Seismic Resilience of RC Structures

Matthew Joyner¹ and Mehrdad Sasani²

ABSTRACT

Buildings subjected to extreme seismic events can sustain significant damage due to excessive transient drift. Current codes, the main objective of which is to preserve life safety and prevent collapse, account for this transient drift by implementing provisions which enhance element and system ductility, thus allowing for large transient drift while preventing collapse of the building. However, another source of building damage after an earthquake which does not pose as significant a threat to life safety and is therefore not designed for in current codes is permanent drift. When one or more stories in a building experiences excessive permanent drift, it can be unfeasible to repair the building. In such cases the building must be demolished and re-constructed. This paper will explore the impact of both transient and permanent drifts on resilience over the life of a building, expressed in terms of the expected repair cost and loss of function for a 7-story reinforced concrete moment frame structure designed in San Francisco based on the current codes and standards. Transient and permanent drift demands will be evaluated using nonlinear time history analysis under a suite of ground motions. The results will then be used along with existing hazard and capacity models to evaluate building performance and estimate the life span repair costs and loss of function associated with earthquake damage. It is recommended that limiting permanent drift should be included in seismic design provisions, as its effect on building resilience can be significant.

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Buildings subjected to extreme seismic events can sustain significant damage due to excessive transient drift. Current codes, the main objective of which is to preserve life safety and prevent collapse, account for this transient drift by implementing provisions which enhance element and system ductility, thus allowing for large transient drift while preventing collapse of the building. However, another source of building damage after an earthquake which does not pose as significant a threat to life safety and is therefore not designed for in current codes is permanent drift. When one or more stories in a building experiences excessive permanent drift, it can be unfeasible to repair the building. In such cases the building must be demolished and reconstructed. This paper will explore the impact of both transient and permanent drifts on resilience over the life of a building, expressed in terms of the expected repair cost and loss of function for a 7-story reinforced concrete moment frame structure designed in San Francisco based on the current codes and standards. Transient and permanent drift demands will be evaluated using nonlinear time history analysis under a suite of ground motions. The results will then be used along with existing hazard and capacity models to evaluate building performance and estimate the life span repair costs and loss of function associated with earthquake damage. It is recommended that limiting permanent drift should be included in seismic design provisions, as its effect on building resilience can be significant.

Introduction

In this paper, cost and loss of function due to earthquake damage for a reinforced concrete building designed based on current codes and standards is quantified in order to evaluate resilience. A 7-story RC moment frame structure is designed with six 7.9 m (26 ft) bays in one direction and two 9.1 m (30 ft) bays in the other direction. The height of the first story and stories above are 3.9 m (12'-8") and 3.5 m (11'-6"), respectively. The floor system is comprised of 102 mm (4 in) slab with joists. Member dimensions and steel reinforcement are designed per ASCE 7-10 [1] and ACI 318-14 [2] based on analysis of an elastic structure using the finite element software OpenSees [3]. The building is designed as a special moment frame (SMF) structure. All elements are designed with 34 MPa (5 ksi) concrete and 413 MPa (60 ksi) steel.

Hazard

Hazard data from the 2008 national seismic hazard maps, which are used as the basis for the design ground motions in ASCE 7-10 [1] and ACI 318-14 [2] based on analysis of an elastic structure using the finite element software OpenSees [3]. The building is designed as a special moment frame (SMF) structure. All elements are designed with 34 MPa (5 ksi) concrete and 413 MPa (60 ksi) steel.
Demand

Structural demands imposed by earthquakes can be estimated by creating a nonlinear model of the structure and subjecting it to earthquake ground motion records. Aleatoric demand uncertainty is accounted for by selecting a suite of ground motion time histories from PEER’s NGA West 2 database \[5\]. For this study, ground motions were selected and scaled such that a return period range of 50-10,000 years was covered in terms of \(S_a\). Furthermore, ground motions were clustered around (within +/- 15%) \(S_a\) values corresponding to return periods of 73, 475, and 2500 years in order to increase accuracy at those return periods.

A 3-dimensional nonlinear model of the structure utilizing fiber section elements with core concrete, cover concrete, and steel fibers is used to model the structure. The maximum transient interstory drift index (\(\hat{I} \bar{D} I_{max,n}\)) is the chosen engineering demand parameter (EDP) for evaluating damage to drift-sensitive structural and nonstructural elements. The maximum permanent interstory drift index (\(I_D I_p\)) among all stories is the selected EDP for repairability assessment of a building after an earthquake. The median of the IDI resulting from nonlinear time history analyses can be modeled by

\[
I_D I = \alpha (S_a)^\gamma
\]

where \(I_D I\) is either \(I_D I_{max,n}\) (for the maximum transient response of story \(n\)) or \(I_D I_p\) (for the largest permanent value among all stories), \(S_a\) is the spectral acceleration for 5% damping at the fundamental period of the structure. \(\alpha\) and \(\gamma\) are model parameters that are calculated in the vicinity (taken here as one order of magnitude in terms of return period) of \(S_a\), where the contribution to the total probability integral is greatest \[6,7\] along with the associated logarithmic standard deviation \(\beta_{IDI|S_a}\) for a heteroscedastic error term, from regression analysis of \(IDI\) as a function of \(S_a\).

Capacity

Element fragility data based on prior research of drift damage to structural and nonstructural elements is provided in FEMA document P-58 volume 3, Performance Assessment Calculation Tool (PACT) \[8\]. Median capacity, \(\hat{I} D I_{DS}\), and logarithmic standard deviation, \(\beta_{DS}\), for structural and nonstructural damage states are obtained from the PACT fragility database \[8\]. Repairable structural damage is based on sequential damage states for SMF structures.

In addition to damage from transient drift, this paper also considers unrepairability based on the permanent interstory drift index, \(I_D I_p\). Thus, an additional damage state with a median \(I_D I_p\) of 1%, referred to here as damage state \(RD_L\) (repairable damage limit), is defined and is associated with total demolition and replacement of the building.

Fragility

Considering lognormal distributions for interstory drift index capacity and demand, the mean fragility for a given damage state, \(DS\), can be calculated based on \[9\] by

\[
F_{DS|S_a} = P[IDI > IDI_{DS}|S_a] = \Phi \left( \frac{\ln \left( \frac{aS_a^\gamma}{\hat{I}D I_{DS}} \right)}{\sqrt{\beta_{ID I|S_a}^2 + \beta_{DS}^2}} \right)
\]

(2)
where $\Phi[\cdot]$ is the standard normal cumulative distribution function (CDF), $IDI_{DS_l}$ is the capacity for damage state $DS_l$ in terms of $IDI$, and $\bar{IDI}_{DS_l}$ and $\beta_{DS_l}$ are the median and logarithmic standard deviation for that damage state’s capacity.

**Annual Probability of Failure**

Resilience evaluation necessitates calculation of the annual probability of damage for each damage state. This can be estimated by [6]

$$P_{f,DS_l} = P[IDI > IDI_{DS_l}] = \int_0^\infty F_{DS_l|Sa} |dH|$$  \hspace{1cm} (3)

The above integral is evaluated numerically over the range of $Sa$ for which hazard, $H$, is available in order to arrive at the annual probability of failure for a given damage state at a given story.

**Earthquake Damage Cost and Loss of Function**

Given the probability of failure for each damage state and the cost and repair time associated with failure obtained from PACT [8], expected repair costs over the life of the building can be computed.

Figure 1a shows the contributions of different types of seismic damage to the repair cost. As can be seen, more than half of the cost is associated with damage to partitions, curtain walls, and structural damage state 1 (SDS1). Given this high contribution to cost of damage, it may be time to explicitly consider a lower level of performance (i.e. other than life-safety and collapse prevention) in building design.

It is important to point out that there are no repair costs or loss of function associated with SDS3. Given that permanent deformations are caused by excessive inelastic deformations, it follows that the conditional probability of repairability can be expected to be smaller for more severe damage states. This conditional probability is evaluated based on the intersection probability of exceeding SDS3 and remaining repairable. In this case, the estimate of that intersection probability is zero, resulting in zero cost for SDS3.

Figure 1b shows the contributions of different types of seismic damage to loss of function. As can be seen, nearly half of the loss of function is associated with unrepairable damage due to excessive permanent deformation. Therefore, in addition to the effort made by researchers and engineers to enhance deformation capacity of structures for improving life-safety and collapse prevention performance, there is a need for reducing permanent deformation of structures to better control and limit loss of function and in turn increase building resilience.

![Figure 1. Contributions to (a) cost and (b) loss of function for structural and nonstructural repairs and demolition](image)
Conclusions

Both the maximum interstory drift index of each story ($IDI_{max,n}$) and the maximum permanent $IDI$ among all stories ($IDI_p$) are considered for resilience evaluation. In order to evaluate the probability of occurrence of each transient sequential damage state over the life of the building, and in turn the repair cost and loss of function associated with those damage states, the conditional probability associated with each damage state, conditioned on repairability of the building, is considered to exclude the conditions in which the value of $IDI_p$ render the building unrepairable. The results show that

1. About a quarter of the expected repair costs and half of the loss of function are due to unrepairable damage caused by excessive permanent deformation, which suggests a need for explicit consideration of limiting permanent deformation of structures after seismic events to better control and limit this cost and loss of function and in turn increase building resilience.

2. The estimate of repair costs due to severe transient drift damage can be significantly diminished when the probability of transient drift damage state occurrence is conditioned on repairability of the building.

3. More than half of the building repair cost is associated with partition and curtain wall damage as well as structural damage state 1 (SDS1), which suggests a need for explicitly accounting for such performance levels, in addition to life-safety and collapse prevention, in building design.

Thus, the governing factors for repair cost and loss of function are minor-to-moderate repairable damage from transient drift and unrepairable damage from permanent drift.

References

2. ACI (2014). *ACI 318-14: Building code requirements for structural concrete and commentary*. American Concrete Institute, Farmington Hills, MI.