DEFORMATION VS. STIFFNESS. MOTION VS. FIXITY. NEW VISIONS IN SEISMIC CONCEPT DESIGN

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ABSTRACT :

The paper deals with the interaction between the seismic performance of buildings and their global and local configuration. When traditional material were used, technological aspects and structural solutions guided the architectural concept design. In the modern era architects used the new materials to free the morphologies, but the classic design principles based on the Vitruvian "firmitas" with reference to the vertical loads were maintained and when the earthquake engineering gave a number of earthquake-resistant morphological rules, they were received as constraints on the global shape. Nowadays, the up-to-date seismic protection techniques provide for building performances based on the principles of the mechanics more than on those of the statics. The new principles of motion and deformation capabilities of buildings that should guide the architectural design are summarized and discussed. The class of the regular buildings equipped with dissipating bracing systems is used for exemplifying the possibilities got from the application of the new principles.

KEYWORDS: concept design, principles, earthquake protection, innovative systems

1 INTRODUCTION

The strong influence of the structural configuration and global morphology in the building response is well known in the world of the earthquake engineering, and the principles that must guide the design choices have been well established since a number of years: the classic book of Arnold and Reithermann (1982) is usually referred. Nevertheless these principles are not spread in the community of designers due to a number of different motivations. The main reason is that in reality they are not known, because most of the designers have not received an education including the seismic design. In Italy, for example - an earthquake prone country, where a strong earthquake with damage and casualties occurs every ten-fifteen years - earthquake engineering is not included among the fundamental compulsory courses of the graduates in architecture or in civil engineering, only the post-graduation in structural engineering includes such a course. Anyway, this is not the argument of this paper, it has been only reminded for highlighting the fact that the principles guiding the conceptual design of buildings, are still based on accounting for the only vertical loads. An effective earthquake resistant design should account for two other principles: the structure should sustain the seismic lateral load, the structural system should be able to dissipate, without collapsing, the input energy. The innovative seismic protection systems - like base isolation, dissipating bracing, active or hybrid systems - enhance the dynamic capacity of the building with reference to the energy management. The systems provide for enhancing the internal dissipating capacity of the building, or for reducing the input energy, or for inputting additional energy for sustaining a counter-movement. These systems, as it will be discussed in the following, require a conceptual approach to the seismic design based on dynamics and mechanics, more than on statics.
The paper deals with a research path that started since some years (Mezzi et al., 2004, 2006, 2007). It is structured in three parts. In the first part the correlation between structural configuration and morphology is discussed making reference to the arguments of tradition. In the second part, the principles related to the use of new earthquake resistant systems are listed. The purpose is to outline criteria leading the architectural concept and the selection of new architectural morphologies, for achieving a suitable seismic behavior, allowing the optimum performances of the devices. New concepts can lead the design of buildings, even overwhelming some traditional rules considered as inalienable. In the last part, as an illustration of new design routes, some considerations are reported, derived from a parallel study concerning the structural configuration and the related morphology of the class of buildings including an energy dissipating bracing system.

2 EVOLUTION OF THE CORRELATION BETWEEN CONFIGURATION AND MORPHOLOGY

The history of the architecture is dominated by the reference to the vertical loads and by the request for strength. The three main goals of the building were pointed out by Vitruvius, who wrote: *"Haec autem ita fieri debent ut habeatur ratio firmitatis, utilitatis, venustatis" (I,VI)* (Vitruvius, 1997). From the engineering point of view, according to the principle of *firmitas* (stability), the building should have solid foundations and should be built using appropriate materials. This principle was extended by Andrea Palladio, who, in place of the *firmitas*, introduced the concept of *perpetuitas* (long-lasting), but obviously applied it within the knowledge level of his epoch, recommending strong foundations, strengthening of walls at lower stories, verticality of columns, alignment of windows (Palladio, 1990). We can now appreciate the modernity of this concept that we can interpret in terms of building life-cycle.
The concept of building configuration is a complex issue because it includes considerations concerning the shape, technology, structural solution and aesthetics. The correlation between morphology and structural configuration becomes particularly relevant when accounting for the capacity of the construction against extreme, or exceptional, actions. The capacity against the extreme loads is enhanced when all the elements can develop their maximum contribution in terms of energy dissipation, that is of both strength and deformation capacity. This behavior is possible only if the configuration and morphology do not induce a concentration of strength or ductility demand. The fundamentals of the seismic design are controlled by this concept therefore the correlation between morphology and structural configuration is a primary issue of the earthquake engineering. Considering the evolution of the construction history from this point of view, four stages have been pointed out.

2.1 First stage: the traditional materials

A first class of correlations between morphology and configuration can be identified as a consequence of the use of traditional or historical materials, characterized by significant compressive strength, but by the practical absence of tensile strength. The correlations result by the application of the classical form of the structural problem: the data are the known external forces; the goal are the stability, stiffness, and strength of the construction; the solution consists of a structural configuration defined by the paths allowing the forces to flow from the area of application toward the restraints, inducing compressive forces in all the structural elements. Because the best way to carry a force is to use a structural element directed as the force or its components, and considering that the main external forces that a building shall contrast are the gravity loads, the dead load as the first, the main load carrying structures consist of vertical compression-resistant structural elements. The exaltation of this concepts can be found in the legendary high-rise buildings, going from the myth of the Babel tower to the still standing Egyptian pyramids (Figure 1).



Figure 1 Vertical load carrying high-rise buildings. The myth: the Babel tower; the tale: the Faro of Alexandria; the witness: the Cheope pyramid

The second structural requirements of a construction system derives from the necessity to cover free spaces. Also in this case the material guides the structural solution and then the morphology (Figure 2): the low tensile strength limit the covered span, the compressive strength leads to built arches and vaults. In some cases a mutual interconnection exists among shape, structural solution, and technology: a typical example is represented by the wooden trusses used for inclined roofs. The morphology, even if it is a condition, is not an independent variable.

Figure 2 Vertical load carrying spanning structures. Architraves of the Temple of Karnak, Luxor, Egypt. Vault of the Pantheon dome, Rome.

In the architecture of the traditional materials the technology and the structural solution prevail on the morphological solution that is fundamentally governed by the material: the optimum use of the material, from an economic and mechanic point of view, requires specific shapes for the structural elements and their assemblage The same happens in the current applications of masonry or stone buildings, where the global configuration depends on the configuration of the structural elements, the walls, depending on the material.
Compressive resistant materials do not allow for configurations able to resist the forces induced by lateral loads, especially if relevant, as those ones consequent to a seismic attack: the only way to support lateral loads is related to the interaction with the vertical load. This is true at both global and local level. At global level the resultant of the vertical and horizontal load shall maintain a compatible stress status in the section, on this aspect the shape can play a role. At local level the compressive stress from the vertical loads control the shear strength.

2.2 Second stage - modern materials

The use of modern materials identify a second class of correlations between morphology and configuration. We are calling "modern materials", for differentiating them from the traditional ones, those materials characterized by strength capacity both in tension and in compression and in general by high or very high values of the strength. We include in this category steel and reinforced concrete that characterize the constructions of the last 100-150 years.
The possibility of designing structural elements capable of sustaining every kind of forces leads to a conceptual design where the structural configuration can be practically independent of the shape. The morphology is now unrestrained by the requirements of the optimum structural configuration and by the material technology. Free-shaped structures, often made of r/c but also of steel or other materials (Figure 3), were the consequence arising from those principles. Moreover, the development of the modern architecture in countries out of the earthquake prone areas and, most of all, the lack of knowledge on structural dynamics and the delay of the birth of the earthquake engineering allowed the spreading of morphological solutions unsuitable for the seismic resistance, like those providing for soft stories or exalting the overturning effects.

Figure 3 Vertical load carrying modern free-shaped buildings. Villa Savoye (Le Corbusier); Museo Guggenheim Bilbao (Frank Gehry); Toronto Sharp Centre for Design (Will Alsop)

2.3 Third stage - earthquake engineering

The catastrophic earthquakes occurred at the end of the 19th century and, most of all, those occurred in the first part of the 20th century (San Francisco, 1906; Messina, 1908; Tokyo, 1923) pushed the research and the development of seismic-resistant systems based on the principles of the seismic protection. But the earthquake engineering became definitively established after the second world war and we observed the development of engineered structural systems based on seismic-resistant schemes capable of sustaining the lateral actions and also of dissipating energy. The earthquake engineering recognized the importance of the morphological aspects on the seismic response of constructions leading to the formulations of design principles based on the dimensions, compactness, symmetry, regularity, that are the parameters describing the shape (Figure 4).
The control of the global buildings dimensions was the first parameter included in codes and it is still present in guidelines. The dimension that is really controlled is generally the height of the building but the effectiveness of this control decreases when modern and innovative materials are used.
Symmetry and compactness - avoiding the spreading in the distribution of masses, resistances and stiffness - have the goal of avoiding the irregular distribution of the seismic forces, guaranteeing that all the structural members contribute to the resistance and energy dissipation. These requirements mainly concern the architectural configuration and can imply significant constraints on the morphology.
Also uniformity and regularity are aimed at eliminating premature collapse of critical zones where concentrations of stress or large ductility demands are present. These principles, limiting the variation of shape, mass, stiffness and resistance in plan and along the height of the building, constrain the configuration and consequently guide the morphological design.


Figure 4 Morphology for earthquake resistance: Transamerica Building in San Francisco (William Pereira); Mitsui Building, Tokyo (Nihon Sekkei)

Many of the morphological principles for enhancing the seismic performance of the structures are in contrast with some visions of the modern architecture, previously reminded and derived by a vision based on accounting for the only vertical loads and by a substantial independence of the creative aspect of the morphological assumption from the structural demand, that, it is assumed, can be evaluated and always satisfied at a successive stage of the design. In spite of the advance of the knowledge concerning the seismic protection of constructions, the fundamental vision of the architecture is always anchored to the classical one: construction is devoted to sustain vertical loads with systems characterized by stability, strength, fixity.

2.4 Fourth stage - new technologies

In the last three decades new technologies were developed allowing for an high level of seismic protection. The seismic resistant systems are capable to modify the dynamic interaction between the excitation and the structure response. A reference can be done to the fundamental equation (2.1) of the dynamics of a SDOF system - having mass M, damping C, internal force R_i - excited by a seismic input characterized by a ground acceleration history, a_g ,and to the corresponding equation (2.2) in terms of energy equilibrium

$$M\left(\ddot{x}+a_g\right)+C\,\dot{x}+R_i=0 \tag{2.1}$$

$$E_I=E_s+E_k+E_h+E_\xi \tag{2.2}$$

where E_s is the recoverable elastic strain energy, E_k is the kinetic energy, E_h is the irrecoverable plastic hysteretic energy, and E_ξ is the irrecoverable damping energy, E_I is the input energy.
Three are the terms of the dynamic equation and three are the energy factor that the protection system can modify: three strategies of protection derive from the application of the new technologies.
Base isolation act on the stiffness reduction of the isolation system obtaining a shift of the fundamental period toward higher values, where the input energy of the earthquake is strongly reduced.
Energy dissipation is based on the insertion of special dissipating devices within the structural mesh so increasing the damping energy or the hysteretic energy.
Tuned mass systems provide the manipulation of the mass components: a secondary mass is inserted within the structure and connected through a system allowing for tuning the local frequency on that of the whole building, so obtaining a reduction of the response.
New technologies for seismic protection imply new design visions, for some aspects they partially coincide with the traditional ones, whilst for other aspects they are very innovative, as discussed in the next chapter.

3 NEW PRINCIPLES OF DESIGN

Some new techniques enhancing the seismic performance of the structural schemes may require a new conceptual approach to the morphological design of building. Some restrictions of the traditional earthquake engineering are overcome, but new concepts shall be introduced: deformation, motion, discontinuity, shape, comfort, aesthetics of devices. Generally the new concepts contrast with the classical Vitruvius' principle of "firmitas", which imagines a solid construction, rigidly connected to a firm soil.

3.1 Motion versus fixity

The principle of motion consists of the capacity of a construction, or of a part of it, to change its spatial position in the time (Figure 5a). We can have "global movements" affecting the entire structure or "local movements" involving only a building section or concerning junctions. In the first case, the movement allows to decouple the building oscillations from the ground motion. In the other cases, the motion deforms devices that, connecting the building and the firm soil or connecting different building sections having a relative movement, are able to dissipate energy, thanks to their rheological behavior, so reducing the lateral response.

3.2 Deformation versus rigidity

The principle of deformation (Figure 5b) expresses the capacity of the construction to undergo large displacements inducing the deformation of dissipative devices inserted within the structural mesh. Diagonal or K-shaped dissipative braces can be inserted within the grid of frames, and dissipate energy thanks to the relative displacement through adjacent floors (story drift). Also an horizontal bracing equipped with dampers can be hypothesized, dissipating energy through the horizontal shifts of the braced floors. If a significant energy dissipation and consequent response reduction is requested, large values of the displacements are required.

3.3 Discontinuity versus monolithicity

The principle of discontinuity is related to that of movement, that is allowed only if discontinuities are present. External continuity with the ground and internal continuity among members are no more required, if the motion of the total construction or components is possible. Different situations can be hypothesized: disconnection between the whole building and the ground (Figure 5a); separation among portions of the building (Figure 5c); mobile sections of building separated from the firm portions integral with the ground; structural elements separated from the main structure; local separation of structural elements. The discontinuities usually require the adoption of dedicated technological solutions and always represent an architectural challenge.

3.4 Shape freedom versus shape slavery

The shape still remains a factor influencing the effectiveness of the seismic response, it has not to be considered anymore as an absolute parameter, but it is related to the characteristics and locations of the devices. Therefore, more complex concepts regarding the shape must be applied when new seismic protection systems are inserted for enhancing seismic performances.
Two fundamental criteria should guide the morphology of a building equipped with enhanced seismic protection system. The application of new criteria can even lead to innovative global shapes or structural arrangements (Figure 5d).
The first principle concerns the optimization of the performances of the protection system and requires specific shaping criteria for each case. In base isolation, for instance, the stiffness centrifugation of the isolation system and the perimeter concentration of vertical load have been proven to optimize the device behavior and the building response.
The second principle concerns the integrated effect of global shape, discontinuities and devices' location that overcomes the traditional shape constraints controlling the symmetry, compactness and regularity. The integrated effect of the different contributions controls the real behavior of buildings: for example, even a building with complex irregular in-plan shape can have a "regular" response, without significant torsion effects, if an optimized base isolation system is provided, avoiding the eccentricity between mass and stiffness centers and having a suitable torsion stiffness obtained through a centrifugation of the isolation system stiffness.

3.5 Comfort versus life safety

In traditional earthquake design - based on the use of stiff, strength, ductile structures - the goal of the design concerning the occupants is to guarantee their safety in occasion of the maximum expected earthquakes. When advanced systems are used the protection of buildings is strongly enhanced, limiting the damage status corresponding to the maximum expected earthquakes, toward the goal of the integral building protection. Therefore, the life safety of occupants is not anymore a design goal. On the contrary, the motion and deformation capability of the buildings, that is a constant characteristic of the construction equipped with innovative protection systems, could create troubles to the occupants under the ordinary dynamic service loads. The comfort of the occupants should be checked under these loads, frequent and long-lasting, that could provoke the same earthquake-induced movements, even though with reduced amplitude.
This aspect is not critical for the application of the innovative systems, because the experience shows that the presence of systems for the reduction of the seismic response usually has a favorable effect on the construction dynamics, reducing the impact of vibrations on the occupants. The criteria for controlling the perception, comfort and panic under vibrations, well established in current guidelines and based on the evaluation of cinematic response parameters, can be applied. The effect of the movement induced by a strong earthquake does not require specific checks, assuming that a preparedness of the occupants is provided; in any case larger values of the acceptance limits can be assumed, because the event is rare and characterized by short duration.

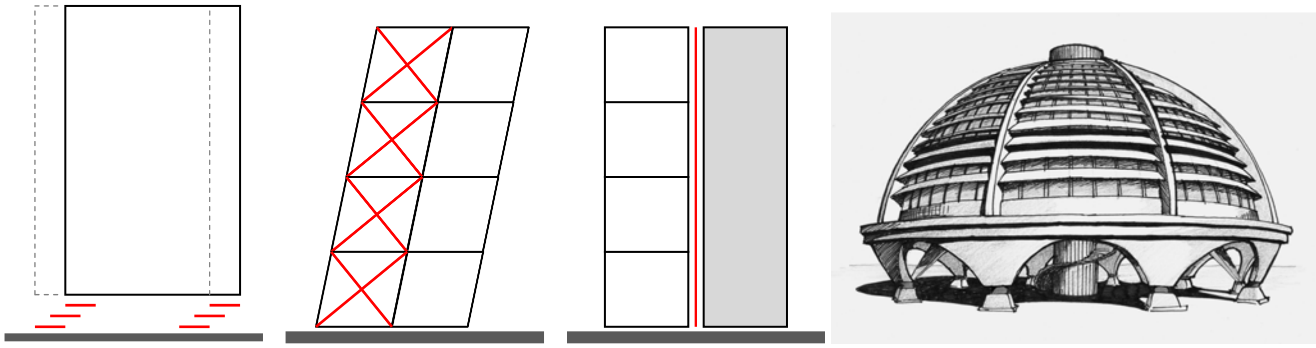

Figure 5 Motion, deformation, discontinuity, shape

4 ARCHITECTURAL CONSEQUENCE OF INSERTING DEVICES - RULES OF ESTHETICS

The last class of architectural themes deriving from the application of the new technologies concerns the aesthetics, in this case we can speak of an aesthetics of the technology versus an aesthetics of feeling. The aesthetics of the technology is a theme of the architecture independently of the use of seismic devices, but it concerns all the technological aspects of a building, i.e. the equipment and their visibility.
The reduction of the seismic response does not depend on the structural deformations or displacements but on the deformation of the special devices induced by those deformations or displacements. The enhanced protection systems provide for devices that are, or appear as, mechanisms (viscous, friction or plastic dissipating elements) or machines (active dampers), or are made of special materials, unusual in constructions. Their presence introduces the architectural theme of their visibility. A first solution consists of hiding the devices and the building appears as an ordinary one. A different solution provides for showing the devices that become an expressive sign and evidencing their characteristic of special earthquake protection tool.

4.1 Aesthetical rules of devices location - The case of dissipating bracing

The visibility of the devices is related with the principles that must be applied for defining their location within the building. In some solutions the location of devices depends only on the structural configuration, as in the case of the base isolation where the isolators shall be located below the columns and walls. In other cases the location can be chosen, basing the choice on structural or architectural criteria. A study (Mezzi and Comodini, 2008) has been carried out considering the insertion of diagonal dissipating bracing members consequent to optimum structural location or to building aesthetics.
Braced frames, characterized by diagonal elements included within the vertical alignments of the framed grid, represent one of the most effective configurations of earthquake resistant structural scheme. In the last years the performance of this scheme has been improved, reducing the demand of post-elastic performance to the structural members, thanks to the use of dissipating braces. They are able to dissipate energy when deformed according to the inter-story drifts associated to the lateral forces, with a consequent increment of the energy dissipation capacity of the building.
In (Mezzi and Comodini, 2008) some different layouts of the façade bracing of regular 3D r/c frames, have been assumed (Figure 6) and dimensioning data, carried out analyses and detailed results can be found. Variants going from regular schemes to absolutely irregular ones, making reference to schemes hypothesized in (Elsesser, 2000), have been considered. The dynamic response, in terms of inter-story drift does not vary significantly among the different variants, always remaining below the levels corresponding to the absence of significant damage. The random distributions give drifts of the same entity and often even lower than the regular ones.
Figure 7 reports the graphs of the bending moments of the monitored columns (external, internal and central) of the braced façade frame and of the bare internal frames. Apart from differences in details, according to which an optimum distributions of the braces could be identified, the main result shown by the analysis of the diagrams is that the flexural forces are not significantly influenced by the location of the braces. Moreover random distributions can give lower forces than the regular ones. Even if larger differences characterize the column axial forces associated to the interaction with the diagonal, it is evident that the results demonstrate the freedom in configuration and, as an extrapolation, in related morphology allowed by the tested technology.

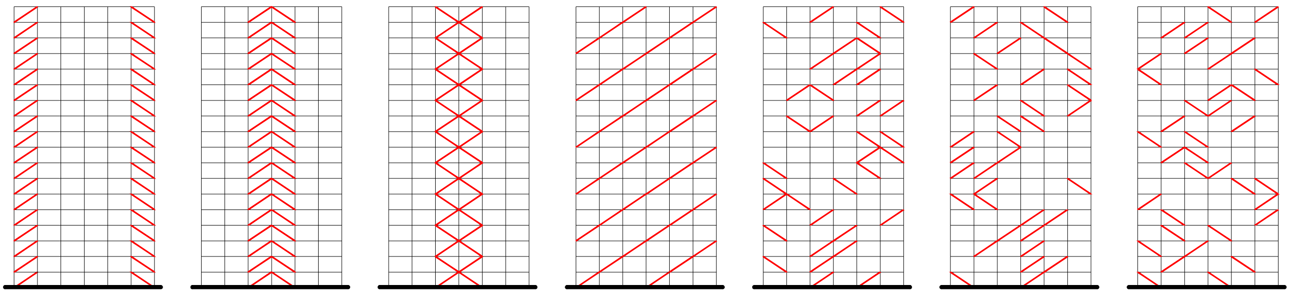

Figure 6 Façade layouts of the considered variants of the bracing system (Mezzi and Comodini, 2008)

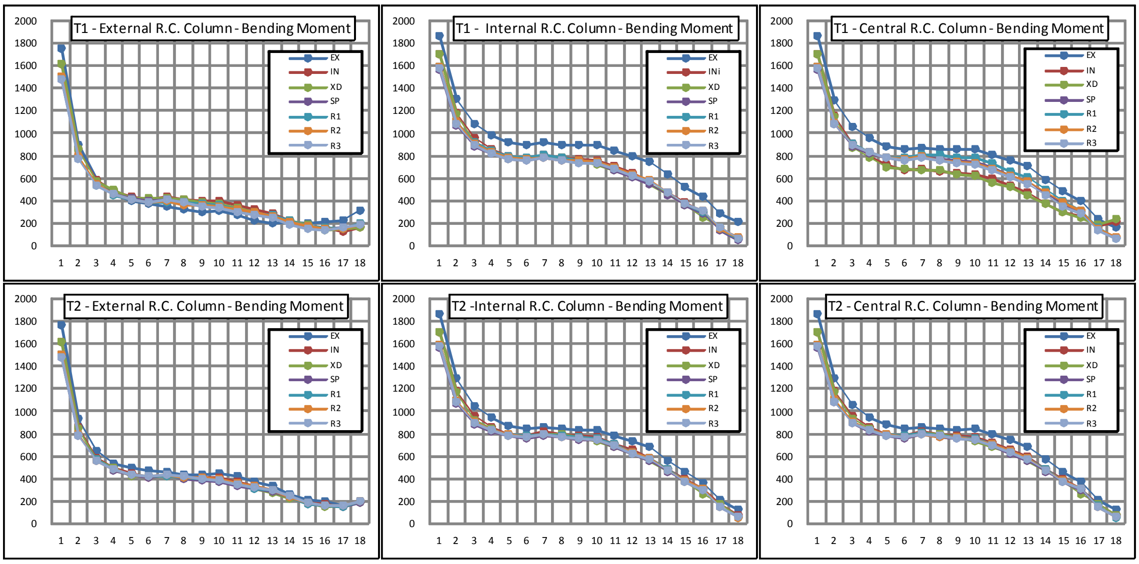

Figure 7 Column bending moments for different bracing variants: façade frame (above) and interior frame (below)

5 CONCLUSIONS

The conceptual design of buildings has been, and it is still, dominated by the reference to the vertical loads and, in any case, to the traditional rules of fixity and rigidity correlated to them. This is also true for building in seismic areas. Recent earthquake protection techniques, like isolation, energy dissipation, active and hybrid control, demonstrated to significantly enhance the seismic performances of buildings. These innovative protection systems require to account for new principles correlating architectural morphology and structural configuration: motion, flexibility, discontinuity, shape, comfort of occupants. The presence of devices also open a new vision in aesthetics. Rules and principles should be done by the specialists concerning the location and insertion of devices. Innovative systems usually offer a larger freedom to the designers as witnessed by the reported sample regarding regular buildings equipped with diagonal dissipating braces.

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