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Earthquake-Resistant and Environmental Advantages of DIAGRID Systems in High Seismicity Zones

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Abstract: A comparison of the seismic response and environmental impact potential of two building systems is presented. Both buildings have 24 floors and a total height of 114 m, and are located in the Lake Zone of Mexico City. The first building, denominated traditional, uses composite (steel and reinforced concrete) moment-resisting frames and concentric diagonals. The second one, denominated innovative, is structured with steel perimetral diagonal grids and steel frames. Despite its lower weight, and smaller lateral strength and stiffness, the innovative system exhibits a superior seismic performance characterized by light damage on approximately 8% of its seismic-resistant elements for the design seismic excitation. In addition, the construction of the innovative system reduces emission of greenhouse gases by two thirds compared to its traditional counterpart. The example presented here provides an idea of the benefits that the use of innovative systems can bring to the Mexican design and building practices.

Key words: DIAGRID (diagonal grid); seismic-resistant structures; displacement based design; sustainability; LCA

1. Introduction

Recently, the structural system known as DIAGRID has been used in high-rise buildings to reduce the potential environmental impact of projects of this size. Within the architectural community, several professionals have highlighted the possibilities that this system offers in terms of combining aesthetic expression, geometric versatility and structural efficiency (Mele et al. 2014). DIAGRID (diagonal grid) is a perimeter system, consisting of large steel (or other material) frames arranged in triangular modules. The horizontal elements located at the height of the floor systems form perimeter rings that ensure the integrity of the system.

In spite of the great advantages that perimeter gratings have represented from a sustainability point of view, their application in medium and high seismic zones has not been studied in detail. Based on the use of perimeter gratings in non-seismic zones, it has been considered that there are two global design requirements: A) Strength and B) Stiffness. In the case of high seismicity zones, explicit consideration of their lateral deformation and energy dissipation capacities, as well as their stability under lateral loads, is required.

Sustainability plays a fundamental role in the conception, design and construction of tall buildings. Although sustainability encompasses several aspects, including energy efficiency and efficient use of available resources, it is interesting to note that this concept is often ignored in the design of structural systems for buildings located in areas of high seismicity. It is also important to mention that, according to Gonzalez (2010), worldwide resource consumption due to construction reaches approximately 40% of raw materials such as clay, sand and stone, 25% of virgin wood and approximately 16% of usable water. Due to this, the environmental costs generated by the construction of structures gain importance in relative terms as the years go by (Terán-Gilmore, 2012). Therefore, it is urgent to consider the use of innovative systems that considerably reduce the amount of structural materials invested during the construction of tall buildings located in areas of high seismicity.

2. Background

The evolution of structural systems for tall buildings has been driven by efficiency, with a focus on conserving building materials. In the 1930s, the Empire State Building in New York City, the world's first 100-story building, was constructed. It used moment resisting steel framing, which resulted in an extensive use of structural materials. Since the 1960s, there have been remarkable technological advances in the analysis and design of structural systems for tall buildings. In particular, tubular structures were used, which placed the resistant structural elements at the perimeter of the building. This made the use of materials more efficient and significantly reduced the ultimate weight of structural systems such as the Twin Towers in New York.

Two decades later, it was realized that perimeter diagonals were one of the alternatives available for designing tubular systems. This approach resulted in significant weight reductions. Global shear forces, caused by factors such as wind or earthquakes, are more effectively supported through axial deformations in diagonal elements than through bending deformations in the members of a moment resisting frame.

Currently, there is a renewed interest in using perimeter trusses in tall buildings, which has been reflected in several major international projects. It is worth mentioning that the difference between a conventional braced tube and a perimeter grid is that the latter lacks vertically oriented elements, since the diagonals simultaneously support vertical and lateral loads. In addition, different structural materials have been used to construct the rigid gratings. Examples of gratings that have been built with materials other than structural steel are shown in Figure 1. In general, the low consumption of structural material makes rigid gratings part of far-reaching sustainable projects, which have won important international recognition. For example, according to the Hearst Consortium, its headquarters located in New York, with a total area of 79,800 m^2, were structured with a rigid perimeter grid, which resulted in savings of approximately 2,000 tons of structural steel (about 21% less than that required by a conventional framing system). In addition, 30% of the raw material weight came from recycled sources.

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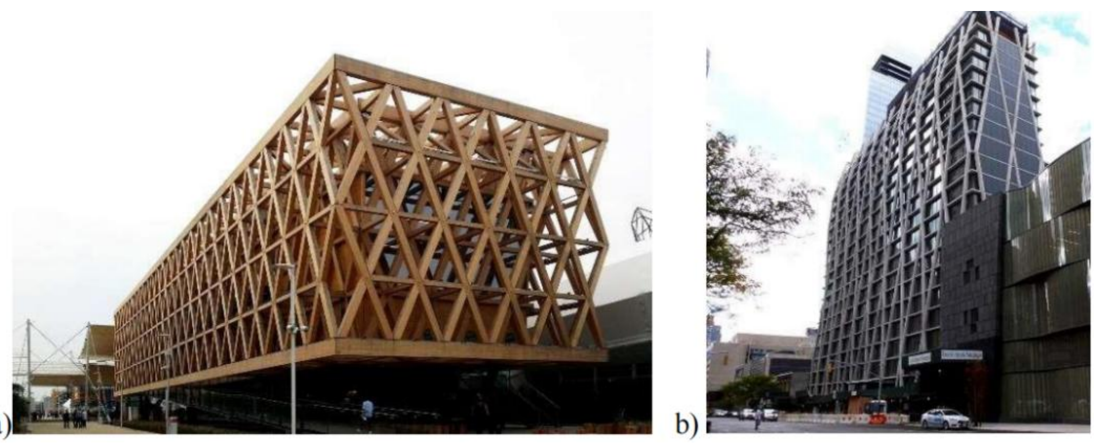

Figure 1. a) Chile Pavilion Expo Milano 2015 (Cristián Undurraga). b) 170 Amsterdam Avenue in New York (Handel Architects).

In the case of Mexico, several tall buildings have been built in the downtown area of Mexico City in recent years. Examples of this are the Torre Mayor, considered as the tallest building in Latin America until a few years ago, the Torre Bancomer and the recently inaugurated Torre Reforma. In addition, several more are under construction and many more are in the planning stage. Within this context, it is important to study the use of perimeter grids as the main structural system in buildings located in areas of high seismicity, in order to understand their potential to significantly reduce the potential environmental and monetary impact of structural systems that provide earthquake resistance to high-rise towers.

2.1 Perimeter grids

The concept of the rigid grid as a structural system dates back to the period between the late 19th and early 20th centuries, when Russian engineer Vladimir Grigorievich Shukhov examined the desirability of using rigid grids in high-rise structures. Between 1886 and 1895, Shukhov developed and patented the concept of structural roofs configured with exceptionally lightweight rhomboidal cells, which eventually evolved into what is now known as DIAGRID.

After a series of successful tests and experiences, Shukhov was entrusted with a series of projects that culminated in the design and construction of a radio tower located on the outskirts of Moscow. Almost immediately, the project attracted attention due to its lightness; although the tower had an initial height similar to that of the Eiffel Tower, the former would only weigh 30% of the latter. Material shortages caused by the Russian civil war made it impossible to achieve the original project, and forced the development of a second version limited to a height of 160 m, which did not prevent, once again, the tower from attracting attention due to its structural stability and light weight (1000 tons, Figure 2). Shukhov's design logic focused on having sufficient structural rigidity by using straight elements in large numbers, which generate hyperboloid shapes in each of the six modules that make up the tower, in addition to the fact that the open lattice significantly reduces the lateral load due to wind (Edemskaya and Agkathidis, 2016). Likewise, it should be mentioned that at that time there was no information on seismic hazard in the Moscow area, starting this type of studies around the 60's of the twentieth century, although at present it has been observed that it is relatively low (U.S.G.S 2002).

Figure 2. Shukhov's radio tower (1922).

In a perimeter grid, the triangular arrangement of the structural elements located at the perimeter of the building allows the structural behavior to be dominated by axial forces and deformations. Given the absence of columns, the diagonals must simultaneously accommodate vertical and lateral loads resulting from design actions (Mele et al. 2014). This differs from a structural system consisting of frames and diagonals, where lateral deformations due to global shear and bending behaviors are controlled by different structural members (wind bracing and supporting columns, respectively).

The study of perimeter gratings and their response to lateral loads was initially limited to the wind case (Moon et al. 2007, Moon 2008). Observations of great interest were made, particularly with regard to the optimal inclination of the diagonals. In particular, Moon et al. (2007) indicate that for high-rise buildings, this angle measured with respect to the horizontal plane, is in a narrow range, with a mean value close to 70°. Recently, Mele et al. (2014) have noted that the geometry of perimeter grids built around the world closely follows the recommendation of Moon et al.

Recently, efforts have been made to better understand the implications of the use of perimeter grids in areas of high seismicity. In this regard, Kim and Lee (2010 and 2012) comment that earthquake loads can govern the design of high-rise buildings structured with perimeter grids. In their work, Kim and Lee mention that grids can exhibit high over-resistance due to their redundancy, and a high capacity to control the lateral deformation demand imposed by seismic effects. They mention that in order to stabilize the lateral response of this system when it enters its plastic behavior, it is convenient to control the buckling of the diagonal elements.

2.2 Objectives and limitations

The main objective of this study is to present the advantages that an innovative structural system is able to offer in terms of seismic response and environmental impact.

One limitation of the work is that the comparison established is between a traditional structural system designed and built several years ago, and an innovative structural system using a design methodology that incorporates very recent advances in terms of seismic resistance. A second limitation concerns the scope of the environmental analysis. Specifically, it only considers the construction cost in units of carbon dioxide equivalent generated by the consumption of concrete, steel reinforcement, and structural steel. This ignores medium and long-term costs, such as consumption for the use, maintenance and repair of the structural system, as well as the disposal of structural materials and their hypothetical recycling in case of demolition of the structural system.

2.3 Displacement-based design

For the design of the innovative structural system, the displacement-based approach proposed by Terán-Gilmore and Coeto (2011) for stiffened frames with buckling-restrained wind bracing was adapted. This approach considers that the structural system works as a large cantilever beam and, therefore, its lateral response is dominated by two global components of deformation; the first is a global component in shear due to the axial deformation of the wind girders; and the second is a global component in bending due to the axial deformation of the columns supporting the wind girders.

In this paper, the innovative system considered is a dual structural system that integrates the work of two sub-systems; one that resists most of the gravity loads, and a second that provides seismic resistance. While the first one is constituted by moment resisting steel frames with standard detailing, the second one is formed by perimeter grids whose diagonals exhibit an angle of inclination close to 70º. Although it will not be mentioned in the following text as this topic will not significantly affect the comparison, it is important to mention that the connection that makes the integration of the two subsystems possible must be correctly designed, detailed, and constructed.

The idealization shown in Figure 3 for a perimeter grid considers the following assumptions: A) The floor systems function as rigid diaphragms; B) The perimeter grid provides the lateral stiffness required by the building; and C) The global shear and bending deformation components of the grid can be estimated independently. As shown, it is possible to idealize the perimeter grid as an equivalent one-degree-of-freedom system with two springs working in series; the first one representing the global stiffness in shear, and the second one representing the global stiffness in bending.

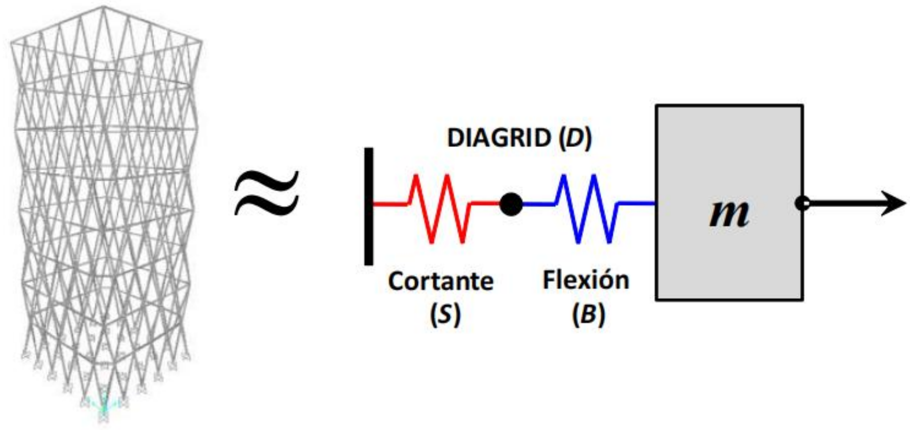

Figure 3. Idealization of the perimeter grid as an equivalent system of one degree of freedom.

Figure 4 summarizes the methodology used for the sizing of the perimeter grid diagonals, which considers the idealization shown in Figure 3 and a level of seismic intensity. In summary, the first step is to establish a qualitative definition of the expected performance. This is done by explicitly considering the acceptable levels of damage in the different subsystems that make up the structure (perimeter grid, gravity system, non-structural elements). The second step corresponds to the numerical characterization of the expected performance by establishing response thresholds. In the third step, a target value for the fundamental period of the structural system is set by using a displacement design spectrum. In the final step, the area of the perimeter grid diagonals is estimated as a function of the target period. An in-depth discussion of the methodology and a detailed example of its application will be published shortly. In the following, the methodology is outlined to provide a reasonable understanding of its use.

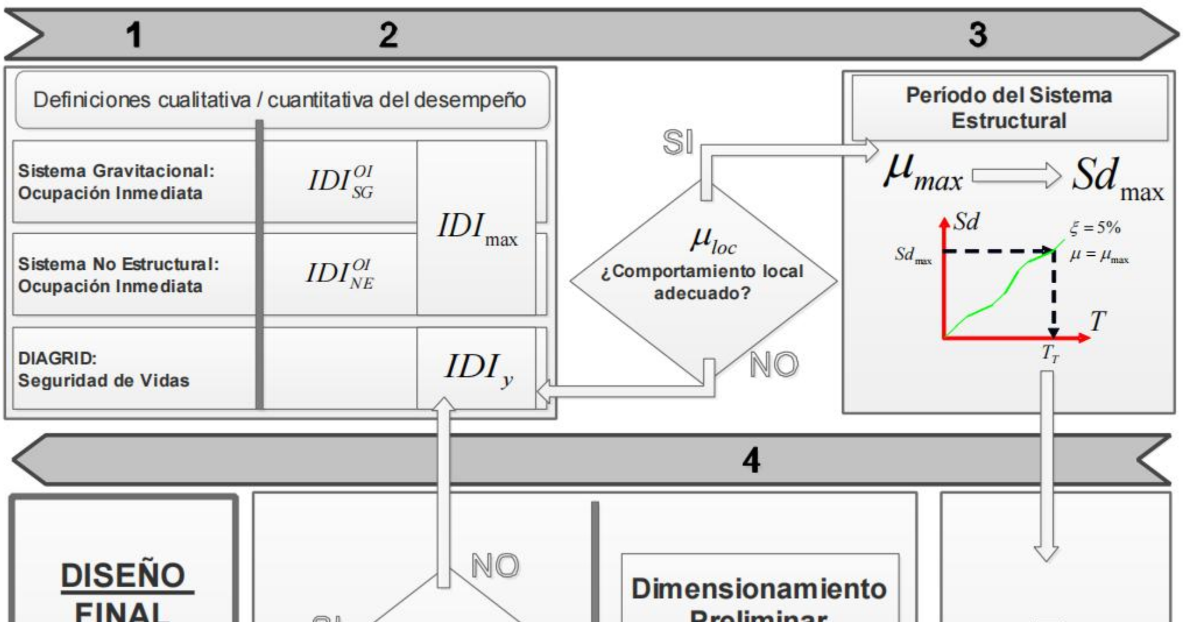

Figure 4. Preliminary design methodology.

In Figure 4, IDI_{SG}^{OI} and IDI_{NE}^{OI}, correspond to the maximum interstory distortions that can be accommodated by the gravity and nonstructural systems to satisfy the immediate occupancy performance level (FEMA 356, 2000). To achieve adequate damage control in the gravity and nonstructural systems, the maximum distortion that can be accommodated by the structural system (IDI_{max}), which should be limited to the lesser of the values of IDI_{SG}^{OI} and IDI_{NE}^{OI}. As for the structural performance of the perimeter grid, it is allowed to incipient in its nonlinear behavior. To characterize its level of plastic behavior at the interstory level, the maximum interstory ductility (μ_{loc}) must be established by normalizing the value of IDI_{max} by the distortion at which the diagonals of the rigid grid flow (IDI_y). Once the maximum global ductility demand (μ_{max}) is estimated from the value of μ_{loc}, a displacement design spectrum is established, which corresponds to the ductility μ_{max} and the percentage of critical damping (ξ) assigned to the structural system (usually 5% of the critical).

Once the gravity system has been designed, it is possible to establish the value of IDI_{SG}^{OI} by means of a nonlinear static analysis. For this purpose, a maximum acceptable value of plastic rotation for the gravity system frames is usually defined for the immediate occupancy performance level. Based on experience, it is possible to say that one option to carry out this analysis is to consider a value of 0.01 for IDI_{SG}^{OI}. In case of non-structural elements, it is convenient to design their connections to the structural system in such a way that they are able to accommodate a distortion of 0.01 without damage, so that they do not restrict the lateral deformation capacity of the structural system. As for the geometry of the perimeter grids, the angle of inclination of their diagonals with respect to the horizontal (θ) is of enormous relevance. The value of IDI_y used to calculate the interstory ductility depends on this angle and the yield stress of the steel used to fabricate the diagonals. According to Moon et al. (2007), an angle close to 70° optimizes the use of steel.

As shown in step 3 of Figure 4, the displacement design spectrum is used to establish the design value for the fundamental period of vibration of the perimeter grids (T_T). Note that this implies having a maximum pseudo-displacement threshold (Sd_{max}) for an equivalent one-degree-of-freedom model of the perimeter gratings (see Figure 3). In summary, once IDI_{max} is available, it is possible to estimate a design displacement threshold for the roof level (δ_D). The value of Sd_{max} results is derived from $\delta_{D,}$ considering that the first one corresponds to an equivalent one degree of freedom model of the structural system, and the second one corresponds to the roof of a detailed three-dimensional model with multiple degrees of freedom.

Under the assumption that the perimeter grid system provides the total lateral stiffness of the building, step 4 proposes a preliminary sizing based on the stiffness of the diagonals. This sizing is considered to be successful if the fundamental period of vibration estimated with a detailed analysis model of the perimeter grids is similar to T_T.

Once the size of the diagonal is determined, the final stage of design is to verify whether the structural system exhibits qualitative and quantitative defined performance that meets the required performance through stepwise nonlinear dynamic analysis. If it is necessary to adjust the preliminary design to achieve the desired performance, please iterate. Otherwise, the design will terminate.

There are several considerations to be made during the design, sizing and detailing of a rigid perimeter grid. The first has to do with controlling and delaying the buckling of the grid diagonals, to prevent the structural system from losing its stability at low deflections when subjected to lateral loads. In case of moderate demands of plastic behavior, it is possible to resort to the use of stiffeners or hollow steel sections filled with concrete. In the case of high demands of interstory ductility, the use of buckling restrained wind bracing has been suggested (Kim and Lee, 2010 and 2012).

For the purposes of this paper, the design of the perimeter grid is made to limit μ_{loc} to 1.5. Under these circumstances, the use of stiffeners should ensure steel diagonals with relatively stable hysteretic behavior. A second consideration is the percentage of vertical loads to be resisted by the perimeter grid. In general, it is important to minimize this percentage, and for this purpose geometries that maximize the contribution of the gravity system to the resistance before vertical loads should be used. This is achieved by making the areas of the floor system tributary to the perimeter grid as small as possible. Finally, although the lateral deflection of the structural system is controlled in such a way as to enable the gravity system to satisfy the immediate occupancy performance level, it is desirable to use design-for-capacity concepts during the design of the gravity system.

2.4 Life cycle analysis

Life Cycle Assessment allows to evaluate the environmental, social and economic impacts of a product, process or system throughout its useful life. In this article, it is of interest to consider the structural system of a building. In general, Life Cycle Assessment covers the procurement of raw materials, the production (construction) and use of the system, and the disposal or recycling process. It also considers transportation in all phases.

The environmental impact can be expressed, among others, in terms of global warming potential (which is usually quantified in terms of greenhouse gas (GHG) emissions), exploitation of water resources, and eutrophication. GHG emissions are usually reported in tons of carbon dioxide equivalent (CO_2-e), and include emissions of carbon dioxide and other gases such as methane and nitrous oxide. The basis of the Life Cycle Assessment is the Life Cycle Inventory, which quantifies the raw material and energy consumption, and the solid waste and air emissions resulting from all the processes associated with the system under study. In this article, only the materials that constitute the structural system of the superstructure are considered and contributions from the foundation, non-structural elements and finishes are not considered. For the traditional superstructure, concrete and steel slabs, moment resisting composite frames, and concentric wind bracing are considered. For the innovative superstructure, the concrete and steel reinforcement of the slabs, and the structural steel of the perimeter grids and steel frames are considered. The environmental cost is expressed in terms of the global warming potential (based on CO_2-e emissions) associated with the structural materials of the superstructure.

With respect to the concrete mix, Cementos Mexicanos (CEMEX 2015) provides the CO_2-e/m^3 values of the concrete mix placed on site (i.e., emissions derived from the extraction of aggregates and materials used in the manufacture of cement, the transportation of materials, as well as the manufacture of the mix itself are already included), which corresponds to 265 kg- CO_2-e/m^3 (CEMEX, 2013).

On the other hand, the crude steel emission factor value indicated in Hasanbeigi et al. (2015) for Mexico was chosen. This emission factor takes into account emissions due to the manufacture of crude steel, but does not include emissions derived from finished products such as reinforcing or structural grade steel. However, it should be noted that the higher emissions are considered in this factor. For example, the emission factor indicated for Mexico is 1,080 kg-CO_2/ton, lower than that indicated for other countries such as the United States (1,736 kg-CO_2/ton) and Germany (1,708 kg-CO_2/ton). It should be clarified that this value corresponds to an average of the emissions produced when using the blast furnace and electric arc steel-making process.

3. Structures Considered in the Study

This article considers the design of two structural systems with similar geometric characteristics. The first, called traditional, uses reinforced concrete and structural steel composite frames and was designed in accordance with the Building Regulations for the Federal District. The second, called innovative, is structured based on a rigid perimeter grid and structural steel frames, and was designed with the displacement-based methodology summarized in Figure 4.

3.1 Description of the traditional building

The traditional structural system is described in greater detail in Montiel and Terán-Gilmore (2013). It has 24 levels and is used to house offices. It was designed according to the Building Regulations for the Federal District in force in 1993

(RCDF, 1993), and is located in the Lake Zone. Figure 5 shows that the system has a floor plan of 45 by 45 m, and has variable mezzanine heights of 4.0, 5.65, 6.0 and 6.5 m along the total height of the structure. The total height of the system is 114.8 m. Its fundamental period of vibration is estimated to be 2.67 seconds.

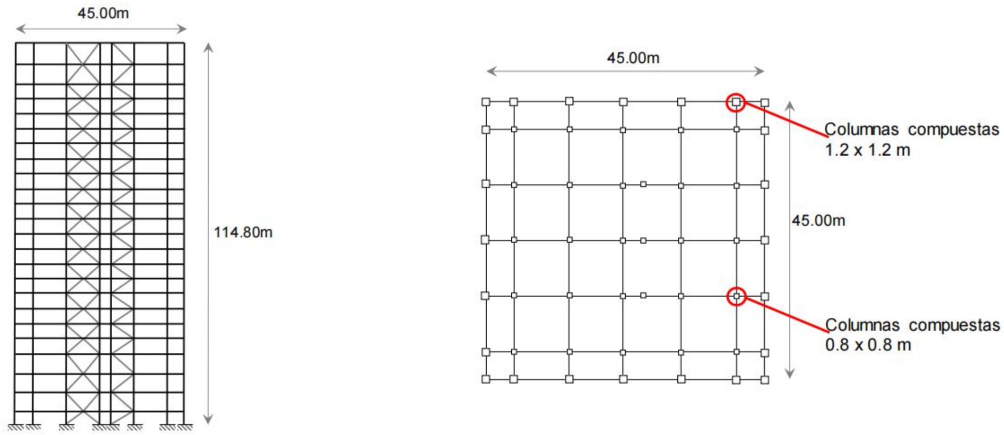

Figure 5. General geometry of the traditional structure.

The traditional structural system has seven composite frames (steel beams with concrete encased steel columns) in both directions. The three central frames in each direction of analysis have been stiffened with ductile concentric wind bracing. The floor systems, considered as rigid diaphragms, consist of primary and secondary steel beams, and a slab-steel system connected to the top skids of the beams by means of shear connectors. While the composite perimeter columns have a cross-section of 1.2 by 1.2 m, the interior columns have dimensions of 0.8 by 0.8 m. Structural steel with a strength of 350 MPa (3,515 kg/cm^2) and concrete with a strength of 35 MPa (350 kg/cm^2) are used for columns, and 25 MPa (250 kg/cm^2) is used for floor systems.

For the nonlinear dynamic analyses of the traditional system, the RUAUMOKO program was used. The main reason for this was the ability of this program to model the nonlinear behavior of traditional wind buckling, including the possibility of buckling.

The main considerations made to formulate the nonlinear analysis model are: a) The beams are assigned a bilinear behavior with a post-elastic slope equal to 1. 5% of the elastic slope; b) In the case of the columns, the axial load-bending moment interaction and a bilinear model without stiffening are considered; c) For the estimation of the structural properties of beams, columns and wind girders, the expected properties of the structural materials are used (in particular, the expected yield stress of the steel considered an over-resistance of 20% with respect to the nominal stress); d) The floor system slabs behave as rigid diaphragms; e) P-Δ effects are considered; f) Neither bidirectional effects of seismic forces nor torsional effects are considered (the analysis is flat); g) The columns are considered embedded in the base; and h) Buckling effects are explicitly considered in the hysteretic behavior of the wind girders.

3.2 Description and design of the innovative system

The innovative system was sized according to the displacement-based design methodology summarized in Figure 4. While a set of steel frames forms the gravity system, a rigid perimeter grid form an exoskeleton that is designed to withstand the full seismic action. The floor system of the innovative system is very similar to that considered for the traditional structural system.

The final design, presented in Figure 6, resulted in a gravity system of 4 steel frames in each main direction, covering 9-meter spans; plus two perimeter grid axes, located on the perimeter. For the perimeter grids, a linear variation with 8 section changes in height was considered, so that the area of the diagonals and perimeter belt remains constant in a triangular module, and the area of the diagonals of the triangular modules located in the upper part of the building is equal to 60% of the area used for the lower modules. The innovative structural system exhibits a fundamental period of vibration of 3.35 seconds.

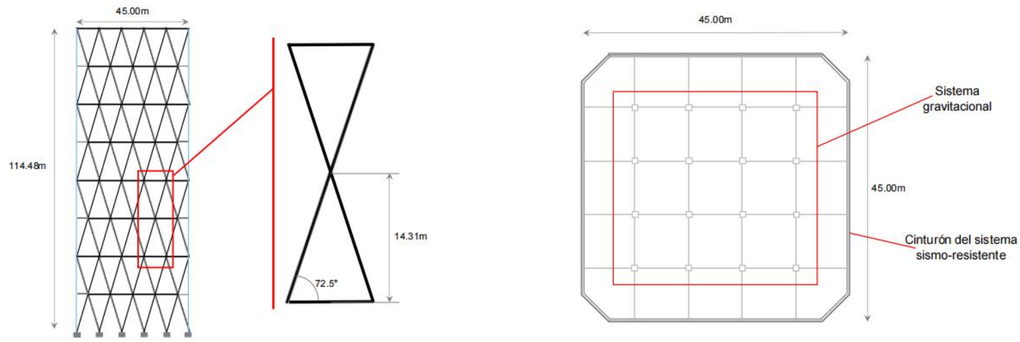

Figure 6. Final configuration of the innovative system.

The mezzanine heights were slightly modified with respect to those considered for the traditional structural system in order to maintain a constant height (14.3 m) in the triangular modules that make up the perimeter grid.

The selection of inclination angle of the diagonal system sought to balance two needs. The first involves the use of triangular modules of few stories with angles less than 45º, which provides high overall shear stiffness. The second considers the use of triangular modules spanning several levels in order to achieve angles close to 90º, which provides higher overall stiffness in bending. An angle around 70º represents a good balance in terms of meeting both needs. Hence, an angle equal to 72.5º has been selected for the triangular modules of the innovative system. The main parameters considered for the design of the rigid grid are a steel yield strength of 350 MPa (3,515 kg/cm^2), IDI_{max} = 0.01, and μ_{loc} = 1.5.

Figure 7 shows with a continuous black line the spectrum used for the design of the innovative structural system. The design spectrum corresponds to the mean plus one standard deviation of the spectra corresponding to 10 synthetic accelerograms established with the methodology proposed by Kohrs-Sansorny et al. (2005). The movement used as seed for the generation of the accelerograms was recorded at the MCT site (Ministry of Communications and Transportation) during the event of April 25, 1989 (BMDSF 2000). The simulation method used allows reflecting the dynamic characteristics of the soil at the site because it inherently considers propagation and site effects without the need to resort to theoretical factors or other mechanisms (Quiroz-Ramírez et al. 2014).

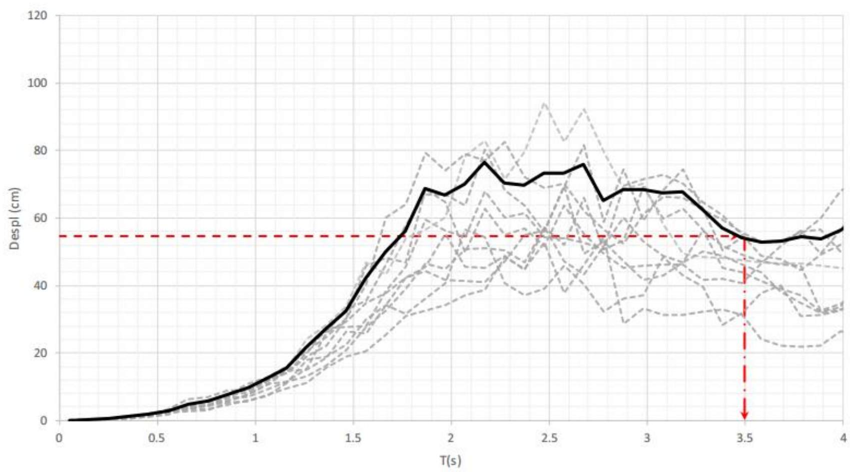

Figure 7. Spectra considered for the design of the innovative system, $\xi = 0.05$, $\mu_{max} = 1.5$.

A three-dimensional nonlinear model of the innovative system was generated with the SAP2000 program. The modeling considerations were very similar to those considered to develop the nonlinear analysis model of the traditional structure. In the case of the diagonal elements that make up the perimeter grid, reinforcing elements with perfect elasto-plastic behavior were considered on the understanding that axial deformation effects predominate in them. In the case of diagonal elements forming the surrounding grid, consider reinforced elements with perfect elastic-plastic behavior, provided that axial deformation effects dominate. The possibility of diagonal buckling was not considered, as the deformation requirements in innovative buildings would be carefully controlled to be within the threshold range, resulting in fully reinforced steel components exhibiting perfect elastic-plastic behavior.

It is worth mentioning that the perimeter grid will always take a portion of the vertical loads, regardless of the configuration used for the gravity system. In the case of the innovative superstructure, the grid carries 17% of the total vertical load. Figure 8 shows the capacity curves for the grid with and without its vertical load. Note that the lateral resistance of the grating is reduced by about 7% in the presence of its vertical load. Therefore, it is possible to say that the expected seismic performance of the innovative system is not significantly affected by the presence of gravity loads.

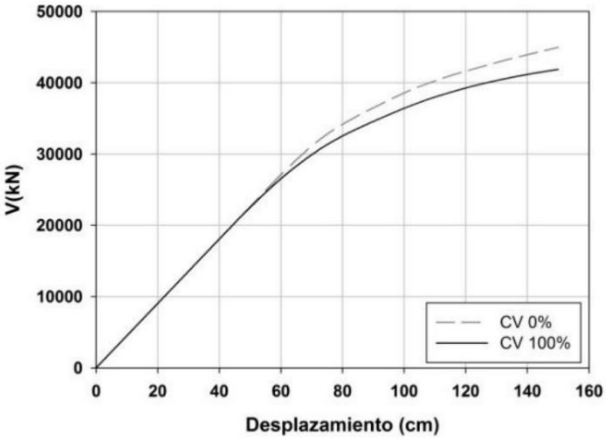

Figure 8. Non-linear static analysis curves of the innovative system considering 0% and 100% gravity load on the perimeter grid.

4. Comparison of the Seismic Response of Both Buildings

Initially, a nonlinear static analysis of both building structures was carried out. Figure 9 presents the capacity curves of the traditional and innovative structural systems. It can be seen that for a ductility of 1.5, the innovative system is able to absorb a roof displacement of 1 m. The traditional system has lateral stiffness and lateral resistance that are about 50% higher than the values corresponding to the innovative system.

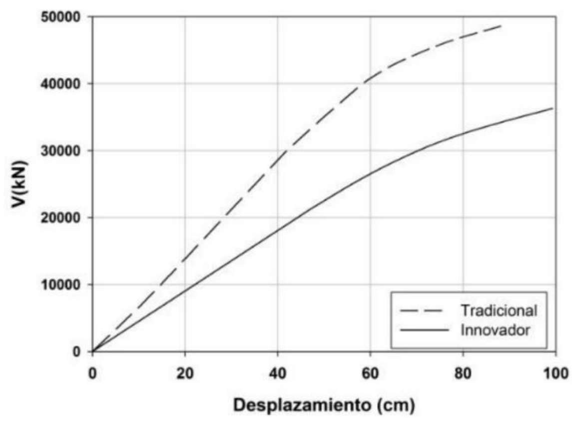

Figure 9. Capacity curves of the traditional structure and the innovative system.

Figure 10 shows how the height distributions of the floor-to-ceiling distortion evolve as the roof displacement of both versions of the building increases. It can be said that both systems distribute reasonably evenly their lateral deflection over the different mezzanine floors. In the case of the innovative system, the distribution of distortions exhibits greater variations, specifically in the zones where area changes occur in the diagonals that make up the different modules.

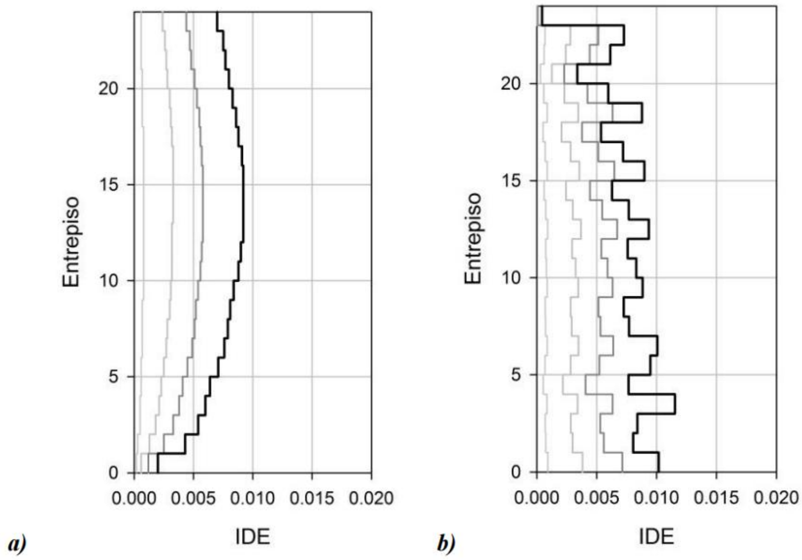

Figure 10. Comparison of floor-to-ceiling drift rates at different values of roof displacement. a) Traditional building b) Innovative building.

To evaluate the seismic performance of the two structures, two sets of nonlinear dynamic analyses were performed. The 10 data sets were used to generate the design spectrum shown in Figure 9. Figure 11 summarizes the means plus one standard deviation of the lateral deformations in height. While Figure 11a considers the lateral displacements and Figure 11b illustrates the interstory distortions. It is observed that the innovative system develops demands that are slightly higher than the design value of 0.01 (associated during design at the immediate occupancy performance level). Despite this, the plastic joint mapping indicated that the sub-system intended to support gravity loads does not develop plastic behavior during the different ground motions considered in the analyses, implying that it satisfies, for all of them, the immediate occupancy performance level.

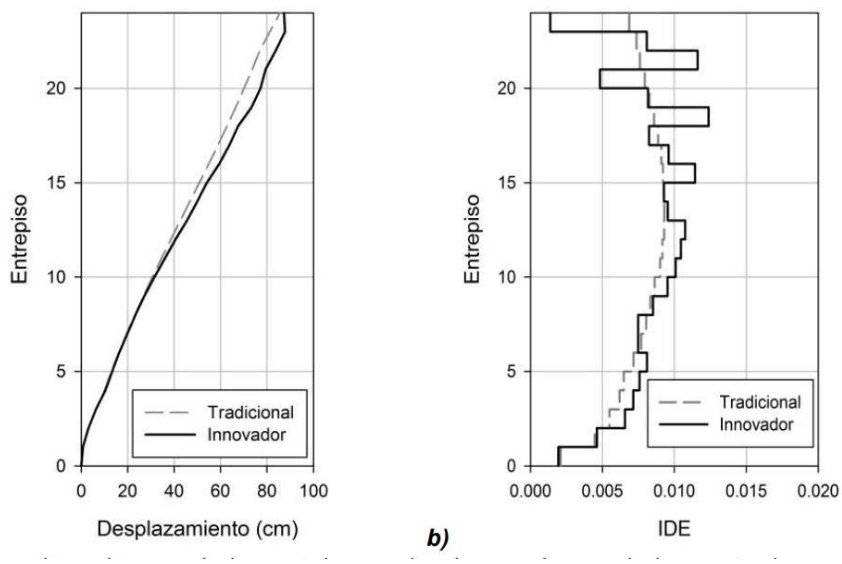

Figure 11. Estimated maximum displacements and drifts for the seismic motions considered.

Figure 12 presents the mean values plus one standard deviation of maximum plastic rotations for the traditional building (Montiel and Terán, 2013). It is possible to appreciate severe plastic rotation demands for the case of the exterior beams (Figure 12a). The value of these rotations is so large that it prevents satisfying the life safety performance level. In the case of the perimeter columns, rotations slightly greater than 0.03 are observed, which implies an extreme level of damage.

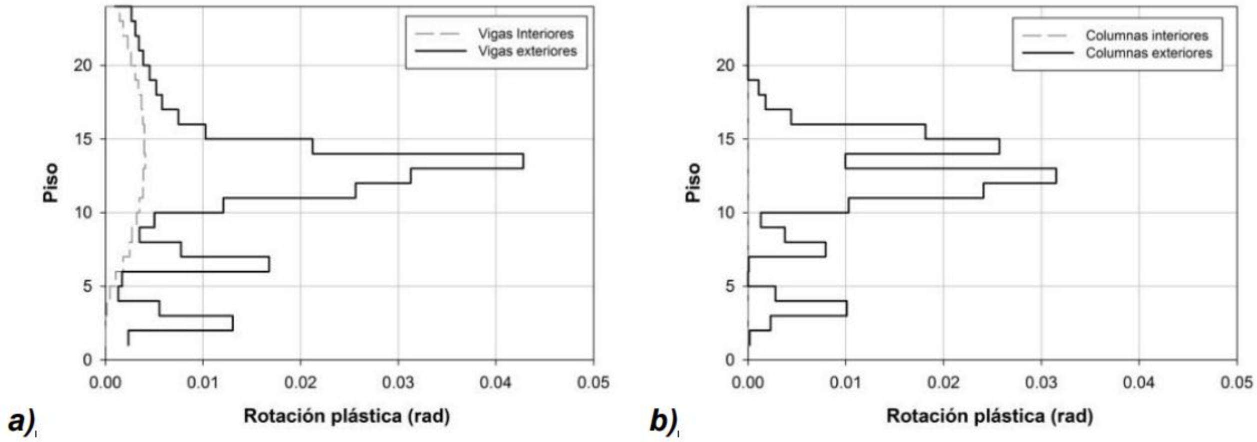

Figure 12. Plastic rotations observed in the traditional building: a) Beams b) Columns.

Figure 13 illustrates the plasticizations exhibited by the structural elements of the innovative system for the ground movement that induces the highest plastic demands. It is observed that the damage is incipient in a reduced number of the diagonals that make up the rigid grid. The internal frames, intended to support gravity loads, do not enter the range of plastic behavior and, therefore, are free of structural damage.

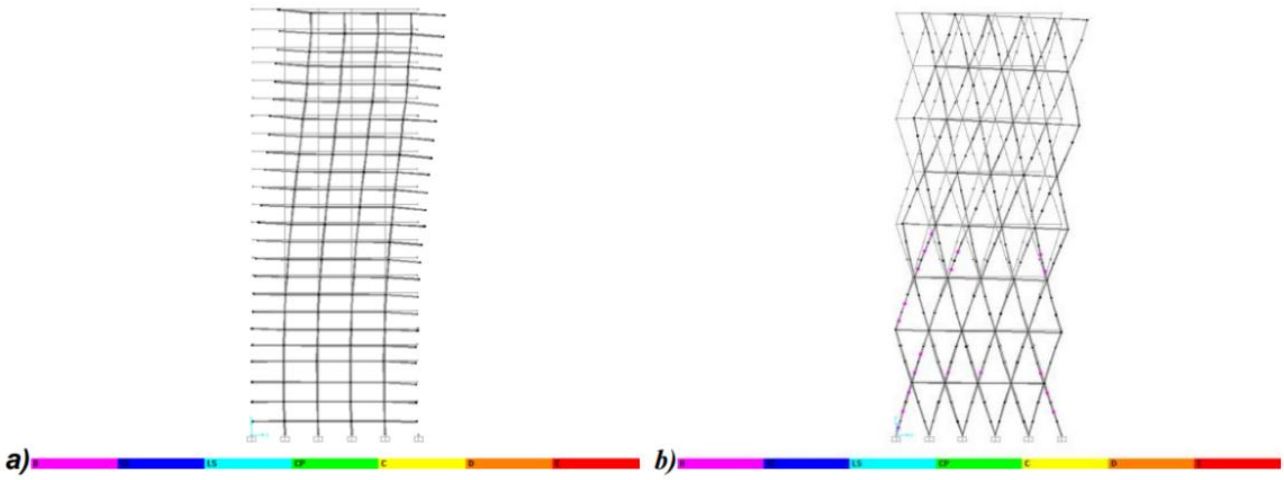

Figure 13. Damage condition in innovative system. a) Inner frame b) DIAGRID.

5. Carbon Dioxide Emissions Analysis

Table 1 presents the quantification of concrete, reinforcing steel and structural steel used in the traditional and innovative buildings. Considering the emission factors noted above, Table 2 indicates, for both structures, the emissions corresponding to each material. It is important to mention that the same emission factor was considered for reinforcing steel and structural steel, and that emissions are reported in terms of CO_2. The subscript e, which is used to identify concrete emissions, indicates that other greenhouse gases in addition to CO_2 are being considered.

Table 1. Quantification of the structural materials used in each building

Building/Material	Concrete (m^3)	Reinforcing steel (ton)	Structural steel (ton)	Total (ton)
Traditional	12,764.2	327.3	5,661.6	18,753.0
DIAGRID	270.9	0.0	2,407.1	3,057.0

Table 2. Quantification of the estimated emissions in each building

Building/Emissions	Concrete (ton-CO_2-e)	Reinforcing steel (ton-CO_2-e)	Structural steel (ton-CO_2-e)	Total (ton-CO_2-e)
Traditional	1,409.4	353.5	6,114.6	7,877.5
DIAGRID	71.8	0.0	2,599.7	2,671.5

From the values in the tables, it can be concluded that the GHG emissions associated with the innovative building are considerably lower. While the traditional building emits 7,877.4 ton-CO_2-e, the innovative system reduces these emissions to 2,671.5 ton-CO_2-e. It is worth mentioning that, although there is no information on additional emissions from other GHGs for the case of steel, the above estimates represent a lower limit in terms of CO_2-e. In this context, it is possible to say that the innovative building is capable of mitigating GHG emissions by 66%.

6. Conclusions

The seismic performance and environmental cost (in terms of carbon dioxide emissions) of two structural systems were compared. While one consists of a traditional system based on moment-resisting frames composed of reinforced concrete and structural steel, the other represents a theoretical example of a dual system consisting of a rigid grid and a flexible structural steel frame system.

Initially, this comparison may not seem very fair, since the traditional structural system corresponds to an existing design, which follows the seismic design regulations of the 1990's for Mexico City and which also fulfilled an architectural need, while the innovative theoretical example resorts to the advances and considerations of the state of the art in seismic-resistant design issues. The intention of this work is that it also allows to appreciate the benefits offered by the emerging design philosophies, as well as the inclusion of innovative structural systems within the Mexican practice of seismic design.

Regarding seismic behavior, it was found that the traditional structure develops a higher level of structural damage despite having about 50% more lateral strength and stiffness than the innovative system. The higher damage in the traditional system occurs despite the fact that its lateral distortion demands are comparable and even lower than those estimated for the innovative system. Although the innovative system exhibits less uniformity in the height distribution of its interstory distortions, during the ground movement that caused a greater lateral deformation, it is observed that only about 8% of the elements that make up the perimeter grid are plasticized.

From a sustainable point of view, it is of enormous relevance to reduce the use of structural materials, which not only pollute the environment during the manufacturing, transportation and erection process, but also deplete non-renewable natural resources. The use of the innovative system offers an opportunity to reduce greenhouse gas emissions by two thirds. This does not take into account aspects related to the maintenance and operation of the entire life cycle of the structural system, such as repairs after strong earthquake events. In the latter case, the traditional structural system is more prone to damage (both in terms of severity and distribution in the structural elements).

It is important in the future to conduct more detailed studies on the life-cycle cost of traditional and innovative structural systems in order to fully understand the importance of innovation in the field of seismic-resistant design. It is possible that the use of innovative structural systems designed and built in a rational and careful manner, together with the quick and reasonable estimation of the environmental impact, and the use of environmentally responsible materials in their production and transportation, will allow Mexican structural engineering to better satisfy the multiple and complex needs of civil societies that inhabit environments built in areas of high seismicity.

The ultimate goal of this work is not to indicate the need for comprehensive modifications to building structure practices in Mexico, since they are commonly referred to as traditional structural systems. Of course, if properly designed according to current regulations and with proper consideration, these systems can still demonstrate advantages that rigid peripheral grid systems cannot provide in terms of stiffness and ductility levels. However, mixing the use of this innovative system with traditional systems would undoubtedly help to obtain benefits both in seismic response and in achieving significant reductions in potential environmental impact.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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