INFLUENCE OF REDUCED SEISMIC HAZARD LEVEL IN REHABILITATION CONSIDERING REMAINING LIFE SPAN

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ABSTRACT

In seismic evaluation and retrofit methodology proposed by FEMA 356 and seismic rehabilitation of existing buildings No. 360, the selected seismic hazard level is 475-year return period earthquake with probability of occurrence 10% in 50 years expected remaining lifespan for an existing building, while expected remaining existing building life span is much less than 50 years. Hence, reducing seismic hazard level is used to enable cost-effective seismic evaluation and retrofit of existing building. In the current study, based on the equivalence of probability of exceedance of a specific hazard level between existing and new building, seismic hazard reduction factors are calculated for different locations in Iran. Then, the existing building is retrofitted for the reduced seismic hazard level. A validation procedure is proposed to investigate the objective performance of nonlinear SDOF system.

1. INTRODUCTION

Retrofitting the existing buildings is sometimes very expensive. It may cost as much as building a new one. To avoid inefficient allocation of resources, benefit cost considerations are needed in seismic codes for existing buildings.

Proportional cost limits for retrofitting can be efficiently determined by the risk-based rules introduced in Swiss Pre-standard SIA 2018 (SSEA, 2004). The framework is based on the probability seismic hazard assessment elaborated by the Swiss Seismological Service and the main parameters of this assessment are the compliance factor, the occupancy, and the remaining useful life of the existing structure (Jamali et al., 2012) and (Wenk, 2014). Compliance factor as a ratio of seismic demand over capacity has a main influence. Pre-standard SIA 2018 presents a minimum value for compliance factor that must be preserved in order to maintain life safety standards (Wenk and Beyer, 2014). Based on equal probabilities of exceedance within different remaining building lifespans, seismic hazard reduction factors have been recommended to enable cost-effective seismic evaluation and retrofit of existing building (Park, 2019).

In the following section based on the equivalence of probability of exceedance between existing and new building in their remaining building lifespan (RBL) calculate the seismic hazard reduction factors for four different seismicity zones of Iran, one of the seismically active regions. For validation an analysis carried out to investigate the equivalence of performance between an existing building and a new building.
2. SEISMIC HAZARD REDUCTION FACTORS BASED ON REMAINING BUILDING LIFESPAN

In many codes, seismic hazards are described as the probability of exceedance in 50 years which is the expected lifespan of the buildings. However, existing buildings have remaining building lifespan shorter than 50 years. Therefore, the seismic hazard level for evaluation and retrofit of existing building can be reduced according to the RBL as given in the following equation:

\[ P_E = 1 - (1 - \lambda_{\text{exist}})^{L_{\text{exist}}} = 1 - (1 - \lambda_{\text{new}})^{L_{\text{new}}} \]  \hspace{1cm} (1)

In Equation (1) \( L_{\text{exist}} \) is the expected RBL for an existing building and \( L_{\text{new}} \) corresponds to a new one. Moreover, \( \lambda_{\text{exist}} \) is defined as the annual rate of exceedance of the seismic hazard level for the evaluation and retrofit of the existing building, and \( \lambda_{\text{new}} \) is the annual rate of exceedance related to designing a new building. Therefore, the annual rate of an existing building given the RBL can be computed in the following equation:

\[ \lambda_{\text{exist}} = 1 - (1 - \lambda_{\text{new}})^{L_{\text{exist}} / L_{\text{new}}} \]  \hspace{1cm} (2)

The seismic hazard reduction factors are listed up in Table 1 for 475 years return period for four seismicity zone of Iran and each zone contains four cities.

<table>
<thead>
<tr>
<th>Seismicity zones</th>
<th>( L_{\text{exist}} / L_{\text{new}} ):</th>
<th>( \lambda=0.0021049 )</th>
<th>( \lambda=0.0026305 )</th>
<th>( \lambda=0.0035058 )</th>
<th>( \lambda=0.005254 )</th>
<th>( \lambda=0.01048 )</th>
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<td>0.78 0.78 1.00 0.78 0.69 0.88 0.78 0.59 0.75 0.78 0.45 0.68 0.78 0.28 0.36</td>
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<tr>
<td>Boroujerd</td>
<td>0.47 0.47 1.00 0.47 0.42 0.90 0.47 0.37 0.78 0.47 0.29 0.63 0.47 0.20 0.42</td>
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<td>Ardabil</td>
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<td>Bandar abbas</td>
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<tr>
<td>Esfahan</td>
<td>0.25 0.25 1.00 0.25 0.22 0.88 0.25 0.19 0.74 0.25 0.15 0.59 0.25 0.10 0.40</td>
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<tr>
<td>Ahvaz</td>
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<tr>
<td>Ilam</td>
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<td>Yazd</td>
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</table>

For instance, the seismic hazard reduction factor is 0.4 at building lifespan ratio equal to 0.2 for 475 years return period in Esfahan, which means that an existing building with 10 year RBL can be retrofitted against 40% of design earthquake for a new building with 50 year RBL.

3. DESCRIPTION OF THE MODEL

The proposed seismic hazard reduction factor is assigned to an existing building retrofitted for unreduced and reduced design earthquakes. Structural behavior of existing building subjected to ground motion is idealized with inelastic SDOF
system with trilinear envelope curve proposed by (Park, 2019). The SDOF model has been retrofitted with two different strategies as follows enhancing ductility capacity and increasing the strength of the model. Both strategies plotted in Figure 1.

![Figure 1. Force-Displacement relationship for basis SDOF systems with and without retrofitting (T=0.3s)](image)

Retrofitting the existing building executed for 50, 30 and 10 years RBL. For instance, STR30 means the existing building with 30 years RBL is retrofitting with consideration of reduced seismic hazard level for 30 years RBL.

In this study, the objective performance level is LS2 which is approximately equal to life safety. Also, the behavior of structure is being studied in LS1 which is related to elastic limit and immediate occupancy and LS3 that is related to the collapse prevention. The mentioned performance levels are corresponding to ductility ratio $\mu_1$, $\mu_2$ and $\mu_3$ as illustrated in Figure 2.

![Figure 2. Objective Performance](image)

The characteristics of retrofitted SDOF system are calculated by Equation (3) as in ASCE 41-17.

$$\delta_t = C_1 \cdot C_2 \cdot \delta_0 \cdot \frac{T_t^2}{4\pi^2} g$$  \hspace{1cm} (3)

$S_a$ is response spectrum acceleration at the effective fundamental period and damping ratio of the building in the direction under consideration, $g$ is acceleration of gravity, $C_1$ is modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response, $C_2$ is modification factor to represent the effect of pinched hysteresis shape, cyclic stiffness degradation, and strength deterioration.
on the maximum displacement response. Since the model is single-degree-of-freedom, the modification factor to relate spectral displacement of an equivalent single-degree-of-freedom system to the roof displacement of the building multiple-degree-of-freedom system is not required.

The details of the components of retrofitted SDOF system against reduced seismic hazard level is in Table 2.

### Table 2. Components of the retrofitted SDOF systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Retrofitting strategies</th>
<th>Enhancing ductility</th>
<th>Strengthening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designation</td>
<td>DUC10</td>
<td>DUC30</td>
<td>DUC50</td>
</tr>
<tr>
<td>target remaining lifespan</td>
<td>10</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Increased ductility capacity</td>
<td>1.45</td>
<td>2.88</td>
<td>3.72</td>
</tr>
<tr>
<td>Added strength ratio (Fd/Fu)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Fu: initial strength of existing buildings before retrofit

The increased ductility demand is 3.72 for retrofitting SDOF system with 50 years RBL while it drops about 60% for increased ductility demand for retrofitting SDOF system with 10 year RBL. The same results are observed in strengthening strategy which added strength ratio decreased approximately 80% from building with 50 years RBL to 10 years RBL. The fragility curves with and without retrofitting extracted from (PARK, 2019) are plotted in Figure 3.

![Figure 3. Seismic Fragility Curve](image)

However, fragility curves are not enough to investigate the equivalence in seismic performance for two different RBLs. Hence, the validation of equivalence between existing and corresponding new building is investigated by comparing their limit state probabilities, of which definition and evaluation procedure are proposed in the next section.

### 4. LIMIT STATE PROBABILITY

The limit state probability consists of integral convolution of fragility curves to probability density function (PDF) of the maximum intensity measure that occur during a remaining building lifespan.
The PDF of maximum intensity measure can be derived by differentiating the probability of non-exceedance in corresponding RBL in Equation (4).

\[ P_{NE} = [1 - f(Sa)]^{L_{exist}} \]  

\( P_{NE} \) is the probability of non-exceedance of hazard level that converges to zero for the lowest IM and 1.0 when IM goes to infinity and \( f(.) \) is the inverse seismic hazard function, which gives us the annual rate of exceedance of the hazard level corresponding to a supposable spectral acceleration.

The PDF of maximum intensity measure for 50, 30 and 10 years remaining building lifespan in Esfahan is plotted in Figure 4.

Figure 4. PDFs of the maximum Sa within the remaining building lifespan for the Esfahan seismic hazard curve of Iran

As a result, the limit state probability given the building lifespan is computed as follows:

\[ P_{LS}(L_{exist}) = \int_0^\infty \left( \frac{dP_{NE}(x,L_{exist})}{dx} \right) \times P(D > C|IM = x) \, dx \]  

(5)

In Equation (5) \( P_{LS}(L_{exist}) \) is the limit state probability for a building lifespan \( L_{exist} \) and \( P \) is the fragility function of the selected limit state.

The PDFs of the limit state probability for three limit states are plotted in Figure 5.

As it is noticeable, the strengthening strategy is more suitable for LS1 and LS3 limit states since it does not relate to the plasticity behavior of the structure. In converse, enhancing ductility is more appropriate for LS2 because in the same intensities, the probability of exceedance is lower than strengthening strategy. Generally the probability of exceedance for Esfahan is much more in comparison with the same case in (PARK, 2019).

The results show that as much as the remaining building life span decrease, the probability of exceedance goes lower, but in some level, lower than 10 years is too short lifespan and it is not cost-effective.
5. CONCLUSIONS

Seismic hazard reduction factors can be an appropriate method in conjunction with cost-effective seismic evaluation and retrofit of existing building. The seismic hazard coefficient factors were proposed for four different seismicity zones of Iran, one of the seismically active regions. Then a case study in Esfahan with moderate seismicity level has been chosen to assess the influence of reducing the seismic hazard level on the increasing ductility demand and added strength ratio demand in retrofitting the existing building. The results show that the demand decreases about 50% according to 10 years remaining building lifespan.

The current study propose the probability of limit state to investigate the validation of mentioned method. The probability of limit state determined by multiplying probability density function of the maximum intensity measure within the remaining building lifespan to the fragility curve. Finally adopting reduced seismic hazard level according to the remaining building lifespan can be permitted with the consideration of appropriate lower bounds of the remaining building lifespans.

REFERENCES


