold back at a certain level, as far as the horizontal direction is concerned. This increase is unprofitable and without giving the desired protection compared to the required heavy economic investments and the resulted difficulties for good architectural solutions.

Most of the damages at epicentral regions, as already mentioned, are caused by the vertical seismic component (standing alone or in combination to the horizontal ones) and not by the as inadequate considered horizontal. Also, in epicentral regions a large number of damages are in new buildings. This is for regions where already high design ground accelerations are used. The existing

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

earthquake resistance of structures designed according to modern codes must be considered as more than just adequate and very satisfactory, if only horizontal seismic components were dominating in epicentral regions of shallow earthquakes. But the resistance against the strong vertical impulsive type of shocks is only partially achieved through existing marginal safety factors and over-design of new structures.

On the other hand the geometrical form of the design response spectrum due to the vertical component is much more flat due to the impact type of motion and it has little relation to the soil conditions as the horizontal motion does, especially in medium or long distance earthquakes. Therefore, the relevant dynamic characteristics of the structures except damping are insignificant in the behavior of the structures as well as in the interpolation of the damages observed in the epicentral areas.

6 Qualitative and analogous design of structures

As it is well known the fundamental requirements for a sound and safe earthquake response of a structure is, according to various seismic codes: (a) the avoidance of collapse (the probability of collapse to be very small) despite the intensity of the seismic motion and especially how many times higher is the intensity compared to the design values; (b) the damages to be limited and repairable due to the design earthquake and (c) to be assured a minimum level of functioning of the structure according to its use.

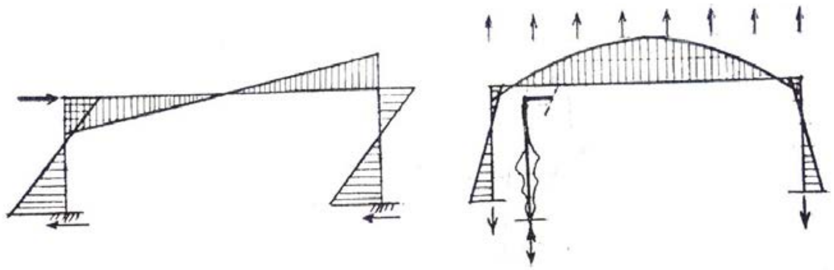
These requirements, nevertheless, cannot be met unless the deformational and loading state that is developed in its members during a real earthquake are analogous to the designed ones. This requires that the design and construction give almost constant ratios between the constructed seismic capacity and the resulted capacity due to an earthquake. And this must be the case for all members (at least the important ones). In usual earthquake design, the member moments are almost null in the center of beams and columns. If the loading is vertical the member moments in the beams will be maximum at this point, as this is illustrated in fig (20).

In the laboratory it has been verified that when structures are well designed and are loaded according to their design with consecutive input motions of increasing intensity, the structures really present a high seismic capacity. Values of over-strength like two or even three times the design accelerations are common for buildings and civil structures. Once the excitation and the response of the structure create member forces, which are not analogues to the design values, the structure easily may reach its ultimate state without having being exhausted its "common seismic capacity", because it has been designed according to the existing codes mainly against the horizontal component.

The available damping parameters in a bare structure might be inadequate unless special care has been taken. Due to the high frequency content and the impact type of the vertical seismic input motions the damping is very effective in reducing the consequences of this type of motion. Therefore, structures or structural members that provide damping are very profitable to be included in a

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

structure. For example, see Benedetti and Carydis [1] for masonry structures that spent more than the 50% of their strength and stiffness in order to anticipate the vertical component. Also, the brick wall partitions in reinforced concrete framing structures must be considered as the basic mechanism to absorb seismic energy and most of the effects due to the vertical component.



(a) (b)

Figure 20: The principle with analogous design to the real response of a structure. The key point is the maximum loading to occur in the same positions where it was foreseen during the design. The magnitude of the loads comes as a secondary requirement. The design loading is shown in fig (20a) and the real impact loading is shown in fig (20b).

7 Proposals for design and constructional considerations

The proposed measures in order to anticipate the vertical impact seismic component are the following:

a. The design response spectrum should be more flat than the one used in various codes based on the horizontal component and respective considerations.
b. Construction of the foundation body on a soft layer in order to absorb the shock.
c. Very good confinement of columns (with close stirrups) and column to beam joints with crossing beams on the joint.
d. Double the axial loads of the ground floor columns, and try to create elongated cross sections which are less sensitive to axial load variations.
e. Check analytically in order to prove that the structure is safe under creation of tensional forces in columns.
f. Check analytically that the safety of slabs and beams for about duplicating their vertical loads.
g. Try to create stiffer horizontal load bearing systems (slabs and beams). Frequencies of more than 20 Hz should be achieved.
h. Provision of the necessary details in the joints, in order to anticipate an upwards motion of beams and slabs, and design the beams and slabs against reverse vertical loading.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)

i. In existing structures non bearing partitions should be strengthened mainly at the ground floor, in order to undertake vertical loading and horizontal displacements.

References

[1] Benedetti, D. & Carydis, P., Influence of the vertical component on damage during shallow – near field earthquakes, European Earthquake Engineering, Vol. 3, pp. 3-12, 1999.

[2] Carydis, P., The vertical seismic component, "The Columbus egg in earthquake Engineering„. 12th European Conference on Earthquake Engineering, Elsevier Science Ltd. London, paper ref. 868, 2002.

[3] Carydis, P., Tilford, N. R., Brandow, G. E. & Jirsa, J. O., The central Greece earthquakes of February – March 1981, A reconnaissance and engineering report, National Academy Press, Washington, USA, pp. 160, 1982

[4] Kontoes, C., Elias, P., Sykioti, O., Briole, P., Remy, D., Sachpazi, M., Veis, G. & Kotsis, I., Displacement field mapping and fault modeling of the September 7th, 1999 Athens Earthquake based on ERS-2 satellite radar interferometry, Geographical Research Letters, 27, No 24, pp. 3989-3992, 2000.

[5] Mukhadje, T. & Timchenko, I., Epicentral Earthquake of April 2002, Tbilisi, Georgia: The capital in front of serious problems, Conference proceedings, SE 40 EEE Skopje – Ohrid, 2003.

[6] Sali, T., Greek traditional stone vault lintels and their response to earthquake environment. Proceedings of the International Conference Hazards and Modern Heritage, Rhodes, Greece, April 2-5, 2002.

Structures Under Shock and Impact VIII, N. Jones & C. A. Brebbia (Editors)