Using Combination of Suspension and Isolation as An Innovative Aseismic Technique to Achieve High Seismic Performance

S.P. Seyedinnoor
Young Researchers Club, South Tehran Branch of the Islamic Aazd University (IAU), Tehran, Iran

M. Hosseini
Department of Civil Engineering, Graduate School, South Tehran Branch of Islamic Aazd University (IAU), Tehran, Iran

SUMMARY:
From architectural point of view, suspension makes free-of-column spaces but its structural efficiency depends in a great extent to the seismic behavior especially in regions with high seismicity. In this paper after reviewing new seismic design techniques of buildings equipped with innovative seismic systems, alternatives which are compatible with the nature of suspended structure are explained. The alternatives stand around the principles of discontinuity, movability, flexibility and devices location which greatly affect the architectural form and respectively the configuration. Architectural considerations in seismic design such as regularity in plan and height and symmetry are no longer decisive and innovative architectural complex forms can be safely designed using the concept of suspension and isolation in combination. This concept has great potential of creating complex architectural forms with various functions even seismically safer than regular forms designed with conventional seismic rules if new conceptual strategies are adopted during the form generation process.

Keywords: suspension, isolation, new architectural configuration

1. INTRODUCTION

There has been always a prominent interaction between architectural form generation process and seismic resistant system. In practice, for the buildings does not benefit from active, passive or hybrid protection systems, the interaction is replaced with limitation! For these buildings constructed in seismic prone areas, so many architectural regulations are imposed by seismic codes. Since the advent of new seismic protection systems, seismic performance of protected buildings has been improved and complex irregular architectural form can benefit a relatively sound structural design (FEMA 2006). The point is that correct use of passive and hybrid systems greatly influence the architectural form generation process but not as limitation but as a source of inspiration for new and, attractive and complex forms!

For so many irregular architectural forms with long spans, suspension could be pointed out as first alternative. In seismic prone areas using the concept of suspension requires good seismic alternatives. In this regard some researches have been addressing alternatives for increasing seismic performance of suspended building but almost none of them investigated the new seismic alternatives which are conformed to the basic concepts of suspension. The paper discuses new seismic means of buildings equipped with new protection systems, such as base isolation, and comes up with new architectural configuration based on new seismic means and aims at use of suspension concept to introduce the new configuration which basically conformed to inherent characteristics of passive and hybrid systems like isolation. Since it is highly important for architects to know how to design a building which is deemed to be equipped with passive and hybrid systems, the contents of the paper is started with some explanations with regard to basic structural and seismic design concepts, and then the more sophisticated issues are discussed.

2. GLOBAL APPROACHES FOR SIGNIFICANT DAMAGE REDUCTION

Generally speaking, to avoid significant damage to the structure during the earthquake, three approaches could be followed:

1. To provide the building with unreasonably high strength: this approach may not be economically justified and is not reliable because the level of ground motion could not be determined with certainty. Some level of ductility should always be provided to secure the buildings form collapse but non repairable damages are probable.
2. To design the building with normal strength even less than seismic force and provide it with ability to undergo large displacements: this approach could be cost-effective but careful design is needed to avoid non repairable damages. New code provision for displacement-base seismic design uses this approach.
3. To alter the building's characteristics through external devices to reduce the response of the structure or the input ground motion acceleration.

2.1. New seismic protection systems

New seismic protection systems allow for capacity level larger than that resulting from conventional design methods without dangerous damages even in the case of the maximum credible earthquake. They reduce structure's responses in three ways (Mezzi et al. 2004):

- Reduction of input earthquake energy
- Dissipation of input earthquake energy
- Active interaction with building's motions

New seismic protection systems are classified in passive and active systems. Passive systems like base isolators and energy dissipaters modify the dynamic parameters of structure like mass, damping and stiffness. Passive systems could not be adjusted to react to every single oscillation dynamically during the earthquake but active systems can do it well by active participation of mechanical devices whose characteristics are used to change the building response and supply energy to the structure. Hybrid systems combine passive and active systems in a manner such that the safety of the building is not compromised, even if the active system fails. In practice, semi-active or hybrid systems are used.

2.2. Isolation

In conventional seismic approach, to reach the structural resistance (reducing enter-story drift), lateral stiffness should be increased but the floor acceleration is also increased that is not favorable for human comfort [3]. This problem can be well solved by the concepts of isolation. In base isolated structures, there is a gap between foundation and upper structure filled by materials with characteristics of both dissipation and flexibility. The upper structure ideally acts rigidly during the oscillations of earthquake. Two important points for considering the base isolation as one of the best alternatives:

1. To avoid non-structural components damage and increasing human's comfort, the floor acceleration should be reduced, in the other hand, reducing floor acceleration requires flexibility. Base isolation could provide the required flexibility at the base of the structure in the isolator devices.
2. For keeping inter-story drift low requires great energy dissipation. This can be achieved by dissipation characteristic of isolation devices.

The structure can reach the mentioned desirable points simultaneously, thus overcoming the opposite criteria in conventional seismic design which is both reducing inter-story drift and increasing energy dissipation.

2.3. Energy dissipation

Application of energy dissipation devices is not limited to special bracing systems. They could be located between two adjacent buildings or two sections of the same buildings and utilize the relative displacement between the two bodies.

Since the application of new seismic protection systems greatly enhances the performance of building during the earthquake, unlike the conventional seismic design (based on strength, stiffness and ductility), life safety of occupants is not the main goal of design. Instead, comfort can be set as a main goal. On the other hand, the ability of buildings quipped with passive protection systems to motion and deformation, can cause excessive displacements and trouble for occupants especially in rare and short period earthquakes. But in this case large values are usually acceptable.

3. PASSIVE PROTECTION SYSTEMS, INNOVATIVE SEISMIC DESIGN CONCEPTS AND INFLUENCE ON BUILDING CONFIGURATION

When beginning the design of buildings equipped with passive systems, optimization of both the device location and the structural and architectural configurations to reach the optimum performances of the building in terms of its seismic response should be considered (e.g. in the case of base isolation, distribution of vertical elements at the perimeter of circular plan results in high performance). Also influence of applying these systems in architectural design from the first stages of design to those final in addition to stated point at the beginning of this paragraph, leads to achieve a high degree of earthquake architecture; both high structural performance and architectural aesthetic. These aspects will be discussed in the following sections. The principles of seismic design of building with innovative aseismic systems were first proposed by Mezzi (Mezzi 2006).

3.1. Discontinuity

Isolation is not limited to the base of the structure. Discontinuity means isolation of some parts of buildings (whole building, two or more sections of building and/or some elements of it) so that the isolated parts of the building are allowed to move relatively during the earthquake. Figure 1 (left) which is a proposal of Mezzi, schematically illustrates this principle.

3.2. Movability

For a building to have good performance during the earthquake, the fundamental period of the building should be high (generally more than 2 seconds). To reach the high natural period (and partially energy dissipation), large lateral displacements are required. In the other hand, large displacements cause relatively large enter-story drifts (in usual buildings). So, to avoid large inter-story drifts, the principle of motion should be considered in the design of buildings equipped with passive systems (Figure 1).

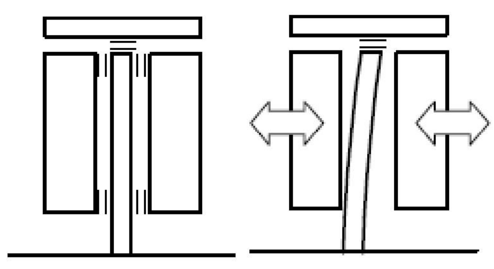

Figure 1. Discontinuity and movability in a building structural system (Mezzi et al. 2004, Mezzi 2006)

3.3. Flexibility

In practice, to have rigid portions of the structure separated and movable, one with respect to another, a good flexibility has to be pursued for structures internally equipped with dissipative devices (Mezzi 2006). Devices location should be determined with the aim to eliminating morphological irregularities. In this case, connections have the duty of making deformation compatibility.

3.4. Basic natural energy-dissipating configurations

In conventional seismic means, to achieve good seismic performance simple and regular forms are prescribed. By advent of energy dissipative devices, complex architectural forms began to design but the extremely important and innovative concepts (which are the aims of this research) stayed hidden. The resulting irregular, random, free-form grids and systems have just begun to be explored from the structural engineering viewpoint; energy dissipative devices should be determined before the global architectural form is confirmed because they needs special and even complex geometry to work in their best during the earthquakes. The complex architectural forms were already rejected because of various cost issues, and because of unproven real earthquake behavior but now they can be accounted as good alternatives to achieve good seismic performance. Buildings must dissipate energy; how does one configure a structure to dissipate energy? There are natural forms and design concepts that act as springs, rocking mechanisms, flexural stories, yielding links, articulated cable-restrained configurations, pyramid forms, cable anchors, etc. Any system that can dissipate seismic energy without damage is a candidate. Figure 2 illustrates some special concepts utilizing building configuration to dissipate energy.

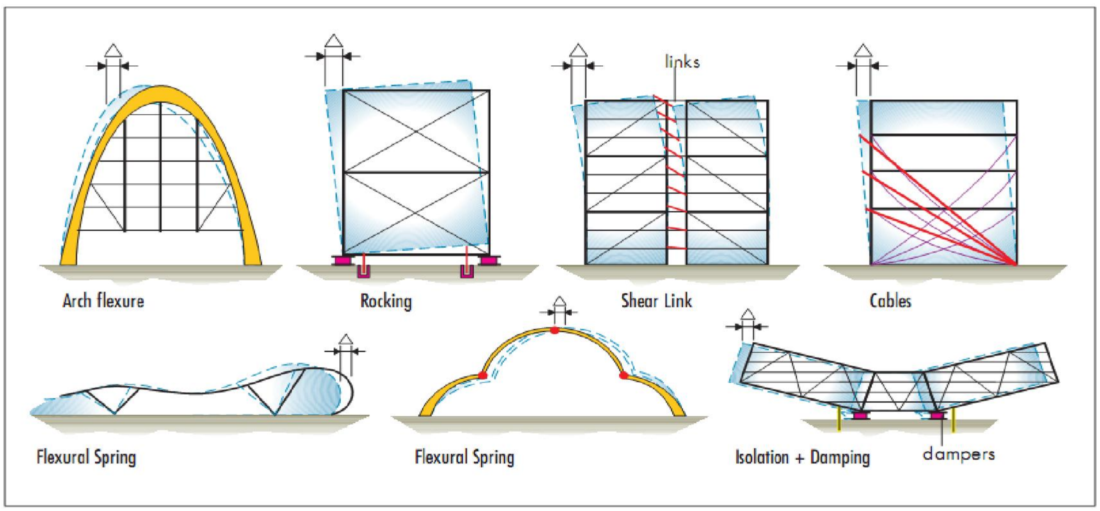

Figure 2. Concepts that use the building configurations to dissipate energy (FEMA 454, Chapter 7)

4. SUSPENSION, ISOLATION AND SEISMIC-ADAPTIVE ARCHITECTURAL CONFIGURATION

Understanding the principles of new seismic design leads architect to apply this approach to introduce new architectural forms which are more complex, attractive and compatible with innovative seismic rules rather than buildings designed by conventional seismic codes. The alternatives investigated in this paper, have been partially investigated before (Paraducci et al. 2005) but have been rarely applied to real buildings. The alternatives are based on suspension of parts or elements of buildings aiming to meet the new seismic design principles.

4.1. Bell-form configuration

In bell building a set of stiff floating stories is suspended to the head of a central rigid core. The unusual form of bell building, allows the first floor to be almost completely free thus overcoming one of the most common architectural-structural problem in building configuration (soft and weak first story). Suspended floors are connected to the core and head by dissipative devices thus meeting the discontinuity and motion requirements. The main motion is due to the manner of connection between floors and the head and the main source of energy dissipation is laterally located energy dissipative devices between core and floors. The suspended floors can be peripherally braced to avoid excessive drifts. The system works better for mid to high-rise buildings. The prefabrication procedure and industrialization could be feasible in these kinds of buildings.

4.2. Bridge-form configuration

Some contemporary architecture represents a building form like bridge called bridge building. In bridge buildings, the entire building form is reproduced by a large opening that could be also filled by suspended or floating floors (Seyedinnoor, S.P. and Hosseini, M. 2011). Like the case of bell building, the floors could be laterally connected to the main body by dissipative devices. The dissipative devices absorb the earthquake energy and limit the transmitted forces. Concepts of bridge building could be useful for those irregular architectures in the way of suspension of the irregular sections and therefore make a free architectural space. The system performance increases when applying to buildings with much height (Figure 3).

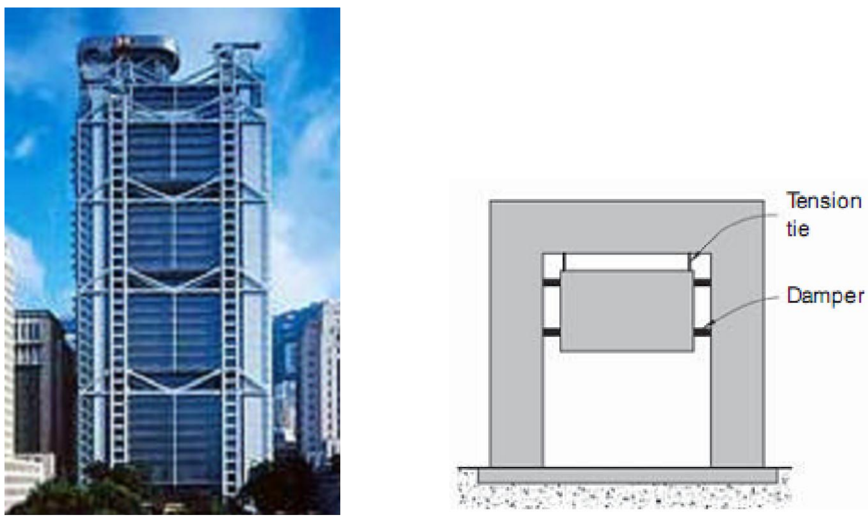

Figure 3. Bridge building with suspended floors; and Hong Kong and Shanghai bank building (left) schematic figure (right) (Charleson 2009)

One of the rich examples of using this innovative approach can be seen in the main building of civil protection service built in Foligno (Parducci et al. 2005). Figure 4 shows the dome building of the emergency management center in Foligno, Italy (Paraducci et al. 2005).

Figure 4. The dome building of the emergency management center in Foligno, Italy (Paraducci et al. 2005)

As shown in Figure 4, the round shape of the building has been conceived to enhance the compactness of the structure and to achieve the optimum criteria for the distributions of masses and stiffness (Mezzi 2006). The structural configuration consists of a suspended central core and semi domes located at the perimeter of circular plan constructed on peripheral isolators to act in compression even during the earthquake (Paraducci et al. 2005). The scheme allows the first story to be safely open and used as gathering and passages space. The design covers the mentioned principles as well in addition to meet the functional architectural requirements and can be a great symbol of using the innovative seismic approach for buildings in seismic zones to create interesting functional architecture.

The concepts of all stated alternatives are the same. In each alternative, there are suspension parts isolated from one or more rigid bodies connected by dissipative devices to meet discontinuity and motion principles. Thus other alternatives like floating floors laterally connected with dissipative devices to a rigid frame like Future University of Hakodate in Japan (Figure 5) or seismically isolated roof slab could be proposed (the case of floating floors is appropriate for designing the irregular and complex spaces as floating floors) but in detail seismic and structural analyses adopted by structural and earthquake engineers are necessary to demonstrate the seismically healthy of different proposals.

Figure 5. Suspended floors, Future University of Hakodate in Japan

4.3. Suspended-Isolated configuration

What is suspension practically?! From architectural point of view, suspension means making a space free-of-column whose upper floors are suspended by hangers. From structural point of view, suspension means altering the load pattern of the structure from top to bottom into bottom to top and then transferring it from top to the foundation. Based on this approach, lateral loads like wind and earthquake are resisted through tension action of horizontal cables. But there is a turning point here when we explore the concept of suspension from seismic point of view. From seismic point of view, suspension means isolation! When a building, some parts or elements of it are suspended, they are actually isolated but there are differences between usual isolation and suspension.

During the earthquake, the energy and acceleration of earthquake enter to the structure through the connection surface of the structure and ground which is foundation. In base isolation the input ground motion are absorbed at the level of isolation above the foundation but in building with suspension (if there is no lateral connection between fixed-base and suspended part) the input energy goes to the top of the structure and enter to the suspended part. This phenomenon is occurred with lower intensity if the fixed-base part benefits a usual base isolation system. To achieve high seismic performance the concept of suspension and isolation could be blended. For example for the last mentioned condition the connection of fixed-base part and suspended part can consist of energy absorber and/or dissipative devices. For the case of a suspended building with central base-isolated compression core (to transfer the tension loads of hangers carrying gravity loads of suspended floors), the connection surface of suspended part and base isolated part at the top can be equipped with rollers (isolators with no lateral stiffness). The seismic behavior of the suspended buildings can be improved by integrating the concept of isolation but requires exact seismic analysis.

The proposed architectural and structural configuration for the Earthquake Disaster Management Multi-purpose Complex (EDMMC) for the different districts of the city of Tehran proposed by the author shows a proper use of the concept of isolation and suspension (Figure 6).

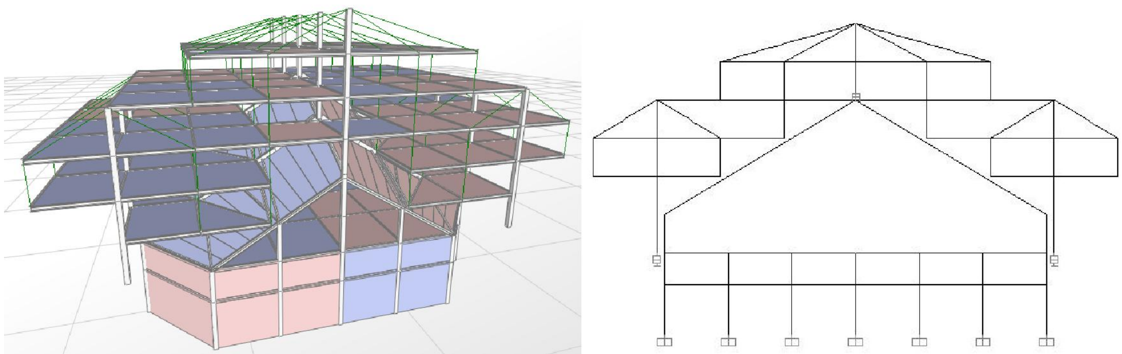

Figure 6. Proposed "EDMMC" for the city of Tehran by author

As it can be seen in Figure 6, a free-of-column space at the ground level which was required due to architectural demands, is created with four stories above. The alternative is to suspension of upper floors and then isolation of suspended part at the base of three line of compression column carrying gravity loads of suspended part (Hosseini, M. and Seyedinnoor, S.P. 2012). During the earthquake the suspended-isolated part is deemed to move over the fixed-base part thus following the discontinuity, movability and flexibility.

5. EARTHQUAKE ARCHITECTURE AND NEW CONFIGURATION

Earthquake architecture can encapsulate metaphorical references to seismic issues, or at a more practical level, express a design response to seismic loads (Charleson 2000). As shown before, correct design approach of buildings equipped with innovative seismic protection systems results in new building forms. The proposed building forms as itself introduce different views in architecture of building located in seismic zones. Also the visibility of innovative seismic protection systems could be used as architectural inspiration as it has been done as well before in rich traditional seismic resistant architecture and may open up new trends in aesthetics of these buildings. In fact, different structural vision again makes different architectural vision; the concept of structure-based architecture is inspired by the concepts of earthquake engineering and this is where the Earthquake Architecture could grow dramatically under the shadow of great cooperation between architect and structural engineer.

6. CONCLUSIONS

The paper reviewed the concepts of passive and hybrid protections system having keen eye on architectural design integration. Conventional seismic design means of stiffness, strength, redundancy and regularity which impose limitation on architectural design become subordinate and could be replaced with new seismic means of discontinuity, movability, flexibility and device location when using passive and hybrid systems which open up new vision in architectural configuration of seismic resistant buildings. Following points are to be concluded:

1. This is vital for the architect of the structure equipped with passive and hybrid systems to be familiar with innovative seismic-architectural principles and integrate them from the first stages of the architectural design.

2. Based on innovative seismic-architectural means, new configurations can be proposed using the concept of isolation, suspension and energy dissipation including bell, bridge and suspended-isolated configuration featured with complex geometry.
3. Concept of suspension leads the designer to use the concept of isolation and blend them together using his/her creativity while considering seismic principles to achieve high seismic performance in a building with complex geometry.

Finally, it should be noted that discussion about the aspects of "earthquake architecture" regarding to new architectural configuration which is equipped with new protection systems is extensive and deserve more researches.

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