ASSESSMENT OF EARTHQUAKE-INDUCED LOSS OF FUNCTIONALITY IN REINFORCED CONCRETE BUIDLINGS

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Abstract

The main objective of most seismic design methods is to produce structures that meet the performance levels of immediate occupation and life safety. In the first performance level, it is expected that the building does not developed structural and non-structural damage; hence, the users could occupy the buildings short after the earthquake occurs. For the latter performance level, it is expected that the structure does not collapse, in order to safeguard the lives of its occupants. However, codes generally accept the development of significant damage for this performance level; therefore, repairs can be technically or economically unfeasible.

There are several methodologies to evaluate the structural performance in terms of decision variables, *e.g.*, expected cost and repair time given a pre-established seismic intensity. Currently, the most popular and robust of these methodologies is the one developed by PEER and adopted by FEMA P-58. Unfortunately, this approach does not enable estimating the loss of functionality due to different earthquake intensities. Assessing the loss of functionality is crucial for decision-making processes aiming at adequate resilient performance levels, *e.g.*, estimating indirect economic losses, corresponding to the suspension of economic and social activities during the time interval in which the restauration activities take place.

This article presents a methodology to assess the loss and recovery of functionality in typical reinforced concrete, RC, buildings located in the Valley of Mexico City. The proposed methodology is based in the concept of resilience, developed by the MCEER, in the methodology to inspect buildings affected by earthquakes proposed in ATC-20, and both implement into the performance-based earthquake engineering methodology developed by PEER. This methodology can predict the probable sources that cause the loss of functionality in specific areas of the buildings. This information can be used to predict probable indirect losses due to lack of functionality during the system restore time. Likewise, with this information corrective mitigation measures can be implemented to improve structural resilience, *e.g.*, by using devices to control the structural and non-structural damage.

In order to demonstrate the application of the approach for assessing the loss of functionality, a case study consisting of a seven-story RC building is presented. The results are expressed in terms of probability of loss of functionality limit state given a probable seismic intensity, *i.e.*, the probability that the building cannot be occupied due to structural/non-structural damage, but will be repairable within a given interval of time. The analysis is carried out considering seven levels of seismic intensities.

Keywords: seismic resilience, loss and recovery of functionality, time recuperation

1. Introduction

Historically, it has been shown that the loss of functionality in buildings can occur at seismic intensities lower than those used in structural seismic design. For example, in the 2011 Christchurch earthquake, the spectral accelerations registered exceed the design demand intensities in a few geographical sites; therefore, the seismic event as such was not classified as a design intensity earthquake. Unfortunately, a significant portion of the affected buildings had to be demolished and the other was substantially repaired. From the point of view of the design code used for the design these buildings, the performance presented was adequate, since the buildings did not collapse and, therefore, the level of performance associated with life safety was met. In general, most of the damaged buildings were designed with the current design codes in 2011. Therefore, it was concluded that the level of life safety performance was satisfied in this event. However, from the point of view of the users and owners, this performance was not satisfactory, as they expected that their buildings would not present severe damage because they were designed with a modern code. As a result, the damaged buildings in Christchurch caused that the Central Business District (CBD) was cordoned for a period of two years, and the reconstruction works did not begin until three years after the earthquake. In addition, many companies were forced to relocate, and many others never returned to their original place of operation [1].

As with the Christchurch earthquake, which caused loss of functionality of the CBD by more than two years, several seismic events have had similar consequences in large demographic areas, *e.g.*, Northridge, 1994; Chile, 2010; and Mexico, 2017, to name a few. These events have demonstrated that it is possible to reduce the loss of human lives following the current seismic design guidelines codes. However, it must also be understood that it is very likely that relevant damage will occur in structural, non-structural components and in contents. Consequently, the functionality, *i.e.*, the main objective for which the owners or investors of the buildings decided constructed it, may not be achieved. The facts mentioned above demonstrate the need to develop methodologies that allow assessing the performance of buildings, whether new or existing, in terms of decision variables intuitive and easy to interpret not only by structural engineers but also by stakeholders, investors and architects. Examples of variable decisions are: 1) direct economic losses, caused by structural, non-structural and content damage; 2) indirect economic losses, corresponding to the time the facility return to be operable; 3) number injured people and 4) loss of functionality.

This paper presents a methodology for assessing the loss and recovery of functionality of concrete buildings reinforced with unreinforced masonry walls. The methodology is consistent with the conceptual definition of structural resilience proposed by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) [2], with the performance-based earthquake engineering (PBEE) methodology developed by the Pacific Earthquake Engineering Research Center (PEER) [3, 4, 5], and with the post-seismic inspection criteria developed by the Applied Technology Council (ATC-20) [6].

2. Definition of the concept of structural resilience

The resilience is the property that determines the capacity of a building to recover its functionality, disrupted by a catastrophic natural event, in a specific period of time. In 2003, the MCEER developed a theoretical framework scheme to explain its principal characteristics [2]. In this scheme, the structural resilience is represented into two stages: the first one that consists of estimating the loss of functionality, and the second one in quantifying the recovery of the functionality to the original condition. Regarding destructive seismic events, the loss of functionality occurs immediately after the catastrophic event takes place, see Fig.1. For example, total or partial collapse in structural, non-structural members, damage in building services and usable space compromised are possible sources of loss of functionality. The second stage, corresponding to the recovery of functionality, it depends mainly on factors such as the activities involving the evaluation of residual structural capacity, planning of activities to carry out necessary repairs, planning of economic financing and repair and/or replacement of contents and furniture to reactivate the functionality of the facility [7].

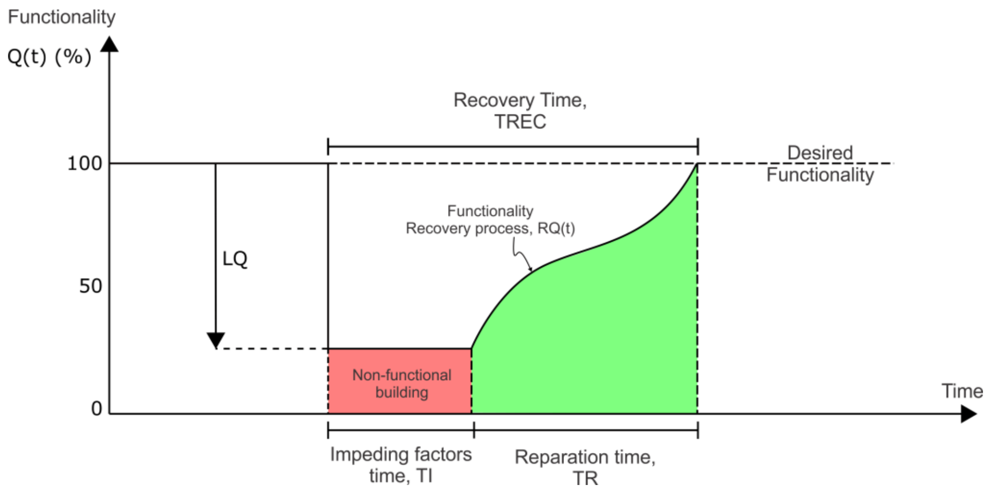

Fig. 1 – Conceptual representation of loss and recovery of functionality proposed by MCEER [2]

3. Methodology

3.1 ATC-20 methodology for post-earthquake safety evaluation of buildings

After a potentially destructive earthquake has affected a city or community, there is the need to inspect buildings and facilities to assess the potential damage to determine if they are safe and can be occupied to continue in operation or, if not, they need to be repaired [6]. To restore the functionality of the damaged buildings, and consequently, the functionality of a city or community, the inspection and assessment of all damaged buildings must done in the shortest possible time. Therefore, to optimize and reduce the inspection time, there must be a large number of specialized personnel to make the post-seismic evaluations. Our experience from past seismic events is that it is unlikely that the affected society will have a large number of qualified personnel to make this task due to the large number of buildings and their location within a city [8].

Due to this problem, the ATC-20 [6] developed a methodology for inspecting conventional buildings with the goal of optimizing the inspection time and issuing a report that defines the activities to mitigate the damage and to recover the functionality of the affected buildings. The methodology developed by ATC-20 is designed to be used by construction officials and structural engineers, and is divided into three levels of inspection: 1) Rapid Evaluation, 2) Detailed Evaluation, and 3) Engineering Evaluation. The first two assessments are visual, while the third requires an engineering calculation process to determine the residual load capacity of the building in question. The objective of the evaluation is to represent post-seismic structural safety using one of three types of posting: inspected, restrained entry, or unsafe, and are represented by the tags green (G), yellow (Y), and red (R), respectively. A fourth category involves non-structural elements inspection, which, although they do not affect the stability of the structure, are the cause of risk falling and therefore injure people inside and/or outside the building. Examples of this type of elements are ceilings, fire suppression systems, exterior windows, and unreinforced masonry walls. The post assigned to these elements damaged is area unsafe, and a R tag is given. The details of each type of evaluation are described below.

3.1.1 Rapid Evaluation

The rapid evaluation is done at the exterior of the building with the goal of determining the amount and severity of structural damage. If severe structural damage is clearly present, then the building is posted as structurally unsafe, and tagged with R color. If only severe non-structural damage is present, the posts assigned are structurally safe and an area unsafe. This process may be completed from 10 to 20 minutes. If the severity of the structural and non-structural damage to the exterior building is not clear, and the inspector thinks that in the interior could exist any kind of damage, the building is posted with a restrained entry (Y tag) and a detailed inspection of the interior of the facility is required. If there is slight or no damage on the structural and non-structural elements then the building receive a post inspected, i.e., building safe (G tag).

3.1.2 Detailed Evaluation

This type of evaluation aims to determine the safety of the building in situations where damage on the outside of the building may cause doubt of the structural safety. At least two structural engineers must make the detailed evaluation of both exterior and interior of the structure. The main objective of this type inspection is to ensure that the structural elements, as well as the non-structural ones that are susceptible to falling, are safe enough for the building to be re-occupied, i.e., inspected (G tag). If, on the other hand, moderate or severe damage to structural and/or non-structural elements occurs inside, then the building receives a restrained entry or unsafe post (Y and R tags), respectively. This type of evaluation may be completed from 1 to 4 hours.

3.1.3 Engineering Evaluation

Engineering evaluation is performed when the first two visual inspections are not sufficient to determine the structural safety of the building. This evaluation must be performed by a team of structural engineers. The result of this type of inspection is detailed maps of the structural and non-structural damage, which serve as support for performing structural analyses and numerically inferring the amount and severity of the damage. The possible outcomes of this evaluation are the post unsafe (R tag) or inspected (G tag). This type of assessment may be finished from 1 to 7 days, or even more.

3.2 PEER Performance based earthquake engineering methodology

Currently the most robust tool for assessing structural performance is the PEER method [3, 4, 5] whose main objective is to estimate the consequences of earthquake damage to individual buildings in terms of decision variables, DV. This methodology is divided in four probabilistic analyses: 1) seismic hazard analysis, 2) structural analysis, 3) damage analysis and 4) analysis of decision variables, as presented in [3, 4, 5]. These analyses are combined using the total probability theorem to obtain either the expected value or the average annual rate of exceedance of the decision variable. The first stage of these analyses involves a seismic hazard analysis. This analysis allows to determine the probability of exceedance of one or several selected seismic intensities, IM, and are represented by means of the seismic hazard curve: Pr(IMm), e.g., pseudo spectral acceleration. The seismic hazard curve is used to select the set of seismic records, which are needed in the second step where non-linear dynamic analyses (NLDA) are carried out. From the NLDA, the probability distribution of the structural response of the structural components conditioned to a seismic intensity is obtained, e.g., story drifts, floor accelerations, rotations of cross sections of structural elements, among others. These physical variables are called demand engineering parameters, EDPj, and their probability distribution function is defined by the following expression: Pr(EDPj|IMm). The third step consists in transforming the structural response of the several components, i.e., structural and non-structural elements, denominated as performances groups, PG, into discrete damage states, DSk, which represent the severity of the damage: null, light, moderate and severe. The result of this step is the probability distribution of the damage states of the components: Pr(DSk|EDPj). The fourth step consists in quantifying the consequences of the damage obtained in the previous step in terms of decision variables: Pr(DVn|DSk). The result is expressed by means of the total probability theorem, where the uncertainties associated in each analysis are taken into account by the following expression:

$$\Pr(\mathrm{DV_n}|\mathrm{IM_m}) = \sum_{m}\sum_{j}\sum_{k} \Pr(\mathrm{DV_n}|\mathrm{DS_k})\Pr\left(\mathrm{DS_k}\middle|\mathrm{EDP_j}\right)\Pr\left(\mathrm{EDP_j}\middle|\mathrm{IM_m}\right) \tag{1}$$

Although the performance evaluation scheme proposed by PEER represents an important step towards the quantification of the seismic risk of individual buildings, it is necessary a much broader and deeper interpretation of the performance buildings. There is a need to understand how the functionality is affected by the damage induced by moderate to high intensities earthquakes and what recovery strategies should be taken to return the buildings to its original/optimal functionality.

3.3 Numerical simulation of building safety using the ATC-20 inspection criteria

In 2007, Mitrani-Resier [9], developed a probabilistic methodology to estimate the post-seismic structural safety posts, i.e., R, Y or G tags, based on the ATC-20 visual inspection criteria. This methodology reproduces numerically the rapid and detailed evaluation. For the first one, in case of obtaining a Y tag, i.e., a restricted entry post, the process of a detailed inspection is then simulated. In the end, the probabilities of each type of inspection are combined to obtain the probability that the facility will be tagged as safe or unsafe given a seismic intensity. This methodology was adopted in [10].

In this work, a methodology similar to the proposed in [9] is used to assess the probability of a building being posted as unsafe, restricted entry or safe, from both structural and non-structural points of view, and with these results, five discrete states of functionality are inferred. The original methodology is modified in two points. The main difference is that in this work only the detailed inspection is simulated numerically, instead of doing the rapid and detailed inspection because, as mentioned in section 3.1, the rapid inspection proposed by ATC-20 is performed due to the lack of a large quantity of personnel specialized to inspect many buildings potentially damaged in a short time. From the computational simulation viewpoint, it is not necessary to perform the two first numerical inspections since it is relatively simple to do using computers. The second modification is that in the method proposed in this document, non-structural components are explicitly evaluated in a similar way as it is done for structural elements. Although the presence of non-structural damage combined with null structural damage is not a reason for post the building as structurally unsafe, it is a cause to consider a potential risk due to the possibility of the non-structural elements falling, and naturally, induce injury to people and loss of functionality during the time interval in which their repair is carried out. The probability that the building is R tag, Y or G are calculated with the following equations:

$$\mathrm{Pr(TAG = R|STR, IM, DE) = Pr(severe\ str.damage|IM, DE, NC)Pr(NC|IM) + Pr(C|IM)} \quad (2)$$

$$\mathrm{Pr(TAG = Y|STR, IM, DE) = Pr(moderate\ str.damage|IM, DE, NC)Pr(NC|IM)} \quad (3)$$

$$\mathrm{Pr(TAG = G|STR, IM, DE) = Pr(light\ or\ null\ str.damage|IM, DE, NC)Pr(NC|IM)} \quad (4)$$

where STR indicates that the tag is conditioned to the inspection of the structural elements given a seismic intensity, IM, product of a detailed evaluation, DE. The term Pr(C|IM) indicates the probability of collapse and Pr(NC|IM)=1-Pr(C|IM) the probability of survival. The terms Pr (severe str.damage|IM,DE), Pr (moderate str.damage|IM,DE) and Pr (light or null str.damage|IM,DE), are the probability of experiencing severe, moderate, light or null structural damage given that the building does not collapse, and are calculated in the third step of the PEER methodology. On the other hand, the probabilities in R, Y or G tag given that a non-structural inspection are calculated in the Eqs. 5 to 7:

$$\begin{aligned}\mathrm{Pr(TAG = R|NSTRD, IM, DE)} \\ \mathrm{= Pr(severe\ non-str.damage|NSTRD, IM, DE, NC)Pr(NC|IM) + Pr(C|IM)}\end{aligned} \quad (5)$$

$$\mathrm{Pr(TAG = Y|NSTRD, IM, DE) = Pr(moderate\ non-str.damage|NSTRD, IM, DE, NC)Pr(NC|IM)} \quad (6)$$

$$\mathrm{Pr(TAG = G|NSTRD, IM, DE) = Pr(light\ or\ null\ non-str.damage|NSTRD, IM, DE, NC)Pr(NC|IM)} \quad (7)$$

where the term NSTRD indicates that the probability of the building being tagged as unsafe, restricted entry or safe, is conditioned on the presence of null structural damage. The other probabilities are estimated in a similar way as in the Eqs. 2 to 4.

3.4 Generic states of loss and recovery of functionality

From the post-seismic numerical inspection of structural and non-structural safety, and of the amount of damage, it is possible to define generic states that measure the loss and recovery of functionality, LQi and RQi, respectively, similar to those proposed by [11]. The functionality recovery is influenced by several events such as: 1) post-seismic inspection, 2) revision and/or structural redesign, 3) financing process, 4) bidding process to determine who will perform the repair work, and 5) government permits. This series of events have been referred by Comerio (2006) as irrational factors because their inherent nature involves large uncertainties, and because their execution sequence cannot be a priori established. The number of irrational factors to take into account depends on the amount and severity of the damage experienced.

- LQ0: Complete functional, safe building, TAG=G. This state corresponds to an undamaged state, whether structural or non-structural, so the building remains operational after the seismic event. However, it is possible that the owner may ask for an inspection to verify that there is no minor damage, Fig.2a.
- LQ1: Restricted use, safe building, TAG=G. This state corresponds to the combination of a null structural damage state and moderate non-structural damage. Since there is moderate damage to nonstructural components, system recovery, RQ1, may be represented by the following generic pattern of events: 1) post-seismic inspection, 2) repair of nonstructural elements, see Fig.2b.
- LQ2: Restricted entry, TAG=Y. This state may occur due to the presence of null structural damage and severe non-structural damage, or moderate structural damage and any state of non-structural damage. The recovery path, RQ2, of the system may be described by three states, defined by the following events. For the first state: 1) post-seismic inspection; after completion of the inspection and having tagged the building as restricted use, the functional state changes to restricted entry. During this state, the following events are carried out: 1) financing process, 2) bidding process, and 3) structural repairs. Once this last event is finished, the facility is safe to be reoccupied; however, the non-structural repairs must be done, and upon completion, the facility would have recovered its functionality, see Fig.2c.

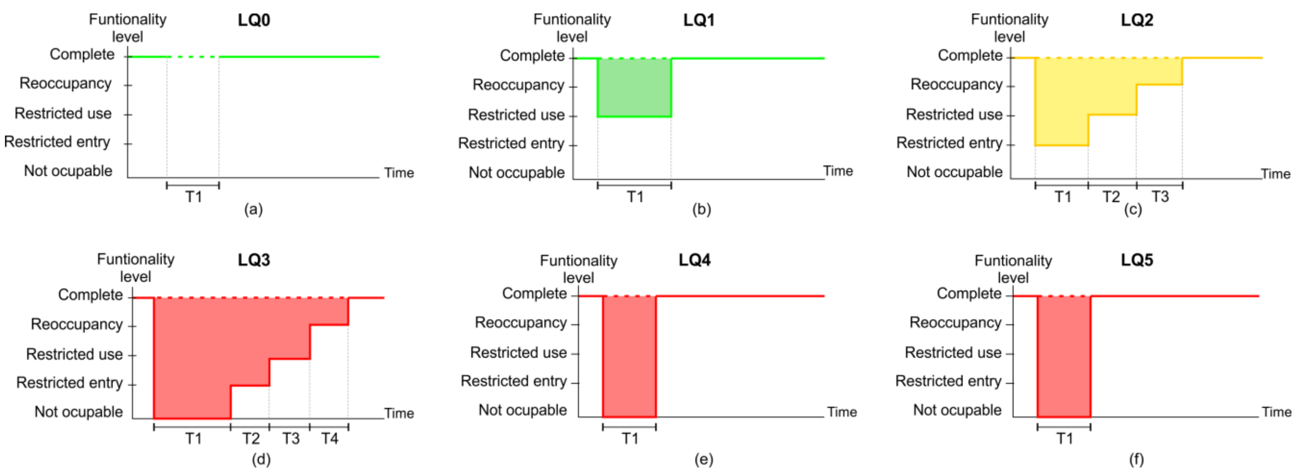

Fig. 2 – Generic paths of loss and recovery of functionality process

- LQ3: Not occupational building, unsafe, TAG=R. This state is caused by the combination of severe structural damage, and any state of non-structural damage. The recovery process, RQ3, consists of four states. In the first one, the post-seismic inspection is performed, in which it is determined that the structure must be tagged as unsafe but repairable, given that it did not experience significant residual deformations. After this event, the building condition becomes restricted entry. During this state, the following events are presented: 1) financing process, 2) structural redesign and repair planning, 3) bidding process. Once the structural redesign has been determined and the financing is obtained, the functional state becomes restricted use, a stage in which repairs and/or structural reinforcement are carried out. After this stage, the building is safe to be reoccupied; however, in order to be fully functional, non-structural repairs must be done, see Fig.2d.

- LQ4: Not occupational building, unsafe, TAG=R. This state corresponds to an unsafe building as it experienced excessive residual deformations or local structural collapse, so it is determined that it must be demolished either the cost of repair may be excessive and/or the system is technically irreparable. The recovery process, RQ4, is given by the demolition and reconstruction of the building, Fig.2e.
- LQ5. Structural collapse, TAG=R. This state corresponds to structural collapse, and its recovery process is given by the cleaning of debris and the reconstruction of the building, see Fig.2f.

3.5 Numerical simulation of recovery time

The recovery time, TRE, of a building that has experienced damage can be discretized in two states, as already mentioned above. The first one corresponds to the time consumed by irrational factors, and the second to the rational, i.e., repairs [7]. To estimate the time consumed in each state, the generic recovery patterns described in the previous section will be used. The recovery time is computed according to the methodology proposed in [12], which is based on Project Evaluation and Review Techniques (PERT). The PERT method is a technique of analysis, control and coordination of projects. The method consists in defining specific related tasks through a logical sequence, i.e., activities, which are defined based on the amount and severity of damaged structural and non-structural elements, located on each floor of the building. Repair activities are performed by a pre-established set of crews. Details of the method may be found in the proposal made in [12].

4. Numerical example

This section presents the evaluation of the functionality loss and recovery of a RC building, which includes the unreinforced masonry walls. The building has seven floors and three bays in each orthogonal direction. The height of each interstorey is 4m, and the horizontal distance between columns is 6.5m. For illustrative purposes, it is considered that the use of the building is destined to offices, and it is integrated by seven performance groups: 1) columns, 2) column-beam connections, 3) unreinforced masonry walls in the periphery frames, along all its height, 4) gypsum partition interior walls, placed from the second to the last floor, 5) exterior windows, placed on the entire building facade, 6) ceilings and 7) sprinklers. The spatial location of each component of the performance groups is illustrated in Fig.3. Table 1 shows the parameters of the probability distributions of the damage states for each performance group and their unit repair time, respectively. To estimate the time corresponding to the irrational factors, the probability distributions proposed in [13], Table 8, were used.

The building was designed in accordance with the 2004 Seismic Code and Complementary Technical Standards for Mexico City [14]. With the proposed structural design, the fundamental period of the building turned out to be 0.61s. The details of the design of this building can be found in [12].

The evaluation of the proposed methodology was done for seven levels of seismic intensity, with return periods of 50, 125, 250, 500, 1000, 1500 and 2500 years, respectively. To represent the seismic demand, sets of 20 pairs of accelerograms were simulated, associated to each return period using the model proposed in [15]. The April 25, 1989 earthquake of magnitude Mw 6.9 was used as an empirical Green function. The value of 2.50x1026 was used for the seismic moment, Mo, and the value of 150 bars for the stress drop, $\Delta\sigma$, according to what was reported in [16]. The target mean spectral accelerations for each seismic intensity level used are: 0.15g, 0.22g, 0.29g, 0.36g, 0.47g, 0.54g and 0.63g.

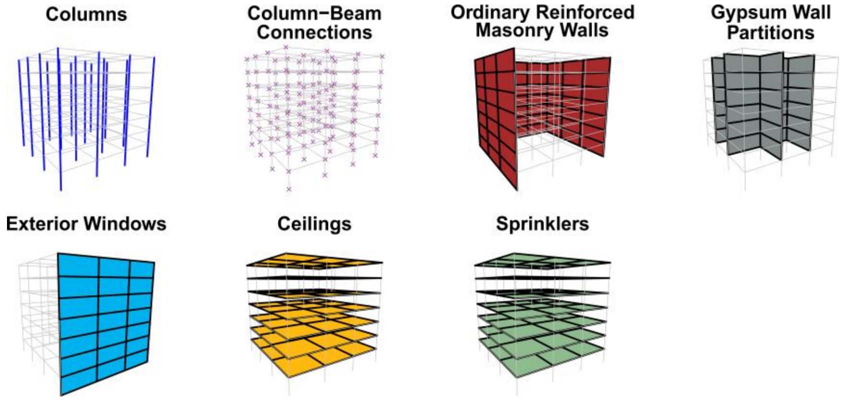

Fig. 3 – Peformance groups that integrate de building

The nonlinear dynamic analyses were performed in the open source program OpenSees [17]. The columns and beams were modeled using bar elements with five integration points. Its inelastic behavior was modeled using fibers. The behavior of concrete was modeled using the constitutive model proposed in [18], and of the longitudinal reinforcement steel with the model developed by [19]. To take into account the stiffness contribution of the masonry infill walls, and capture its eventual damage explicitly, its inelastic behavior was modeled using the methodology proposed by [20]. The parameters of the constitutive model for the masonry were calculated in accordance with [21]. The probability of collapse was estimated using the sidesway criteria, similar to the incremental dynamic analysis proposed in [22]. The evaluation of the demolition limit state was done using the methodology developed in [23].

5. Analysis of the results

Figure 6 schematically presents the vulnerability of the performance groups, considering the seismic hazard return period levels of 125 and 2500 years. For the first seismic hazard levels, it was slight damage in some of the infill masonry walls, while in the second the vulnerability of the system changed completely, since light damage is expected in the columns and moderate damage in the column-beam connections; with respect to the non-structural elements, severe damage to the infill masonry walls of the first four floors of the building is expected, and moderate and slight damage to the walls of the rest of the floors; with respect to the interior gypsum walls, moderate and slight damage is expected. Similarly, some of the exterior windows are expected to show moderate damage.

The probabilities of tagging the building in safe post, restricted entry, and unsafe, are presented in Fig. 7a and 7b, given that the structural and nonstructural elements are evaluated by means the numerical simulation of the detailed evaluation, respectively. These probabilities were calculated using the Eqs. 2 to 7. The probabilities of the null, light, moderate and severe damage states for each performance group are shown in Fig.5c, and Fig.5d shows the probability of each functionality limit state for each of the seismic intensities considered in the analysis. It can be observed that, if only the inspection of structural damage is performed, the tagging that most contributes to distribution probabilities, from the first to the fifth seismic intensity, is the structurally safe one, i.e., TAG=G. For the sixth and seventh seismic intensity, the structural unsafety of the building, i.e., TAG=R, starts to dominate mainly due to the damage in columns and column-beam connections. If these results were used to define a functionality limit state, the result would be that the building would continue in operation for earthquakes corresponding to the first five seismic intensities considered in the analysis, i.e., LQ0, while for the intensities with return periods of 1500 and 2500 years the building would have a functionality state of LQ2 and LQ3, respectively, and the respective activities would have to be carried to recover the functionality. However, if the non-structural components are considered in the post-seismic evaluation, the inspection results would be completely different. It may be observed in Fig.5b, corresponding to a Sa (T1) = 0.22g, that the probability of the building being tagged with restricted use, i.e., TAG = Y, given that moderate and light non-structural damage occurs is approximately 50%, probability not negligible. This result can be verified in Fig.5c, which indicates approximately that the probability of experiencing light and moderate damage is 50% and 10%, respectively. The state of functionality that most contributes to the functionality loss is the LQ1, with a 70% probability, as can be seen in Fig.5d.

Table 1 – Probability distribution parameters for damage states and unit time reparation [24]

Item	Performance Group	Engineering Demand Parameters (EDP)	Damage State (DS)	Probability Distribution	Parameters for Damage States		Unit	Probability Distribution	Parameters for Reparation Time (days)	
					μ	σ			μ	CV or σ
Structural	Columns	Drift	DS1 (sec.)	Lognormal	0.02	0.4	unitary	Normal	15.1	0.46
			DS2 (sec.)	Lognormal	0.0275	0.3		Normal	24.3	0.39
			DS3 (sec.)	Lognormal	0.05	0.3		Normal	28.9	0.39
			DS4 (exc. DS2, DS3)	Lognormal	0.05	0.3		Normal	24.3	0.39
	Column-Beam Connections	Drift	DS1 (sec.)	Lognormal	0.015	0.4	unitary	Normal	15.1	0.46
			DS2 (sec.)	Lognormal	0.0175	0.4		Normal	24.3	0.39
			DS3 (sec.)	Lognormal	0.02	0.4		Normal	28.9	0.39
Non-structural	Masonry Walls	Drift	DS1 (sec.)	Lognormal	0.0018	0.73	100 m^2	Lognormal	0.376	0.44
			DS2 (sec.)	Lognormal	0.0051	0.65		Normal	2.71	0.27
			DS3 (sec.)	Lognormal	0.0086	0.56		Normal	4.76	0.29
	Gypsum Walls	Drift	DS1 (sec.)	Lognormal	0.005	0.4	120 m^2	Normal	1.47	0.51
			DS2 (sec.)	Lognormal	0.01	0.3		Lognormal	2.8	0.61
			DS3 (sec.)	Lognormal	0.021	0.2		Lognormal	5.74	0.32
	Exterior Windows	Drift	DS1 (sec.)	Lognormal	0.0156	0.35	unitary	Lognormal	0.696	0.28
			DS2 (sec.)	Lognormal	0.0561	0.3		Lognormal	0.696	0.28
	Ceilings	Max. Floor acceleration (g)	DS1 (sec.)	Normal	1.47	0.3	55 m^2	Normal	0.463	0.6
			DS2 (sec.)	Lognormal	1.88	0.3		Lognormal	3.7	0.58
			DS3 (sec.)	Lognormal	2.03	0.3		Lognormal	7.67	0.32
	Sprinklers	Max. Floor acceleration (g)	DS1 (sec.)	Normal	1.1	0.4	30 m	Lognormal	0.369	0.7
			DS2 (sec.)	Normal	2.4	0.5		Lognormal	0.313	0.48

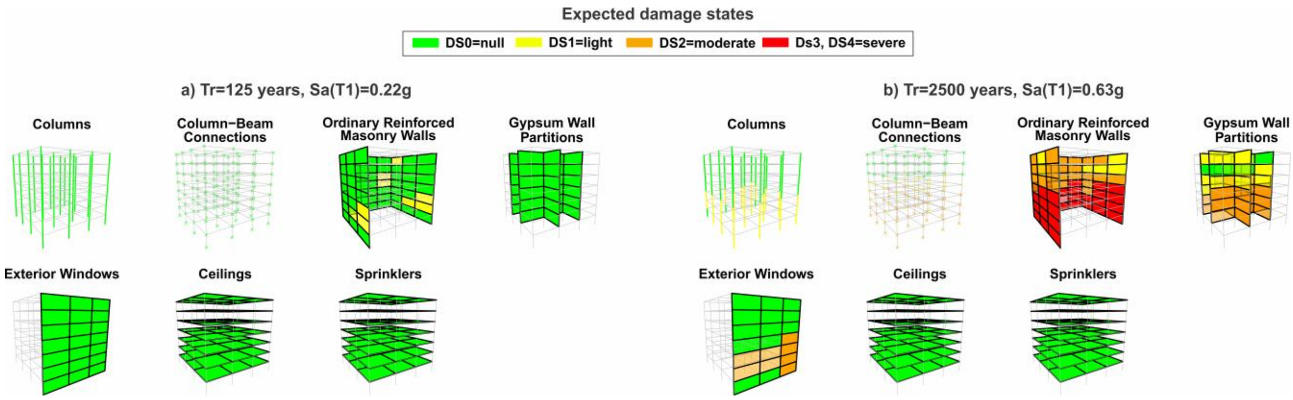

Fig. 4 – Expected damage states for the performance groups for (a) 125 and (b) 2500 years return period

Performing a similar analysis for the seventh intensity, i.e., Sa(T1) = 0.63g in a return period of 2500 years, it is observed that the probability of the building being tagged as unsafe, given the occurrence of severe structural and non-structural damage is between 80 and 100%. These results can be verified visually in Fig.4b, where it may be observed that most of the columns in the first three levels of the building experience slight damage, while the column-beam connections experience moderate damage in the first four floors. This pattern of damage causes the building to be declared unsafe since the structural elements were inspected. Regarding the non-structural components, in the same figure, it may be observed that the masonry walls experience severe damage in the first four floors, and moderate damage in most of the elements located in the rest of the floors; gypsum interior walls are also expected to experienced moderate and light damage. At this intensity, it is also expected that exterior windows, located on the first three floors, will experience moderate damage, and may fall either inside or outside the building, causing serious injuries to users or bystanders. Another way to verify these results is from the probabilities of the different damage states of all the performance groups, indicated in Fig.5c. Given this intensity, the functionality limit states that most contribute to the distribution of probabilities are LQ3 and LQ5, both with 50% probability. The latter corresponds to the probability of the building will collapse. For lower intensities, this probability event is practically null.

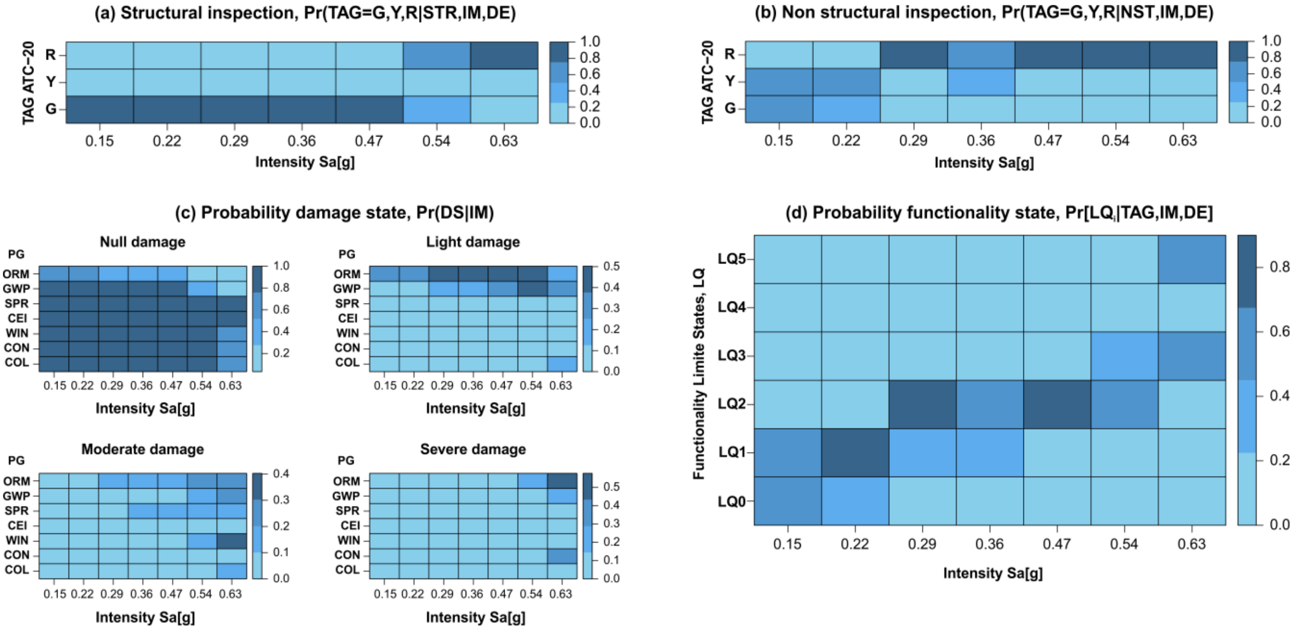

Fig. 5 – (a) and (b) probability TAGS for structural and non-structural inspection; (c) probability of damage states given a seismic intensity; (d) probability for functionality states

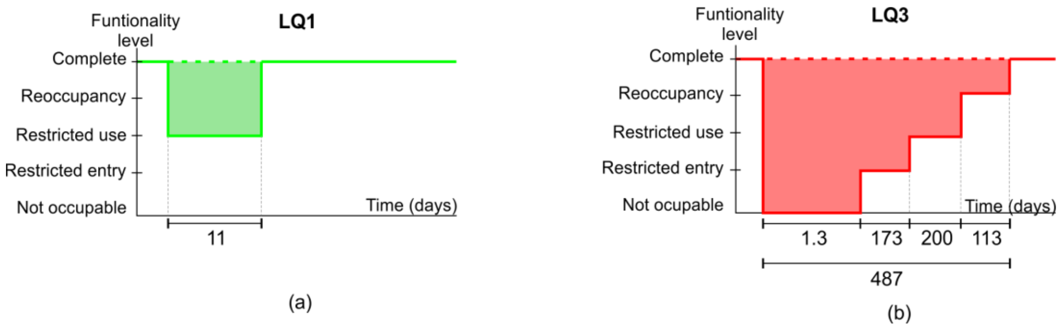

Fig. 6 – Mean recovery time for the (a) LQ1 and (b) LQ3 limit functionality states

Figure 6 schematically shows the generic pattern of functionality loss and recovery for the analyses corresponding to the 0.22g and 0.63g intensities, associated to a return period of 125 and 2500 years, respectively. For the first case, as mentioned earlier, the functionality state that contributes the most to the distribution is LQ1. The generic activities that must be carried out in this state are inspection, where it is concluded that the building is safe, but the non-structural elements experience slight damage, and the repair of these elements need to be done. The mean recovery time of the building for this seismic intensity is approximately 11 days, see Fig.6a. In the second case, from the inspection it is determined that the building is not safe due to the amount and severity of the structural and non-structural damage. In this functionality limit state, LQ3, the generic activities that must be carried out for the building to be functional again are: 1) post-seismic inspection, 2) structural redesign, 3) obtaining financial resources to pay for repairs, 4) biddings to determine who will perform the repairs, 5) obtaining government permits, 6) structural repairs to make the building re-occupiable, and 7) non-structural repairs so that the building recovers its functionality completely. The mean recovery time to restore the functionality for this intensity is approximately 487 days.

6. Conclusions

This paper presented a methodology to evaluate the functionality loss and recovery of RC buildings considering non-reinforced masonry walls damaged by moderate and high seismic intensities. The methodology presented allows to know the damage patterns that are likely to affect structural and non-structural safety. In turn, these damage patterns can be associated with generic events of functionality loss and recovery, to which certain recovery activities can be assigned. With this information, it is possible to calculate the mean time that it takes to recover the functionality in probabilistic terms. The evaluation of recovery time can represent a valuable parameter in decision making regarding a particular structural design or evaluation of an existing facility. Often, the decision variable used in the practice structural risk is the direct costs; however, several authors have indicated that the recovery time of a damaged building is easier to interpret by decision makers since, from this variable, the indirect financial economic losses can be roughly estimated, that is, those corresponding to the time the building stopped operating. Likewise, trying to reduce the magnitude of this decision variable can indirectly reduce the risk associated with the loss of human lives. The methodology presented in this document is consistent with the definition of structural resilience proposed by the MCEER, with the probabilistic methodology for evaluating seismic performance developed by PEER, and with the post-seismic inspection criteria recommended by ATC-20, including the evaluation of the non-structural elements.

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