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ESTIMATION OF SEISMIC VULNERABILITY IN REINFORCED CONCRETE STRUCTURES CONSIDERING CUMULATIVE DAMAGE

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Abstract

This study assesses the seismic vulnerability of structures in the Valley of Mexico, considering the impact of intense seismic events and weathering on structural response. It accounts for changes in the chemical and mechanical properties of materials, using current probabilistic criteria for hazard, performance, and vulnerability.
This research aims to determine the change in structural response over time, compared to the design expectations, due to aging and intense seismic events. It considers factors like initial cracking, concrete carbonation, and corrosion of steel reinforcement, influenced by the climate. Additionally, it accounts for the uncertainty of seismic intensities and potential loss of capacity due to weathering. The study uses a conceptual framework based on estimating structural vulnerability with synthetic seismic events that are exhaustive and mutually exclusive.
This work will result, in addition to a better approximation, in estimating the seismic vulnerability of already built structures, in city-level maps of the expected damage on buildings located in the soft soil zone of Mexico City. These maps will help identify which structures require an immediate intervention to minimize the damage that affects not only buildings but society in their normal quality life.

Keywords: Dynamic analysis, corrosion, seismic vulnerability, cumulative damage.

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1 INTRODUCTION

In order to guarantee the safety of structures, it is necessary, in addition to an adequate design, to be able to estimate, with sufficient approximation, their response to the different actions to which they may be subjected during their useful life. This requires taking into account those phenomena that may have an effect on structural behaviour. While, in some cases, not taking these phenomena into account may be conservative (e.g. from a design or vulnerability analysis point of view), it is unacceptable when it is not. Two of these phenomena, which are of particular interest in the case of the assessment of the behaviour of reinforced concrete structures located in Mexico City, are carbonation and seismic soil-structure interaction.

Carbonation is a phenomenon by which the reinforcing steel in concrete is depassivated. This phenomenon results from chemical reactions of the alkaline components of cement (e.g. sodium hydroxide, potassium hydroxide, calcium hydroxide and calcium silicate hydrate) with atmospheric carbon dioxide (Böhni, 2005). Once the reinforcing steel is depassivated, corrosion of the reinforcement will occur if water and oxygen are available on the surface of the reinforcement. Corrosion of the reinforcement leads to a reduction in its cross-section, which consequently reduces its tensile and fatigue strength and elongation (Bertolini, 2014). In turn, the corrosion products occupy a larger volume than the steel from which they originate, resulting in an increase in radial pressure at the steel/concrete interface, which ultimately leads to cracking/cracking of the concrete, generating a loss of adhesion between the concrete and the reinforcement, an increase in the corrosion rate, and the detachment of the concrete coating (Robuschi, 2021; Bertolini, 2014).

The corrosion effects on a structure can be assessed by knowing the rate of diffusion of potentially aggressive substances through the structural elements (usually through Fick's first law), the rate of corrosion of the reinforcing steel once these substances have reached the reinforcing steel and it has been depassivated (usually through Faraday's laws of electrolysis) and finally by applying models relating the reduction of the cross-sectional area of the reinforcing steel to the deterioration of the mechanical properties of the reinforcing steel (usually through Faraday's laws of electrolysis), Fick's laws of electrolysis) and, finally, through the application of models relating the reduction of the cross-sectional area of the reinforcing steel to the deterioration of the mechanical properties of the steel and the concrete.

Although most reinforced concrete structures exhibit good long-term performance and high durability, the number of failures associated with premature corrosion of reinforcing steel is still considerable (Böhni, 2005). However, the likelihood of corrosion of reinforcing steel is minimal in well-designed structures containing sufficient depth of good quality concrete topping that has been properly placed and compacted (Bentur, 1997).

The phenomenon of carbonation is of particular interest due to the urban environment of Mexico City and its weather conditions. On the other hand, Mexico City has a significant number of relatively old structures that, in addition to being designed with standards that did not explicitly consider the effects of weathering, have, of course, been exposed to the elements for a longer period of time.

Therefore, many structures have been subjected, during their service life, to various large-magnitude seismic events and their aftershocks, which have caused their structural properties to change. However, although the effect of accumulated damage in structures is widely known, the vast majority of efforts in seismic structural evaluation have focused on assessing behaviour only under design conditions or, in other words, under the occurrence of a single event that will affect the structure during its service life (Bazzuro et al., 2004a; Bazzuro et al., 2004b; Maffeti et al., 2008, FEMA, 2019). However, some researchers have studied the behaviour of structures once major events have occurred and the impact that aftershocks have on structures (e.g. Jalayer and Ebrahimian, 2017; Sarhosis et al., 2019, Massone et al., 2020). Similarly, other researchers have studied the effects that previous high-magnitude earthquakes have had on structural response due to the occurrence of new seismic events (e.g. Rodríguez, 2020; Ruiz-García and Ramos-Cruz, 2023). All these authors have demonstrated that buildings behave considerably differently (up to collapse) when previous events are considered than when only a single seismic event is considered.

There is a large amount of information related to the two aspects covered in this project (e.g. Revert et al., 2018; Chen et al., 2020; Di Sarno and Pugliese, 2020; Gopal and Sangoju, 2020; de Borbón et al., 2020; Liu et al., 2020; Xu et al., 2020); however, there are few studies on the combined impact that corrosion and accumulated damage have on structural vulnerability, and even fewer on the seismic risk of reinforced concrete (RC) structures (Biondini et al., 2015; Motlagh et al., 2020), which, over time and due to a lack of maintenance, have had their mechanical properties modified due to weathering.

In consequence, this study will not only provide a more accurate estimation of the seismic vulnerability of existing structures but also produce city-level maps that indicate the expected damage to buildings located in Mexico City soft soil zone. These maps will be a useful tool to identify which structures need immediate attention to minimise damage, thus protecting not only the buildings themselves but also the well-being of society and its normal quality of life.

2 METHODOLOGY

The proposed methodology for evaluating the effects of weathering and damage caused by previous earthquakes on the seismic vulnerability of structures begins by defining, in some detail, the characteristics of the buildings to be analysed: their location, the characteristics of the site where they are located and structural design based on the year they were constructed.

Later, to consider the previous seismic events that might have affected the studied structures seismic excitation is defined considering the most important earthquakes that have occurred from their construction until the date of evaluation. Besides, to compute the expected behaviour due to future earthquakes Incremental Dynamic Analyses (Vamvatsikos and Cornell, 2002) are performed. The ground motion records employed in the IDA's should realistically reflect the regional seismicity and site conditions, therefore, they must be obtained from areas with similar soil and seismo-genetic conditions. Simultaneously, an analytical model of the structures to be analysed is developed, which must adequately represent the expected structural behaviour.

At the same time, the effects of weathering on the structures are defined, which generally includes identifying the weathering mechanisms to which the structure may be subject, defining the rates of transport and diffusion of potentially aggressive substances in the structural elements based on their exposure, and estimating the effects of weathering mechanisms on the material properties.

Subsequently, the response of the analysed structures is obtained through the generated analytical models, which must include all the actions to which the structure is subjected (and that are intended to be considered in the analysis), as well as the various phenomena to be considered.

Next, a damage analysis is carried out on the structures, which involves numerically quantifying the damage to a structure or one of its components based on its response.

The methodology involves obtaining the seismic vulnerability functions of the analysed structures. This is achieved by determining loss levels (associated with the damage or performance states reached by the structure) based on the different values of seismic excitation intensity to which the structure is subjected.

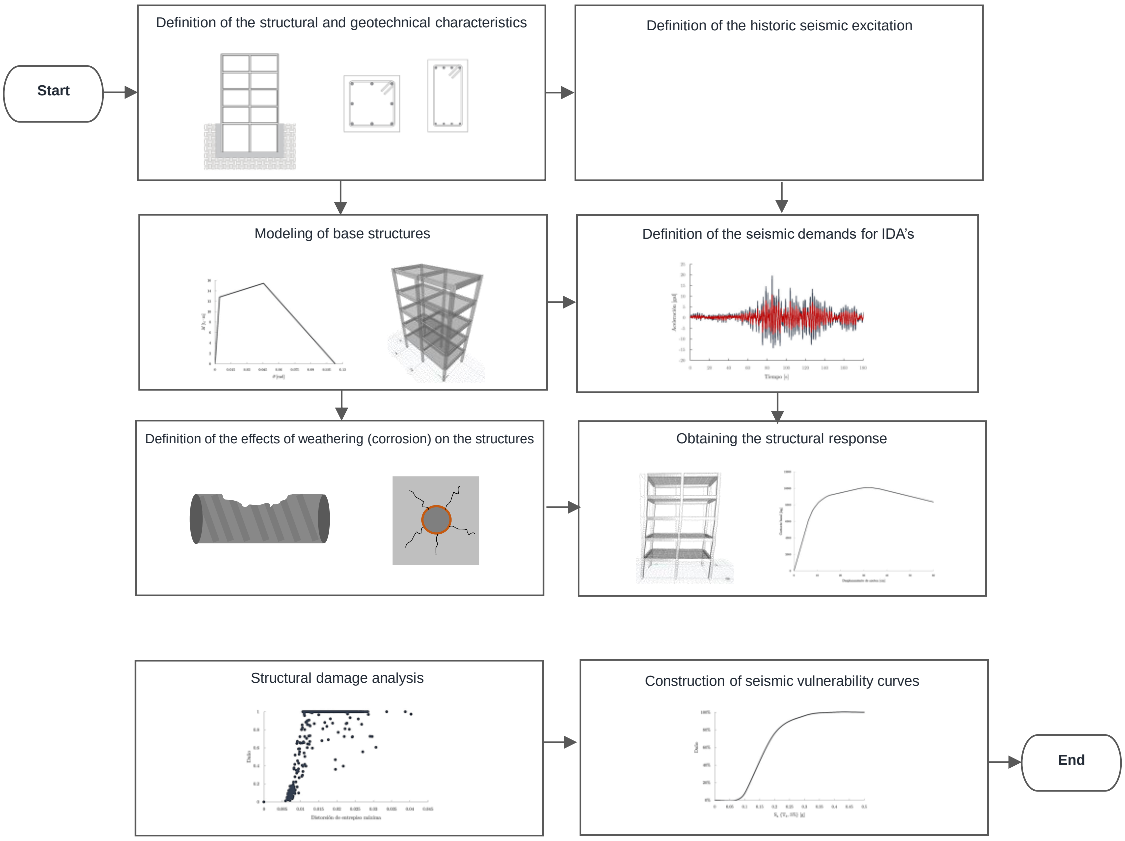


Figure 1: Flowchart of the proposed methodology.

3 CASE STUDY

To characterise the buildings in the area of interest, the soft soil building database for Mexico City, created by González et al. (2022) for the purpose of structural vulnerability studies, was used, specifically in the Cuauhtemoc borough (Figure 2). The database shows that the buildings located in this area are structured with frames and mostly have between five and seven storeys, with one to three bays, and were predominantly built before 2004. Three representative structures, assumed to have been constructed in accordance with the 1976 Mexico City Building Code (DDF, 1976) and their Complementary Technical Norms for the Design and Construction of Concrete Structures (DDF, 1977) for residential or office use, were analysed.

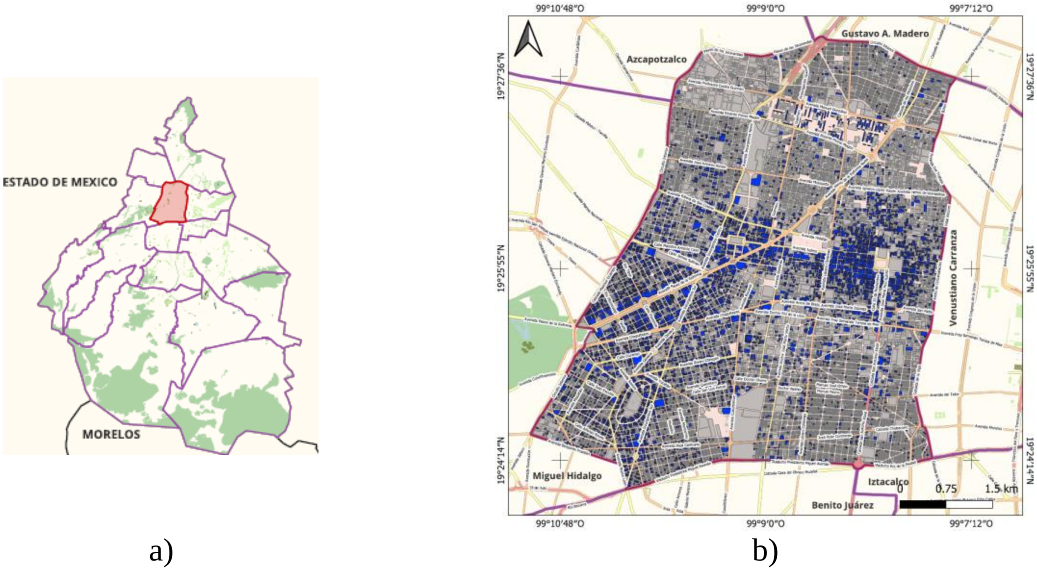
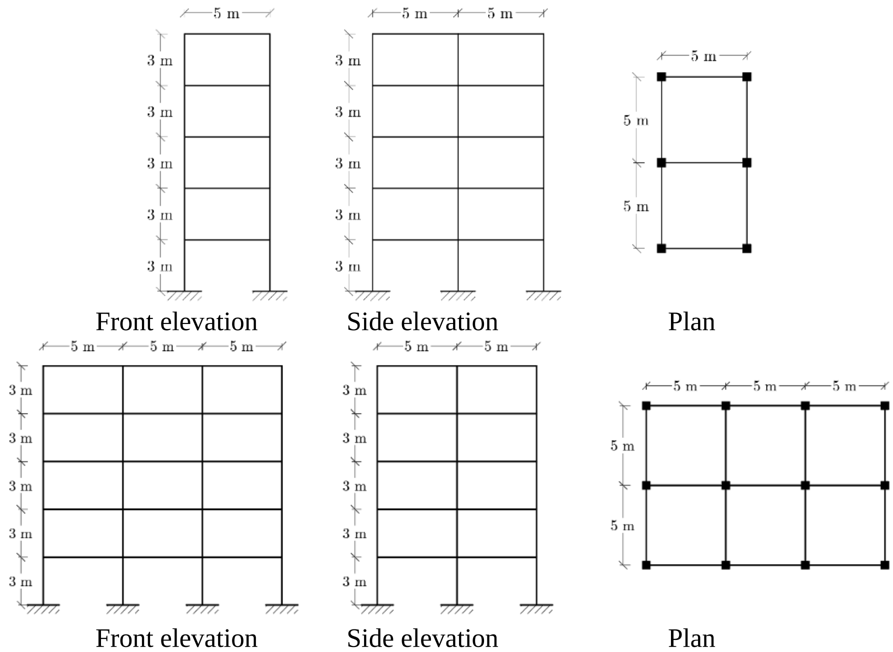


Figure 2: Area of study: a) Cuauhtemoc borough and b) studied buildings (blue)

3.1 Definition of the structural and geotechnical characteristics

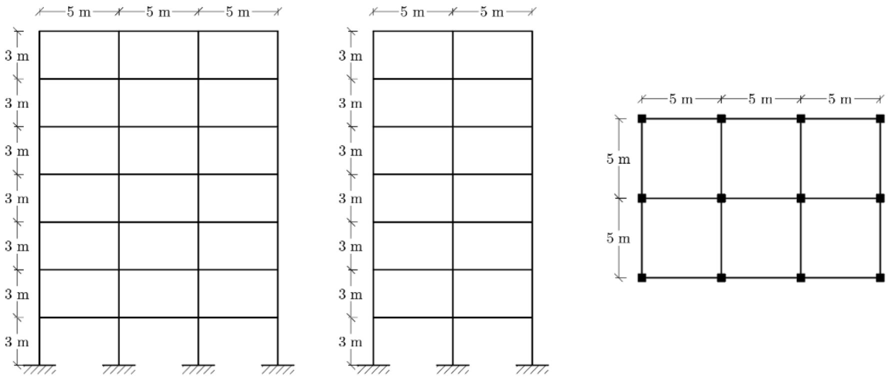
The index structures considered for the case studies were: 1) a five-story structure with one bay in one direction and two in its orthogonal direction (5S-1×2B), 2) a five-story structure with three bays in one direction and two in its orthogonal direction (5S-3×2B), and 3) a seven-story structure with three bays in one direction and two in its orthogonal direction (7S-3×2B). In all cases, bays of 5 m., in length and storey heights of 3 m., were considered. Figure 3 illustrates the global geometry configuration of the structures.

a)



b)

c)



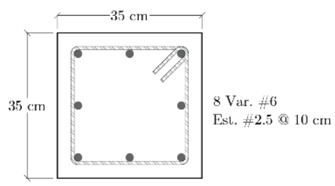
Front elevation Side elevation Plan

Figure 3: Global geometry configuration of the study structures: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B.

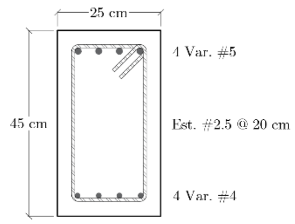
Given the lack of structural information on this type of buildings, their local geometric and mechanical characteristics were proposed through a structural analysis and design, in accordance with the abovementioned code and norms. Buildings were considered to be for residential/office use, and a ductility factor (Q) of 2 was adopted. The structures were designed assuming concrete with a compressive strength *f'c* of 250 kg/cm^2 and reinforcing steel (longitudinal and transverse) with a yield stress *fy* of 4200 kg/cm^2. The strong column-weak beam criterion was used in the design. Regarding the floor system, the use of two-way solid reinforced concrete slabs with a 10 cm thickness was considered in all cases.

Figure 4 shows the sections of beams and columns of the superstructure of buildings 5S-1×2B, 5S-3×2B, and 7S-3×2B. It is worth mentioning that, in the design of these elements, a 5 cm effective cover was considered in all cases.

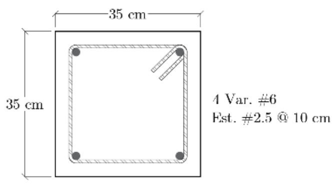
a)



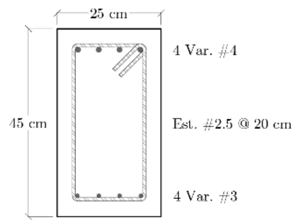
Columns, three lower stories



Beams, three lower stories

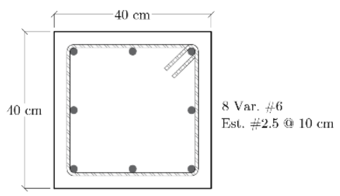


Columns, two upper stories

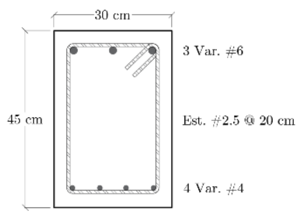


Beams, two upper stories

b)



Columns, three lower stories



Beams, three lower stories

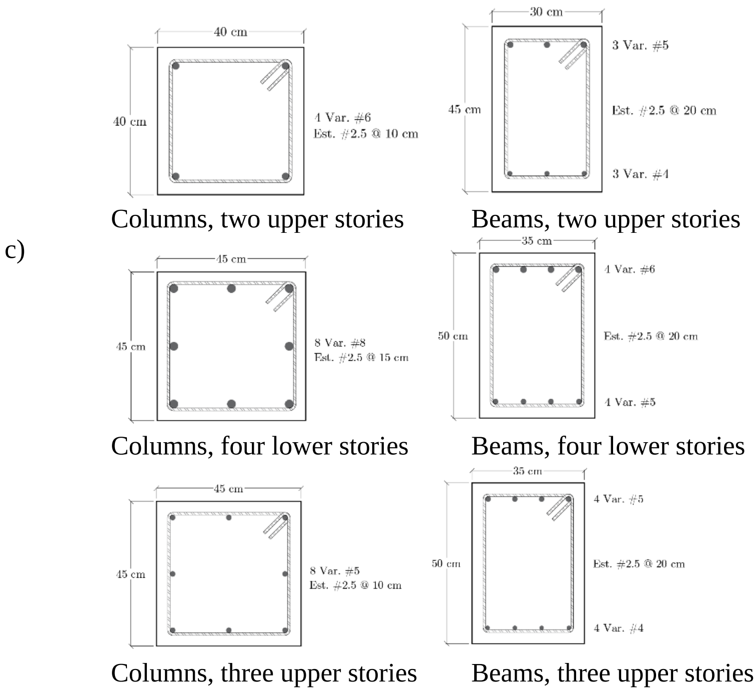


Figure 4: Cross section of the buildings elements: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B.

However, the structures were modelled as planar moment-resisting frames using the Open-Sees software (Open System for Earthquake Engineering Simulation) (McKenna et al., 2024) preserving the stiffness and the corresponding mass to maintain the fundamental vibration period in the direction of the analysis.

3.2 Definition of the seismic excitation

In this study, considering the economic conditions of the area under investigation, it is assumed that many private buildings were inspected but never retrofitted following an earthquake during their lifespan, as evidenced by a survey conducted with the residents. Therefore, the seismic demand is divided into two groups. The first group will be used to assess the current damage state of the studied structures, defined by two sets of ground motion records associated with 24 seismic events ranging from M6.5 to M8.1. These events are considered the most significant ones to have impacted the area since the buildings were constructed (Table 1). Each set of ground motion records corresponds to one of the two horizontal components (NS and EW) of seismic ground motion data obtained at the SCT station.

Date	Magnitude	Date	Magnitude	Date	Magnitude
19/09/1985	8.1	11/01/1997	7.1	18/04/2014	7.2
25/04/1989	6.8	19/07/1997	6.7	08/05/2014	6.5
24/10/1993	6.6	15/06/1999	7.0	19/09/2017	7.1
10/12/1994	6.6	30/09/1999	7.4	16/02/2018	7.2
14/09/1995	7.3	09/08/2000	7.0	23/06/2020	7.4
09/10/1995	8.0	21/01/2003	7.6	07/09/2021	7.1
24/02/1996	7.1	10/12/2011	6.5	19/09/2022	7.7
15/07/1996	6.6	20/03/2012	7.5	22/09/2022	6.9

Table 1: Seismic events employed to assess the current damage state

On the other hand, to compute the expected structural behaviour due to future earthquakes, were employed 100 accelerograms recorded on the ground surface, corresponding to the two horizontal components (NS and EW) obtained during the occurrence of different seismic events between 1985 and 2018 at different accelerographic stations (RAII-UNAM, 2018) in, or near the study area with the similar characteristic as the study site (Table 2).

Date	Magnitude	Station Code	Date	Magnitude	Station Code
19/09/1985	8.1	SCT1	21/07/2000	5.1	DFRO
25/04/1989	6.9	DFRO	21/07/2000	5.1	DFVG
25/04/1989	6.9	DFVG	21/07/2000	5.1	SCT1
25/04/1989	6.9	SCT2	09/08/2000	6.5	DFVG
31/05/1990	5.9	DFRO	08/10/2001	5.4	PMOS
15/05/1993	5.9	DFRO	22/01/2003	7.6	CAOE
24/10/1993	6.6	DFRO	22/01/2003	7.6	CAOO
24/10/1993	6.6	SCT2	22/01/2003	7.6	CAOT
23/05/1994	5.6	DFRO	22/01/2003	7.6	CLON
10/12/1994	6.3	DFRO	22/01/2003	7.6	JPSK
10/12/1994	6.3	DFVG	22/01/2003	7.6	PMOS
10/12/1994	6.3	SCT2	22/01/2003	7.6	PRJS
14/09/1995	7.2	DFRO	22/01/2003	7.6	PROM
14/09/1995	7.2	DFVG	22/01/2003	7.6	SCT1
14/09/1995	7.2	SCT2	13/04/2007	6.3	SCT2
09/10/1995	7.3	DFRO	22/05/2009	5.7	SCT2
09/10/1995	7.3	SCT2	11/12/2011	6.5	SCT2
15/07/1996	6.5	DFRO	20/03/2012	7.4	SCT2
11/01/1997	6.9	DFRO	16/06/2013	5.8	SCT2
11/01/1997	6.9	SCT1	21/08/2013	6	SCT2
15/06/1999	6.5	DFRO	18/04/2014	7.2	SCT2
15/06/1999	6.5	DFVG	08/05/2014	6.4	SCT2
15/06/1999	6.5	SCT1	08/09/2017	8.2	SCT2
21/06/1999	5.8	DFRO	19/09/2017	7.1	SCT2
30/09/1999	7.5	SCT1	16/02/2018	7.2	SCT2

Table 2: Seismic events considered to perform IDA

3.3 Modelling of base structures

The three base index structures, *i.e.*, without yet considering the effects of weathering (corrosion) and soil-structure interaction, were modelled through the OpenSees software (McKenna et al., 2021). To reduce computational time, the structures were modelled as two-dimensional moment-resisting frames. The modelled frames correspond to those shown in the front elevations in Figure 2.

To represent the behaviour of the structures through the different loading and displacement conditions to which they may be subjected, nonlinear models were used. The nonlinearity was modelled using the concentrated plasticity approach, through plastic hinges that adhere to the modified Ibarra-Medina-Krawlinker deterioration model with peak-oriented hysteretic response (Ibarra et al. 2005; Lignos and Krawlinker, 2013).

Once the base structures were modelled, the effects of weathering (corrosion) were defined.

3.4 Definition of weathering effects

Since the structures analysed are in an urban area and due to the atmospheric conditions of their location, the effects of weathering were represented through the phenomenon of corrosion due to carbonation of the structural elements. To determine the effects of weathering, the analysis of eighteen structures was considered derived from the proposed base structures, which characteristics and nomenclatures associated are shown in Table 3.

Nomenclature	Exposure time, *t* (years)	Effective cover, *r* [cm]
5S-1x2B, r = 3 cm, t = 0 years	0	3
5S-1x2B, r = 3 cm, t = 50 years	50	3
5S-1x2B, r = 3 cm, t = 80 years	80	3
5S-1x2B, r = 4 cm, t = 0 years	0	4
5S-1x2B, r = 4 cm, t = 50 years	50	4
5S-1x2B, r = 4 cm, t = 80 years	80	4
5S-3x2B, r = 3 cm, t = 0 years	0	3
5S-3x2B, r = 3 cm, t = 50 years	50	3
5S-3x2B, r = 3 cm, t = 80 years	80	3
5S-3x2B, r = 4 cm, t = 0 years	0	4
5S-3x2B, r = 4 cm, t = 50 years	50	4
5S-3x2B, r = 4 cm, t = 80 years	80	4
7S-3x2B, r = 3 cm, t = 0 years	0	3
7S-3x2B, r = 3 cm, t = 50 years	50	3
7S-3x2B, r = 3 cm, t = 80 years	80	3
7S-3x2B, r = 4 cm, t = 0 years	0	4
7S-3x2B, r = 4 cm, t = 50 years	50	4
7S-3x2B, r = 4 cm, t = 80 years	80	4

Table 3: Characteristics and nomenclatures of the eighteen structures proposed for the analysis of the effects of weathering (corrosion).

The effects of weathering on the structures were considered through the determination of five parameters, for each structural element: 1) the time it takes for the atmospheric carbon dioxide to reach the reinforcing steel (initiation time), 2) the percentage of corrosion of the reinforcing steel of the section, 3) the residual mechanical properties of the reinforcing steel (transverse and longitudinal) and the concrete of the section, and, 4) the effect of the modifications of the mechanical properties of the materials in the plastic hinge and elastic zone corresponding to that element.

To assess the effects of weathering, the side faces of the structural elements were categorised as exposed or covered, based on the element's position. The time (initiation time) for carbon dioxide to reach a specific rebar, whether longitudinal or transverse, was calculated using Fick's first diffusion law. The carbonation coefficient values applied are those reported by Moreno et al. (2016), which were derived from concrete specimens with a water/cement ratio of 0.65 exposed to weathering in Mexico City and are: 5.6 mm/year$^{1/2}$ for exposed side faces, and 5.1 mm/year$^{1/2}$ for covered side faces.

The corrosion percentage (i.e., the relative difference between the base and residual areas) of the reinforcing steel for a given section was determined. The residual steel area was calculated using the formula provided by Alonso et al. (1998), which is based on Faraday's laws of electrolysis. For the case studies in this paper, a carbonation corrosion rate of 0.5 μA/cm^2 was applied based on the information presented by Stefanoni *et al*. (2017) and considering the atmospheric conditions of Mexico City, and the assumed concrete characteristics.

The residual mechanical properties of the reinforcing steel for a section were derived using the semi-empirical expressions proposed by Rodriguez and Botero (1995) and Lee *et al*. (2009) for uniform corrosion (equations 1) and the parameters defined by Moreno-Herrera et al. (2023) and Lastra (2023).

$$E_{s(corr)} = \left[1 - 0.75\left(\frac{C_w}{100}\right)\right](E_s)$$
$$\varepsilon_{su(corr)} = \left[1 - 1.95\left(\frac{C_w}{100}\right)\right](\varepsilon_{su}) \tag{1}$$

where:

C_w, is the percentage of corrosion of the reinforcing steel, for a given section.

E_s and $E_{s(corr)}$, are the original and residual elastic modulus of steel, respectively.

ε_{su} and $\varepsilon_{su(corr)}$, are the original and residual ultimate strain of steel, respectively.

On the other hand, the residual compressive strength of concrete for a given section was obtained using the semi-empirical expression proposed by Shayanfar et al. (2016) for concrete mixes with a water-to-cement ratio of 0.5.

3.5 Structural response

After generating the models for the eighteen structures that account for only the weathering effects, their lateral response was obtained using the seismic record trains previously described. Following this, the incremental dynamic analysis (IDA) approach was applied.

In developing vulnerability functions, the chosen intensity measure is typically the parameter that most accurately represents the damage to each individual structure. Hazard studies allow for the identification of intensity parameters that have an impact on structures. In this paper, seismic intensity used to define vulnerability is measured in terms of spectral acceleration, which varies with different structural periods and is expressed as the elastic structural response for a specific damping factor using the spectral pseudo-acceleration corresponding to the structures fundamental period and a critical damping ratio of 5% (Sa).

From these analyses, it was possible to obtain the roof displacement, base shear, and interstory drifts of the studied structures at each time step. Thus, once all IDAs are performed to compute the structural response, interstory drift are used to define structural damage. For the sake of simplicity, Fig. 3 shows only results in terms of interstory drift *vs*. spectral acceleration for the three original buildings. In Figure 3, the solid black lines represent the average of all IDA performed; while the gray lines show the response to each seismic record employed in the IDA.

4 STRUCTURAL VULNERABILITY

Structural vulnerability refers to the potential damage or impact a property could experience if a hazardous event occurs. It is typically quantified as the average percentage of damage, or the economic cost required to repair the affected asset and restore it to its pre-event condition. Vulnerability is described using vulnerability functions, which show the probability distribution of losses based on the intensity of a specific event. These functions are represented as curves that link the expected damage value to the intensity of the hazardous event. For structures, vulnerability functions relate the mean damage ratio (denoted as β) to the event intensity.

In this paper, the global damage was characterised using a damage index. However, any quantitative or qualitative method of characterising damage could be employed, if a quantitative relationship is established between the damage index used and another measure of damage. This is feasible because damage indices can be utilised to assess the seismic vulnerability of existing structures and to design new earthquake-resistant buildings (Rodríguez, 2015).

The authors of this paper propose the use of a damage index defined by Teran-Gilmore and Jirsa (2005) DI_{TJ} (Eq. 2). This damage index ranges from zero to one, where zero indicates no damage and one represents total damage, or a complete loss of strength. The most well-known damage index is the one proposed by Park et al. (1987); however, it has the drawback of assigning values greater than zero for undamaged conditions and values exceeding one for complete damage, which is why it was not considered in this study, besides, DI_{TJ} model has the advantage that it was validated, in its conception, in systems located in Mexico City lake-bed zone.

$$DI_{TJ} = \frac{(2-b_{SMH})(a_{SMH})(E_{H\mu})}{2(r_{SMH})(\mu_u-1)(F_y)(d_y)} \tag{2}$$

$E_{H\mu}$, is the plastic energy, equal to the total area under all the hysteresis loops a structure undergoes during the ground motion.

μ_u, is the ultimate ductility capacity.

F_y, and d_y, are the yield strength and displacement, respectively.

b_{SMH}, is a structural parameter that characterizes the stability of the hysteretic cycle.

a_{SMH}, is a structural parameter that accounts for the energy content of the ground motion.

r_{SMH}, is a reduction factor that characterizes the cyclic deformation capacity of a system.

The parameters used in the model were derived from the IDA and pushover responses of the structural models. The plastic energy was calculated from the IDA response, while the yield strength, yield displacement, and ultimate displacement capacity were determined from the pushover response.

Figure 5 shows, as a reference, the dispersion of the points corresponding to the damage indexes as a function of the maximum inter-story drift of the original structures assuming a bar cover of 4 cm.

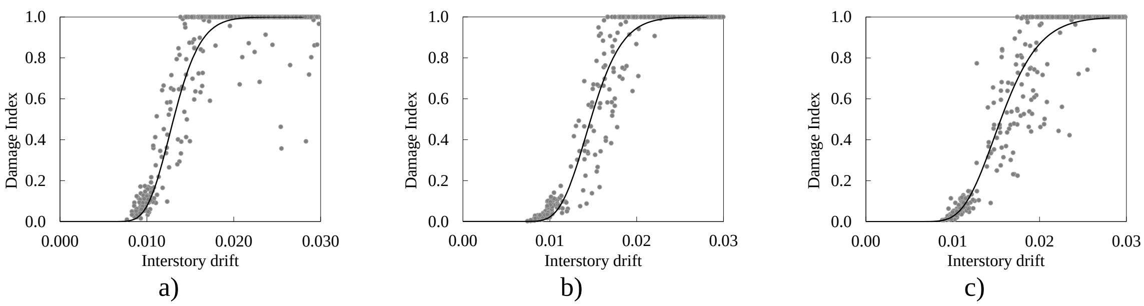


Figure 5: Damage indexes associated to the maximum interstory drift: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B for their initial conditions.

In this figure a non-linear regression (in solid black line) was employed to associate each interstory drift with a quantitative damage level. With the above results now is possible to correlate the expected damage in the structure and the employed seismic intensity parameter (Sa). Results of these relationships are presented in Figure 6 for the structures considered with the original properties (*i.e.*, those that are not affected by ageing and cumulative damage) where each curve might be considered as a vulnerability curve associated to a ground motion synthetic record.

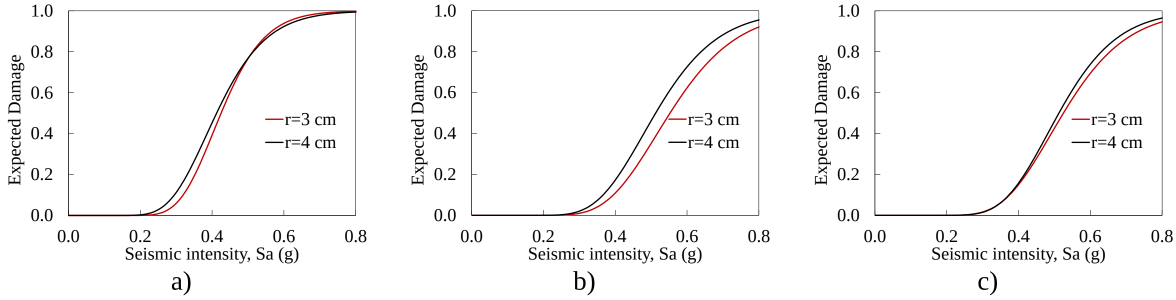


Figure 6: Vulnerability curves for original structures: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B for their initial conditions.

4.1 Ageing effect

Through statistical adjustment, vulnerability functions were derived based on the average values of the damage index previously calculated for the eighteen structures under study. As reference, Figure 7 presents the vulnerability functions of the structures the combinations of cover depth and exposure time considered in this study.

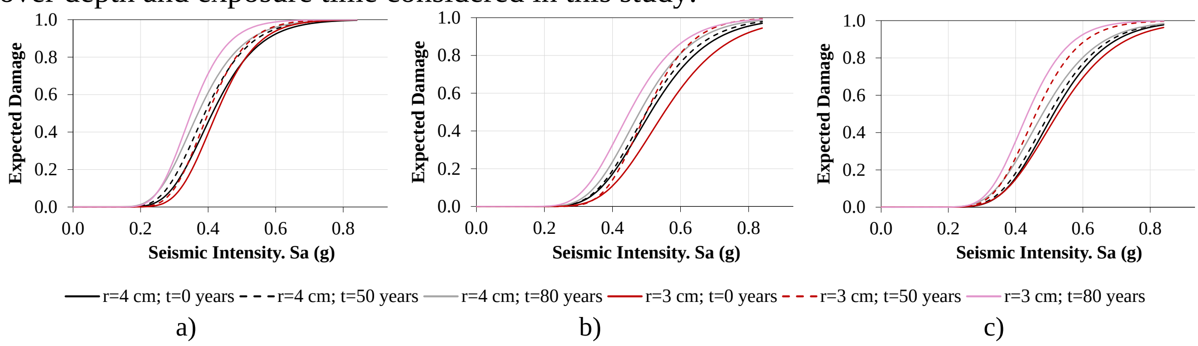


Figure 7: Vulnerability curves considering ageing effects: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B for their initial conditions.

In general, for structures with exposure time greater than the corrosion initiation time of their elements, a direct relationship was observed between their exposure time and their vulnerability, and an inverse relationship between the depth of cover of their elements and their vulnerability. Despite these tendencies, in general, only those structures with an element cover depth of 4 cm and an exposure time of 80 years present a relatively significant change in their vulnerability with respect to the vulnerability of the structures with the other combinations of cover depth and exposure time.

The case studies presented indicate an inverse relationship between the number of bays and levels within a structure and its vulnerability. This tendency is related to the capacity of the structures studied, which depends, of course, on their characteristics. It could also be related to their structural redundancy, which allows a redistribution of stresses once the plastic hinges begin to form.

4.2 Cumulative damage

It has been assumed that some moderate earthquakes might not produce important damages that diminish the strength capacity of the structure because the demanded lateral strength is considerably lower than the yield capacity; in addition, the recovery capacity of the society is poor due to economic aspects, therefore, many structures with small cracking remain with these minor damages unrepaired.

To take into account the above, a train of 24 earthquakes were used before performing the IDA to compute the expected damage on the studied structures.

Figure 8 shows the effect of the cumulated damage due to previous earthquakes and the carbonation (corrosion) on the vulnerability assessment.

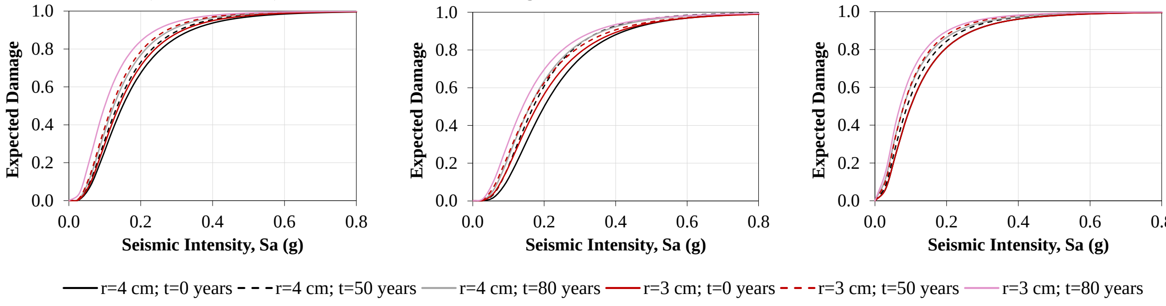


Figure 8: Vulnerability curves considering cumulative damage due to ageing and previous earthquakes: a) 5S-1×2B, b) 5S-3×2B, and c) 7S-3×2B for their initial conditions.

5 CONCLUSIONS

- This study examined the impact of weathering (carbonation) and cumulative damage due to the prior occurrence of earthquake events during the structure life-span on its seismic behaviour and vulnerability of reinforced concrete structures. The case studies focused on reinforced concrete framed structures located in the lake-bed area of Mexico City.
- In the case studies, an overall increase in the structures vulnerability was observed when carbonation effects were taken into account. These effects were nearly negligible for structures with a cover depth of 4 cm and an exposure time of 50 years. However, they were more significant for structures with combinations of cover depth and exposure time such as 3 cm and 50 years, 4 cm and 80 years, and particularly 3 cm and 80 years.
- It was observed that considering the cumulative damage due to previous earthquakes is important to assess the current capacity of the structures, mainly for those places as Mexico City where, due to the lack of economic resources, these minor damages are not repaired.
- While the most recent regulations in Mexico City define the depth of cover for structural elements to ensure adequate protection of reinforcing steel for at least 50 years across various exposure environments, older regulations were less stringent. As a result, structures designed under older standards are more likely to experience greater weathering effects due to potentially smaller cover depths and longer exposure times in addition of the micro-cracking produced by previous earthquakes.

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REFERENCES

[1] J. A. Moreno Herrera, R. Visairo Méndez, J. L. Varela Rivera, M. Balancán-Zapata and P. Castro Borges, Electrochemical Behavior of Reinforced Concrete Beams with Different Flexural Tensile Stresses in the Steel Reinforcement. *Corrosion of Reinforced Concrete Structures*, 79(4), 440-448, 2023.

[2] A. Lastra, Constitutive Stress-Strain Model for 10 mm Diameter Steel Bars Subjected to Corrosion Conditions. *Master thesis*, Faculty of Engineering, Autonomous University of Yucatan, 2023.

[3] DDF. (1976). Federal District Building Code, Federal District Official Gazette. (In Spanish)

[4] DDF. (1977a). Complementary Technical Norms for the Design and Construction of Concrete Structures, Federal District Official Gazette. (In Spanish)

[5] González, R., González, M., Niño, M. (2022). "Creation of a database of buildings on soft ground in Mexico City for structural vulnerability purposes". XXIII National Congress on Earthquake Engineering, Juriquilla, Mexico. (In Spanish)

[6] McKenna, F., Fenves, G. L, Scott, M. H. (2021). Open System for Earthquake Engineering Simulation (OpenSees) (Versión 3.3) [Software]. University of California, Berkeley. http://opensees.berkeley.edu

[7] Terán, A., Jirsa J. O. (2005) "A damage model for practical seismic design that accounts for low cycle fatigue". Earthquake Spectra, 21(3), 803-832.

[8] Vamvatsikos D, Cornell CA (2002) Incremental dynamic analysis. Earthquake Engineering & Structural Dynamics, 31(3), 491-514.

[9] Rodríguez M (2015) Evaluation of a proposed damage index for a set of earthquakes. Earthquake Engineering and Structural Dynamics, 44, 1255-1270.

[10] Park YJ, Ang AH, Wen YK (1987) Damage-limiting aseismic design of buildings. Earthquake Spectra, 3(1), 1–26.