CONFIGURATION AND MORPHOLOGY FOR THE APPLICATION OF NEW SEISMIC PROTECTION SYSTEMS

Marco MEZZI

SUMMARY

New seismic design methods should address the system ability to dissipate energy and the effects of lateral deformation to improve the safety of buildings. These considerations, involving the structural configurations of buildings as well as their morphology, however, have not significantly influenced the behaviour of the community of the architectural designers. The analysis of the relations among morphology, structural solution and seismic response of buildings equipped with innovative protection systems, leads to outline new basic criteria in architectural conception. Isolation, damping, energy dissipation are able to enhance the building performance and certain morphological characteristics, usually considered to be inappropriate, become subordinate. At the same time, new design principles, such as flexibility, discontinuity, motion, device insertion, shape, comfort must be taken in consideration. With reference to new buildings, the criteria guiding the conceptual design of a class of configurations, characterized by the suspension of portions or elements, are illustrated.

1. INTRODUCTION

New design methods, improving the seismic safety of buildings, should consider the system ability to dissipate energy and the effects of the lateral deformation. These considerations involve both the morphological and structural configurations of buildings, nevertheless, so far they have not significantly influenced the fundamental concepts guiding the architectural design.

New relations between architectural morphology, structural configuration and seismic behaviour of buildings arise, when innovative protection systems, like base isolation or energy dissipation, are used. The criteria leading the architectural conception and the selection of even complex forms, or new architectural morphologies, to achieve a suitable seismic behaviour must be outlined. Some essential characteristics usually considered inappropriate, can be used to enhance damping effects and energy dissipation.

The study presented is included in a larger research which goals consist of organic lists of structural solutions allowing for the optimum articulation of architectural morphologies aiming at seismic protection; suitably outlined architectural configurations including their significant seismic performances; optimum classification of innovative protection systems for the defined morphological classes. Applications on study cases and actual buildings are illustrated.

The concept of building configuration must be regarded in all its aspects including morphology, technology, structural solution and aesthetics. These aspects, although they may be separated from a logical point of view, are interconnected and sometimes interdependent.
2. TRADITIONAL MORPHOLOGICAL RULES

2.1 Global shape

The conventional morphological parameters included in the classic principles of earthquake engineering are absolute dimensions, compactness and symmetry, regularity.

The basic configuration parameter, linked to the seismic behaviour of structures, consists of buildings dimensions. It was the first parameter included in codes and it is still cited by certain guidelines. The dimension that is really controlled is generally the height of the building, but, in fact, the parameter relates to seismic resistance in connection to structural material. Prescriptions on dimensions have worked, and work out well for masonry buildings. Their effectiveness decreases when it comes to modern and innovative materials: in this case, the principle can be still effective in controlling some building performances as overturning and tension in columns.

The principles of symmetry and compactness come to the forth since one objective is avoiding the irregular distribution of forces induced by the earthquake: the optimum goal of a correct seismic design being that all the structural members contribute to the resistance and energy dissipation [Arnold, 1982]. Avoiding spreading in the distribution of masses, resistances and stiffness eliminates large eccentricities and limits the torsion effect. Symmetry and compactness requirements not only concern the structural configuration but also strongly involve architectural morphology and may impose significant constraints on the building shape that should be "simple" both in plan and in elevation (Figure 1), where the concept of "simplicity" corresponds to the absence of concavity [Arnold, 1982].

Also the principles of uniformity and regularity aim at eliminating the occurrence of critical zones where concentrations of stress or large ductility demands might cause premature collapse. Actually, these principles, imposing significant limits to the variation of shape, mass, stiffness and resistance in plan and along the height of the building, actually introduce other severe constraints on the configuration and consequently guide the morphological design. They can often be in contrast with some visions of the modern architecture: a typical case is represented by the soft-first-story, which has been, and still is, widely used by architects because it corresponds to one of the leading principle of the modern architecture: the "pilotis-story", one of the five basic points presented by the French architect Le Corbusier in its "Vers une architecture" on 1923.

Figure 1: Simple and complex shapes for in-plan and in-elevation configurations

2.2 Technology

The technological aspect of configuration is fundamentally related to structural material. The physical and mechanical characteristics of the material can determine or strongly influence the building configuration. In fact, the optimum use of the material, from an economic and mechanic point of view, requires specific shapes for the structural elements and their assemblage: for example, bracing is required in steel frames characterized by slender elements to resist to lateral forces. In some historical cases - Egyptian or Mayan pyramids or Babylonian ziggurats (Figure 2) - material and morphology seem to coincide and can be confused. The same happens in the ordinary applications of masonry or stone buildings, where the global configuration depends on the configuration of the structural elements, the walls, depending on the materials.
2.3 Structural solution and aesthetics

Sometimes the structural solution determine the morphology like in the case of arches and vaults: the Roman aqueducts and the domes of the Italian Renaissance well express this principle (Figure 3 a and b). But, usually the structural solution can slightly influence, and not necessarily determine, the final configuration. It can be considered a "second level" parameter which can be determinant only when linked to the architectural choice of making evident a structural aspect. On the contrary, in some architectural solutions structure is slave to morphology, which is chosen on the base of aesthetical or expressive considerations (Figure 3c).

3. NEW CONFIGURATION RULES FROM INNOVATIVE SOLUTIONS

New design concepts are required for making the performance of the enhanced system of seismic protection possible [Mezzi et al., 2004]. They consist of deformation, motion, discontinuity, visibility of devices, shape and comfort.

This principle of deformation can be described as the capacity of the construction to perform large local displacements so as to permit the displacement of dissipative devices inserted in the structural grid (Figure 4). Vertical dissipative bracing can be inserted in the frame grid and dissipate energy in the relative displacement through adjacent floors. Horizontal bracing can be equipped with dampers dissipating energy through the horizontal shifts of braced floors. In both cases, large displacements via adjacent connections guarantee remarkable energy dissipation and response reduction.
Another performance guaranteeing for a significant energy dissipation consists of the capacity of a construction to undergo movements, that is to change its spatial position in time. The concept contrasts one of the four classical Vitruvius' principles: the "firmitas", which represents the solidness of the construction, rigidly connected to a firm soil. The movement may affect the entire structure or only a section, it deforms devices that, mounted between the building and the firm soil or between building sections which have relative movement, dissipate energy and reduce lateral response.

![Figure 5: Movement capability](image)

The principle of discontinuity relates to that of movement and challenges the architect. Making the motion of the total construction or its parts possible, requires forgetting about external continuity with the ground and internal continuity among members (Figure 6). Motion can be allowed only if a solution of continuity is present: (a) the whole building disconnected from the ground, as in base isolation; (b) mobile sections of building separated from the firm portions integral with the ground, as in suspended building with floating stories; (c) total portions of the building separated to benefit from relative displacements; (d) local structural elements separated from the main structure, as in suspended or floating floors.

![Figure 6: Discontinuity](image)

The reduction of seismic response does not depend on deformations or displacements but on the movement of special dissipating or isolating devices in function during those deformations or displacements. The presence of devices introduces another theme in the architectural design of buildings equipped with these enhanced protection systems, consisting in the visibility of "devices" that look like and generally are mechanisms (viscous, friction or plastic dissipating elements), machines (active dampers) or are made of special materials, unusual in constructions, such as laminated rubber isolators. In some case the devices are hidden and the building appears as an ordinary one, but in other cases devices have been shown (Figure 7), becoming an expressive sign and evidencing their characteristic of special earthquake protection tool.

![Figure 7: Visibility of devices. (a) and (b) Global view and detail of Union House, Auckland; (c) and (d) Global view and detail of Jovine School, Potenza (Italy)](image)
More complex concepts regarding the shape must be applied when new seismic protection systems are inserted for enhancing seismic performances. The shape is not an absolute factor directly influencing the effectiveness of the seismic response anymore, but it must be related to the presence and position of the devices. Two principles guide the morphology of a building equipped with enhanced protection system.

1) The shape must optimize the performance of the seismic protection system. Specific criteria must be found for each system. In base isolation, for instance, the stiffness centrifugation of the isolator system and the perimeter concentration of vertical load have been proven to optimize the device behavior and the building response [Mezzi, 2003]. The application of new criteria can even lead to innovative global shapes as shown in Figure 8 [Parducci, 2001].

2) The innovative systems allow to overcome the traditional shape constraints related to symmetry, compactness and regularity, considering the whole effect of global building shape, discontinuities and devices position. These factors interact and determine the real behaviour of buildings: for example, buildings with complex irregular in-plan shapes can have a "regular" response, strongly mitigating torsion effects, if an isolation system, characterized by the absence of eccentricity between mass and stiffness centers and by good stiffness centrifugation, is provided.

A different class of problems derives from the special performances of buildings equipped with innovative protection systems and relates to their deformability. The motion capability of the buildings, to be developed under seismic attacks, remains a constant characteristic of the construction and could create troubles under ordinary service loads. Strong earthquakes that induce movement in buildings are rare events, characterized by short duration, therefore motion is admissible or large values of the acceptance limits can be assumed, but flexible and movable buildings must be checked, for the comfort of the occupants, under service lateral loads which are frequent and can have a long duration that could provoke the same movements, even though with reduced amplitude. Comfort and panic controls criteria, generally well established both in national and international codes and based on the examination of the cinematic parameter, can be applied. Even though the effects must be checked, this cannot be considered a real problem creating difficulties on the application of the innovative systems, actually, the presence of isolating or dissipating devices and, even more so, of active or hybrid systems for the control of vibrations, usually has a positive effect on the construction dynamic, reducing the impact that vibrations may have on occupants.

4. A CLASS OF ENHANCED CONFIGURATIONS FOR NEW BUILDINGS

Two design aspects are involved in the application of state-of-the-art seismic protection systems and their relation with building configuration. One consists of the possibility, prompted by the new systems, to sustain the seismic performance of configurations that would otherwise be incompatible with earthquake resistance, and then enable the enhancement of existing unsuited configurations [Mezzi and Parducci, 2005; Mezzi, 2006]. The other one concerns the possibility, or need, to develop new configurations made possible, or required, by the new performances. This last options is illustrated in this chapter with reference to the class of configurations characterized by the presence of suspension system.

A typical category of structural solutions, making configuration rules compatible with innovative solutions, particularly in discontinuity and motion, is that provided for the suspension of parts or elements of a building. Different structural schemes with these characteristics have been investigated: the "bell buildings", the "floating floors" schemes, and the "bridge buildings".
4.1 "Bell buildings"

Some years ago, a research was carried out [Mezzi et al., 1994] on the configuration of suspended buildings, aimed at analyzing seismic behaviour, pointing out design criteria, designing special dissipating devices and a prefabricated structural system and planning its industrialized production. Different global configurations, shown in Figure 9, were compared. They differ in the internal connecting system between the structural parts: in scheme A the top connection is rigid, in scheme B the connection is pinned, in scheme C a balancing beam is provided as suspension deck. Six schemes were compared considering - apart from the basic schemes A, B and C in Figure 9 - a reference configuration (B0) with rigid lateral connections and two variants: in variant B1 the upper lateral connection was omitted, in variant C1 a rigid head connection was considered.

![Figure 9: Schemes and performances of suspended buildings [Mezzi et al., 1994]](image)

On the right of Figure 9 the graph shows the bending moment ratio (against the reference configuration rigidly connected) at the bottom section of the core wall versus the building height (in terms of number of floors of the suspended block), of the different configurations. Schemes B and C have rather similar response reductions, but the latter was preferred because it permits reducing the rotations of the suspended story-block and the additional tension in the suspension ties associated to lateral oscillations.

4.2 Floating floors

Another class of suspended configurations can be discussed by referring to floors suspension when the main vertical structures remain rigidly connected. This class of configurations can be used for the structural solution of those architectural themes which implies a regular framed structure as support and container of a free distribution of floors occupying only part of the building plan and having irregular shapes differing at different levels so that a complex distribution of spaces with different heights can be obtained within the container-structure. The Future University of Hakodate in Japan, designed by Riken Yamamoto, represents a good example of this distribution, Figure 10 shows an external and internal views of the building where the space articulation can be appreciated.

This class of solutions was investigated in depth in a thesis [Ottaviano, 2002] addressing various solutions that differed in the dissipating system adopted to limit the horizontal forces transmitted to the main structure. Figure 11 shows the three solutions that were studied: suspended floors laterally connected with plastic devices (SP); suspended floors braced with viscous devices (SV); isolated floors (IF). The schemes have a span length of 12 m and a story height of 5 m, the story mass is 1.066 t/m². Two solutions were adopted for the main structure, the first including ground-roof free columns, the second framing beams at floor level.

![Figure 10: External and internal view of the Future University of Hakodate in Japan](image)
Dynamic analyses carried out on simple schemes, using four artificial accelerograms having PGA equal to 0.35 g and fitting the spectrum B of [Eurocode, 2003], show the effectiveness of the isolated or dissipated solutions. Table 1 shows the ratio of shear force, V, and bending moment, M, (average of the four responses) at the column base for the different enhanced solutions to the reference solution (REF) of the conventional continuous frame. The base shear and bending moment can be reduced to about one third of their nominal value, with reduction effectiveness practically independent of the type of enhancing solution used.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>V/V&lt;sub&gt;REF&lt;/sub&gt;</th>
<th>M/M&lt;sub&gt;REF&lt;/sub&gt;</th>
<th>Scheme</th>
<th>V/V&lt;sub&gt;REF&lt;/sub&gt;</th>
<th>M/M&lt;sub&gt;REF&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>0.33</td>
<td>0.35</td>
<td>IF</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
<td>SP</td>
<td>0.37</td>
<td>0.36</td>
<td>SP</td>
<td>0.37</td>
<td>0.38</td>
</tr>
<tr>
<td>SV</td>
<td>0.32</td>
<td>0.35</td>
<td>SV</td>
<td>0.30</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The study has been extended by taking in consideration simplified three-dimensional schemes as well as complex arrangements as those shown in Figure 12. The last model simulates a real structure with floors irregular shapes and free columns on the total height.

Table 2 features the results obtained on the last complex scheme. The ratios of the maximum forces at column base (shear forces, VX and VY, and bending moment, MX and MY) and roof beam (shear, VB, and moment, MB) are shown in comparison to the reference scheme. The reduction factors range from 0.231 to 0.419 for the columns, doubling the seismic capacity of the enhanced structure when compared to the conventional configuration.
Table 2: Ratio of the forces at column base and roof beam with respect to the reference scheme

<table>
<thead>
<tr>
<th>Scheme</th>
<th>VX</th>
<th>VY</th>
<th>MY</th>
<th>MX</th>
<th>VB</th>
<th>MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>0.345</td>
<td>0.321</td>
<td>0.321</td>
<td>0.415</td>
<td>0.514</td>
<td>0.441</td>
</tr>
<tr>
<td>SP</td>
<td>0.392</td>
<td>0.230</td>
<td>0.290</td>
<td>0.419</td>
<td>0.509</td>
<td>0.434</td>
</tr>
<tr>
<td>SV</td>
<td>0.307</td>
<td>0.240</td>
<td>0.290</td>
<td>0.379</td>
<td>0.562</td>
<td>0.430</td>
</tr>
</tbody>
</table>

4.3 "Bridge buildings"

One of the themes of contemporary architecture is represented by the so-called "bridge buildings" where the entire shape of the structure reproduces the opening typical of bridges: well known and impressive examples of this kind of buildings are shown in Figure 13. The void of the bridge building can be "filled" with a suspended block of stories thus obtaining the structural scheme of suspended "bridge buildings", consisting of a main bridge structure where the floors are suspended, like in Figure 14a.

In this case, the lateral connections between floors and the main structure can consist of dissipative devices that limit the force transmitted and dissipating energy. Analytical evaluations have been carried out on simplified plane models like that shown in Figure 14, to check the efficiency of the enhanced dissipative scheme of the suspended "bridge buildings". The model reproduces the lateral behaviour of a thin building or a unit depth of a thick one. Different plastic threshold values have been assigned to the laterally connecting devices. Optimized threshold distribution along the height have been found, generally using reduced values at lower levels.

Figure 13: "Bridge buildings". (a) Grand Arche de la Défense, Paris (design Johan Otto von Spreckelsen), (b) Umeda Sky Building, Osaka (design Hiroshi Hara),

Figure 14: Hong Kong and Shanghai Bank Building, Hong Kong (design Norman Foster); (c) Models of low-rise and high-rise suspended "bridge building"
Figure 15a shows the shear along the pier height for different device characteristics. Evidently, optimized device
distribution reduces the column base shear of about 40%. The scheme becomes even more efficient by increasing
height: with triple height the base shear and moment remain about the same, as shown by the graphs of the base
shear vs. the plastic threshold of the isolators in Figure 15b. In this case, a better structural response can be
obtained if the piers are framed with horizontal beam at one third and two thirds of the height.

Figure 15: (a) Shear force along the pier height; (b) Base shear force

5. CONCLUSIONS

Isolation, damping, energy dissipation, active control, can greatly enhance the performances of buildings. A
correct design, taking into account these innovative seismic protection systems, requires new basic criteria
controlling the relation between architectural morphology and structural configuration. The traditional rules
become subordinate, while new design principles must be used. These are summarized by the concepts of
flexibility, discontinuity, motion, device insertion, shape and comfort. The definition of tentative rules for the
application of these principles to new buildings has been accomplished by making reference to special sample
configurations based on suspended schemes.

6. ACKNOWLEDGEMENTS

M. Mezzi acknowledges the financial support of the ReL UIS program of Dipartimento della Protezione Civile.

7. REFERENCES

Eurocode no.8, (2003), Design of Structures for Earthquake Resistance, prDraft No.3.
Proc. 10th ECEE, Balkema, Rotterdam.
Conceptual Approach to Structural Design, Milan, Italy.
Innovative Aseismic Systems, 13th WCCE, Vancouver, Canada.
Mezzi, M., Parducci, A. (2005), Preservation of Existing Soft-First-Story Configurations by Improving the
Mezzi, M., (2006), Enhancing the Seismic Performance of Existing "Pilotis" Configurations, IABSE Conference
"Responding to Tomorrow’s Challenges in Structural Engineering", Budapest.
Ottaviano, L., (2002). Configurazione architettonica e prestazione sismica: applicazione di sistemi innovative per
la protezione degli edifici (in Italian), Graduation Thesis, University of Perugia, Italy.
experience, International Post-Smirt Conference Seminar Isolation, Energy Dissipation and Control of
Vibration of Structures, Cheju, Korea.
Parducci, A., (2001), Seismic Isolation and Architectural Configuration, Special Conference on the Conceptual
Design of Structures, Singapore.