QUANTIFYING IMPROVEMENTS IN SEISMIC PERFORMANCE POSSIBLE THROUGH RETROFIT OF RC FRAMES

C. Harrington1 and A. Liel2

ABSTRACT

This study quantifies the benefits of retrofitting RC frames through the identification and definition of dimensionless structural indicators that are strong predictors of retrofit effectiveness in terms of reducing loss of life and repair costs in future earthquakes. To identify these indicators, first, a set of archetypical models, representative of U.S. buildings designed to pre-1976 standards, is defined. These buildings exhibit common deficiencies in older concrete buildings, including weak-stories, shear-critical columns, weak-column-strong-beam arrangements, and overall weakness. Buildings are then retrofitted with concrete jacketing, steel jacketing, or fiber-reinforced polymer (FRP) wraps according to the U.S. standard for seismic evaluation and retrofit, ASCE 41. Each of the deficient and retrofitted buildings are assessed through the performance-based earthquake engineering (PBEE) framework. Nonlinear models of design archetype are created in OpenSEES, and time-history analysis is performed. Dollar losses associated with repairing earthquake-induced damage and earthquake-induced casualties are quantified using the FEMA P-58 methodology. These results are used to predict U.S. Resiliency Council (USRC) Safety and Damage ratings for each building. Through comparison of the ratings for the retrofitted and un-retrofitted building models, structural indicators that quantify retrofit effectiveness in protecting life safety and preventing future losses are defined. Results show that retrofitted buildings earn higher Safety and Damage ratings than the unretrofitted buildings, although the ratings for the retrofit buildings are highly variable. In addition, the study shows that the retrofit strategy’s ability to increase ductility capacity and reduce the drift demand to capacity ratio at the design level (through increased strength or stiffness) are the most highly correlated with improved building performance.

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This study quantifies the benefits of retrofitting RC frames through the identification and definition of dimensionless structural indicators that are strong predictors of retrofit effectiveness in terms of reducing loss of life and repair costs in future earthquakes. To identify these indicators, first, a set of archetypical models, representative of U.S. buildings designed to pre-1976 standards, is defined. These buildings exhibit common deficiencies in older concrete buildings, including weak-stories, shear-critical columns, weak-column-strong-beam arrangements, and overall weakness. Buildings are then retrofitted with concrete jacketing, steel jacketing, or fiber-reinforced polymer (FRP) wraps according to the U.S. standard for seismic evaluation and retrofit, ASCE 41. Each of the deficient and retrofitted buildings are assessed through the performance-based earthquake engineering (PBEE) framework. Nonlinear models of design archetype are created in OpenSEES, and time-history analysis is performed. Dollar losses associated with repairing earthquake-induced damage and earthquake-induced casualties are quantified using the FEMA P-58 methodology. These results are used to predict U.S. Resiliency Council (USRC) Safety and Damage ratings for each building. Through comparison of the ratings for the retrofitted and un-retrofitted building models, structural indicators that quantify retrofit effectiveness in protecting life safety and preventing future losses are defined. Results show that retrofitted buildings earn higher Safety and Damage ratings than the unretrofitted buildings, although the ratings for the retrofit buildings are highly variable. In addition, the study shows that the retrofit strategy’s ability to increase ductility capacity and reduce the drift demand to capacity ratio at the design level (through increased strength or stiffness) are the most highly correlated with improved building performance.

Introduction

Performance-based seismic evaluation methods provide robust, building specific, methodologies by which to probabilistically estimate a building’s risk. The FEMA P-58 methodology is one example of a performance-based evaluation procedure [1]. It evaluates building performance and

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associated risks in terms of decision variables that include earthquake-induced repair costs, repair times, and fatalities. The United States Resiliency Council (USRC) Building Rating System [2] combines FEMA P-58 decision variables into a rating that is easily communicated to the general public.

Performance-based evaluation methods are particularly important for seismic retrofit design because they quantify benefits in performance resulting from different retrofit design decisions, and retrofit actions can be costly [3]. However, it is unclear how benefits and shortcomings of different retrofit design actions compare in terms of global performance, because systematic performance assessments for retrofit buildings are rare. In part, this is due to a limited number of observations on the performance of retrofitted buildings in strong earthquakes, and a lack of experimental research on system level performance (most retrofit studies have focused on element effects). Recent work has benchmarked the performance of new code-designed buildings [4], but uncertainties about the performance of retrofit buildings persist.

This study systematically examines benefits of retrofitting by identifying relationships between common retrofit design parameters (e.g. strength and ductility) and measures of life safety and economic risk. This is accomplished by first designing a set of nonductile reinforced concrete (RC) space-frame buildings for high seismic regions of the U.S according to the 1967 Uniform Building Code (UBC) [5]. Next, buildings are retrofit to the ASCE 41-13 [6] standard – the most commonly used document for retrofit design in the U.S. - using steel jacketing, concrete jacketing, and fiber-reinforced polymer (FRP) wraps. Original (buildings that have not been retrofit) and retrofitted buildings are then evaluated using the FEMA P-58 [1] methodology and USRC Building Rating System [2]. We focus on nonductile RC frames because of the national and international interest in retrofitting these structures [7]. Relationships are developed between retrofit design parameters and the USRC building ratings to empower stakeholders with tools to aid in the selection of the effective retrofit design strategies.

**Building Designs**

**Existing Buildings**

To represent existing structures that may be candidates for retrofitting, a set of RC frame buildings is designed following the working stress design method outlined in the 1967 UBC [5]. These are office buildings, assumed to be located near downtown Los Angeles. Heights of 3-, 6-, and 9-stories are chosen to represent low, mid, and high-rise RC frame buildings, respectively. All buildings are square in plan with 5 bays in each frame-line. Each bay is 25 ft. in width; the first story of each building is 15 ft. in height; all subsequent stories have 13-ft. story heights. The number of bays is selected based on the median number of bays for RC frames in a dataset of Los Angeles pre-1980 buildings [7]. As a result of following the older code, the building set analyzed herein have deficiencies such as shear critical columns, weak-column to strong-beam arrangements, and overall weakness.

Architectural layouts and associated contents for each building in this study are representative of a commercial office building, with an assumed replacement cost $230/ft². Inventories of structural and nonstructural components are based on occupancy, lateral load resisting system and building design era according to component libraries defined in the SP3 software (described in more detail below; [8]). Nonstructural components are presumed not to have seismic detailing, as was typical in the 1960s.
Retrofit Buildings

The existing buildings are retrofit to the 2013 version of ASCE 41 [6] standards using three strategies: steel jacketing, concrete jacketing, and FRP wraps. These are local retrofit strategies, applied only to columns, which are generally the most vulnerable component of nonductile RC frames. Retrofits are conducted by first identifying columns that are deficient (i.e., not complying with acceptance criteria) based on the nonlinear static evaluation procedure in ASCE 41. Then, each deficient member is retrofitted until the outcome of the ASCE 41 evaluation indicates that the performance criteria have been met. In order to generate a building set that contains a range of possible retrofit design characteristics, each 1967 building is retrofit to multiple performance levels listed in Table 1. In total, 24 retrofits are designed and studied for the three original buildings, considering the different performance levels and retrofit strategies.

Steel Jacketing

The addition of circular steel jackets is one strategy for retrofitting the existing square columns, as shown in Fig. 1a. Circular steel jackets are chosen because they provide continuous confining action and are installed by welding two halves together; rectangular steel jackets are significantly less effective in improving flexural ductility, and are more difficult to install because each side of the jacket must be epoxied to column, then all sides welded together [9]. The jacket design followed the procedures described by Priestley et al. [9]. Steel jackets are assumed to be made of A36 steel, and the void between the jacket and existing member is filled with normal strength ($f'_c = 4$ ksi) concrete.

Concrete Jacketing

Square RC jackets are designed for deficient members following the design procedures proposed by Priestley et al. [9], and the requirements of ACI 318-14 [10]. A typical cross-section of the jacketed columns is shown Fig. 1b. RC jackets are assumed to have concrete with $f'_c = 4$ ksi, and transverse reinforcement consisting of hooped bars. During design, the contribution of the concrete in the jacket to shear strength is neglected as the bond between the jacket and the original member may be insufficient.

Fiber Reinforced Polymer Wraps

In the third strategy, carbon FRP sheets are externally bonded to existing RC members by an adhesive, as shown in Fig. 1c. Externally-bonded CFRP wraps are designed in accordance with ACI 440.2R-08 [11] and the wrap is assumed to extend over the full height of the column. FRP wraps commonly consist of plies with unidirectional fibers. Here, plies are applied with the fibers oriented in the transverse direction, and the shear strength of a member is increased and, in most cases, the addition of FRP wraps switches the member’s governing failure mode from shear.
to flexure.

Figure 1. Illustration of column retrofit strategies showing: (a) circular steel jackets, (b) rectangular concrete jackets, and (c) FRP wraps.

Evaluation of Building Performance

The seismic performance of the retrofitted buildings is evaluated using the FEMA P-58 loss assessment framework [1], in combination with the USRC rating system [2]. The loss assessment is carried out in four stages: hazard analysis, structural analysis, damage analysis, and loss analysis. In this study, structural analyses are performed on nonlinear models in OpenSEES, while damage and loss assessments, and USRC ratings are performed using the Seismic Performance Prediction Program (SP3) [8], an online tool largely based on FEMA P-58 [1].

Hazard Analysis

All buildings are located at a southern California site (33.996°N, -118.162°W). The site-specific hazard curve is obtained from the USGS hazard maps, and assuming Site Class D soil [12]. This site is not subject to near fault directivity effects. This study quantifies the ground motion intensity measure (IM) as the spectral acceleration measured at the effective fundamental vibration period of the building, $S_a(T_i)$. The effective fundamental period for each building is computed from an idealized force-displacement curve as per ASCE 41 Section 7.4.3.2.5 [6].

Structural Analysis

The structural analysis stage relates the IM to engineering demand parameters (EDPs). EDPs include peak floor accelerations, story drifts, residual story drifts, and other measures that are correlated with seismic losses. In order to relate the IM to EDPs, two-dimensional nonlinear, distributed plasticity (fiber) models of each of the existing and retrofit buildings are created and analyzed in the OpenSEES software. Nonlinear component models are selected that are capable of capturing significant response characteristics and failure modes for the original and retrofit structures [13]. Table 2 provides a list of the element models used for primary structural components comprising the original and retrofit buildings.

EDPs are estimated through dynamic analysis at five hazard intensities or stripes. At each hazard level, the Conditional Mean Spectra (CMS) method [14] is used to select 22 records (11 pairs) based on the site hazard. Each building’s collapse capacity is estimated through incremental dynamic analysis [15] using the FEMA P-695 far-field ground motion set [4].
Damage Analysis

Damage to building components is probabilistically evaluated using empirically-derived fragility functions through the SP3 software. These fragility functions quantify the probability that individual components experience discrete damage states as a function of the EDPs from dynamic analysis. Damage states correspond with repair efforts to restore a component to its original state. In addition to component damage, damage due to structural collapse and residual drift are computed based on probabilistic structural capacity models.

Table 2. Element models and associated responses used for primary structural components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Element Model(s)</th>
<th>Responses Captured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing columns</td>
<td>layered fiber element in series with shear and axial springs</td>
<td>elastic behavior; steel yielding; steel buckling; concrete crushing; concrete tensile failure; column shear failure and subsequent column axial failure</td>
</tr>
<tr>
<td>FRP-wrapped columns</td>
<td>layered fiber element</td>
<td>elastic behavior; steel yielding; steel buckling; concrete crushing; concrete tensile failure</td>
</tr>
<tr>
<td>Steel-jacketed columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete-jacketed columns</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beams</td>
<td>elastic panel</td>
<td>elastic behavior</td>
</tr>
</tbody>
</table>

Most of the fragility functions are defined directly in the library provided in SP3, based on FEMA P-58. However, FEMA P-58 and SP3 do not contain fragility functions for members retrofit with FRP, steel, or concrete jackets. Although we directly simulate the dynamic response of each retrofit strategy, to assess damage and repair costs we assign any component that has been seismically retrofit using FRP wraps, steel jackets, or concrete jackets the damage states and damage fragility curves for an “Ordinary Moment Frame with weak joints and beam flexural response”. In these systems, columns are flexurally-governed and damage tends to concentrate in beams and joints. Therefore, damage states for OMFs are reasonable substitutes for RC subsystems where the columns have been jacketed because the damage patterns are similar. However, the cost associated with repair of OMF systems and the retrofit systems may differ, and this difference is not considered herein.

Loss Assessment and Determination of USRC Ratings

During loss analysis, damage measures are related to Decision Variables (DV), such as repair costs and casualties, through probabilistic models. Repair costs are calculated based upon damage to structural components, nonstructural components, and collapse, and quantify the economic cost needed to restore the building to its undamaged state. Fatality estimation accounts for the building population as a function of time of day for office buildings, and consider the fatalities from global collapse, partial collapse, and falling hazards. Here, we focus on USRC ratings, as these ratings combine information from the underlying collapse and loss assessments.

The USRC Building Rating System quantifies the expected consequences of an earthquake through building ratings that range from 1 to 5 stars. Ratings are based upon the performance of a building’s structural system; its mechanical, electrical, and plumbing systems; and architectural components – when subjected to a shaking intensity with probability of
The occurrence of 10% in 50 years [2]. USRC ratings are assigned in three dimensions: safety, damage, and recovery. The safety dimension (see Table 3) considers potential for loss of life and injury caused by falling hazards and building collapse. The damage dimension (Table 3) expresses the repair cost needed to restore a building to its undamaged state following an event. Damage is presented as a fraction of the total building replacement, and depends on damage caused to structural, architectural, mechanical, electrical and plumbing components. In this study, we exclude the recovery dimension because it is sensitive to owners’ choices and actions to expedite repair that are outside the scope of this analysis.

Table 3. USRC rating threshold definitions for the safety and damage dimensions.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Safety</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Injuries and blocking of exit paths unlikely</td>
<td>Minimal damage: &lt; 5% of building replacement cost</td>
</tr>
<tr>
<td></td>
<td>Serious injuries unlikely</td>
<td>Moderate damage: &lt; 10% of building replacement cost</td>
</tr>
<tr>
<td></td>
<td>Loss of life unlikely</td>
<td>Significant damage: &lt; 20% of building replacement cost</td>
</tr>
<tr>
<td></td>
<td>Loss of life possible in isolated locations</td>
<td>Substantial damage: &lt; 40% of building replacement cost</td>
</tr>
<tr>
<td></td>
<td>Loss of life likely in the building</td>
<td>Severe damage: 40%+ of building replacement cost</td>
</tr>
</tbody>
</table>

Results: Relationship between Retrofit Design Parameters and Building Ratings

Classification and regression tree (CART) analysis is a useful tool for analyzing large datasets with complex, nonlinear, interactions [16]. Here, we examine the relation between retrofit design parameters (as input variables or $x$) and USRC safety and damage ratings. We employ classification trees since the response variable of interest, the USRC ratings, $y$, is categorical. CART analysis splits the data into subsets, identifying the “splitting variables”, $x$, and “splitting points” that most reduce the variance in the prediction of $y$. The final tree can be used a predictive sense, with the values of the (input) retrofit building parameters used to identify the relevant branch of the tree for a particular case, with the final leaf taken as the predictor of the USRC building rating for that branch. Fig. 2 shows the USRC damage and safety ratings for the 27 original and retrofitted buildings analyzed in this study. USRC damage ratings of 1 – 4 stars are present in this building set; no building was assigned a 5 star damage building rating.

Retrofit Design Parameters

The retrofit design parameters input to the CART (i.e. $x$) considered are quantities that are easily calculated during a retrofit design: drift demand to capacity ratio ($\delta_{DCR}$), ductility capacity ($\mu$), strength normalized by the building weight ($V_y/W$), effective stiffness ($K_e$), effective period ($T_e$), and strength demand to capacity ratio ($\mu_{strength}$). Here, $\mu$ is computed from pushover analysis of a nonlinear model of the retrofit building [4], and $\mu_{strength}$ is defined as in ASCE 41 [6]. The term $\delta_{DCR}$ compares the structure’s expected displacement demand at the hazard level of interest (here, 10% in 50 years) to its effective yield displacement, thereby providing a displacement-based measure that gauges the extent of nonlinear behavior to be expected during that level of shaking. The effective yield displacement of the structure is measured from an idealized bilinear force-displacement curve [6]. The expected displacement demand at the roof of the building, as calculated by Eq. (1), is taken directly from ASCE 41 [6]:

$$\delta_{DCR} = \frac{\text{Expected Displacement at Roof}}{\text{Effective Yield Displacement}}$$
\[
\delta_D = C_0 C_1 C_2 S \frac{\tau_e^2}{4\pi^2} g
\]

(1)

C₀, C₁, and C₂ are factors that modify the spectral displacement to account for the difference between single and multi-degree of freedom systems, effects of inelasticity and pinched hysteresis [6]. The ranges of these retrofit design parameters for the buildings examined in this study are provided in Fig. 2.

![Graphs](a) Relationship between selected retrofit design parameters and USRC safety and damage building ratings, showing: (a) \(\delta_{DCR}\), (b) \(\mu\), and (c) \(V_y/W\). The original (unretrofitted) buildings are enclosed by the blue boxes.

**Important Parameters for USRC Safety Building Rating**

The classification tree for predicting the USRC safety rating as a function of the retrofit parameters is shown in Fig. 3a and contains three terminal nodes, or leaves, marked A – C. The starting (or root) node asks a question about the magnitude of the building’s \(\delta_{DCR}\) value, therefore immediately sorting buildings by the expected level of nonlinear response at the design level. More detailed discussions of the three leaves are provided below.

Leaf A: Buildings with the highest USRC safety rating are identified as those with \(\delta_{DCR} \leq 1.5\). These buildings are expected to remain elastic or experience limited nonlinear behavior at the design level because the expected displacement demand barely exceeds the yield displacement. These buildings pose a low risk to occupant safety because the building is far from the collapse state. Hence, the only threats to life safety are due to falling hazards from acceleration sensitive components; these too are minimal due to small acceleration demands.
Leaf B: Buildings with the worst safety rating (one star) are found on leaf B. These buildings are expected to have significant nonlinear behavior ($\delta_{DCR} \geq 1.5$) and have low ductility capacity ($\mu < 3$). These buildings are high collapse risks because they lack the needed deformation capacity to withstand the expected nonlinear demands. Furthermore, falling hazards of nonstructural components may pose a high threat to occupant safety.

Leaf C: The tree assigns a two star USRC safety rating to buildings with $\delta_{DCR} \geq 1.5$ and $\mu \geq 3$. These buildings are expected to experience extensive nonlinear behavior at the design level or higher, but have a significant ductility capacity. However, the impact of falling hazards on occupant safety is significant due to the large drift demands, and the building may be in a near collapse state.

**Important Parameters for USRC Damage Building Rating**

Fig. 3b presents the classification tree for the USRC damage rating. The resulting classification tree sorts buildings by $\delta_{DCR}$ and $\mu$. As with the tree for the USRC safety rating, the root of the USRC damage rating classification tree is based upon $\delta_{DCR}$, effectively sorting buildings by the expected level of nonlinear behavior. The classification tree contains four leaves, marked A – D.

Leaf A identifies those buildings that have the worst USRC damage building rating, one star. Buildings contained in this group have $\delta_{DCR} \geq 3.5$, and are therefore expected to experience extensive nonlinear behavior. This behavior leads to large drifts, which damage both structural components and drift-sensitive nonstructural components such as partition walls. Furthermore, these buildings may be near collapse.

Buildings classified in leaf B are those with $\delta_{DCR} < 1.5$ and earn a three-star rating (the highest rating classified by the tree). These buildings are expected to behave (nearly) elastically. Therefore, significant damage in structural and drift-sensitive nonstructural components is unlikely. Furthermore, these buildings are likely far from collapse. However, damage to acceleration-sensitive nonstructural component restricts these buildings from attaining a higher rating.

Leaf C contains buildings with $1.5 \leq \delta_{DCR} < 3.5$ and $\mu < 4.3$. This type of building is assigned a USRC damage building rating of one star. Here, the building is expected to behave nonlinearly, and have relatively low ductility capacity. Therefore, these building may pose high collapse risks and have drift demands that severely damage structural and drift-sensitive nonstructural components.

Buildings in leaf D have $1.5 \leq \delta_{DCR} < 3.5$ and $\mu \geq 4.3$. These buildings are expected to behave nonlinearly. However, the extent of nonlinearity is less than 3.5 times the buildings yield drift, and the buildings have significant ductility capacity (distinguishing them from Leaf C). These buildings are likely not near collapse, but will sustain damage in structural components due to large drift demands. The mitigated collapse risk in these buildings, but combined with the damaging drift demands results in a USRC damage building rating of two stars.
Conclusions

This study relates retrofit design parameters for RC frame buildings to USRC building resiliency ratings for the safety and damage dimensions. Relationships were developed based upon a set of 27 buildings that included three 1967-era RC building designs, representative of existing nonductile concrete buildings that are potential priorities for retrofit, and 24 buildings retrofit to ASCE 41 standards using steel jackets, concrete jackets, and FRP wraps. The study also shows that the best retrofits increase the safety rating by 4 stars and the damage rating by 3 stars. However, some retrofits do not improve the ratings at all.

Classification trees for the USRC building ratings for both safety and damage dimensions are based upon the displacement demand to effective yield capacity, $\delta_{DCR}$, and the ductility capacity, $\mu$. These results imply that retrofit changes to strength and stiffness, which reduce $\delta_{DCR}$, and ductility capacity are highly correlated to improved performance. From a design standpoint, the regression trees created in this study are useful because they provide the designer with guidance on which combinations of design parameters may correspond with a selected USRC rating.

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