# Probabilistic Evaluation of Post-earthquake Functional Recovery of a Seismically Isolated RC Building

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**Abstract.** All earthquakes throughout history have taught us that damage to non-structural elements and content has serious repercussions on the direct economic cost of damage and functionality. In essential buildings such as hospitals, rapid functional recovery is essential to safeguard the lives of the occupants and the injured who arrive after the earthquake. This study presents the detailed evaluation of the functional recovery of a RC seismically isolated 8 story hospital building located in an area of high seismicity. The study is carried out using the probabilistic analytical framework F-Rec, which has been recently proposed in the literature for the evaluation of the functional recovery of buildings after an earthquake. This framework complements the FEMA P-58 performance evaluation methodology allowing a complete and detailed evaluation of post-earthquake functionality, duration of damage and the path of functional recovery, considering structural and non-structural elements and content. In this study, a non-linear model of the building is created in OpenSees and the seismic response is studied for three hazard scenarios, Service Level Earthquake (SLE), Design Based Earthquake (DBE) and Maximum Considered Earthquake (MCE). Based on the results of the non-linear analyses, the damage losses are calculated using the FEMA P-58 tool, while the building recovery process is evaluated using the F-Rec framework. The efficient functional recovery time and route are analyzed for each scenario. The results show that the F-Rec framework is a viable tool for the evaluation of the post-earthquake functionality of isolated hospital buildings, but that there is a need to develop specific fragility and recovery curves for medical equipment.

**Keywords:** Functional Recovery, Non-Structural Elements, Seismic Isolation, Probabilistic Recovery Curve, Hospital Building.

# 1. INTRODUCTION

Lessons learned from past earthquakes indicate that hospitals or health centers are the most important buildings after a seismic event. To date, structural seismic performance and design is a well-studied subject, and there are advanced techniques that allow structural protection of this type of building. However, seismic performance today is still a delicate and little studied issue due to the complexity involved in understanding what would be the best methodology that allows continuous functionality of all components and non-structural elements after an earthquake. One of the most notable events in history is the Loma Prieta earthquake in 1989 with Mw=6.9, which caused great economic and human losses due to damage to the content and non-structural elements. As a solution, seismic base isolation is currently the most accepted and effective means of protecting this type of essential building. The safety of the occupants has been the main objective of the system, therefore, guaranteeing zero damage to the structure is essential and also minimizing accelerations and speeds, which are the cause of damage to non-structural elements and highly expensive components.

As medical technology advances, hospital-type buildings are becoming more expensive due to the implementation of new medical equipment and the high performance that hospitals in general must have. The seismic design of this type of buildings is controlled by the seismic performance design methodology based on a set of strict performance criteria for the structure and the non-structural elements and contents, ensuring life, the non-probability of collapse and continuity of use. However, seismic resilience and functional recovery time after an earthquake are not considered in structural design as the tools and methodologies to assess these parameters were not available until recently. Everything mentioned refers to a hospital-type building on a fixed base, however, considering the same building, but on an isolated base, there is still no information that explains how the functional recovery curve is, taking into account that the performance of the building isolated is very different from a building on a conventional basis.

Currently the most significant methods for modeling the post-earthquake recovery of buildings, these being the REDi model that complements the FEMA P-58 methodology and estimates the recovery time (downtime), without explicit consideration of the post-earthquake functionality of the building in a limit state, this being one of its main disadvantages. On the other hand, recently there is a new tool called F-Rec (Figure 1) that suggests a complete and detailed evaluation of the seismic performance of buildings considering all the structural and non-structural components/systems of the building and the calculation of performance metrics relevant to the building and evaluation of the entire recovery process, including the post-earthquake functionality of the building along with the duration and path of functional recovery. The new framework for modeling functional recovery is in line with the PBEE (probabilistic performance-based earthquake engineering).

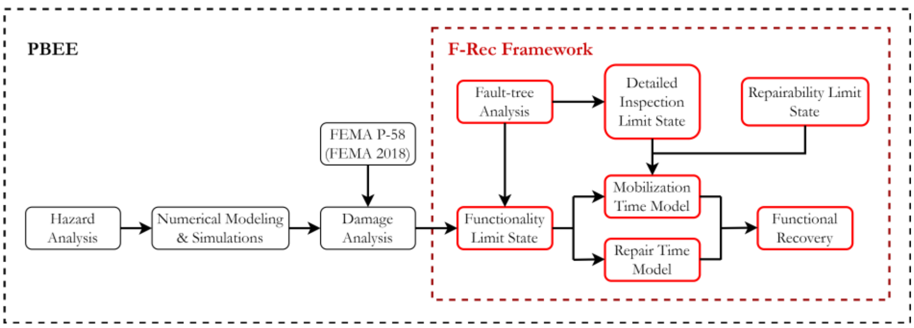



Figure 1. F-Rec framework for modelling functional recovery in conjunction with PBEE/FEMA P-58 methodology (Terzic et al. [2021]).

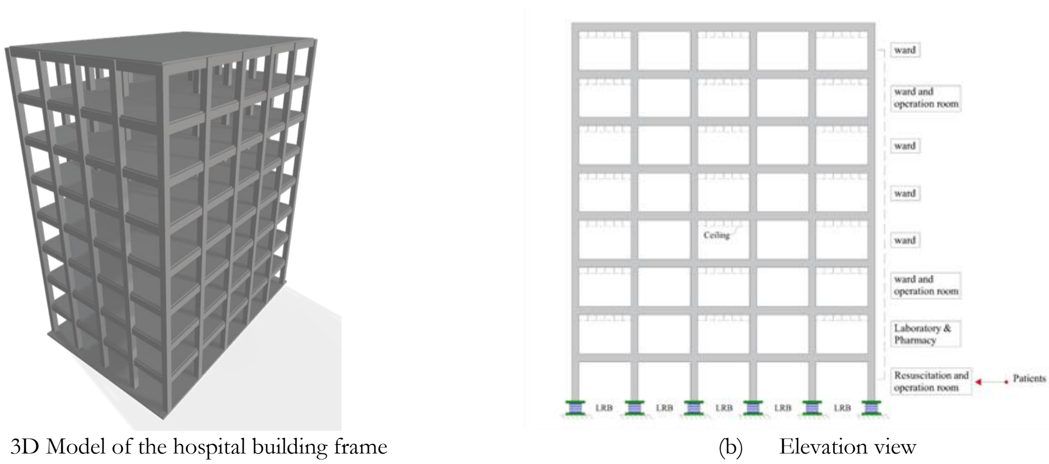
## 2. RESEARCH METHODOLOGY

The present study applies the new probabilistic functional recovery method F-Rec proposed by Terzic et al. [2021] to an essential hospital-type building with a regular structure of 8 floors. The building has been designed in a zone of high seismic hazard and includes base isolation. First, the seismic response of the building is analyzed for a set of far-field seismic records selected following FEMA P-695 [2010] recommendations. To this end, nonlinear time-history dynamic analyses of the typical building frame are conducted using OpenSees (Open System for Earthquake Engineering Simulation) platform (McKenna [2000]). The story drift and accelerations demand obtained from the analyses are used to estimate probabilities of damage in structural and non-structural components following the FEMA P-58 methodology through the PACT software [2018b]. Fault trees and component recovery functions are then used to evaluate the functional recovery of the building following the F-Rec method. The main result obtained by applying this new method is the functional recovery curve which provides information on the post-earthquake functionality expressed as a percentage of the area within the building with preserved functionality.

## 3. BUILDING DESCRIPTION AND DESIGN

The analyzed building has eight floors and is located in Los Angeles. It has a height of 32 m and a total weight of 62229 kN. The building has reinforced concrete moment-resisting frames in each direction and is isolated at the base using elastomeric isolators with a central lead core (Figure 2).

The structure has been designed for a CD type soil and has a seismic risk category IV. The spectral acceleration parameter for short periods is $S_S = 2.22$ and the acceleration parameter for a period of one second is $S_1 = 0.74$, in accordance to current ASCE 7-22 recommendations. The basic design spectrum (DBE) shown in Figure 3 has been considered for the analysis and design of the building. The design is carried out using the method of forces and the final drifts are verified with nonlinear analysis to comply with the HAZUS damage-drift relationship methodology [2013]. The ductility reduction factor R have been taken as 1.5 following ASCE 7-22. The columns have square sections with side of 0.60 m and are spaced 5 m on the X axis and 4.30 m on the Y axis. The beams are 0.35 m wide by 0.75 m high, and the slabs are solid with a thickness of 0.25 m. The design of all the structural elements has been carried out to maintain the building structure elastic against a maximum considered earthquake (MCE), the cross sections are the minimum to be used to obtain drifts and accelerations below the limit of structural and non-structural damage.




(a) 3D Model of the hospital building frame (b) Elevation view

Figure 2. Scheme of hospital building structure

# 4. GROUND MOTION SELECTION

A set of 44 seismic records has been used from the FEMA P-695 far-field ground motions set, comprising 22 pairs of earthquakes records for C/D type soils ($V_{s30} = 365$ m/s). The building site is located at a longitude = -118.2074° and latitude = 34.042°. The set consists of large magnitude (magnitude 6.5 $M_w$ or greater) slip or reverse earthquakes, of which 16 earthquakes were recorded in type D soil (rigid soil) and 6 earthquakes in type C soil (very rigid soil), which coincide appropriately with the location of the building. Each seismic record went through the process of baseline correction, bandpass filtering and scaling to 3 levels of seismic hazard, service earthquake (SLE), design earthquake (DBE) and maximum considered earthquake (MCE). SeismoSignal software [2022] was used for the filtering and correction process and SeismoMatch [2022] for scaling and spectral adjustment, the adjustment and scaling process was carried out for the entire response spectrum, considering not to be below 90 % and 110 % of the target spectrum. Shown in Figure 3 are the 44 earthquakes and the spectra for each level of seismic hazard, respectively.

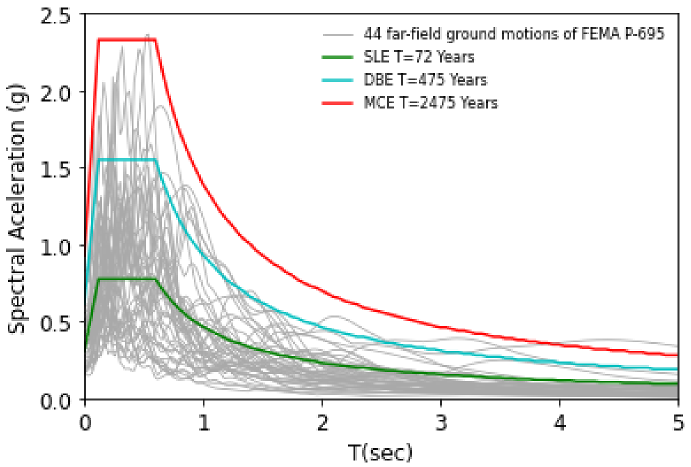
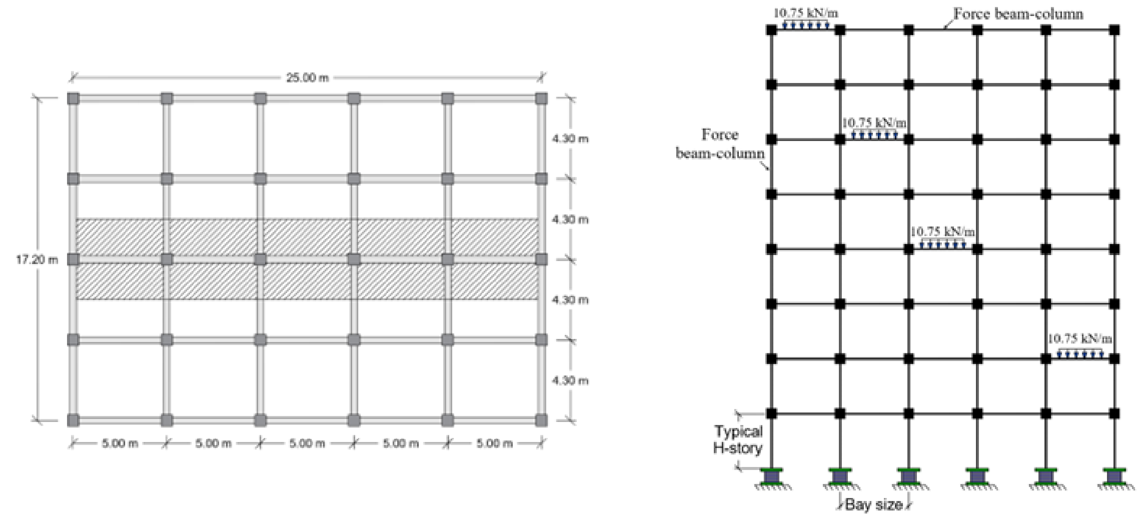



Figure 3. Design spectra and individual spectra of 22 pairs of unscaled records

# 5. STRUCTURAL MODELING

## 5.1 BUILDING MODELING

The central main frame was chosen in the X axis of the building for the modeling, Figure 4b shows the scheme of the model developed in the OpenSees [2000]. All building elements were modeled to allow entering the plastic range using forceBeamColumn elements with distributed plasticity. The analysis was performed in two dimensions and the total tributary weight was evenly distributed among the six nodes corresponding to each floor, including the base floor. According to Ryan and Polanco [2008], the damping for an isolated building has to be only proportional to the stiffness, thus avoiding applying excessive artificial damping at frequencies lower than the fundamental frequency of the superstructure. The fundamental period of the fixed base building analyzed here is 1.00 s, inserting the seismic isolation system, the period of the building is 3.10 s.




(a) Plan view with a tributary area of the main frame (b) Frame model in OpenSees

Figure 4. Building modeling

## 5.2 SEISMIC ISOLATION MODELING

Lead rubber bearings (LRB) were used as isolators. The lateral response of the LRB is represented by a bilinear load-displacement law, following the approach of Erduran et al. [2011], consisting of an assembly of an elastic column, an elastic-perfectly plastic horizontal spring and a nonlinear vertical elastic spring, as shown in Figure 5. The general properties of these isolators are shown in the following table:

**Table 1. Properties of LRB isolators**

| Device | $K_l$ (kN/m) | $Q_d$ (kN) | $\alpha_1$ | $D_{ext}$ (m) | $H_t$ (m) | $\xi_D$ (%) |
|---|---|---|---|---|---|---|
| **LRB** | 11298.30 | 105.75 | 0.02 | 1.00 | 0.40 | 20 |

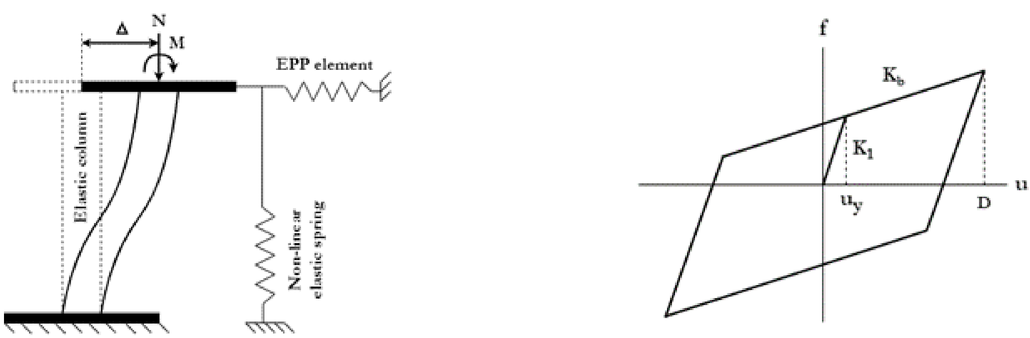
$Q_d = Characteristic\ Strength$

$\xi_D = Equivalent\ Damping\ Ratio$

$D_{ext} = Outer\ Diameter$

$H_t = Total\ Height$

$\alpha_1 = Ratio\ of\ Initial\ Stiffness\ to\ Post-yield\ Stiffness$

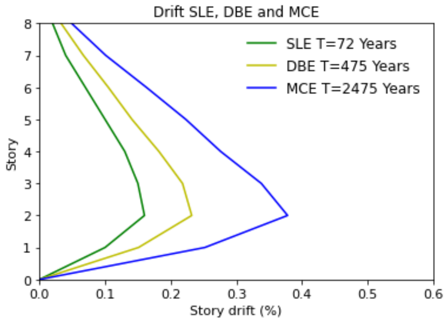



(a) Column model with lateral and vertical non-linear spring (b) Resultant lateral force–displacement hysteresis of the model

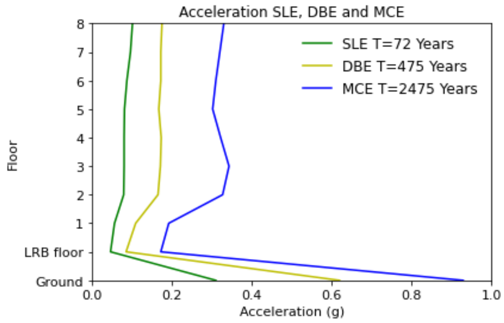
Figure 5. LRB hysteretic model

# 6. NONLINEAR ANALYSIS RESULTS

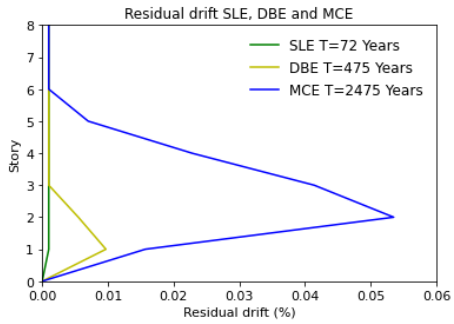
The results of the nonlinear time-history dynamic analyses for the three hazard levels are shown in Figure 6. The plotted results correspond to the mean values of the peak story drift values, peak floor accelerations and residual story drift at each level as obtained from the 44 seismic records. As a reference, these results are compared with the recommended limits in REDi [2013], which indicates that a hospital has a platinum category with downtime of maximum 72 hours. The HAZUS [2013] indicates that the maximum drift for an essential building should be 0.33 % to avoid structural damage and acceleration 0.30 g to avoid non-structural damage. It can be observed that for the service earthquake (SLE) the maximum value of the average peak story drift is 0.16 % (second story) and the maximum average value of the peak acceleration is 0.1 g (eighth floor). For the design earthquake (DBE) and maximum considered earthquake (MCE), the maximum value of the average peak story drift is 0.232 % and 0.378 %, respectively, in the second story, while the maximum average value of the peak acceleration is 0.175 g and 0.33 g, respectively, in the eighth floor. It can be seen that thanks to the isolation system, the drifts are relatively small even for the MCE. Accelerations are also greatly reduced thanks to the isolation system; it is observed that they are very similar at all levels. Finally, Figure 6d shows the hysteretic loop of a central isolator for an MCE earthquake, where it is observed that the maximum displacement is 0.75 m.



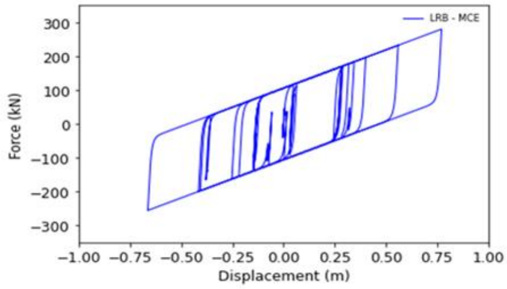

(a) Mean values Drift




(b) Mean values Accelerations




(c) Mean residual drift




(d) Hysteretic model example for an isolator in MCE

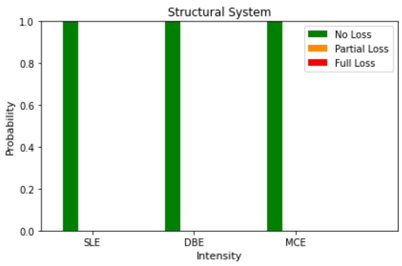
Figure 6. Non-linear response of hospital building

# 7. PERFORMANCE AND FUNCTIONAL RECOVERY EVALUATION

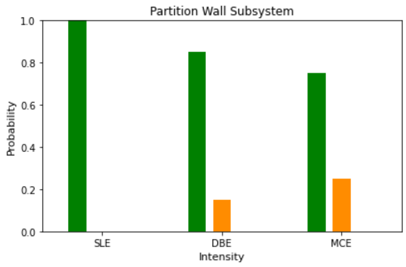
## 7.1 PERFORMANCE EVALUATION PER FEMA P-58

The results of the nonlinear analyses obtained in section 6 were incorporated into the FEMA P-58 PACT software, which creates a performance model for the evaluation of damage to structural and non-structural elements. The performance model in PACT includes fragility curves suitable for all types of structures, architecture, and mechanical components in the building. To evaluate the damageability performance in a probabilistic way, Monte Carlo simulations of building response and damage are conducted considering 2000 realizations for each level of seismic hazard. For the calculation of the residual drift, the recommendations of volume 1 of the FEMA methodology P-58-1 [2018a] will be taken, in this case since it is a building with seismic isolation, the structural damage is null, which it is more important to evaluate the damage in the nonstructural elements and content. In the FEMA volume 1 methodology, 4 states of damage are indicated (DS1, DS2, DS3 and DS4), for this work it will be considered to limit the residual drift to the DS1 state, which indicates that structural realignment is not necessary for the stability of the building, however, the building may require adjustments and repairs to mechanical and non-structural components that are sensitive to the alignment of the building. Figure 6c shows how the residual drifts appear at the DBE and MCE earthquake levels, but with very low values.

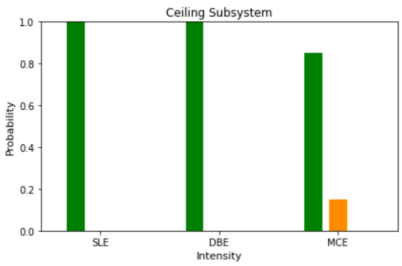
The types and quantities of structural elements (beams, columns and slabs) have been determined from the building design and introduced in PACT. The non-structural components and general building equipment (elevators, stairs, exterior walls and partitions, roofs, water system, medical gas systems, etc.) are modeled in their respective locations and their quantities are determined using FEMA P-58 recommendations and hospital architecture research references by Yu et al. [2019] and Elfante et al. [2019]. In PACT, each component of the building is associated with a fragility curve that correlates the seismic demand (story drift or acceleration) with the probability that this element reaches a particular state of damage. In figure 7a it can be seen how the structural system presents zero damage for the 3 levels of seismic hazard evaluated, thanks to the base isolation. In Figure 7b, 7c y 7d, it can be seen that for the dividing walls there is a 15 % and 25 % partial loss for DBE and MCE earthquakes, respectively. However, for the ceiling there is a 15 % partial loss only for the MCE earthquake and for the piping there is no loss in the 3 hazard levels.



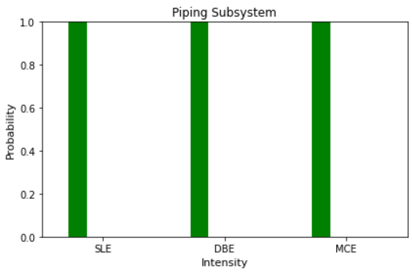

(a) Probability of structural system damage




(b) Probability of the partition wall damage



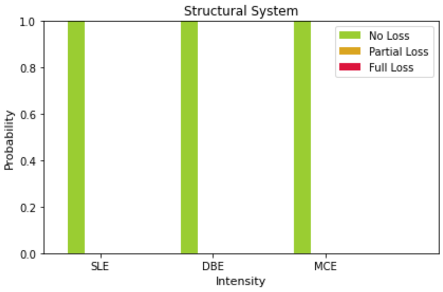

(c) Probability of the ceiling damage



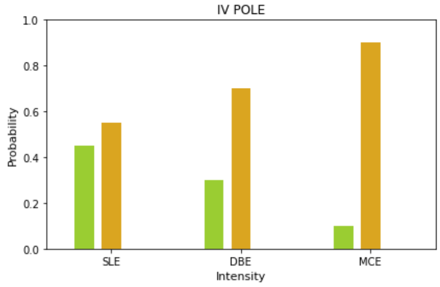

(d) Probability of the piping damage

Figure 7. Damage states without medical equipment

A second model of the model has been defined in PACT by also considering basic medical equipment for a hospital with an operating room. In the chapter 3 Figure 2b presents the distribution of operating rooms in the building. The fragility functions for this medical equipment were not available by default in the software and have been defined from the investigations by Yu et al. [2019] and Elfante et al. [2019]. As shown in Figure 8b, the IV Pole equipment in ward rooms presents a probability of partial loss of 55 %, 70 % and 90 % for SLE, DBE and MCE respectively. For the hospital bed there is a partial loss of 40 % for the MCE earthquake (Figure 8d). For the operating rooms, damage is only seen in the trolley carts with a partial loss of 10 %, 20 % and 30 % for SLE, DBE and MCE earthquakes, respectively (Figure 8d).

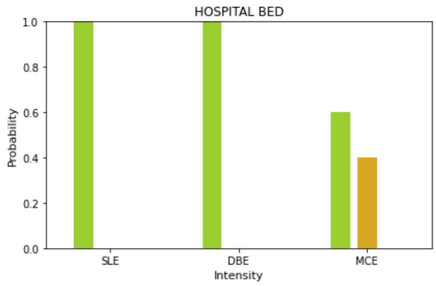



(a) Probability of structural system damage




(b) Probability of the IV Pole damage


(c) Probability of the trolley cart damage




(d) Probability of the hospital bed damage

Figure 8. Damage states with medical equipment

## 7.2 FUNCTIONAL RECOVERY EVALUATION

The functional recovery analyses are conducted based on the results of the damage assessment obtained with the FEMA P-58, the fault trees of the building and its subsystems, and the limit state functions of the building components that define probabilistically the damage thresholds affecting the building. This study uses fault trees proposed for components of basic and essential medical care in a hospital. Figure 9 shows the process that has been followed for the evaluation and recovery of the isolated hospital building.

Data for the evaluation of damage and functionality in core elements in the F-Rec tool (Terzic and Villanueva [2021]) were originally obtained from recommendations from facility managers, builders, and structural engineers. It is worth mentioning that the present study considers two models for recovery evaluation: one neglecting basic medical equipment and the other considering it.

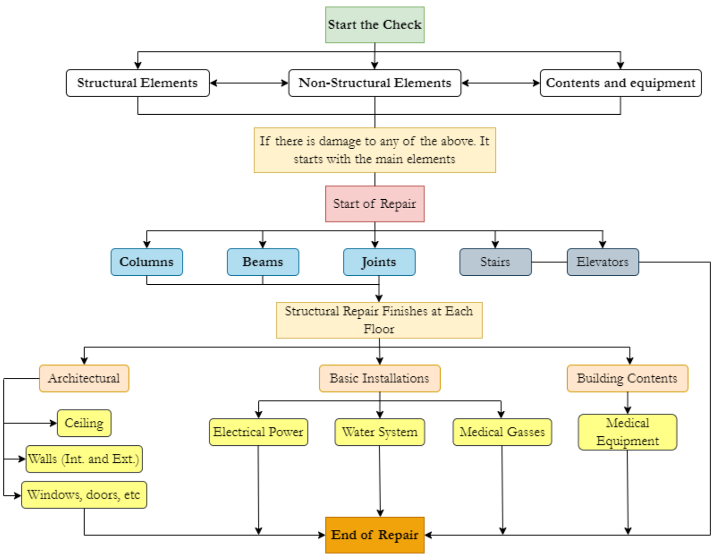
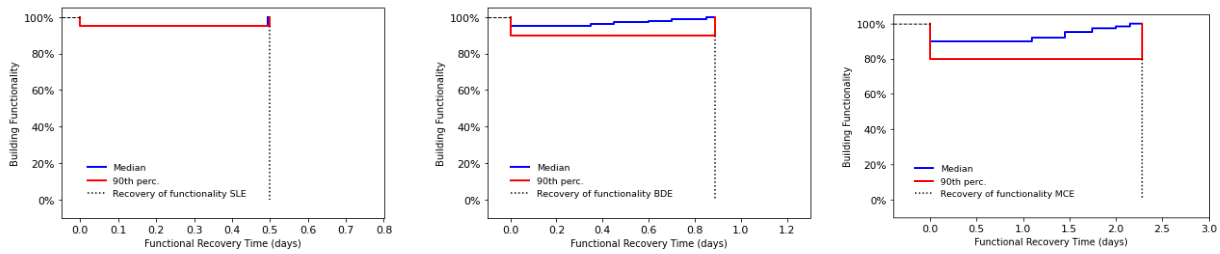



Figure 9. Proposed flowchart for evaluation and functional recovery of the isolated hospital

Figure 10 shows the functional recovery curves for the 3 levels of seismic hazard when neglecting medical equipment. This figure provides the median and the 90th percentile that show the change in the capacity of the building from the occurrence of the earthquake (time = 0) until the building fully recovers its function. Figure 11 shows also the cumulative distribution functions of functional recovery time for the 3 hazard levels. The building is expected to fully regain its function in 12.00 hours for frequent earthquakes (SLE), it takes 21.36 hours for rare earthquakes (DBE), and 2.28 days for very rare earthquakes (MCE).



(a) SLE hazard level (b) DBE hazard level (c) MCE hazard level

Figure 10. Functional recovery evaluation without medical equipment

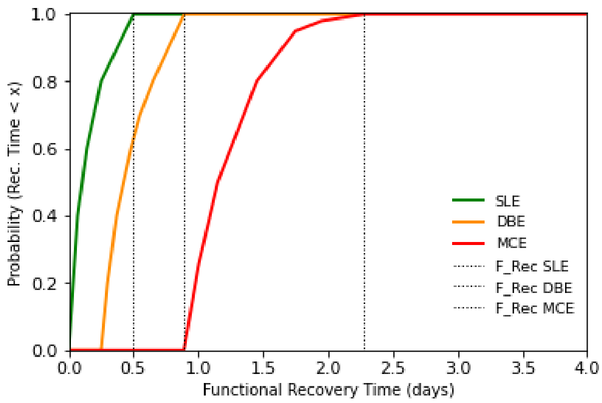
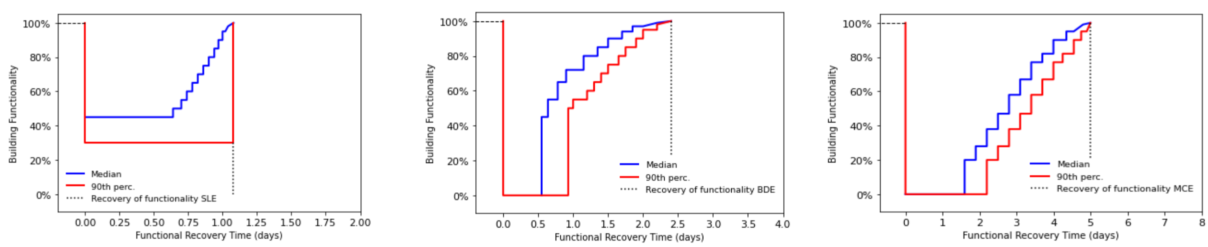


Figure 11. Functional recovery evaluation results at three considered hazard levels without medical equipment

Figure 12 shows the functional recovery curve for the 3 levels of seismic hazard in the hospital considering the influence of the medical equipment. As shown in Figure 13, the building is expected to fully recover its function in 1.08 days for frequent earthquakes (SLE), 2.40 days for rare earthquakes (DBE) and 5.00 days for very rare earthquakes (MCE). Hence, the expected recovery time increase by a factor of 2 to 5 when considering medical equipment



(a) SLE hazard level (b) DBE hazard level (c) MCE hazard level

Figure 12. Functional recovery evaluation with medical equipment

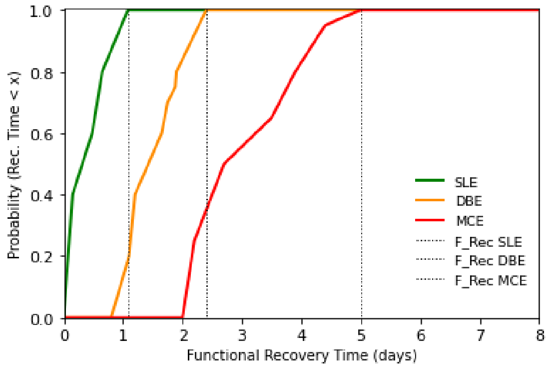



Figure 13. Functional recovery evaluation results at three considered hazard levels with medical equipment

## 8. CONCLUSIONS

The present study has investigated the functional recovery of an eight-story hospital with base isolation located in an area of high seismicity. Based on the results of nonlinear analyses, damage impaired losses are calculated using FEMA P-58 tools, while the building's post-earthquake functionality along with the path of the building's functional recovery are evaluated using the recently-proposed F-Rec framework.

The results of the present study indicate that post-earthquake functionality of the building with base isolation is mainly governed by the performance of the non-structural elements and equipment. Full functional recovery is expected to be achieved at 12 hours, 21 hours and 2.3 days for SLE, DBE and MCE, respectively when neglecting medical equipment. When considering basic medical equipment, recovery times increase to 1 day, 2.4 days and 5 days for SLE, DBE and MCE, respectively. Based on these results, it is concluded that a detailed assessment of the medical equipment damage is necessary for an accurate estimation of the functional recovery of this type of buildings. Hence, it is critical to develop specific fragility and recovery functions for such equipment.

## ACKNOWLEDGEMENTS

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