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SEISMIC RELIABILITY OF TWO TWENTY-FOUR STORY BRACED BUILDINGS: EVALUATION AND COMPARISON. PART I.

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ABSTRACT

The seismic reliability of two twenty-four story buildings that exhibit the same geometry and structural layout is evaluated and compared. The structural system of the first building consists of ductile steel braces and composite moment-resisting frames (traditional building). The structural system of the second building consists of non-ductile flexible steel frames stiffened through a system of buckling restrained braces (innovative building). While the former was designed according to the Mexico City Building Code, the latter was designed according to a displacement-based design methodology and the concept of damage-tolerant structures. Both buildings are assumed to be located in the Lake Zone of Mexico City. The reliability study shows that in spite of being considerably lighter, the innovative building exhibits higher levels of reliability for three performance levels: serviceability, life safety and collapse prevention.

Introduction

After studying the reasons why several recent seismic events have resulted in excessive socio-economic loss, the international community of structural engineers has concluded that the level of structural, non-structural and content damage is a consequence of excessive deformation or level of motion within the earthquake-resistant structure. Innovation in earthquake-resistant engineering implies the conception of structural systems, either traditional or innovative, that can adequately control the level of seismic damage through adequately controlling their dynamic response during ground motions of different intensity.

This paper evaluates and compares the seismic reliability of two twenty-four story buildings. One of the buildings was designed according to the Mexico City Building Code by a prestigious Mexican design firm. Its structural system is formed of composite frames (steel beams plus steel columns encased in concrete) laterally stiffened through ductile steel braces. The other one is an "academically" redesigned version of the first, in which a displacement-based methodology was used together with the concept of damage-tolerant structures (Teran and Coeto 2009). Although

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the original geometry and structural layout was kept practically the same, the structural system of the second version of the building is formed by flexible non-ductile steel frames stiffened through a system of buckling-restrained braces.

The confidence levels for both versions of the building are established using a Demand and Capacity Factor format. The format considers explicitly the randomness and uncertainty associated to the estimation of the structural demands and capacities in the buildings (Cornell et al. 2002, Jalayer and Cornell 2003). Confidence levels are evaluated for three performance levels: 1) Serviceability, associated to incipient yielding of the structural system; 2) Life Safety, associated to the physical integrity of the occupants; and 3) Incipient Collapse, associated to prevention of global instability.

Buildings under consideration

The two versions of the twenty-four story building practically have the same geometry and structural layout, and are assumed to be located in the Lake Zone of Mexico City (the original version of the building has been built in this zone). While the original version, denoted herein as *traditional building*, was designed by a prestigious Mexican design firm according to the latest version of the Mexico City Building Code; the redesigned version, denoted herein as *innovative building*, was designed by a graduate student using a displacement-based approach (Teran and Coeto 2009).

Traditional Building

The original building has a basement, twenty-three stories used for office space, and a roof level. Figure 1 shows that the building has a 45 by 45 meter plan, and that the inter-story heights are 4.5 meters, except for the four lower stories, which exhibit heights of 4.0, 5.65, 5.65 and 6.0 meters, and for the two top stories, which exhibit heights of 6.0 and 6.5 meters. Overall, the building has a total height of 114.8 meters. The structural system of the building is formed by composite frames made of steel beams plus steel columns encased in concrete, which are braced, as shown in Figure 1, by a core of ductile steel braces.

Figure 1 shows one of the frames of the building. The frame has composite columns at its ends (axes B and H) manufactured by encasing their structural steel shape with a 1.2 × 1.2 meter reinforced concrete section. Composite columns on axes C, D, E, F and G have their structural steel shape encased by a 0.8 × 0.8 meter concrete section. Beams and braces were made out of structural steel shapes.

While the yield stress of steel is 3515 kg/cm^2, the concrete exhibits design compressive stresses of 350 and 250 kg/cm^2 in columns and slabs, respectively. Within the context of the Mexico City Building Code, the building is classified as type B (office space is considered standard occupation), and is located in Zone IIIB of Mexico City (near downtown, in the Lake Zone). The design threshold for inter-story drift was equal to 0.012. More details of the building and its design procedure can be found in (Hernández et al. 2004).

Innovative Building

The innovative building exhibits the same overall geometry and structural layout, and is assumed to have the same use and to be located at the same site. While the gravitational loads in the building are supported through flexible steel non-ductile frames, seismic resistance is provided by a system of buckling-restrained braces. The floor system is very similar to the one used for the traditional building. Figure 2 shows the structural layout of the innovative building. A detailed discussion about the building, its design procedure and member sizes can be found in (Teran and Coeto 2009).

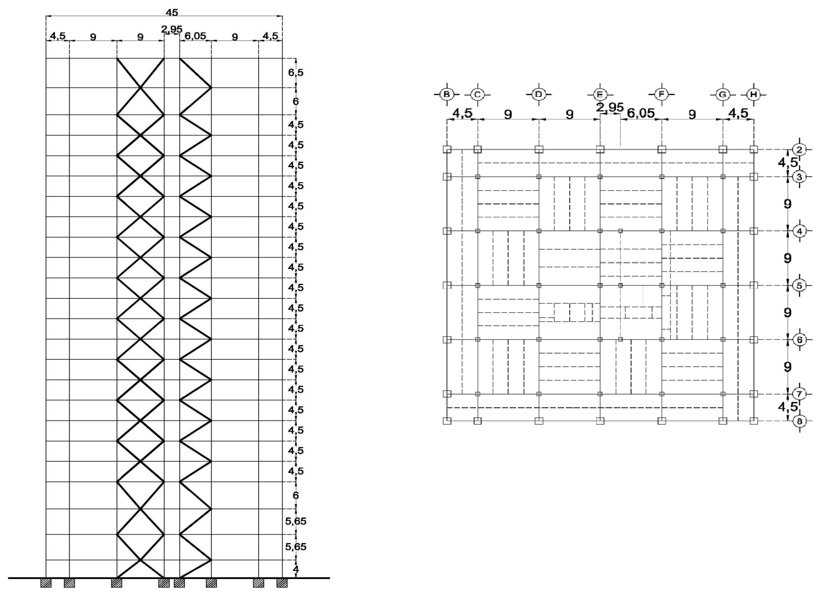

Figure 1. Elevation and plan view of traditional building.

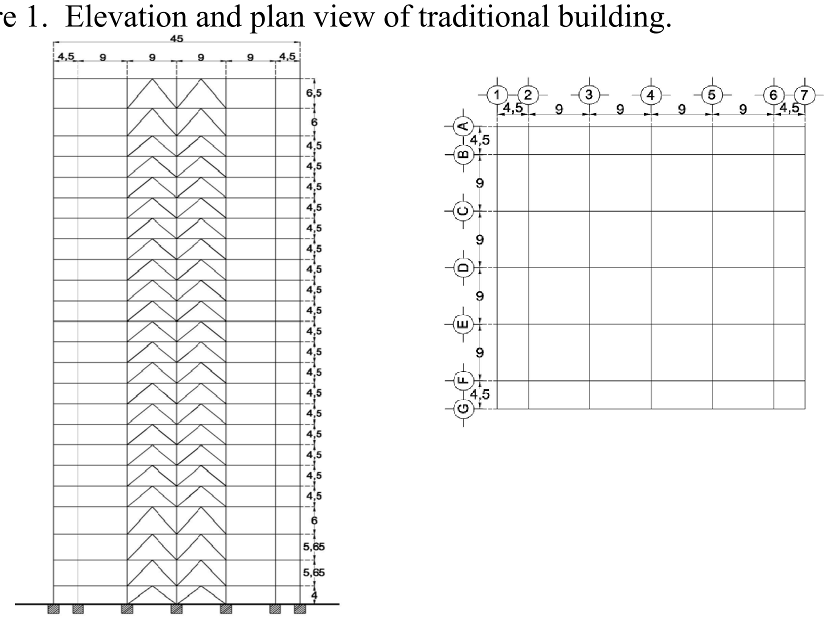

Figure 2. Elevation and plan view of innovative building.

Nonlinear models

Two-dimensional models for the nonlinear analysis of both buildings were established. While the model for the innovative building was prepared for DRAIN 2DX (Prakash et al. 1993), the one corresponding to the traditional building was prepared for RUAUMOKO (Carr 2004).

As shown in Figure 3, the nonlinear model of the buildings considered three different frames (one to model the two external frames, another one to model the two internal frames, and a third one to model the three central frames). All frames were interconnected through rigid diaphragms at the floor levels. While the columns in the ground story were assumed to be clamped at their bases, P-Δ effects were accounted for explicitly during the nonlinear analyses. A percentage of critical damping of five percent was considered through a Rayleigh matrix that assigned the indicated damping to the first two modes of the building.

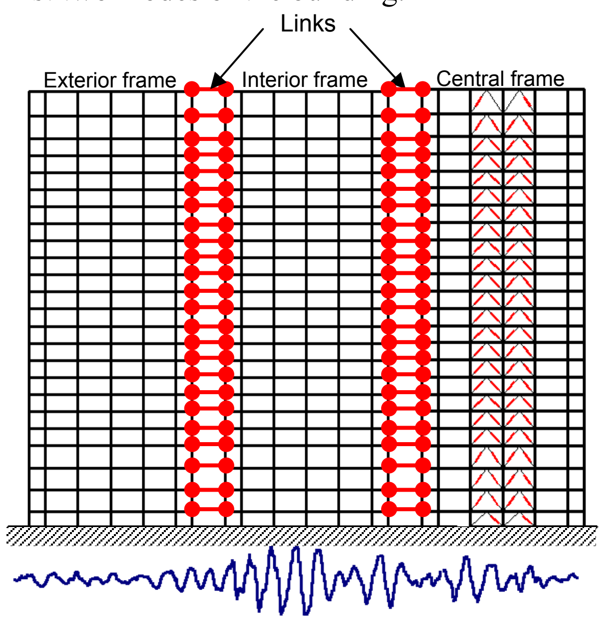

Figure 3. Nonlinear modeling of buildings under consideration.

Structural Reliability

In this paper, the confidence levels for both versions of the building are established using a Demand and Capacity Factor format that explicitly considers the randomness and uncertainty associated to the estimation of their structural demand and capacity (Cornell et al. 2002). The following steps were used to evaluate the confidence level implicit in the buildings.

1. Thirty-one motions generated during sub-duction earthquakes and recorded in the Lake Zone of Mexico City were selected.
2. Mean annual rates of exceedance (ν_0) of the seismic intensities were proposed for the different performance levels under consideration: serviceability, life safety and collapse prevention.

3. The selected motions were scaled to the seismic intensities ($S_a^{\nu_0}$) obtained from seismic hazard curve associated to the fundamental period of the structure. Where $S_a^{\nu_0}$ is defined as the acceleration spectral level (S_a) with annual exceedance rate (ν_0).
4. The buildings under considerations were subjected to the action of the motions scaled and the median value of the demand ($\hat{D}^{\nu o}$) was estimated for the serviceability, the life safety and the collapse prevention performance levels.
5. The total uncertainties (aleatory σ_R and epistemic σ_U; where σ denotes standard deviation) associated to the structural demands in the buildings were established.
6. The median structural capacity ($\hat{C}$) of the buildings was obtained for the three performance levels through incremental dynamic analyses (Vamvatsikos and Cornell 2002).
7. The total uncertainties (aleatory σ_R and epistemic σ_U) associated to the capacity of the buildings were estimated.
8. The *capacity factor* value for each building was estimated as (Jalayer and Cornell, 2003):

$$\phi = \exp\left[-\frac{1}{2}\frac{r}{b}\sigma_{CT}^2\right] \tag{1}$$

where r and b depend on the seismic hazard at the construction site and the structural demand, respectively; and σ_{CT}^2 is the variance of the structural capacity (C). The subscript T represents the total variance that includes both the aleatory σ_R and the epistemic σ_U uncertainties.
9. The *demand factor* value was estimated as (Jalayer and Cornell, 2003):

$$\gamma = \exp\left[\frac{1}{2}\frac{r}{b}\sigma_{DT}^2\right] \tag{2}$$

where σ_{DT}^2 is the total variance in terms of structural demand (D).
10. The *confidence factor*, which relates the median factorized demand and capacity, was estimated for each building as (Jalayer and Cornell, 2003):

$$\lambda = \frac{\phi\,\hat{C}}{\gamma\,\hat{D}^{\nu o}}$$

(3)
11. After establishing the total epistemic uncertainties associated to the demand and capacity (σ_{UT}), the *confidence level* for each building was established as (Jalayer and Cornell, 2003):

$$K_x = \left[\frac{1}{2}\frac{r}{b}\sigma_{UT} + \frac{\ln(\lambda)}{\sigma_{UT}}\right] \tag{4}$$

where K_x is the standard Gaussian variate and the corresponding *confidence level* for K_x can be estimated from a normal distribution table as:

$$\Phi\,(K_x) \tag{5}$$

The hypotheses behind the expressions mentioned in steps 8, 9, 10 and 11 are discussed in detail by Jalayer and (Cornell 2003).

Ground motions and seismic hazard

For the study reported herein, thirty-one motions recorded in the Lake Zone (Zone *IIIb*) of Mexico City were selected. All motions were generated during sub-duction events with epicenters located in the Mexican Pacific Coast. All motions are narrow-banded; that is, their frequency content is centered around a narrow frequency band. Figure 4 shows elastic strength spectra for the unscaled motions. A percentage of critical damping (ξ) of 5% was used to establish the spectra. The seismic hazard curves shown in Figure 5 were used for scaling the motions and it´s necessary for evaluating the structural reliability, (Alamilla 2001) for the *Secretaria de Comunicaciones y Transportes* site (located in the Lake Zone of Mexico City).

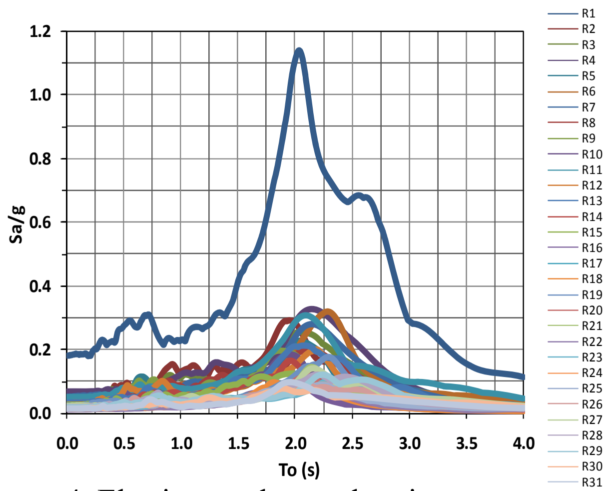

Figure 4. Elastic pseudo-acceleration spectra for $\xi = 0.05$.

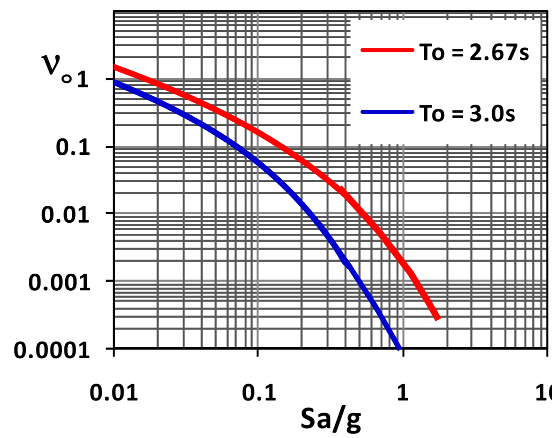

Figure 5. Seismic hazard curves for $\xi = 0.05$, Secretaría de Comunicaciones y Transportes.

Median demands

The median demand ($\hat{D}^{\nu o}$) in the buildings for the thirty-one motions was estimated for different exceedance rates (ν_o). Table 1 summarizes the exceedance rates used as well as their corresponding return periods and probabilities of exceedance in 50 years.

The median demands for the innovative and traditional buildings are summarized in Table 2.

Table 1. Annual exceedance rates associated to performance levels under consideration.

Performance Level	ν_o	T_R (years)	Exceedance probability in 50 years (%)
Serviceability	1.38×10^{-2}	72	50
Life Safety	1.00×10^{-3}	1, 000	5
Collapse Prevention	4.04×10^{-4}	2, 475	2

Table 2. Median inter-story drift index demand, $\hat{D}^{\nu o}$

Building	Serviceability	Life Safety	Collapse Prevention
Innovative	0.0066	0.0119	0.0154
Traditional	0.0087	0.0176	0.0227

Uncertainties associated to demand

Table 3 shows the random uncertainties associated to the estimation of the median demands.

Table 3. Random uncertainties associated to structural demand, σ_{DR}

Building	Serviceability	Life Safety	Collapse Prevention
Innovative	0.14	0.15	0.25
Traditional	0.10	0.22	0.38

Table 4 shows the epistemic uncertainties associated with the structural demands.

Table 4. Epistemic uncertainties associated to structural demand, σ_{DU}

Building	Serviceability	Life Safety	Collapse Prevention
Innovative	0.15	0.20	0.25
Traditional	0.15	0.20	0.25

Median capacities

To estimate the capacity factor (ϕ) for the buildings, it is first necessary to evaluate the capacity of the buildings in terms of inter-story drift index through Incremental Dynamic Analyses (IDA, Vamvatsikos and Cornell 2002), (Montiel and Terán 2009).

Table 5 summarizes the median structural capacities obtained from the IDA curves for the three performance levels under consideration.

Table 5. Median capacity of buildings, $\hat{C}$

Building	Serviceability	Life safety	Collapse Prevention
Innovative	0.0067	0.02	0.067
Traditional	0.0068	0.02	0.050

Uncertainties associated to capacity

Table 6 summarizes the random uncertainties established through Equation 6 for the three performance levels under consideration.

Table 8 summarizes the epistemic uncertainties associated to the capacity of the buildings.

Table 6. Random uncertainties associated to capacity, σ_{CR}

Building	Serviceability	Life safety	Collapse Prevention
Innovative	0.125	0.145	0.220
Traditional	0.195	0.194	0.192

Table 7. Epistemic uncertainties associated to capacity, σ_{CU}

Building	Serviceability	Life safety	Collapse Prevention
Innovative	0.15	0.175	0.20
Traditional	0.15	0.175	0.20

Capacity and demand factors

Factors ϕ and γ were established with Equations 1 and 2, respectively. Tables 8 and 9 summarize the ϕ and γ factors established for both buildings.

Confidence factors

With the values of the ϕ and γ factors plus the median capacities and demands, it is possible to estimate the confidence factors with Equation 3. Table 10 summarizes the confidence factors estimated for both buildings.

Confidence levels

The *confidence level* can then be estimated from Equations 4 and 5. Table 11 summarizes the confidence levels estimated for the buildings (Montiel and Terán 2009).

Table 8. Values of ϕ factor.

Building	Serviceability	Life safety	Collapse Prevention
Innovative	0.95	0.89	0.82
Traditional	0.93	0.90	0.89

Table 9. Values of γ factor.

Building	Serviceability	Life safety	Collapse Prevention
Innovative	1.05	1.15	1.32
Traditional	1.04	1.15	1.38

Table 10. Confidence factors, λ

Building	Serviceability	Life safety	Collapse Prevention
Innovative	0.92	1.31	2.69
Traditional	0.70	0.89	1.40

Table 11. Confidence Levels.

Building	Serviceability	Life safety	Collapse Prevention
Innovative	42 %	92 %	99 %
Traditional	7 %	53 %	94 %

Conclusions

From the evaluation and comparison of the seismic reliability of two twenty-four story buildings, the following can be concluded:

a) The median demand in the traditional building is larger than that of its innovative counterpart for all three performance levels under consideration (Table 2).

b) In the case of the standard deviation of the demand, the innovative building exhibits a larger value for serviceability. The opposite occurs for life safety and collapse prevention (Table 3).

c) The median capacity associated with serviceability is practically the same for both buildings (Table 5). In the case of collapse prevention, it is larger for the innovative building.

d) The random uncertainties associated to the capacity are larger for the traditional building for serviceability and life safety. The opposite occurs for collapse prevention (Table 6).

e) The value of the capacity factor is very similar for both buildings for serviceability and life safety. In the case of collapse prevention, the traditional building exhibits a larger value (Table 8).

f) The value of the demand factor is very similar for both buildings for serviceability and life safety. In the case of collapse prevention, the innovative building exhibits a larger value (Table 9).

g) In some cases, the confidence factors are less than one. The innovative building exhibits a larger confidence factor for the three performance levels under consideration (Table 10).
h) The innovative building exhibits larger confidence levels for the three performance levels under consideration (Table 11).

Independently of the intensity of ground motion, the innovative building exhibits larger levels of reliability than its traditional counterpart. This occurs in spite of the fact that the structural skeleton of the innovative building is considerably lighter than that of its traditional counterpart. The use of a displacement-based design methodology in combination with an innovative structural system has resulted in a lighter structure with improved performance.

Acknowledgements

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