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ARCHITECTURAL DESIGN AND EARTHQUAKE CONSEQUENCES IN BUILDINGS

Marsida Tuxhari [(1)], Markel Baballëku [(2)], Merlin Asllani [(3)]

[(1)] *Lecturer, Department of Restoration and Architecture Technology, Faculty of Architecture and Urbanism, PUT, Albania*
marsida.tuxhari@fau.edu.al
[(2)] *Lecturer, Structural Mechanics Department, Faculty of Civil Engineering, PUT, Albania*
markel.baballëku@fin.edu.al; markel77@gmail.com
[(3)] *UTS-01 Design Studio. Tirana, Albania*
merlin.asllani18@gmail.com

Abstract

This paper focuses on earthquake consequences in buildings, analyzed in terms of architectural design choices. The Durrës earthquake of 11.26.2019 showed lot of damages of non-structural nature, in buildings of various ages, structural systems, and volumetric shapes.

The object of the article is precisely the treatment of the variety of these "types of damages", which require to be carefully analyzed in order to understand the causes of which some of the consequences came from. The behavior of the building during the earthquake showed that the reasons for the damages were also related to the architect's choices and the corresponding conditions in the technical design codes. For example: the shape of the building, the regularity of the structure, seismic joints, cantilever volumes, parapets, stairs, doors etc. So, the purpose of the article is to highlight the damages that come as a result of those design factors, which directly involve the architect. The article does not undertake to limit the functional and aesthetic choices on buildings but emphasizes the importance of the early collaboration of the architect and structural engineer in seismic-prone areas, taking into account that construction works should be built at optimal cost, with the aim of minimizing such damages in the future.

Keywords: nonstructural damages, irregularities, seismic joint, architectural design.

1. Introduction

The earthquake of November 26th, 2019 in Durrës, which was preceded by another earthquake, approximately of the same magnitute on September 21th, 2019 with almost the same epicenter, caused significant damages on buildings which was followed by strong debates even among the engineers themselves. The earthquake caused a lot of non-structural but still significant damages, in more buildings than those that were structurally demaged.

These damages cannot only be addressed to a specific construction discipline. They have come for various reasons which can be summarized in these 4 main groups:

1. Damages related to the design of the buildings;
2. Damages coming from the lack of knowledge and non-implementation of technical design conditions;
3. Damages related to construction details in the project;
4. Damages related to the construction process and necessary construction details.

A critical look at earthquake damage to buildings, shows that the architectural configuration, which (according to Arnold) is defined as: the building's size, three-dimensional shape, two-dimensional shape and location of structural elements, as well as the nature and location of non-structural components that can affect the seismic performance, aesthetic choices and technical details implemented in many cases, although not the only factors, have contributed to serious structural and non-structural damage to buildings. [1]

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All of the four groups above require full attention of the civil engineer, but for some of them, the role of the architect is a major influencing factor and should not be avoided. Engineers often say that the configuration given by the architects for the building makes their job more difficult, increases construction costs and decreases the safety of the building. So the architectural design of the building is also decisive for its structural configuration, and both of these factors are responsible for the seismic behavior of the entire building.

Many experienced earthquake engineers say that the architect plays a key role in ensuring the satisfactory seismic performance of a building. [1]

So designing for seismic safety should not always be seen as a task only for the structural engineer. In fact, this paper does not aim to limit architects in their functional and aesthetic choices for buildings, but through some case studys, to emphasize the importance of knowing the technical guidelines for architectural design decisions in seismic-prone zones and the importance of cooperation with the structural engineer from the early stages project idea. This way, past mistakes can be avoided and future construction works can be built at optimal cost, because cost and safety issues are top priorities.

Seismic Design Code (KPT-N.2-89) is the official design document in Albania, which gives principles, design rules and recommendations about seismic design of buildings, and other construction works. [3]

Eurocode 8 (EN 1998-1) is also being adapted in Albania, but not yet approved by the relevant State authorities. Due to this, it’s unofficial and not mandatory to be followed and implemented by engineers. However, it is used by all as a guide in the design of engineering projects. [4]

2. Earthquake consequences (case studys of damaged buildings)

According to Albania Post-Disaster Needs Assessment Document (Government of Albania; European Union; United Nations agencies; World Bank, February 2020) (CEN, 2005) 18% of housing units in Albania are overall affected by the earthquake.

In their multitude, this paper focuses on the damages caused to multi-story buildings in Durrës and Tirana regions in Albania, which indirectly or directly involve the architect.

The inspection and analysis of earthquake-damaged buildings plays an important role in understanding the causes of damage and justify the importance and effectiveness of seismic design and construction. There have been damage models, related only to the configuration characteristics of particular buildings, which have resulted in structural damage consequently the destruction of buildings. There were damage models related to the configuration and simultaneously to technical aspects of the construction details. As there have been models of non-structural damage, due to technical details far from anti-seismic design conditions.

Through an architetct’s lens, confronting: cause-and-effect of the actual models and patterns of earthquake damage in buildings can be interpreted related to 3 elements of the building, such as:

1. The volume configuration of the building;
2. The facade of the building;
3. The inside of the building.

The volumetric configuration is related to the both architectural and structural features of the overall building (geometry in plan and elevation), cantilever volumes, height of the building and changes in floor heights, transparency and the height of the ground floor, regularity of the structure in plan and elevation, dimensioning of the seismic joints and taking them into consideration during architectural design.

The facade of the building is related to: the envelope of the building in its opaque and transparent parts, facade cladding and parapets. The interior of the building is related to: stairs and common space of movement, partitions between diferent residential units and those inside the same unit and main apartment door clearance.

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Some of the features mentioned above may be associated with more than one building element, e.g. transparent coatings are related to both the volumetric configuration and the facade; seismic joints are related to the volumetric configuration and in some cases to the interior of the building.

2.1 Residential buildings with irregular configuration

In the multitude of damaged buildings due to irregular volumetric configuration, the following case is singled out, in which there are damages caused by the effects of the interaction of the neighboring buildings with each other, the irregular configuration in the plan and the increased volume on the upper floors.The buildings are located at the entrance to the city of Durrës and were built one after the other in the period 2006-2012, the first with 9 floors above ground (on the right) while the second with 12 floors above ground + attic (on the left). Fig. 2. During the construction of the second building, an additional volume has been proposed in the form of a "connecting bridge" with the first existing building, which is attached with 3 floors and there are 3 more floors above the "bridge".

This volume added to the form of the bridge is partly supported on two columns attached to the facade of the first building but not connected to it and not far from it (on the right) and partly emerges as a cantilevered volume on the last three floors of of it, on the terrace of the existing building.

Due to the irregular configuration in plan, the added mass on the upper floors of the second building and the irregular and large-amplitude seismic waves, two effects were produced: the buildings collided with each other in the joint area and the cantilever volume has increased the height of the center of mass of the second building and has had the effect of increasing its behavior as an inverted pendulum. As a result, parts of walls have fallen from the facade. Fig. 1.

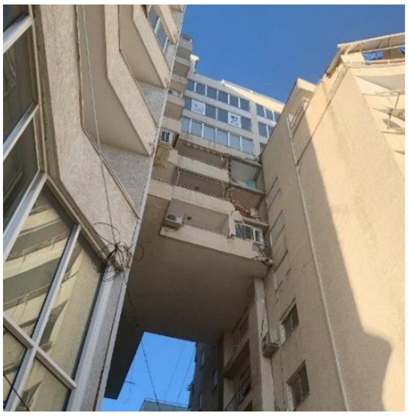

Figure 1. Collapse of the facade walls in the "connecting bridge" area

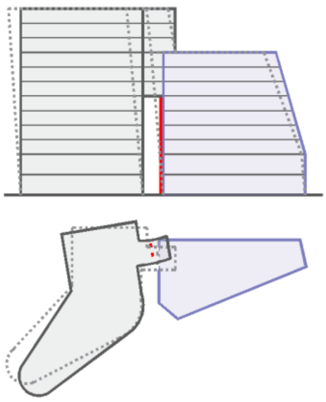

Figure 2. Behavior of buildings during the seismic event

Most of the buildings after the 1990s in Albania are cases of irregular volumetric configuration, dictated by the geometry of the property, the use of the building for several functions and the demand of investors or the architects themselves, who are always looking for the most accurate volumetric form. nice, they wanted to achieve something "unusual", but in this way the project creates a conflict with the seismic design codes and rules. Skilled engineers have taken these projects as a professional challenge to execute them, but experience has shown that the construction of these types of constructions can cost on average about 20% more than the construction of a building with conventional configuration. And yet their behavior during the earthquake has again caused increased damage to the non-structural elements of many buildings and therefore increased cost which is difficult to calculate. On the other hand, in seismic areas, "unusual" buildings cannot provide the same safety as those with a regular configuration.

The main responsibility of the geometric configuration of the building lies with the architect from the first stages of conception. If architectural design geometry and structural design geometry are determined independently of seismic considerations, it is not possible to simultaneously achieve a

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building with appropriate architectural design, desirable seismic behavior, and optimal construction cost. [10]

In these cases, there is a deviation from the code instructions for regular volumetric configuration in plan and height of the building. Both documents, as KTP-N.2-1989, in chapter 1, part 1.4, as well as EN 1998-1, in chapter 4, in general terms recommend the conception of buildings with regularity in plan and height in terms of compactness and volumetric symmetry, looking for: non-pronounced breaks in plan and in height.

According to EN 1998-1, (part 4) uniformity in the development of the structure along the height of the building is important, because it tends to eliminate the occurrence of sensitive zones, where stress concentrations or high ductility requirements can cause significant damage or structurally irreversible.

2.2 Irregular distribution of non-structural components of the building (infill walls and partitions)

The building in Figure 3, with 6 floors and a reinforced concrete supporting structure, built during 2008-2010, is one of many buildings with the same irregularities in their configuration. The building's volatility has been high, among other issues, due to the following factors: low stiffness on the first two floors; low stiffness in twisting and irregular distribution of strucutural elements in the added mass of upper floors and non-uniform distribution of non-structural elements, with added mass on upper floors.

Damage observed in this building after the November earthquake is concentrated on the first floor. The reason why the "soft story" mechanism was developed on the first floor and not on the ground floor is related to the largest shifts that took place on this floor. The best design of the ground floor (the size of the columns and their reinforcement) may have also influenced. On the other side, the lack of non-structural walls in these two floors has contributed to the structural damages, taking into consideration the shape of the damage, it can be estimated that the low rigidity in the torsion and the increased mass of the upper floors (console volumes on both sides) also had their impact. Figure 4

Figure 3. Non-uniform distribution of non-structural components

Figure 4. Damage due to “soft story” and torsional effect

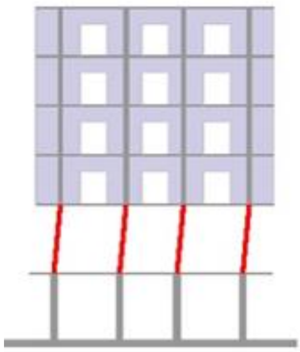

Figure 5. “soft story" mechanism was developed

This damage mechanism has been observed in many other buildings with similar geometric configuration and structural features of which are probably design factors.

Irregular distribution of non-structural elements in height, e.g. in cases where the resistance of the infill walls on one floor is very small compared to the other floors... the result of all this is the creation of a soft floor. This happens, especially in the case of open ground floors with infill walls on one or both sides or without infill walls. [4]

According to Ambrose and Vergun (1985) state that reduction of the soft story effect can be possible. The remedies for soft story are:

- to brace some of the openings;

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- to keep the building plan periphery open, while providing a rigidly braced interior;
- to increase the number or the stiffness of the ground floor column;
- to use tapered or arched forms for the ground floor;
- to develop a rigid ground story as an upward extension of heavy foundation structure;
- to equalize the rigidity of the stories by separating the non-structural elements from the structural ones or using light and less rigid non-structural elements for infill walls and exterior claddings. [14]

All of the above guidelines relate to design issues, most of which structural engineering is responsible for. The architect must be cooperative and prepared to accept structural forms (such as increased size and number of columns and beams).

2.3 Cantilever volumes

From a seismic point of view, cantilever volumes present at least two complications in the dynamic behavior of the building: First, they affect the overall structural irregularity, a problem that requires careful handling in the distribution of primary seismic structural elements. Second, it requires attention to the self-sustainability of construction elements in the area of the cantilever volume. The impact on the overall behavior of the building requires proper structural treatment and is not the scope of this paper.

Due to the simultaneous oscillation in the vertical and horizontal direction, the cantilever volumes are in a delicate situation of balance. In the cases shown in Fig. 6 and Fig. 7, this state of the cantilever volumes is also accompanied by the lack of implementation of technical details to properly connect the walls at the ends of the cantilevers. As a result, the walls of the facade on several floors of the cantilevered volume have collapsed, exactly at the outer corners of the cantilevers.

The main cause of this damage model is the deviation from the anti-seismic design conditions, due to the irregular volume configuration with the cantilevers and the added weight of the walls in them, because the architect has chosen to treat the cantilever as a volume attached to the rest of the facade.

Figure 6. Walls collapse in the cantilever volumes

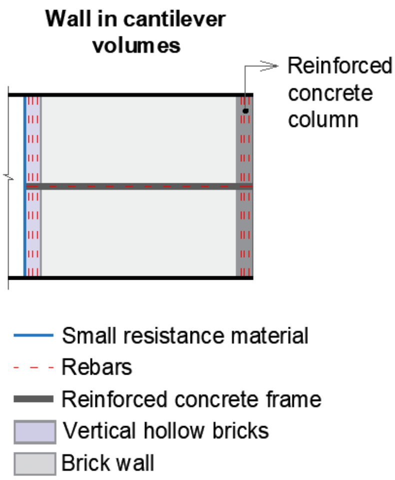

Figure 7. Wall above cantilever reinforcement model

Sandwich walls, which are designed for heat insulation, are also to be tied to each other with cramps in order to prevent overturning due to seismic forces. [9]

Due to their behavior during seismic events, cantilever volumes on facades are recommended to be avoided. If cantilever volumes are a must, technical measures with special construction details must be taken to avoid damage to this model in buildings. These types of damages are the result of simultaneous combinations of some of the 4 groups of causes as outlined in the introduction of this article.

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Many architects believe that seismic design is totally controlled by the engineers in their team and they should not be involved in the conception or coordination of seismic design. But successful seismic design begins and ends with the architect. It is true that engineers can control the details of many components within the building, but it is the architect who must understand the interrelationship between the various systems within the building for successful performance during and after an earthquake. [6]

2.4 Sizing and inclusion of anti-seismic joints in architectural design

Generally, buildings that are separated by an anti-seismic joint have suffered damage in the joint area, generally due to the collision of the buildings during the seismic action. In all these cases, it is understood that their cause is the incorrect dimensioning of the joint. The case of Fig. 8, shows the breaking of the wall up to its separation (also due to the inertial forces caused by the collision of the supporting structures of the buildings). Another consequence of this cause is the damage to the neighboring buildings on the upper floors due to the collision with the greater displacement of the top floors and their uneven swaying.

Also, both documents, [3] and [4], respectively in chapters 1 and 4, recommend the use of anti-seismic joints in cases where the building and structure deviate from the regular configuration on the plan. Anti-seismic joints should turn the building into two or more dynamically independent units, although the parts may function as a single building. The size of the joint must be designed to ensure that its parts do not collide during seismic shaking. During the design process, it is the structural engineer who decides on the position and dimension of the anti-seismic joint. In cases where parts of the building serve as a single functional unit, it is important that the architect respects the position of the seismic joint and its geometry, possibly by revising the project.

Figure 8. Damage caused during the collision in the joint position

A visit to the damaged buildings was neccessary after the earthquake of November 26, 2019, in order to point out the phenomenon of organizing the same functional space of the apartment over the anti-seismic joint. The photos in Fig. 9, were made in the same apartment in a multi-storey residential building built before 2000 in the center of the Albanian capital. Proving whether this choice was design avoidance during implementation was not possible, but the fact shows that the housing unit falls on the seismic joint. This either shows unfair solutions of the architect, for the above mentioned, or shows a complete lack of cooperation and coordination of the design work between the architect and the structural engineer. This must be a widespread phenomenon because the same situation of the extension of the same residential apartment over the seismic joint of 2 neighboring buildings was also found in a building in the city of Durrës. Fig. 10.

Everyone could imagine the experience of residents in an apartment in two dynamically separated buildings during the seismic event, when the floor and the ceiling of the same space in their apartment experienced double shaking.

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a) interior of a room b) Interior of a sanitary unit

Figure 9. Interior view from an apartment in Tirana. Source: Marin Zaimi

a) interior of the corridor b) Interior of the sanitary unit

Figure 10. Interior view from an apartment in Durrës city. Source: Entela Kapllani

2.5 Balconies and terraces parapets

During the earthquake of November 26, 2019, there were cases of terrace parapets falling for various reasons. In Fig. 11, the case of a building whose parapet collapsed due to non-implementation of the technical detail of the brick parapet reinforcement and the thickness of the terrace layers. During the seismic event, a 20 years old girl lost her life, struck in the head by a piece of parapet going out of the building, although the building itself did not sustain significant damage.

Gable walls and the parapets of balconies and terraces, which tend to overturn in an earthquake, should not be built out of masonry construction. They are to be made of reinforced concrete in order not to be separated from the structure. The damage of gable wall may be prevented by placing it between the frames. [13] A solution to the reinforcement of the brick parapet is given in Fig. 12.

Figure 11. Collapsed brick parapet. 1970s construction building

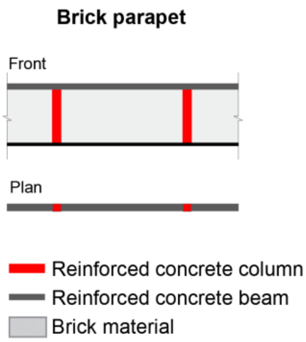

Figure 12. Brick parapet reinforcement model

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

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2.6 Facade cladding

The pictures below show 2 different buildings with concrete construction to which coatings of different materials have been applied but with the same technique. In the building in Fig. 13, natural stone slabs were applied with glue adhesion on one of the facades, during the implementation and outside the forecast of the project, while in the building in Fig. 14, ceramic tiles are applied by gluing.

In the first case, not only the detachment of the stone slabs from the facade occurred, but also the structural damage of the columns in the facade covered with stones, because during the seismic event they could not withstand the increased stress as a result of the unforeseen weight of the natural stones on the facade. The destruction of the building was identified as a consequence of the deviation from the design during implementation and the loading of the structure with a weight outside of the design. In other cases of cladding facades with natural stone tiles with mortar adhesion, their detachment from the facade has also occurred.

In the second case, the ceramic tiles were detached from the facade due to their gluing assembly with mortar on the exterior facade. However, the adherence, breaking and tensile strength of the mortar are restrictive. The consecutive drift movement due to earthquake forces between stories makes the mortar exceed its strength and makes the finishes separate from the walls due to properties of mortar in between. [13]

Hence, chemical connections, such as mortar, are inconvenient, which are also prohibited in western countries prone to earthquakes. Instead of chemical connections, mechanical connections such as cramp anchorage with proper details and intervals are appropriate to be used. [9]

Figure 13. Cladding with natural stone

Figure 14. Cladding with ceramic tiles

According to KTP-N.2-1989, Chapter 3, Point 3.4.2, the plates used for covering external walls with a surface area greater than 0.1 m^2 ... are anchored to the walls with the help of metal ties.

Selection for the wall and its finishes must be realized taking into considerations whether the main structure is flexible or rigid. For rigid structures, finishes such as stone facing can be utilized, if precautions are taken in the method of attachment. In flexible structures, wall finishes, which can adapt themselves to deflections of the main structure, can be used. [11]

The types of damage so that cases of damage to non-structural elements on the facades are not repeated, the implementation project must be completed with technical details of the realization of the connections of the component elements of the facade with each other and with the supporting structure of the building at the same time to avoid the detachment of the tiles due to "fatigue of the material", from the cyclic change of air temperatures.

2.7 Common stairwell space

Stairs and corridors provide exits from the building. In many cases of high-rise buildings in the Durrës area, the damage to the stairs itself, accompanied by the fall of parts from the damaged surrounding walls of the stairwells, which have occupied the bases and landings of the stairs, making it even more

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difficult to move residents during and after the seismic event. As the panic grew during the descent to quickly leave the building, many people fell and suffered physical injuries. Fig. 15, shows cases of inerts falling down stairs.

One of the solutions is to design fixed bearing from one corner of the staircase to the frame and unrestrained bearings from the other corners. Another solution is to separate the staircase as a separate building block with seismic joints. Hence, the staircases and the corridors of them should be surrounded by shear walls in order to form cores. [9]

Figure 15. Damaged stair ramps

Figure 16. Inerts fallen down stairs.

2.8 Masonry opening for exterior apartament doors

Also, due to the deformation of the walls, the door frames have suffered deformations, especially those of the outer doors of the apartments, which have blocked the opening. As a result, residents experience increased panic due to the inability to immediately leave the building during and after the seismic event and also to enter the apartment after the seismic event in the case that they went to the apartment after the earthquake. In Fig. 17, shows door with damaged lock to enable opening.

When the walls surrounding the doors and windows are subject to their deformation or blocking, then the solution is: appropriate framing of the cracks in the walls with reinforced concrete and the plastering of the walls is accompanied by galvanized steel mesh, as shown in Fig. 18, and Fig. 19.

Figure 17. Exterior door with damaged lock

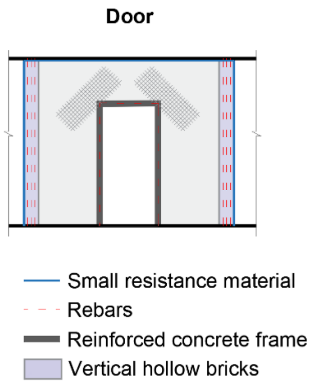

Figure 18. Exterior door reinforcement model

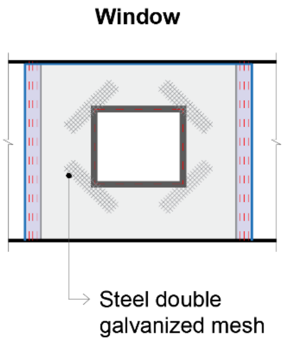

Figure 19. Exterior window reinforcement model

2.9 Partition walls, suspended ceilings.

In Albania, in most buildings, the dividing walls are made of brick masonry. In many residential buildings, complete parts of the walls were detached from their initial position, similar to the case

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given in Fig. 20. Usually, rigid partitions need to be anchored top and bottom to provide lateral support or stability, against toppling. To avoid stiffening the structure, upper anchors must accommodate both in-plane and vertical movement. [16]

Light partition walls is recommended when they do not conflict with the requirements for acoustic insulation and fire resistance.

Figure 20. Collapse of the partition wall

Figure 21. Collapse of suspended ceiling and light fixtures during the earthquake of September 21th, 2019. Faculty of Geology and Mining. PUT. Tirana. Sourse: http://redaktori.net/?p=17147

Since suspended ceiling often falls during earthquake, Figure 21, connections with the suspended members must be properly designed. As the suspended ceiling is subjected to horizontal movement due to seismic forces, a gap should be made at the perimeter of it in order to prevent the ceiling pounding to the walls. The suspension system for the ceiling should also minimize vertical motion in relation to the structure. [10]

The types of damage mentioned in the last three cases so that cases of damage to internal non-structural elements are not repeated, because their fall has the potential to injure users, the implementation project must be completed with technical details of the implementation of the elements as appropriate and take into consideration the lessons learned from previous earthquakes.

3. Findings (Lessons to be learned)

The findings are based on post-earthquake damage observation and assessments performed for this purpose, both in the examples presented in this paper and in other similar examples investigated during and after the earthquake. The following findings refer to those damages that are directly or indirectly caused by the interweaving of structural and architectural choices and solutions. Summarized in groups these are:

1. The earthquake showed that the seismic action in some areas was higher than predicted by the seismic code; in these cases many non-structural elements suffered significant damage in both old and new buildings: parapets, cladding, partition walls and anti-seismic joints between buildings;
2. In earthquake-damaged areas, there are lot of cases where the functional solution and architectural design do not fully take into account the guidelines of the seismic design code. They are related to: the regularity of the building in plan and height, anti-seismic joints, flat slabs, changing the transparency of the facade in height, non-structural construction details related to the facade and the interior of the building;
3. Functional solutions for medium- and/or high-rise buildings, especially when they combine different functions of use, have helped to create the conditions for earthquakes that cause significant damage and increased panic to users: masonry built and interwoven with the

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elements of others (doors, windows, etc.) inappropriately; the high number of apartments on the floor and the solution of the main staircase, also helped by the stability of the doors, has created panic and injuries when leaving the building.

4. Conclusions

Because configuration is important, and since the architect creates and controls the configuration, it follows that he is a key participant during the seismic design process. The configuration problem is a universal concern, affecting all types of buildings and constructions. To the extent that the architect is influencing seismic performance through his choice of configuration, he should be better informed about the consequences of his actions. [2]

The challenge for architects, engineers and builders is to ask why so much damage occurs and what can be done to prevent the problem. [5]

Architects and engineers learn from detailed investigations of damage from past earthquakes and can document important issues and lessons about particular problems. Some problems occur due to improper design or construction or irregular volume configuration. Some because the building or structure cannot uniformly distribute the seismic energy, and some because of excessive loads caused by dynamic resonance between the ground shaking and the building.

Geometrical concepts of the correct volumetric and structural configuration of buildings should be given to architects from school grades. The architect at any time of his professional development can be familiar with the irregular volumetric models or the irregularity of the configurations of structural systems, etc., given schematically according to (SEAOC) and Arnold. [1]

At the same time, the architect can become familiar with the seismic behavior of irregularly shaped buildings, understand where their weakest point is and the danger they may present during an earthquake. Even engineers may seek to convince architects to use conventional, regular and preferably symmetrical forms in seismic locations. If reference is made to history, there is evidence of buildings of antiquity and those of several hundred years which have resisted many earthquakes and this is thanks to their shape.

Seismic design is utilitarian and should be considered more important than aesthetic design. To resolve the conflict, it is required to increase the level of collaboration between the architect and the engineer in the building's conception stages. For this process to be successful, the architect and the engineer must have mutual knowledge of the fundamental principles of their disciplines. Therefore, it is always necessary for the architect to familiarize himself with the newest codes of seismic design, to which he can look for recommendations and principles of design of volumetric forms, configuration and constructive systems of buildings. On the other hand, the engineer must understand and respect the functional and aesthetic context within which the architect works.

It is necessary that the legislation and technical construction regulations, especially those of urban and architectural design, include as best as possible the general principles and criteria of seismic design and be in line with the seismic design code;

The damage in the areas affected by the earthquake highlighted a series of weaknesses of the buildings that are also related to the architecture, both in conception and construction details, such as regularity, seismic joints, facades, stairs, interior, etc. These damages and the technical solutions for them should serve both for the repair and reinforcement of damaged buildings as well as for the design of new buildings, in areas affected by the earthquake and in areas with high seismicity;

Special recommendations:

1. The rregularity of the building should be part of an exhaustive discussion from the conception of the design. In cases where this rregularity can be avoided, should be taken all the necessary measures;

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2. It is advised to avoid cantilever volumes in regions with high seismicity. If unavoidable, their impact on the overall seismic behavior of the building, as well as design construction details with a focus on the stability of the cantilever elements themselves must be taken into account;
3. During the design and implementation, it is recommended that for elements inside the building, such as partition walls, windows, doors, stairs and their vertical outline, etc., should take into account the rules of seismic design that limit damage to non-structural elements of the building;
4. Seismic joints need to have adequate dimensions; to be provided in well thought out areas (not inside the dwellings) in advance; to be disguised, "furnished" in a distinctive way so that during future seismic events the dividing line appearing should not misinterpreted as serious damage;
5. Parapets, especially in existing buildings, should be checked and where they result with insufficient ability to withstand seismic action or where they are damaged, they should be reinforced.

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