17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

RESILIENCE-BASED DESIGN, THE MEXICAN EXPERIENCE

A. Terán-Gilmore [(1)]

[(1)] *Professor, Universidad Autónoma Metropolitana – Azcapotzalco, tga@azc.uam.mx*

Abstract

Recently, the concept of resilient-based design has attracted worldwide attention from researchers and practicing engineers devoted to earthquake-resistant design. In notable contrast with the recent past, the design of standard earthquake-resistant structural systems will require the use of displacement-based methodologies to promote superior seismic-performance.

This paper discusses the evolution of resilience-based design in Mexico. Particularly, it refers to a series of analytical and experimental studies carried out on dual systems conformed by moment-resisting frames and buckling-restrained braces. First, the displacement-based methodologies developed during the first years of the XXI Century are presented. It is emphasized that their formulation was aimed, within the scope of the damage-tolerant approach, to the design of structural structural systems capable of controlling their maximum and residual (permanent) drifts, in such a way as to achieve the Immediate Occupancy performance level. Second, a series of studies focused at comparing the seismic performance of traditional and damage-tolerant dual systems are presented. Experimental results, including those obtained from a 4-story dual system studied in a shake table are discussed. After identifying the research accomplishments, a discussion is offered on how the developments are being transferred from the research centers to the practicing consulting firms and educational arena. Several examples of actual Mexican structures designed per the damage-tolerant approach are presented. Other examples on the use of control systems are presented. Finally, the current direction of Mexican research and development is discussed, and an outlook on their practical impact offered.

It is concluded that despite its traditional and conservative views, the Mexican structural engineering community is evolving towards innovation and change. Currently, several buildings designed with displacement-based methodologies are under construction, and several projects for resilient buildings are underway.

Keywords: displacement-based design, damage-tolerant system, resilience-based seismic design

1. Introduction

To understand *natural disasters*, and how to mitigate the effects of *natural phenomena* and facilitate recovery, it is convenient to break away from a series of misinterpretations. First, the need to avoid using as synonyms two terms that imply completely different situations: natural phenomenon and natural disaster. Not only are they not the same, but the first does not presuppose the second. A natural phenomenon is an expression that nature adopts because of its internal dynamics. Although at first glance their occurrence may appear as extraordinary, the fact is that they occur with regularity. Natural phenomena such as an earthquake in the Mexican Pacific coast or a high intensity hurricane in the coasts of the Gulf of Mexico are predictable, although some details such as the date they occur, or their intensity and location can't be known in advance.

Some natural phenomena, because of their nature and intensity, and the uncertainty associated to their occurrence constitute a hazard. An intense ground motion can be considered hazardous because it is potentially damaging. In some cases, the large recurrence cycle of the natural phenomena results in a loss of conscience regarding the importance of taking preventive measures. A fundamental step in avoiding natural disasters is for human societies to accept that they live within a dynamic environment, that has its own natural laws. A natural phenomenon can produce negative changes in the way of life of human societies; it is within this context that natural disasters occur.

A natural disaster results from the combination of hazardous natural phenomena and vulnerable socio-economic and physical conditions. It can be said that a natural disaster occurs when one or more hazardous natural phenomena significantly affect a vulnerable built environment. Being *vulnerable* to a natural phenomenon implies being susceptible to suffer damage, and to have difficulty recovering from it. Vulnerability tends to accumulate progressively, and to give place to high-risk situations that can go unnoticed or ignored. Usually, the conditions of extreme vulnerability are a product of socio-economic causes. If a human society creates a vulnerable habitat is due to two reasons: extreme need and generalized ignorance (the lack of prevision is a consequence of the last). Both reasons have detectable and modifiable causes. From this perspective, it is possible to understand the role that authorities and the civil society have in the occurrence of natural disasters. It is important to understand natural phenomena as much as humanly possible, and to build and rehabilitate our habitat according to this knowledge.

In terms of what it is possible to anticipate, mankind can't modify the cycles and internal rhythm of nature; therefore, the only option available to human societies is to reduce its vulnerability. First, it is possible to identify the physical vulnerability of the built environment, expressed in terms of the susceptibility that buildings have of developing damage when subjected to the action of natural phenomena. When for socio-economic and cultural reasons, a country can't avoid building an important part of its built environment in hazardous geographical regions, the existence and proper use of an adequate building code, and the use of innovative technologies and structural systems, represent the best tools available to a human society to reduce the physical vulnerability of its built environment. There is a second area in which the vulnerability of a society is expressed, and it falls in the social ambit. Given a level of physical damage to the built environment, the consequences that it has on a society can vary significantly as a function of the levels of training, solidarity, planning and order, that individuals have. It is possible to anticipate that while a conscious and well-trained community will minimize the impact of the physical damage suffered by its built environment, one that is poorly informed and individualistic will exacerbate the initial impact of the natural phenomenon.

2. Seismic Resilience

A concept that allows for the reduction of the physical vulnerability of a built environment is that of *resilience*. The reason for this is that this concept allows for a contrast with that of vulnerability. Although it is possible to find different definitions, this paper establishes that resilience quantifies the abilities of a system to control the level of damage it suffers during a seismic excitation, and of recovering its functionality in the shortest possible time. According to this definition, a resilient built environment should have two qualities: a) the ability to control damage in its different components; and b) the ability to recuperate its functionality in a brief time despite damage to individual components. A resilient built environment is constituted by resilient components (individually) that constitute a system whose interactions make possible the recovery of its essential functions soon after the occurrence of a natural phenomenon. In this paper, it is considered that each individual structural system is a component of the built environment. Within this context, reference is made to the physical resilience of individual structural systems. Redundancy of the built environment is not addressed herein.

To discuss some of the options available to provide resilience to individual structural systems, it is necessary to first establish a way to quantify it. Although there are many available options, herein the one offered by *REDi™ Rating System Resilience-based Earthquake Design Initiative* [1] is considered. According to REDi, resilience can be categorized into platinum, gold and silver levels. It should be noted that it is not a coincidence that these levels are consistent with those used by environmental evaluation standards for building projects. REDi establishes a framework in which the resilience of an earthquake-resistant structural system improves its environmental rating, in such a manner that it can be integrated into the total environmental cost of a given project. To classify the level of resilience, downtime is considered in terms of the time needed to re-occupy the building as well as that needed to achieve functional recovery. Economic and human losses are also considered.

To qualify for a REDi rating (Platinum, Gold or Silver), it is necessary to satisfy mandatory criteria in the following categories:

- Organizational Resilience: Contingency planning for utility disruption and business continuity;
- Building Resilience: Minimize expected damage to structural and architectural components, as well as mechanical, electrical and plumbing installations, and diverse contents;
- Ambient Resilience: Acknowledge and reduce external earthquake-induced hazards to the building and reduce their impact to site access.

In addition, a Loss Assessment must be performed. It is interesting to note the wide range of considerations that should be made and assessed to achieve what REDi describes as a *truly resilient facility*. Because of the complexity involved and the need for extensive and carefully established definitions, discussions in Mexico on how to achieve a seismic resilient built environment have not mirrored the technical capacity of the local community of structural engineering. Well meaning social actors and members of local governments have complicated the achievement of any meaningful societal goals by oversimplifying or overcomplicating the issue, and taking limited actions that fall short of making possible a *truly resilient built environment*, or indefinitely postponing meaningful actions under the impression that it is not realistic to achieve *true resiliency*.

In this paper, the discussion on resilience-based design will be limited to the scope that it has been given in Mexico to this concept. Basically, resilience-based design has only addressed Building Resilience, and specifically, the control of expected damage to the structural system in such a manner as to achieve the Immediate Occupancy performance level for the design basis earthquake. Recently, engineering efforts were explicitly invested to address the Operational performance level, and thus, damage control, in architectural components, installations and contents, of a base-isolated hospital located in Mexico City. In another project, a Loss Assessment was carried out to provide information to local authorities on the convenience of base-isolating another hospital (the hospital, still in its planning stages, will be base-isolated). Organizational and Ambient Resilience are yet to be acknowledged and addressed by the Mexican civil society, investors, authorities and the structural engineering community.

3. Traditional Approach to Earthquake-Resistant Design

The level of resilience of current structural systems can be understood from the design objectives currently under consideration for earthquake-resistant design. At an international level, building codes usually indicate their scope. In the case of the current version of the *Complementary Technical Standards for Seismic Design* of the Mexico City Building Regulations, published on December 2017, the following scope is established for the design of standard occupancy buildings:

"*As established by Article 137 of the Building Regulations, these standards should be applied to the seismic design of urban buildings; …*

The requisites of this document have the purpose of achieving and adequate performance such that:

a) *Under the action of earthquakes that can occur several times during the lifetime of the structure, there is, at most, damage that does not result in the interruption of the occupancy of the building.*

b) *Under the action of the earthquake for which the revision of collapse prevention is carried out according to these standards, no major structural failures or loss of life occur, although considerable damage and/or residual deformations may occur with the possibility of affecting the functionality of the building and requiring major repair*."

Requisite b) establishes that structures properly designed should not collapse during the design earthquake and discusses the possibility for these structures to suffer heavy damage and result in significant losses (in some case, this implies the possibility of total loss and demolition). Under the main considerations made by this design approach, it is likely that a relevant percentage of properly designed standard occupancy buildings develop significant levels of damage when subjected to the action of an intense ground motion. It is important to mention that this approach is not particular to Mexico, and that it is widely used worldwide. It is no wonder that the largest international insurance companies have reported that the economic losses that have resulted from major recent seismic events have increased in the last decades.

It seems somehow contradictory that major earthquakes that have recently affected highly developed countries have resulted in huge monetary and environmental losses [4, 13]. Is it possible to say that there has been no progress in the field of seismic engineering in the last 50 years? As in any field of human endeavor, it must be said that there have been spectacular advances. In such a context, it is necessary to recognize that the current design approach has changed little in decades, and that buildings nowadays possess greater capability to prevent collapse than ever before. Nevertheless, they are incapable of preventing considerable losses in built environments that are increasingly growing in terms of size and refinement.

Voices coming from various disciplines express disagreement with the current earthquake-resistant design approach. Of interest to this paper is the *Resilience-Based Design Initiative* for the Next Generation of Buildings [1]. It is also of interest to note that academia has identified resilient and sustainable communities as the overarching long-term goal of seismic engineering [3]. Finally, it is important to mention that the last world conference on seismic engineering, arguably the most important event worldwide of its type, had as its theme *Resilience, the new challenge in earthquake engineering*. Initiatives such as these begin to outline a new path for earthquake-resistant design. The central objective being to provide large socio-economic benefits to communities located in high seismicity zones through the conception, design and construction of resilient built environments.

4. Seismic Damage

To be vulnerable to a natural phenomenon implies being susceptible to develop damage, and to have difficulty recovering from it. A built environment is seismically vulnerable because it is susceptible to develop heavy damage during intense ground motions. Experimental evidence and field studies have allowed for the understanding that the level of damage and degradation that a structural system exhibits after a seismic excitation depends on its maximum deformation/displacement demands (which also affect architectural components), and velocity and acceleration demands (which affect acceleration-sensitive architectural components and installations, contents, equipment). Particularly, as these demands increase, larger is the level of damage and degradation suffered by the structural system and its contents. Based on this, it can be said that the structural properties that should be supplied to a structural system, independently of the structural material that is used, should be so that it can control its dynamic response within response thresholds that are consistent with the required seismic performance. In terms of structural and architectural components, the response thresholds should be formulated in terms of inter-story drift index or lateral displacement.

Control of velocity and acceleration demands will not be addressed in detail in this paper. Within the scope given today in Mexico to resilient-based design, emphasis will be made on the control of expected damage to the structural system through the formulation and use of displacement-based methodologies.

5. Need for Change

As shown in Figure 1, current approaches to seismic design of standard occupancy buildings allow structural systems to develop considerable damage during the design ground motion. This entails a significant incursion into the nonlinear range of behavior. Given the loss levels that this implies, it is important to discuss the origin and justification for such approach. To achieve this, the case of the structural system most used by the Mexican building industry, *moment-resisting frames* (which will be denoted from here on *frames*), will be considered.

Frames emerged during the final years of the XIX Century and first years of the XX Century as efficient structural systems. They were used in Europe and the United States of America in non-seismic zones to carry the vertical loads of medium-height and tall buildings. With the advent of glass panes and the industrial production of high strength materials, such as steel and reinforced concrete, frames made possible modern and contemporary architecture. Its use soon spread to areas of high seismicity with disastrous results in terms of their susceptibility to collapse. Because of this, several decades of the XX Century were invested in understanding how to stabilize their dynamic lateral behavior when subjected to lateral seismic loading. Structural engineers soon became aware that the sizes of beams and columns of earthquake-resistant frames needed to be considerably larger than those corresponding to similar frames designed for vertical loading. Also, it was learned that an earthquake-resistant frame needs structural integrity and plastic deformation capacity. To develop these two properties, they require refined detailing for its structural members and connections, limits to their geometric configuration, and a proper conceptualization during their strength design (e.g. capacity design).

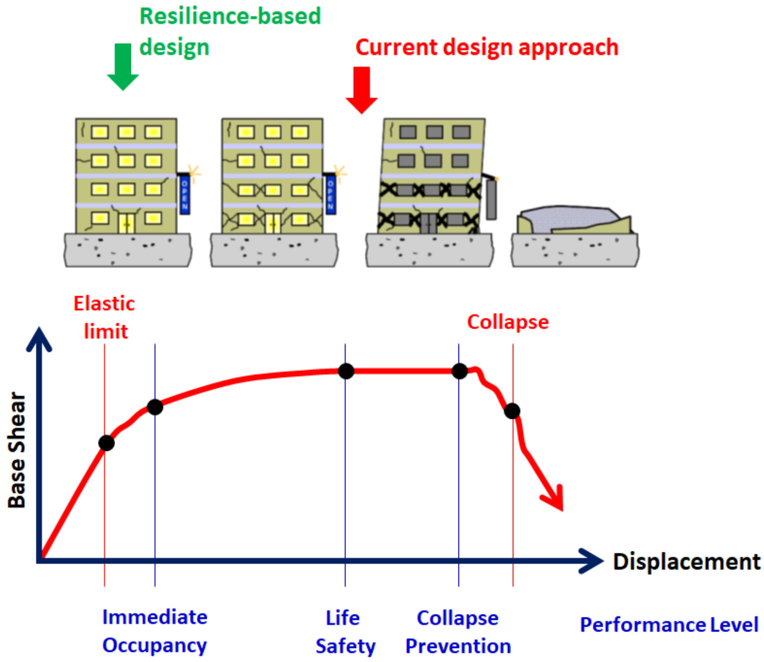

Fig. 1 – Capacity curve for structural system

Although frames became popular in areas of high seismicity (a good example of this is Mexico), the costs derived from the need for larger amounts of structural material and refined detailing led to the consideration of alternative approaches to reduce their direct cost. The current design approach emerged in response to this concern, and represented an attempt to balance the initial cost of the frames with the likely cost of the losses that could result from earthquake. The desirability of reducing the initial investment (expense that must be made inevitably) at the expense of allowing considerable damage during intense seismic excitations (expense that may or may not occur due to the low probability of occurrence of an intense seismic excitation during the lifetime of a structural system) was found attractive, and gained immediate worldwide acceptance.

In terms of the increasing and unacceptable social, economic and environmental losses that have occurred during recent seismic events, the need to rethink current design approaches has emerged as one of the most important topics within the international structural engineering community. In summary, it has been pointed out that the fundamental objective of earthquake-resistant design should be to reduce the consumption of structural materials, and to protect them through adequate damage control. In striking contrast with the past, it is being argued that the performance of modern buildings must transcend the prevention of catastrophic structural failures, so that they can satisfy the multiple and complex socio-economic needs of modern human societies. Within such context, innovation in the field of seismic engineering can be understood as the conception and design of efficient and lightweight structural systems that can control their level of damage through efficiently controlling the amplitude of their seismic vibration (and therefore, of their lateral deformation). A design focused on loss control, basis for a resilience-based design, is highlighted in Figure 1 with the green arrow.

6. Damage-Tolerant Systems

Voices coming from diverse disciplines see resilience-based design as the short-term integrative theme in seismic engineering. Although this approach receives more attention as time goes by, and eventually there will be a standardization of definitions and design criteria, currently there is an ample variety of proposals in terms of providing seismic resilience to structures. A detailed discussion of such proposals as well as on the need for acceleration control goes beyond the scope of this paper. As an alternative, it is considered of interest to discuss the development that in Mexico has taken place around an approach, which among many others that have arisen in this country, makes possible the design of structural systems explicitly aimed at achieving the Immediate Occupancy performance level. The approach discussed in the following paragraphs illustrates well the capacity of the local building industry to develop technical solutions to the complex problems that need to be solved by the Mexican society to enable its sustained and ascending socio-economic development.

An approach that makes possible the conception and design of resilient structural systems is that of *damage-tolerant systems* [22]. Particularly and as shown in Figure 2, the Mexican take on damage-tolerant structural systems integrates the work of two highly specialized sub-structural systems: a) One that supports vertical loading (usually known as primary system); and b) A second one in charge of controlling the lateral response of the building (usually denoted control system). The control system needs to limit the lateral deformation of the building in such a way that the primary system remains damage-free, and can satisfy either the Operational or Immediate Occupancy performance levels (this will depend on damage that may occur on acceleration-sensitive contents and nonstructural components). In some cases, the control system may be damaged during intense ground motion, in which case it is known as a *sacrificial system*. Its operation can be understood as that of a structural fuse, that accommodates the structural overload that can occur during the seismic excitation and protects the primary system. In this case, damage to the sacrificial elements should be limited to acceptable levels, and such elements should be located at points in the structure where they are easily accessible for prompt replacement.

The use of the damage-tolerant approach in Mexico implies, on the one hand, the use of lightweight frames to support the gravitational loads. This results in large savings in terms of the weight of structural materials and possibly, of their required detailing. Given the low earthquake resistance of such a primary system, it is necessary to develop, on the other hand, advanced earthquake-resistant technology, consisting mainly of control devices that, with unprecedented efficiency, can reduce the amplitude of the seismic vibrations of the integrated structural system. The development of technology has been such that it has made possible an adequate and reliable control of the lateral deformation of gravitational primary systems with devices that usually weigh significantly less than 5% of the total weight of the building. This allows the primary systems to meet the Operational/Immediate Occupancy performance level as part of integrated structural systems that exhibit smaller structural weight than that of their traditional counterparts.

One of the most used control devices is the *buckling-restrained brace* [2, 14, 20, 21]. There are hundreds of buildings in Japan that use this technology, many of which were designed with a damage-tolerant approach. A buckling-restrained brace is a structural element that exhibits stable behavior under large compressive strains because it does not develop global buckling. Since braces usually work in a stable manner in tension, what is achieved is a device capable of providing lateral stiffness and energy dissipation in a stable manner in the presence of several deformation reversals. Figure 3 schematically shows a buckling-restrained brace and illustrates its hysteretic behavior. A more detailed discussion of the concept and use of buckling-restrained braces can be found in [2, 21]. Currently there are several patents at the international level, and their use has spread to several countries, including Mexico. In qualitative terms, this device can be considered as a sacrificial element, since it is a structural fuse that tends to concentrate seismic-induced damage without detrimental effects on a properly designed primary system [16, 18]. The use of buckling-restrained braces has been studied in several Mexican public universities since the beginning of the XXI Century, and the research developments are impacting in a positive and incipient manner, the local building industry.

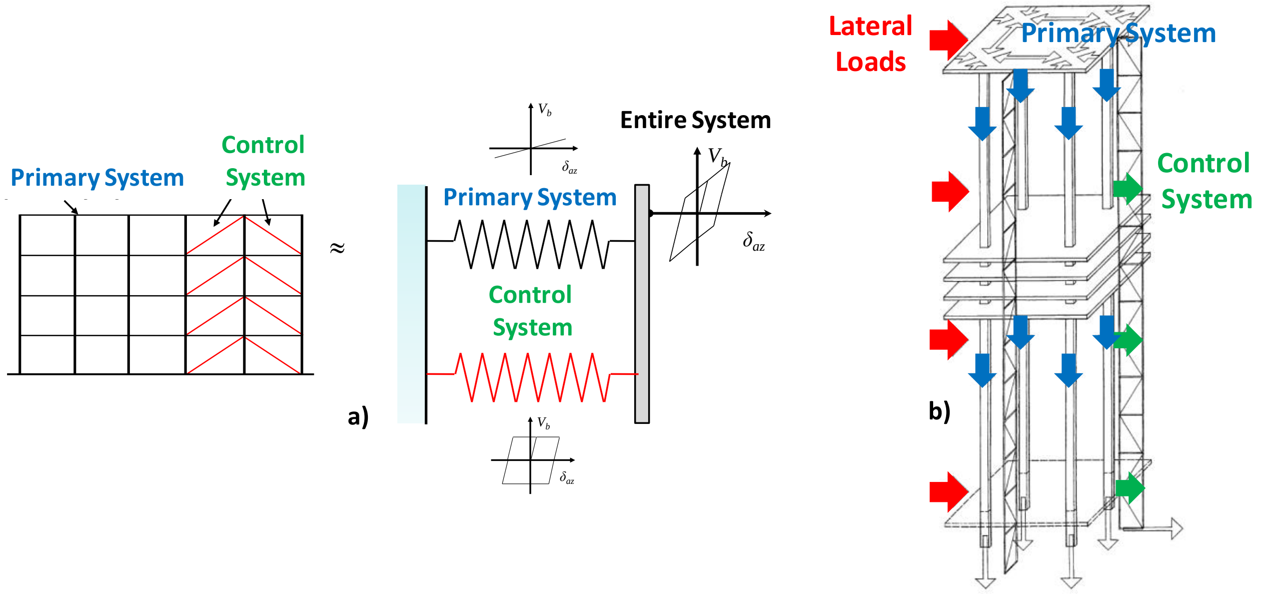

Fig. 2 – Damage-tolerant system: a) Concept; b) Schematic View

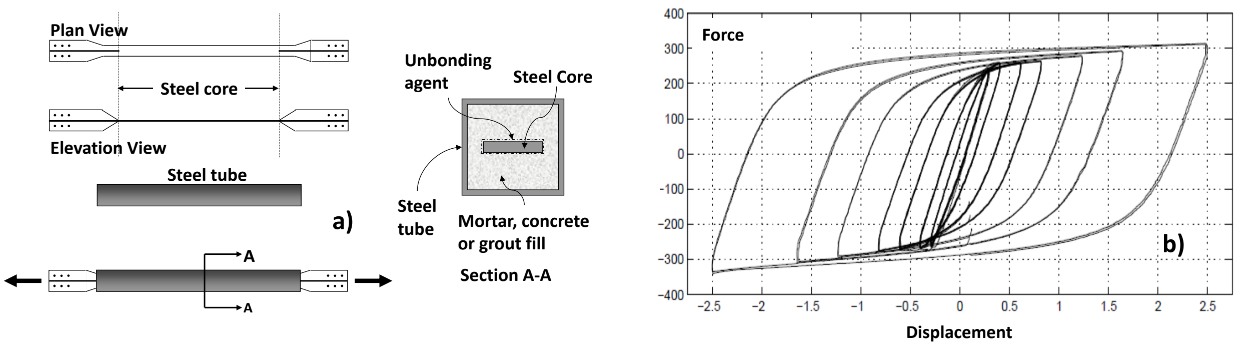

Fig. 3 – Buckling-restrained brace: a) Schematic View; b) Hysteretic behavior [2]

Among other things, displacement-based design methodologies have been proposed for the use of buckling-restrained braces in low and high-rise buildings. Focus has been made on resilience-based design and loss control [5, 15, 16, 18]. Several examples have been developed comparing the structural weight of traditional systems designed according to current building codes, and that of a damage-tolerant equivalent system. Perhaps the most illustrative is that of a 24-story building, where the damage-tolerant solution was established as a redesign of an actual building located in the Lake Zone of Mexico City and having a traditional structural system composed of conventional steel braces and composite frames [12]. As for the weight of both structural systems without regard to their floor systems, the structural skeleton of the traditional building weighed about 12,500 tons. In the case of the damage-tolerant system, the structural skeleton weighed 4,800 tons. Using a demand-capacity factor format, Montiel and Teran evaluated and compared the reliability of both versions of the two 24-story building [12]. They concluded that the damage-tolerant system exhibits higher levels of reliability than its traditional counterpart, despite its much lower weight.

The effect of seismic sequences on dual systems composed of frames and buckling-restrained braces has been studied [7, 8]. The self-centering capacities of damage-tolerant systems have been analyzed, and based on this, strategies have been formulated to control residual displacements on this type of systems [19].

The feasibility and suitability of using the damage-tolerant approach in rehabilitation projects has also been studied [17]. It has been concluded that, in many cases of practical interest, controlling the response of an existing deficient building (in terms of earthquake-resistance) with buckling-restrained braces is feasible and attractive. Recently proposed displacement-based design formats allow greater flexibility during the conception and design of damage-tolerant structural systems that use buckling-restrained braces [5, 15]. Also, some studies have focused on establishing and comparing the life cycle cost of structural systems designed according to different approaches [9]. It has been found that the lowest total cost usually corresponds to that of damage-tolerant structural systems; and the largest, to traditional structural systems.

Part of the Mexican development has contemplated the experimental study of buckling-restrained braces [6, 10, 11]. Small-scale devices have been fabricated, and their cyclic behavior studied. Also, and as shown in Figure 4, the response of large damage-tolerant specimens has been studied on the shaking table of the *Universidad Nacional Autónoma de Mexico*. The results that have been obtained support the design methodologies formulated at the local level, and clearly indicate the pertinence of the Mexican design approach. The expertise derived from experimental testing has led to the first Mexican manufacturer of seismic control devices, that in 2020 will make available to the local market buckling-restrained braces and viscous dampers.

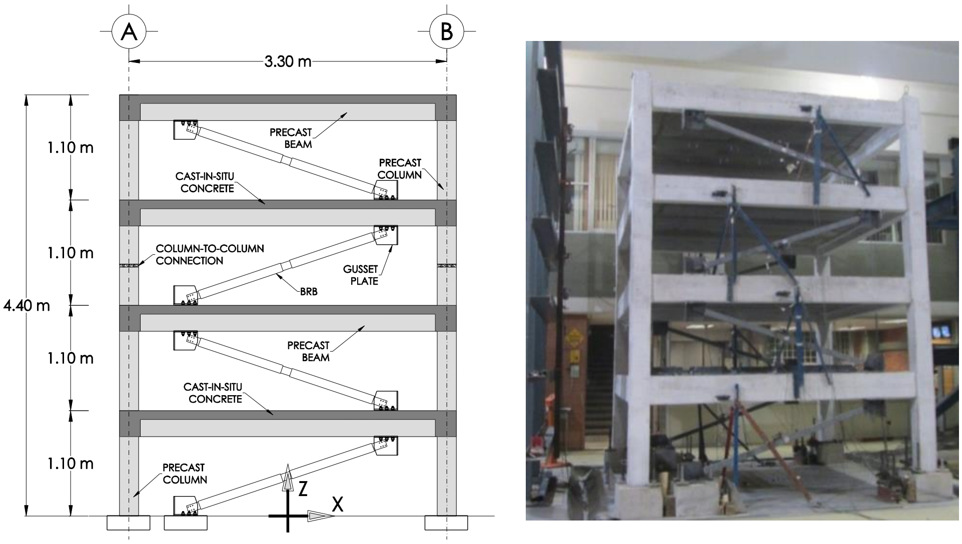

Fig. 4 – Experimental setting for shaking table studies of dual system

It is of importance for this paper to mention that the Mexican development has permeated higher education institutions and the local earthquake-resistant design practice. Particularly, several Mexican structural engineering firms are currently considering the use of damage-tolerant systems within the context of resilience-based design and loss control. One of the projects designed according to this approach is shown in Figure 5a. The direct cost of the rehabilitation system conceived with a damage-tolerant approach for Building G of the *Universidad Autónoma Metropolitana Azcapotzalco* was lower than that of several traditional alternatives that were considered (this independently of the advantages provided in the medium and long terms by the damage-tolerant approach). In a way, this project offers a good example that innovation in the field of earthquake-resistant design does not contradict the commercial success of the Mexican building industry. Rather, it represents, in an area where there is an urgent need to protect the built environment, an issue of opportunity and growth.

Other projects that used buckling-restrained braces are the Oncology Hospital of the State of Mexico (Figure 5b), and a 30-story steel building in Guadalajara (Figure 6a). In both cases, the damage-tolerant approach was used. There are several other projects that have used the damage-tolerant approach, and several more that are at the initial stages of design. The damage-tolerant approach has been adapted in such a manner that it can consider the use of viscous dampers as control devices as an alternative to buckling-restrained braces. Figure 6b shows a building located in the Transitional Zone of Mexico City that was designed to achieve the Immediate Occupancy Performance level with a system of nonlinear viscous dampers.

a)

b)

Fig. 5 – Low-rise buildings designed for Immediate Occupancy: a) Building G, Universidad Autónoma Metropolitana; b) Oncology Hospital, Estado de México

The know-how developed in Mexico has been introduced in several national graduate programs. Additionally, a professional environment that until some years ago did not contemplate the use of innovative structural systems, is steadily increasing its demand for continuous education courses. While several consulting firms are paying for courses to be offered at their professional facilities, professional associations, such as the Mexican Society of Structural Engineering and the Mexican Society of Seismic Engineering, are formulating courses that will enable the Mexican structural engineer in the use of control systems and displacement-based design. It may be worth talking about several courses that have taken place in different civil engineering colleges in Mexico during the last 3 years, and that have addressed the issues of performance-based structural assessment and resilience-based design. Parallel to this, the *Complementary Technical Standards for Seismic Design* of the Mexico City Building Regulations are, in full agreement with the evolution of the local structural engineering community, updating its normative requirements to make possible the use of control systems and displacement-based methodologies.

Fig. 6 – Tall and medium-rise buildings designed for Immediate Occupancy: a) Midtown Tower, Guadalajara; b) Laguna de Términos, México City

As discussed before, the damage-tolerant approach is one of the many available in Mexico to make possible, from an earthquake-resistance standpoint, a resilient built environment. The discussion offered in this paper is only intended to illustrate the technical capacity of Mexican engineers, and to make it clear that there is a viable solution to the great national needs in terms of resilience.

7. Base-Isolation and Contents

This paper would not be complete if it does not address the issue of base-isolation and contents. In the past few years, several structural systems have been base-isolated, and there are currently several projects to isolate large structural systems in different parts of the country (including Mexico City). Of interest to this paper are two projects for their implications in terms of the way Mexicans interpret the concept of resilience-based design.

The first project, shown in Figure 7a, is a Hospital built in Mexico City, and base-isolated with sliders and elastomeric lead-rubber bearings. One relevant fact of this project is that, it was designed in two phases. In the first phase, a consulting firm was made responsible for the structural design of the reinforced concrete super-structure and the isolation system. In a second phase, acceleration demands in the different installations and contents of the hospital were estimated by a second consulting firm (with floor spectra derived from nonlinear analyses), with the objective of explicitly designing anchors and supports to make possible the Operational performance level for the design basis earthquake. Perhaps, this may be the first project in Mexico that fully acknowledges Building Resilience. The second project, under construction, is a large resort in the Mexican Pacific. The reinforced-concrete super-structure has been isolated with friction pendulum devices. Although the client was made aware of the advantages of a resilient facility from a structural point of view, base-isolation was selected for this project mainly because of its lower direct cost with respect to that of traditional structural alternatives. The designer in charge offered, free of charge, acceleration floor spectra to the developer so that, in case it becomes important, an explicit design of anchorages and supports can be made in such a manner as to achieve a *truly resilient* facility.

Fig. 7 – Base-isolated facilities: a) Hospital, Mexico City; b) Resort, Mexican Pacific Coast

8. The Future

Mexican civil engineers have the technical knowledge and practical tools that allow them to increase the seismic resilience of the built environment and, therefore, to contribute to mitigate the local seismic risk. Despite the great challenge that this has represented, Mexico has developed a know-how that, if used in an extensive manner, would represent enormous social, economic and environmental benefits for the local civil society. So far, much of the talent of Mexican engineers has been devoted to remove the major obstacles that usually hinder innovation in their country.

Although the subject was not discussed in this paper, it is important to understand that providing an elevated level of resilience to individual components of a built environment is not sufficient to achieve a resilient community. For this to be possible, it is important for socio-economic needs to guide the formulation of performance requirements for the built environment. This implies the consideration and understanding, through a systemic approach capable of relating the design of a single component to the needs of the community, of the interdependency of the different components of the built environment. In such a context, it is necessary to establish public policies aimed at achieving a resilient built environment, and to channel available human and material resources to achieve this goal. It is important that, through education, the different members of the Mexican society understand which are, individually and collectively, the tasks with which they can contribute to this goal.

More than in any other time in the past, the essence of a what it means to be a structural engineer has come into questioning. Not only is there a need to *transform structural engineering education, training, and practice in ways that will foster an enduring and creative profession*, but of a profound reflection on what should be the role of structural engineers in modern human societies. Perhaps, in a few years, the profession of *Structural Engineer* will give place to that of *Structural, Non-Structural and Contents Engineer*.

8. References

[1] Almufti I. and Willford M., "REDi™ rating system resilience-based earthquake design initiative for the next generation of buildings", ARUP, 2013.

[2] Black C., Makris N. and Aiken I., "Component testing, stability analysis and characterization of buckling-restrained unbounded braces", *Report PEER 2002/08*, University of California at Berkeley, 2002.

[3] Dyke S.J., Stojadinovic B., Arduino P., Garlock M., Luco N., Ramirez J.A. and Yim S., "Vision 2020: An Open Space Technology Workshop on the Future of Earthquake Engineering", *A Report on the NSF Funded Workshop*, 2010.

[4] Fleischman R.B., Restrepo J.I., Pampanin S., Maffei J.R., Seeber K. and Zahn F.A., "Damage evaluations of precast concrete structures in the 2010-2011 Canterbury earthquake sequence", *Earthquake Spectra*, 30 (1), 227-306, 2014.

[5] Guerrero H., Ji T., Teran-Gilmore A. and Escobar J.A., "A method for preliminary seismic design and assessment of low-rise structures protected with buckling-restrained braces", *Engineering Structures*, 123, 141-154, 2016.

[6] Guerrero H., Ji T. and Escobar J.A., "Experimental studies of a steel frame model with and without buckling-restrained braces", *Revista de Ingeniería Sísmica*, 95, 33-52, 2016.

[7] Guerrero H., Ruiz-Garcia J., Escobar J.A. and Teran-Gilmore A., "Response to seismic sequences of short-period structures equipped with buckling-restrained braces located on the lakebed zone of Mexico City", *Journal of Constructional Steel Research*, 137, 37-51, 2017.

[8] Guerrero H., Ruiz-Garcia J. and Ji T., "Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City", *Soil Dynamics and Earthquake Engineering*, 98, 206-221, 2017.

[9] Guerrero H., Teran-Gilmore A., Ji T. and Escobar J.A., "Evaluation of the economic benefits of using Buckling-Restrained Braces in hospital structures located in very soft soils", *Engineering Structures*, 136, 406–419, 2017.

[10] Guerrero H., Escobar J.A. and Terán-Gilmore A., "Experimental damping on frame structures equipped with buckling-restrained braces (BRBs) working within their linear-elastic response", *Soil Dynamics and Earthquake Engineering*, 106, 196-203, 2018.

[11] Guerrero H., Ji T., Escobar J.A. and Terán-Gilmore, "Effects of Buckling-Restrained Braces on Reinforced Concrete Precast Models Subjected to Shaking Table Excitation", *Engineering Structures*, 163, 294-310, 2018.

[12] Montiel-Ortega M.A. and Teran-Gilmore A., "Comparative reliability of two twenty-four story braced buildings: traditional versus innovative", *The Structural Design of Tall and Special Buildings*, 22(8), 635-654, 2013.

[13] Parashar S., Uy N., Nguyen H., Fernandez G., Mulyasari F., Joerin J. and Shaw R., "Mega disaster in a resilient society, The Great East Japan (Tohoku Kanto) Earthquake and Tsunami of 11th March 2011", Report of the International Environment and Disaster Management, Graduate School of Global Environmental Studies, Kyoto University, 2011.

[14] Sabelli R., Mahin S. and Chang C., "Seismic design on steel braced frame buildings with buckling-restrained braces", *Engineering Structures*, 25(5), 655-666, 2003.

[15] Segovia V. A. and Ruiz, S. E., "Direct displacement-based design for buildings with hysteretic dampers, using best combinations of stiffness and strength ratios", *Journal of Earthquake Engineering*, 21(5), 752-775, 2017.

[16] Teran-Gilmore A. and Virto N., "Preliminary design of low-rise buildings stiffened with buckling restrained braces by a displacement-based approach", *Earthquake Spectra*, 25(1), 185-211, 2009.

[17] Teran-Gilmore A. and Ruiz-Garcia J., "Comparative seismic performance of steel frames retrofitted with buckling-restrained braces through the application of force-based and displacement-based approaches", *Soil Dynamics and Earthquake Engineering*, 31, 478-490, 2010.

[18] Teran-Gilmore A. and Coeto G., "Displacement-based preliminary design of tall buildings stiffened with a system of buckling-restrained braces", *Earthquake Spectra*, 27(1), 153-182, 2011.

[19] Teran-Gilmore A., Ruiz-Garcia J. and Bojorquez-Mora E., "Flexible frames as self-centering mechanism for buildings having buckling-restrained braces", *Journal of Earthquake Engineering*, 19 (6), 978-990, 2015.

[20] Tremblay R., Bolduc P., Neville R. and DeVall, R., "Seismic testing and performance of buckling-restrained bracing systems", *Canadian Journal of Civil Engineering*, 33, 183-198, 2006.

[21] Uang C. and Nakashima M., "Steel buckling-restrained braced frames", *Earthquake Engineering: Recent Advances and Applications*, Chapter 16, CRC Press, 2003.

[22] Wada A., Huang Y. and Bertero V.V., "Innovative strategies in earthquake engineering", *Earthquake Engineering: Recent Advances and Applications*, Chapter 10, CRC Press, 2003.

