CUMULATIVE DAMAGE OVER TIME OF 2D-FRAMES SYSTEMS SUBJECTED TO MULTIPLE LONG-DURATION RECORDED EARTHQUAKES IN THE LAKEBED ZONE OF MEXICO CITY

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Abstract

The globally accepted approach to seismic-resistant design states that structural damage should be minimized for frequent, low-intensity events, and that collapse and irreparable damage should be avoided for rare high-intensity ones. While there are broader structural design analysis criteria, such as performance-based design, most design regulations require estimates of the dynamic response of earthquake-resistant systems, and for their evaluation, they include prescribed values of relevant parameters, such as maximum displacement. However, there is evidence that, in certain circumstances, the response of a single parameter may not be a good indicator of structural damage, particularly in the case of long-duration earthquakes, aftershock sequences or, as is the case with soft soil sites in Mexico City, where intense and long-duration earthquakes occur every 10 to 20 years. These events generally lead to the failure of structural elements at deformation levels that are significantly lower than those established for monotonic loading. This is because the amount of dissipated energy accumulated during the earthquake, and, even more, due to several intense long-duration earthquakes during their lifespan. From this, it is necessary to answer: which is the accumulated damage of a structure during its useful life? How does structural vulnerability change after an earthquake? How many intense earthquakes a structure can withstand during its lifespan to ensure any desired level of behavior?

This article analyzes the seismic demands of input energy, hysteretic energy and normalized hysteretic energy in Mexico City, based on September 19, 2019 earthquake (Mw7.1) that caused serious damage to hundreds of buildings. Likewise, the cumulative damage over time, in terms of dissipated plastic energy, is analyzed for a twelve-story 2D-frame system using the strong ground motion records of the network in the lakebed zone of Mexico City gathered during the last 35 years. From this, the time-changing vulnerability and the residual strength of structures is evaluated. These types of results are necessary to improve the seismic risk assessment of buildings and infrastructure in Mexico City.

Keywords: cumulative damage, seismic-resistant design, structural vulnerability, dissipated plastic energy

1. Introduction

Structural damage reported during intense earthquakes produced human and economic losses in many ways in the affected areas. This has been evidenced after strong ground motions worldwide, such as Mexico 1985, Northridge 1994, Kobe 1995, Taiwan 1999, Chile 2010, Japan 2011, Ecuador 2016, Mexico 2017, among others. The adequate estimation of damages can effectively help decision-makers in the development of necessary risk mitigation actions.

On September 19, 2017, Mexico intraslab-earthquake, whose epicenter was located between the limits of the states of Puebla and Morelos, 120 km from Mexico City [1], severe damage was reported in cities close to the epicenter. Only in Mexico City, 44 buildings collapsed, and more than 800 were seriously damage, of which, 93 have been demolished or have been ordered to do so (GCDMX, 2019).

As was evidenced during the two most intense earthquakes recorded in Mexico City (September 19, 1985, and 2017 earthquakes), the cumulative damage due to low-cycle fatigue could be playing a crucial role in the structural response. A structural system may undergo severe plastic deformations during intense seismic events and may suffer structural damage at lower intensities than the design one. Traditional design concepts, where strength and displacements are the main control parameters, are not enough to consider low-cycle fatigue. Moreover, the cumulative damage could be more significant when a sequence of strong ground motion is analyzed.

Most of the seismic regulations have exclusive adopted an isolated and rare “design earthquake” while the influence of cumulative damage due to a sequence of severe earthquakes has been ignored. This is crucial in zones with long-dominant soil periods such as the bay zones of San Francisco and Tokyo [2], and even more in the lakebed of Mexico City, where narrow-banded and long-duration ground motions occur every 10 to 20 years.

An alternative to current design methodologies is an energy-based seismic design approach that considers ground motions characteristics such as duration, frequency content, and energy [3], [4], [5], [6], [7]. The energy spectra could relate damage to structural performance since it considers hysteresis cycles and duration, for complete ground motion records. One of the advantages of using energy as a design parameter is that the duration, the number of inelastic cycles and the dynamic instability, can be considered directly and explicitly [8].

In this article, we start presenting the hysteretic energy demands for the September 19, 2017 earthquake, and its relationship with the structural damage reported during the earthquake. Then, we analyze cumulative damage over time of a steel 2D-frame located in the lakebed zone of Mexico City to a sequence of actual severe intense earthquakes recorded in Mexico City during the last 35 years. The objective is to study the plastic demands to which this type of structures has been subjected, and the corresponding structural degradation and the available solutions to increase its seismic resilience.

2. Hysteretic energy demands of the September 19, 2017 earthquake

Damage reported during any earthquake depends not only on the peak accelerations recorded but on the duration, frequency content, and energy dissipation. Structural damage is associated with the plastic behavior of the system, which could be studied from the hysteretic energy dissipated by a structure during an earthquake ($E_{H\mu}$). In this section, we show the spectral intensities distribution of $E_{H\mu}$ in Mexico City during the September 19, 2017 earthquake. For this, we use single-degree-of-freedom (SDOF) systems with elasto-perfectly-plastic behavior and a 5% of viscous damping.

Fig. 1 shows the interpolated hysteretic energy ($E_{H\mu}$) spectral demands of all 77 accelerometric stations that recorded the September 19, 2017 earthquake, for a ductility of μ=3.0 and structural vibration periods of T=1.0, 1.5, 2.0 and 3.0s. Due to the amount of information only some representative accelerometric stations are shown in the maps. In the charts are also included the damaged buildings, classified according to their level of damage.

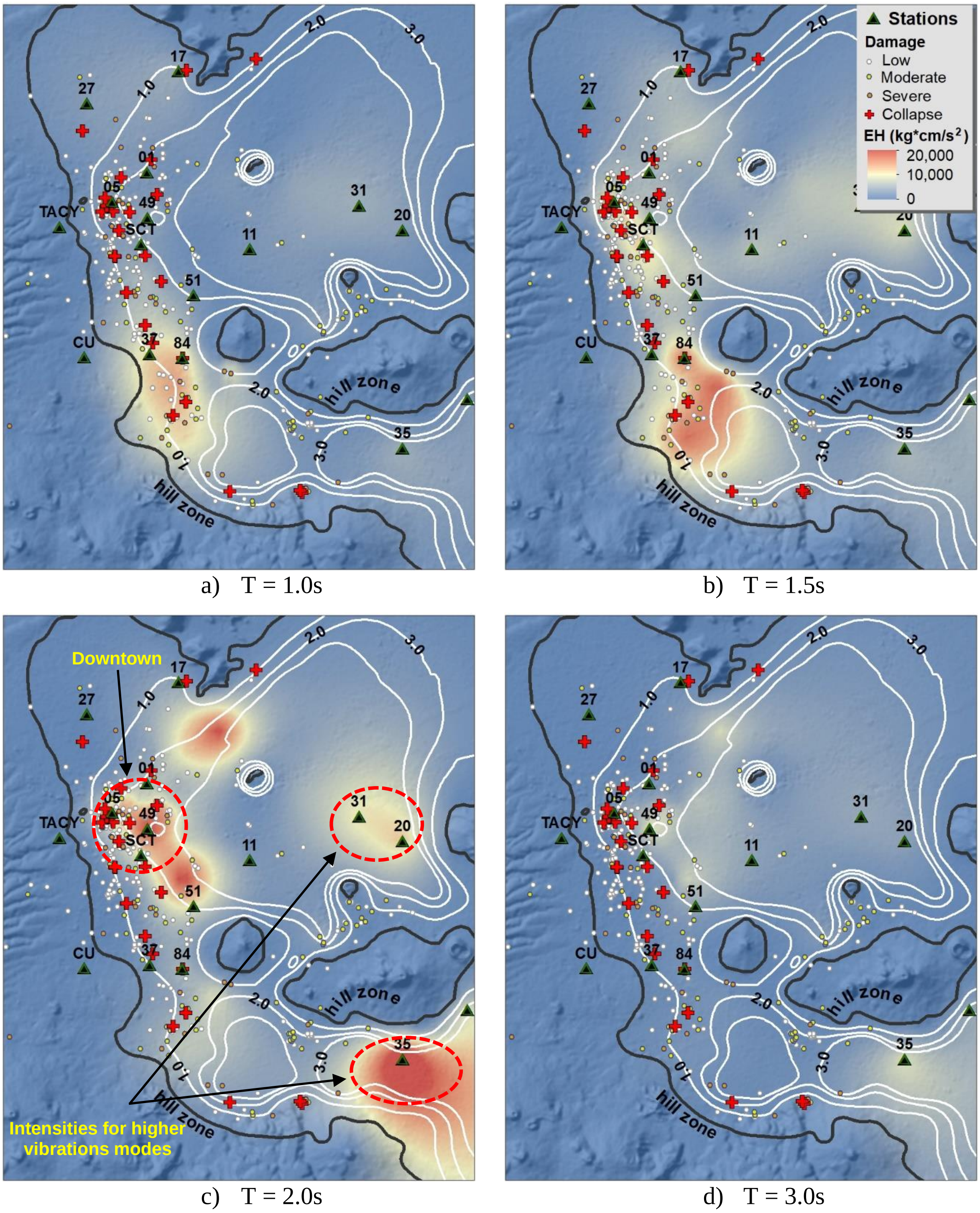


Fig. 1 – Hysteretic energy maps for the September 19, 2017 earthquake, for an elasto-perfectly plastic behavior, ductility $\mu = 3.0$ and for four different structural periods. For comparison purposes, all maps have been plotted with the same scale. In each figure, the contours lines represent the soil periods of the lakebed area (Figures adapted from [9]).

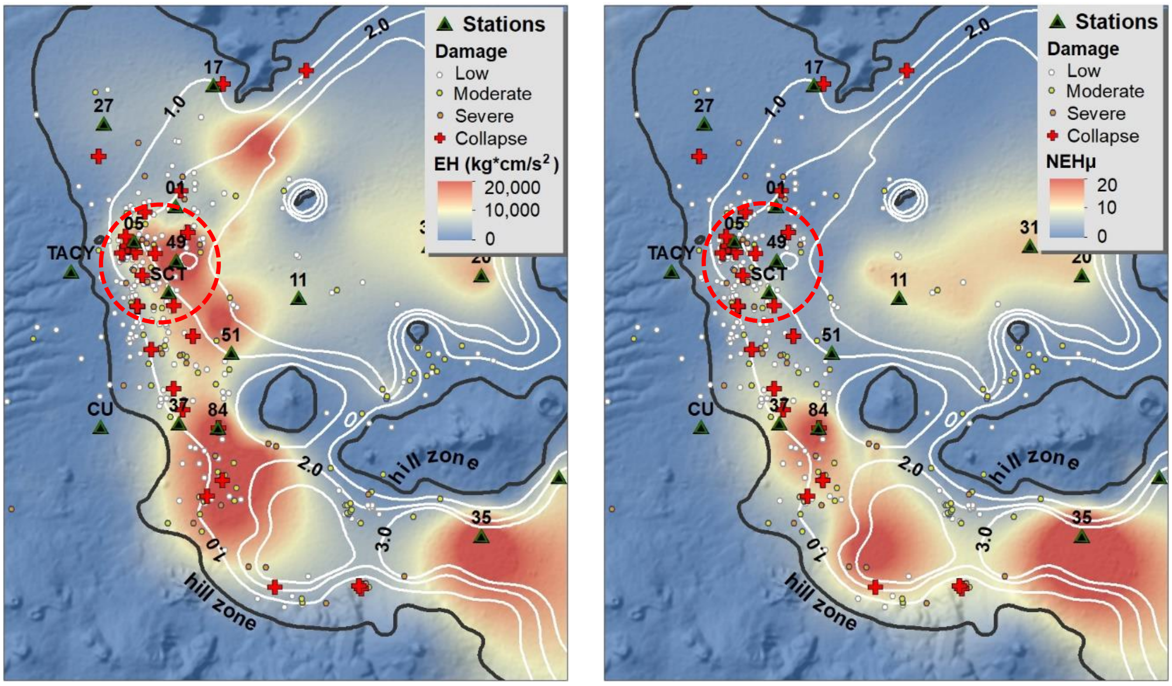
As shown in Fig. 1, the hysteretic energy demands are large for some areas with soil periods between 1.5s and 2.0s (Figure 1b and 1c), due to the characteristics and frequency content of the 2017 earthquake. There are areas with very deep clay-layers, with large dominant soil periods (Tg~5s), where the demands of $E_{H\mu}$ are considerable for T=2.0s, such as in and around stations 35, 20, and 31 (Figure 1c). In these stations, the large intensities for T=2s correspond to higher vibrations modes of the soil [9]. Although there is a considerable density of accelerometric stations in the city, the soft-soil behavior in Mexico City varies significantly within dozens of meters due to the clay depth, so detailed intensity information may not be entirely captured by the triangulation scheme used for interpolation. A particular interpolation scheme ([10], [11]) should be used to obtain a reliable and definite intensity map, which is beyond the scope of this article.

Although hysteretic energy ($E_{H\mu}$) defines the amount of energy that a system must dissipate, it does not contain enough information to fully associate it with structural damage since the total dissipated energy could be similar for two or more different structural responses [12]. Due to this, it is convenient to use the normalized hysteretic energy, which can be used to quantify the severity of plastic energy demands:

$$NE_{H\mu} = \frac{E_{H\mu}}{F_y x_y} \tag{7}$$

where F_y and x_y are the strength and displacement at first yield, respectively, and whose values for different SDOF systems were obtained from Mexican seismic regulations [13].

Fig. 2 shows maps where it is possible to compare between both intensities $E_{H\mu}$ and $NE_{H\mu}$. The intensities are associated with the peak energy distribution, no matter at which vibration period (maximum envelope demands), for a ductility μ = 3.0. As can been seen, structures in the downtown area (shown inside the circle in both maps of Fig. 2), despite the significant plastic demands (Fig. 2a), did not experience large normalized hysteretic plastic cycles (Fig. 2b). However, severe building damage was reported in this area, although, this could be due to a different structural problem.



a) Hysteretic energy b) Normalized hysteretic energy

Fig. 2 – Comparison of the hysteretic energy and normalized hysteretic energy intensities for a ductility of $\mu = 3.0$. The maps correspond to the envelope of maximum demands, regardless of the vibration period. Buildings with reported damage are also shown with small circles (Figure adapted from [9]).

2. Cumulative damage assessment

Most seismic regulations require estimates of the dynamic response of earthquake-resistant systems and, for their evaluation, they use prescribed values of relevant parameters, such as maximum displacement. Under certain circumstances, the response of a single parameter may not be a good indicator of structural damage. This is particularly true in the case of long-duration ground motions, in sequences of intense aftershocks or, as is the case of Mexico City lakebed zone, where severe and long-duration earthquakes occur every 10 to 20 years. These events generally lead to the failure of structural elements at deformation levels that are significantly lower than those established for monotonic loading, due to the accumulated energy dissipated during each ground motion.

2.1 Analysis of seismic demands

To study the cumulative damage and residual capacity of a structure located in the Mexico City lakebed, we analyzed the last 35 years of earthquake-history at the SCT accelerometric station, located in the lakebed zone (Tg=1.9s). Table 1 shows the characteristics of the most intense earthquakes that have been recorded in SCT since 1985.

Table 1. List of the most intense strong ground motions recorded in Mexico City since 1985

ID	Event	Magnitude (Mw)	Fault type	Epicentral distance (km)
E1	19/09/1985	8.0	Subduction	394
E2	25/04/1989	6.9	Subduction	303
E3	24/10/1993	6.6	Subduction	299
E4	10/12/1994	6.4	Subduction	288
E5	23/05/1994	6.2	Normal	206
E6	14/09/1995	7.3	Subduction	320
E7	15/06/1999	6.9	Normal	218
E8	21/06/1999	6.3	Normal	295
E9	30/09/1999	7.4	Subduction	420
E10	21/07/2000	5.8	Normal	136
E11	22/05/2009	5.6	Subduction	157
E12	20/03/2012	7.4	Subduction	335
E13	19/09/2017	7.1	Normal	130

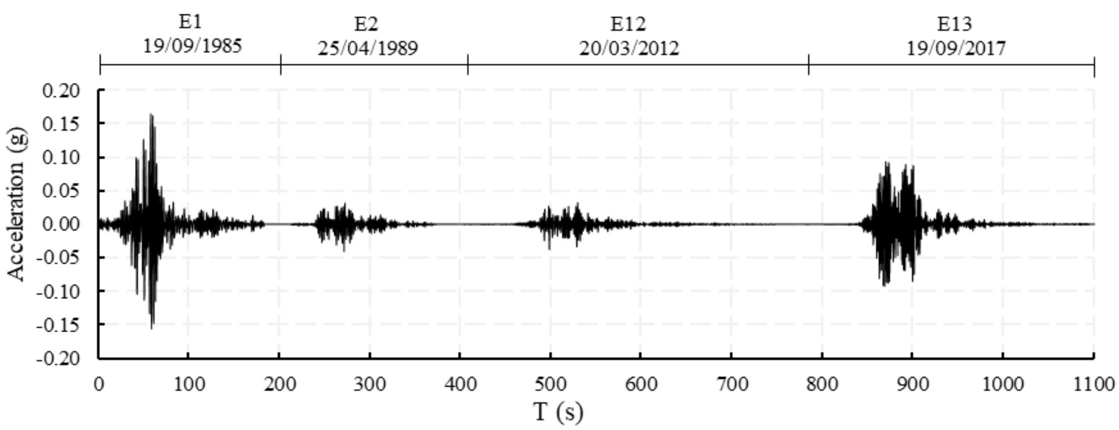


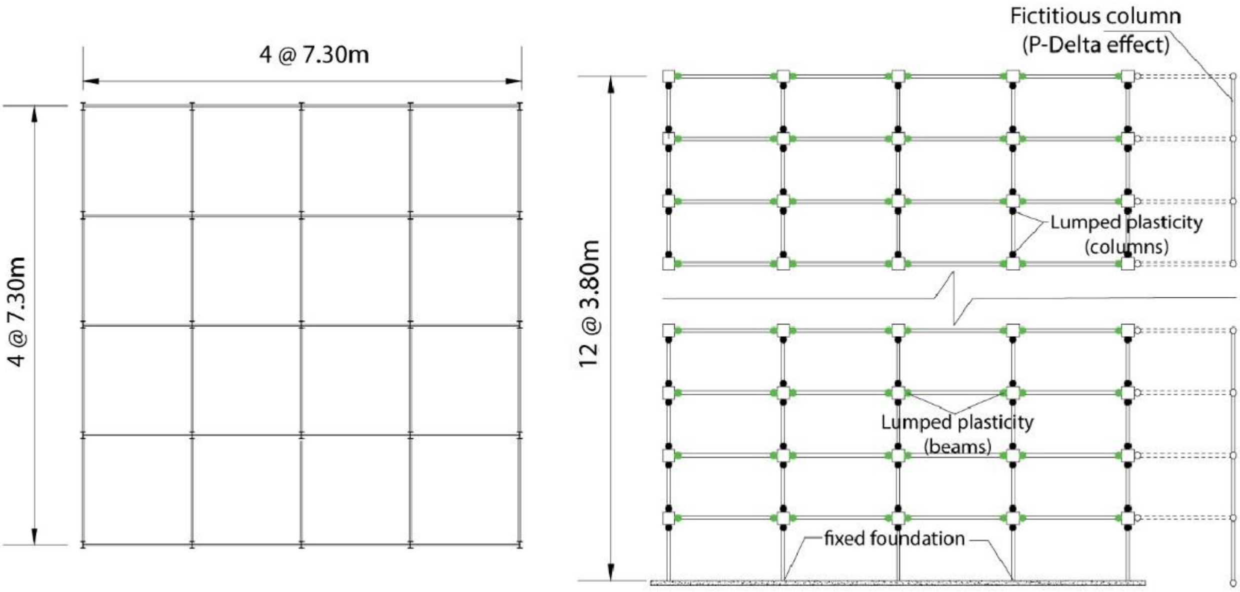
Fig. 3 – Seismic sequence for station SCT (Tg=1.9s)

Out of these thirteen events, only four reported damage in the city: earthquakes E1, E2, E12, and E13 (Table 1). These earthquakes were used to study the accumulated damage in a hypothetical structure located there.

The frequency content and amplitude of the individual records within the sequence shown in Fig. 3, can be significantly different. This agrees with what was stated in previous works ([14], [15] and [2]), that it may not be accurate to consider acceleration sequences with identical frequency content.

2.2 Description of the structural model

In this study, a 2D-Frame building subjected to multiple long-duration narrow banded strong ground motions recorded in SCT station of the lakebed zone of Mexico City was analyzed. The plan view and elevation of the frame is shown in Fig. 4, and corresponds to a 12-story steel-frame building. The lateral strength was designed using the Mexican seismic standards for a Q=3.0 [11]. In terms of defining the design spectra, Q can be considered the maximum ductility demand, in such a manner that Q=1 implies elastic behavior; the maximum Q value allow by the code is 4.0. The analyzed frame belongs to a building following a design similar to one already studied [16], with four steel-frames in each orthogonal direction, as shown in Fig. 4a. The 2D-Frame was modeled in OpenSees [17], and was idealized with concentrated plasticity approach using the Modified Ibarra-Medina-Krawinckler (IMK) behavior model that considers strength and stiffness deteriorations of steel components [18]. Rotational springs, located at the plastic hinge regions, are used to model the nonlinear behavior of the columns and beams. For the structural damping behavior, the Rayleigh damping model was used, assigned only to the elastic column and beam, using a viscous damping ratio of 5%. The mass-proportional was assigned to all the frame-nodes using the methodology discussed by [19]. Additionally, a fictitious column was added to the model to considerer the P-Delta effect. This column was connected to the main structure using axially rigid truss elements. The cross-sections are shown in Table 2.



a) Plan view b) Elevation

Fig. 4 – Schematic of 12-story steel building: a) plan view, and b) elevation

In addition, the frames were designed to meet a weak-beam/strong-column criterion according to a capacity design approach. From a modal analysis, it was found that the first two vibration modes of the frame were 1.45s and 0.8s.

2.2 Cumulative damage analysis

The response of the 2D-frame was analyzed at the end of each of the next sequences: a) E1, b) E1+E2, c) E1+E2+E12 and d) E1+E2+E12+E13. For each sub-sequence the hysteretic behavior, displacement time-history and the frame capacity were obtained. The cumulative damage was determinate from the normalized hysteretic energy (Eq. (1)). Fig. 5 shows the displacement time-history at the end of each earthquake sequence.

Table 2. Cross sections for structural elements

Columns			Beams		
Axis	**Story**	**Section**	**Axis**	**Story**	**Section**
Exterior	1-3	W14x193	All	1-3	W30x99
	4-6	W14x159		4-6	W27x94
	7-9	W14x109		7-9	W27x94
	10-12	W14x74		10-12	W24x76
Interior	1-3	W30x173			
	4-6	W27x146			
	7-9	W24x104			
	10-12	W21x68			

As can be seen in Fig. 5, the 1985 and 2017 earthquakes reach the largest displacement and, in both cases, there are considerably residual deformations. To analyze the accumulated damage, besides the displacements, the dissipation of plastic energy during each earthquake was analyzed.

Fig. 6 shows the hysteretic behavior of the 2D-frame at the end of each earthquake. To analyze the cumulative damage, the final conditions of the structure after each earthquake are used as the initial one for the analysis of the next earthquake sequence. Thus, the stiffness and strength degradation of the structure is considered over-time. The accumulated area of each chart represents the dissipated plastic energy.

As shown in Fig. 6, the structure remained elastic during the 1989 earthquake, and had a slight hysteretic behavior during the 2012 earthquake. By contrast, the earthquakes of 1985 and 2017 caused considerable damage to the structure showing large displacements and high-energy dissipation.

To show the cumulative damage throughout the entire earthquakes sequence, the normalized hysteretic energy was calculated, accumulating the responses for all earthquakes. Figure 7 shows this cumulative normalized hysteretic energy, $NE_{H\mu}$, which could be directly related to the structural damage since this energy represents the dissipated plastic energy. These large cumulative demands are observed in all stations in the lakebed zone, so the cumulative damage must be considered in the vulnerability assessment of old buildings in order to mitigate the seismic risk and increase the resilience of Mexico City.

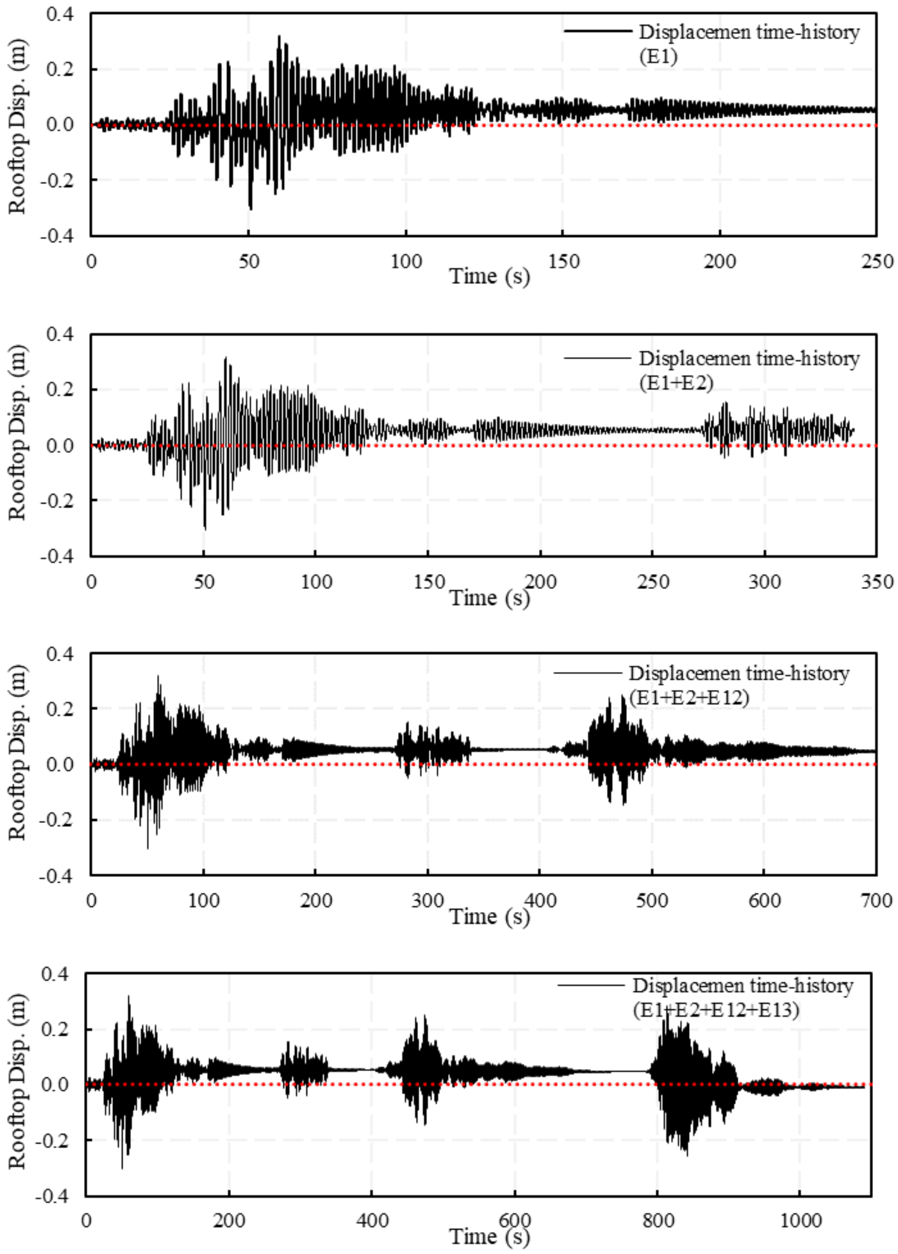
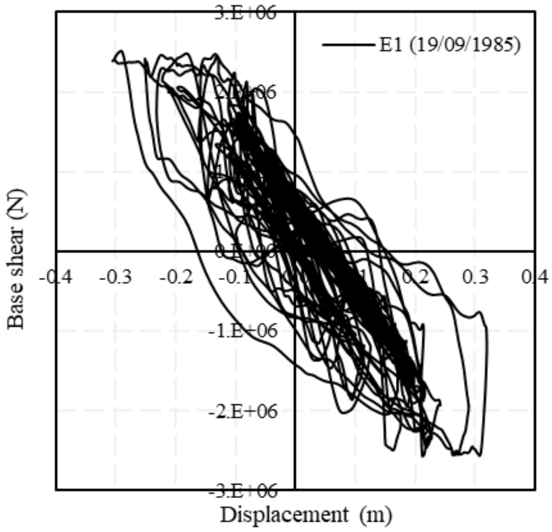
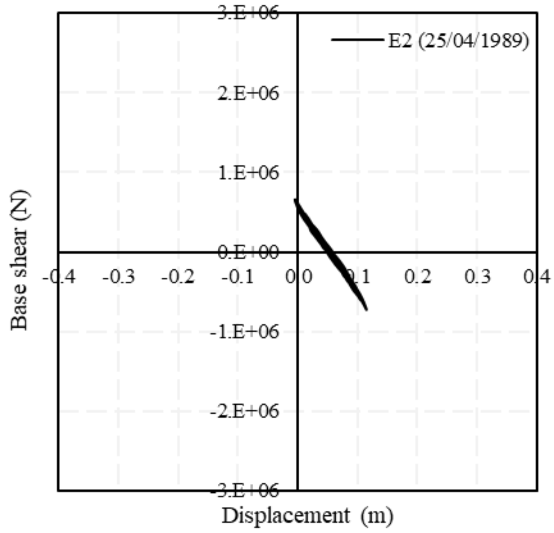


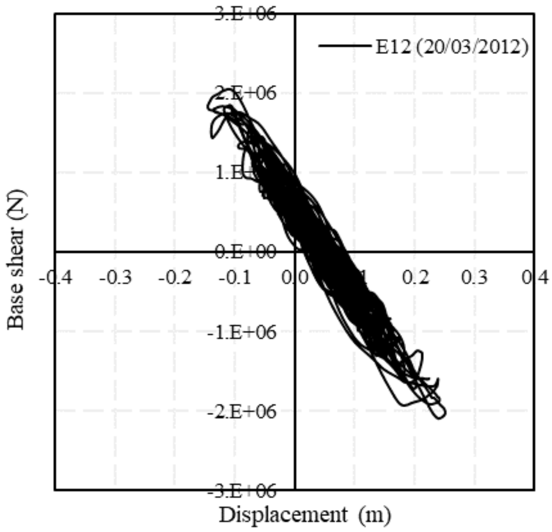
Fig. 5 – Cumulative displacement time-history for the rooftop of the 2D-frame



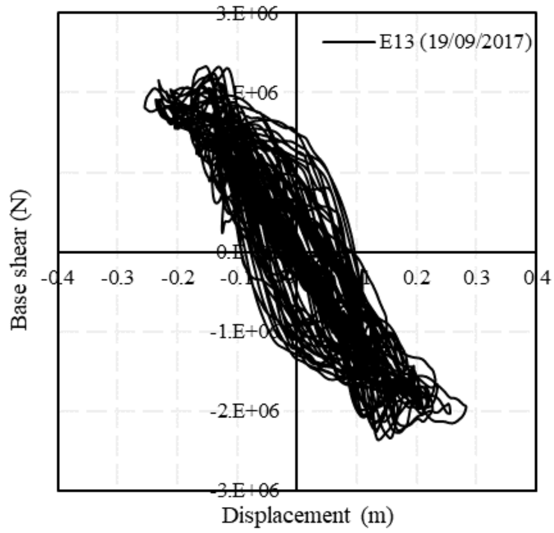
a) Hysteretic cycles for E1



b) Hysteretic cycles for E2



c) Hysteretic cycles for E3



d) Hysteretic cycles for E4

Fig. 6 – Cumulative displacement time-history at the rooftop of the 2D-frame

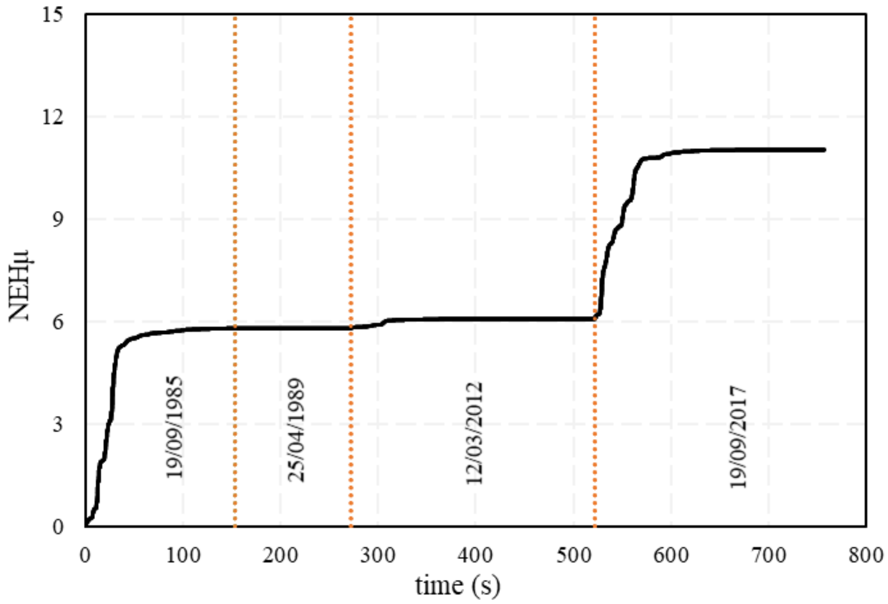


Fig. 7 – Cumulative normalized hysteretic energy ($NE_{H\mu}$) time-history for the 2D-frame, for the four intense earthquakes reordered in SCT. The earthquakes are: 19/09/1985 (Mw8.0), 25/04/1989 (Mw6.9), 12/03/2012 (Mw7.4) and 19/09/2017 (Mw7.1)

4. Conclusions

Few sites worldwide are affected by so many intense and long-lasting earthquakes in such a short time. The cumulative damage has been studied previously, however, few efforts have focused on the particular problem facing lakebed zone sites such as Mexico City. The objective of this article was to analyze the behavior of hysteric energy in the Valley of Mexico during the 2017 earthquake, and show the problem of the cumulative damage over time, so these issues could be considered in future seismic standards updates and public policies of Mexico City.

The seismic resilience of existing structures in Mexico City decreases considerably for structures built before 1985 (the year in which the seismic regulations were modified accordingly to the recorded site effects during the Michoacán earthquake). Besides, being designed with less rigorous seismic-standards, the cumulative damage that old structures have been experiencing over the last 35 years is very large, comparable only, and even larger, to the plastic energy dissipated during the most intense earthquakes recorded worldwide.

Likewise, to increase the seismic resilience in Mexico City, it is necessary to consider the cumulative damage that a structure has presented due to the high frequency of intense earthquakes. It is therefore required to consider this degradation in the structural vulnerability studies and projects, and to retrofit the poorly designed (old standards) and fatigued structures due to the cumulative damage.

5. Acknowledgements

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