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Seismic Engineering Technology: Changing the face of Architecture

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Abstract

Since the beginning of times architecture has been used as an instrument to demonstrate political and economic power, so architects have been looking to create spaces and buildings that amaze people. Technology has been one of the most important features that have allowed architects to achieve these goals: taller buildings, greater cantilevers, asymmetry in structural topology, etc. Seismic engineering has evolve in a short period of time, developing structural systems and seismic devices that help architecture and engineering to create new solutions in seismic zones, such as: shear walls frames, moment resisting frames, concentric and eccentric brace frames, base isolation systems, elasto-plastic and visco-elastic dampers, metallic yielding dampers, hydraulic external pre-isolators, magnetorheological fluid dampers, etc. These devices and systems, with the use of computational advances for different types of seismic analysis, help to create spectacular buildings in seismic zones, changing the face of architecture and the image of the cities in which they are built. The aim of this paper is to analyze through time the development of different seismic structural systems and the seismic devices which dissipate seismic energy and how their presence in the structural design of iconic architectural buildings all along the world has made possible their dreams in seismic zones.

Keywords: Base isolation; Seismic Technology; Seismic Architecture; Dampers; Braced frames

1. Introduction

Since ancient times architects and engineers have been working together with the same goal: to build functional, safe, durable and beautiful buildings. As buildings have shown a status of power and richness, architecture has been always looking to create innovative spaces and buildings which amaze people. In order to achieve this aim engineering through technology has responded looking for new: materials, structural systems and/or building methods, features that allowed architects to create taller building, buildings with big cantilevers or with asymmetrical shapes. But ¿what could happen with these buildings if constructed in seismic active areas? Every construction built in a seismic zone has to deal with the hazard of earthquakes, and engineers have been creating different solutions in order to avoid buildings from falling. With these issues in mind, seismic engineering began the research on building's seismic behavior and started to develop structural systems and damping devices such as: moment resisting frames, shear walls, braced frames, base isolation systems, inter-story shear dampers, magnetorheological fluid dampers, etc. which help to create iconic and structural challenge buildings, changing the cityscape even of seismic regions. The aim of this paper is to analyze through the history of seismic engineering the development of seismic structural systems and special devices for dissipating seismic energy, in order to show how they are introduced in the design of architecture, especially contemporary architecture, which defies conventional seismic shapes and heights.

The most common seismic devices and structural systems were included in this study, as they are presented in chronological order by device or system. The architectural cases selected and presented along this paper were chosen because they are iconic buildings worldwide changing the paradigm of construction in seismic areas and buildings that lead the way to new heights in an emerging country like Mexico.

2. Development of Seismic Engineering: Technology and Structural Systems.

Earthquake engineering began to develop around 1870 in Japan and began to widespread mainly to New Zealand and after to the United States (USA). It is considered that Seismic Technology began with the creation of the seismograph, circa 1880. In the following years, 1900-1950, great changes would take place: as building seismic behavior was studied in countries with a growing economy such as Japan and USA, seismic codes were made and improved in few years [1]. At the beginning seismic design used static force concepts, but in the later 50´s buildings dynamic response was studied (i.e. period, modal frequency, modal mass, etc.) evolving from the equivalent lateral force procedure (1927) to the response spectrum and linear dynamic analysis (circa 1960). As a result of these advances, structural configuration parameters were suggested to be considered for buildings at seismic zones: a) symmetry, avoiding the irregular distribution of forces induced by earthquake; b) regularity, eliminating the occurrence of critical zones where concentration of stresses might cause a collapse; c) dimensions and selection of a structural system, the height of the building is related to seismic resistance in connection to the structural system and material [2]. The structural systems most commonly used by earlier 90´s were moment resisting frames and shear wall frames.

Moment resisting frames and shear wall frame system are the oldest structural systems used in seismic zones; in most early applications concrete or steel moment frames were used in all framing lines of the building, to avoid seismic lateral deformations, reinforced concrete shear wall frames were introduced. The first tall building built with shear walls was the 32 stories with a height of 127m Pirelli Tower in Milan (1958, Arch. Nervi) [3]. Around 1960´s concrete special moment frame concepts were introduced in the U.S., this system was proposed to give architectural space flexibility using less columns inside the building because fewer framing lines of the building were considered as the seismic force-resisting system and gravity only framing were design apart; it was until 1973 that seismic codes required use of this system in seismic zones [4].

In 1963, taking advantage of advances in seismic analysis, the Japanese Building Bylaws allowed a free approach of earthquake resistant design and structural system layout if the scheme of the building and its seismic analysis were judge appropriate by peer reviewers; the maximum height allowed for buildings in Tokyo was 31m. The Kasumigaseki Building (Arch. Kajima Design) was projected with a height of 147 m. and 36 stories above the ground (plus three basement floors), so it was review to permit the building height. In 1968, K. Muto completed this building, being the tallest construction ever built in a seismic zone. The structure of this building consist of a rigid central core framing and a less rigid exterior steel framing; it used composite reinforced concrete structure with steel sections for the basement and podium level. ***"Slitted shear walls"*** were used as earthquake resisting elements to provide stiffness to the core. These shear wall panels created by Muto were reinforced concrete wall with slits that provided more ductility than the conventional solid reinforced concrete shear wall, changing the shear wall behavior to a series of flexural wall-columns with a high deflection capacity so they would maintain their integrity after cracking only when they are connected between ductile steel frames [5]. The final architectural design features of the building were decided after the appropriate structural design was found, leading to the term structural/architectural configuration.

Around the mid 60´s the use of steel moment resisting frames in the construction of mid-rise buildings in seismic zone demonstrate their susceptibility to large deformations during strong ground shaking, and using shear wall frames in order to limit deformations reduced interior spaces and does not have the sufficient ductility. ***Braced frames*** buildings were proposed in seismic zones, as they were capable of withstand seismic lateral loads. Braced frames systems are stiffer than moment resisting frames and the combination of both systems was possible; they were used for first time in 1892 for the Masonic Temple at Chicago (Arch. Daniel Burham) building composed by 21 stories and 92 m height to withstand wind pressures for tall buildings (Chrysler Building and Empire State in New York, 1930), but they were not used for seismic loads until thirty years after. Computers appeared around 1970, year when the first program of structural analysis was starting to develop, helping to analyze buildings using linear and time history analysis.

Through extensive seismic research from the 70´s to the 90´s, concentrically and eccentrically braced frames became accepted as seismic force resisting systems. There are two main kind of braced frames: concentric and eccentric. ***Concentrically braced frames*** consist of diagonal braces joining at the end points of other framing member forming a truss and creating a high strength and stiff frame. Bracing may be arranged in several configurations such as cross-braced (also called "X" braced) and V-braced (often called K-braced frames). Steel concentrically braced frames are considered an efficient and economical lateral force-resisting system which control lateral deformations in buildings. Damaged to concentrically braced frames during earthquakes in the 80's and 90's raised concern about its deformation capacity rising from the difference between tensile and compression capacity of the brace and the degradation of brace capacity under compressive and cyclic loading. In the 90´s an interesting design approach for buckling-restrained braced frames was proposed, known by the name Special Concentrically Braced Frames. They system is characterized by a full, stable, symmetric hysteretic loop with relatively low post-yield stiffness. Since the braces do no buckle laterally, local damage to adjacent nonstructural elements should be reduced [6]. The direct and simple way of bracing is placing this system over the façade or perimeter frames, being an important part of the architectural design of the building. The Alcoa Building in San Francisco (1964, Arch SOM) is a good example of the structural/architectural building configuration using this type of braces.

Eccentrically braced frames (EBFs) consist of diagonal braces where one or both ends of the brace do not join at the end points of other framing members. EBFs brace forces are introduced to the frame through shear and flexure in the link (length of beam between the braces) so it acts as a seismic fuse; the braces are designed such that they do not buckle under extreme loading conditions so the major inelastic activity takes place in the link. EBF may exhibit greater energy dissipation capabilities and work together with moment rigid frames for mid-height or lower buildings. EBFs successfully combine the high level of ductility of moment rigid frames and the high level of stiffness of concentrically braced frames by introducing eccentricity between the frames cross bracing and columns [7]. These devices can be placed at the façade or inside the building, creating a functional and visual architectural problem for some architects of compositive possibility to others, blending architecture and seismic engineering. The San Diego Bank of America Tower was built in 1981 (Arch. Tucker) with a height of 74.31m this building has a total of sixteen EBFs with shear links at each end of the brace; they are placed in each direction at each end of the tower creating two cores, so EBFs are only in the lateral façade and interior of the building, leaving a large area between the two cores creating an open space to be use as office area and leaving external cores for services. EBFs can´t be seen from the exterior because of its concrete façade, creating a nice structural/architectural solution.

At late 70's and beginning of the 80´s in order to broke the monotony of tower form, high rise buildings look for new architectural expressions and keep getting taller, forcing seismic engineering to develop new seismic devices. During this period structures designed for seismic conditions relied on the strength, stiffness and ductility as the main structural parameters to resist lateral forces. Seismic codes recognized the after mention parameters by considering the energy dissipation capacity of structural systems in reducing the overall seismic design forces for a structure. Even when the structure behaves elastically some degree of energy dissipation is present, which is known as structural damping. New devices added to the structure were created in order to supplement the damping capacity at response levels below the yield limit, and increase the level of ground motion input required to cause significant inelastic deformation in the structure during severe earthquakes. These energy dissipation devices are known as passive seismic protection and can be divided into two major groups: base isolation and inter-story shear dampers.

The ***base isolation system*** control the ground motion input at buildings, which reduces ductility demands and minimizes its deformations; they are most effective when located at the interface between the lowest part of the building and its foundation. This system improved building performance and allowed greater architectural freedom in the choice of the structural system and its layout detailing, because suppresses several factors which acts as constraints on the architectural design like dynamic effects of irregularities and appendages. The earthquake resistance of the structure depends on a combination of elastic strength, inelastic deformability and damping capacity [8]. Recent studies have found that when using this system, the building should have a fundamental frequency that is lower than its fixed base frequency and the dominant frequencies of ground motion, and that if an eccentricity exists between the center of stiffness and the center of mass of the superstructure, coupled lateral-torsion motions occur in base-isolated structures with elastomeric isolation system when subjected to lateral ground motions [9]. There are two types of isolation systems, ***elastomeric bearings*** with the elastomer made of either natural rubber or neoprene, giving the structure a fundamental frequency much lower than its fixed base frequency and much lower than the predominant frequencies of ground motion; the second type is ***sliding system***, which limit the transfer of shear across the isolation interface.

Tod´s Omotesando Building (Arch. Toyo Ito), constructed in Tokyo, Japan (2002); with seven levels and an irregular L-shaped plan this innovative architectural project placed seismic isolation devices in its foundation to avoid cracking of its 30 cm thick reinforced concrete wall façade when an earthquake strikes. The structure of the building consists of the symbolic arborescent reinforced concrete façade, an internal reinforced concrete core and flat reinforced concrete void slabs, among which the façade undertakes most of the building's weight as well as horizontal load by behaving as lattices or seismic walls with openings. The flat void slab covers an span of approximately 10 m. and has a thickness of 50 cm reducing by half along perimeter to suppress the out of plane moment transmission to the façade. The isolation system consists of 14 high-attenuation laminated rubber bearings, reducing drastically earthquake input which enables the building to resist it, mostly by the thin reinforced concrete façade reducing the seismic deformation of the façade [10]. By working together architect and engineer from the inception of the project an effective architectural and seismic design was achieved.

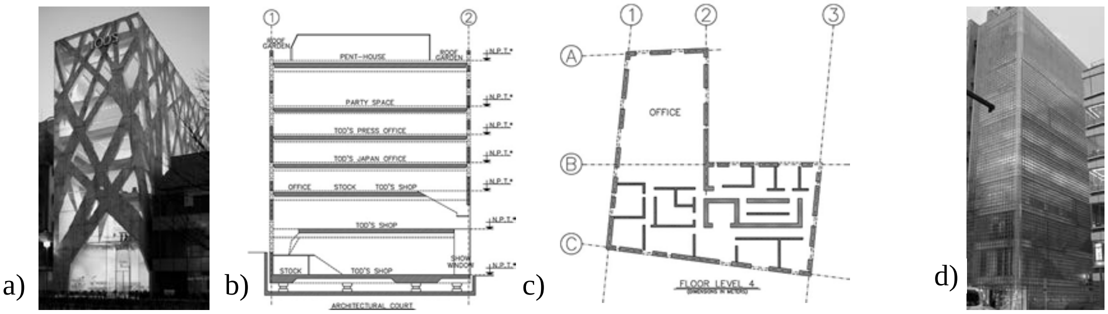

Fig. 1 – Tod's Building: a) Front view; b) Section; c) Floor plan and Maison Hermes d) Lateral View

Most constructions worldwide are masonry residential and small buildings, but masonry is not very suitable in seismic areas due to its low structural efficiency, as result of its scarce tensile strength compared to its high mass and low ductility. Seismic isolation can be very useful for this kind of buildings because its reduction on the seismic actions affecting the structure, achieved by increasing the natural period of the structure and reducing the seismic actions on the superstructure [11]. In Japan, ***sliding bearing isolation***, consisting on a pair of sliding plates composed of PTFE and steel plates jointly with laminated rubber bearing, has been developed for residential houses at low cost; rubber bearing isolators are not necessarily appropriate since houses do not have heavy weight and the vertical load to be carried by each isolator is quite small [12]. In 1985 provisions for seismic regulation were published (NEHRP) setting clear that building configuration as a factor in determining acceptable analysis method and selecting structural systems, was part of architectonical design.

After the damaged caused by the 1989 Loma Prieta Earthquake (San Francisco Bay Area) and the 1994 Northridge Earthquake (Los Angeles), seismic engineers began to ask about the actual earthquake performance of the buildings. Real performance could differ from the solution obtained by simple compliance with the building code and one of the most important issues was the dissipation of seismic energy by the building structure [13]. The pursuit of this issue led seismic engineering to developed a combination of structural systems: moment frames + braces + passive damping systems creating ***inter-story shear damping devices*** ; this devices can be divided depending on its combination: diagonal brace damping systems, moment frames and passive seismic damper, dual system of steel moment frames and eccentric braced frames, etc. The three major types of inter-story shear damping devices are: fluid viscous dampers, viscoelastic dampers, friction dampers and hysteretic/yield dampers.

Hysteretic dampers were created using steel plates that have energy-absorbing capability, reducing structural deformation and forces. This system is to be installed inside the structural body such as walls or beams which absorb energy of the large earthquake preventing damage on the main body of the building while non-structural damage should be lower. As the damper is incorporated into a part of the walls or beams, it does not obstruct space and is free on any architectural interference. They can be also adapted as part of a concentrically braced frame. ***Friction damping devices*** started to develop in late 70´s. These devices consist of series of steel plates which are specially treated to develop most reliable friction; these plates are clamped together with high strength steel bolts and allowed to slip at a predetermined load. During severe seismic excitations, friction dampers slip at a predetermined optimum load before yielding occurs in other structural member and dissipate a major portion of the seismic energy, allowing the building to remain elastic or at least yielding is delayed [14]. Friction for different types of construction have been developed (concrete shear walls, braced steel/concrete frames, low-rise buildings, etc.). The J.W. Mc Connell Building, with ten-storey, was built in 1992; the structural systems used are steel bracing and friction dampers at the junction of steel cross-bracing in the concrete frame, providing greater flexibility in space planning and savings to the total building cost. Architects expose some friction dampers as part of the interior façade as part of their architectural design.

Fluid viscous dampers were studied for seismic use around early 90´s. These devices use a non-toxic and thermally stable fluid from the silicone family that flow through orifices, reducing stress and deflection within a structure subjected to seismic loads. One of the most beneficial aspect of these dampers is they have a relatively compact size, if used as part of a structural bracing frame, having smaller cross-sectional envelope. ***Viscoelastic diagonal dampers*** are effective in reducing floor displacements and inter-story drifts resulting from seismic loadings; they can reduce the drift of a moment resisting frame by as much as 50% without significantly increasing the base shear demand or floor accelerations. The characteristic of viscoelastic dampers is the dissipation of energy at all levels of deformation and over a broad range of excitation frequencies. In addition these devices with large design damping ratio structures may remain elastic or experience minor yielding under most current design earthquakes [15], and can be classified in solid or fluid dampers. Maison Hermes (Arch. R. Piano), built in Tokyo (2001) is a 13-storey slender building, brought a display of seismic technology allowing a complete façade (length and wide long) of fabricated glass-block. A new system was created to allow the rear columns of the seismic frame to lift off their foundation without developing tension and controlled this uplift by using visco-elastic dampers, demonstrating that today’s technology allows to solve any architectural project.

Around mid- 90´s, shape memory alloy (SMA) materials have been used to develop passive dissipation systems called ***SMA dampers***; these systems are achieved by using the energy dissipation capability of austenitic wires subjected to tension or martensitic bars/plates subjected to bending or torsion. This material has been used to develop brace dampers and base isolation dampers being the main drawback of some of these devices the limited energy dissipation capability of austenitic SMA material [16]. An alternative concept of ***semi-active control device*** has been proposed, including variable friction devices, controllable fluid dampers, etc.; this semi-active control device is defined as one that cannot increase the mechanical energy in the controlled system but has the properties that can be dynamically varied. One semi-active device that appears to be promising is the ***magnetorheological fluid damper*** (MR) which uses magnetorheological fluids with their ability to reversibly change form a free-flowing linear viscous fluid to a semi-solid in milliseconds when exposed to a magnetic field; because they behave non-linear the challenge has been to develop the appropriate algorithm to take advantage of this device. ***Base Isolation system considering MR Elastomers***, is another proposal for this new smart material whose stiffness can be adjusted depending on the magnitude of the magnetic field [17]. These devices are still being studied and perfected, so they are not being massive produce like other conventional dampers.

Materials continue to develop and more seismic devices are created. In 2006 a semi-active independently variable damper was developed as a base isolation system called ***semi-active variable damper***; it consists of four linear visco-elastic elements arranged in rhombus configuration so the magnitude of the force in this device can be adjusted in real-time [18]. ***Hydraulic External Pre Isolator system*** is an active isolation system that consists on a single or two stage isolator; these isolators have a six-degree of freedom system, featuring an optical table mounted on a rigid structure suspended in all directions of translations and rotations. Blade springs are used to provide the vertical isolation and horizontal flexures are used for horizontal isolation [19]. This last device was design for vibration isolation and alignment of platforms for observatories and it has not been used for seismic structural use, but that is our future in seismic technology.

3. Seismic technology: changing the face of architecture.

Seismic codes were developed for low and medium rise buildings with rigid or semi-rigid frames and diagonal bracing whose responses are dominated by the first translational mode in each horizontal direction; seismic issues for architectural configuration are stablished: with equal floor heights, symmetrical plan shape, identical vertical resistance, seismic resisting elements at perimeter, to be a regular building. These conditions apply to the design of everyday building; but today post-modern architecture has been challenging seismic engineering with the use of every technology known and creating new one; the design of today high rise buildings in seismic zones or iconic architecture require to meet the imposed drift requirements while minimizing the architectural impact of the structure.

This new architecture do not follow the regular building conditions for seismic design: spans are getting longer, the number of columns is reduced, there is no need of identical resistance on both axes, the geometry of buildings can be irregular, etc. Innovative structural systems involving tubes, mega-frames, core with outrigger systems, composed steel-concrete system, seismic devices and mixed seismic structural systems have been developing in order to reach new heights for tall buildings or new forms for post-modern architecture in seismic zones. Two extreme architectural cases are presented, as an example of what seismic and modern technology together has achieved, leaving behind the classical concepts of seismic conditions. Only the structural seismic system and main structural parameters are presented for each case.

3.1 Case 1: Building Taipei 101 (Arch. Lee & Partners)

This post-modern building was started in 1999 and finished in 2004. It was conceived as an architectural icon of modern Taiwan. This building of 508 m of height is located near potentially severe earthquakes zones including an inactive fault through the site. For high rise building, foundation is important because it can affect the seismic response and performance of the building, adding flexibility and damping, mainly on soft soils. Foundation was solved with slurry walls, a concrete mat 4.7m thick and 380 piers. To provide economical overturning resistance and lateral stiffness the full building floor plan width and depth was used; it has a central braced core improving its strength and stiffness by connections to several perimeter columns on each building face through outrigger trusses with top and bottom chords incorporated within the framing of two adjacent floors and diagonals through occupied space, creating a mega-frame that with the help of the outriggers stabilize the core.

Belt trusses above each module setback gather and transfer perimeter weight to two outrigger super-columns on each face so the member sizes needed for gravity load provide axial stiffness. For seismic lateral stiffness the solution was 8 hollow columns with size up to 8’x10’ filled with high strength concrete placed at the perimeter. EBFs were used to limit buildings lateral displacements, but the open link portion of the beam was strengthened by side plates to maintain stiffness and ensure the link will not control strength across the eccentric link for wind case. Where large rotations were anticipated during seismic events, ductility was provided by a dog bone. The seismic analysis developed for this building considered two design objectives: a) an elastic-structural response, designing non-structural components and internal walls to be undamaged by predicted deformations and accelerations and remain operable; b) Collapse prevention under the largest earthquake shaking that is expected at the site (earthquake demand with a return period of 2500 years) using non-linear response history analysis. [20]

Taipei 101 was the first skyscraper built in a high seismic zone; having a regular plan helped the structural design but its height was a great challenge. Seismic design considered using a combination of seismic systems and new structural devices: moment rigid frames, braced frames, central brace core, outrigger trusses, compose steel-concrete as mega-columns, etc. Today’s computational power and seismic knowledge advances allowed seismic designers to undertake performance based design and all the associated parameters ensuring a safe and comfortable building. Structural system allowed generous space inside the building and architectural design followed the structural building configuration. Its final cost was approx. $1.8 billion US dollars.

3.2 Case 2. China Central TV Headquarters Building (OMA).

Located in Beijing, China, a high seismic zone, this irregular shape mid height building 243 m. tall (51 floors) was finished in 2012 after 8 years of construction. Its foundation was a piled raft that extends beyond the footprint of the towers. To deliver the desired architectural form and resist the bending forces generated by the cranked and leaning form, the entire façade structure was engage in the creation of an external continuous tube system. The tube is formed by fully bracing all façade sides with a perimeter of steel or steel-reinforced concrete columns, perimeter beams and diagonal steel braces set out on a typically two-storey module.

This building architectural configuration had parameters not allowed in the Chinese code, as the number of stories, plan and vertical irregularities, etc., so the structural design must be approved by a seismic design expert panel review. A performance based design approach from the outset was made. Explicit and quantitative design checks using linear and non-linear seismic analysis were made to verify the performance for all levels of design earthquake (different peak ground acceleration and earthquake demand with a return period of 50, 475 and 2475 years). Seismic force and deformation demands were compared with the acceptance limits established to demonstrate performance levels were achieved. Braces were critical to lateral and gravity systems of the building and were also primary sources of ductility and seismic energy dissipation; inelastic deformation acceptance limits for brace members in the continuous tube were determined by non-linear numerical simulation of the post-buckling-behavior. The acceptance inelastic deformation was then determined from the strength degradation backbone curve to ensure there was sufficient residual strength to support the gravity loads after a severe earthquake event.

Every floor has a different configuration, while the external tube structure slope the internal steel columns and cores are kept straight; the spans from core to façade and internal columns to façade change on each level. Additional columns were needed on upper-storeys, where the floor spans increase significantly on one side of the core. Transfer trusses support this additional columns spanning between the internal core and the external tube structure, connecting to the internal core and the external columns at singular pin-joint locations. The bottom two levels of the Overhang contain 15 transfer trusses that support the internal columns and transfer their loads into the external tube [21].

This deconstructivist building has an irregular shape in plan and elevation, an overhang as cantilever, long spans and variation in vertical resistance, failing to comply the regularity conditions stablished by seismic codes. Even though its design and construction was possible through the use of contemporary seismic knowledge and technology available: special braced frames, diagonals and trusses, mixed steel and concrete systems, computational power and the most important, the advances on earthquake effects on buildings and materials behavior. The architectural concept and the exterior form was the most important consideration in the structural design of the building. Seismic engineer dictated the structural solution placing interior braces and diagonals where architects could hide them or did not affect interior space, working together to get the best of everything. The final construction cost or this building was $800 million US dollars.

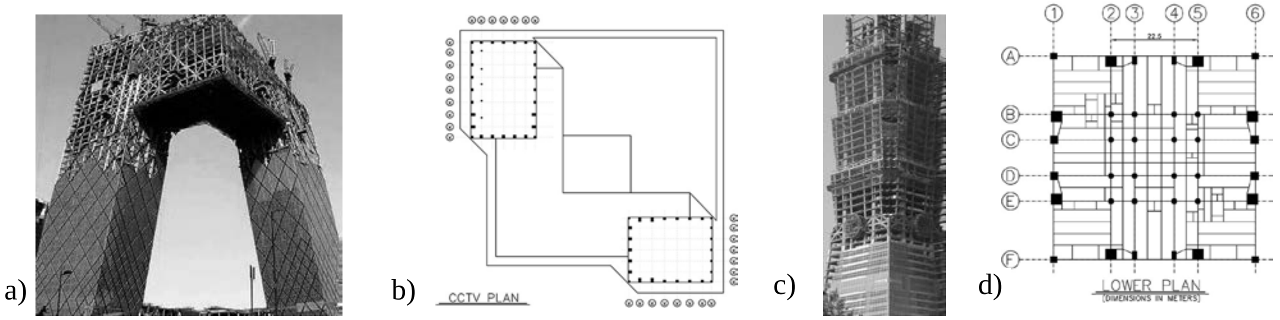

Fig. 2 – CCTV Building: a) Lateral view; b) Floor plan 1st level; and Taipei 101 c) Lateral view; d) Floor plan.

4. Seismic technology: changing the face of a City.

As an emerging country, Mexico City's first Building Code (which includes seismic effects) was published in 1920 and the first mid height building was built in 1929, consisting of 13 stories. The challenges for buildings in the city center of Mexico City have always been: soft soil of a lakebed area and seismic effects. The Building and seismic code was modified three times (1942, 1957, 1976), until in 1985, an earthquake magnitude 8.1 stroke the city, causing great disasters and helping scientist to understand the soil seismic behavior and its relations with buildings dynamics. As a result of soils lakebed conditions in Mexico City center and the lack of importing seismic technology, it took until the final decades of the twenty century to design and built mid-height buildings over 50 floors. Although not so tall as the cases presented before, these new buildings in Mexico City are worth studying as they took into consideration the seismic and geotechnical conditions of the site, and their profile has transformed the cityscape of Mexico City.

4.1 Case I. Torre Mayor (Arch. Zeidler Parnership Architects)

It was until 1999 that started the construction of Torre mayor, a mid-height building of 225 m height and 57 floors, considered a tall building for Mexico Skyline. The building has an 80 m. by 80 m. footprint at below grade levels and it reduces gradually on the upper floors to 48 m. by 36 m. Seismic forces were obtained according the Mexico City 1993 Building Code regulations and a site specific response-spectra. The main structure is steel and mixed steel-reinforced concrete system; the tower's steel columns are encased in concrete up to the 35th floor at the perimeter and core area. The foundation was a combination of slurry walls, caissons and a mat system. The lateral system is based on a redundant one, composed of a primary super braced frame at the perimeter coupled with a perimeter moment frame forming a tube system and a trussed tube at the core of the building. The bracing connecting the composite core columns creates a structural spine in the building core. The perimeter frame and the diagonal system creates an efficient tube joining the spine in the resisting the seismic forces. This system is augmented by a series of supplemental viscous fluid dampers (96 in total) located at the core and perimeter bracing system, reducing the overall inter-story sway of the tower as well as the vibration and seismic forces. Two different seismic analysis were made: an spectral design and a time history analysis to reveal areas with higher force demand; a ductility factor of one was used throughout the study [22].

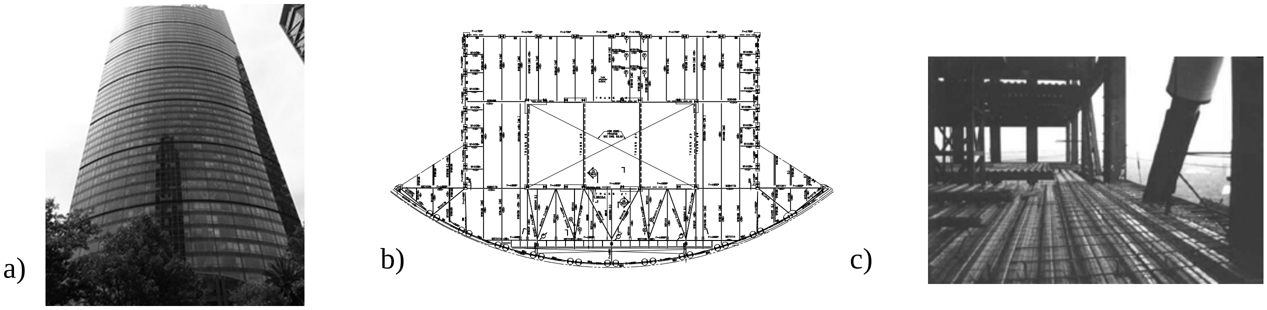

Fig. 3 – Torre mayor building: a) lateral view; b) Floor plan; c) seismic fluid damper.

Even though the height of this post-modern building is smaller than other buildings constructed at that time, this non-regular in plan building was an icon of Mexico City modernity showing that seismic technology and research results on soil-building effect were available and affordable to help architecture going higher even in emerging countries. Braced frames and dampers are exposed as part of the building façade, making a nice architectural solution, while the interior core is used for services. The final cost of this building was $250 million US dollars and it was finished in 2003.

4.2 Case II. Torre BBVA Bancomer (Arch. Rogers and Legorreta)

In 2010 a new high-tech building started its construction in Mexico City, just a cross Torre Mayor; with a height of 235 m. and 52 levels, the Torre BBVA Bancomer is grounded on soft soil. In order to comply with the regulation on the building code for parking spaces in office buildings, an extensive parking and circulation area was required in the tower footprint, using not only in the basement for this purpose but also the first eleven floors of the building. As a consequence, the office space starts at 12th level, circumstance that made impossible to have a concrete core in the building. The structural system considered an eccentrically brace mega-frame (EBMF) which provide the tower's lateral stability, resistance to wind conditions and keep elastic behavior under moderate earthquakes; energy from larger earthquakes will be dissipated through nonlinear yielding of seismic links. In order to achieve a column-free floor, plates of a low structural weight and composite steel framing was selected for the floors; three pair of columns flanks the vertical transportation and technical zone in the central diagonal band, providing large external sky gardens without the need of transfer structures. A clear lateral structural system was developed comprising an external mega-frame with six perimeter columns, continuous eccentric bracing and intermittent eccentric bracing on the shorter sides of the building. The mega-frame module spans three levels of offices and four levels of car parks. Small posts provide intermediate support to the floor plate perimeter within the mega-frame modules, distributing loads through the braces to the corner columns. The floor plates are architecturally independent of the external mega-frame. Lateral stability within each module is ensured by the six perimeter columns spanning across the three or four stories, transferring lateral forces from intermediate floors to the mega-frame levels. The 1.6 m^2 perimeter mixed steel and concrete columns act as small cores stabilizing the floors and interior columns within each module. Restraints for the seismic link articulate in order to allow link beam movement independent of the floor plates. The foundation comprises of a perimeter slurry wall, piles and barrette piles and a mat slab.

Seismic design, in accordance with the Mexico City Building Code 2004, allowed engineer to use other seismic codes because its lack of guidance on some seismic topics. A performance-based seismic verification was made in order to demonstrate acceptable performance during service-level earthquakes, verify column forces at code level and demonstrate acceptable performance at maximum considered earthquake. Analytical results showed than conventional response spectrum analysis does not predict the cumulative plastic strain demand in yielding elements. This is a particular concern for long duration ground motions characteristic of Mexico City. Nonlinear response history analysis was made; highly refined sub-models were used to evaluate the plastic fatigue performance of the inelastic elements under the cumulative strain demand due to the maximum considered earthquake. [23]

This regular building was finished on 2015 with a final cost of approx. $600 million US dollars, being only 10 m higher than Torre Mayor and presenting a new perspective of facing earthquake structural solution and design. EBFs keep evolving proving they can work under different circumstances. The architects adopted the structural seismic systems transforming it into an element of the architectural design of the building.

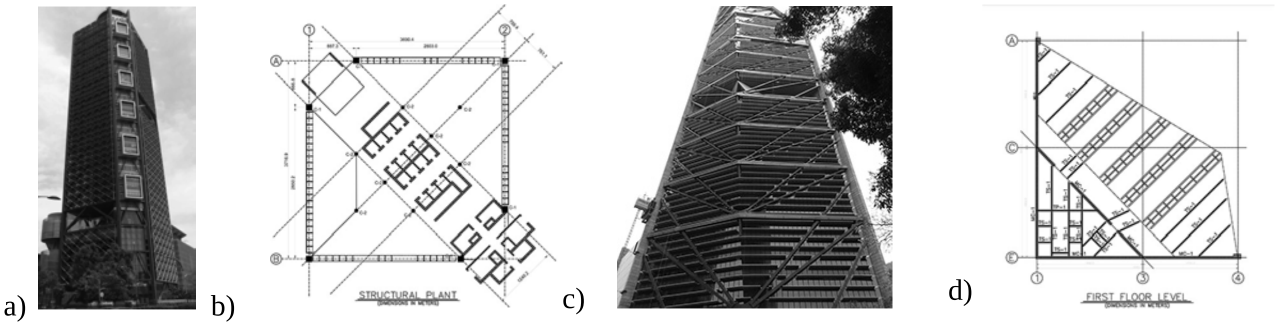

Fig. 4 – BBVA Building: a) lateral view; b) floor plan; Torre Reforma Building c) lateral view; d) floor plan.

4.3 Case III. Torre Reforma.

With a triangular plan and a structural system with an “L” shape (totally seismic irregular) this 245 m height (57 storey) building started its construction in 2008 next, to Torre Mayor Building. The main lateral system is a triangular eccentric reinforced concrete core, coupled with full-storey height coupling beams to two reinforced concrete structural walls in adjacent facades. Since the center of mass in each floor plate is located outside the core in the main building space, the walls and core alone would lead to significant torsional irregularity; therefore the third façade of the building incorporates structural steel braces to resist lateral loads and to carry gravity loads from the floor system back to the main structural walls. The structural design in order to reduce torsional response, used stiff walls and steel braces; to maintain the torsional stiffness of the core, lintel beams over the openings in the core were design for elastic response under the maximum considered earthquake impact while the diagonally reinforced coupling beams connecting core and structural walls were designed to yield and dissipate energy in a ductile way. The floors are grouped into vertical units of four levels, referred as “clusters”; each cluster includes a continuous floor slab at the top and bottom floors, and discontinuous floor slabs at the middle floors allowing an atrium space alongside the core. To transfer the lateral diaphragm forces in the discontinuous floors, large cluster trusses are provided. The main concrete walls run from the basement up to the highest floor on two of the facades; because of their weight, the walls continue 60 m underground, creating a 10 story basement supporting the entire structure. The concrete walls are non-ductile elements that can crack under serious seismic events, the solution was irregularly spaced gaps added to the concrete walls resembling a series of windows that move up the side of the building, allowing the concrete walls to bend when under stress without breaking [24].

This mid-height building was analyzed to achieve performance based design: linear analysis for the service level assessment and nonlinear response history analysis for the collapse level assessment. The construction cost is approximately $930 millions US dollars and it is programmed to be totally finished on 2016. The irregular shape and use of concrete walls all over two of the façade was an architectural requirement to diminished solar radiation; no architectural considerations about seismicity were made because some architects are not familiar with seismic behavior, but that is another background educational problem. Creating links in concrete walls, braces, shear walls, performance base design, etc., this building was possible in seismic zone.

5. Conclusions

Seismic engineering has come a long way in a short time; understanding buildings seismic behaviour has led to the development of seismic analysis methods, structural systems and seismic devices. The correct selection of these systems and devices for a specific building can lead to safe and affordable structural solution. Architectural design decisions influence the building's structural system through its configuration: size and location of structural elements, height, seismicity level, etc.

On this basis there are two architectural perspectives to design a building over a seismic zone: a) Architects that initiate a building project working together since the beginning with an engineer to develop the seismic system or combination of systems that would help create the final project, creating nice and functional buildings; b) Architects that conceived independently architectural to structural concerns, so engineer become an enabler, placing seismic systems and devices with few or a general relation to the architectural concept, sacrificing function most of the times.

"Earthquake architecture" is a relative term; it is always conceived as an architectural solution that followed the regular building conditions stablished by seismic codes, but this term is more meaningful: architects accepting the structural systems and devices proposed by the engineer for a building and considering them as part of their architectural concept.

Contemporary iconic buildings defying seismic engineering and developing its own seismic technology have arrived; thanks to seismic engineering research and computational advances, today analytical seismic analysis can be done considering all parameters know until today that affect building behaviour: soil conditions, site effect, attenuation curves, probabilistic seismic hazard analysis, damping amplification, linear and non-linear dynamic analysis, non-elastic material behaviour, non-structural elements seismic behaviour etc. obtaining a near approximation of its expected seismic behaviour.

In order to achieve newer technical solutions, seismic engineering requires a great amount of economic resources, allowing only the richer countries to develop new technology, pouring its advances years later to emerging countries. Mexico's cases reflect this last statement; with a local stable economy in 2000, high-tech mid-height buildings were constructed on soft soil using imported and local seismic technology.

Architectural and engineering students should learn the main principles of seismic engineering, structural systems and seismic devices; applying these parameters at school projects will make it easier for them to understand their importance over their architectural design and continue the probability of their use in their professional career will be higher.

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7. Copyrights

8. References

[1] Reitherman R (2008): International Aspects of the History of Earthquake Engineering Part I. *Earthquake Engineering Research Institute*, Oakland CA, USA.

[2] Mezzi M, Parducci A (2006): Conceptual Seismic Design and State-of-the-art protection. 100th Anniversary Earthquake Conference EERI, San Francisco CA, USA.

[3] Halis M, Emre H (2014): Tall buildings: structural system and aerodynamic form. Routledge,1st edition. 32-33.

[4] Moehle J, Hooper, J., Lubke, C (2008): Seismic Design of Reinforced Concrete Special Moment Frames: A guide for practicing Engineers. *National Earthquake Hazards Reduction Program*, USA.

[5] Muto K, Ohmori N, Takahashi T (1969): Earthquake resistant design of 36-storied Kasumigaseki Building. *4th World Conference on Earthquake Engineering*, Santiago, Chile.

[6] Sabelli, R., Mahin, S., and Chang, C. (2003): Seismic demands on steel braced frame buildings with buckling-restrained braces, *Engineering Structures*, **25:2003**, 655-666

[7] Popov EP, Engelhardt MD. (1988): Seismic eccentrically braced frames. *Journal of Constructional Steel Research*, 10: 321–354.

[8] Skinner R, McVerry H. (1975): Base Isolation for Increase Earthquake Resistance of Buildings. *New Zealand Society for Earthquake Engineering, Bulletin* Vol. 8–2.

[9] Nagarajalah S, Reinhorn A, Constantinou M. (1993): Torsion in Base-Isolated Structures with Elastomer Isolation Systems. *Journal of Structural Engineering,* Vol. 119–10.

[10] Nakai M (2008): Unique Architectural forms enabled by base-isolation. *14th World Conference on Earthquake Engineering,* Beijing China.

[11] Clemente P, Bontempi F, Boccamazzo A. (2012): Design and Optimization of Base Isolated Masonry Buildings. *15th World Conference on Earhquake Engineering*, Lisboa, Portugal.

[12] Nishitani A. (2000): Structural Control implementations in Japan. *12th World Conference on Earhquake Engineering,* Auckland, New Zealand.

[13] Federal Emergency Management Agency (2006): *Designing for Earthquakes. A manual for Architects*. 454/2006.

[14] Avtar S, Rashmi P. (1996): Friction-dampers seismic control of building “A Canadian experience”. *11th World Conference on Earhquake Engineering,* Acapulco, Mexico.

[15] Chang K, Lin Y., Lai M. (1998): Analysis and design of structures with viscoelastic dampers. *ISET Journal of Earthquake Technology,* No.380, Vol.35-4, 143-166

[16] Li H., Mao, X. Ou P. (2004): Shape Memory Alloy-based smart buildings. *Harbin Institute of Technology, Harbin China.*

[17] Yoshioka H., Ramallo J., Spencer J.(2002): Smart base isolation strategies employing magnetorheological dampers. *Journal of Engineering Mechanics,* Vol. 128, No.5.

[18] Nagarajaiah S., Narasimhan S.(2006): Seismic control of smart base isolated buildings with new semiactive variable damper. *Earthquake Engineering Structural Dynamics,* Vol. 36 No.6.

[19] Matichard F., Abbott B., Abbott S., Barnum S. (2004): Seismic Isolation Enhancements for Initial and Advanced LIGO. *Quantum Grav,* 21,915-921.

[20] Poon D., Shaw-song P (2004): Structural Design of Taipei 101, the World’s Tallest Building. *Council on Tall Buildings and Urban Habitat Conference,* Seoul, Korea.

[21] Carroll C., Cross p, Duan X., Gibbons C., Ho G. (2005): CCTV Headquarters, Beijing China: Structural engineering design and approval. *Arup Journal,* 40 (2) pp 3-9.

[22] Rahimian A., Martinez E. (2003): Standing Tall. *Modern steel construction,* pp 23-29.

[23] Algarrd W., Wilcock T. (2014): An innovative braced megaframe for Torre BBVA Bancomer in Mexico City. *Council on Tall Buildings and Urban Habitat Journal,* Issue II.

[24] Grant D. (2009): Performance-based earthquake engineering Arup. *Earthquake Engineering by the Beach Workshop,* Carpi, Italy.