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SEISMIC ISSUES IN THE DESIGN PROCESS THE ROLE OF ARCHITECT IN SEISMIC SAFETY ISSUES IN THE DESIGN PROCESS

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Abstract: *When a specific building is examined and analysed for its architectural merits, it is the visible, superficial aspects, which are considered, for example: aesthetics, function, spatial relationships, and landscape. One of the most important invisible factors that should be considered in the design process is the safety of buildings against natural hazards, particularly against earthquakes. While the provision of earthquake resistance is accomplished through structural means, the architectural designs and decisions play a major role in determining the seismic performance of a building. In other words, the seismic design is a shared architectural and engineering responsibility, which stems from the physical relationship between architectural forms and structural systems. It is economic to incorporate earthquake resistance in the stage of design than to add it later in the structural calculation or strengthening after completion. In addition, a building with proper earthquake-proof design will be more effective against earthquakes than the one with complementary strengthening. This paper will demonstrate that evidence for this lies in many historical buildings, which have withstood earthquakes throughout the hundreds of years without having been reinforced with special material. The fact is that the master builder or Mimar (traditional architect) of historic buildings was simultaneously designing the architecture as well as choosing the suitable form, proportion, and material for the best structural performance.*

Keywords: *Earthquakes, Seismic safety, Architectural design*

1. Introduction

The main motivation for writing this paper came to my mind when some years ago a well-known architect –Ken Yeang- was describing his latest skyscrapers designs in a seminar held in Sheffield University. When I asked him whether he considered the seismic safety issues in his designs, his reply was negative. I understood from the circumstances that these matters should be dealt with later, after finishing the architects' job. This paper will mainly discuss and review this issue.

In the design process, so many questions have to be answered and choices need to be made among the alternative answers. The most popular factors that are mostly being considered in the design process are the form, shape, geometry, the relation between various functions of the building as well as all other factors related to aesthetics. Besides the geometry of the building other aesthetically efficient factors include of green spaces in the façade, choosing façade elements such as openings, shading devices, projections and recesses, architectural decorations and of course the type and colour of the material. Unfortunately in some cases least attention is being given to the seismic resistance and safety of the building especially where it disturbs the intended appearance of the building.

The entire fault is because of the separate design of the architecture and structure groups for buildings. Planning for architecture and seismic resistant structure of the building simultaneously will result in a safe structure.

A good example of this idea is historic buildings, whose architectural and structural design has been carried out at the same time. Evidence from the past shows the adequate resistance of historic buildings during past seismic events in contrast to the way in which several modern structures have collapsed in

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similar circumstances due to the deficiency in the coherent operation of various involved groups in the construction.

The common tradition leaves the form of the building, as explained above, to architects and structural features to the engineer of the group. Enough care should be paid that the reciprocal relationship is essential between architectural and structural design of the building to achieve a suitable seismic resistant. Popovic and Tyas confirmed this idea as they also believe "In the past, at the time of the construction of the great cathedrals, the Master builder was the person who dealt with the design issues to do with a building, from the very artistic to the very technical.

He was the 'architect' and the 'engineer' for the project. However, since the industrial revolution with the great development in the field of sciences and materials, a clear distinction between the two professions became more evident: the architect came to be in charge of the architectural issues, whereas the engineer was concerned with the more technical issues" [1].

2. Lessons From Past

Experienced earthquakes can teach so many lessons for proper seismic design of future buildings. One apparently strange event is that in some earthquakes such as Armenia earthquake the modern reinforced concrete buildings collapsed while the "older masonry buildings nearby remained mostly intact, providing refuge for the displaced occupants of the newer buildings" [2].

The reason could be pursued in the fabric and the design characteristics of the original historic buildings. Generally speaking, understanding both positive and negative aspects of masonry structures can direct towards the suitable methods of design. One of the facts about historic buildings is that their architectural and structural design, were implemented at the same time and not separately. Therefore, seismic design coefficients have actually being considered in the design process.

The other characteristic of historic buildings is their integrity and also their regular form in their original design. Most historic monuments had fairly compact forms with fairly uniform distributions of mass and stiffness when first built. However, subsequent changes and additions to meet growing needs have resulted in less satisfactory forms.

Another example in this regard is the Great Alaska earthquake that happened in 28th March 1964 in the afternoon of Good Friday, in Prince William Sound in Alaska. Surprisingly, small stiff structures of masonry construction were survived, while many tall buildings, which have long periods of vibration, were severely damaged.

The reason is the predominance of long waves in the ground shaking which affects tall buildings [3]. Therefore, characteristics of earthquake and the type of buildings being damaged during earthquakes, can also affect the type of damage.

The survey of Langenbach (2002) also showed that 'Many traditional timber and masonry houses defied today's conventional wisdom about the safety of masonry by surviving the great turkey earthquakes of 1999 and India's Bhuj earthquakes of 2001 that felled many modern buildings' [4].

3. Seismic Design, the Share Responsibility of Architects and Engineers

Generally, seismic strengthening of buildings is considered as the task of engineers and not a role for architects. To see the importance of the role of architects in the seismic resistance of buildings, we need to evaluate the requirements for seismic resistance of a building and possible damage due to earthquakes. In the case of any damage, we can analyse the extent to which it could have been avoided if it had been taken into account in the design stage of the building.

As in the most historic structures of most countries, the master builder was simultaneously an architect and the structure engineer of the traditional architecture. This paper mainly focuses and explains on the specific features that should be considered in the primitive design stages by architects.

In the other words, the seismic design is a share responsibility of architects and engineers. As earthquake does affect the building as a whole and does not distinguish between different parts or various tasks. Therefore, the architect is a full participant in seismic design [5]. Moreover, the application of earthquake resistance principle in the design stage is more economical than strengthening existing buildings. Maes et al believe that in the design stage many requirements specify quantities and arrangements of materials, which are economical and practical to implement during initial construction, but impractical after a structure is completed [6].

There are numerous items that have to be considered in the design of a new building. Design of buildings must ensure the safety of the building during earthquakes and even the continuing functionality of buildings after earthquakes, especially if the building has a post-disaster function. Selecting the appropriate façade system, the proper structural framing and the suitable foundation system are particularly important in the planning stage and in the minimization of any potential earthquake damage.

Recognizing factors which cause damage to buildings during earthquakes can help to create a proper design. Poor design and construction practices, weak quality of material such as masonry materials that are naturally brittle, insufficient reinforcement, torsion effects, lack of infill walls in pilotis, pounding of adjacent structures, site conditions, and the lack of ductility of buildings have all played an important role in damage caused by various earthquakes in the past.

4. Effects of Earthquakes

Earthquakes are happening in the result of shaking, rolling or sudden shock of the earth's surface or plate tectonics. Various characteristics of earthquakes are acceleration, velocity, displacement, amplitude, duration, magnitude, intensity. Familiarity with these definitions is necessary before dealing with any inspection of earthquake effects.

The effects of earthquakes depends on their characteristics as well as the buildings properties. Ground shaking generates forces within buildings called Inertial force ($F_{Inertial}$), which FInertial = Mass (M) X Acceleration (A). This equation shows that the greater the mass (weight of the building), the greater the inertial forces generated. Lightweight construction with less mass is typically an advantage in seismic design [7].

Earthquakes generate waves that may be slow and long, or short and abrupt. If the period of the shock wave and the natural period of the building coincide, then the building will "resonate" and its vibration will increase or "amplify" several times. In addition, the period of the soil coinciding with the natural period of the building can greatly amplify acceleration of the building and is therefore a design consideration.

5. Seismic Design Factors

The following factors affect and are affected by the design of the building. It is important that the design team understands these factors and deal with them carefully in the design phase. Knowledge of the building's period, torsion, damping, ductility, strength, stiffness, and configuration can help one determine the most appropriate seismic design devices and mitigation strategies to employ.

Torsion: the mass distribution of the building should be as close as possible to the geometric centre of the building otherwise, it will cause torsion. Therefore, the arrangement of masses will prevent unreasonable torsion in buildings.

Damping: the rate of damping of dynamic vibrations by absorbing them is also an important factor.

Ductility: the characteristic of a material to bend or flex will enable them to resist deformations. Good ductility can be achieved with carefully detailed joints.

Strength and Stiffness: the other quality of materials, which cause them to resist forces within a safe limit, called strength. Stiffness of a material is a degree of resistance to deflection or drift [7].

Soft First Story is a discontinuity of strength and stiffness for lateral load at the ground level. *Discontinuous Shear Walls* do not line up consistently one upon the other causing "soft" levels. Variation in *Perimeter Strength* and *Stiffness* such as an open front on the ground level usually causes eccentricity or torsion. The evidence in this regard is the county services building, the main reason of failure was the soft storey, [5].

Building Configuration: This term defines a building's size and shape, and structural and non-structural elements. Building configuration determines the way seismic forces are distributed within the structure. Lorant (2006) states the configuration in buildings as follows:

Regular Configuration: buildings have Shear Walls or Moment-Resistant Frames or Braced Frames and generally have:

- Low Height to Base Ratios
- Equal Floor Heights
- Symmetrical Plans
- Uniform Sections and Elevations
- Maximum Torsional Resistance
- Short Spans and Redundancy
- Direct Load Paths

Irregular Configuration: buildings are those that differ from the "Regular" definition and have problematic stress concentrations and torsion.

Building configuration refers to the **form** of buildings. The following aspects must be considered in order to analyze or design an architectural form: shape, mass / size, scale, proportion, rhythm, articulation, texture, color, and light. In this regard, attention to the shape mostly influences the other features. Shape refers to the configuration of surfaces and edges of a two- or three-dimensional object. The shape is mostly perceived by contour or silhouette, rather than by detail [8].

One of the straight relations of building's form and their seism resistance lies in the re-entrant Corners in the shapes of **H**, **L**, **T**, **U**, **+**, or **[]** develop stress concentration at the re-entrant corner and torsion. Seismic designs should adequately separate re-entrant corners or strengthen them [7].

Finally it is not necessary to threat all buildings same for seismic resistivity and there is a need to determine the extent of seismic resistance for each building. The magnitude of earthquakes, which is set as "Low," "Moderate," or "Large," is a good matrix of grading threat and establishing corresponding building performance goals [7].

5.1. Non-Structural Damage Control

All items, which are not part of the structural system, are considered as "non-structural", and include such building elements as:

- Exterior cladding and curtain walls
- Parapet walls
- Canopies and marquees
- Chimneys and stacks
- Partitions, doors, windows
- Suspended ceilings
- Routes of exit and entrance
- Mechanical, Plumbing, Electrical and Communications equipment
- Elevators
- Furniture and equipment

Loss arising from non-structural damage can be a multiple of the structural losses. Loss of business and

failure of entire businesses was very high in the Loma Prieta, Northridge, and Kobe earthquakes due to both structural and non-structural seismic damages [7].
Suitable remedies are necessary to avoid non-structural hazards, since some cultural resources including collections are included in this category. Securing and anchoring the internal furniture against the wall will prevent risks such as their sliding or falling over in the event of an earthquake.
Interior elements that have to be secured include top-heavy bookcases and storage cabinets, water heaters, tall cupboards and other appliances. Moreover, all pipe works and light fittings have to be fixed in place, as well as providing flexible connections for gas-fired appliances [9]. These items must be stabilized with bracing to prevent their damage or total destruction.

5.2. Suitable Materials

The local climate, the types of construction material available nearby, as well as fashion and tradition generally dictate building styles and construction methods. Even in many of the world's most seismic regions, earthquake-resistant construction is not always the first consideration. URM buildings and especially adobe buildings have a very low resistance to earthquake shaking and are one of the most common building types subject to serious failures that have life safety consequences while they were been used for a long time. The reasons could be their cheap price, easy construction, and readily availability while other materials were scarce and difficult to make [10]. Therefore, during the design of a building, to minimize the damage of earthquake, enough care should be taken to the suitable selection of the building materials.
The integrity is the fundamental in earthquake resistance. Further difficulties arise where, as often happens, several materials are used in a single building. In these cases another structural necessity to a good resistance against earthquake is integrity. Ambrose states: "The integrity of any masonry construction depends on the quality of the mortar, joints, and the structural character of the masonry units [11]." Workmanship also plays an important role in keeping the integrity of the structure. The control of the moisture, early drying of the mortar and the type of mortar during the laying of the bricks all have to be considered for better results. When there is no reinforcing, the skill, and care of the workers becomes critical.

5.3. The Site of Buildings

The location and physical properties of the site are the primary influences the entire design process. Site conditions, local topography, setting, soil profile and physical environment of the building are all important in the seismic resistance of buildings. The location of buildings in geologically hazardous areas causes the poor structural performance during seismic events such as displacement, landslides, or soil liquefaction [12].
The effect of buildings' setting can be shown mostly after earthquake. In general, buildings should be located far enough from high-risk areas such as fault lines. This can be achieved by attention to the site location by using the seismic zoning maps.
Besides, accessibility to buildings after earthquakes by emergency rescue vehicles is another important factor. Enough care should be taken for any loss of utilities, threat of fire, or the release of toxic materials to the site after earthquakes. Moreover, depending on the height of buildings, enough distance should be considered around them. This distance should be wide enough to avoid damaging neighbouring structures in the case of their collapse.
To analyze the site conditions the following items should be checked to identify seismic design objectives:
The location of the nearest fault:

1. The existence of any unconsolidated natural or man-made fills, loose soils or uncontrolled fill that could increase ground motion. "Hard dense soils remain more stable, while solid dense rock is the most predictable and seismically safe building base [7]."
2. The potential for landslide or liquefaction on or near the site
3. The existence of any hazardous materials on the site which needs protection
4. The potential for battering by adjacent buildings
5. The exposure to potential flood from tsunami, dam failure, etc.

6. Seismic Design Devices

Nowadays there are various methods and strategies to help buildings to resist earthquakes. Their through explanation is out of scope of this paper and can be the subject of a separate paper. However to give a general idea their summary can be seen below:
1-*Computer-controlled antiseismic systems* are active control systems, which are driven by mechanical actuators that are controlled by electronic devices that 'sense' the accelerations of the earth's crust due to an earthquake.
2-The mechanical actuators are instructed by the sensing devices to impose on a building forces equal but opposite to those due to the earthquake, thus effectively neutralizing the earthquake's impact on the building. In an application of an active control system used in conjunction with a weak first-floor system, the actuators move the first floor of the building to the right when the earthquake tends to move it to the left and vice versa (Fig.1) [3].

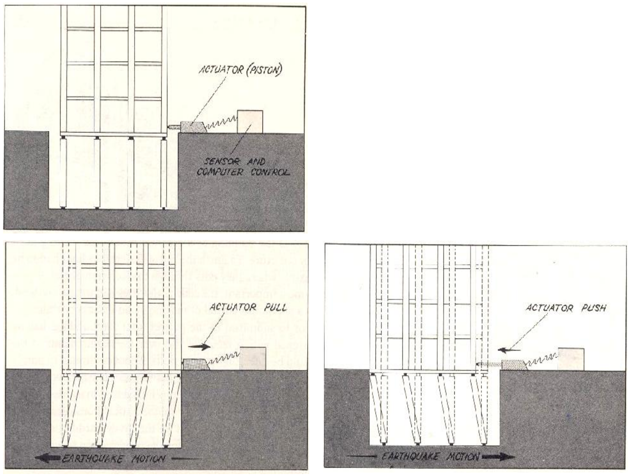

Fig. 1. Active controls – Actuator (Piston) pulling or pushing in the opposite direction of the earthquake motion [3].

The following seismic control devices are passive which are flexibility and damping devices of the isolation systems. These methods respond automatically to the seismic inertial forces.

1. *Diaphragms* can be used horizontally and vertically to transfer lateral forces to vertical resisting elements such as walls or frames
2. *Shear Walls* are stiffened walls, which are transferring lateral forces from floors and roofs to the foundation.
3. *Braced Frames*: where the shear walls are not practical, these Vertical frames are being used to transfer lateral loads from floors and roofs to foundations.
4. *Moment-Resistant Frames*: these frames can be built by steel and reinforced concrete. Their Column/beam joints are designed to take both shear and bending and joints are carefully designed to allow some deformation for energy dissipation [7].
5. *Energy-Dissipating Devices*: Energy-Dissipating Devices or shock absorbers are used to minimize shaking. Energy will dissipate if ductile materials deform in a controlled way.

5.1. There exists two groups of energy isolating and dissipating devices. The first group is limiting the energy entry at source. To do this there is a need to use energy avoiding devices at foundation level such as base isolation. Base isolations are mainly detaching a building horizontally from its footing or the ground. Therefore, the ground shaking cannot transmit to the building or in the case of locating the isolation devices over footing, the footing will vibrate with the building but will not transfer the motion into the building. The principle of isolation is simply creating a discontinuity between two bodies in contact. In reality, horizontal seismic motions are being discontinued from the whole structure. The provider layer of discontinuity may take various forms, ranging from a thin surface to a thicker rubber bearing. The energy from an earthquake is dissipated in the isolators largely through the friction between the sandwiched layers when they slide on one another [13].

Choosing the location and required number of base isolations depends on their cost and other practical consideration of each building. Obviously the best location for the isolating devices is as low as possible to protect as much of the structure as possible. Mostly base isolation is placed between the bottoms of building supports and their foundations [11].

Generally, in buildings the choice may lie between isolating at ground level and under columns or below the basement. Each of these locations has its advantages and disadvantages relating to accessibility, design considerations due to shear displacements, and the extent of structural cost. “Fig. 2” shows different locations for base isolation of buildings.

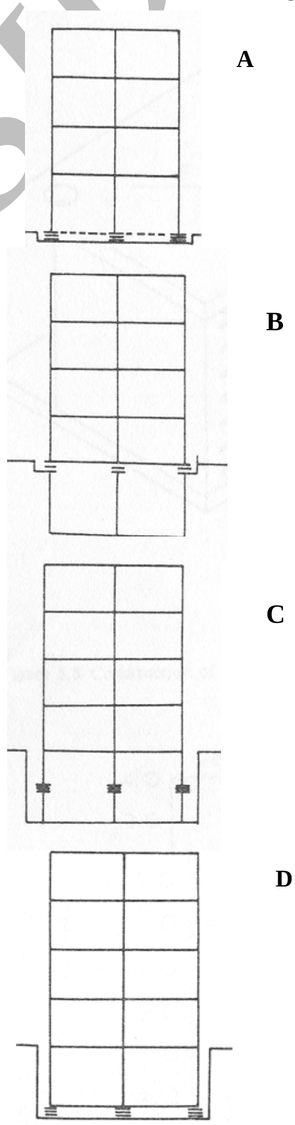

Fig. 2. <u>A.</u> Bearings located at bottom of first story columns: [14] <u>B</u> . Bearings located at top of basement columns: [14] <u>C.</u> Bearings located at mid-height of basement columns [14] <u>D.</u> Bearings located in sub-basement [14]

The important character of these isolation devices is that they "must have a very large compression capacity in order to carry the weight of a building" (Fig. ٣). "Base isolation is usually achieved with two basic elements: a buffering supports device (isolator) and a horizontal restraint system" [13]. Flexible bearings have been used in the most recent type of base isolations, which made from lead-rubber bearings.

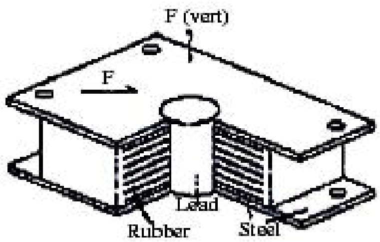

Fig. 3. Construction of a patented lead-rubber bearing [14]

Base isolation was used in the building of parliament house in New Zealand. "Parliament House, 1922, is the central of the three buildings comprising New Zealand Parliament Buildings." The aim was to strengthen the building to resist earthquake with IX intensity shaking. To achieve this aim the building was base-isolated and cast-in-place reinforced concrete structural walls added. Base isolators have been always expensive until today. In this project, also "the base-isolated scheme was 3% more expensive than a conventional solution" [15]. However using base isolation provides an outstanding degree of protection both "to the building occupants and the fabric of the historical and nationally important building" [15].

Base isolators are more specially being applied in two instances. One is in the buildings with contents that are very valuable or costly and are particularly vulnerable to vibrations. The second application of base isolators is in retrofitting old masonry buildings, highly vulnerable buildings, historically significant or buildings with great cultural value.

The insertion of base isolation method is very helpful when seismic strengthening is needed but historical preservation requirements limit the solutions. The reason is that adding energy dissipating systems will have minor structural changes. Modern protective systems use two types including passive and active protective systems. Passive protective systems employ devices that dissipate energy via plastic deformations, viscous fluids, or heat transfer. For example, visco-elastic braces, viscous (shock absorbing) couplers and frictional braces have been used in the construction of several tall buildings.

As an example, foundation isolators installed at the base of structures are passive protection systems. The second type, active protective systems, possesses an intelligence that allows them to direct the energy dissipation in an efficient way. "The active system is composed of solid diagonal tube braces attached to the steel structure at the building's first story." In tall buildings mostly 'smart' active bracing systems reacts fast and accurate to prevent excessive vibration, making "300 complete cycles of correction in one second" [16]. Several experiments proved several advantages for the active bracing system as follow:

1) It can be developed within the limits of current technology; 2) it can be used on buildings with any height; 3) it can be used on new buildings or for retrofitting existing ones; 4) it allows more architectural flexibility because of improved structure design [16].

5.2. The second group provides energy-dissipating devices within the structure, from foundation level upwards. Flexible bearings and damping devices have many energy-absorbing functions in mechanical engineering. These methods will reduce the impact of earthquakes by mitigating seismic effects applied to buildings. Dissipating vibration in the foundation can be achieved by incorporating elasto-plastic spring elements in the foundation. "Fig. ۴" shows the use of in-line shock absorbers for the reduction of energy loading and the damping of seismic movements.

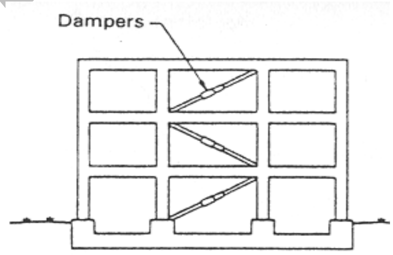

Fig. 4.A: Diagonal bracing with dampers [11]

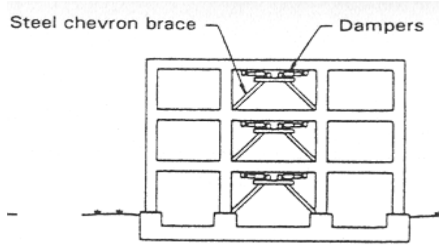

Fig. 4.B: Dampers with Chevron braces [11]

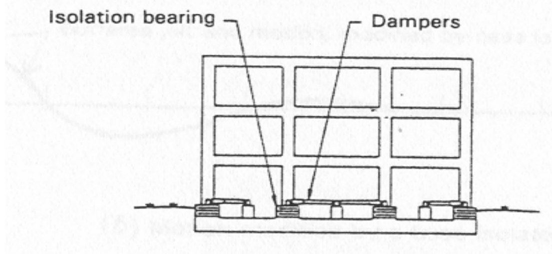

Fig. 4.C: Dampers with base isolation [11]

There are many types of dampers used to mitigate seismic effects, including:

- Hysteric dampers utilize the deformation of metal parts
- Visco-elastic dampers stretch an elastometr in combination with metal parts
- Frictive dampers use metal or other surfaces in friction
- Viscous dampers compress a fluid in a piston-like device
- Hybrid dampers utilize the combination of elastomeric and metal or other parts [7] (Fig. 5).

Fig. 5. Passive Energy Dissipation includes the introduction of devices such as dampers to dissipate earthquake energy producing friction or deformation [7]

The difference between the passive dampers and the active systems (such as the bracing system) is their ways for dissipating energy. “Further research and development of active and passive systems may lead to combined (hybrid) systems that are more advantageous than either alone.” New researches are looking for the more reliable complex intelligent systems to use for vibration protections [16].

7. Relevant Codes and Standards

Many building codes and governmental standards exist pertaining to design and construction for seismic hazard mitigation. As previously mentioned building code, requirements are primarily prescriptive and define seismic zones and minimum safety factors to "design to".

Codes pertaining to seismic requirements may be local, state, or regional building codes or amendments and should be researched thoroughly by the design professional. The seismic standards of these codes depend on the conventional building methods in each region. “Conform to local building codes providing "Life Safety," meaning that the building may collapse eventually but not during the earthquake; while the repairable structural and non-structural damage and loss of business for specific number of days” [7].

There are some codes and standards, which is published in various parts of the world. In Europe different parts of Eurocode deals with the design of structures for earthquake resistance, for example Eurocode 8- part 2, is the European standard for the design of bridges, or the Eurocode 8-part 3, is about the assessment and retrofitting of buildings, and the Eurocode 8-part 6, is about the towers, masts and chimneys [17], [18], [19].

The building code in the United States called UBC (Universal Building Code) which might be different from one state to the other such as 2007 California Building Code (CBC).

The other example is Iranian Building Codes and standards –standard No. 2800- 05 (third Edition) which includes the latest seismic macro-zonation hazard map of Iran, the classification of buildings based on their importance, shape and structural system. One chapter of this issue deals with the regulations for the Un-reinforced masonry buildings [20].

However, these codes determine the regulations required for seismic performance desired for buildings, but considering all those criteria should be in the design stage that is the subject of this paper. Therefore it is necessary to consider the role of architects and even interpret the language of code suitable for architects and conservator architects. Architects required having a through knowledge of earthquakes and damage emerges from it to buildings.

8. Seismic Design Strategies

The following issues should be considered for the structural framing system in order to resist earthquakes successfully:

- Avoiding or eliminating soft storeys, a ‘soft storey’ is a section of the building that varies in stiffness by more than 30% to the floor above or below [11]. Soft storeys typically including open areas, piloties or first floor covered car parks or large open foyers.

- Continuity of load bearing members; avoiding irregular shaped buildings or simplifying the complex building by seismic separation joints; regularity is not only important in one building but also similar stiffness and periods of vibration of adjacent buildings are important in seismic resistance. Otherwise, excessive damage may be caused by pounding between two buildings. Providing sufficient space between buildings can prevent damage. If buildings are different in stiffness, the minimum space between them should be “50mm times the number of floors in the shorter building” [21].

- Considering special detail requirements for masonry elements, for example gable and parapet brick walls are the cause of many failures during earthquakes, therefore sufficient stiffening, or elimination of them is necessary. However any change made to the building has to be evaluated in terms of reducing the capacity of the existing structural system. For example, installation of masonry walls or removal of a section of the structure will result in an anomaly in the distribution of loads and affect their stability under earthquake conditions.

- Locating of stiffening elements, such as bracing walls, stairwells, lift shafts, symmetrically throughout the building. Otherwise, the building will be subjected to torsional forces during an earthquake. Similarly, heavy objects such as water storage tanks should be located within the centre of the building and as low as possible within the height of the building. Heavy objects, therefore, should ideally be situated at ground level where swaying from the imposition of earthquake loads is reduced.

- Protecting foundation systems from the overturning or toppling moment is necessary for resistance of structures.

- Moreover, enough care should be taken in the anchorage of mechanical and electrical components with allowance for the flexible movement of elements. Most failures and damage to buildings occur due to loose items that slide off shelving, or fall from tall, slender and unsecured furniture. Tall slender objects like cupboards have to be fixed in place from top and bottom to the wall or other support structures in order to not slide or fall over. Similarly, partition walls need to be restrained adequately at the top.

- Regarding both the horizontal and vertical direction movement of the building during earthquakes, there is a danger for the items that generally rely on gravity not to remain in place. Ceiling tiles, light fittings and objects suspended from the ceilings or roofs that have no vertical supports are in danger of falling down and injuring occupants below. All remedies have to be thought of after the earthquake such as sufficient exit doors - both in size and number - for the evacuation of occupants within minutes and also to make it possible for emergency officers to enter the building after earthquakes. The moving of buildings during an earthquake can result in jammed doors and windows preventing occupants from exiting, cracked walls or the differential settlement of foundations, etc.

After each earthquake, there is a need to survey the building to ensure its safety. Some samples of those actions include: inspection of brick ties which may have deteriorated before due to industrial elements, to see if they are corroded or rusted, checking that all bolts are fixed into appropriate connections, checking of any change in the water table or moisture content of the soil, checking of masonry cracks and foundation settlement.

8.1. Shape and Form

One of the most important factors that determine the extent of damage during an earthquake is the shape and configuration of the building. The more simple, regular and symmetric the shape, the more resistant it is to earthquakes. The reason for the greater resistance of regular buildings is the equal distribution of mass and stiffness.

The forms most resistant to earthquake consist of circular, octagonal or square buildings. As an example, domes are the most impressive members of a family of structures, called form-resistant by the great Italian structuralist Pier Luigi Nervi because they owe their stability to their curved, continuous shape [22]. The reason is that these shapes are equally strong in resisting loads applied from any direction. Domes, for example, have responded well during earthquakes.

Irregular or compound structures are weak against earthquakes.

The more complicated and irregular the shape and configuration of a building, the more likely it is that it will be damaged during an earthquake because of its uneven strength and stiffness in different directions. Defining an irregularity for a shape depends on the form and also on the proportion between the sides of the shape. “An irregular structure is defined as a building that in plan or elevation varies in width from one section of the building to another by more than 15%” [21]. Different features of irregularity include:

- Compound shaped buildings such as L, U, H, T, or, E, shaped building are considering irregular due to their unequal resistance. Stress concentration at corners and intersections cause damage at re-entrant corners, the location of frequent damage during an earthquake. Large stresses at intersection between the building’s segments appear to be due to their different response to ground vibrations of different frequencies and different directions of motion [23].
- Rectangular buildings that are almost square more strongly resist loads applied to the building in the direction of the longer dimension. On the other hand, longer rectangular buildings are much weaker in resisting loads applied to the building in the direction of the shorter dimension [24]. These long rectangular buildings behave differently at opposite ends, while the presence of projecting wings produces more weaknesses [25].
- As well as width, large stress can happen as a result of height differences at certain points of the building due to the development of large stresses. “Each section will vibrate at its own natural frequency in response to ground shaking” [26]. This type of irregularity can happen in cases such as those where there is a large platform floor plan with a slender tower over it, as in minarets of mosques.

Another type of irregularity is in the case of later additions to the building. In an earthquake, the added parts tend to pull away from and then batter the main structure [27].

Solution: in all these irregular types of configuration, the solution can be separating the building into several parts in order to obtain symmetry and rectangularity of each individual part. The separation should be wide enough to eliminate the risk of battering in the case of the different vibration of the separated parts. It is recommended that the width of separation should not be less than 30 mm, and 10 mm should be added for each storey when the building height exceeds 9.0 m [28]. Moreover, some reinforcement may be necessary on one or both sides of it to compensate for loss of support.

8.2. Joints and Connections

Regardless of any shape and configuration of buildings, enough attention to the safety of joints can prevent damage and loss. It is worth mentioning that joints account for many building collapses, as they form constraints that limit both deformation and stress [29]. Joints play a special role during earthquakes and in the seismic response of the building. Resistance of joints against jolting and shaking due to earthquakes is beyond those usually required for gravity and wind loads. Ambrose believes in any earthquake: "Fracture due to stress concentrations, progressive deformations, and loosening of joints are of particular concern" [11].

8.2.1. Loosening the Joints

*A*dequate connections are necessary to transfer seismic forces. Surveys of wind-damaged and earthquake-damaged buildings have revealed many cases where special connections have been omitted, for example, where timber decay has loosened the joints so that they no longer hold the structure together.

8.2.2. Movements of Joints

Lessons from recent earthquakes show that jointing techniques must allow for movement while simultaneously providing support or attachment. There should be also enough play in the joints to contribute to good energy absorption. For example Window glass must be securely held in a metal frame, but must have a degree of freedom to allow for thermal changes and to prevent structural deformations of the frame from transferring load to the glass.

Sometimes a structural joint for instance, a seismic control joint, is needed to provide for perpendicular forces and to allow for vertical and horizontal movements simultaneously. A successful design is one that has considered the specific requirements of each joint.

8.2.3. Separation of Joints

Serious damage and collapse usually result from separation in joints and from other departures in form-regular, symmetrical plan form and uniform distribution of strength and stiffness.

The chief risk of earthquake damage is separations at the joints between different parts of the building. Bouwkamp specified "Good seismic performance depends on integrity of structure; this means adequate tying together of all walls or overall integrity of the wall, and good diaphragm action of the floor systems" [27]. In other words, the joints should make the structure as strong as a continuously poured roof. As a special case, when a structure is made from more than one piece of material, preventing it from coming apart at the joints is a problem.

Therefore, our ancestors generally avoided tension structures as far as they could and tried to use constructions in which everything was in compression so they avoided tension stresses, especially in the joints. Gordon states that much the oldest and the most satisfactory way of doing this is to use masonry. In fact, the immense success of masonry buildings has really been due to two factors.

The first is the obvious one about avoiding tension stresses, especially in the joints; the second reason may be less obvious. It is that the nature of the design problem in large masonry buildings is peculiarly adapted to the limitations of the pre-scientific mind. He continues that using mortar or cement to fit between the joints will transmit compressive forces over the whole area of the joint and not just at a few spots. In addition, the friction in the joints is so high that failure will not happen because of bricks or stones sliding over each other. In fact, no sliding movements at all will take place before the structure collapses [30].

The investigation of Bouwkamp and his colleagues revealed that such damage stems from the absence of transverse ties at the floor levels, such as diminishing the thickness of the walls below the windows to about half of other places, so vertical cracks can be seen in each window jamb, and further shaking will lead to local collapse. Failure to tie back columns to the walls behind at the level of the column heads, this permitted an outward buckling of the wall [27].

During earthquakes, the corners are particularly weak areas, and are often disconnected partially or totally from the main structure (Fig. 6). Therefore, the proper connections between all walls are essential especially for improving the overall strength of the structure to resist in front of seismic actions. Different materials including bricks or stones, wooden chains, iron or synthetic bars can do this (Fig. 7).

Fig. 6. Detachment between two walls in a corner

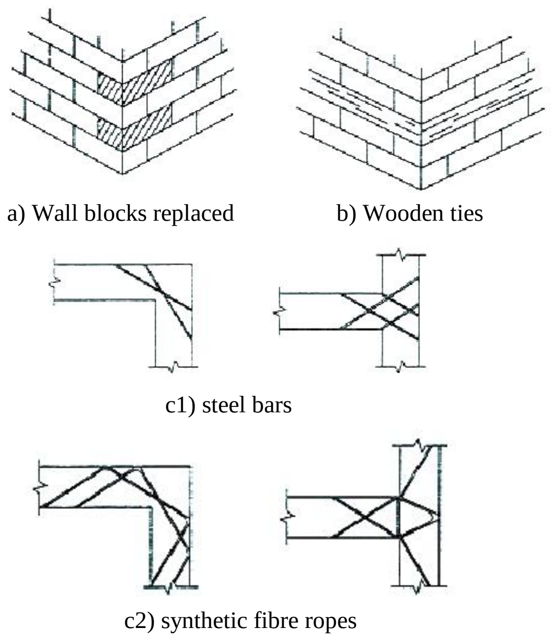

Fig. 7. Connections between two walls with four methods: a) by replacing masonry blocks; b) by wooden lintels; c) by inserting steel bars or synthetic ropes [29].

8-2-4. Seismic Principle of Joints

Flexible joints have a good resistance against shaking. A joint must be able to undergo flexing without breaking. A wooden house properly braced and with all the parts carefully pinned together, will sway, and stretch in response to an earthquake, behaving essentially in an elastic manner. This does not mean that all parts of a house will escape a permanent deformation-a door may not fit squarely in its frame or a window will perhaps be stuck-but the structure will not break or fail in a catastrophic manner. This property of stretch-ability, technically called ductility, is the most important measure of resistance to seismic forces. Modern steel and reinforced concrete structures are carefully detailed to ensure the highest possible level of ductility [22].

9. Seismic Resistance of Iranian URM Historic Buildings

According to the above discussions and reviewing all the required remedies for a building to resist earthquakes, as a practical example, historical buildings of Iran can be mentioned. The experience showed that surprisingly many historic buildings made even from mud-brick survived the hazards of earthquakes, as can be realized in the case of Bam citadel [34]. Investigating the reason could lead the modern architecture to a proper way and learn lessons from them, as the architecture of those days was the result of hundred years of continuous experiences which were gradually evolved through time.

First of all, their integrity was one of the main strengths for their resistance against earthquakes. Application of harmonious material with similar ability such as khesht (mud brick) and wood could be one of the reasons for their integrity. Furthermore, this integrity can be achieved by the form. The structure of Domes, as the mostly used magnificent architectural element in historic buildings, is another reason for their resistance against earthquakes.

Domes are inherently form-resistant in their form thanks to their monolithic structure. Dome behaves differently due to the joints amongst its hypothetical arches along the vertical sections of the dome [35]. The evidence can be seen in figure 8, where this mud-brick dome stands firmly in the hazardous earthquake of December 2003 of Bam, while other structures destroyed.

Fig. 8. The comparison of damage to domed mud brick structure and newer built ones (picture taken by author, 2008)

All of the above shows the simultaneous design for architectural features and structural quality such as seismic resistance. This can be noticed even in the ornaments of historic buildings. One example can be realized in the corner-making methods of domes called Patkana. The result of a computer simulation for the dome of "The major Ab-Anbar of Ghazvin" showed that these architectural elements have structural role as well. The dome with these ornaments showed better performance than the one without these corners.

As can be seen on figure 9, two domes with various corner systems will demonstrate different behavior and specifically different deformation. Therefore, deleting every single element will result in the discrepancy of loads in structural systems. This proves that form and architecture is coherent with the structural system and non-separable.

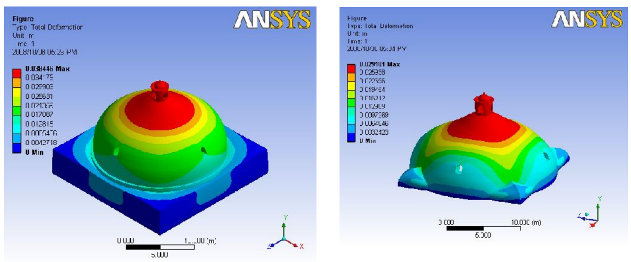

Fig. 9. the comparison of deformation between two domes with different corner systems

10. Conclusions

1) Seismic design coefficients have to be considered in the process of architectural and site design decisions to be effective; otherwise, they cannot ensure the safety of structures.

2) Buildings vibrate during an earthquake and create some problems such as: splitting apart in different locations, pounding between separate parts of the same building or between adjacent buildings. Consequently, buildings will fail during earthquakes unless architects design them so that they will not crash into one another or split apart.

3) Seismic design effort is not just by strengthening structures or defensive actions for controlling their behavior. A different approach is mitigation of seismic effects at the early stages of design for seismic response, which can be applied to buildings by architectural design to reduce vulnerability and unwanted responses.

4) Design of buildings is multi-disciplinary, and many skills have to contribute to achieve a balanced solution. Seismic design criteria are the task of both architects and engineers and need to be considered at the early stages of design. To execute a successful design project, the architect has a role similar to that of the conductor of an orchestra, who has to coordinate all different skills together.

5) Seismic design coefficients have to be considered in the process of architectural and site design decisions to be more effective; otherwise, they cannot ensure the safety of structures.

6) Designing in a seismic area is a shared architectural and engineering responsibility. Concordance between the architectural form and structural system should be started from the inception of the design process and continued throughout the construction process. The architect should review with the engineer even before the beginning of schematic design. In other words, resistance to gravity loads may be achieved through independent architectural and structural decisions. "But in resistance related to earthquake effects, separating the engineer from the architect is a formula for disaster" [31].

7) Considering required seismic coefficients in the architectural design costs nothing and in reality is much more economic than later added strengthening methods such as inserting base isolation and seismic separation joints, or use of shock-absorbing devices within the building structure. The evidence is inserting base-isolations in the building of parliament house in New Zealand. "The base-isolated scheme was 3% more expensive than a conventional solution" [32]. Therefore, the cost of repair is much more than earthquake resistance of the design and construction of buildings.

8) In earthquake countries improving workmanship, higher building standards, and upgrade seismic studies may cause an increase in cost by 2%, but it also provides a 100% higher safety [33].

9) Jumping into considering the base isolation is not acceptable until all possibilities for ground modification and alternatives for the architectural and site designs have been investigated. Seismic separation joints might not be needed at all, if the architectural design is carefully considered the seismic issues.

10) One of the fundamental considerations in seismic resistance of a building is "building configuration," which can directly contribute to architects' principal designing.

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