PART IV: MANAGING EARTHQUAKE RISK

CHAPTER 13
BUILDING AGAINST EARTHQUAKES

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13.1. Introduction

In the complex process of designing a building the designer goes through two complementary stages, unfortunately not too much coordinated. In the first stage, the procedure tends to use methods still anchored in absolute empiricism, where the designer makes use of his intuitions and of his own experiences to try to fit the architectonic forms to a great number of requirements (obvious, among them, resistance to the maximum attributed acceleration). In the second stage, totally rational in its exposition and development, in which theories, norms, codes and legislations are applied, the assumptions made in the first stage are verified and coordinated. This chapter tries to deal with the tools needed in both stages. In the first part, data of qualitative type are provided with the intention of discussing the most intuitive part of the process. In the following, seismic engineering norms and a little history is presented, together with actual design trends.

13.2. Architectural design

Many experts and more than a few regulatory standards erroneously interpret earthquake-proof building design as synonymous with the earthquake-proof structural calculation of buildings. Some standards define vibration periods and construction layouts, for example, only in terms of the structure and its component elements. This approach, which needs a thorough revision, does not help building designers to acquire the insight needed to meet the true aim of any building in an earthquake zone, namely, to reduce personal injuries and property damage in the event of an earthquake of the greatest foreseeable magnitude.

While the objective remains to strengthen the structure of conventionally designed buildings somewhat, no real effort is being made to develop an architecture that must address a very specific issue: resistance to dynamic effects. It is important to have in mind that most insight on the part of buildings designers has been generated on the basis of the behaviour of architectural forms built of stone under the force of gravity, and a huge effort is required to change that insight, which is the fundamental element in decisions on architecture today.

Although structural failure leads to an unusable building, it is important to remember (in connection with what is known as "damage limitation") that the high cost of other aspects of construction can lead to the building being financially unviable even where structural collapse does not occur (the cost of the structure represents no more than around 10% to 15% of the total cost of a building). This leads to two relatively crucial considerations:

C. S. Oliveira, A. Roca and X. Goula (eds.). Assessing and Managing Earthquake Risk, 287 - 308.

a) Earthquake protection must take into account the building as a whole, and constitute a special approach to building design: glass falling to a sidewalk or the collapse of the ceiling in a large hall can cause more victims than a partial failure of the structure, for example.

b) Failure of the façade can make a building financially ruinous owing to the high cost of replacement. Therefore, a certain criticism of the ways in which damages are appraised would be in order, since that appraisal is normally based only on structural damage.

As consequence, before, or while, complex procedures for damage appraisal are implemented based on the effects of earthquakes on structures, a sizeable task relating to quality in the assessment of the risks involved in living in (or near) a building that is not equipped to withstand earthquakes should be carried out.

13.2.1. PRINCIPLE OF ORDER

Order in both composition and structure is a classical architectural requirement. The work must be comprehensible at first glance. The observer must find sufficient known and ordered points of reference to ensure that the created space causes sensations of satisfaction rather than sensations of disquiet and/or disorientation (even though in painting there are styles that aim simply to create sensations, regardless of their nature, even if they are disagreeable).

This classic architectural tendency is also based on the need for the construction to be structured so that it can be rationalised, and to ensure that the behaviour of the structural elements is relatively true to the assumptions made in their calculation (those assumptions being more restrictive where the available calculation methods are more rudimentary).

Thanks to the apparent availability of calculation methods that can be used to simulate the stress states of any form under any action, certain contemporary lines of architecture being developed are making structural disorder a fundamental part of their composition.

In the past, buildings were attractive when erection of the structure was completed, and less so when they were furnished with an outer skin showing their most representative architectonic elements. Just the opposite is true nowadays; the structures of buildings show a considerable degree of disharmony, and they are disordered and difficult to comprehend, but in the end, when all that confusion is covered by a skin (in some cases made of titanium plates), that solves its aspect and in many cases satisfies everyone.

The disparity between calculation methods, euphemistically known today as numerical modelling, and reality is often substantial. This is the case, for example, when partitions limit the structure's freedom of deformation, and calculation models lose their usefulness if they do not make allowance for those limitations on the models themselves, which is not normally the case.

The disparity between the results of the calculations and reality can be so substantial that we have come to accept that most methods have been validated on the basis that, having been used repeatedly, they are found not to cause problems beyond a level that is acceptable by those involved (including the users!), and little more. As structural disorder grows, the results differ more and more from what is predictable by available theories and it becomes increasingly necessary to introduce new hypotheses (or new extrapolations), if we wish to use the same calculation tools. Risk increases, since there is presumably a greater difference between the models and actual behaviour.

The problem is aggravated when dynamic forces come into play, giving rise to local stresses in excess of the elastic limitations of the materials. Immediately prior to collapse, the redistribution of stresses and the appearance of "other" forms of equilibrium in the structural elements, among other factors, give rise to serious doubts as to the validity of the methods used to determine the values of the forces in extreme situations.

Practically, the only way in which we can monitor the validity of models is through the recovery of the structural order mentioned earlier, so as not to add, in view of the largely unrepresentative nature of the calculation procedures, the uncertainty that can result from the use of an inappropriate geometry.

However, we often forget that structures must also be optimised with respect to the stresses to which they will be subjected. This is an engineering principle that will become increasingly important, since it fosters resolution of the principles of environmental protection (such as energy savings and reduction of the use of raw materials) that we must take into account, regardless of the issues that are being dealt with.

All gratuitous formalisms that involve excessive use of materials and therefore excessive weight for buildings have, in addition to the aforementioned environmental effects, a considerable impact on seismic loads. These loads are created by the forces of inertia that arise in the course of an earthquake and these forces are a function of the masses that are placed in motion.

In the case of structures that are meant to be earthquake resistant, all these aspects of optimisation of forms must be carefully considered, since, in addition, they lead to other important considerations:

a) A distribution of masses that tends to accumulate them in the upper part of the building will give rise to deflection forces on the ensemble that are greater than they would be if the centre of gravity was relatively low.

b) A non-homogeneous and disordered distribution of the more rigid elements of the storey (e.g. dedicated screens for resistance to horizontal loads) will give rise to parasitic torsion forces (on the vertical axis) that will substantially increase the shear forces on columns and piers.

c) The more rigid elements of the storey, particularly where they are few in number, will become the focus of a heavy concentration of deflection stresses that could cause them to fracture.

d) Where the dimensions of buildings exceed the wavelength of the oscillation of the surface of the ground (in soft soils), differential deformations can occur in foundations. This effect would be added to the inertial forces caused by the earthquake, giving rise to a complex stress state (deflection-traction-shear) that would lead to extensive fissuring precisely at the moment when the full strength reserve of the building is required.

These considerations are illustrated with an example shown in Figure 13.1.

13.2.2. PRINCIPLE OF INCLUSIVENESS

As mentioned in the Introduction, when planning buildings efforts at prevention in connection with the effects of earthquakes on the buildings must go beyond structural calculation and design. This is a requirement that affects all the elements involved and the complete process from start to finish. In fact, the first step must consist of an analysis of the risks that might exist where the building is to be located.

Ideally, regional planning should be based on a risk map drafted by experts who are familiar with the area, taking into account that an earthquake could impinge upon certain latent risks and activate them (such as the liquefaction or instability of slopes).

The best way of starting off a building project in an earthquake zone is to carry out regional planning that takes into account the area's seismic characteristics, since at that time a building code can be established that tends to make buildings take on the appropriate forms (e.g. with characteristic frequencies that are as different as possible from those of the underlying ground, to avoid amplification caused by resonance). It is also important, at the time of planning, to take into account the presence of wells and troughs filled in with soft soils, since they normally cause a local amplification of the accelerations.

Fig. 13.1. This building successfully withstood the great Managua earthquake, thanks to its suitable distribution of masses, although someone had the idea of placing a large water tank on the roof, supported on a floor of columns that collapsed, and after the earthquake it was observed that the water tank had come to rest directly on top of the lower structure

Once such areas have been identified, they can be eliminated from eligibility for construction use or local values for accelerations can be established that are on the side of safety.

In addition, and focusing more on the building itself, it is important to take into account all aspects relating to access and mobility. It is worthwhile recalling the hospital in Mexico City that, although it withstood the effects of a severe earthquake, was rendered totally inoperative after the incident, since the roof of the ambulance zone collapsed and destroyed all the vehicles.

It is also necessary to consider the elements comprising all meeting places and particularly the emergency exits, since a heavy element situated high up (such as a ceiling or equipment) and inadequately attached to the structure can cause a large number of victims. The same can occur with a poorly-placed staircase or inappropriate flooring. Nevertheless, these aspects are normally the object of careful consideration, since emergency exits are dealt with in a variety of safety hazard prevention regulations (fires, for example).

The elements comprising façades deserve separate consideration, particularly those made of glass. The deformation of frames normally causes their breakage, with a shower of broken glass falling onto sidewalks at the precise moment when alarmed users, not knowing where to go, remain next to the doorways of their buildings. It is important for entryways to buildings in earthquake zones to be protected by canopies that are strong enough to withstand reasonably heavy impacts. It is also important to disregard technology for panes of glass attached simply by means of structural silicone on the market today (an earthquake-proof building bears no resemblance to an automobile). A building can remain standing for centuries, while adhesives have a limited lifetime. These considerations are illustrated by Figure 13.2.

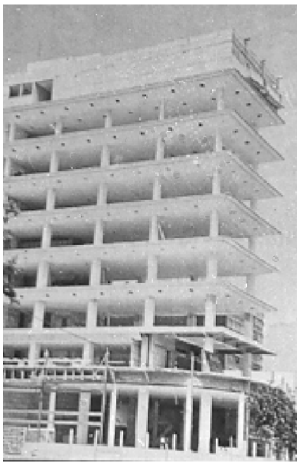


Fig. 13.2. A building that has lost its façade in an earthquake (located in Mexico City), in addition to the effects it may have on frightened pedestrians, can suffer financial damage comparable to the failure of the whole building

The elements supporting the façades must be attached to the general structure using strong, ductile connectors and not just propped against the edges of ceilings as is normally the case, and heavy elements projecting outwards from façades should also be avoided.

The cladding of many buildings needs to be considered, as it is in a state of precarious equilibrium, either because the anchors have aged or because the adhesives and/or mortars, due to fatigue under thermal stress, no longer perform their function.

As a rule, these issues are not addressed by the laws and regulations governing the design of buildings in connection with seismic factors, given the structural bias of the content of those laws and regulations. It would be of most importance that codes can provide detailed guidelines on these issues.

13.2.3. PRINCIPLE OF SHEAR STRENGTH

A building that is exposed to a horizontal action (whether oscillating or otherwise) is subjected to deflection loads, i.e. to a combination of deflection and shear forces. In theory, the increase experienced in comparison with normal forces is relatively small, since the inertia of the ensemble is usually enormous, but the shear forces, which depend only on the size of the section involved, can easily reach the breaking point.

Shear forces are not discriminating and affect the partitions just as much as the structure. In any event, the shear forces are distributed according to the rigidity of each element in respect of the rest, and it is here that the potential for unexpected events arises:

a) The elements of greatest rigidity are the partitions and, in addition, they tend to be the least able to resist this type of force, even though, once they have been fissured by the deflection-shear force, they can maintain additional rigidity thanks to their ability to function as struts in compression, where their ends are confined (a circumstance that is usually taken as an advantage in the ultimate resistance analysis due to an earthquake).

b) The shortest elements of the storey (partitions or columns) are the ones that receive the greatest part of the load and are the first to collapse. This is known as the “short column effect”. Construction in earthquake zones requires great care to be taken with architectural approaches that use mezzanines and with buildings abutting on each other without joints and with floor slabs on different levels from each other.

c) To the forces already mentioned, a substantial increase in shear forces can be added when the shear force created does not act on one of the main axes of the storey (the axes passing through the centre of gravity of the masses), since that circumstance gives rise to torque along the vertical axis that can only be balanced by an increase in the shear forces on the elements that are capable of withstanding that increase.

The model for failure of a building made up of a linear structure (e.g. concrete) and rigid partitions (e.g. ceramics) would be as follows: In the first place, the partitions would undergo stress, since they are the elements of the ensemble that are most rigid to deflection and resist the free deformation of the structural frames. The partitions would break quickly, due to their lack of strength to withstand traction, mainly in the form of sloping cracks. Since the force is of a back-and-forth nature, these cracks often intersect and appear in the form of an X. Once the rigidity of the partitions is lost due to breakage, the structure, where very sizeable nodal forces arise, becomes subject to the load. It is important to bear in mind that at this point the ensemble has lost a great deal of its rigidity. While previously the forces had been amplified as a result of resonance, when the partitions are no longer effective the natural period has changed considerably and it must be assumed that the dynamic forces fall to much lower values.

In other words, after an earthquake a building can have a deplorable appearance, with severe damage to all its partitions, while its structure remains almost intact. In financial terms, even though the building remains standing, it is most often considered a total write-off and needs to be replaced (an approach that is contrary to some of established principles with respect to the "extent of damage").

In any event, if the aim is to attempt to avoid the collapse of the system in the last stages of equilibrium, the structural nodes must be designed in such a way as to retard the formation of mechanisms in the presence of such actions. Structures that are subjected to loads by severe earthquakes often show structural nodes that have been severely damaged by X-shaped fractures, where the stirrups have split and allowed the crushed mass of concrete that had formed the core of the pillars to run out.

When the number of plastic hinges formed allows the creation of mechanisms (either locally or overall), the system can collapse, either all at once, or by falling in a chain reaction, owing to a local failure that destabilises the rest.

One good practice is to make stirrups denser near structural nodes, increase reinforcement against shear, increase the length of overlap of reinforcement and avoid having sections work in service beyond their elastic range, so that in the event of an earthquake they have a reserve of strength to withstand deflection-shear forces.

13.2.4. PRINCIPLE OF MONOLITHISM

By keeping with normal construction methods, conventional construction, attains, almost automatically, a very high degree of continuity. Proper construction (taking into account the principles of bonding) involves the mobilisation of frictional forces (depending upon weights) between different elements that are sufficient to ensure resistance to moderate actions in a horizontal direction.

The same is true in the case of buildings made of amorphous concrete. Where no serious errors are committed, continuity is attained simply through pouring the concrete and overlapping the reinforcing steel bars.

On this structural base (an effectively continuous one, even if it is made up of small elements), the roofs are installed with their strength to withstand traction (required to balance deflection) and, as required by regulations, the connection between roofs and walls or frames is made by means of reinforced concrete bonds that provide the ensemble with a certain degree of ductility. In other words, a conventional building that conforms to current construction criteria (regulated to a greater or lesser extent) shows a degree of monolithism that allows it, where necessary, to bring a variety of resources into play in order to withstand certain overloads of a dynamic nature. Only the degradation of building methods (often the result of the pursuit of greater returns, changes of materials, architectural speculation or structural modifications caused by change of use) will lead such buildings to undergo situations of risk in the event of moderate seismic activity.

In conventional construction, the façades are tied to perpendicular walls, since they are made of the same materials and are normally built at the same time, in keeping with the aforementioned principle of bonding.

These circumstances can be compromised where unconventional construction methods are used in pursuit of a more rational approach to building. In this connection, prefabricated construction methods will be specifically discussed.

Where, in place of conventional continuous finishes, systems are organized into structure (linear) and partition (surface), there is the risk that there will not be sufficient bonds between the façade and the structure to ensure that the façade remains stable in the event of an earthquake. Furthermore, it is being increasingly demonstrated (almost too frequently) that between a structure with relatively deformable edges (slabs resting directly on columns), and rigid partitions supported by those edges, certain types of incompatibilities arise that tend to result in breakage of the more rigid element (the partition) and, in a variety of cases, tend to eject it from its position. This tendency, added to a dynamic effect directed outward, can cause disastrous results.

Blachère established the principle that prefabricated construction should not be any less safe than conventional construction. He was aware that the basic objective of prefabricated buildings is to replace construction with assemblage. Any assemblage procedure is made easier by reducing the number of bonds between the component parts (and by reducing the amount of cement used in establishing those bonds). It is clear, then, that the slightest oversight, where such a prefabricated system (even if it is made up of very high quality components) is not properly attached to the rest of the building, will make the system unsafe, justifying the principle established by Blachère. By extension, this tendency to disintegration can be also found in all procedures for components that are made at the construction site: structures of pre-cast concrete components, bolted metal structures, prefabricated decorative panels, etc.

Fig. 13.3. The failure of the building occurred at the structural nodes. The plastic bearings were formed in unsuitable places, namely where the columns met the beams, when it would have been better that they form where the beams met the columns

These observations are not meant as a criticism of prefabricated systems, but rather as a reminder that the industrialised systems developed in areas prone to earthquakes must pay special attention to the use of procedures that ensure monolithism where this initial discontinuity exists. It is sufficient to think back to how the gas explosions that occurred in the 1960s and 1970s gave rise to crises in several highly-developed prefabrication systems, due to their sensitivity to chain reaction collapse, in the event of failure of any of their components (Roland Point disaster). An illustration of these ideas is shown in Figure 13.3. The Spitak earthquake (Armenia) in 1988 also showed the weakness of pre-fabricated systems due to lack of proper detailing at connections.

13.2.5. PRINCIPLE OF STRUCTURAL DESIGN WITH A LOW LEVEL OF STRESS

At present, thanks to the powerful numerical methods available to us, it is usual to optimise structural design by adopting models of behaviour that allow (without going so far as to constitute mechanisms) the yielding of the various sections of the structure where the greatest deflection loads occur. These sections, where the yielding of the reinforcement is allowed for relatively low load states, are normally concentrated in the structural nodes, at the joints between columns and lintels. This approach is not the most appropriate for providing the structure with the ability to sufficiently withstand incidental actions of great magnitude. A horizontal load (which is the most frequent type in earthquakes) gives rise to bi-triangular moment diagrams that attain their maximum values precisely at the nodes.

Although the vertical component of forces created by earthquakes is normally ignored, it is important to bear in mind that there are elements, usually caused by inadequate architectural design or improper adaptation of an existing building to other uses, that can fail under a relatively small increase of the load produced by an oscillating force. These are the elements that undergo heavy deflection loads from the building components resting on them. More specifically: façades of penthouses, which, since they are set back, rest on the underlying slab; the props of columns on girders to accommodate other functional systems; trimmed joists or large cantilevers, etc. particularly in cases where the shear or torsion forces are predominant.

13.2.6. PRINCIPLE OF FREE DEFORMATION

The models of buildings normally taken as an object for the development of regulations are usually isolated buildings. In these circumstances of free deformation, buildings show certain behaviours in response to the dynamic loads that provide the starting point for the theories that have been taught to most experts as methods for verifying safety. This fact has led to most buildings being studied as individual buildings when, in reality, a substantial proportion, standing within built-up areas, have proximity relations with other buildings.

In order for a building to function as an isolated building in an urban complex, joints between it and the adjoining buildings must be provided. These joints should be large enough to allow freedom of deformation as imposed by the corresponding dynamic effects. The necessary size of the joint (depending on the height of the building, acceleration, type of vibration, etc.) is normally on the decimetric scale, although this circumstance is not usually considered in regional or municipal planning, nor in the regulations governing the thickness of heat-seal. Furthermore, there are no building systems on the market that provide a solution for this problem, since it would require a device that could act as a breakaway strip in the event of an earthquake, establishing weak links between the parts that would, in everyday use, provide a continuous surface for walking, for example.

On the basis of current data, all joints between buildings should be considered to be free deformation joints and all joints separating a complex floor plan into simpler parts should be of sizes on the decimetric scale of free deformation joints in order to ensure a better seismic response. The same should also be true of all heat-seal. However, this problem has not been solved, and, from the standpoint of building it has not even been considered. Could it be that in earthquake zones buildings should not be longer than the compulsory 30–40 metres in order to avoid thermal overloads? Could it be that the joints between different buildings should maintain a distance for free deformation? If so (and this is in fact the case), it is time to inform all officials in charge of planning our cities and all those who draft municipal by-laws so that they can act in accordance with these principles, since it is known that Mediterranean cities are made of buildings that normally abut on one another, in a system sharing a common partition wall.

Depending on the era in which they were built, city centres are composed of coexisting buildings, constructed using very different technologies. Depending on the regulations applied at a given time and the different construction methods used, the limit between two reference buildings can be very different.

In Catalonia, the law governing shared walls was regulated under the *Ordinacions de Santacilia*, an antic text dating from the reign of James II (combining Roman law and Frankish customs). From the date of the *Ordinacions* onwards, buildings were constructed in the following manner: the first builder would make the foundation and the wall that would later be shared by both buildings, and when the neighbour decided to build, they would pay the first builder for half the cost of the common foundation and wall already in place.

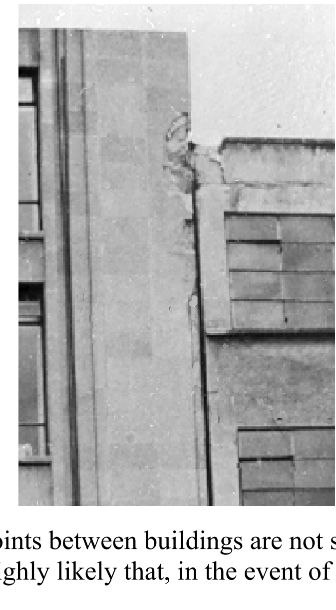


Fig. 13.4. Where the joints between buildings are not sufficiently large to allow them to deform freely, it is highly likely that, in the event of an earthquake, they will collide

13.2.7. PRINCIPLE OF LIGHTNESS

The methods normally used to predict the effects of an earthquake of a given magnitude on a building are based on deduction of the accelerations acting on the various masses that will be put in motion, and, on the basis of those accelerations (a) and masses (m), deduction of the forces (F) that will be released, taking into account the simple formula:

$$F = m \times a \tag{13.1}$$

In fact, the forces calculated are inertial forces that are directly proportional to the masses put in motion and therefore these forces are linked directly to the amount of the materials used and to the construction systems that are created on the basis of the type of materials.

Taking this approach into account, it is obvious, from a purely seismic standpoint, that buildings should be as light as possible. In this respect, there are different building cultures in areas highly prone to seismic activity that are based on wood and paper (traditional Japanese architecture), while other cultures that are equally exposed to seismic activity, possibly owing to scarcity of resources, still construct their buildings of earth and stone (Middle East), with disastrous effects in the event of earthquakes (as we are frequently reminded by events in the Middle East, Central America and North Africa).

In spite of this and driven by a variety of different requirements (some of them relating to fireproofing, strength, soundproofing or durability), modern construction methods have adopted the accumulation of materials, i.e. massiveness, as a means of addressing those requirements. Thus, buildings in the actual economic sphere are increasingly heavy and therefore less able to withstand, economically, the forces that are unleashed when an earthquake occurs.

For some time now, the rationalisation of masonry and formwork has been leading in the direction of construction methods based on flat slabs resting directly on columns, which involve serious problems of lack of ductility in the finished building, as already mentioned, and also imply a failure to optimise sections in relation to forces. The excess use of materials that this approach requires also causes environmental problems, such as overuse of raw materials and excess consumption of energy.

Irreconcilable differences appear to exist between the need to make buildings as light as possible (earthquakes and environmental protection) and the need to satisfy other requirements (durability, fireproofing, soundproofing, etc.). A great deal of regulatory pressure and imagination will have to be brought to bear in order to resolve this incompatibility.

Looking more closely at various aspects of the mentioned issues, the problem that exists about the insufficient durability found in the concrete used in buildings some years ago is now being resolved through regulations that require the use of more cement, improved impermeability of the concrete, greater protection of reinforcing steel bars (thicker and heavier coverings), less fissuring (i.e. less stress on the reinforcing steel bars) and therefore more steel. The manufacturers of construction materials are assured a substantial market share, particularly when considering that this excess weight implies larger and stronger sections to withstand earthquakes, in other words, increased weight.

Most architects design buildings on the basis of relics of classicism. In many cases, the proportions, the basic aspect of the design, still correspond to the proportions found in stone buildings from centuries ago. In the era of plastics and metals, this may seem surprising, but it could be related to an unusual fact that is not normally considered: 54% of the weight of the materials used in modern buildings corresponds to crushed stone (the aggregate used to make different components).

A recent study evaluated the weight of the materials used for an average building in Catalonia taken as a reference. It is believed that the sample is representative of a large spectrum of European construction, since, according to recent figures, 40% of the new buildings under construction in the European Union are located in Spain. Whether owing to the frequency of construction of basements involving the use of heavy retaining walls, or to the fact that foundations are increasingly complex (because they extend into land filled areas), or owing to the fact, mentioned above, that structures are increasingly heavy, the average weight of buildings, based on the available figures, is nearly 2.5 ton/m^2. It is worth noting that just fifty years ago conventional buildings were not even half as heavy.

Building must be one of the few areas of design where the reduction of weight, while maintaining the same or equivalent features, is not one of the main objectives.

In the review of what is the buildings weight, it is worthwhile to take into consideration the opinions of users. In respect of their personal requirements, users tend to prefer conventional stone buildings. There are a number of reasons for this attitude, but the most important ones have to do with apparent durability, ease of maintenance, or a simple reaction against the prefabrication methods used in the past (associated in Spain with times of economic difficulties). In short, the market tends to foster the construction of “heavy buildings”.

Summing up, it can be concluded that modern buildings require greater strength to hold themselves up than to withstand the loads involved in their use. While this, in itself, constitutes an anomaly in our highly evolved world, it is even more anomalous considering that such excess mass, when placed in movement, will possibly result in the failure of the building.

13.2.8. PRINCIPLE OF NON-RESONANCE

At least since the Athens Charter, one of the factors taken into account in urban planning is the characteristics of the region. Aspects relating to environment conditions (based on orientation, humidity, prevailing winds), and aspects relating to risks (flooding, slope stability, etc.) among others, are normally considered to be basic requisites (both in connection with the layout of streets and subdivision into parcels), but seldom is heard, in this field of design, that regional organisation is carried out on the basis of seismic risk taking into account the characteristics of the soil.

It is known that the frequency (and its inverse, the period) of the impacts reaching buildings is determined by the particular characteristics of the underlying soil. This is one parameter that should, in all cases, be known when suitability for building is regulated in a region.

On the basis of this knowledge, urban planners should be capable of defining preliminary plans for buildings and recommending certain architectural forms whose characteristic period is as distant as possible from the period of the soil, to ensure that the accelerations that might impinge on the components of the building will not be made unbearable due to resonance (see Chapters 3, 5 and 8 for details).

An earthquake that affected an extensive area of Mexico caused heavy damage to tall buildings in Mexico City and to low buildings in Acapulco. At the same time, low buildings in the capital and tall buildings in the tourist resort showed hardly any damage at all. This was due to very different dynamic characteristics of the soil in the two cities. While an important part of Mexico City is built in extremely soft soil, the soil under Acapulco is rocky, and the types of buildings that were affected by the earthquake were those that most closely resembled the rigidity of the underlying geological formations.

It is clear that urban planning has a leading role to play in regional organization, by adapting buildings (basically, their slimness) to the deformability of the soil supporting their foundations. This would give rise to substantial savings in buildings in earthquake zones, which would permit not only improved cost control, but would also have considerable impact on the sustainability of actions, since they would apply the desirable and rarely used principle of optimisation.

13.2.9 PRINCIPLE OF DUCTILITY

This principle is based on the fact that buildings should be able to dissipate the kinetic energy generated during an earthquake by means of deformation rather than through cracking.

In order to satisfy this basic requirement for the survival of the building, the architectural forms (partitions, structures and installations) must use materials with a substantial relaxation component in their stress/deformation diagrams and the components made from these materials must maintain a high degree of continuity with other components, allowing them to redistribute the overloads that they are incapable of withstanding.

In short, at the critical moment there must be the possibility for other forms of equilibrium to arise, more or less spontaneously, above and beyond the forms of equilibrium found in normal service (to a greater or lesser extent foreseen by the architect/engineer), before the ensemble is transformed into a mechanism.

In theory, the ductility of reinforced concrete structures (the most commonly used) depends on:

- The characteristic ductility of the steel (it is recommended to have an extensive yielding component before the breakage deformation is reached. There could be nothing worse than the fragile steels that were placed on the market in Germany several years ago).
- The amount of reinforcing steel correctly placed and correctly anchored. It is important to keep in mind that the dimensions provided only in respect of gravitational forces are normally calculated with selective sections in respect of the sign of the moments. It would be worthwhile, in areas with a medium-to-high

earthquake risk, for sections of reinforced concrete to be made with symmetrical reinforcement (already done in countries with frequent earthquakes, such as Mexico).

- Overlaps between reinforcing steel bars ensuring transmission of dynamic forces. Regulations normally call for overlaps longer than would be strictly necessary to withstand static actions, e.g. increments on the order of 10 diameters.
- Adaptation of sections to forces. Slabs resting directly on columns or flat beams are normally components with low ductility, while beams on edge normally form structural ensembles where plastic bearings can be formed on the beams near the structural nodes (the place recommended by all regulations).
- The resistance of elements to shear force. In the case of slabs resting directly on columns, the concrete's own ability to resist shear forces should not be taken into account. That would lead to a form totally lacking in ductility.
- The quality of design and execution, particularly the latter. The most representative image of a building just demolished by blasting is the number of construction defects that are brought to light. In such circumstances, it can be observed that all the preferential breaking points were cold joints (between concrete pours that were not correctly bonded), errors in anchoring, errors in distribution of stirrups, or improper reinforcement (a surprising number of cantilevers are reinforced backwards!).

Planning and building with the goal of ensuring ductile responses requires, under most regulations, consideration of seismic forces with values that are significantly lower than would be the case otherwise. Therefore, even if strictly out of consideration of economic factors, it is worthwhile to work with structural approaches that can satisfy this requirement. An illustration of this principle is shown on Figure 13.5.

Fig. 13.5. Due to a lack of ductility, structures with slabs as ceilings normally provide unsatisfactory responses

13.3. Code design and construction details

Many of the architectural design principles exposed in the previous section are taken in consideration within the seismic provision and guidelines applied in countries with a high level of seismic code, but the application of some of them depend on the seismic conscience of the building designer. The seismic provisions and guidelines applied in a region depend mostly on the seismicity level affecting it. The most advanced seismic code provisions come from regions like Japan and USA where strong earthquakes hit frequently causing high losses. In such regions, the seismic conscience is very high due to the losses past earthquakes have caused. In consequence, regions like these develop high level seismic codes enforcing their application not only to the new buildings but also to the existing buildings to ensure their seismic performance is acceptable.

The situation is very different for regions with a moderate to low seismicity like several European countries. Their seismicity is characterized by important historical earthquakes that occurred centuries ago. Today, cities are more vulnerable than at that epoch, so the damages caused by earthquakes similar to the historical ones can be quite larger than those suffered in the past. Unfortunately, the seismic conscience of the region is almost nonexistent; as a result its seismic design provisions can be classified as a low code level. Regions like this should not wait for the occurrence of a disastrous earthquake to enhance their building's seismic performance by applying a higher level code and evaluating the seismic performance of the existing building stock.

In Europe there has been a great effort launching the Eurocodes (EC), which define all the normative in the building construction industry, including the seismic provisions (EC-8, 2004). These provisions, supported on the most modern knowledge and adapted to the specific regional constrains imposed, for example, by the seismological conditions, will be in the near future the basis for national codes for the European Union.

Seismic design codes have the purpose of providing guidelines for the reduction of both property and life losses due to seismic events. These building design codes define standards for the seismic resistant design and construction of new buildings and for the retrofit of the existing ones. This set of guidelines is developed based on sound theoretical and physical modelling and on the observed damages caused by important earthquakes. These observed damages serve as an evaluation of the provisions and methods used for design by pointing out deficiencies both during the design and construction process. These lessons given by past earthquakes help to promote advances in the development of design methods, the knowledge of materials performance and the enhancement of construction practices. So, through an interactive process each new earthquake that severely affects a region acts as an inspector that shows how effective are the applied seismic provisions and shows the issues that require more attention.

Basically, a seismic code contains specifications for the seismic hazard, soil and possible near fault affects that should be used to design buildings in the considered region, defines the base shear load that should resist the building, makes recommendations about the structural detailing and sets displacements limitations. The first design provisions defined the required base shear as a mere percentage of the structures weight and no distinction was made based on any other characteristic of the building. With a better understanding of the interaction between the natural seismic hazard and the building's behaviour, base shear is now defined using several factors relating to both the seismic hazard and the buildings characteristics. As the development of seismic provisions advanced, more conservative criteria have been adopted for buildings that are essential for the public health and safety, and ductility requirements have become stricter.

Seismic design of buildings at the beginning of the nineteenth century was limited in various countries to apply a lateral force roughly equivalent to 10% of the vertical one. This simple static equivalent method is still used but certainly with many improvements derived from the dynamic analysis suitable from modern computers and past experience with damage observed in previous earthquakes. In general codes allow the use of either code equivalent static loads for simple structures or dynamic analysis for more complex systems. Dynamic analysis may be mode superposition for linear systems (or structures that may be represented by such simplification) or step by step using earthquake time histories for more complex systems.

The equivalent lateral loads are different according to the country but in general they have the following form:

$$V = \text{function}\ (Z, I, C, R, W) \qquad (13.2)$$

where V is the base shear; Z is a zone or local seismicity factor; I is an importance factor; C is a dynamic factor that depends on the structural period and local soil conditions; R is a reduction factor taking into account ductility and redundancy, and W is the reactive weight of the whole building. The Z, I and W factors can be defined more clearly than the other two factors which may vary significantly according to local country regulations.

Besides forces, most codes establish limitations in lateral displacements and structural systems. For example, Peruvian 1998 code establish a maximum inter-story drift for reinforced concrete buildings of only 0,007 for displacements calculated without taking into account any reduction in seismic forced, i.e. R = 1. Reticular slabs are prohibited in various high seismicity areas unless a significant amount of stirrups are added in order to improve their punching shear strength.

Vertical distribution of static equivalent horizontal forces also varies according to local regulations. Combinations of uniform, triangular and/or added local force on top of the building are, in general, distributions assumed in codes. For complex buildings with local discontinuities dynamic analysis is required based on spectra for local soil conditions. For example, CUBE tower, shown in Figure 13.6, is an example of a complex building that requires a dynamic analysis. The building, in Guadalajara, Mexico, is located in a high seismicity area. Certainly a building of this magnitude has to be calculated using modern precise methods but it is as important to provide conceptual design as presented in the introduction. In this case the load transfer mechanism is quite simple since there are three macro-columns corresponding to the services nucleus which carry the full load. Supported on these curve macro-columns there are steel-wall-beams that carry the unidirectional post-tensioning 40 cm slabs that provide a flat office area. The post-tensioning allows spanning up to 22 m without columns and with just 40 cm thickness reducing considerably the self weight (seismic forced are directly proportional to weight). For example, a typical 16 m span posttensioned unidirectional slab of the building weighs only 450 kg/m^2. Moreover, the steel-wall-beams provide a redundancy mechanism. In case that any diagonal in the building is suppressed, the remaining elements provide alternative mechanisms to support the vertical and lateral loads. Finally, shear walls limit lateral deflections due to their large stiffness limiting damage to non-structural elements.

Modern codes, namely the 1997 US Uniform Building Code (UBC-97, 1997) and the EC-8 (2004), specify a base shear that depends on the seismic hazard level of the site, possible site effects from the site's geology, possible near fault effects, and the use, weight, fundamental period and lateral force resisting system of the building. In areas of high seismicity, sufficient ductile detailing to accommodate the inelastic demand (Bachman and Bonneville, 2000) had been mandatory. To achieve this goal codes impose story drift limitations and a maximum inelastic response displacement. They also require the evaluation of the deformation compatibility considering P-Δ effects.

Conventional seismic design of buildings, based on ductility and structural redundancy and developed in the 1970's, allows reduction in seismic design forces between 1 and 10 (R factor in the UBC-97 (1997)), compared to linear elastic forces. The reduction depends on the material and structural system selected for transferring the lateral loads. This approach allows for smaller sections and provides safe systems as long as fiber, sectional and global ductility is provided. An important aspect to note is that the analysis is based on a linear elastic response reducing directly the forces without taking into account the non-linear nature of the problem. This gross simplification allows a simple approach using the wide-spread mode superposition dynamic analysis method applicable to many practical situations. However, this approach has various drawbacks such as that the global ductility demand may require a large local ductility and, consequently, local failures do occur. Besides, large reduction in forces implies structural damage (non-structural damage is controlled limiting inter-story drift) which may be costly to repair after a major earthquake. Finally, minimum steel reinforcement, necessary to provide sectional ductility, is applied to all the elements in the lateral load system, resulting in expensive structures.

Fig. 13.6. CUBE tower in high seismicity area showing strong discontinuities and long cantilevers (The structural design was done by L. Bozzo)

Figure 13.7 shows the reduction in seismic forces that may be achieved providing ductility for a particular earthquake ground motion representative of stiff local soil conditions.

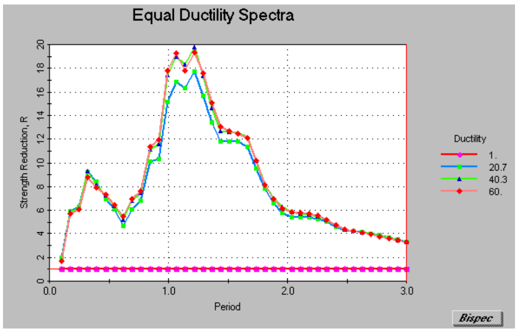


Fig. 13.7. Reduction in seismic forces providing local ductility (Loma Prieta earthquake, ξ=5%)

The ductility levels considered in the figure are μ = 1; 20, 7; 40, 3 and 60. The R factor represents the relation between linear and non-linear forces for various levels of ductility (the first curve for ductility 1 is a straight line corresponding to R = 1 since, clearly, there is no reduction). This figure shows significant reductions for the whole period range considered, particularly for T > 0.5 s with maximum values of R = 20. Certainly, there are other factors such as lateral flexibility and damage to non-structural elements that may limit this reduction but it is clear the advantages of providing ductility for seismic design.

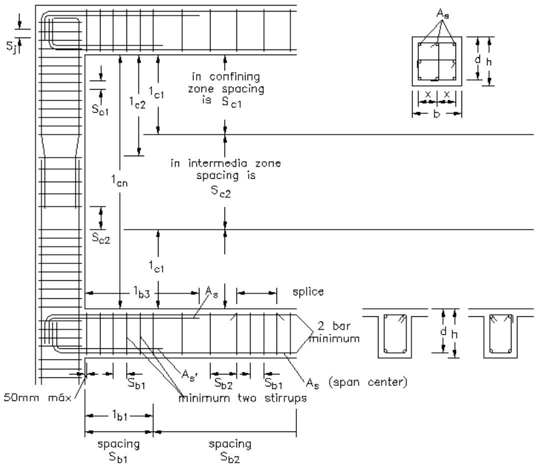


Fig. 13.8. Ductile frames according to UBC-97 (1997)

The practical way to provide ductility for frames is illustrated as an example in Figure 13.8. This drawing represents the UBC requirements for ductile structures and it can be considered a general way to provide this structural response. Stirrups are added at the ends of the columns/beams in order to restrain longitudinal reinforcement from buckling once the concrete cover is spelled during a strong earthquake. In these zones, plastic hinges would be formed during a strong movement and the stirrups allowed developing a ductile sectional response. Splices should be done at the centre of the column (minimum moment zone) and stirrups should be added. Figure 13.9 shows the construction practice in Mexico where steel reinforcement for columns is placed up to 12m high in order to reduce splices. In the photo a construction worker is on top of the longitudinal reinforcement.

Fig. 13.9. Column construction practice in Mexico to reduce reinforced splicing

13.4. Actual trends for seismic design

An alternative to improve current design practice based on ductility and redundancy is the development of structural systems that localize the non-linear structural response. Examples of these systems in reinforced concrete structures are coupled shear walls or, in steel, the eccentric braces (Bozzo and Barbat, 1999). In the first one the link between the walls acts as a "seismic fuse" that controls the response during earthquakes. Similarly, in the second one the horizontal "link" between the diagonal elements provides a ductile response based on the stable hysteretic steel response under shear stresses. Both alternatives have two important drawbacks since interaction with surrounding elements may affect the ideal response of the "seismic fuse" or "link" and they are difficult to repair since they are an integral part of the overall structure.

On the other hand, alternatives for seismic design have been developed in the 1980's using the so-called base isolation (Naeim and Kelly, 1999) and energy dissipaters. Base isolation is an established technique for small to medium size buildings that allow significant reduction in seismic forces by either shifting the fundamental natural period of the building or introducing a low-friction-interface that limits the force transmitted to the upper structure. There are hundreds of buildings constructed with this technique, which, however, have some important drawbacks. Among them, the non-linear response of the upper structure may be conditioned by the base-isolation connection (Ordoñez et al., 2003); the cost is increased; a flexible (usually about 30 cm) gap must be provided around the building and for all the service lines; the effectiveness is reduced as the number of stories (or natural period) is increased.

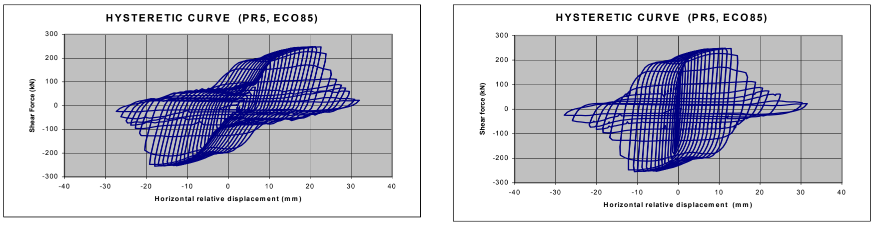
On the other hand energy dissipaters are a different alternative suitable for medium to high rise buildings that do not require special construction techniques or analysis. There are various systems such as the "Adding Damping And Stiffness (ADAS)" (Scholl, R, 1993) or the honeycomb (Kobori et al., 1992). There are also many examples of structures equipped with these systems.

Fig. 13.10. BOZZO-GERB energy dissipater

Shown in Figure 13.10, the BOZZO-GERB dissipater is an innovative shear link type dissipater. This proposed dissipater is based on the aforementioned eccentric braces since the overall shape is a well stiffened wide-flange section. However, the system is not based on standard shapes or specially welded ones. Instead, the device is milled from a plane standard shape. This fabrication process proposed by Cahis et al. (2000) allows very thin dissipative areas without welding. In the other hand, as in eccentric braces, dissipation of energy is uniform in the whole section, and it is very stable provided web buckling is avoided. Another important feature of this dissipater is that it presents a double mode work. Initially the energy is dissipated mainly in the web by uniform shear stresses in a "shear mode". After the web degrades, the stiffeners continue dissipating energy in a "flexural mode". The deflected shape changes significantly among those modes from a linear one to a curved one. The importance of this feature is that it provides a robust system that continues dissipating energy even after the web is degraded. Even though the design of the connection counts only with the first working mode, the second one provides an additional safety factor.

Figure 13.11 shows typical hysteretic experimental curves for a device performed at ISMES (Italy) in 2002. The Figure 13.11, part (a) includes the slippage in the connection while the curve in part (b) does not include any slippage. This indicates that the first curve is obtained using displacement transducers above the holes and the second curve within the holes and, consequently, does not include the slipping of the bolts. The experimental yielding force was about 150 kN and the yielding displacement about 0.5-1 mm. The total cumulative dissipated energy before any degrading of the devices was 77.528 kN.mm and 53.851 kN.mm for the first and second curves, respectively. For the second case the total dissipated energy after degradation of the device, i.e. including the flexure mode, was 97.210 kN.mm. This indicates that a significant additional energy may be attained by the flexural mode as well as by the slipping of the connection. However, slippage is not considered a good response characteristic since it is difficult to predict, and so the tolerance is reduced as much as possible, just to accommodate for installing the devices.

The basic concept behind the proposed dissipater is to provide a general plastic-hinge available in different yielding forces and displacements. Therefore, it is not intended to have a unique system or specific geometry but a set of alternatives from which the designer can choose. All the connections should, however, have similar response characteristics and behaviour.



(a) Hysteretic curve including slippage of the bolts

(b) Hysteretic curve without slippage of the bolts

Fig. 13.11. Typical experimental hysteretic curve for devices

Recently many seismic design codes had been setting requirements relating to the performance of the buildings. This performance-based design sets an acceptable performance for a building that depends on the building's function and the level of seismic hazard considered. The acceptable performance is usually defined as an allowed damage condition, always avoiding achieving the collapse of the structure. Therefore, the challenge for designers is to ensure that cumulative damage is to remain within acceptable bounds so that people within and around buildings are able to escape from damaged buildings even after a major earthquake (King and Shelton, 2004). The use of the so-called "push-over analysis" (Fajfar, 2000) is a feature already included in commercial software to allow the designer a first non-linear analysis of buildings.

Several publications such as ATC-40 (1996) and the Vision 2000 (SEAOC, 1995) have introduced the definitions of the performance levels. The performance level required for a building is described by the physical damage within the building, the threat to the life safety of its occupants due to the damage, and the post serviceability of the building (ATC-40, 1996; SEAOC, 1995). The performance level definitions proposed by Vision 2000 are shown in Table 13.1.

Figure 13.12, from Rodgers and Mahin (1999), shows the building performance requirements as a function of the intended occupancy and use of the building. As can be seen, under a given level of hazard or earthquake probability, the damage considered acceptable decreases as the importance of the building's use and occupancy increases. For buildings designed using the performance based concepts, moderate or worse damage levels are considered to be an unacceptable performance when affected by a frequent level of hazard, while for rare hazard levels even collapse is considered an acceptable performance level. This performance based design philosophy is being recommended as a useful tool to evaluate the seismic performance of existing buildings in order to verify if they comply with new performance requirements (Comartin et al. (2000).

Table 13.1. Definition of the performance level from Vision 2000

Performance Level	Condition
Fully Operational	Continuous to give service. Negligible structural and non-structural damage.
Operational	Most operations and functions can be resumed immediately. Structure is safe for occupancy. Essential operations are protected, non-essential operations are disrupted. Repair is required to restore some non-essential services. Damage is light.
Life Safety	Damage is moderate, but the structure remains stable. Selected buildings systems, features, or contents may be protected from damage. Life safety is generally protected. The building may be evacuated following the earthquake. Repairs are possible, but may be economically impractical.
Near Collapse	Damage is severe in structural elements, but structural collapse is prevented. Non-structural elements may fall. Repair is generally not possible.
Collapse	Partial or total loss of structural integrity. Partial or total collapse. Repair is not possible.

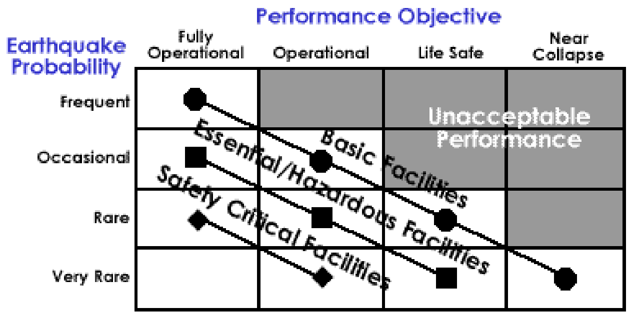


Fig. 13.12. Building performance requirements from Vision 2000

13.5. Final Remarks

Having a set of seismic design provisions and guidelines appropriate for a given region is an important step for reducing its seismic risk. This chapter has exposed both architectural design principle and design provisions that are considered to be the most important aspects for having earthquake resistant buildings. It must be mentioned that as important as having an appropriate design code, this seismic code has to be enforced in order to be as effective as it can be. Laws should be implemented requiring adequate supervision through the design and construction stages in order to ensure projects truly conform to the seismic design codes. Such concept has been implemented in Turkey after the 1999 earthquakes Kocaeli and Düzce with the establishment of the new role of building supervision specialist (Spence, 2004) in order to certify that new buildings do follow the seismic design provisions.