CONVENTIONAL EARTHQUAKE RESISTANT DESIGN AND CUMULATIVE DAMAGE. THE CASE OF THE MEXICO CITY SEPTEMBER 2017 EARTHQUAKE

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Abstract

This research studies the observed severe damage and collapse of buildings during the 19 September 2017 earthquake in Mexico City. The major part of these damage and collapses were in RC frame buildings with less than 10 stories, which also experienced the 19 September 1985 earthquake in Mexico City. This study shows that the spectral demands for earthquake ground motions recorded in 1985 and 2017 in the affected area were comparable, and the demands in 2017 were smaller than the demands specified by the building code in Mexico City at the time of the 2017 earthquake. These study intents to explain why the damaged or collapsed buildings in 2017 experienced the 1985 earthquake without considerable damage. The study uses a damage index, I_d, previously proposed by the author, which considers the concept of cumulative damage. This index is defined either as the ratio of a hysteretic energy and an elastic energy or as a ratio of an equivalent velocity square and a linear elastic pseudo-velocity square. This damage measure is aimed at determining the damage potential of a ground motion, on average, for a regional stock of a particular building type. Results of this study indicate that the effect of cumulative damage in buildings subjected to subsequent earthquake ground motions explains the observed severe damage and collapses of buildings during the 2017 earthquake. Recommendations are given for possible improvements of seismic building codes in Mexico. This study concludes that is convenient limiting the use of frame buildings in seismic prone areas and recommends the use of wall buildings for significantly reduce the damage potential or collapses of buildings in strong earthquakes.

Keywords: building damage and collapse, Mexico City earthquakes, cumulative damage, building code

1. Introduction

On 19 September 2017 Mexico City experienced an earthquake with epicenter at 120 km from the city. This earthquake was of the intraplate type, and had a magnitude M_w equal to 7.1. As a result of this event, about 50 buildings either collapsed or were in a stage near collapse, with about 200 casualties, and several hundreds of buildings had moderate or severe structural damage. As September 2019, Mexico City officials stated that out of about 430 residence buildings that needed rehabilitation, only 43 buildings were completely rehabilitated at that time. Most collapsed or severely damaged buildings were Reinforced Concrete (RC) frames, which had less than 10 stories. Statistics of damage evaluation [1] show that these buildings were constructed before 1985; i.e., these buildings also experienced the M_w 8.1 earthquake on September 19, 1985 in Mexico City, with little or no observed damage in that earthquake in most cases.

The buildings with damage or collapse in the 2017 event typically were of the frame type, in most cases constructed with masonry infilled frames, and in several cases, they had a "soft story" at the ground level due to the need for parking space. These frames also had low lateral stiffness (if ignoring the contribution of infilled frames or when considering the street's direction), and in several cases, this stiffness was exhausted during the earthquake. In addition, the damaged buildings contained reinforcing details that were less stringent than those currently required in international building codes, such as those specified in ACI 318-19 [2], because in its current and past versions, the Mexico City Building Code [3] allows designers to use poor reinforcing detailing with the argument that such low ductility structures are designed with higher values of seismic forces compared with the seismic design forces assumed for ductile structures. It is of particular interest that typically low ductility structures are favored by designers in Mexico.

Fig. 1 shows a map of equal soil periods with the distribution of observed collapses (blue marks) for the September 19, 2017 earthquake in Mexico City as reported by reconnaissance teams organized by the Mexican Society of Structural Engineering [4]. Fig. 1 also shows (green marks) the location of a group of several ground motion recording stations located in the area of the highest rate of observed building collapses in the September 19, 1985 earthquake. This group of stations includes the SCT station. Also shown is the location of the CUIP station at the UNAM Campus, which recorded typical ground motions in rock in Mexico City in the 1985 and 2017 earthquakes. It must be mentioned that in the 1985 earthquake in Mexico City, only the SCT station recorded ground motions in the area of the city with the highest rate of observed collapse or damage of buildings in this seismic event. In the September 19, 2017 earthquake, the SCT station recorded ground motions together with a large number of accelerometers in Mexico City that were installed in several stations after 1985. Due to this unique feature of the SCT station, this study considers only buildings damaged in the 2017 event that are located near this station.

This study was conducted to better understand the reasons for the damage and collapse of buildings observed in the September 19, 2017 earthquake in Mexico City. As shown later, the conventional procedures used in this task, such as the use of spectral response analysis, cannot explain the damage observed in this earthquake, which led to exploration of the effect of cumulative damage in a building caused by a subsequent seismic event. The findings of this study are used to suggest changes to the building code in Mexico aimed at reducing the seismic risk of new buildings and defining procedures for seismic rehabilitation of buildings after a seismic event.

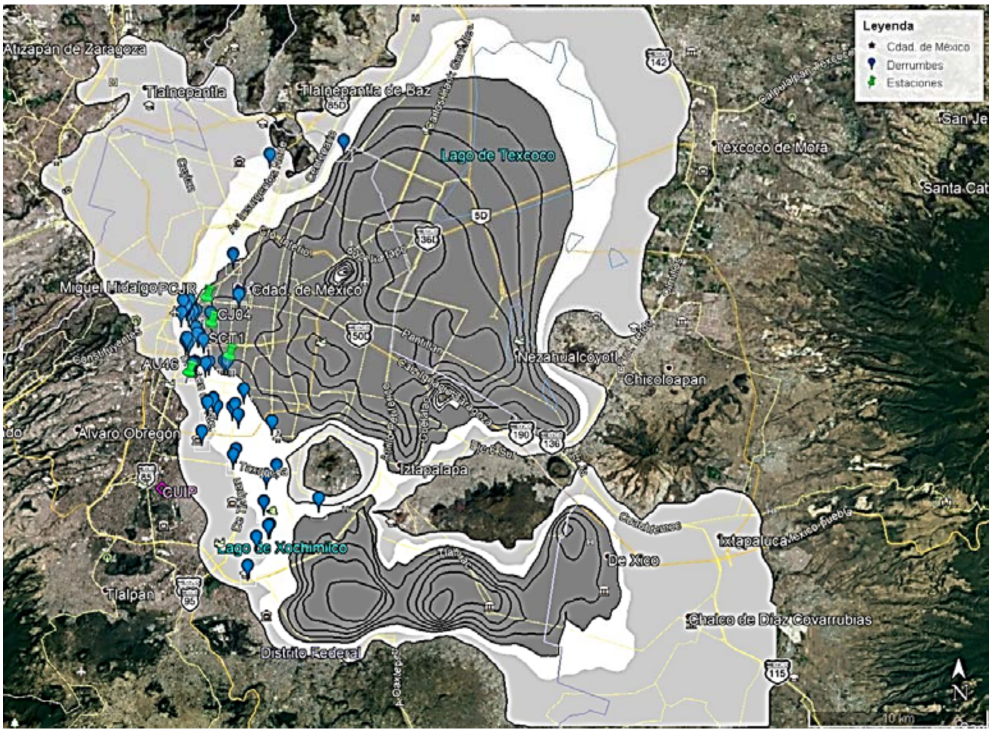


Fig. 1 – Distribution of building collapses observed in Mexico City in the September 19, 2017 earthquake (blue marks), ground motion recording stations near observed collapses in the September 19, 1985 earthquake (green marks) and CU station (CUIP) at the UNAM campus.

2. Analysis of displacement response spectra for ground accelerations recorded by the SCT and CUIP stations in Mexico City for the earthquakes of September 19, 1985 and September 19, 2017

2.1 CUIP Station

The CUIP station situated on rock and the SCT station located on soft soil in Mexico City recorded the ground motions in the 1985 and 2017 seismic events. The response spectra for accelerations recorded by these two stations in both seismic events are analyzed to gain insight into the observed damage to buildings in Mexico City in the 1985 and 2017 earthquakes.

Fig. 2 compares the elastic displacement spectra S_d for the ground motions recorded by the CUIP station in the 1985 and 2017 earthquakes. These spectra were calculated assuming a fraction of critical damping ξ equal to 5%. The results from the CUIP station show that the spectral ordinates for the 2017 earthquake are slightly higher than those for the 1985 earthquake only in the period range of 1.3 s to 1.8 s. Nevertheless, it can be shown that the design response spectra for S_d specified by the MCBC 2004 [3] are significantly higher than the spectral demands for the 2017 seismic event.

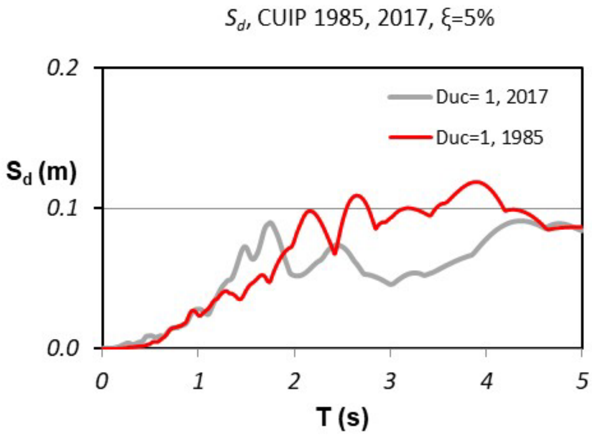
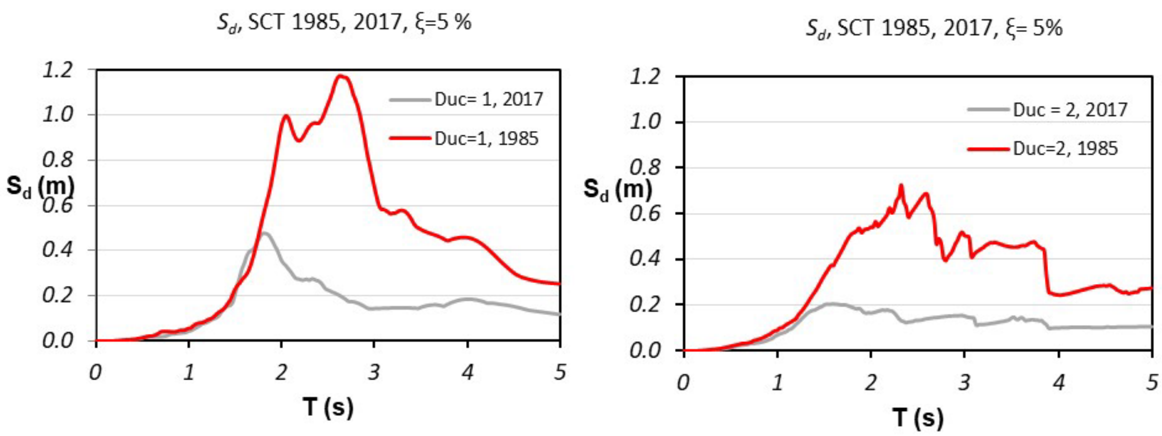


Fig. 2 – Displacement response spectra for the ground motions recorded by the CUIP station in the 1985 and 2017 earthquakes in Mexico City.

2.2 SCT Station

This station is located at a distance less than 1 km from the location of several collapsed buildings observed in the 2017 event (see Fig. 1). Because the SCT station is the only station that recorded ground accelerations in the 1985 and 2017 seismic events, the analysis of the response spectra for these recorded accelerations is relevant to understanding the reasons for the damage and collapse observed in buildings located in an area near the SCT station during the September 19, 2017 earthquake.

Fig. 3(a) shows the elastic spectral displacement S_d for the ground motions recorded by the SCT station in the 1985 and 2017 earthquakes, assuming 5% for ξ. It can be observed that for periods less than approximately 1.5 s, the spectral S_d ordinates are comparable for the recorded accelerations in both earthquakes, and for periods greater than approximately 1.5 s, the spectral demands in the 1985 earthquake are higher than those of the 2017 earthquake, with the highest demands occurring in the range of approximately 2 s to 2.8 s. Fig. 3(b) shows the inelastic S_d spectra for the same ground motions, assuming a displacement ductility factor μ equal to 2. The inelastic spectra were obtained using the Takeda hysteresis rule [5]. These results for the inelastic case indicate trends similar to those observed in Fig. 3(a) for the elastic case.



(a) (b)

Fig. 3 – (a) Elastic spectral displacements (b) Inelastic spectral displacements (μ=2) for accelerations recorded by the SCT station in the 1985 and 2017 earthquakes.

Fig. 4 shows (gray line) the spectral displacement demands computed with the accelerations recorded by the SCT station in the 2017 earthquake, considering that ξ is equal to 5%. The continuous, dotted, and dashed lines correspond to the results for the design spectral displacement demands according to the MCBC 1976 [6], 1987 [7], and 2004 [3] (zone IIIb), respectively, and assuming an overstrength factor equal to 2. As shown in Fig. 4, the values of the spectral displacement demands for the SCT 2017 record exceed the design values specified in the MCBC 1976 [6] only in a small period range, and in most cases, these demands for the SCT 2017 record were smaller than the demand values specified by several versions of the MCBC. The results indicate that buildings in the area under study should not have collapsed or suffered severe damaged in the 2017 earthquake, which is not consistent with the numerous cases of severe damage or collapse of buildings observed in this seismic event. This feature is discussed later.

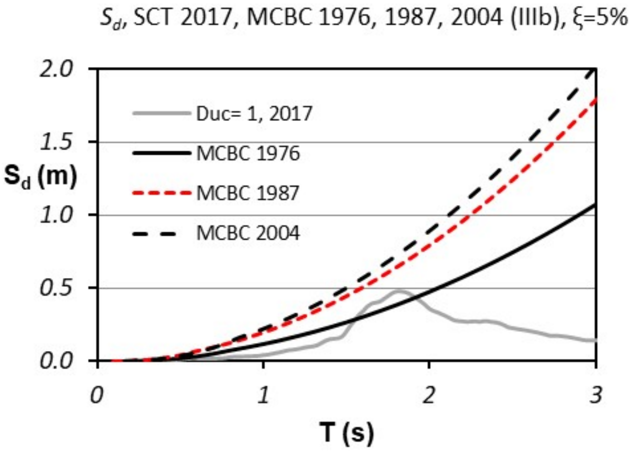


Fig. 4 – Design elastic spectral displacement demands and elastic spectral displacement demands computed with accelerations recorded by the SCT station in the 2017 earthquake.

The results from analyzing the response spectra for ground accelerations recorded by the SCT station in the 1985 and 2017 seismic events discussed above lead to several unanswered questions, the answers of which are relevant not only for interpreting the reasons for the damage and collapse of buildings observed in the 2017 earthquake but also for evaluating the adequacy of conventional current seismic design approaches, such as those of the 2004 MCBC [3] and 2017, as well as for defining proper seismic rehabilitation strategies for buildings. For the analysis of the structural response of buildings damaged by the 2017 earthquake, if we consider the cases of damaged buildings in an area near the SCT station, then this analysis leads to the following relevant questions:

(1) The buildings damaged in the 2017 earthquake in an area near the SCT station also experienced the 1985 earthquake, with comparable seismic demands in both events for critical fundamental periods less 1.5 s, i.e., for frame buildings with approximately less than 12 stories. Why did these buildings collapse in 2017 and not in 1985?

(2) The spectral demands S_a and S_d for the SCT record in the 2017 earthquakes were less than those specified by the MCBC of 1987 and 2004, and nevertheless, collapse or severe damage was observed in buildings in an area near the SCT station. Are the specifications of the current seismic building codes adequate for seismic design of new buildings and/or for seismic rehabilitation of existing buildings?

(3) An evaluation of the damage statistics for buildings in the 2017 earthquake in Mexico City indicates that most damaged or collapsed buildings in this seismic event also experienced the 1985 earthquake with no relevant observed damage. In contrast, in most buildings constructed after 1985 in Mexico City, little or no damage to buildings was observed. How do we explain the better structural behavior of buildings built after 1985 with respect to buildings that experienced both the 1985 and 2017 earthquakes?

3. Interpretation of the damage and collapse of buildings observed in Mexico City during the September 19, 2017 earthquake

The observation of building damage in the 2017 earthquake in Mexico City suggests the need to explore the effects of cumulative damage due to sequential ground motions in a building. To study the effect of cumulative damage in buildings, in addition to an analysis of conventional spectra demands, this study uses a damage index from the literature, and it is briefly described in the following.

3.1 Damage index I_d

Rodriguez [8] proposed the damage index I_d, which is equal to zero if the structure responds in the linear elastic range and equal to one if potential exists for collapse, and I_d is defined as:

$$I_d = \frac{\Gamma^2 E_H}{(2\pi \lambda h D_{rc})^2} \tag{1}$$

Parameter Γ is the first-mode participation factor, and E_H is the hysteretic energy per unit mass dissipated by an equivalent SDOF system with a period equal to the fundamental period of a multistory building T, with a displacement ductility ratio μ equal to the global displacement ductility ratio of the building responding to an earthquake ground motion. The hysteretic energy E_H in this study was computed using the modified Takeda hysteresis rule [5] and assuming a fraction of critical damping ξ equal to 2% [9]. The parameter h is the story height, which is assumed constant in a building and equal to 3.0 m, and the parameter λ is used to compute T in a building with n floors by means of the following expression:

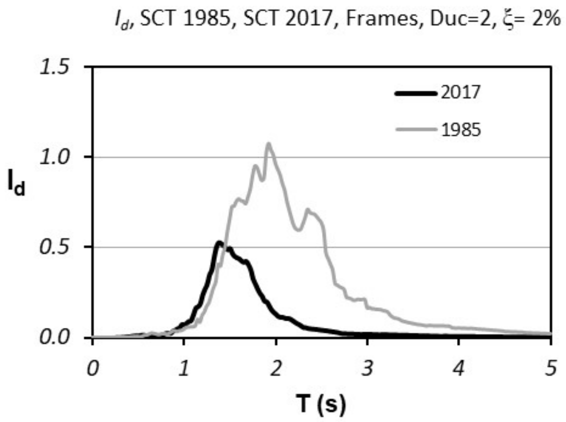
$$T = \frac{n}{\lambda} \tag{2}$$

The parameter D_{rc} is the roof drift ratio of the above described equivalent SDOF system with a linear elastic response absorbing deformation energy in a complete cycle ($+D_{rc}$ and $-D_{rc}$) equal to the value of E_H associated with the potential of collapse in the structure. Parameter D_{rc} was found to be equal to 0.025 to obtain the best correlation between the observed global building damage and the computed values of I_d for a set of ground motions recorded in 11 earthquakes, including the 1985 Mexico City earthquake, the 2010 Chile earthquake, the 2011 Christchurch earthquake, and the 2011 Great East Japan earthquake [8].

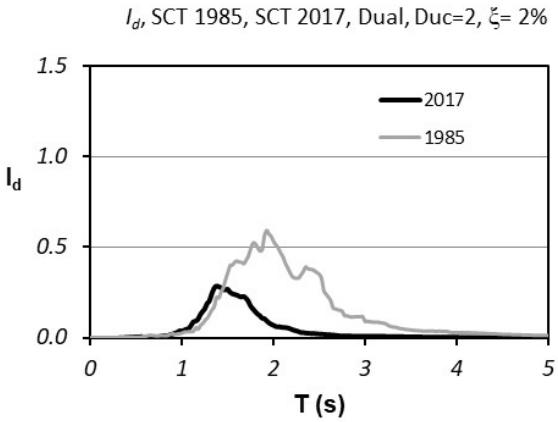
The damage index I_d was computed in this study using the accelerations recorded by the SCT station in the September 19, 1985 and September 19, 2017 earthquakes. Two structural systems were considered, i.e., frame and dual structural systems, and the parameter λ in Eq. (2) was assumed equal to 7 and 10, respectively [10], where the selected value of λ for a dual structural system was based on the assumption that this system can be considered an intermediate case between frame buildings and structural wall buildings. The results of the evaluation of the damage index I_d are discussed in the following.

3.2 Results of the evaluation of I_d for the 1985 and 2017 earthquakes in Mexico City

Fig. 5(a) shows a plot of values of I_d computed using Eq. (1) as a function of period T for the case of frame buildings (λ= 7), I_d = 2, and the EW component of accelerations recorded by the SCT station in Mexico City in both the September 19, 1985 and September 19, 2017 earthquakes. As observed in Fig. 5, the computed values for I_d for the 1985 seismic event (gray line) are consistent with the observed damage and collapse of buildings in Mexico City in this seismic event, where the damage was concentrated in buildings for periods near 2 s, and this is also the period with the highest computed values of I_d in this seismic event (see Fig. 5). However, the computed values of damage index I_d for frame buildings in the 2017 seismic event, shown with a black line in Fig. 5, were significantly smaller than one, indicating that frame buildings should not have collapsed in the 2017 earthquake. This finding is not in agreement with the fact that a number of frame buildings were damaged or collapsed in the 2017 earthquake, suggesting the need to perform damage analysis of these buildings.



(a) Frame buildings



(b) Dual systems

Fig. 5 – Damage index I_d computed for RC buildings responding to accelerations recorded by the SCT station in the September 19, 1985 and September 19, 2017 earthquakes: (a) Frame buildings, (b) Dual systems

Fig. 5(b) shows the computed values of I_d for dual systems (λ= 10), μ= 2, when responding to the EW component of accelerations recorded by the SCT station in Mexico City in the September 19, 1985 and September 19, 2017 earthquakes, as shown with gray and black lines, respectively. These values of I_d are smaller than one, indicating that the dual system could have experienced the 1985 or the 2017 earthquake without significant damage or collapse. These results are consistent with the observed structural behavior of dual systems in both earthquakes, although in 1985, the number of RC buildings with dual systems was significantly smaller than that of frame buildings. The number of buildings in Mexico City with dual systems significantly increased after 1985 because later building codes increased the seismic design forces and reduced the allowable interstory drifts, which encouraged the use of dual systems. Nevertheless, it remains to be observed whether the effects of a subsequent earthquake in dual systems might be relevant when considering cumulative damage. This case is discussed later.

3.3 Results of the evaluation of I_d considering the combination of ground motions during the September 19, 1985 and September 19, 2017 earthquakes

Damage analysis is discussed in the following with consideration of a ground acceleration record defined as the combination of the accelerations recorded in the SCT station in the 1985 and 2017 seismic events. Such a record is shown in Fig. 6, in which the left portion of the record (approximately 150 s) corresponds to the EW component of ground accelerations recorded in the SCT station in the 1985 earthquake, and the right portion of the record (approximately 130 s) corresponds to the EW component of ground accelerations recorded in the SCT station in the 2017 earthquake, giving a total duration of 280 s for the record

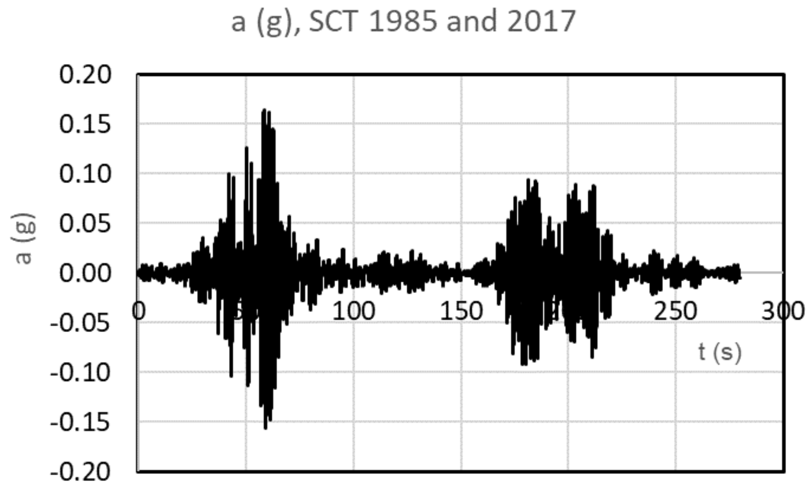


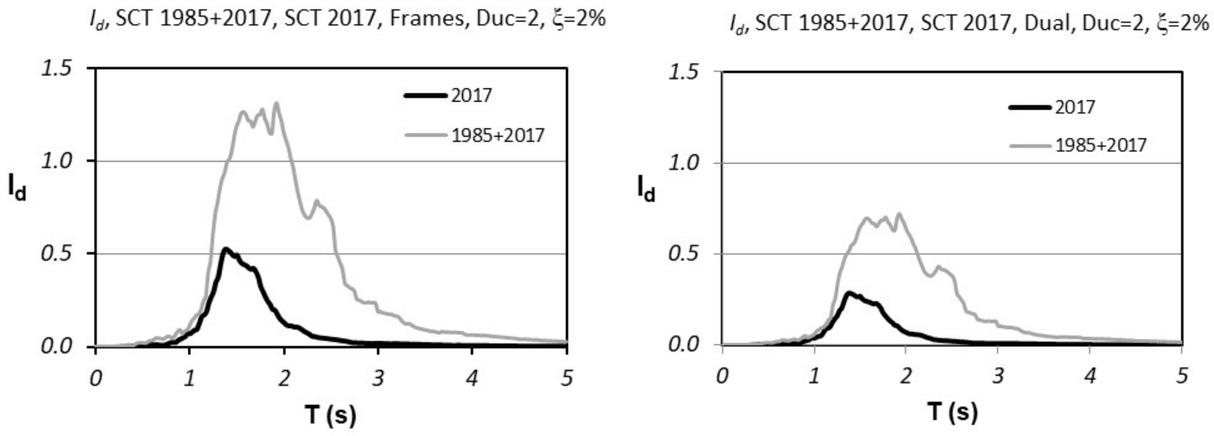
Fig. 6 – Ground acceleration record result of adding the ground acceleration recorded by the SCT station in the September 19, 1985 earthquake (left) and the ground acceleration recorded in the September 19, 2017 earthquake (right).

3.3.1 Frame Buildings

The gray line in Fig. 7(a) shows a plot of the computed values of I_d as a function of period T, considering frame buildings (λ= 7), μ= 2, and the ground acceleration record shown in Fig. 6. For the sake of comparison, the black line in Fig. 7(a) shows the computed values of I_d for the same buildings but using the input ground motion given by the EW component of accelerations recorded by the SCT station in the 2017 earthquake, as also shown in Fig. 5(a). The results shown in Fig. 7(a) indicate that if considering the building damage analysis using only the accelerations recorded in the SCT station in the 2017 earthquake, we could conclude that frame buildings had low potential for collapse or severe damage, which goes against the fact that damage or collapse of frame buildings was observed in this earthquake. In contrast, in a period range of approximately 1 s to 2 s, the values of I_d computed by considering the combined acceleration records for both earthquakes indicate severe damage or collapse of buildings. For the combined records, it is of interest that in a period range of approximately 1 s to 1.5 s, small increases of T lead to increases of I_d that are significantly larger than those computed using only the 2017 record. The period range of 1 s to 1.5 s corresponds to frame buildings in the range of approximately 6 to 10 stories, which displayed the highest rate of damage or collapse in the 2017 earthquake.

3.3.2 Dual systems

The results of evaluating the damage index I_d for dual systems (λ= 10), μ= 2, and the EW component of accelerations recorded by the SCT station in Mexico City in the September 19, 2017 earthquake are shown with a black line in Fig. 7(b). These results are also shown in Fig. 5(b). The damage index I_d for dual systems responding to the combined record is shown with a gray line in Fig. 7(b). These results suggest that buildings with dual systems in the area of Mexico City under study that were constructed before or after 1985 should not have collapsed in the 2017 seismic event, which is consistent with the observed behavior of dual systems in the 2017 earthquake in Mexico City. It must be mentioned that most existing buildings with dual systems in Mexico City and 10 or less floors were constructed after 1985; i.e., most experienced only the 2017 seismic event, and the effect of cumulative damage in these buildings remains to be observed in a subsequent earthquake.



(a) Frame buildings (b) Dual systems

Fig. 7 – Damage index of buildings with dual systems. computed for RC buildings responding to the accelerations recorded by the SCT station in the September 19, 2017 earthquake and the record obtained by combining the records of the September 19, 2017 and September 19, 1985 earthquakes: (a) Frame buildings, (b) Dual systems

The higher collapse potential of frame buildings compared with that of buildings with dual systems found in this study (Figs. 7(a) and 7(b), respectively) shows the importance of lateral stiffness for reducing the collapse potential in buildings subjected to earthquakes. It follows that wall buildings should be favored as the structural system in multistory buildings, not only to protect human life but also as an economical solution for a building with the capacity to withstand severe earthquakes (Rodriguez, 2018).

4. Conclusions

The results found in this study indicate that to explain the damage or collapse of buildings that experience more than one strong earthquake or to assess the vulnerability of existing buildings, it is necessary to consider cumulative damage. Frame buildings showed severe damage or collapse in the September 19, 2017 earthquake, but the same buildings responded to the September 19, 1985 earthquake with little or no observed damage. This result is consistent with the damage index computed for the combined record.

It was shown in this study that the seismic demands in the September 19, 2017 earthquake in the area of Mexico City selected for this study were lower than the demands of the design earthquake. Nevertheless, a significant number of buildings collapsed or were damaged, demonstrating that current seismic design provisions in Mexico should be revised, and cumulative damage should be considered in the seismic design of new and existing structures. Since incorporating new provisions into building codes that consider cumulative damage in seismic design procedures might be a long-term task, building codes in Mexico need to change. One of the needed changes is that RC buildings in seismic regions of Mexico should be designed using the seismic design provisions specified in ACI 318-19 [2], which means that buildings with limited ductility should not be allowed in seismic regions of Mexico.

During the 2017 earthquake in Mexico City, it was observed a better structural behavior of buildings built after 1985 with respect to buildings that experienced both the 1985 and 2017 earthquakes. One of the reasons postulated to explain this behavior is that buildings in 2017 experienced only one severe earthquake, therefore they did not experience cumulative damage. Another reason is the use of buildings with dual systems, which started after 1985. It was shown that for this structural system computed values of I_d were less than one, even for the combined records of 1985 and 2017. These results suggest that in seismic design practice, buildings with structural walls should be used in multistory buildings.

5. Acknowledgements

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