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Seismic life-cycle functional recovery analysis of corroded reinforced concrete buildings

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Abstract

Rapid economic and population growth in high-seismic regions and increased vulnerability of aging infrastructure has raised seismic risk around the globe. Recently, functional recovery paradigm has been introduced as a holistic approach to include not only conventional safety criteria but also novel resilience measures in seismic performance assessment and design of buildings. This paper presents a new component-based seismic multi-dimensional functional recovery analysis method for reinforced concrete (RC) building structures and explores corrosion impact on its lifecycle functionality. Various structural and non-structural components affecting occupancy or serviceability of the building are included in loss analysis using FEMA P-58 fragility specification database. Multi-dimensional functionality curves, including asset, occupancy, and serviceability functionality curves, are developed to depict the post-earthquake recovery path. A new method is introduced to evaluate a holistic resilience index evaluated based on functionality curves. Intensity-based approach is used to quantify seismic monetary loss and downtime. Time-history and incremental dynamic analyses are used to develop fragility functions. A set of 4-story RC building archetypes located in a high seismic region are studied. Further, the impact of corrosion in various stories on seismic resilience and functional recovery of RC frames is studied. Uncertainty in demand, modelling, and component-level seismic losses are included. Finite element models of corroded and uncorroded RC archetypes are developed in OpenSees. The recently developed SFI-MVLEM element is used to model the dynamic nonlinear behavior of shear walls. Results indicate that high-intensity earthquakes result in significant loss of occupancy while low-intensity earthquakes cause a noticeable loss of serviceability and minor loss of occupancy.

Key words: Seismic Resilience, Functional Recovery, Life-cycle Assessment, Corrosion, RC Buildings

1 Introduction

Rapid population growth and economic developments in earthquake-prone regions and increasing vulnerability of aging buildings and lifeline infrastructures have significantly increased the seismic risk in the last decades. Per National Geophysical Data Center (NGDC), 128 significant earthquakes (M7.0 or greater) have occurred worldwide in last decade which have claimed 335,000 lives, destroyed around 600,000 houses, and caused hundreds of billion US dollar damage [1]. To minimize seismic loss and casualties, recent studies advocate an all-inclusive resilience-based approach that incorporates functional recovery on top of traditional safety-based approach [2–4].

Resilience is the capability of the system to resist, adapt to, and recover from a disruptive event. Resilience can be studied in four phases: anticipation, absorption, adoption, and recovery [5]. Seismic resilience can be achieved by reducing the probability of failure, the seismic consequence/loss, and the time needed to restore the intended functionality. Post-event recovery time may include the time required for inspection and safety evaluation, finance and engineering planning, repair of various structural and non-structural components, repair of access routes and utility services, and inhabiting the building again [6]. For building environments, the consequence and loss due to an earthquake may include monetary loss, casualties, injuries, fatalities, and any other economic and social impacts. Asadi et al. [7] proposed a multi-criteria decision model to include various economic, social, and environmental criteria in resilience assessment of building structures. The model quantifies resilience indicators such as seismic loss and downtime discretely and then integrates them using multi-attribute utility theory. Reinhorn and Cimellaro [4] considered two scales, i.e. spatial and temporal scales, for resilience evaluation of a community and proposed a seven-dimension framework for community functionality assessment which includes population, environmental, governmental, economic, and social/cultural dimensions. For their case study, they study a health care facility and used asset loss as an indicator of the functionality of a building facility. In a number of publications including a recent book, Cimellaro et al. provide various methodologies to assess community resilience and quantify resilience based on asset losses [8,9].

The new paradigm of functional recovery aims to introduce new design provisions based on recovery time, a much-needed supplement to the widely-integrated safety-based design provisions [3]. Design for functional recovery is supported by National Earthquake Hazards Reduction Program (NEHRP) and Earthquake Engineering Research Institute (EERI) as an imperative element of resilience-based community management. Recent studies focus on community resilience [6,10]. However, building facilities are commonly designed as a discrete structure based on the owner's preference and design standards. Therefore, a functional recovery design framework needs to present a quantitative method to find the recovery time for a distinct facility considering the interdependent impact of lifeline infrastructure. The partial interdependency between buildings and lifeline systems further complicates the problem indicating the need for a multi-dimensional approach in resilience quantification of building facilities. For building facilities, the first objective following an earthquake is to reoccupy or re-enter the building and restore the shelter-in-place function of the building. The next step is to achieve functional recovery where all building's services need to be restored to achieve the intended operation/function of the building [3].

This paper presents a new multi-dimensional framework for functional recovery analysis and resilience quantification of reinforced concrete (RC) building facilities. Three measures defining the seismic functionality of building facilities are considered, which are asset, occupancy, and serviceability losses. The model is consistent with FEMA P-58 approach for loss analysis and considers the loss and downtime due to various structural and non-structural components of the building in resilience quantification. The framework is implemented on two groups of RC buildings archetypes located in a highly seismic region using a scenario-based approach. The impact of corrosion in various stories on seismic resilience and functional recovery of RC frames is studied. Uncertainty in demand, modelling, and component-level seismic losses are included. Finite element models of corroded and uncorroded RC archetypes are developed in OpenSees [11].

2 Multi-dimensional functionality analysis

2.1 Functionality based on Loss of Occupancy

The area under the functionality curve is commonly used to quantify resilience. Burton et al. [6] considered the number of occupants (housing capacity) as an indicator of the functionality. Occupancy (housing capacity) is measured in person-days for a community. To restore occupancy, the components affecting the occupancy need to be repaired, which include structural components such as beam, columns, shear walls, braces, slabs, and connections and non-structural components such as exterior walls, curtain wall with windows, roof finishes, chimney, partition, stairs, doors, suspended ceilings, floor finishes, etc. Hence, occupancy-based recovery function of the building, $f_{R,Occ}$, is a function of repair time of those components, $t_{Rk,Occ}$, on various floors. Assuming a floor-by-floor repair scheme, the total time to restore occupancy is the summation of the repair time of all occupancy-related components for all floors.

$$f_{R,Occ} = \sum_{f=1}^{q} \sum_{k=1}^{p} \int_{t_{Rk,Occ}} f_{Rk,Occ}\left(t, t_E, t_{Rk,Occ}\right) dt \tag{1}$$

where f = 1, ..., q is the floor number, $f_{Rk,Occ}$ is the repair time function for component k among all p occupancy-related components of floor f.

2.2 Functionality based on loss of serviceability

The functional recovery of the building is not achieved until all utility services are restored as well. Services such as water/wastewater, electricity, conveying, air-conditioning, fire protection, gas, Internet, and equipment and furnishing need to be restored in order to achieve full functionality. Similar to occupancy, loss of serviceability of a building is due to damage to the components providing those services. Most of the non-structural components which provide serviceability are vulnerable to excessive absolute floor acceleration (ACC). Serviceability-based recovery function of a building, $f_{R,Serv}$, can be defined as a function of repair time of serviceability-related components on various floors, $t_{Rk,Serv}$. Similar to occupancy, the total time to restore serviceability is the summation of the repair time of all related components for all floors.

$$f_{R,Serv} = \sum_{f=1}^{q} \sum_{k=1}^{p} \int_{t_{Rk,Serv}} f_{Rk,Serv}\left(t, t_E, t_{Rk,Serv}\right) dt \tag{2}$$

Where $f_{Rk,Serv}$ is the repair time function for component k among all components required for restoring serviceability to floor f.

2.3 Functionality based on loss of asset

Functionality depends on (1) total loss, L_t, which is the summation of all monetary losses to all damageable structural and non-structural components due to earthquakes and (2) recovery function, f_R, which represents system rapidity. Recovery function can be developed using repair/recovery time and repair scheme which could be parallel, i.e. concurrent repairing all floors, or series, i.e. repairing each floor after completing the repair of lower floors. Therefore, functionality (Q) is defined as follows [8].

$$Q\left(t_E < t < t_R\right) = \left[1 - L_t\left(IM, t_R\right)\right] \times f_R\left(t, t_E, t_R\right) \tag{3}$$

where t_E, t_R, and IM are earthquake effective occurrence time, recovery time, and earthquake intensity, respectively.

3 Archetype building structures

The proposed model is implemented on a series of reinforced concrete (RC) buildings located in a small community near downtown Los Angeles, CA. The 4-story archetypes are designed per ASCE 7-16 [12] and ACI 318-14 [13] standards. Typical floor plan is adapted from (See Figure 1) [14,15]. To study corrosion impact on building functional recovery, the reinforcing steel of RCF model is assumed to experience corrosion. A strength decay method is adapted to model corrosion where the variation of steel stress-strain relationship is used to model the material degradation due to corrosion [16]. The corroded model is named RCF-C.

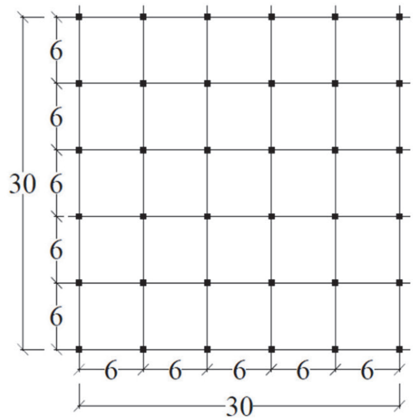

Figure 1. Typical floor plan for archetypes

4 Scenario-based seismic vulnerability analysis

Seismic resilience of buildings is assessed using a scenario-based approach. To find seismic intensity at the site, Boore and Atkinson [17] ground-motion prediction equations (attenuation function) are used. Three scenario earthquakes are considered: (S1) a M6.5 earthquake with an epicentral distance of 40 km, (S2) a M7 earthquake with an epicentral distance of 15 km, and (S3) a M8 earthquake with an epicentral distance of 5 km from the building site all with a shear-wave velocity from the surface to 30 m (V_{S30}) of 300 m/s. OpenSees models are validated by experimental studies [18]. More details on building structures and numerical models are presented in [15, 19, 20]. Collapse fragility curves are developed using Incremental Dynamic Analysis (IDA) and maximum likelihood method is used to fit a lognormal distribution function over the empirical collapse fragility curve [21]. Collapse fragility curves of archetype buildings are depicted in Figure 2. The horizontal axis is $S_a(T_1,5\ \%)$, the normalized pseudo-spectral acceleration for 5 % damped design spectra for the region at the fundamental period of the building structure. As depicted, the collapse capacity of the corroded RCF is noticeably smaller than that of original RCF model (with $S_a(T_1,5\ \%)$ of 2.98g for RCF compared to $S_a(T_1,5\ \%)$ of 2.04g for RCF-C). The corroded model fails at a noticeably smaller interstory drift ratio as well indicating smaller ductility for RCF-C model. The values are for RCF-C with an assumed 10 % corrosion level.

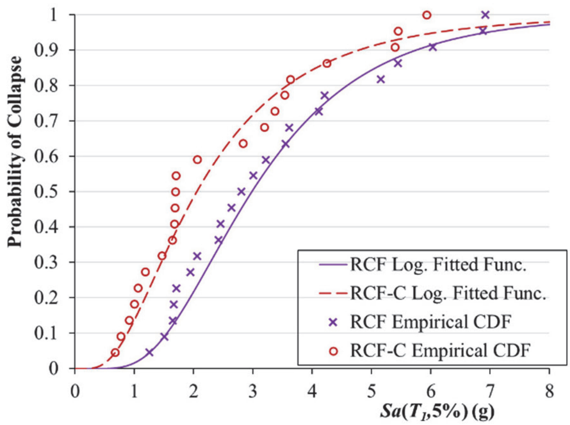

Figure 2. Empirical CDF of Sa (T_1,5 %) and fitted lognormal fragility functions for RC building archetypes

5 Functional recovery analysis

The proposed framework utilizes the repair time for components affecting various dimensions of functional recovery, which are occupancy or serviceability. Figure 3 depicts the floor-by-floor repair time for structural and non-structural components affecting occupancy or serviceability for various archetypes and scenarios. Non-structural damages are categorized to damages causing occupancy loss and damages causing serviceability loss. Structural damages primarily affect occupancy. Note that the non-structural damage and downtime shown at Roof are caused by damage to chiller and air-handling unit located on the Roof. As depicted, the downtime increases from Scenario S1, a low-intensity major earthquake, to Scenario S3, a significant earthquake. The RC archetypes experience little structural damage and downtime under S1 and relatively small non-structural damage and downtime under S2. Special RC frames can tolerate large lateral deformation before reaching minor damage limits. The downtime due to both occupancy and serviceability components increases significantly under S3. This indicates that a number of non-structural components have reached the severe damage state under S3. The corroded RCF collapsed under earthquake S3 (an M8 earthquake with an epicentral distance of 5 km) which highlights the undesirable impact of corrosion in a high intensity earthquake.

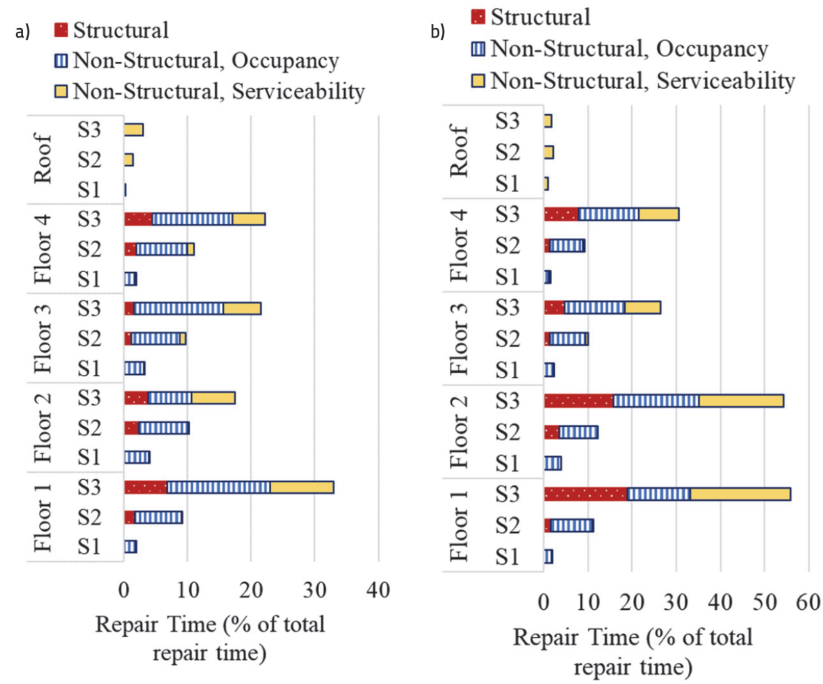

Figure 3. Floor-by-floor repair time for structural and non-structural components affecting occupancy and serviceability for (a) RCF and (b) RCF-C archetypes

5.1 Multi-dimensional functional recovery curves

The component-based loss and downtime fragility functions and median outputs are used to develop multi-dimensional functionality curves for archetype building and calculate the resilience index *R*. Three groups of functionality curves are produced. Figure 4 shows a sample FAL for RCF archetype under earthquake S2. The dashed lines in Figure 4a show the repair time for various components and the stepwise process by which the initial functionality is restored.

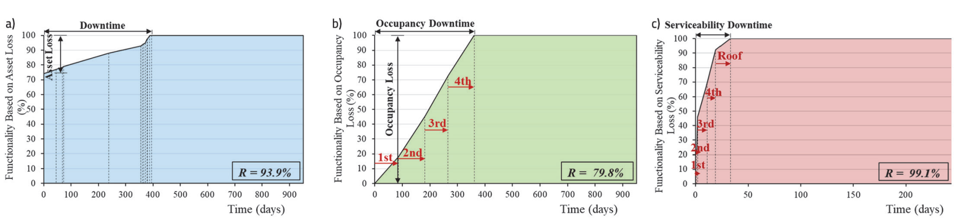

Figure 4. a) Functionality curve based on asset loss, b) functionality curve based on occupancy, and c) functionality curve based on serviceability for RCF archetype under Scenario 2 earthquake, numbered arrows show the repair time for various floors

The majority of loss of functionality is due to structural components and non-structural components affecting occupancy. About 77 % and 92 % of total loss and downtime for RCF is due to damage to components related to occupancy. Figure 4b shows the functionality curve based on occupancy loss (FOL) for RCF under S2. Based on the proposed approach, it takes about 362 days (occupancy downtime) to repair occupancy-related components and re-occupy the building after an S2 earthquake assuming a floor-by-floor repair scheme. This key output is significantly important for post-earthquake decision-making and community resilience assessment and can be used as the critical parameter for functional recovery design of building facilities. For RCF archetype, the S2 earthquake has caused a loss of functionality on all floors. It is assumed that if a lower floor is unsafe for re-occupancy, the upper floors will remain unoccupied as well. The loss of occupancy is primarily due to minor damage to a number of beams and to a lesser extent, moderate damage to internal partition walls. For most cases, the occupancy downtime for the 2nd floor is the largest among all floors which is mainly due to damage to structural components. For the 4th floor, the damage to non-structural components vulnerable to ACC increases significantly which leads to significant loss of serviceability at this floor but not a significant loss in occupancy, as depicted in Figures 4b and 4c.

5.2 Multi-dimensional resilience indices

Table 2 summarizes the resilience indices based on three dimensions. The total loss and downtime are approximately equal to the summation occupancy and serviceability loss and downtime, respectively. As listed, the downtime for occupancy and serviceability, quantified using the proposed approach, can be a design parameter in a functional recovery design approach. As listed, RCF achieves a slightly larger resilience indices compared to RCF-C for earthquake S1 and S2. However, for earthquake S3 where RCF-C collapses, the post-earthquake resilience of the corroded structure is technically zero which indicates the impact of corrosion on RC building seismic performance and recovery in major earthquakes.

Table 1. Resilience index based on functionality curve for asset loss (FAL), occupancy loss (FOL), and serviceability loss (FSL) for various archetypes for Scenario 1, 2, and 3 earthquakes

Archetype	**R per FAL** [%]			**R per FOL** [%]			**R per FSL** [%]		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**	**S1**	**S2**	**S3**
RCF	99.5	94	67.2	100	79.9	59.9	100	99.2	83.9
RCF-C	99.5	93.3	-	100	76.5	-	100	99.6	-

6 Conclusions

A new framework is introduced for multi-dimensional functionality assessment and resilience quantification of building facilities under seismic hazard. Three key dimensions of building functionality loss, asset, occupancy, and serviceability losses, are considered and a component-based method is presented to develop functionality curves and surfaces based on each dimension. The framework is implemented on a series of RC building archetypes.

The proposed framework is consistent with FEMA P-58 loss analysis approach and uses FEMA P-58 component-based seismic fragility specifications to: (1) identify the occurrence occupancy or serviceability loss in any floor and (2) quantify the monetary loss and downtime. Most non-structural components of the building which contribute to serviceability are vulnerable to floor acceleration. Therefore, floors with large floor acceleration are likely to have serviceability loss. For instance, at the 4th floor of RCF archetype, large floor acceleration led to significant loss of serviceability compared to other floors while the occupancy loss and downtime of the 4th was similar to that of the 1st to 3rd floors. The downtime for occupancy and serviceability are particularly important for risk-informed functional recovery design of building facilities and this framework identifies the tradeoffs and difference in occupancy loss and serviceability loss in various floors. The greater part of total downtime is to restore occupancy and the smaller part for restoring serviceability of the building. For instance, based on the proposed approach, it takes about 362 days to repair occupancy-related components and re-occupy the RCF building after a significant earthquake (scenario 2) while it takes only 33 days to restore the serviceability under the same earthquake.

The collapse capacity and collapse interstory drift of the corroded RCF is noticeably smaller than that of original RCF model. This resulted in significant vulnerability of corroded RCF archetype in earthquake S3 with the highest intensity among studied earthquakes (an M8 earthquake with an epicentral distance of 5 km). The downtime due to both occupancy and serviceability components increases significantly under S3 as well. This indicates that a number of non-structural components have reached the severe damage state under S3. The corroded RCF collapsed under earthquake S3 which highlights the undesirable impact of corrosion in high intensity earthquakes and on building recovery.

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